



Specificity of extreme El Niño atmospheric teleconnections in present and future climates

Margot Beniche

► To cite this version:

Margot Beniche. Specificity of extreme El Niño atmospheric teleconnections in present and future climates. Climatology. Université de Toulouse, 2024. English. <NNT : 2024TLSES332>. <tel-05071176>

HAL Id: tel-05071176

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Doctorat de l'Université de Toulouse

préparé à l'Université Toulouse III - Paul Sabatier

Spécificité des téléconnections atmosphériques des El Niño extrêmes dans les climats actuels et futurs

Thèse présentée et soutenue, le 26 novembre 2024 par

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École doctorale

SDU2E - Sciences de l'Univers, de l'Environnement et de l'Espace

Spécialité

Océan, Atmosphère, Climat

Unité de recherche

LEGOS - Laboratoire d'Etudes en Géophysique et Océanographie Spatiale

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ABSTRACT (EN)

El Niño-Southern Oscillation (ENSO) originates from ocean-atmosphere interactions in the tropical Pacific. It is the main driver of interannual climate variability, and influences seasonal climate globally through atmospheric teleconnections. ENSO is therefore an important source of seasonal climate predictability. The dominant ENSO teleconnection is the Pacific-North American (PNA) pattern. While previous studies underline different teleconnection patterns between warm (El Niño) and cold (La Niña) ENSO phases, others argue that it is rather the ENSO "flavour" (i.e. whether ENSO anomalies peak in the eastern or central Pacific, EP or CP events) or amplitude (some EP events escalate into extreme warm anomalies) that determines its teleconnection pattern. The ENSO teleconnection pattern knowledge is in addition limited by its large aliasing by internal atmospheric variability. Finally, recent studies indicate that the ENSO teleconnection pattern changes in our warming world. A better understanding of how the ENSO teleconnection pattern changes depending on the type of ENSO, and in response to global change is needed to fully tap in the associated predictability potential.

This PhD examines these questions for boreal winter teleconnections over North America. How does the ENSO teleconnection pattern depend on the ENSO event type and amplitude? Are some ENSO types associated with more reproducible teleconnection patterns? Are ENSO teleconnection patterns faithfully reproduced by climate models? Does the future ENSO teleconnection pattern change depend on the ENSO type? I examine these questions through the analysis of numerous climate model AMIP6-CMIP6 simulations, with a focus on extreme El Niño teleconnections.

I show that La Niña, moderate CP El Niño and moderate EP El Niño events are all associated with a PNA teleconnection pattern. Only extreme El Niño events - such as in 1982-83, 1997-98 and 2015-16 - display different, eastward-shifted anomalies similar to the Tropical North Hemisphere (TNH) pattern, in response to large rainfall anomalies over the central/eastern equatorial Pacific. Atmospheric nonlinearities associated with the threshold for deep atmospheric tropical convection play a key role in this pattern formation. Extreme El Niño events yield highly reproducible impacts such as warm conditions over Northeast America (70% chances), wet anomalies over California (80%) and Florida (97%). Impacts associated with the PNA are less reproducible, due to a less favourable signal to noise ratio than that associated with stronger TNH-like signals during extreme El Niño events. Such findings are robust in 22 out of 23 atmospheric ensemble simulations from the AMIP6 database. 16 out of the 42 coupled ocean-atmosphere models (CMIP6 database) I examined do not produce extreme El Niño events. Despite a degradation (e.g. underestimation of wet anomalies for California and Florida) relative to their atmospheric-only counterpart, 18 out of the remaining 26 CMIP6 models capture the specific extreme El Niño TNH-like teleconnections. These models indicate a weakening of the TNH teleconnection over North Pacific and America and development of a NAO-like teleconnection over the Atlantic during extreme El Niño events under strong globally-averaged warming ($> +3.5$ °C). Those changes are qualitatively similar, but of much larger amplitudes than La Niña and moderate El Niño teleconnection changes under warmer climate discussed by previous studies. The extreme El Niño typical impacts (warm Northeast America, wet California and Florida, dry northeast Brazil) weaken under warmer climates, and become less distinct from those of moderate El Niño events.

Keywords: El Niño - Southern Oscillation (ENSO), Atmospheric teleconnections, Extreme El Niño, North American climate, Climate Change, Atmospheric internal variability

ENSO (El Niño-Oscillation Australe) se développe grâce aux interactions océan-atmosphère du Pacifique tropical et constitue la principale source de variabilité climatique interannuelle. ENSO influence le climat saisonnier à l'échelle mondiale via ses téléconnexions atmosphériques, et représente une source majeure de prévisibilité climatique. La téléconnection principale d'ENSO dans l'hémisphère nord est le pattern Pacific-North American (PNA). Il n'y a actuellement pas de consensus sur ce qui contrôle la diversité des téléconnexions d'ENSO. Certaines études soulignent des patterns différents pour El Niño et La Niña, alors que d'autres pointent la diversité d'ENSO (c.-à-d. la localisation des anomalies de SST: dans le Pacifique central -événement CP- ou dans le Pacifique est-événement EP), ou encore l'amplitude des anomalies (certains événements EP donnant lieu à des El Niño "extrêmes"). Notre connaissance des téléconnexions d'ENSO est en outre limitée par la variabilité interne de l'atmosphère. Enfin, des études récentes suggèrent une modification des téléconnexions d'ENSO en réponse au réchauffement climatique. Une meilleure compréhension de la diversité des téléconnexions d'ENSO dans le climat actuel et futur est cruciale pour exploiter pleinement le potentiel de prévisibilité offert par ENSO.

Cette thèse examine les téléconnexions d'ENSO pendant l'hiver boréal en Amérique du Nord. Comment le pattern de téléconnexions d'ENSO varie-t-il selon le type et l'amplitude des événements ENSO ? Certains types d'ENSO sont-ils associés à des téléconnexions plus reproductibles ? Les téléconnexions d'ENSO sont-elles fidèlement reproduites par les modèles climatiques ? Le changement futur du pattern de téléconnexions d'ENSO dépend-il du type d'ENSO ? Ces questions sont explorées à travers l'analyse de nombreuses simulations de modèles climatiques AMIP6-CMIP6, avec un focus sur les téléconnexions des El Niño extrêmes.

Je montre que les La Niña et El Niño modérés sont associés à un pattern de téléconnection de type PNA, mais que seuls les El Niño extrêmes (1982-83, 1997-98 et 2015-16) affichent un pattern de téléconnection décalé vers l'est, dit "Tropical-North Hemisphere" (TNH). Ce pattern s'active en réponse aux fortes pluies dans le Pacifique équatorial est pendant El Niño extrêmes. Les non-linéarités atmosphériques associées au seuil de convection profonde atmosphérique jouent un rôle clé dans l'activation du TNH. Les El Niño extrêmes sont associés à des impacts hivernaux spécifiques et fortement reproductibles sur l'Amérique du Nord: réchauffement sur le nord-est de l'Amérique (70% de chances), et anomalies humides sur la Californie (80%) et la Floride (97%). Les impacts associés au PNA sont moins reproductibles en raison d'un rapport signal-bruit (SNR) plus défavorable que pour les forts signaux TNH lors des El Niño extrêmes. Ces résultats sont robustes dans 22 simulations d'ensemble de modèles AMIP6 (sur 23 examinés). 16 des 42 modèles couplés océan-atmosphère CMIP6 que j'ai examinés ne produisent pas d'El Niño extrêmes. Malgré une dégradation (par exemple, sous-estimation des anomalies humides sur la Californie) par rapport à leur version atmosphère-seule, 18 des 26 modèles CMIP6 restants capturent raisonnablement les téléconnexions spécifiques associées aux El Niño extrêmes. Ces modèles indiquent un affaiblissement de la téléconnexion TNH au-dessus du Pacifique Nord et de l'Amérique ainsi que le développement d'une téléconnexion de type NAO au-dessus de l'Atlantique lors des événements El Niño extrêmes sous un réchauffement global moyen fort ($> +3,5$ °C). Ces changements sont qualitativement similaires, mais d'amplitude beaucoup plus importante que les changements de téléconnexion associés à La Niña et aux El Niño modérés. Les impacts typiques d'un El Niño extrême (nord-est de l'Amérique chaud, Californie et Floride humides, nord-est du Brésil sec) s'affaiblissent sous des climats plus chauds et deviennent moins distincts de ceux des événements El Niño modérés.

Mots clés: El Niño-Oscillation Australe (ENSO), téléconnexions atmosphériques, El Niño extrêmes, climat nord Américain, changement climatique, variabilité interne atmosphérique

ACKNOWLEDGMENTS

Même si on travaille seul derrière son écran, une thèse est loin d'être aussi solitaire que le Vendée Globe ! Je n'aurais jamais pu survivre sans toutes les personnes qui m'ont soutenue, aidée et encouragée, et envers qui j'ai une immense gratitude (ainsi qu'une belle dette en bières!):

Un énorme merci à Jérôme et Matthieu, indétrônables Dupont/Dupond de l'océanographie tropicale, devenus gourous suprêmes des téléconnexions atmosphériques extratropicales ! Vous m'avez accompagnée sans être étouffants, poussée à donner le meilleur de moi-même sans me mettre la pression (si, si, c'est possible !). Malgré la distance, vous avez su instaurer un cadre de travail sain, dans une ambiance de respect, de bonne humeur et de confiance. Résultat : on a bossé, cherché, rigolé, appris, réduit 50 slides en 6... le feu ! Merci pour les opportunités de conférences et d'interactions scientifiques, les discussions passionnantes, votre relecture méticuleuse (oh, une mouche !) de mes manuscrits et présentations, votre vision de la recherche et votre engagement, tant dans ma thèse que pour la science en général, merci pour ce joyeux partage de connaissances ! Mention spéciale à Jérôme pour avoir repris la direction de ma thèse et avoir cru en moi dans le moment le plus critique : je t'en suis infiniment reconnaissante. Et à Matthieu, pour ta présence à ma soutenance : c'était incroyable et infiniment réconfortant. Au final, on se sera bien amusés dans ce drôle de monde des téléconnexions, avec José-Luiz le TNH, qui vient piquer la vedette à Bernardo le PNA, et Gisela la variabilité interne extratropicale qui vient mettre le bazar ([Seasoned Chaos](#) : spoiler, les principaux protagonistes de cette thèse sont en réalité des acteurs hollywoodiens stars de *Teleconnection Telenovela* !)

Then, I would like to express my deepest gratitude to Andréa Taschetto and Fabio D'Andrea for kindly agreeing to review this manuscript, as well as to Juliette Mignot, my examiner. I sincerely thank you all for your valuable comments and constructive questions during the defense, your insightful feedbacks on this work were greatly appreciated and taken into account.

Merci également à toi aussi Serena, pour toutes ces discussions, que ce soit des conseils pour survivre à cette thèse, sur les stats, les waves et le déferlement, les tips publication et m'avoir conseillée pour réaliser ma première review d'un autre papier :o !

L'équipe GESSEC du labo mérite aussi des remerciements chaleureux pour leur aide infaillible dans la jungle administrative des ordres de mission. Un grand merci à Agathe, toujours là pour m'aider avec mes galères de voyage, Brigitte pour son aide avec les contrats et Bertrand pour sa bonne humeur !

A la team du labo, Amélie, Hanh, Julia, Juliette, Elisa, Adrien, Gabriella, Manon, Alexandra, Simon, Micaël, Karim, Quentin, Marie, Jérôme, Mahmoud, Nolween, Marion L ... et à tous les autres qui ont contribué, même de manière discrète, à rendre cette thèse un peu moins solitaire et bien plus agréable, merci pour la super ambiance LEGOS !

Aux copains du master SOAC, Ethel, Paul, Marine, Fleur, merci pour votre amitié, les sorties, et bon vent à tous !

To the ENSO Summer School friends I keep meeting around, Ned, Jakob, Kevin, Sara, Isma, Paloma (see you at BSC!), thanks for the scientific discussions and drinks!

Aux copains, vous avez prouvé qu'une team dynamique et solidaire, généreusement arrosée de bières, ça permet d'affronter toutes les galères de thèse. Vous êtes une source d'énergie inépuisable ! Donc pêle-mêle, (toute façon si vous êtes là c'est que - coeur sur vous - vous êtes tous méga importants) :

- Marco, fantástico vecino de oficina, gracias por todas las fascinantes discusiones, sesiones de chat, degustaciones de café y consejos sobre mis presentaciones y graficos! Espero que todo te vaya bien en Florida !

- Camille B pour Bretagne, autre co-bureau/ex team SOAC, pour ta gentillesse et ton écoute, merci pour toutes nos discussions existentielles/gossip/organisationnelles, les verres au Café Adjacent cet été, les boutures, merci d'être une incroyable amie sur qui on peut compter les yeux fermés <3 ! Ta présence au bureau était une large source de motivation pour y venir le matin. Big Up aussi à Jerem, merci à toi aussi pour ton soutien, nos discussions covidienness/lofi, ta bonne humeur depuis toutes ces années !

- Camille C (team Ramonville/Marseille représente!!), un énorme merci à toi aussi pour ton soutien, m'écouter quand je me râlais à longueur de temps cet été (désolée encore!), idem, trafic d'orchidées, d'animal un peu flou de près, chocolat, bref t'es l'autre rayon de soleil du LEGOS ! Bon courage pour ta thèse, on sera là pour l'animation à ta soutenance tkt avec les lumières et le DJ :D !

- Marion, également pilier non officiel de cette thèse, experte en éditorial JGR /Adum /tricot /Overleaf/ figures en tous genres, et surtout : « mais pourquoi on fait une thèse déjà? », fameuse question posée à 23h47, suivie souvent par « en vrai les allers simples (en train svp) pour la Patagonie, ce n'est pas si cher en ce moment ». Merci d'avoir répondu à mes milliards de questions cet été, pour ta curiosité et rigueur scientifique monstrueuse, éclate-toi bien au pays des glaçons !

- Greg, compère en séance de footing du dimanche, compagnon de bar fidèle (t'inquiète, on va avoir notre place bien méritée sur le mur!), puis nouveau co-bureau team chocolat chaud sur la dernière ligne droite, merci encore d'avoir géré la technique à ma soutenance, tu gères fougère!!

- Et à Nico, adorable, cumul de mandat avec le GESSEC, qui n'a jamais râlé lorsque je perdais régulièrement mon badge, mon téléphone, mes clés, voire ma tête (je suis encore désolée pour toutes ces mésaventures, et surtout pour l'exploit d'avoir explosé mon badge sur le portail vélo... oopsi !). Merci pour ton sourire et tes éclats de rire !

Les potins, les cafés, les soirées bières et jeux, les expo plantes alors qu'on a tout(e)s trooop de plantes, discuter de tout et de rien avec vous (et surtout des loups, c'est ouf comment y'en a plein à Toulouse !), a rendu ces 4 années tellement plus douces !

A Thibault, merci pour ton soutien aussi, cette si longue amitié (c'est chaud quand on n'a plus assez de doigts sur deux mains pour compter les années !), ton soutien dans les moments de crise, de rendre mes passages à Paris plus doux, j'ai hâte de repasser me balader le long de la Seine en refaisant le monde avec toi. Et surtout, merci encore pour les relectures sur ce manuscript, la motivation des derniers jours, et les stickers gagnés à chaque paragraphe écrit !

Ensuite, un immense merci à Marie et Guillaume pour tout ce que vous m'avez apporté au piano ces 6 dernières années. Merci pour ces merveilleuses opportunités musicales, auditions/masterclasses/ cours, et pour votre passion. Le piano, c'est la vie.

Enfin, la séquence émotion !

Un énorme merci à Brigitte, merveilleuse voisine, qui aura rendu ces 4 années infiniment plus supportables, toujours prête à rendre service avec le coeur sur la main (merci encore de venir chasser les araignées chez moi!), les séances de papotage à l'heure du goûter dominical, un vrai parfum de famille à l'étage du dessus ! Merci encore pour la clim, le chauffage, faut reconnaître que sans vous je n'aurais jamais pu télécharger ces fameuses simu CMIP au coeur de cette thèse ! Enfin, merci encore pour gérer mes galères barcelonaises avec les minets, de les garder bien au chaud en attendant mon futur appart !

A la Bench'Industry, délocalisée aux 4 coins de la planète :

Yann, pour ton cartésianisme à toute épreuve, ta façon de voir les choses franco sans tergiverser (merci encore pour ton appel la veille de la soutenance, j'm'y serai peut-être jamais pointée sans ça!),

Seb, (bisous à Christine!), pour les bonnes barres de rire, le ski, les sorties à Annecy,

Eva, qui, de toute façon, n'ouvrira jamais cette thèse d'astrologie (hein !). Merci pour le chaos, hurler dans mes oreilles, le trou dans mon porte feuille, les tartes aux citrons (et l'impôt à payer sur ces fameuses tartes aux citrons), les battles de poireaux pendant le confinement, la course aux rats avec le Mumuj,

의미가... 전혀 없는 (맞아 맞아, 프랑스로도, 한국어로도 ㅋㅋ) 복잡한 표현들, 고마워! 아무튼, 네가 없으면 (거의) 심심할 것 같을 정도로 항상 즐겁게 해줘서 고마워!

Papa, standard téléphonique/bureau des lamentations sur cette fin de manuscript, mais toujours prêt pour une rando ski ou un tour à vélo pour s'aérer les neurones,

Mamoune, pour être venue me nourrir avec tes bons petits plats cet été, d'avoir pris soin de moi, de manière générale; merci d'avoir été là, toujours !

Et enfin, Charlie. Rien, mais alors rien de tout ça – les études, de la licence à la thèse, le bonheur, la paix – n'aurait été possible sans toi. Cette réussite, c'est autant la tienne que la mienne. Merci pour nos vadrouilles, que ce soit dans les Pyrénées ou au Brésil (Guyane bientôt!). Merci simplement d'être là, depuis si longtemps, dans les hauts, les bas, et pour tout ce joyeux bazar entre les deux.

Sur ce, bonne lecture, et à plus dans le bus !

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Acronyms

AMIP Atmospheric Model Intercomparison Project

CMIP Coupled Model Intercomparison Project

CP Central Pacific

CT Cold Tongue

ENSO El Niño-Southern Oscillation

EP Eastern Pacific

ERA5 ECMWF European Reanalysis V5

GPCP Global Precipitation Climatology Project

GMST Global Mean Surface Temperature

GWL Global Warming Level

ITCZ Inter Tropical Convergence Zone

MJO Madden-Julian Oscillation

NAO North Atlantic Oscillation

NH North Hemisphere

ONI Oceanic Niño Index

PNA Pacific-North America

PR Precipitation

PSA Pacific South America

SLP Sea Level Pressure

SOI Southern Oscillation Index

SPCZ South Pacific Convergence Zone

SST Sea Surface Temperature

SSP Shared Socioeconomic Pathway

TNH Tropical-Northern Hemisphere

WP Warm Pool

General introduction (EN)

El Niño Southern Oscillation (ENSO) is a coupled ocean-atmosphere phenomenon originating in the tropical Pacific Ocean. ENSO events are characterized by irregular shifts between warmer-wetter, El Niño, and colder-drier, La Niña, conditions in the central and/or eastern equatorial Pacific. ENSO events can be seen as disruption of the seasonal cycle of the tropical Pacific, at a 2-7 years time scale. Typically, El Niño events present strong positive Sea Surface Temperature (SST) anomalies centered in the central-eastern equatorial Pacific, whereas La Niña events have weaker and westward-shifted SST anomalies. In addition, ENSO events exhibit a wide variety of SST anomaly patterns and amplitudes. The term “ENSO diversity” ([Capotondi et al., 2015](#)) captures the inter-event variability expressed in the zonal shift in the position of the maximum SSTa, with Central Pacific (CP) and Eastern Pacific (EP) events. This diversity is more pronounced for El Niño events than for La Niña events ([Kug & Ham, 2011](#)). Finally, some EP events reach reach large SST anomalies in the eastern equatorial Pacific, such as the 1982/83, 1997/98 and 2015/16 El Niño events ([Santoso et al., 2017](#)), and are therefore referred to as extreme El Niño events.

ENSO SST anomalies trigger tropical deep convection and diabatic heating anomalies. This leads to upper tropospheric divergence that forces extratropical large-scale Rossby waves. The associated standing wave expands eastward and northward into the extratropics, along curved pathways that are determined by the background atmospheric circulation. The signature of those waves on atmospheric variables such as the geopotential height, precipitation or temperature are referred to as *atmospheric teleconnections*. These teleconnections make ENSO the primary source of natural interannual climate variability at the seasonal scale, not only in the tropical Pacific, but globally ([McPhaden et al., 2006](#); [Taschetto et al., 2020](#)). In the North Hemisphere (NH) during the boreal winter, ENSO teleconnections significantly influences North American climate, causing seasonal anomalies in precipitation, winds and surface temperature ([Larkin, 2005](#)). Since ENSO events can be predicted several seasons in advance, these teleconnections are critical for accurate seasonal forecasts over North America.

ENSO atmospheric winter teleconnections are mostly associated with the Pacific-North America (PNA) pattern ([Wallace & Gutzler, 1981](#); [Horel & Wallace, 1981](#)). In its positive phase, the PNA is associated with an anomalously deep Aleutian Low, promoting the intrusion of tropical warm air over the northwestern US and western Canada, as well as precipitation anomalies along the southern coast of Alaska. Early studies have also noticed that another, eastward-shifted pattern in quadrature with the PNA could also occur in association with ENSO: the Tropical Northern Hemisphere (TNH) pattern ([Mo & Livezey, 1986](#); [Livezey & Mo, 1987](#)). The negative phase of the TNH pattern presents eastward shifted seasonal impacts, resulting in precipitation anomalies along the southwestern US coast and warm anomalies extending over the

northern US and Canada. As a result, there is a considerable diversity of ENSO teleconnection patterns over North America (Zhang et al., 2014; Taschetto et al., 2020).

The drivers and mechanisms behind the teleconnections diversity remain uncertain. Early studies focused on differences between El Niño and La Niña events teleconnections, with eastward-shifted teleconnections during El Niño (Hoerling et al., 1997, 2001). They proposed that this diversity results from the non-linear response of tropical deep convection to SSTs, related to the fact that SSTs above 28°C are required to initiate tropical deep convection (Gadgil et al., 1984). Climatological SST increases toward the west in the equatorial Pacific, crossing the 28°C threshold around the dateline. Cold La Niña anomalies therefore tend to suppress convection west of the dateline, whereas warm El Niño anomalies tend to enhance convection east of it. Overall this yields an eastward shift of El Niño tropospheric heating anomalies, which was designated as the main source of teleconnection differences between El Niño and La Niña events (Hoerling et al., 1997, 2001). Later studies then questioned the role of ENSO diversity, suggesting that the eastward shifted SST pattern during EP events yields different teleconnection patterns relative to SST anomalies in the central Pacific during CP events (Mo, 2010; Ashok et al., 2007; Yu et al., 2015), in particular when they are associated with sufficiently large SST anomalies (Chiodi & Harrison, 2015; Johnson & Kosaka, 2016). Finally, recent studies further narrow down the ENSO event type that increases the likelihood of precipitation anomalies over the state of California to Extreme El Niño events, such as in 1982/83, 1997/98 or 2015/16 (Hong Lee et al., 2023; Hoell et al., 2016). These specific results for Californian rainfall raise the more general question of whether a different winter teleconnection pattern arises over North America specifically during extreme El Niño events.

Identifying the main driver of ENSO teleconnection diversity is challenging due to the substantial internal atmospheric variability, which is particularly large in the extratropics (Kumar & Hoerling, 1995). For instance, the PNA pattern also displays considerable internal variability at various timescales (Straus & Shukla, 2002), which aliases signals attributable to ENSO. Other modes of internal atmospheric variability can further obscure ENSO-driven signals, leading to substantial uncertainties and sampling errors (Garfinkel et al., 2012, 2018). It makes the identification of the ENSO teleconnection pattern difficult in the observed record (which is accurate since the satellite era in 1980) due to the relatively small sample of ENSO events (especially when examining differences between various ENSO types). Therefore, to effectively separate the ENSO-driven response from atmospheric noise, it is necessary to utilize large ensembles of atmospheric general circulation model simulations (Deser et al., 2018).

To assess climate features within a large model database, model experiments must be conducted using standardized procedures to facilitate multi-model comparisons. In this context, the Atmospheric Model Intercomparison Project, Phase 6 (AMIP6) and the Coupled Model Intercomparison Project, Phase 6 (CMIP6), provide an extensive database of model simulations and ensemble members. However, these models have inherent biases that can distort the accurate

representation of climate processes. Some of these biases are of atmospheric origin and already present in AMIP simulations, but additional SST biases develop in coupled models. Coupled General Circulation Models (GCMs) for instance display colder than observed climatological SST in the equatorial Pacific (Planton et al., 2021; Bellenger et al., 2013). This bias has been linked to an underestimation of ENSO diversity in coupled models (Guilyardi et al., 2009), a failure to capture the extreme El Niño events SST signals (Bayr et al., 2024), and a reduction in ENSO impacts over California (Bayr et al., 2019). Additionally, some coupled models are unable to simulate extreme El Niño events at all (Cai et al., 2014). Therefore, even the use of a large model database does not guarantee a reliable investigation of ENSO teleconnections, and particularly those of extreme El Niño teleconnections.

Finally, ENSO events need to be considered in the context of global warming driven by increased anthropogenic greenhouse gas concentrations. Coupled model projections indeed indicate an eastward shift of the overall ENSO teleconnection pattern, and more specifically of the Pacific-North American (PNA) pattern (Lee & Jin, 2024; Chen et al., 2017; Drouard & Cassou, 2019) and a reduction in warm anomalies over Northwest America during El Niño boreal winters (Beverley et al., 2021). Future changes in ENSO teleconnections also feature a strengthening of the ENSO-North Atlantic Oscillation (NAO) connection (Geng et al., 2024; Johnson et al., 2022; Drouard & Cassou, 2019), which may lead to a more pronounced ENSO influence over Europe (Beverley et al., 2024). However, studies investigating changes in ENSO teleconnection patterns under global warming have not specifically decomposed these changes by ENSO type. Consequently, the question of how extreme El Niño teleconnections will change under global warming remains unresolved.

In this thesis, I will focus on North American boreal winter ENSO teleconnections, and will address the following questions : **How does the ENSO teleconnection pattern depends on the ENSO event type and amplitude? Are some ENSO types associated with more reproducible teleconnection patterns? Are ENSO teleconnection patterns faithfully reproduced by climate models? Does the future ENSO teleconnection pattern change depend on the ENSO type?**

The manuscript is organized as follow :

- Chapter I is a more detailed version of this short introduction, introducing the scientific and methodological challenges at the core of this manuscript before addressing the issues in details.
- Chapter II presents an overview of the methods and atmospheric-only (CNRM-CM6.1.AMIP, AMIP6) and ocean-atmosphere coupled (CMIP6) experiments used to investigate the variability of ENSO teleconnections.

- In chapter [III](#), I test the core hypothesis of this thesis, that only extreme El Niño drive a different teleconnection pattern over the North hemisphere than the PNA pattern traditionally associated with ENSO. I show that this is the case, based on a single 16-member AMIP-type ensemble from the CNRM-CM6.1 model. I also demonstrate that extreme El Niño events induce very reproducible climate impacts over North America. I finally investigate the atmospheric nonlinearities and SST pattern diversity respective contributions to the formation of the extreme El Niño teleconnection pattern.
- In chapter [IV](#), I assess the robustness of chapter 3 results in the large AMIP6 database. This large sample allows to verify the robustness of my core hypothesis to sampling and model error. This large sample also allows explaining the cause for the stronger reproducibility of extreme ENSO teleconnections based on a signal-to-noise ratio analysis. I will also investigate the realism of extreme El Niño teleconnections in coupled CMIP6 models.
- In chapter [V](#), I investigate future changes in ENSO teleconnections under global warming projections, based on the CMIP6 database. The original aspect of the work in this chapter will again be to specifically assess extreme El Niño teleconnection changes : are they different from those that were already described when considering ENSO overall ?
- Finally, chapter [V.4.2](#) presents overall conclusions and perspectives for future investigations.

Introduction générale (FR)

L'oscillation australe El Niño (ENSO) est un phénomène couplé océan-atmosphère prenant naissance dans l'océan Pacifique tropical. Il se manifeste par des alternances entre des conditions plus chaudes et humides (El Niño), et des conditions plus froides et sèches (La Niña) dans le centre et/ou l'est du Pacifique équatorial, avec une période irrégulière comprise entre 2 et 7 ans. En général, El Niño présente de fortes anomalies positives de température de surface de la mer (SST) centrées sur le centre et l'est du Pacifique équatorial, tandis que La Niña présente des anomalies SST plus faibles, décalées vers l'ouest. En outre, les événements ENSO présentent une grande diversité de patterns et d'amplitudes d'anomalies de SST. Le terme « diversité ENSO » ([Capotondi et al., 2015](#)) rend compte de cette variabilité inter-événements, exprimée par le déplacement zonal de la position du maximum de SSTa, avec des événements de Pacifique central (CP) ou oriental (EP). Cette diversité est plus prononcée pour El Niño que pour La Niña ([Kug & Ham, 2011](#)). Enfin, certains EP atteignent des amplitudes d'anomalies de SST très élevées dans le Pacifique équatorial oriental, comme en 1982/83, 1997/98 et 2015/16 ([Santoso et al., 2017](#)), et sont ainsi qualifiés d'El Niño extrêmes.

Les anomalies de SST d'ENSO déclenchent une convection tropicale profonde et des anomalies de chauffage diabatique, induisant une divergence en haute troposphère, provoquant des ondes

de Rossby extratropicales. L'onde stationnaire ainsi générée se déploie vers le nord-est, le long de trajectoires extratropicales déterminées par l'état moyen de la circulation atmosphérique. La signature de ces ondes sur les variables atmosphériques telles que le géopotentiel, les précipitations ou la température est appelée *téléconnexions atmosphériques*. Ces téléconnexions font d'ENSO la principale source de variabilité climatique interannuelle naturelle, non seulement dans le Pacifique tropical, mais aussi à l'échelle mondiale (McPhaden et al., 2006; Taschetto et al., 2020). Dans l'hémisphère nord (NH), en hiver boréal, les téléconnexions d'ENSO influencent considérablement le climat nord-américain, provoquant des anomalies saisonnières de précipitations, vents et température de surface (Larkin, 2005). Comme les événements ENSO peuvent être prévus plusieurs saisons à l'avance, ces téléconnexions sont essentielles pour des prévisions saisonnières précises en Amérique du Nord.

Les téléconnexions atmosphériques hivernales de l'ENSO sont principalement associées au pattern Pacifique-Amérique du Nord (PNA) (Wallace & Gutzler, 1981; Horel & Wallace, 1981). Lors de sa phase positive, le PNA se caractérise par un renforcement de la dépression des Aléoutiennes, favorisant l'intrusion d'air chaud tropical sur le nord-ouest des États-Unis et l'ouest du Canada, ainsi que des anomalies de précipitations le long de la côte sud de l'Alaska. Des études antérieures ont également observé qu'un autre pattern, décalé vers l'est et en quadrature de phase avec le PNA, peut également être associé à ENSO : le schéma Hémisphère Nord Tropical (TNH) (Mo & Livezey, 1986; Livezey & Mo, 1987). La phase négative du TNH présente des impacts saisonniers décalés vers l'est, entraînant des anomalies de précipitations le long de la côte sud-ouest des États-Unis et des anomalies de température élevées sur le nord des États-Unis et le Canada. Par conséquent, il existe une diversité des schémas de téléconnexion d'ENSO en Amérique du Nord (Zhang et al., 2014; Taschetto et al., 2020).

Les causes de cette diversité des téléconnexions (PNA ou TNH?) restent incertaines. Les premières études se sont concentrées sur les différences entre les téléconnexions des événements El Niño et La Niña, avec des téléconnexions décalées vers l'est pendant El Niño (Hoerling et al., 1997, 2001). Ces études proposent que ce décalage résulte de la réponse non linéaire de la convection profonde tropicale à la SST. Des SST totales supérieures à 28°C sont en effet nécessaires pour déclencher la convection profonde tropicale (Gadgil et al., 1984). La SST climatologique augmente vers l'ouest dans le Pacifique équatorial, franchissant le seuil de 28°C autour de la ligne de changement de date. Les anomalies froides de La Niña ont donc tendance à supprimer la convection à l'ouest de cette ligne, tandis que les anomalies chaudes d'El Niño ont tendance à renforcer la convection à l'est. Dans l'ensemble, il en résulte un déplacement vers l'est des anomalies de réchauffement troposphérique d'El Niño, désigné comme la principale source des différences de téléconnexion entre les événements El Niño et La Niña (Hoerling et al., 1997, 2001). Des études ultérieures ont ensuite souligné l'importance de la diversité d'ENSO, suggérant que les anomalies de SST décalées vers l'est lors des événements EP induisent des téléconnexions différentes de celles des événements CP (Mo, 2010; Ashok et al., 2007; Yu et al.,

2015), en particulier lorsque les EPs sont associés à des anomalies de SST suffisantes pour générer des anomalies de convection profonde dans le centre-est du Pacifique tropical (Chiodi & Harrison, 2015; Johnson & Kosaka, 2016). Enfin, des études récentes montrent que seuls les événements El Niño extrêmes comme ceux de 1982/83, 1997/98 et 2015/16, augmentent la probabilité d'anomalies de précipitations en Californie (Hong Lee et al., 2023; Hoell et al., 2016). Ces résultats pour les pluies Californienne soulève la question plus générale de savoir si les El Niños extrêmes donnent lieu à un pattern spécifique de téléconnection hivernale en Amérique du Nord.

La connaissance précise des patterns de téléconnexion d'ENSO est limitée par la variabilité atmosphérique interne, particulièrement importante dans les régions extratropicales (Kumar & Hoerling, 1995). Le PNA présente par exemple une variabilité interne considérable à différentes échelles de temps (Straus & Shukla, 2002), qui se superpose aux signaux attribuables à l'ENSO. D'autres modes de variabilité atmosphérique interne vont également se superposer à la réponse à ENSO, ce qui entraîne des incertitudes et des erreurs d'échantillonnage considérables (Garfinkel et al., 2012, 2018). Cela rend donc difficile l'identification des téléconnexions d'ENSO dans les observations satellites récentes (post-1979), en raison de tailles d'échantillons relativement faibles (en particulier lorsque l'on contraste différentes catégories d'ENSO). Par conséquent, pour séparer efficacement la réponse induite par l'ENSO du bruit atmosphérique, il est fortement recommandé d'utiliser de grands ensembles de simulations de modèles de circulation générale atmosphérique (Deser et al., 2018), afin de démultiplier le nombre de réalisations ENSO.

Les projets AMIP6 et CMIP6 offrent une base étendue de simulations, tant en conditions atmosphériques forcées par des SST observées (AMIP) qu'en simulations couplées océan-atmosphère (CMIP). Ces bases sont essentielles pour étudier le climat global et les téléconnexions de l'ENSO. Cependant, ces modèles présentent parfois des biais importants. Ces biais peuvent être d'origine atmosphérique et donc présents dans les simulations AMIP. On s'attend toutefois à des biais plus importants dans les simulations couplées, où de forts biais de SST se développent en général. Par exemple, la plupart des modèles des différentes générations de CMIP ont des SST climatologiques plus froides que les observations dans le Pacifique équatorial (Planton et al., 2021; Bellenger et al., 2013), un biais souvent qualifié de "cold tongue bias" ou "biais de langue d'eau froide". Ce biais a été associé à une sous-estimation de la diversité ENSO et à des difficultés à capturer les anomalies de SST des événements El Niño extrêmes (Guilyardi et al., 2009; Bayr et al., 2024). De plus, certains modèles couplés ne simulent pas du tout d'événements El Niño extrêmes (Cai et al., 2014). Ainsi, même avec une vaste base de données, l'étude des téléconnexions ENSO, et en particulier des El Niño extrêmes, reste délicate.

Enfin, il s'agit de replacer les événements ENSO dans le contexte du réchauffement climatique induit par l'augmentation des émissions de gaz à effet de serre d'origine anthropique. Si la variabilité ENSO est à l'origine naturelle, elle peut être modifiée en réponse au changement climatique. Les projections futures de CMIP indiquent par exemple un déplacement vers l'est

des patterns de téléconnexion ENSO. Sur le Pacifique et l'Amérique du Nord, cela se traduit par un décalage vers l'est du PNA (Lee & Jin, 2024; Chen et al., 2017; Drouard & Cassou, 2019) et une réduction des anomalies positives de température de surface au-dessus de l'Amérique du Nord ouest pendant les hivers boréaux El Niño (Beverley et al., 2021). En outre, les changements dans les téléconnexions suggèrent un renforcement du lien ENSO-Oscillation Nord Atlantique (NAO) (Geng et al., 2024; Johnson et al., 2022; Drouard & Cassou, 2019), ce qui peut conduire à une influence d'ENSO plus prononcée sur l'Europe (Beverley et al., 2024). Cependant, les études portant sur les changements dans les schémas de téléconnexion ENSO dans le cadre du réchauffement climatique n'ont pas spécifiquement décomposé ces changements en fonction du type d'ENSO. Par conséquent, la question de savoir comment les téléconnexions associée aux El Niños extrêmes changeront sous l'effet du réchauffement climatique reste en suspens.

Dans cette thèse, je me concentrerai sur les téléconnexions hivernales d'ENSO vers l'Amérique du Nord, et j'aborderai les questions suivantes: **Comment le schéma de téléconnexion ENSO dépend-il du type et de l'amplitude de l'événement ENSO ? Certains types d'ENSO sont-ils associés à des schémas de téléconnexion plus reproductibles ? Les modèles climatiques reproduisent-ils fidèlement les schémas de téléconnexion ENSO ? Le changement futur du schéma de téléconnexion ENSO dépend-il du type d'ENSO ?**

Le manuscrit est organisé comme suit :

- Le chapitre I présente une version plus détaillée de cette brève introduction, introduisant les défis scientifiques et méthodologiques au cœur de ce manuscrit avant d'aborder les problématiques détaillées.
- Le chapitre II présente une vue d'ensemble des méthodes et des expériences atmosphériques (CNRM-CM6.1.AMIP, AMIP6) et couplées océan-atmosphère (CMIP6) utilisées pour étudier la variabilité des téléconnexions ENSO.
- Dans le chapitre III, je teste l'hypothèse de travail centrale de cette thèse, à savoir que les El Niño extrêmes donnent lieu à des téléconnexions vers l'Amérique du Nord différentes de celles associées aux autres catégories ENSO (La Niña, El Niño modérés). Je me base sur un ensemble de 16 membres de type AMIP provenant du modèle CNRM-CM6.1. Je montre également une forte reproductibilité des impacts des El Niño extrêmes sur l'Amérique du Nord. J'étudie enfin les contribution relatives des non-linéarités atmosphériques et de la diversité des patterns d'anomalies de SST à la formation du schéma de téléconnexion des El Niño extrêmes.
- Dans le chapitre IV, j'évalue la robustesse des résultats du chapitre trois à l'erreur modèle et d'échantillonnage, en utilisant la grande base de données AMIP6. Le grand nombre

d'échantillons dans cette base permet en outre une analyse signal sur bruit qui explique la reproductibilité accrue de la réponse de l'Amérique du Nord aux El Niño extrêmes.

- Dans le chapitre [V](#), j'étudie la réponse des téléconnexions d'ENSO au changement climatique dans la base de donnée CMIP6. L'originalité de ce chapitre par rapport aux études précédentes réside encore dans l'accent sur les El Niños extrêmes. Leurs changements de teleconnections sont-ils comparables à ceux déjà décrits pour ENSO en général?
- Enfin, le chapitre [V.4.2](#) présente les conclusions générales et les perspectives pour les recherches futures.

Chapter I

Introduction

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I.1 El Niño–Southern Oscillation

I.1.1 Tropical Pacific Mean State

As a natural mode of climate variability, El Niño–Southern Oscillation (ENSO) events are characterized as seasonal anomalies relative to the seasonal cycle of the tropical Pacific mean state. To understand the characteristics of ENSO and its remote climatic impacts, it is crucial first to describe the mean state of the Pacific, which is influenced by large-scale thermally driven atmospheric circulations.

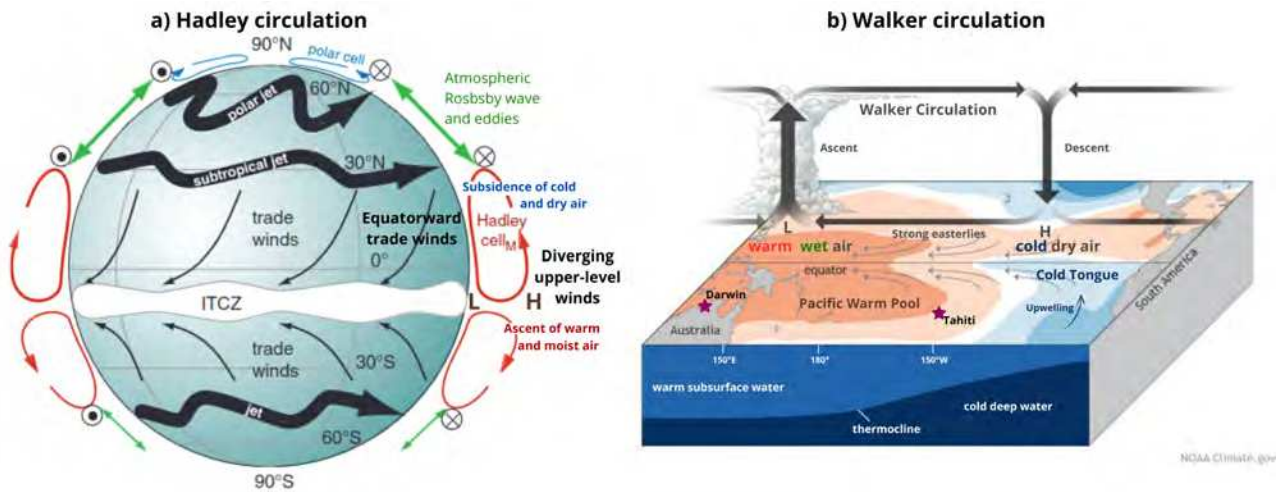


Figure I.1: (a) Schematic of the meridional Hadley and thermally-driven planetary extratropical and polar circulations, reprinted from [Stull \(2017\)](#); and of the (b) zonal Walker overturning circulation, defining the tropical Pacific atmospheric and oceanic climatological mean state. The Western Pacific Warm Pool and Eastern Pacific Cold Tongue regions are indicated, as well as the climatological position of the thermocline, adapted from the [National Oceanic and Atmospheric Administration](#) website.

The Sun, as the primary external driver of the climate system, creates meridional temperature and surface pressure gradients by generating an energy surplus at the equator and a deficit at the poles. Thus, the net energy gain warms the equatorial Pacific, resulting in Sea Surface Temperatures (SST) that exceed the convective threshold of 27–28°C, thereby triggering deep convection ([Gadgil et al., 1984](#); [Graham & Barnett, 1987](#)). Those warm waters and associated convective areas are distributed along the equator and the western tropical Pacific, defining the convective cloud band of the Intertropical Convergence Zone (ITCZ) and the South Pacific Convergence Zone (SPCZ), respectively. The resulting warm moist air rises, forming the ascending branch of the north-south oriented Hadley Circulation, leading to heavy precipitation over the warm waters and low pressure equatorial regions, and a tropopause above 15 km altitude in the equatorial belt. The ascending motion, thus forming a large equatorial Pacific belt, is further reinforced by latent heat supplied from the precipitation in the ITCZ ([Bjerknes,](#)

1969). In the upper troposphere, dry air diverges from the equator, cools through radiative losses to space, and subsides in the subtropics around 23° N/S, allowing the Hadley cell to redistribute the energy surplus from the tropics toward the extratropics. The downdraft creates high surface pressure regions in the subtropics of both hemispheres, contrasting with the low pressure regions in the equatorial region (Figure I.1a). The resulting meridional pressure gradient produces equatorward surface winds, known as trade winds, which complete the meridional Hadley cell circulation.

A second large-scale circulation shapes the Pacific mean state, the east-west oriented Walker circulation. Due to the Coriolis effect, trade winds generated by the Hadley circulation are deflected to the right in the Northern Hemisphere and to the left in the Southern Hemisphere, resulting in trade winds blowing westward within 10° from the equator. Similarly to the Hadley circulation, the upper-level divergence of the ascending air over the western Pacific leads to zonal westward upper-level winds transporting dried and colder air, which subsides over the high surface pressure region of the eastern equatorial Pacific Cold Tongue, completing the Pacific Walker circulation, as shown on Figure I.1.

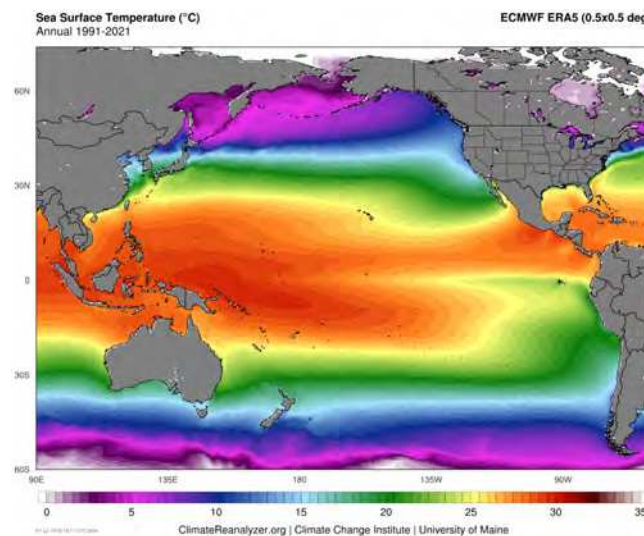


Figure I.2: Annual mean of the Pacific SST ($^\circ\text{C}$) for the period 1991-2021, derived from the ECMWF European Reanalysis V5 (ERA5) dataset. Figure obtained from the [Climate Reanalyzer](#).

In addition, the equatorial easterlies apply a westward force on the upper ocean, that needs to be balanced by an opposing pressure gradient, leading to an accumulation of warm subsurface waters in the western Pacific (Yan et al., 1992). The Pacific part of the Indo-Pacific Warm Pool (WP), therefore defined as an area with SSTs warmer than 28°C exceeding 10^6 km^2 (De Deckker, 2016), extends from the Maritime Continent to the west of the dateline. In the equatorial Eastern Pacific, zonal wind stress induced by the equatorial trade wind blowing westward

triggers northward (in the Northern Hemisphere) and southward (in the Southern Hemisphere) Ekman transport, causing equatorial Ekman divergence and the upwelling of cool subsurface water (less than 25°C) by mass conservation. This results into the formation of the Cold Tongue (CT) region, that extends from the coast of Peru to the east of the dateline (Wyrтки, 1981). The tropical Pacific climatological SSTs are thus marked in surface by a strong zonal SST-gradient, as shown on Figure I.2 for the annual mean climatological SST, and in subsurface by the east-west tilt of the thermocline, defined as the depth of the 20°C isotherm, ranging from 150 meters deep around 160°E to 40 meters deep at 100°W. Finally, the resulting surface pressure and SST zonal gradient act to reinforce the convective ascending motion of the Hadley/Walker circulations over the western Pacific.

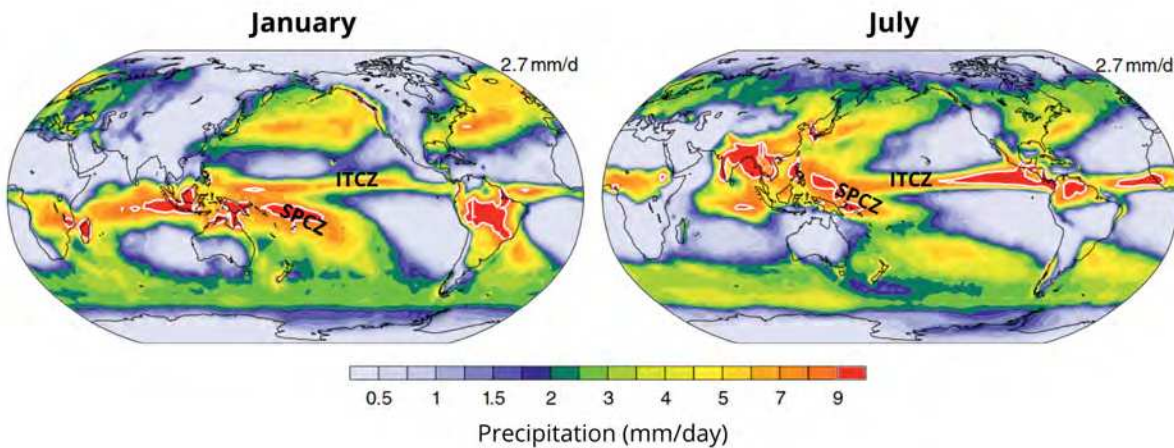


Figure I.3: 1979-2008 mean precipitation(mm/day) for January (left) and July (right), illustrating the seasonal shifts of the ITCZ and SPCZ, key elements of the tropical Pacific mean state. January and July correspond to months of maximal contrast of in-land temperature. Precipitation is from the Global Precipitation Climatology Project (GPCP) v2.1. The value in the upper right indicates the global mean precipitation. Reprinted from Trenberth (2020).

The annual cycle of insolation drives variations in Sea Surface Temperature (SST), which in turn modulate the seasonal cycles of the ITCZ and SPCZ by displacing areas where SST exceeds the convective threshold. During boreal spring (March-April), increased insolation in the Northern Hemisphere compared to the Southern Hemisphere causes SST to rise northward of the equator. This induces the northward migration of the ITCZ, along with its associated heavy precipitation and thunderstorm systems, and initiates the northward movement of the Hadley cell, which reaches its northernmost position in boreal summer. The equatorial trade winds weaken in boreal spring, leading to reduced Cold Tongue activity through diminished coastal upwelling, and maximum equatorial SSTs can be observed until the end of boreal summer (Horel & Wallace, 1981). The SPCZ also shows reduced activity and a northeastward shift during boreal summer compared to boreal winter. Inversely, in boreal winter, the ITCZ shifts equatorward and the SPCZ strengthens and shifts southwestward (Vincent, 1994). Finally, it is

important to note that the variability of the ITCZ and SPCZ is modulated by ENSO events (Webster et al., 1998; Trenberth, 1976; Folland et al., 2002). These events are associated with shifts in the convective areas in the tropical Pacific, leading to corresponding shifts in the ITCZ and SPCZ. The details of the large-scale atmospheric circulation reorganization during ENSO events will be addressed below.

I.1.2 A bridge from the Southern Oscillation to El Niño

ENSO events, by their very name, indicate a strong coupling between an oceanic counterpart, the *El Niño* phenomenon, and an atmospheric component, the Southern Oscillation. Historically, the first documented reference to El Niño dates back to the late 19th century, in Peru. Between 1891 and 1985, the Lima Geographic Society, based on observations by fishermen, established a link between anomalous intense precipitation over the Peruvian desert areas (normally under the influence of dry air subsidence from the Walker Circulation downdraft motion) and the presence of a warm coastal surface current (Carrillo, 1892). This warm current, flowing southward along the coasts of Peru, reflects a weakening of the northward-flowing, cold, and nutrient-rich Humboldt Current caused by the eastern Pacific upwelling. Consequently, the region experiences anomalously warm and nutrient-poor waters, disrupting local fisheries and leading to the appearance of unusual aquatic species. Since this warm counter-current occurred around Christmas, the local population named it El Niño, which is the Spanish nickname for the Christ child.

Then, in the 1920s and 1930s (Walker, 1924; Walker & Bliss, 1932, 1937), Walker identified a significant large-scale atmospheric pattern, which he named the *Southern Oscillation*. By analyzing in situ observations of surface sea level pressure (SLP) and precipitation (PR), he detected a spatial oscillation in the SLP field between the Indian and Pacific basins, characterized by two centers of action. One is located in the subtropical eastern hemisphere over Indonesia/Northern Australia, and the other in the western hemisphere to the east of the dateline. These centers exhibit opposite pressure anomalies, creating a zonal SLP gradient where an anomalously high SLP over the Indian and western tropical oceans is paired with an anomalously low SLP over the southeastern tropical Pacific, as illustrated in Figure I.4a. The Southern Oscillation Index (SOI) quantifies this zonal sea level pressure gradient, and is defined as the difference in SLP between Tahiti and Darwin in Australia (Ropelewski & Jones, 1987). Thus, a negative (positive) phase of the SOI indicates under-normal (above-normal) pressure in Tahiti and above-normal (under-normal) pressure in Darwin, corresponding to a weakening (strengthening) of the easterly trade winds and Walker Circulation.

Finally, Bjerknes's work put the pieces of the ENSO puzzle together. First, Bjerknes (1966) observed that during the El Niño winter of 1957-58, anomalously warm waters in the eastern and

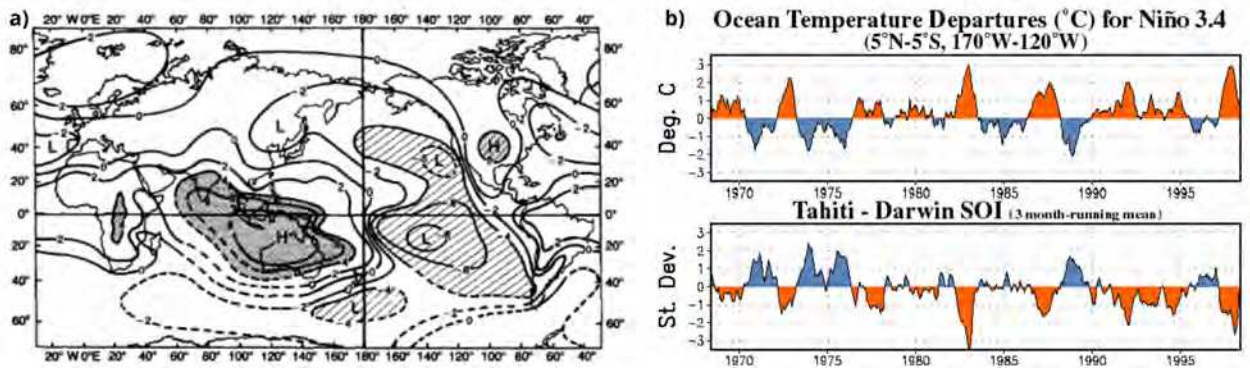


Figure I.4: (a) The annual mean sea level pressure anomalies associated with the Southern Oscillation pattern negative phase associated with El Niño events (Trenberth, 1997). (b) Time series of the Niño3.4 mean SST anomalies (top, °C) and the Southern Oscillation Index (bottom, standard deviation of SLP), reprinted from the National Oceanic and Atmospheric Administration website.

central equatorial Pacific were associated with unusual westerlies in the northeastern Pacific and an anomalous low pressure system in the Gulf of Alaska, and realized that El Niño events were not confined to the Peruvian coast but were a Pacific basin-wide phenomenon. Then, Bjerknes (1969) linked fluctuations in the Walker circulation as the trigger for the surface pressure seesaw of the Southern Oscillation, and made the link between the strengthening or weakening of the zonal gradient of SST in the central-eastern equatorial Pacific and the strength of the equatorial easterlies, hence the Walker circulation. Therefore, Bjerknes linked the anomalous warming associated with El Niño, which he recognized as extending not only along the coastal eastern tropical Pacific but also to the dateline in the central equatorial Pacific, to the Southern Oscillation seesaw (see I.4b). To an unusual warming of the central equatorial Pacific, hence a El Niño events (in red in Figure I.4b upper panel), corresponds a negative phase of the SO (in blue in lower panel), hence a weakening of the Walker circulation, and inversely for La Niña events. In addition, Bjerknes further recognized ENSO as a coupled ocean-atmosphere phenomenon and introduced the Bjerknes feedback mechanism, wherein anomalous warming in the eastern equatorial Pacific weakens the zonal SST gradient and the Walker circulation, resulting in reduced equatorial easterlies and wind stress, which in turn amplifies the initial SST anomaly and promotes the development and growth of El Niño events.

I.1.3 ENSO characteristics

ENSO events therefore involve a strong coupling between the ocean and the atmosphere. Emanating from the central-eastern equatorial Pacific Ocean, ENSO events can be described as a year-to-year disruptions of the seasonal cycle in the tropical Pacific, and are characterized by positives or negatives sea surface temperatures seasonal anomalies (SST) of up to 3 degrees, inducing diabatic heating anomalies in the atmosphere, resulting in a major modification of the

tropical atmospheric deep convection (Bjerknes, 1969).

El Niño events (Figure I.5a) are characterized by a weakening of the Walker circulation, leading to a weakening of the trade winds. This reduces the accumulation of warm water in the Pacific Warm Pool, causing the western thermocline to flatten. In addition, short-lived westerly wind events replace the usual trade winds, generating equatorial downwelling Kelvin waves (Vecchi & Harrison, 2000) that propagate eastward, deepening the thermocline in the eastern equatorial Pacific and disrupting the upwelling of cold water. As a result, the zonal equatorial SST gradient diminishes, facilitating the eastward propagation and amplification of initial positive SST anomalies through the Bjerknes feedback (Bjerknes, 1969; Jin, 1997). Consequently, regions of deep convection and intense precipitation shift eastward from their usual positions, and the atmospheric latent heating associated with the ascending branches of the Walker and Hadley circulations is now centered in the central-eastern Pacific (Ropelewski & Jones, 1987). This shift results in the southward movement of the ITCZ towards the equator and the northeastward shift of the SPCZ Rasmusson and Carpenter (1982). As a result, climatological precipitation over the western Pacific, the Maritime Continent and subtropical Australia are suppressed, whereas unusual wet anomalies in the central and eastern Pacific occur. Inversely, La Niña phases are characterized by a strengthening of the Walker circulation (Philander, 1985). Enhanced trade winds steepen the thermocline by promoting cold water upwelling in the eastern Pacific and westward advection that extends the CT westward along the equator, leading to an enhanced deep convection in the western Pacific, increased precipitation over the Maritime Continent and Australia, while the eastern and central Pacific are unusually dry.

Several regions where ENSO anomalies are prominent are often used to display anomalous time series that describe ENSO variability. From east to west, the most commonly used are (Figure I.6a) :

- the Niño 1+2 box (0-10°N, 90°W-80°W), corresponding to the region of the historical El Niño discovery by the Peruvian fishermen, in the far eastern equatorial Pacific near the Peruvian coast,
- the Niño 3 box (5°N-5°S, 150°W-90°W), covering the central-eastern equatorial Pacific,
- the Pacific Niño 3.4 box (5°N-5°S, 170°W-120°W), situated in the equatorial central Pacific,
- the Niño 4 box (5°N-5°S, 160°E-150°W), spanning the western equatorial Pacific.

In particular, the Niño 3.4 box is used to compute the Oceanic Niño Index (ONI), an index that serves as the operational definition for monitoring ENSO phases by the NOAA/CPC (n.d.) : an El Niño (La Niña) event is defined as five consecutive 3-month running averages of SST anomalies in Niño 3.4 SST anomalies above +0.5°C (below -0.5°C). Figure I.6a illustrates typical

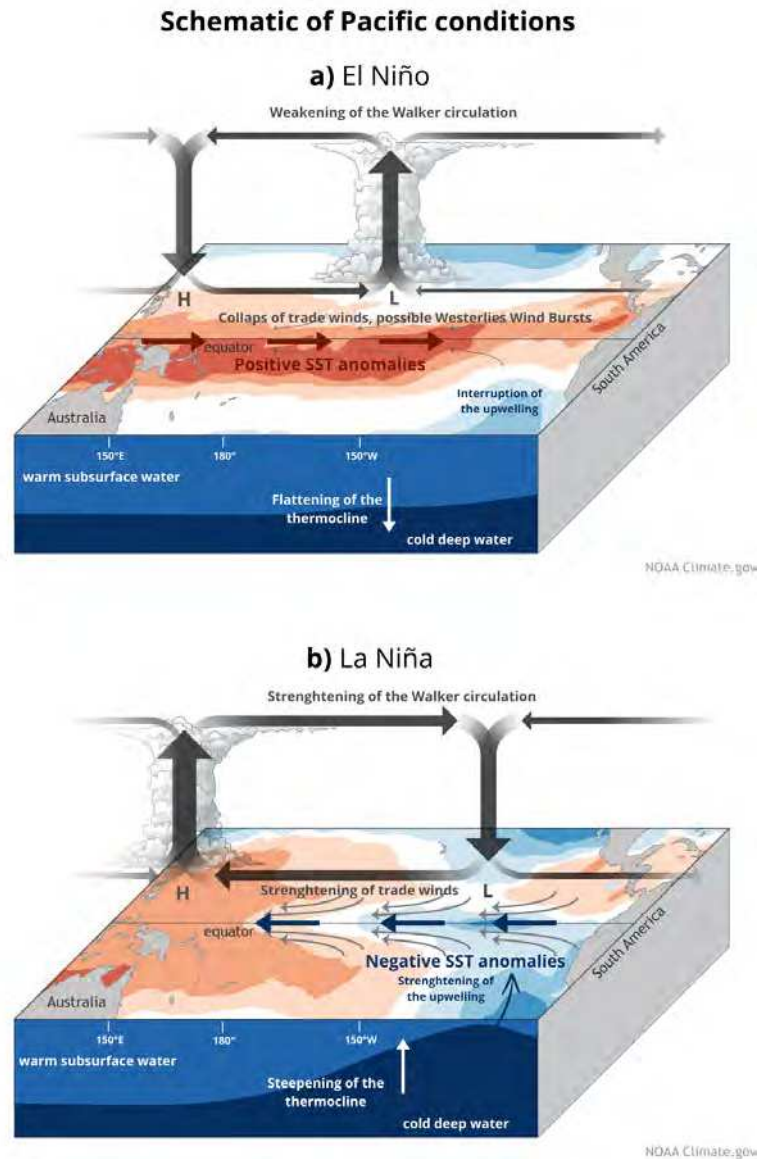


Figure I.5: Schematic of the tropical Pacific Ocean during a phase (a) El Niño and (b) La Niña, corresponding to departures to neutral conditions of the Walker circulation, as shown in Figure I.1b. The zonal shift of the Walker circulation during ENSO events is contingent upon the intensity of the ENSO event. A stronger collapse of the easterlies during a El Niño event results in a more pronounced eastward shift of the convective areas of the Walker ascending branch, and inversely for a La Niña event. Adapted from L’Heureux (2020).

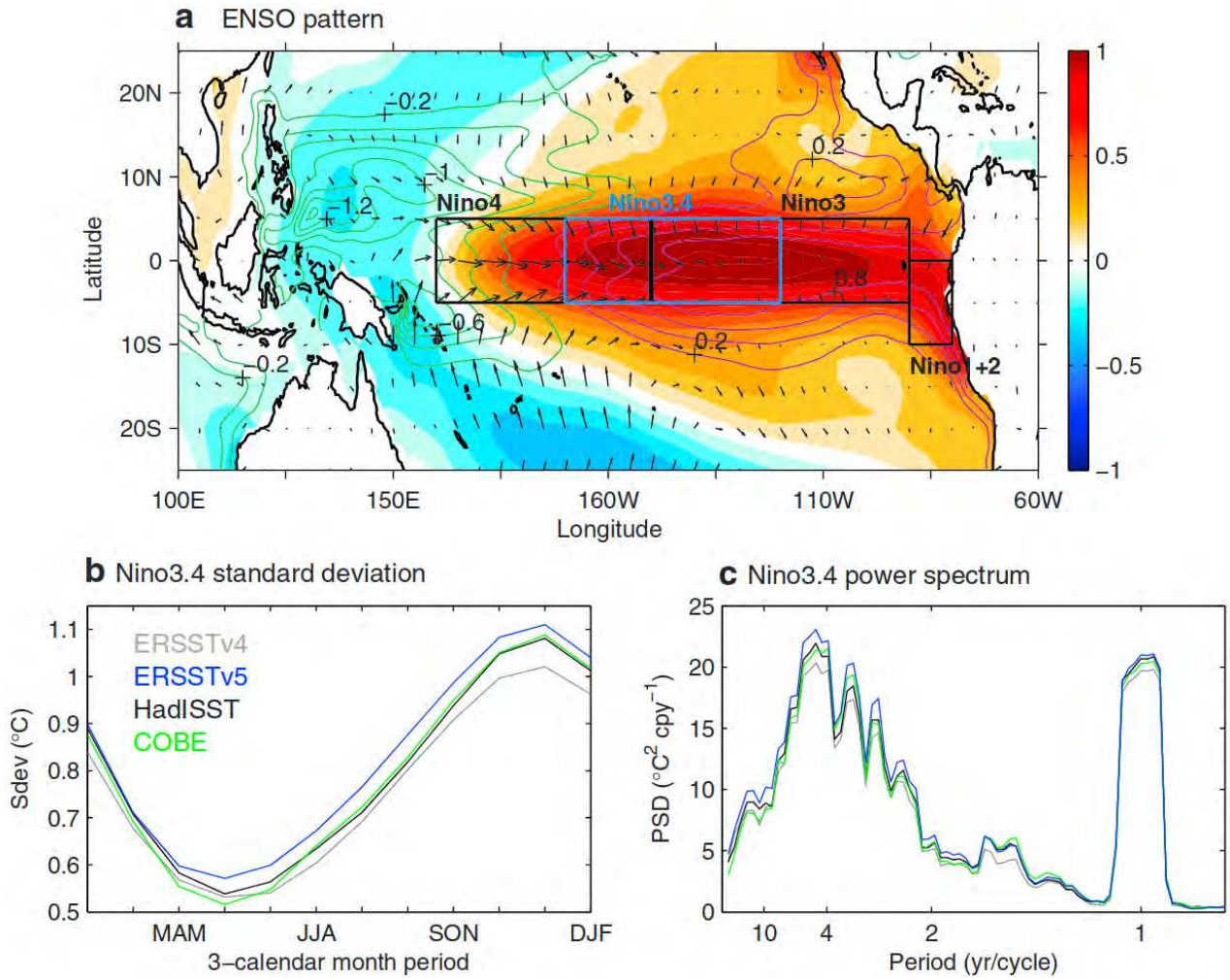


Figure I.6: (a) Anomaly patterns of ERSST v5 SST (shading), GODAS mean Ocean Temperature above 300 m (contours) and NCEP surface wind velocities (vectors) regressed onto the Niño 3.4 index. (b) Seasonal (3 month sliding window) of the standard deviation of the Niño 3.4 index, over 1950–2017 for various observational datasets. (c) Power spectrum of the Niño3.4 index computed over January 1950 and December 2016, indicating the characteristic frequency of ENSO at about 4 years/cycle. Reprinted from [Santoso et al. \(2017\)](#).

ENSO tropical anomalies, and was obtained by regressing SST, upper 300 m ocean temperature and surface winds anomalies onto the ONI. The overall ENSO pattern displays a pronounced warming in the central-eastern equatorial Pacific (Niño 3.4–Niño 4 regions), associated with an anomalously shallow thermocline (or enhanced heat content, see contours). Westerly wind anomalies are most prominent over the western equatorial Pacific (Niño 4 region). ENSO is phase-locked, in other words synchronized, with the seasonal cycle of Pacific SSTs ([Rasmusson & Carpenter, 1982](#); [Timmermann et al., 2018](#); [An & Wang, 2001](#)), as illustrated by the seasonal cycle of the Niño 3.4 SSTa variability in Figure I.6b). During boreal spring, as the Pacific SSTs warm north of the equator, the reduced coastal upwelling activity induces a warming of the coastal region, establishing a favorable mean state for the onset and growth of an ENSO event

or a phase transition. Consequently, El Niño events typically begin in boreal spring (Philander, 1983), enter a growth phase characterized by maximal air-sea coupling generated by the positive Bjerknes feedback in late summer to early fall (Tziperman et al., 1998; Li, 1997), and their associated SST anomalies reach peak magnitude in boreal winter, accompanied by reduced air-sea coupling. A rapid decline in growth rate then marks the termination of El Niño during the subsequent boreal spring, usually around March, and a delayed negative feedback of the ocean dynamical adjustment might induces a phase transition (Cane & Zebiak, 1985; Wyrski, 1975). ENSO phases alternate irregularly, with return periods of 2 to 7 years (Li, 1997; An & Wang, 2001). This broad interannual spectrum of the Niño 3.4 Index, shown in Figure I.6c, reflects the considerable variability in duration and phase transitions of ENSO events (Larkin & Harrison, 2002; An et al., 2020a). Typically, El Niño events peak in intensity during boreal winter and decay rapidly, whereas La Niña events can persist through late spring to early summer (Okumura & Deser, 2010; Ohba & Ueda, 2009). As a result, El Niño events often last less than a year, while a significant number of La Niña events can extend for up to two to three years, as observed in the 1998-2001 and 2020-2023 triple-dip La Niña events (Li et al., 2023; Jiang et al., 2023). Additionally, strong La Niña events frequently follow a year after strong El Niño events whereas the reverse is uncommon (Dommenges et al., 2012), underlying the significant diversity in ENSO characteristics.

I.1.4 ENSO diversity

ENSO spatial patterns are more varied than described above. The specificity of each ENSO realisation that has long been acknowledged (Wyrski, 1975; Trenberth, 1997), with significant variations in SST patterns, intensity, and duration observed between events. This inter-events variability is commonly referred to as ENSO diversity (Capotondi et al., 2015) or ENSO "flavors" when focusing on spatial SST patterns diversity, and ENSO complexity (Timmermann et al., 2018) when also considering temporal characteristics, predictability, and teleconnection patterns diversity.

First, the patterns of sea surface temperature (SST) anomalies during El Niño events do not mirror those of La Niña events, with El Niño typically exhibiting stronger and more eastward-shifted SST anomalies, whereas La Niña events tend to peak in the central Pacific with a more moderate amplitude (Hoerling et al., 1997; Burgers & Stephenson, 1999; An & Jin, 2004; Frauen & Dommenges, 2010). Early evidence of this nonlinear distribution of ENSO SST anomalies were provided by (Burgers & Stephenson, 1999), who demonstrated in observations that the SSTa distribution in the eastern equatorial Pacific (Niño 3 and Niño 1+2) were positively skewed, indicating stronger amplitudes of El Niño events relative to those of La Niña events in the region.

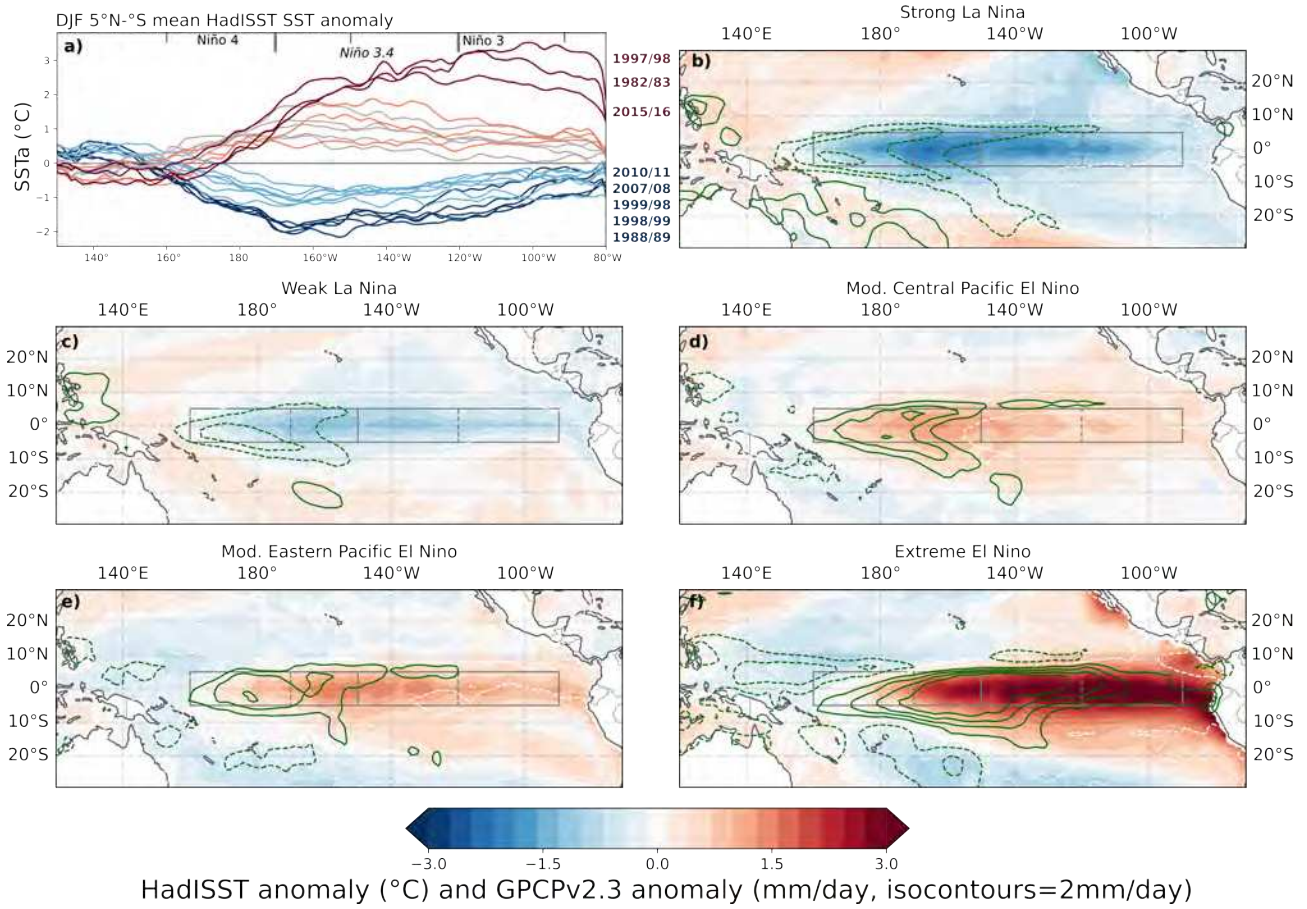


Figure I.7: (a) Meridional 5°N–5°S mean DJF SST anomalies from HadISST over the 1979–2019 period for Strong La Niña (dark blue), Weak La Niña (light blue), Moderate Central Pacific (CP) El Niño (light pink), Moderate Eastern Pacific El Niño (salmon), and extreme El Niño (red) events. (b–f) show the associated composites of anomalies in SST (shading) and precipitation (contours), from HadISST and GPCPv2.3.

In fact, this overall asymmetry between El Niño and La Niña hides a strong variety of SST patterns, now referred to as diversity ([Capotondi et al., 2015](#)) and illustrated on Figure I.7, which displays equatorial SST anomalies for El Niño (red-pink lines) and La Niña (dark-light blue lines) events from 1979 to 2019. La Niña events all to have maximum SST anomalies around 170°W, while some El Niño events tend to have maximum SST anomalies in the eastern Pacific (EP), and some in the central Pacific (EP events, also referred to as dateline or Modoki events; [Ashok et al. \(2007\)](#)). Various definitions have been proposed for classifying ENSO into CP and EP events. [Takahashi et al. \(2011\)](#); [Takahashi and Dewitte \(2015\)](#) for instance introduced the E and C indices, obtained from a 45-degree rotation of the phase-space defined by the two leading principal components of tropical SST anomalies in the Pacific. The SST pattern associated with the C index exhibits strong amplitude and negative skewness in the equatorial central Pacific, capturing La Niña and Moderate El Niño events. In contrast, the SST pattern associated with

the E index shows strong amplitude and positive SST skewness in the eastern equatorial Pacific, identifying the strongest SST anomalies typical of extreme warm El Niño events.

Another approach is indeed to differentiate ENSO events based on their intensity. As shown in Figure I.7, some El Niño events exhibit significantly stronger SST anomalies than others. Events such as the 1982/83, 1997/98, and 2015/16 El Niños are characterized by SST anomalies exceeding 2°C in the central-eastern equatorial Pacific, making them the strongest El Niños recorded under satellite observation. Usually classified into the EP El Niño category, these events can be labeled as extreme El Niño events (see Santos et al. (2017)). Although the recent observational dataset (1979 to present) contains only three realizations of such extreme events, their crucial role in shaping the ENSO asymmetric SST and precipitation distributions previously noted by Hoerling et al. (1997) and Burgers and Stephenson (1999) has been acknowledged in recent studies (Srinivas et al., 2024; Liu et al., 2024; Bayr et al., 2024). A simple way to describe things is that extreme EP events are EP events, but that some EP events can be moderate ENSO events (e.g. Figure I.7e composite, and Santos et al. (2017)).

Other metrics focusing on tropical convection features have been developed to characterize ENSO diversity. Chiodi and Harrison (2010, 2013) proposed distinguishing El Niño events based on Outgoing Longwave Radiation (OLR) anomalies in the central-eastern equatorial Pacific. Strong negative OLR anomalies indicate El Niño events associated with anomalously intense tropical atmospheric deep convection. They argue that these events are distinct from non-OLR El Niño events due to their ability to generate intense atmospheric heating anomalies, which trigger distinct remote atmospheric teleconnections (Chiodi & Harrison, 2010; Lau et al., 1997), and specific associated precipitation anomalies (Chiodi & Harrison, 2015). Similarly, Lengaigne and Vecchi (2009); Cai et al. (2014) differentiated moderate from extreme El Niño events based on eastern equatorial Pacific (Niño 3) precipitation anomalies. They defined extreme El Niño events as those associated with precipitation anomalies over Niño 3 exceeding 5 mm/day, indicating a major reorganization of tropical deep convection in the eastern equatorial Pacific and a southward shift of the ITCZ. Figure I.7f presents observed (from HadISST and GPCPv2.3 products) composites of tropical SST and precipitation anomalies for such extreme El Niño events, and illustrates a) a clear SST maximum in the eastern Pacific (i.e. EP type) and b) that they are the only El Niño-type associated with intense precipitation anomalies over Niño 3. In comparison, both CP and EP moderate El Niño events (panels d,e) do not exhibit heavy eastern Pacific rainfall Ren and Jin (2011).

During El Niño events, Southern Africa can for instance experience dry boreal winter conditions (Ratnam et al., 2014), whereas the boreal summer Indian monsoon can be weaker than usual (Kumar et al., 1999; Shukla & Paolino, 1983). Droughts and heatwaves impact Australia during boreal fall and early winter (Chiew et al., 1998; Reddy et al., 2022; Taschetto & England, 2009), which can in turn favor Australian wildfires (Abram et al., 2021; Harris & Lucas, 2019). Other examples include flooding in Ecuador-Peru-Columbia and drought in the Amazon region and north-east Brasil (Cai et al., 2020a). El Niño-induced wet conditions also increase the risk of malaria and mosquito-borne disease outbreaks in South America and South Asia (Kovats et al., 2003), while drought can result in respiratory diseases due to wildfires, as was experienced by Indonesia in 1997/98 (Siegert et al., 2001). In particular, the extreme El Niño events of 1997/98 (McPhaden, 1999) alone was associated with more than 20,000 casualties due to disease outbreaks and economic losses exceeding 30 billion dollars (McPhaden et al., 2006), as well as the catastrophic outcomes over Bangladesh during the following La Niña of

1998/99 (50% of the country was flooded and more than 20% of the total population affected (Glantz, 2001; Hossain et al., 1998), highlighting the necessity of accurately forecasting ENSO events and the associated impacts (Santoso et al., 2017).

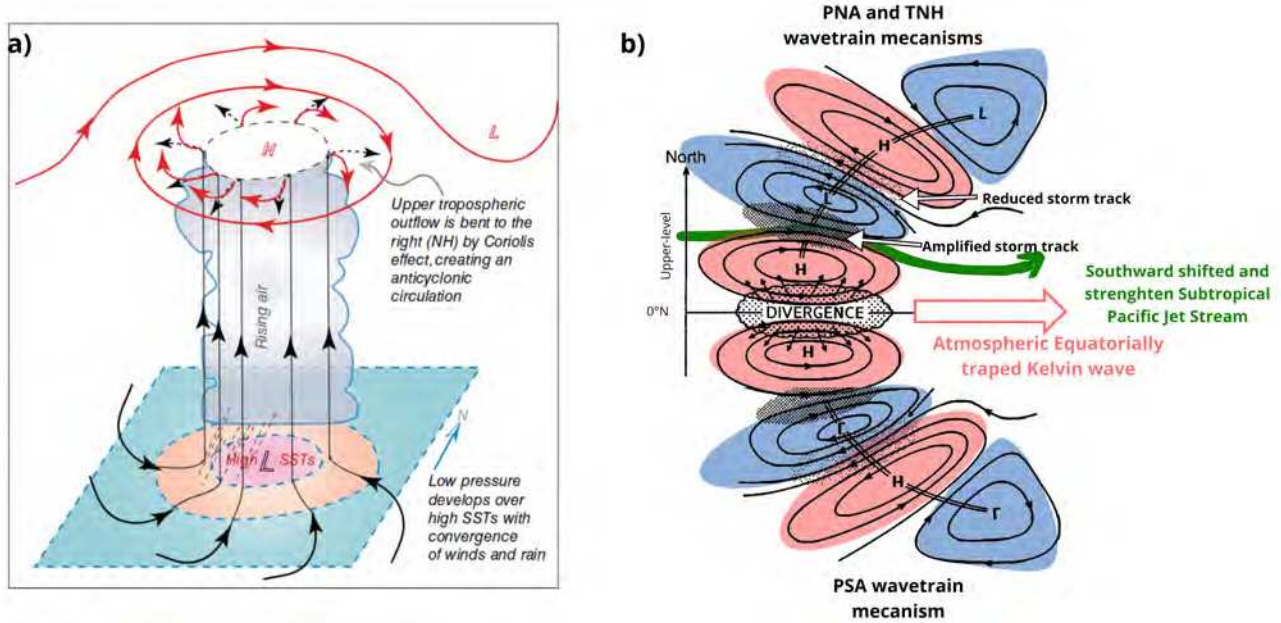


Figure I.9: Anomalous upper-level anticyclonic circulation triggered by warm SSTs in the tropical Pacific Ocean, resulting in the formation of a Rossby wave and ENSO-driven teleconnections, from (Trenberth, 2020). (b) Pathways of propagation of theoretical zonal symmetric teleconnections in the upper troposphere, adapted from Trenberth (1997).

Atmospheric teleconnections usually correspond to recurring patterns of atmospheric variability, that can either arise as internal atmospheric variability, or respond to an external forcing, such as tropical ENSO-related SST anomalies (Liu & Alexander, 2007). In this section, we will focus on describing the Rossby wave train mechanisms associated with the latter situation. Over the tropical Pacific, climatologically warm SSTs drive the ascending motions of the Walker and Hadley circulations, leading to organized regional heavy precipitation. However, occurrence of a positive El Niño SST anomaly induces anomalous equatorial low-level wind convergence and upwelling of moist surface air. The cooling and condensation of this moist air leads to an anomalous increase in local equatorial precipitation and the release of latent heat, creating an atmospheric tropical diabatic heating source anomaly shifted eastward from its climatological position (Bjerknes, 1966, 1969). As a result, the anomalous upward motion enhances deep convection and Hadley circulation overturning, forcing a stronger than normal upper-level divergence. This tropical baroclinic divergence structure driven by ENSO SST anomalies is schematized in Figure I.9a by illustrating the low-level convergence and upper-level divergence of the SST-induced anomalous convective flow.

East of the heat source, an equatorially trapped atmospheric Kelvin wave propagates anomalous signals eastward in the tropics (Gill, 1980; Matsuno, 1966). The anomalous upper-level divergent flow then advects the vorticity gradient, establishing an anomalous Rossby wave source (Hoskins & Karoly, 1981; Sardeshmukh & Hoskins, 1988) that propagates signal to the extratropics. A pair of upper-level anticyclonic (cyclonic) structures develops on both sides of the equator, resulting in the formation of an equatorial baroclinic Rossby wave on both sides of the equator. This upper-level anticyclonic circulation induced in the tropics then leads to convergence and subsidence in the subtropics (Trenberth et al., 1998; Taschetto et al., 2020), strengthens and shifts the subtropical Pacific jet stream southward, and induces a second anomalous cyclonic circulation in the extratropics over the North Pacific (Trenberth et al., 1998; Horel & Wallace, 1981), resulting in the formation of a stationary barotropic planetary Rossby wave train of alternating low and high geopotential anomalies (Bjerknes, 1969; Hoskins & Karoly, 1981; Trenberth et al., 1998), which propagates the perturbation poleward and eastward over North and South America before being refracted towards the equator at high latitudes (Horel & Wallace, 1981; Trenberth et al., 1998). In addition, the formation of the extratropical cyclonic circulation is associated with a modulation of the subtropical and subpolar upper-level jets, thus inducing an amplification (reduction) of storm track activity south (north) of the cyclonic circulation and a reduction to its north (Horel & Wallace, 1981; Trenberth et al., 1998). The schematic in Figure I.9 illustrates the propagation of such wave trains along preferred pathways, generating quasi-stationary anomaly wave-like patterns in geopotential height, stream-function, or sea level pressure fields (marked by "a trough of low pressure" for under-normal conditions, and "a ridge of high pressure" for over-normal conditions), as well as large-scale seasonal anomalies in precipitation, wind, and surface temperature.

I.2.2 Teleconnection patterns over North America

Wallace and Gutzler (1981) originally identified a dozen teleconnection patterns in the Northern Hemisphere. The most prominent of those patterns include the North Atlantic Oscillation (NAO) and Western Atlantic (WA) over the North Atlantic; the East Atlantic/Western Russian pattern, Scandinavia pattern, and Polar-Eurasia patterns over Europe and Asia; the Pacific-North America (PNA), Tropical/Northern Hemisphere(TNH), West Pacific (WP) patterns and North Pacific Oscillation patterns over the North Pacific. The main regions affected by these patterns are summarized on figure I.10, which outlines regions where these patterns explain more than 36% of the 500 hPa winter geopotential height anomalies. This highlights the importance of these teleconnection patterns for modulating the NH climate. Similar teleconnection patterns also exist in the Southern Hemisphere (Mo & White, 1985; Mo & Ghil, 1987), such as the Pacific South America (PSA1 and PSA2) patterns, which are considered the Southern Hemisphere equivalent of the PNA (Mo & Higgins, 1998; Irving & Simmonds, 2016).

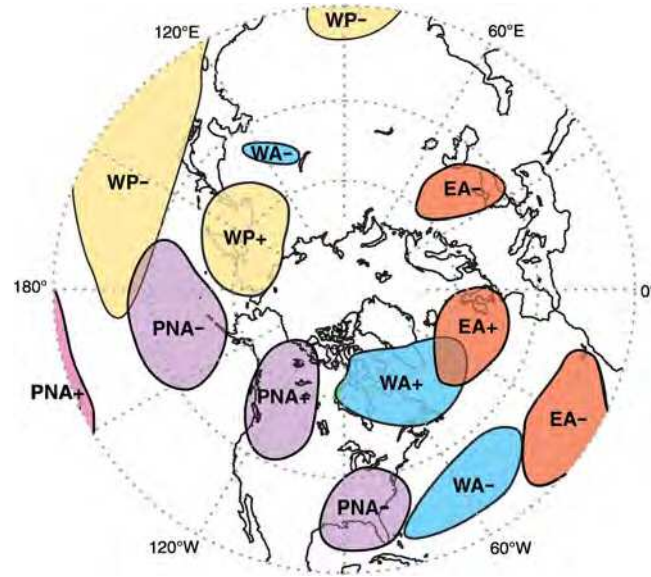


Figure I.10: North Hemisphere teleconnectivity map (based on grid point-by grid point correlation coefficients) of the 500 hPa geopotential height, showing the centers of action associated with five main teleconnection patterns : the PNA (pink shading), the Western Atlantic (WA, green shading), the Eastern Atlantic (EA, orange shading), the Eurasian (blue shading) and the Western Pacific (WP, yellow shading). Original figure from (Wallace & Gutzler, 1981), colored version taken from An et al. (2020b).

These patterns are usually generated by internal atmospheric dynamics, as mentioned above. Some of them can however also be externally forced by tropical convection changes, such as those associated with ENSO SST anomalies (or the Madden-Julian Oscillation, which is outside the scope of this thesis) through the Rossby wave train mechanism described above. Given that ENSO SST signals are predictable several seasons in advance (L’Heureux et al., 2020; Newman, 2013; Lenssen et al., 2020) and that forecasts skills continue to improve (Barnston et al., 2012), ENSO atmospheric teleconnections are essential for accurate seasonal forecasts. In fact, ENSO is the major driver of year-to-year climate variability in the Northern Hemisphere (Timmermann et al., 2018), and by consequence a primary source of predictability for the North American climate, particularly in boreal winter (Yu et al., 2012; Kumar & Hoerling, 1995, 1998; Gershunov & Barnett, 1998). Unless indicated otherwise, I discuss boreal winter (December to January, also noted DJF, averages) below.

I.2.2.1 The Pacific-North American teleconnection pattern

SST anomalies in the Niño 4 region strongly drive the Pacific-North American (PNA) pattern (Barsugli & Sardeshmukh, 2002; Simmons et al., 1983). The PNA is widely recognized as the dominant boreal winter ENSO teleconnection pattern over North America (Horel & Wallace, 1981; Hoerling et al., 1997; Trenberth et al., 1998). Its temporal index (PNA index (Wallace & Gutzler, 1981)) is indeed highly correlated with North American winter temperature and

precipitation fluctuations (Leathers et al., 1991; Leathers & Palecki, 1992; Yu et al., 2015; Ropelewski & Halpert, 1986). The pattern is characterized by four centers of action, a term first coined by Bjerknes (1969). The aforementioned centers of action are driven by the Rossby wave mechanisms described in Figure I.9, which shape the spatial specificity of the PNA pattern. Finally, it should be noted that the PNA pattern can be forced by internal atmospheric variability and exist in absence of ENSO SST forcing.

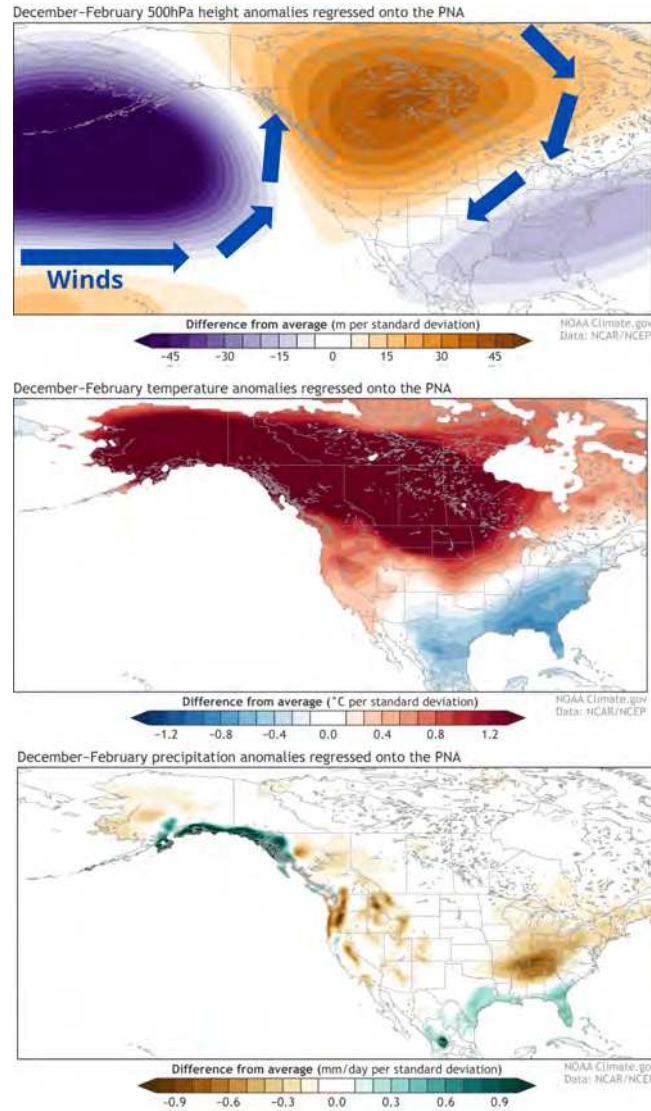


Figure I.11: North American patterns of (a) 500 hPa geopotential height (Z500), (b) surface temperature (TS), and (c) precipitation observed anomalies during DJF regressed onto the PNA index, reprinted from L’Heureux (2019), depicting the positive phase of the PNA. Winds induced by the anomalous circulations are illustrated with blue arrow.

Figure I.11 presents a regression of DJF North American climate anomalies onto the PNA index. A positive phase of the PNA (often associated with El Niño) (Trenberth, 1997), features an anticyclonic circulation centered over Hawaii, a cyclonic circulation centered in the vicinity of

the Aleutian Islands, a large anticyclonic circulation over western-central Canada, and a smaller cyclonic circulation over the southeastern United States coast. The cyclonic circulation of the Aleutian Low facilitates the northward advection of warm and moist air from the subtropical region towards the western coast of North America by mid-level winds. Combined with the high-pressure ridge over Northwest Canada, this tends to hamper cold air outbreaks over Alaska and Northwest Canada, increasing the likelihood of warmer-than-average temperatures over Northwestern America, and an increased precipitation over the Southern coast of Alaska and far Northwest Canada coast. In addition, the high-pressure ridge over western North Canada and southern incursion of the polar jet stream over Northeast America promotes cold air outbreaks in the southeastern United States, resulting in below-normal temperatures in this region, and a southeast shift of the precipitation associated with the Polar Jet cyclonic activity results in drier than average Southwestern-central US (Leathers et al., 1991). Moreover, as mentioned above, the strengthening of the subtropical jet stream drives more active storm track activity over the southern United States, resulting in wet anomalies along the southeastern U.S. coast (Eichler & Higgins, 2006). During La Niña winters, a negative phase of the PNA is usually observed, associated with opposite sign climate impacts (Hoerling et al., 1997; Cayan et al., 1999; Hannachi, 2001).

I.2.2.2 The Tropical/Northern Hemisphere teleconnection pattern

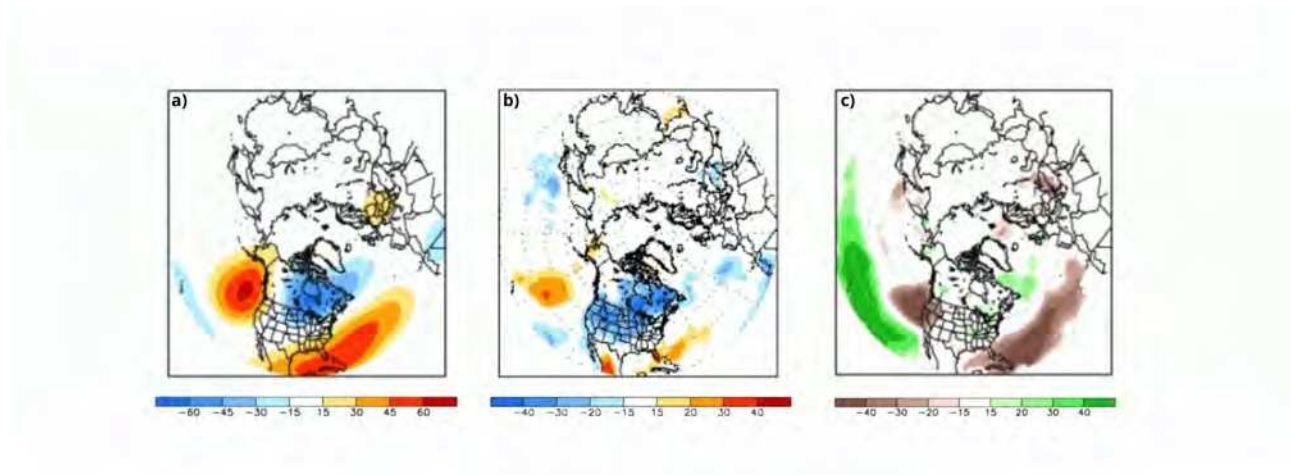


Figure I.12: Positive phase of the TNH pattern correlated with the January 1950-2000 (a) geopotential height (b) surface temperature (c) precipitations anomalies. Flip sign for the negative phase associated by Hoerling et al. (1997) with El Niño events. Reprinted from National Weather Service, Climate Prediction Center (2012).

Although less prominent than the PNA pattern, the negative phase of the Tropical/Northern Hemisphere (TNH) pattern is also recognized as another ENSO teleconnection pattern over the North Pacific-North America region (Mo & Livezey, 1986; Livezey & Mo, 1987; Hoerling et al., 1997; Yu et al., 2015; Soulard et al., 2019). I will confirm that this pattern is indeed associated

with ENSO (and specifically with extreme El Niño events) in chapters III and IV. Figure I.12a presents the TNH pattern signature in the mean geopotential height, surface temperature and precipitations anomaly for January (the TNH pattern explains a maximal amount of variability of 9.8% in January, 6.3% in December, and 7.4% in February (Barnston & Livezey, 1987)). This pattern is usually obtained as the 4th leading rotated EOF pattern - with the NAO, PNA, and WPO representing the first, second, and third leading modes of variability in the Northern Hemisphere, respectively (Wallace & Gutzler, 1981; Mo & Livezey, 1986) - and features a wave train in phase quadrature (eastward shifted) with respect to the PNA pattern. The TNH depicts a stronger and eastward-shifted climatological Aleutian Low, now extending to the North American West Coast. The large positive center is now over the US Great Lakes region, and a negative center appears over Cuba and the Gulf of Mexico. Surface temperature and precipitation anomalies associated with the TNH pattern also appear eastward-shifted compared to the PNA pattern (see Figure I.12b and c). The advection of warm and moist tropical air is facilitated eastward and northward, resulting in strengthened precipitation anomalies along the Western US coast, including the state of California. In particular, it has been shown that a southward shift of the jet during the 1998 January and February were associated with strong precipitation anomalies over California (Wang et al., 2017). Additionally, the high-pressure system over the Great Lakes blocks the southward advection of cold air from polar regions, leading to warmer than usual surface temperatures across a broad band stretching northeastward over North America. Finally, this pattern is associated with a strong extension of the subtropical Pacific Jet towards the southwestern US coast (Straus & Shukla, 2002; Soulard et al., 2019), increasing the likelihood of precipitation anomalies over the Gulf of Mexico and Florida through a more active storm track.

I.2.3 Diversity of ENSO-teleconnections

A first approach to explore ENSO teleconnections involves assuming a single pattern, i.e., that atmospheric teleconnections scale linearly with ENSO SST forcing. This typical ENSO patterns is often obtained by regressing climate variables onto the Niño 3.4 SST index, as can be seen for wintertime global scale on figures 14.4 and 14.5 of Taschetto et al. (2020), for continental US regional scale in L’Heureux et al. (2024) or for mid-level geopotential height anomaly, in Figure II.1. However, the recognition of the existence of different ENSO teleconnection patterns illustrates the nonlinear nature of ENSO teleconnections (Taschetto et al., 2020), adding some complexity in the assessment of ENSO teleconnection. In this section, we will describe two possible drivers of this teleconnection diversity.

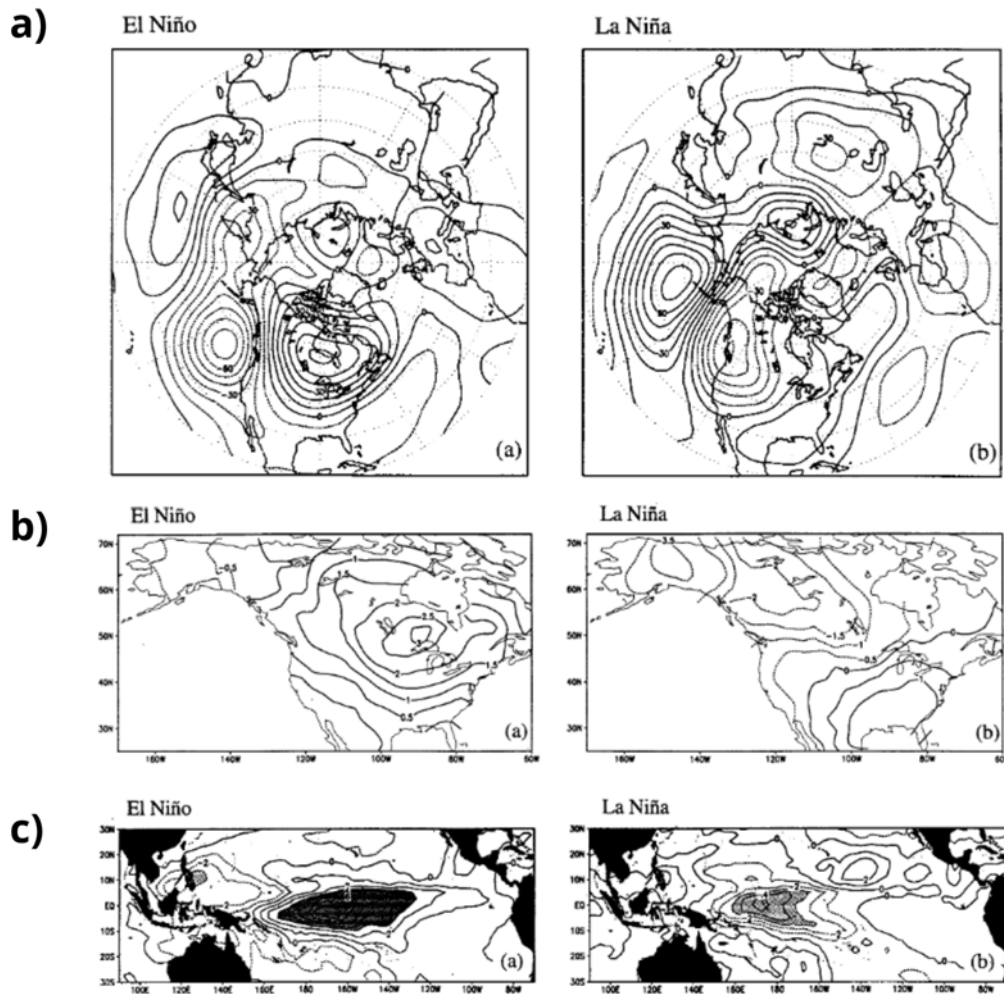


Figure I.13: Composites of observed seasonally averaged DJF (a) 500 hPa geopotential height, (b) surface temperature and (c) precipitation anomalies during El Niño (left) and La Niña (right) events. Reprinted from [Hoerling et al. \(1997\)](#).

I.2.3.1 El Niño-La Niña : role of atmospheric nonlinearities

[Hoerling et al. \(1997, 2001\)](#) found a 35° longitudinal phase shift between El Niño and La Niña teleconnections in observations and idealized Atmospheric General Circulation Model (AGCM) experiments (Figure I.13). Although they did not name the teleconnection patterns, they showed that while La Niña events were associated with a negative PNA-like teleconnection pattern, El Niño teleconnection patterns were more alike the THN pattern.

The authors attributed this warm/cold event teleconnection diversity (also noted by [Livezey et al. \(1997\)](#); [Zhang et al. \(2014\)](#); [Hannachi \(2001\)](#); [Peng and Kumar \(2005\)](#)) to the nonlinearity of the tropical deep convective precipitation response to SST. [Graham and Barnett \(1987\)](#); [Gadgil et al. \(1984\)](#) indeed showed that total SSTs above 27.5°C are a necessary, although not sufficient, condition for initiating deep convection in the tropics, as shown in Figure I.14. In the equatorial Pacific, there is a strong climatological SST zonal gradient—with $24\text{--}25^\circ\text{C}$ SST

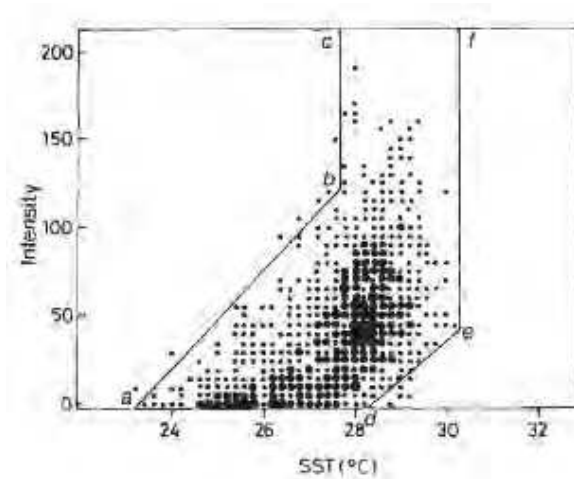


Figure I.14: Cloudiness intensity plotted against SST for June-September 1966-1972, illustrating the nonlinear regime shift of the deep convective response to SSTs around 27-28°C. Taken from Gadgil et al. (1984).

in the eastern Pacific Cold Tongue region and SST above 28°C in the Western Pacific Warm Pool (see Figure I.2), crossing the SST convective threshold west of the dateline. Positive SST anomalies during El Niño increase the total SSTs east of this threshold, while negative La Niña SST anomalies suppress climatological precipitation further west. This nonlinear mechanism is assumed to explain the eastward shift of El Niño anomalous tropical convective sources relative to those of La Niña's, in turn shifting in its turn the extratropical atmospheric responses. The atmospheric dynamics nonlinear response to tropical diabatic heating may provide an additional source of atmospheric nonlinearities. Most previous studies however concluded that this nonlinearity is weak (DeWeaver & Nigam, 2002; Ting & Yu, 1998; Jiménez-Esteve & Domeisen, 2019). This suggest that the primarily source of atmospheric nonlinearities is the nonlinear relation between convection and SST in the tropical Pacific.

I.2.3.2 Role of the SST forcing diversity

Another potential source of changes in teleconnection patterns is the diversity in ENSO SST patterns. Several studies have linked variations in climate impacts over North America to shifts in the zonal position of maximal SST anomalies across the equatorial Pacific. Specifically, the distinction between SST anomalies in the Central Pacific (CP) versus the Eastern Pacific (EP) has been identified as a major driver of teleconnection diversity over various regions, including East and Southeast Asia (Yang & Jiang, 2014; Nguyen-Thanh et al., 2023), the North Atlantic and Europe through modulation of the NAO (López-Parages et al., 2015; Jiménez-Esteve & Domeisen, 2018; Zhang et al., 2018; Graf & Zanchettin, 2012), Australia (Taschetto & England, 2009; Ma et al., 2022).

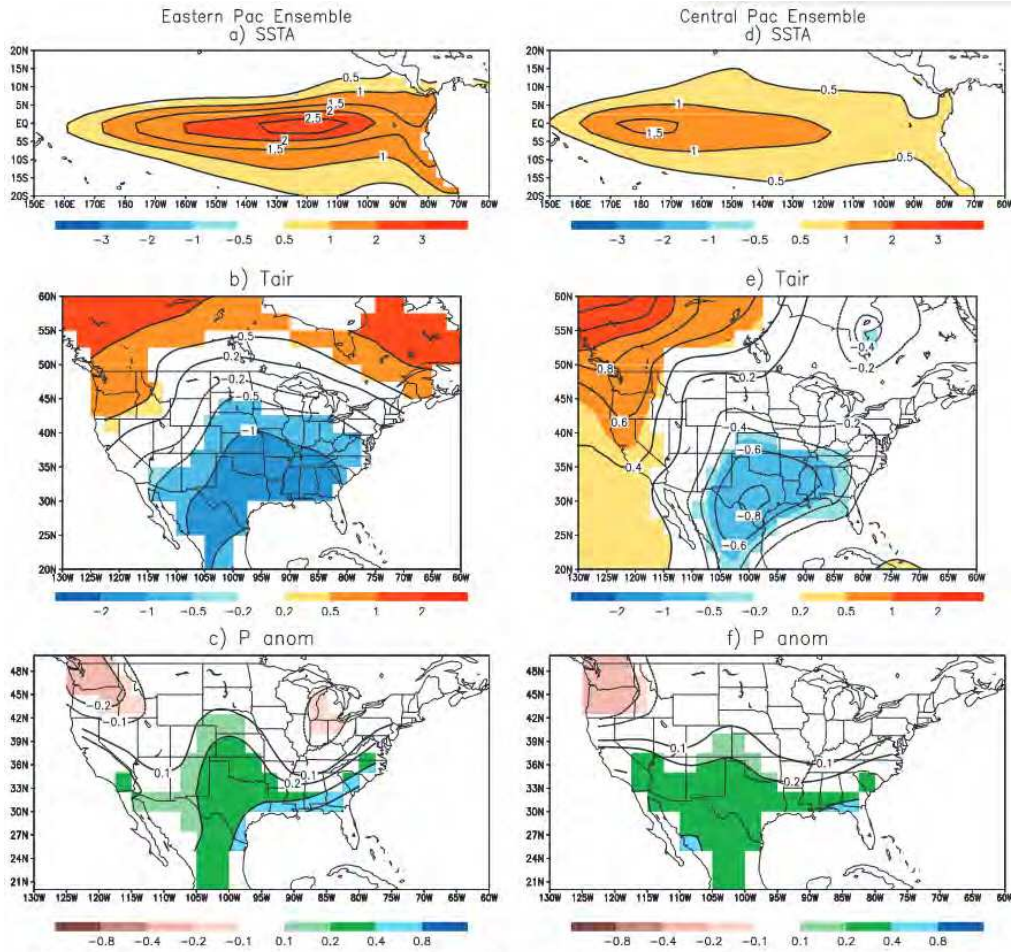


FIG. 8. (a) Composite of the SSTA ensemble mean for the EPAC ENSO. Contour interval is 0.5°C . Zero contours are omitted. Areas where values are statistically significant at the 5% level are colored. (b) As in (a), but for the air temperature T_{air} . Contour interval is 0.5°C . Contours -0.2° and 0.2°C are added. (c) As in (b), but for P . Contour interval is 0.2 mm day^{-1} . Contours -0.1 and 0.1 mm day^{-1} are added. (d)–(f) As in (a)–(c), but for the CPAC ENSO.

Figure I.15: (a) Composite of the SSTA IPCC 20C3M models ensemble mean for the EPAC ENSO. Contour interval is 0.5°C . Zero contours are omitted. Areas where values are statistically significant at the 5% level are colored. (b) As in (a), but for the air temperature T_{air} . (c) As in (b), but for precipitations. Contour interval is 0.2 mm/day . (d)–(f) As in (a)–(c), but for the CPAC ENSO. From Mo (2010).

For North America, Barsugli and Sardeshmukh (2002) demonstrated that regional circulation and precipitation anomalies are particularly sensitive to the zonal position of SST anomalies in the equatorial Pacific. In agreement with Larkin (2005), Ashok et al. (2007); Garfinkel et al. (2012) noted that CP El Niño (Modoki El Niño/Dateline) do not significantly impact winter precipitation over North America in observations. In contrast, they found that EP El Niño (traditional El Niño/conventional) events cause precipitation anomalies along the US west coast and Florida, along with a warming along a large band spanning the US-Canada border region. Similarly, Yu et al. (2012, 2015) demonstrated that while a PNA-like response can be induced by both CP and EP events, a TNH-like response is found to be associated only with EP events, with distinct precipitation and temperature impacts over North America. They also noted a

stronger statistical significance of teleconnections for EP events than for CP events. In CMIP3 IPCC 20C3M ensembles simulations, [Mo \(2010\)](#) also connected the TNH pattern to EP events, reproducing the as shown on figure [I.15](#). However, they noted a limited robust response for precipitation anomalies during EP events over California and southwestern US, associated with a large diversity of responses in the different models used for the study. Finally, [Ding et al. \(2018\)](#); [Shi et al. \(2019\)](#) related the EP El Niño pattern to an increased convection in the eastern Pacific, triggering a TNH-like teleconnection pattern, in contrast with CP events. In particular, the latter study related the contribution of the SSTa located east of 150°W in the EP pattern with an increase of precipitation anomalies over the west US Coast, therefore California.

I.2.3.3 Contribution of strong convective/extreme El Niño events

Conventional methods for distinguishing CP and EP events often fail to account for the varying amplitudes within the EP category. Moderate EP events, such as the 1986/87 or 2006/07 EP events (classified by [Yu et al. \(2012\)](#); [Ren and Jin \(2011\)](#); figure [I.7](#)), exhibit weaker and westward-shifted precipitation responses than those during strong/extreme EP El Niño events. This questions the attribution of teleconnection diversity to the ENSO type, as not all EP events are strong EP events, but all strong events are EP events. In other words, are the specific teleconnection patterns associated with EP events just associated with a subcategory of these EP events: extreme events. This is one of the main question I will investigate from chapter [III](#) onward. Here I review the studies closest to that question, which have classified ENSO events based on their capacity to induce a convective response in the eastern Pacific, assuming that this convective response is instrumental in shaping North American teleconnections. [Chiodi and Harrison \(2013, 2015\)](#) demonstrated that El Niño events with convective perturbations in the eastern-central Pacific (160°W to 110°W) yield more statistically significant teleconnections than other El Niño events. They defined "OLR El Niño events" as those associated with eastern equatorial Pacific Outgoing Long-wave Radiation (OLR) anomalies below -20 W/m^2 . [Johnson and Kosaka \(2016\)](#) refined these results using ensemble AGCM experiments, identifying statistically significant differences in teleconnection patterns between El Niño events with and without convective perturbations in the eastern-central Pacific. Only the former events were associated with a TNH-like teleconnection pattern, pronounced warming over Canada, and increased precipitation over the west and southwest US. Notably, they demonstrated a gain in predictability of teleconnection patterns for convective El Niño events, underlining the relevance of distinguishing between events associated or not with nonlinear SST-deep convection relationship in the eastern Pacific rather than with SST anomalies in the central or eastern equatorial Pacific.

Finally, some EP El Niño events, such as those in 1982-83, 1997-98, and 2015-16, reach much larger SST anomaly magnitudes than other types of events, leading to their classification as

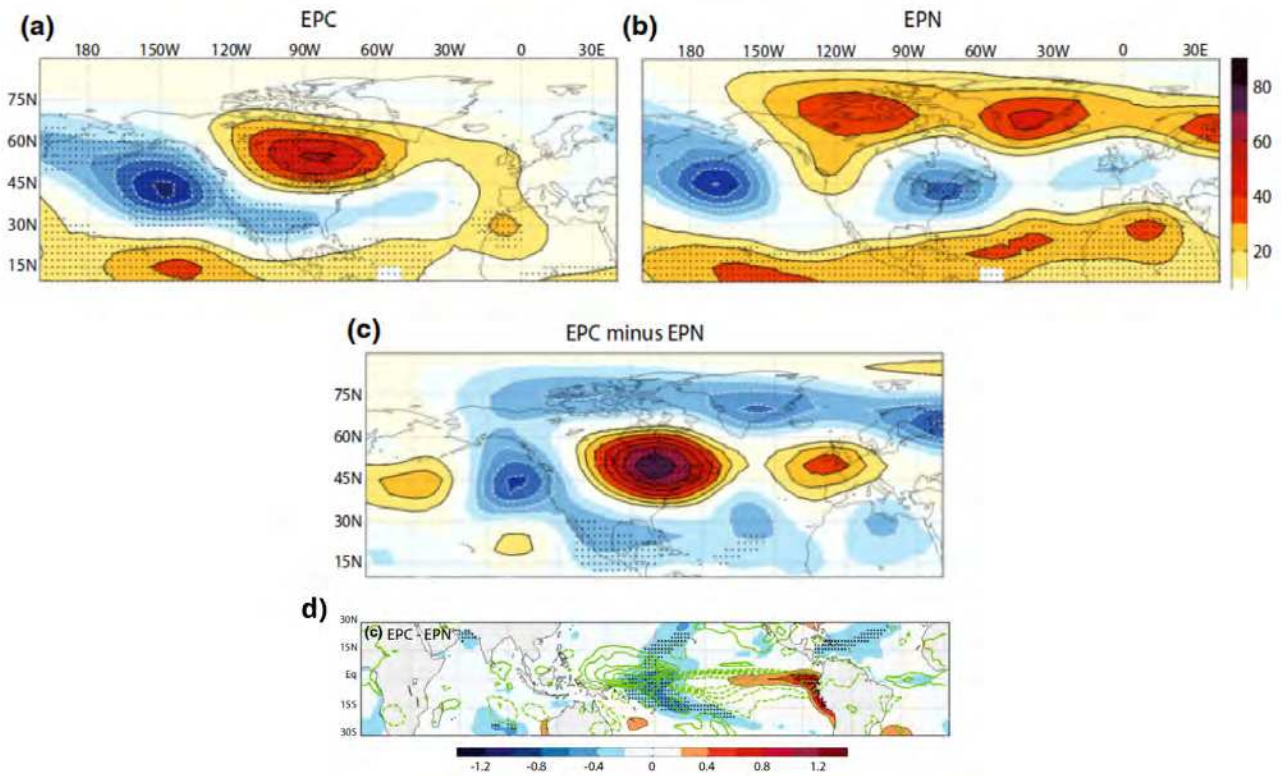


Figure I.16: December-March composites of 300 hPa geopotential height anomalies normalized by Niño 3.4 SSTa, for (a) eastern convective (EPC) El Niño, (b) non-convective eastern Pacific (EPN) El Niño, (c) their difference. (d) December–March normalized composite anomalies of SST (color shading °C°C⁻¹) and OLR (green contours in Wm⁻²°C⁻¹) for the EPC-EPN difference. From [Johnson and Kosaka \(2016\)](#).

extreme El Niño events (see their SSTa composite in Figure I.7, or in [Santoso et al. \(2017\)](#); [Dewitte and Takahashi \(2019\)](#)). Although only three such events have been recorded since the start of the satellite era, they exhibit distinct characteristics. These extreme ENSO events play a pivotal role in shaping the SST and rainfall asymmetry between El Niño and La Niña ([Bayr et al., 2024](#); [Liu et al., 2024](#); [Srinivas et al., 2024](#)). They are associated with precipitation anomalies stronger than 5 mm/day in the eastern equatorial Pacific, where climatologically cold SST anomalies usually act as a barrier to tropical deep convection. Only their strong SST anomalies allow the total SST to surpass the convection threshold, inducing massive precipitation anomalies in the eastern Pacific ([Srinivas et al., 2022, 2024](#)).

Focusing on Californian winter precipitation anomalies, [Lee et al. \(2018\)](#) demonstrated that persistently warm far eastern Pacific SSTs associated with such extreme El Niño events can excite an optimal stationary wave pattern. This pattern depicts an anomalous cyclonic circulation over the North Pacific extending to the western US coast, increasing the likelihood of precipitation anomalies over California. The connection between strong El Niño events and increased Californian precipitation has been supported by other studies ([Hoell et al., 2016](#); [Jong](#)

et al., 2016). This opens the question of whether the category of El Niño events that induce a different teleconnection pattern and specific impacts over North America should not be narrowed down to extreme El Niño events (a subcategory of convective El Niño, itself a subcategory of EP events, itself a subcategory of El Niño).

I.2.4 The internal variability challenge

However, attributing ENSO teleconnection diversity to a specific event type in observations is challenging due to the considerable uncertainties in the teleconnection pattern itself. Internal climate variability, i.e. the unforced variability internal of the observed or simulated climate (Deser et al., 2010, 2012), needs to be considered, as mid-latitude internal atmospheric variability is considerable (Jha et al., 2018; Madden, 1976; Kumar & Hoerling, 1998; Deser et al., 2017). It constitute a source of unpredictable noise modulating precipitation and surface temperature signals, and is often found to be of a greater magnitude than the SST-forced extratropical atmospheric variability (Madden, 1976; Hoerling & Kumar, 1997). This large internal variability can thus obscure ENSO signals, leading to substantial sampling errors in ENSO teleconnection patterns obtained from observations (Garfinkel et al., 2012; Deser et al., 2017) or too small ensemble simulations (O'Reilly, 2018; Sardeshmukh et al., 2000; Brands, 2017). The PNA pattern itself displays considerable internal variability (Straus & Shukla, 2002; Soulard et al., 2019; Lin & Derome, 1999; Zhang et al., 1996), and can also be forced by other convective sources than ENSO such as the Madden-Julian Oscillation MJO (Seo & Lee, 2017; Mori & Watanabe, 2008; Johnson & Feldstein, 2010).

Therefore, addressing this internal variability issue requires large sample sizes (Garfinkel et al., 2018; Deser et al., 2018), which can be achieved using large ensemble simulations. The Coupled Model Intercomparison Project version 6 (CMIP6) database (Eyring et al., 2016) offers a considerable database with multiple models, providing up-to-date versions of state-of-the-art climate models. In their Atmosphere-only configuration, large AMIP model ensembles forced with observed SST and sea ice fields also allow circumventing internal variability and sampling issues.

I.2.5 The model bias challenge

It is thus best to investigate ENSO teleconnections using large model ensembles. However, AMIP models, for instance, often suffer from biases due to imperfect parameterizations, such as underestimated ITCZ precipitation (Zhang et al., 2024), overestimated surface latent and sensible heat fluxes (Zhou et al., 2020a; Xiang et al., 2017), and surface wind biases (Feng et al., 2023), and missing atmospheric eddy feedbacks (Hardiman et al., 2022). Coupled CMIP models suffer from even larger systematic biases (see Guilyardi et al. (2020) for a review), affecting

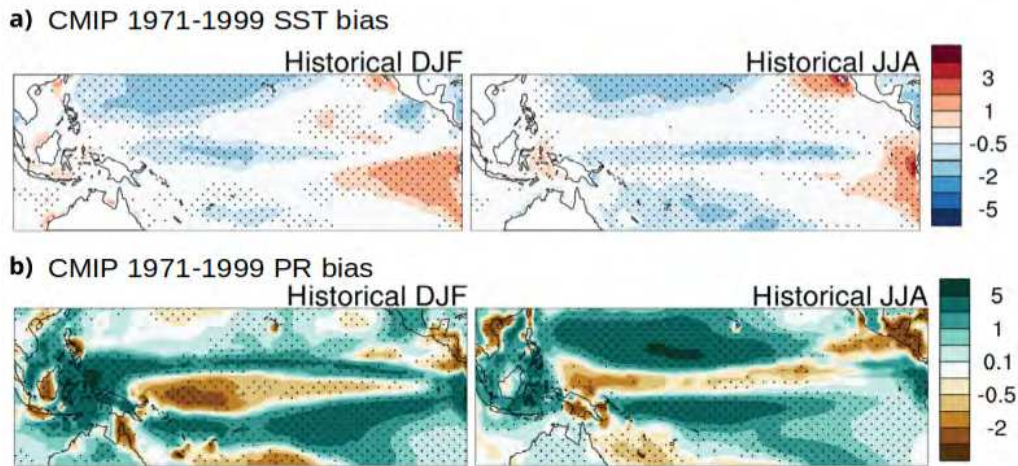


Figure I.17: (a) The equatorial Cold Tongue SST bias from an large ensemble of CMIP5/PMIP3 and CMIP6/PMIP4 models (CMIP), calculated over the 1971-2000 period, relatively to HadISST dataset, and (b) the equatorial dry precipitations (PR) bias in CMIP, relatively to 1979-1999 GPCP observations. Reprinted from [Brown et al. \(2020\)](#).

their representation of ENSO, and ENSO teleconnections. Notably, persistent biases include the double ITCZ bias, where models inaccurately extend precipitation into the southern equatorial band (10°S) of the western Pacific, resulting in a drier than observed eastern equatorial Pacific ([Tian & Dong, 2020](#); [Ma et al., 2023](#)), the equatorial zonal wind stress bias, with stronger than observed zonal winds in the western Pacific and weaker winds in the central Pacific ([Li et al., 2020a, 2022](#)), or overestimate surface latent and sensible heat fluxes ([Zhou et al., 2020a](#); [Xiang et al., 2017](#)). Finally, atmospheric mean state biases in CMIP models, such as the North Pacific jet bias (where models presents a too equatorward shifted North Pacific jet), can also affect Rossby wave patterns that drive teleconnections to the Pacific-North American sector during El Niño events ([Li et al., 2020b](#)).

Another critical issue of CMIP bias is the equatorial Pacific zonal SST bias, or the "equatorial cold tongue bias," where models simulate colder than observed SSTs along the equatorial Pacific ([Zhou et al., 2020a](#); [Planton et al., 2021](#); [Zhang et al., 2023](#)). This bias leads to El Niño SST anomalies peaking too far west compared to observations ([Bellenger et al., 2013](#); [Guilyardi et al., 2009](#); [Brown et al., 2020](#)) and results in an underestimation ([Zhao & Sun, 2022](#); [Fang & Yu, 2020](#)) or failure in capturing the ENSO diversity ([Ineson et al., 2021](#)), such as CP and EP El Niño types ([Ham & Kug, 2011](#); [Sun et al., 2016](#)). The SST bias is also linked to the dry equatorial bias, as shown in Figure I.17 for a large ensemble of various CMIP5-CMIP6 models ([Brown et al., 2020](#)), and is found to hinder the initiation of deep convection ([Bayr et al., 2024](#)), even during extreme El Niño events, thereby limiting the occurrence of significant eastern Pacific rainfall anomalies as defined by [Cai et al. \(2014\)](#). Indeed, [Cai et al. \(2014\)](#) showed that not all CMIP3 and CMIP5 models can reproduce extreme El Niño events, whereas those events are

crucial for capturing ENSO asymmetry and amplitude in CMIP6 (Bayr et al., 2024). Overall, these biases raise doubts about the robustness of the teleconnection patterns derived from a single model. Therefore, assessing ENSO teleconnections and the potential reproducibility of their climate impacts requires a multi model-multi member ensemble approach and large number of ensemble members.

I.3 ENSO teleconnections in a warming world

I.3.1 Global warming : observation, model projections

I.3.1.1 Global scale changes

Characterizing and assessing the diversity of ENSO teleconnections over North America is challenging in both observations and models under current climate conditions. The global warming of the climate system, driven by increased greenhouse gas (GHG) concentrations due to anthropogenic activities, introduces additional complexities. It is therefore essential to understand if, how, when, and why ENSO characteristics and associated atmospheric teleconnections are projected to change in a warmer climate, to improve the forecasting of future impacts (Karamperidou et al., 2020; Cai et al., 2020b).

Since the pre-industrial era (1850), the planet has experienced unprecedented changes in radiative forcing due to unabated GHG emissions. For example, from 1850 to 2019, carbon dioxide concentrations in the atmosphere has increased from 285 ppm to 410 ppm, reaching their highest levels in 800 000 years (IPCC AR6-WG1, 2021). Consequently, the Global Mean Surface Temperature (GMST) over the 2011-2020 decade increased by 1.09°C compared to the 1850-1900 baseline (IPCC AR6-WG1, 2021), peaking at +1.26°C in 2020. This warming rate is not constant in time, as illustrated in Figure I.18a, which depicts the temporal evolution of surface temperature changes relative to 1850-1900 across several datasets. The rate of warming has accelerated in recent decades (see Figure 1.12 of IPCC AR6-WG1 (2021) Chapter 1). In addition, not all areas warm at the same rate, with land areas warming faster than oceans (relatively to the 1850-1900 period, over the last decade, +1.59°C for land versus +0.88°C for oceans, see Figure 2.11 of IPCC AR6-WG1 (2021) Chapter 2), particularly in the high latitudes of the Northern Hemisphere, with the fastest warming rate obtained in the Arctic (Rantanen et al., 2022).

Future climate change assessments can be made using CMIP6 projections for the 21st century, especially from the CMIP6.ScenarioMIP global-scale simulations (see O'Neill et al. (2016) and Chapter II for further definitions), which are based on different Shared Socioeconomic Pathways

(SSP). These CMIP6 future scenarios predict varying levels of additional radiative forcing by 2100, ranging from 2.6 W/m², the sustainable scenario assuming GHG emissions reductions, which projects a limited warming of the annual surface air temperature by 2100 of +2°C and an 2.9% increase in global precipitation anomaly, to 8.5 W/m², business-as-usual fossil-fueled development scenario associated with global warming of +4.8°C and a 6.0% increase in global precipitation anomaly (values relative to 1850-1900 ; see O'Neill et al. (2016) and Tables 4.2 and 4.3 from Chapter 4 of IPCC AR6-WG1 (2021)).

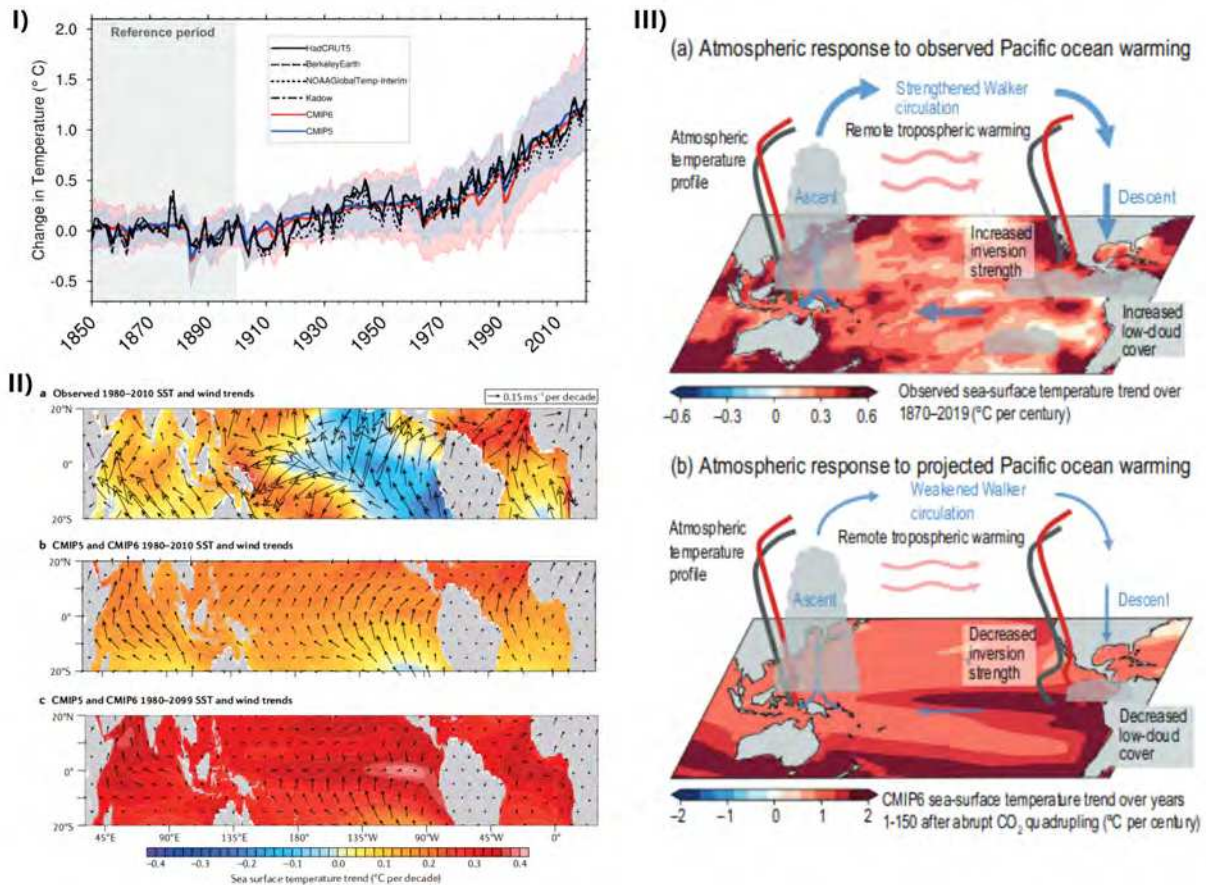


Figure I.18: (I) Global mean surface air temperature changes (in °C) from several observational datasets (in black, HadCRUT5, Berkeley Earth, NOAA Global Temp-Interim and Kadow et al. (2020)), Multi-Model Mean of CMIP5 historical and post-2006 RCP4.5 ensemble simulations (in red), CMIP6 historical and post-2015 SSP2-4.5 ensemble simulations (in blue), and their associated 5th-95th percentile ranges (shading). Changes are computed by respect to the 1850-1900 reference period. Taken from Figure 3.4, Chapter 3 of IPCC AR6-WG1 (2021). (II) SST (shading) and surface winds (vectors) trends for (a) observations (HadISST, ERSSTv5, COBE-SST for SST and 20CRv3, ERA5-20C and JRA-55 for winds) over 1980-2010, (b) 28 CMIP5 RCP8.5 and 23 CMIP6 SSP5-8.5 models over 1980-2010, and (c) same as (b) but over 1980-2099. Reprinted from Cai et al. (2020b). (III) Schematics of the observed and projected tropical Pacific SST and Walker circulation linear trends, from Figure 7.14 of Chapter 7 of IPCC AR6-WG1 (2021).

I.3.1.2 Changes in the tropical mean state

Observed trends over the last decades in the tropical Pacific are shaped by a strengthening of the zonal SST and surface pressure gradients (Seager et al., 2019; England et al., 2014), and equatorial trade winds strengthening (Ma & Zhou, 2016; Takahashi & Watanabe, 2016). As a result, the western tropical Pacific warms whereas its eastern counterpart cools, describing a horseshoe-shaped pattern, as shown on Figure I.18 IIa. Those changes correspond to a strengthening and westward shift of the Walker circulation observed since the 1980s (L’Heureux et al., 2013; McGregor et al., 2014; Zhao & Allen, 2019), indicating a swing of the tropical Pacific towards a La Niña-like mean state, with the western equatorial Pacific warming faster than the eastern equatorial Pacific (Kohyama et al., 2017; Lian et al., 2018).

However, climate models, from early CMIP3 to the recent CMIP6 projections, fail to replicate those recent observed trends (Figure I.18 IIb and references below). In addition, they project a long-term swing of the tropical Pacific mean state towards an El Niño-like SST mean state, in response to increased GHG forcing (see Figure I.18 IIc, Power et al. (2021); Collins et al. (2010); Cai et al. (2014); Kociuba and Power (2014)). This long-term trend is particularly robust in CMIP6, where Erickson and Patricola (2023) showed that more than half of the 29 models they analyzed shift toward an El Niño-like mean state, while none projected a La Niña-like mean state, in agreement with Cai et al. (2020b). This El Niño-like pattern is associated with a decrease in the zonal SST and surface pressure gradient and weakening and eastward shift of the Walker circulation (Collins et al., 2010; Xie et al., 2010; Vecchi et al., 2006; Ying et al., 2016; Cai et al., 2021; Bayr et al., 2014). The projected enhanced warming facilitates the triggering of tropical deep convection in the eastern Pacific (Vecchi & Soden, 2007; Power et al., 2013; Power & Delage, 2018; Chadwick et al., 2013; Cai et al., 2014), following the "warmer-gets-wetter" mechanism of Xie et al. (2010).

Finally, causes of the disparity between model projections and observed Pacific mean state trends remain contested. One explanation points to the role of internal decadal-to-multidecadal variability (Meehl et al., 2013; Chung et al., 2019; Watanabe et al., 2020), and in particular the fact that a negative phase of the Pacific Decadal Oscillation can mask global warming by leaving a cooling footprint on observed SSTs (Kosaka & Xie, 2016). CMIP models tend to underestimate tropical interdecadal SST variability and the negative trends of Pacific Decadal Variability (Zhao & Allen, 2019; Chung et al., 2019; Trenberth & Fasullo, 2013; McGregor et al., 2018). On the other side, inherent systematic biases in state-of-the-art models may contribute to the misrepresentation of global warming patterns (Luo et al., 2017), for instance the cold tongue bias (see Seager et al. (2019)). Finally, the ocean dynamical thermostat mechanism proposed by Clement et al. (1996) has been suggested to cause a multi-decadal delay in the

warming of the eastern equatorial Pacific, and may be underestimated in models (see [Watanabe et al. \(2024\)](#) for a review).

I.3.2 ENSO in a warming world

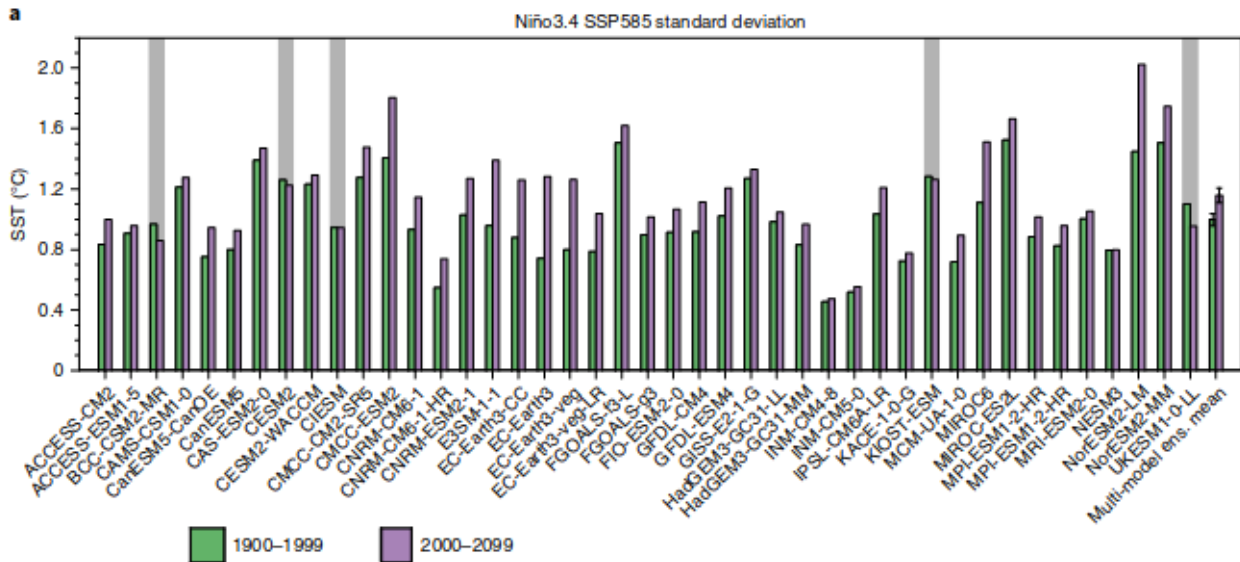


Figure I.19: Standard deviation of ENSO SST in the Niño3.4 region (°C) for CMIP6 models under the SSP5-8.5 scenario, computed over the periods 1900-1999 (gray bars) and 2000-2099 (purple bars), illustrating the inter-model consensus in CMIP6 on the increased ENSO SST variability, reprinted from [Cai et al. \(2022\)](#).

In 21st-century warmer climate projections, ENSO is expected to remain the dominant mode of interannual variability ([IPCC AR6-WG1, 2021](#)), with significant changes in tropical SST and precipitation variability. ENSO precipitation variability display a robust long-term increase across models and forcing scenarios ([Brown et al., 2020](#); [IPCC AR6-WG1, 2021](#); [Power et al., 2013](#); [Power & Delage, 2018](#); [Perry et al., 2017](#); [Cai et al., 2021](#)). This increased precipitation variability occurs even when SST variability does not change (see the review by [Yeh et al. \(2018\)](#)), in relation with the increased atmospheric water vapor content in response to increasing temperature ([Hu et al., 2021](#); [Yun et al., 2021](#)). Furthermore, there is a projected eastward shift of tropical El Niño precipitations in response to global warming, with convective regions extending eastward from the central to the eastern equatorial Pacific ([Yeh et al., 2018](#); [Yan et al., 2020](#); [Zhou et al., 2014](#); [Kug et al., 2009](#)).

[IPCC AR6-WG1 \(2021\)](#) and following studies have highlighted a lack of inter-model consensus on projected ENSO SST variability—attributed to large inter-model spread, internal variability, and the use of diverse metrics of ENSO changes ([Collins et al., 2010](#); [Stevenson et al., 2021](#);

Chen et al., 2017; Maher et al., 2018; Bellenger et al., 2013). On the contrary, Cai et al. (2022, 2015, 2018) suggest that consensus can be achieved by selecting models based on their ability to accurately reproduce ENSO SST diversity (e.g., CP/EP types) or extreme El Niño events, as indicated by large precipitation anomalies in the Niño 3 region. Robust increases in ENSO SST variability have been thus noted in CMIP3 (Cai et al., 2014), CMIP5 (Cai et al., 2018) and CMIP6 under different SSPs (Cai et al., 2021) models, particularly in the eastern equatorial Pacific (Cai et al., 2018; Fredriksen et al., 2020; Geng et al., 2022). This increase is accompanied by a reduction in the equatorial SST zonal gradient, which facilitates stronger El Niño events in the eastern Pacific (Fredriksen et al., 2020; Shin et al., 2022). Notably, studies indicate a doubling in the frequency of extreme El Niño events (Heede & Fedorov, 2023; Cai et al., 2014, 2018), even for the lowest global warming levels (+1.5°C) (Wang et al., 2017). Additionally, extreme La Niña frequency is also projected to increase (Cai et al., 2015, 2018), in association with the enhanced CP-variability projected (Cai et al., 2021).

I.3.3 Projected changes of teleconnections under global warming

In response to global warming, ENSO teleconnections are expected to change, making it essential to first understand how these patterns vary with ENSO type, and then identify the mechanisms driving these changes to improve future projections. A key feature of these changes is the consistent eastward shift of global teleconnection patterns that occurs consistently from the CMIP3 generation of models (Kug et al., 2009) to that of CMIP6 (Brown et al., 2020). These changes can result from modifications in ENSO SST characteristics (e.g., amplitude, pattern, frequency) and/or changes in the atmospheric background state (Yeh et al., 2018).

Specifically, over North America, the projected eastward shift of the tropical ENSO source is found to cause the PNA teleconnection pattern to shift eastward for both El Niño (Kug et al., 2009; Lee & Jin, 2024) and La Niña events (Zhou et al., 2014). Notably, although not explicitly named by the authors, Figure 4 in Kug et al. (2009) indicates that the projected eastward shift of the positive (negative) PNA pattern of El Niño (La Niña) resembles the negative (positive) phase of the TNH pattern. This is further supported by Chen et al. (2017), who found an eastward shift of the PNA and a strengthening of the Aleutian Low in association with CP events in response to increased CP SST variability in CMIP5-RCP8.6 simulations. Similarly, Drouard and Cassou (2019); Johnson et al. (2022) demonstrate that in warmer climates, the overall ENSO-regressed teleconnection pattern changes from the PNA toward an eastward-shifted pattern by $\approx 20\text{--}30^\circ$ over North America.

Both Beverley et al. (2021); McGregor et al. (2022) and Johnson et al. (2022) show a weakening of the PNA-related surface temperature anomalies over northwestern Canada and

Alaska, as well as a weakening of the US west coast precipitation anomalies in the future El Niño composite. When considering ENSO diversity, [Cai et al. \(2021\)](#) also found an eastward shift of Rossby wave trains over the North Pacific and America, but solely for EP events. Finally, [Yeh et al. \(2022\)](#), investigated changes in surface temperature by categorizing El Niño events in 7 CMIP6 models based on their intensity (weak, moderate, and strong El Niño/La Niña). They did not find significant changes for this last category, attributing this to their small sample. Therefore, it seems critical to explore future changes in ENSO teleconnections using the largest possible sample sizes to address such uncertainties. For instance, [\(Michel et al., 2020\)](#) show that in low global warming scenario, more than 50 realizations are necessary to obtain significant results.

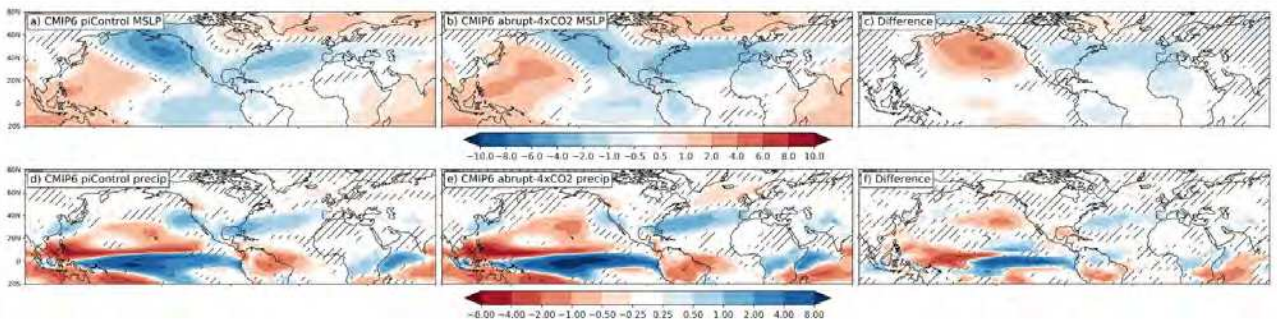


Figure I.20: DJF mean of (a) sea level pressure and (b) precipitation anomalies from the CMIP6 Multi-Model Mean piControl (left), CMIP6 MMM abrupt 4xCO2 (middle) and their difference (4xCO2-piControl). Reprinted from [Beverley et al. \(2024\)](#).

Projected changes in the ENSO teleconnections also reveal a development of a NAO-like teleconnection over the North Atlantic. In the current climate, El Niño events are already found to be associated with signals over the North Atlantic ([Herceg-Bulić et al., 2023](#)), associated with a negative North Atlantic Oscillation (NAO)-like teleconnection pattern ([Zhang et al., 2018](#); [Jiménez-Esteve & Domeisen, 2018](#)) in late winter, in response to tropospheric features such as transient eddies propagating downstream of the equatorward-shifted North Pacific storm track during El Niño winters ([Li & Lau, 2012](#); [Drouard et al., 2015](#)), or stratospheric pathways, such as the deepening of the Aleutian low in the positive PNA pattern during El Niño, inducing a weaker polar vortex, sudden stratospheric warming and negative phase of the NAO ([Trascasa-Castro et al., 2019](#); [Ineson & Scaife, 2008](#); [Jiménez-Esteve & Domeisen, 2019](#)). In future climate, this ENSO-NAO-like teleconnection is projected to strengthen ([Drouard & Cassou, 2019](#)). This change is robust: it is found in idealized doubled CO2 concentration experiments ([Herceg Bulić et al., 2011](#)), in CMIP5, [Fereday et al. \(2020\)](#), in recent CMIP6 models ([Beverley et al., 2024](#)), in the El Niño/La Niña teleconnections pattern from large ensembles with the GFDL SPEAR GCM ([Johnson et al., 2022](#)), or other studies based on single models ([Drouard & Cassou, 2019](#); [Müller & Roeckner, 2008](#)). This strengthened ENSO-NAO link under increased CO2 levels results in stronger ENSO-induced precipitation anomalies spanning

from the central north Atlantic to Southern France and Spain in future climates (Drouard & Cassou, 2019; Beverley et al., 2024). These studies attributed this stronger ENSO-NAO link to shifts in ENSO-related precipitation anomalies over the eastern Pacific, combined with changes in the global-scale background mean state, with a stronger contribution of the latter effect. The contribution of changes in the background circulation is further supported by Lee and Jin (2024), who, using ESM-CMIP6 models, demonstrated that alterations in the zonal mean wind state lead to an increase in the wavelength of the standing Rossby waves that establish the teleconnection pattern. Drouard and Cassou (2019) also found that the strengthening of the ENSO-NAO teleconnection was driven by changes in the background circulation, rather than modifications in ENSO SST, but Beverley et al. (2024) found that the two effects contribute.

Overall, studies broadly agree to indicate a future change in ENSO teleconnections, that features an eastward shift of the North Pacific teleconnection pattern, and a stronger NAO response over the Atlantic. Those changes appear to be more related to changes in the background atmospheric circulation than to changes in ENSO sources. Several studies have distinguished El Niño from La Niña, or considered ENSO diversity when examining these teleconnection changes. Yet, no study has specifically investigates extreme El Niño events teleconnection changes in future climate in the large CMIP6 database (the closest study being Yeh et al. (2018), but this study only involves 6 CMIP6 models and their "strong" El Niño definition is a broader category than our "extreme" El Niño one). That will be one of the objectives of this PhD.

I.4 PhD objectives

The general objective of this thesis is to investigate the diversity of ENSO-related winter atmospheric teleconnections over North America, focusing on their drivers, mechanisms and reproducibility.

In other words, we will question whether the ENSO forced atmospheric response is characterized by a single teleconnection pattern, or are associated with several distinct teleconnection patterns? More specifically, how are those teleconnection patterns related to ENSO diversity (i.e. which type of ENSO event induces a different teleconnection from the usual PNA pattern)? By focusing on the North American region and using state-of-the-art atmosphere-only and coupled ensemble simulations, this research seeks to address several key gaps identified in the scientific literature.

I. What are the drivers and mechanisms of the winter ENSO teleconnection diversity over North America?

A significant body of literature investigates North American boreal winter teleconnections. However, there is no consensus on the drivers of this pattern diversity, with past studies successively attributing it to El Niño / La Niña asymmetries, to El Niño diversity (CP vs EP events). Recent studies suggest a specificity of extreme EP events (a subcategory of EP events), at least as far as Californian rainfall are concerned.

Using a CNRM-CM6.1 AMIP-type ensemble, I address the following questions:

1. Previous studies suggested that an eastward-shifted (TNH-like) teleconnection pattern occurs either for El Niño relative to La Niña, EP vs CP El Niño events, or more specifically for EP events that generate convective anomalies in the central-eastern Pacific. Here, we want to test the hypothesis that this eastward-shifted pattern only specifically occurs for extreme El Niño events such as 1982-83, 1997-98 or 2015-16, i.e. for a subcategory of all the above mentioned types of El Niño events.
2. What are the respective contributions of the ENSO SST pattern diversity and atmospheric nonlinearities to the eastward shift of the TNH relative to the PNA teleconnection pattern ?
3. Are teleconnection patterns and their associated climate impacts on North America more robust and reproducible for some ENSO-types (more specifically for extreme El Niño events) ?

These questions will be explored and addressed in Chapter III.

II. How well do state-of-the art climate models reproduce the North American teleconnection diversity ?

I demonstrate in the CNRM-CM6.1 AMIP type ensemble that in boreal winter, only extreme El Niño events triggers a TNH-like teleconnection pattern, leading to highly reproducible precipitation and surface temperature impacts over North America. However, strong extratropical internal atmospheric noise can obscure ENSO teleconnections, introducing significant uncertainty in detecting robust teleconnection patterns, highlighting the need for large sample sizes. Additionally, atmosphere-only GCMs have biases due to imperfect parametrizations, and coupled GCMs exhibit systematic biases like the equatorial SST cold tongue and dry biases, potentially hindering deep convection initiation even during large eastward-shifted SST anomalies associated with extreme El Niño events.

Using the extensive multi-model AMIP6-CMIP6 database, I therefore investigate:

- 1. Do AMIP6 models reproduce the North American teleconnection diversity driven by extreme El Niño found in recent observations and the AMIP-CNRM-CM6.1 model ?**
- 2. Is the enhanced reproducibility of the extreme El Niño climate impacts over North America robust in AMIP6? Does it arise from stronger signals and/or reduced atmospheric internal variability ?**
- 3. Given that current ENSO impact forecasts rely on coupled climate models rather than AMIP models, how do biases inherent to coupled models (such as the equatorial Pacific cold tongue bias) affect their ability to reproduce the extreme El Niño teleconnection patterns and impacts?**

These questions will be explored and addressed in Chapter [IV](#).

III. How are the extreme El Niño teleconnection patterns projected to change in a warmer world?

In response to global warming, ENSO tropical characteristics and teleconnection patterns are projected to change. Recent studies suggest an increased frequency of extreme El Niño events, leading to a stronger ENSO-related SST and rainfall variability. Over North America, an eastward shift of the PNA pattern in association with the strengthening of the anomalously deep Aleutian Low are predicted. A robust strengthening of ENSO-NAO teleconnections is also projected in the North Atlantic. However, future changes in extreme El Niño teleconnections have not been fully assessed, with studies warning about uncertainties arising from short sampling periods and atmospheric internal noise.

Using future projections from large ensemble CMIP6-ScenarioMIP simulations, I address :

1. **How teleconnections associated with different ENSO categories (La Niña, moderate El Niño, extreme El Niño) are projected to change under future climate conditions?**
2. **What is the contribution of extreme El Niño events frequency teleconnection patterns future changes to those in the overall ENSO teleconnection pattern ?**

These questions will be explored and addressed in Chapter [V](#).

Finally, in the Chapter [V.4.2](#), I will resume the mains conclusions to these questions, and provide some leads for future work.

Chapter II

Methods and data

Contents

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In this chapter, I provide a general description of the observational products and numerical simulations I used to investigate the diversity of ENSO teleconnections. Section II.1 presents the observational datasets used to validate model results. Section II.2 presents the CNRM-CM6.1 AMIP simulations that were used in chapter III. Sections II.3 and II.4 presents the AMIP6 and CMIP6 datasets used in chapter IV and V. Data processing methods are not detailed in this chapter, as they vary depending on the type of simulation (in particular AMIP versus CMIP-type) and are therefore discussed in the corresponding chapters.

II.1 Observational datasets

To evaluate the models performance in simulating boreal winter ENSO teleconnection patterns, we use several observational and reanalysis global-scale datasets.

For Sea Surface Temperature (SST, °C), I use the 1° resolution, monthly Hadley Centre Sea Ice and Sea Surface Temperature dataset (HadISST version 1.1, Rayner (2003)) provided by the Met Office Hadley Center. This dataset spans 1871 to present and is available at <https://www.metoffice.gov.uk/hadobs/hadisst/data/download.html>.

For atmospheric variables, I use the 5th generation European Centre for Medium-Range Weather Forecasts (ECMWF) atmospheric reanalysis, ERA5 (Hersbach et al., 2020) monthly-average values available on a 0.25°x0.25° grid from 1979 onwards. The 500 hPa geopotential height (Z500, m) and 2m height Temperature (T2m, °C) can be downloaded from <https://cds.climate.copernicus.eu/cdsapp#!/dataset/reanalysis-era5-pressure-levels-monthly-means?tab=form>.

Finally, for rainfall, I use the Global Precipitation Climatology Project Monthly Analysis (GPCPv2.3, Adler et al. (2018)) available on a $2.5^\circ \times 2.5^\circ$ grid from 1979 to present. This product is obtained from an optimal interpolation that uses a combination of satellite products and rain gauge data and can be downloaded at <https://www.ncei.noaa.gov/data/global-precipitation-climatology-project>. All observational datasets were bi-linearly interpolated to a $1^\circ \times 1^\circ$ grid.

II.2 CNRM-CM6.1 Atmosphere-only simulations

Chapter III uses Atmosphere-only sensitivity experiments performed by Srinivas et al. (2024), which uses the atmospheric component of the CNRM-CM6.1 climate model, the AGCM ARPEGE-Climate v6.3 (Voldoire et al., 2019; Roehrig et al., 2020), and 10 CNRM-CM6.1 AMIP6 members from the AMIP6 database (see section II.3 for AMIP6 database).

ARPEGE-Climate v6.3 is a global spectral AGCM that participated in the sixth phase of the Coupled Model Intercomparison Project (CMIP6) as part of CNRM-CERFACS contribution to various Model Intercomparison Projects (MIPs), including DECK experiments, OMIP, and ScenarioMIP (see Eyring et al. (2016) and references above). The model features a dry dynamical core that resolves vorticity and divergence from momentum equations, while diabatic processes are physically parametrized (complete description in Roehrig et al. (2020)). The model employs a linear T127 triangular truncation and a reduced Gaussian grid, providing an approximate horizontal latitude/longitude resolution of 150 km (1.4°) at the equator. On the vertical, the model spans from surface to 0.01 hPa over 91 levels using a progressive hybrid σ -pressure grid. In comparison to its previous version (CNRM-CM5.1), the atmospheric component of the model has been revised and improved, in particular for the representation of shallow and deep convection, microphysics and turbulent processes (Voldoire et al., 2019).

In Chapter III, I will consider monthly values of the geopotential height (Z500, m) at 500 hPa, surface "skin" temperature (TS, $^\circ\text{C}$), and precipitation (PR, mm/day). I will also refer to ARPEGE-Climate v6.3 as the CNRM-CM6.1.AMIP6 version - I will also use its coupled CMIP version later: ARPEGE-climat6.3 and the CNRM-CM6.1 involves the same model configuration (Roehrig et al., 2020).

In addition to the existing 10 members from the AMIP6 database, Srinivas et al. (2024) performed two AMIP-type ensembles, each containing six members and spanning the 1979–2019 period. Following the AMIP protocol (detailed in section II.3), the control (*CTL*) ensemble was forced with observed HadISST and GHG concentrations over 1979–2019. Then, observed interannual SST anomalies relative to the 1979–2019 climatology were subtracted from the climatology, creating a 'mirrored' anomalous interannual SST forcing, used to force the second ensemble. Further details are provided in Chapter III, in particular the methodology developed

by [Srinivas et al. \(2024\)](#) that I will use to decompose and assess the contributions of atmospheric nonlinearities and SST pattern diversity to the ENSO teleconnection diversity.

Additionally, to investigate the potential reproducibility of teleconnection patterns, I also extended the CTL ensemble by including 10 AMIP6 members covering the period 1979–2014, produced by [Voldoire et al. \(2019\)](#) for the AMIP6 exercise. As a result, findings from the original 6-member CTL ensemble will be compared and validated against those from the expanded 16-member ensemble.

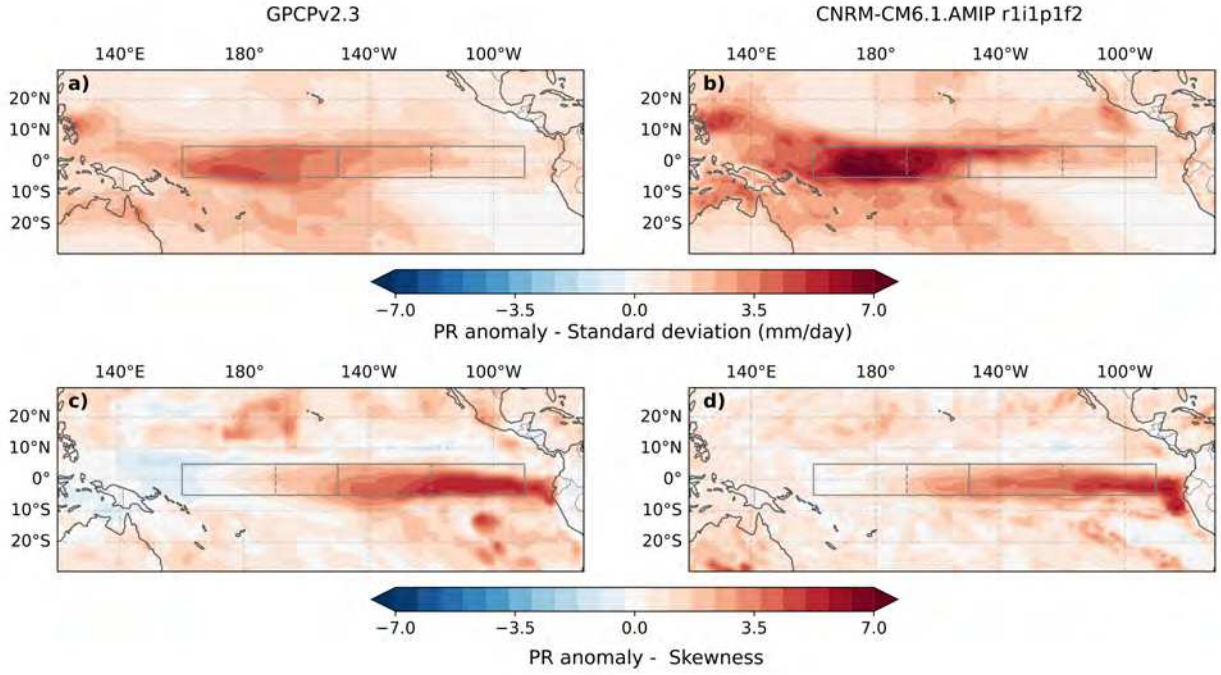


Figure II.1: Standard deviation of precipitation anomaly over 1979-2014 from (a) GPCPv2.3 and (b) the first variant of the CNRM-CM6.1-AMIP ensemble used in the study. (c-d) same as (a-b) but for precipitation anomaly skewness.

Finally, Figure II.1 and Figure II.2 briefly evaluates the CNRM6-CM6.1-AMIP6 simulation to replicate key observed ENSO features. At first, I verify that the model can reproduce equatorial precipitation interannual DJF variability, which is largely driven by ENSO at a seasonal scale. Figure II.1 thus compares the observed and CNRM-CM6.1-AMIP tropical precipitation anomalies standard deviation and skewness, based on 1979-2019 DJF averages. Similarly to observations, the model displays larger STD values in Niño 4-Niño 3.4 than Niño 3 region, indicating that the model captures the spatial pattern of ENSO precipitation well, despite an overestimation in the western equatorial Pacific. The model is also able to reproduce the asymmetrical precipitation response to ENSO, with large positive anomalies in the eastern Pacific during extreme El Niño events, and much weaker dry anomalies during La Niña (see figure I.7). The linear regression of the mid-level geopotential height anomaly onto the standardized

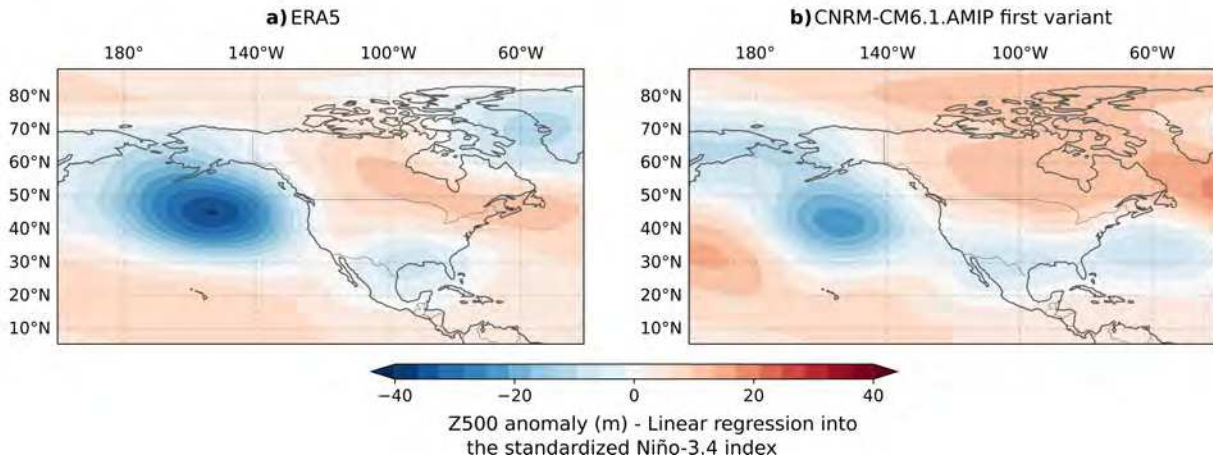


Figure II.2: Linear regression of the 1979-2019 ERA5 (a) and CNRM-CM6.1 AMIP first variant (b) 500 hPa geopotential height anomaly into the standardized Niño 3.4 SST index.

Niño 3.4 SST index over the 1979-2019 period, shown in Figure II.2, allows assessing ENSO teleconnections over the North Pacific and American sectors. Again, the model is able to reproduce the main spatial patterns of the observed ENSO extratropical response, despite an underestimation of the amplitude of the anomalous Aleutian low. The model also reproduces surface temperature and rainfall teleconnections well (not shown). I will also show in Figure 1 of the chapter III that the model is able to reproduce the observed ENSO teleconnection asymmetry between El Niño and La Niña over the North Pacific-North America region.

II.3 AMIP6 dataset

The chapter IV uses the extensive Atmospheric Model Intercomparison Project, phase 6 (AMIP6) climate model database, part of the Diagnosis, Evaluation, and Characterization of Klima (DECK) sub-MIP, coordinated by the World Climate Research Programme (WCRP). To ensure consistent comparison across models and enable robust diagnostic analysis, the Atmosphere-only GCMs simulations participating the historical AMIP (*amip*) exercise are performed using a standardized procedure, as recommended by Eyring et al. (2016). For instance, all AMIP models should cover at least the recent decades since the beginning of satellite observations, from January 1979 to December 2014. The following informations are taken from Eyring et al. (2016).

AMIP6 models are externally forced using observed SST and sea ice concentration from observational products. As a result, the modelled climate response is primarily influenced by the external forcing and the unforced atmospheric variability. To facilitate comparison between the atmospheric-only and coupled versions of the same model during the historical period (*amip* vs. *historical CMIP*), other natural and anthropogenic forcings (denoted as f_1 , f_2 or f_3 depending on the model and including volcanic aerosols, solar, anthropogenic aerosols extracted from

observations and prescribed CO₂ concentration) should be consistent with the historical CMIP simulations.

Experiments performed under the AMIP protocol allow for a fair comparison between models, such as the evaluation of possible model errors in parametrization (Xiang et al., 2017; Zhang et al., 2024). In addition, the generation of large ensembles is recommended to assess internal atmospheric variability, with Eyring et al. (2016) recommending the use of at least three ensemble members. Initial conditions for ensembles are recommended to be extracted from previous model integrations (e.g., the 10-member ensemble with which we extended the 6-member ensemble performed with the CNRM-CM6.1.AMIP of Srinivas et al. (2024) is extracted from a *piControl* experiment - pre-industrial simulation with invariant 1850 forcings - after a spin-up period required to reach equilibrium.

Therefore, in chapter 4, I consider 23 AMIP6 models that meet the criteria of covering at least the 1979-2014 period and having at least three ensemble members available under the same forcing f . Table II.1 lists the selected models, their versions, and the number of ensemble members included in our analysis. All AMIP6 (and CMIP6) simulations were downloaded from the ESGF search interface <https://esgf-node.ipsl.upmc.fr/search/cmip6-ipsl/>. The complete dataset corresponds to almost 5000 years of simulation. Specific details of the analysis performed with the AMIP6 models will be detailed in Chapter IV.

Model version	Model Name	Members	Forcing	Reference
ACCESS-CM2	Australian Community Climate and Earth System Simular	4	f1	Dix et al. (2020)
ACCESS-ESM1-5	–	10	f1	(Ziehn et al., 2020)
BCC-CSM2-MR	Beijing Climate Center, Climate System Model	3	f1	Xin et al. (2018)
BCC-ESM1	–	3	f1	(Wu et al., 2020)
CAMS-CSM1-0	Chinese Academy of Meteorological Sciences–Climate System Model	3	f1	Rong (2019)
CAS-ESM2-0	Chinese Academy of Sciences Earth System Model	4	f1	Zhang et al. (2020)
CESM2	Canadian Earth System Model	10	f1	Danabasoglu et al. (2020)
CESM2-FV2	–	3	f1	Danabasoglu (2019)
CESM2-WACCM	–	3	f1	Gottelman et al. (2019)
CNRM-CM6-1	Centre National de Recherches Météorologiques Coupled Global Climate Model	16	f2	Roehrig et al. (2020)
E3SM-1-0	EC-Earth: European Consortium Earth System Model	3	f1	Caldwell et al. (2019)
E3SM-2-0	–	3	f1	Golaz et al. (2022)
FGOALS-f3-L	Flexible Global Ocean–Atmosphere–Land System Model	3	f1	HE et al. (2020)
GISS-E2-1-G	Goddard Institute for Space Studies	5	f1	Kelley et al. (2020)
IPSL-CM6A-LR	Institut Pierre Simon Laplace Climate Model	22	f1	Boucher et al. (2020)
MIROC6	Model for Interdisciplinary Research on Climate	10	f1	Shiogama et al. (2019)
MIROC-ES2L	Model for Interdisciplinary Research on Climate, Earth System Model	3	f2	Hajima et al. (2020)
MPI-ESM1-2-HAM	Max Planck Institute Earth System Model	3	f1	Neubauer et al. (2019)
MPI-ESM1-2-HR	–	3	f1	Gutjahr et al. (2019)
MPI-ESM1-2-LR	–	3	f1	Wieners et al. (2019)
MRI-ESM2-0	Meteorological Research Institute Earth System Model	3	f1	Yukimoto et al. (2019)
NESM3	Nanjing University of Information Science and Technology Earth System Model	5	f1	Cao et al. (2018)
NorCPM1	Norwegian Climate Prediction Model	10	f1	Bethke et al. (2021)
Total		135		

Table II.1: List of the 23 AMIP6 models with at least 3 ensemble members available, analyzed over the period 1979-2014. The center column indicates the number of members M , and the middle-left column indicates the forcing variant of the model.

II.4 CMIP6 dataset

II.4.1 Historical simulations

Chapter IV also analyses fully coupled ocean-atmosphere GCM experiments from the Coupled Model Intercomparison Project Phase 6 (CMIP6) *historical* simulations. A full description of the simulations is available in [Eyring et al. \(2016\)](#), from which the following information are taken.

Spanning from 1850 to 2014, the historical simulations are designed to reproduce the climate over the recent past, and aim at providing a consistent model evaluation, by comparing the simulated climate with observed historical climate. As in the AMIP exercise, CMIP models are run by integrating time-varying historical forcings (seasonal GHGs, solar forcing, land-use forcings, stratospheric volcanic aerosol forcings ...) based on estimates and observations from 1850 to 2014, thus following the observed long-term trends in external historical forcings variability. Due to internal climate variability, observations and historical simulations are not directly comparable on an event-by-event basis, but rather allow for a comparison of statistical properties (e.g. globally averaged warming trends, etc...).

I analyze historical simulations (1850-2014) from 42 CMIP6 models (see Table 2) using the first variant, namely r1i1p1-f1, -f2 or -f3, when available (i.e. I only consider one member per CMIP6 model, even if multiple members are available).

CMIP6 model first variant	
ACCESS-CM2 ^{a,b}	HadGEM3-GC31-LL
ACCESS-ESM1-5	HadGEM3-GC31-MM ^a
BCC-CSM2-MR	INM-CM4-8
BCC-ESM1	INM-CM5-0
CAMS-CSM1-0 ^{a,b}	IPSL-CM6A-LR
CanESM5	KACE-1-0-G ^a
CESM2 ^{a,b}	KIOST-ESM ^a
CESM2-FV2 ^{a,b}	MIROC6 ^a
CESM2-WACCM ^{a,b}	MIROC-ES2L ^a
CMCC-CM2-HR4 ^a	MPI-ESM-1-2-HAM
CMCC-CM2-SR5 ^a	MPI-ESM1-2-HR
CNRM-CM6-1 ^{a,b}	MPI-ESM1-2-LR
CNRM-CM6-1-HR	MRI-ESM2-0 ^{a,b}
CNRM-ESM2-1 ^a	NESM3
E3SM-1-0	NorCPM1 ^{a,b}
E3SM-1-1	NorESM2-LM ^a
FGOALS-f3-L ^{a,b}	NorESM2-MM ^a
GFDL-CM4	SAM0-UNICON ^a
GFDL-ESM4	TaiESM1 ^a
GISS-E2-1-G ^{a,b}	UKESM1-0-LL ^a
GISS-E2-1-G-CC	
GISS-E2-1-H	

Table II.2: List of the 42 CMIP6 first variant used (one member per model) for the analysis over 1850-2014. The symbol *a* indicates models capable of simulating extreme El Niño (see chapter IV for details) and the symbol *b* indicates models that possess an AMIP6 equivalent ensemble (see Table1).

II.4.2 SSPs simulations

II.4.2.1 Presentation

Finally, chapter V relies on projections of the future climate with global-scale simulations from the CMIP6 Scenario Model Intercomparison Project (ScenarioMIP) experiments (O'Neill et al., 2016). The CMIP6 ScenarioMIP provides future climate projections which form one of the bases of the IPCC assessments reports. These multi-models simulations extend the historical CMIP6 simulations from 2015 to 2100, and simulate the response to the climate system under different SSPs (Shared Socioeconomic Pathways) narratives (O'Neill et al., 2017). These SSPs correspond to future radiative forcing are designed to cover a broad range of possible future climates under 5 plausible evolution scenarios that consider different societal, demographic, economic, technological, governance, and environmental factors (O'Neill et al., 2017; Riahi et al., 2017). More details can be found in O'Neill et al. (2016, 2017); Riahi et al. (2017); IPCC

AR6-WG1 (2021).

We consider four main SSP (Shared Socioeconomic Pathways) scenarios from the Tier 1: SSP1-2.6, SSP2-4.5, SSP3-7.0 and SSP5-8.5, corresponding to the following narratives:

- SSP1-2.6 : *Sustainability - The Green Path*. This scenario corresponds to a low radiative forcing of 2.6 W/m² in 2100, the path towards a more sustainable trajectory that respects environmental limits by minimizing energy and material resources. This scenario integrates a strong reduction of GHGs (toward a net zero CO₂ emission by 2050) and corresponds to a global warming below of +2°C with respect to pre-industrial levels.
- SSP2-4.5 : *Middle of the road*, a medium path towards a forcing of 4.5 W/m² by 2100, taking into account the protection of climate measurements, despite uneven efforts by countries to reduce emissions, which remains at current levels until 2050. The best estimate of global warming in 2100 is around 2.7°C.
- SSP3-7.0 : *Regional rivalry - A rocky road*. This scenario integrates a high forcing of 7.0 W/m² by 2100, characterised by a doubling of CO₂ emissions by 2100, inducing a projected median warming of +3.9°C.
- SSP5-8.5 : *Fossil-fueled development - Taking the highway*, corresponding to a high forcing of 8.5 W/m². This scenario assumes a doubling of current CO₂ emissions by 2050 rather than by the end of 2100, leading to a projected warming of +4.8°C.

Table II.3 lists CMIP6 models that are able to produce extreme El Niño (see chapter 4 for details), and for which an SSP1-2.6, SSP2-4.5, SSP3-7.0 and/or SSP5-8.5 realization is available, and the number of available SSP variants by model analyzed. The types of forcing f are not given for better readability, but the same members is considered for consistency when regrouping the 2015-2100 SSPs with their corresponding 1850-2014 historical experiment (for example, the historical CMIP6.CNRM-CM6.1 r1i1p1f2 was concatenated with its corresponding r1i1p1f2 SSPs members).

II.4.2.2 Overview of the estimation of global climate warming

Projections of Global Mean Surface Temperature GMST changes by the end of the 21st century, and regional climate predictions, are subject to three sources of uncertainties (Hawkins & Sutton, 2009; Lee et al., 2021; Kirtman et al., 2013), as shown on figure II.3 : the climate model uncertainty (blue curve, how models respond to identical forcings), internal variability uncertainty (red curve), and SSP/forcing scenario uncertainty (green curve, uncertainties in the supposed future CO₂/GHGs/emissions estimations in forcing applied), those latter being found to dominate

Models selected in Chapter IV	ssp126	ssp245	ssp370	ssp585	Total
ACCESS-CM2	10	10	10	3	33
CESM2	2	2	2	2	8
CESM2-WACCM	1	3	1	3	8
CMCC-CM2-SR5	1	1	1	1	4
CNRM-CM6-1	6	6	6	6	24
CNRM-ESM2-1	5	10	5	5	25
FGOALS-f3-L	1	1	1	1	4
GFDL-CM4	0	1	0	1	2
GISS-E2-1-G	5	7	8	5	25
GISS-E2-1-H	5	5	5	5	20
HadGEM3-GC31-MM	0	0	0	4	4
MIROC6	10	10	10	10	40
MIROC-ES2L	10	10	10	10	40
MRI-ESM2-0	5	5	5	5	20
NorESM2-LM	1	3	1	1	6
NorESM2-MM	1	2	1	1	5
UKESM1-0-LL	7	7	7	7	28
Total members	70	83	73	70	296

Table II.3: Models able to perform extreme Niño in historical simulations obtain in chapter IV, for which a corresponding SSP realization is available. The SSPs columns indicate the number of members (thus covering historical + SSP) considered for Chapter V analysis.

at long-term range (see Figure II.3 and Hawkins and Sutton (2009); Lehner et al. (2020)). Therefore, as illustrated by figure V.1, which displays the DJF (December-January-February)

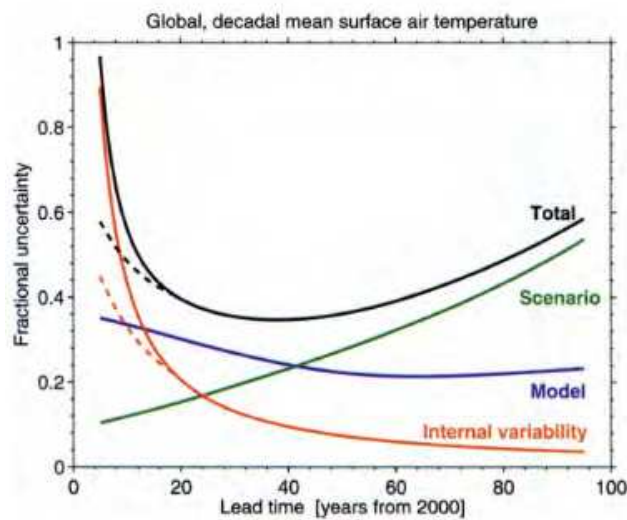


Figure II.3: Relative contributions of sources of uncertainty in global mean surface temperature over the decade (scenario uncertainties, model uncertainties and uncertainties in internal variability), from Hawkins and Sutton (2009).

GMST anomalies relative to the 1850-1900 average for each SSP experiment and model used in chapter V, large warming level disparities exist by the end of century between models and scenarios, with some models projecting significantly stronger warming than others (e.g., CNRM-CM6.1 compared to NorESM2-LM), even when considering the same forcing scenario. Analyzing projected changes in ENSO-related extratropical teleconnections by considering fixed future epochs (e.g., 2020-2040 vs. 2080-2100) would thus aggregate climate responses across different warming levels (Lee et al., 2021), obscuring my analyses. To address this issue, I will assess model's response to climate change by Global Warming Levels (GWL) (Lee et al., 2021; Schleussner et al., 2016; King et al., 2017), selecting years from various SSP scenarios over 2015-2100 based on specific levels of globally averaged warming over a decade.

In essence, I estimated the nonlinear GMST warming index using a 4th order polynomial fit on model realizations from 1850-2100, following Hawkins and Sutton (2012); Gopika et al. (2024) (see Chapter V). This index identifies periods from 2015-2100 with decadal mean warming of +1.5°C to +4.5°C relative to 1860-1920, enabling model, scenario, and decade years resampling. Assuming that local changes scale with global temperature Hawkins and Sutton (2012), I regressed 1850-2100 PR, Z500, and TS time series onto the smoothed GMST index, and extracted anomalies from regressed variables. Although comparison with a 0°C warming excluding the most recent decades (1990s–2014) would be the most accurate strategy, I will discuss, unless indicated otherwise, historical vs. +2°C/+3.5°C/+4.5°C due to computation and time limitation. In a way, historical composites will thus serve as a final validation of the robustness of the results obtained in Chapter IV, which were derived from a single historical member per model, as opposed to multiple ensemble members used in Chapter V.

Chapter III

Drivers and mechanisms of North American ENSO teleconnection diversity

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III.1 Preamble

This chapter explores the diversity of ENSO teleconnections over North America during boreal winter, using a single AMIP-type CNRM-CM6.1 ensemble and recent observations. The analysis aims to shed light on the drivers of this diversity in relation to ENSO variability, given the lack of clear consensus in the existing literature. The contents of this chapter correspond to a study entitled "A distinct and reproducible teleconnection pattern over North America during extreme El Niño events", published in *Scientific Reports* (Beniche et al., 2024).

Early studies noticed a 30° eastward shift of El Niño relative to La Niña winter teleconnections over the North Pacific and American sector (Hoerling et al., 1997, 2001). They attributed this shift to the non-linear response of tropical atmospheric deep convection to underlying SSTs rather than to the eastward-shifted SST anomalies of El Niño relative to La Niña.

Recent studies have emphasized the diversity in location of the peak SST anomalies in the Pacific. Some El Niño events peak in the central Pacific (CP events), while others peak in the eastern Pacific (EP events), whereas La Niña events are less variable and typically peak more uniformly in the central Pacific. This variability in SST patterns is known as ENSO diversity (Capotondi et al., 2015). The tropical precipitation response to ENSO therefore also displays a considerable diversity in both pattern and amplitude (see Figure 3 of Timmermann et al. (2018)). This leads to changes in the position and amplitude of the tropospheric heating anomalies, and therefore of the Rossby wave source, potentially forcing different teleconnection patterns. Studies have thus pointed an eastward-shifted teleconnection pattern for EP relative to CP El Niño events (Mo, 2010; Ashok et al., 2007; Yu et al., 2015; Larkin, 2005) (i.e. a TNH- versus a PNA-like pattern). Some studies have further suggested that only EP events associated with sufficiently large SST anomalies to induce the occurrence of large deep convective anomalies in the east-central tropical Pacific could induce the eastward-shifted teleconnection response (Chiodi & Harrison, 2015; Johnson & Kosaka, 2016).

In addition, some EP events escalate into very large SST anomalies in the eastern and central Pacific Extreme El Niño events, such as during 1982/83, 1997/98 or 2015/16. Recent studies have suggested that only such type of EP events increase the likelihood of wet anomalies over California (Hong Lee et al., 2023; Hoell et al., 2016). The extreme El Niño events limited sample (3 over the satellite area) and the absence of wet anomalies during the 2015-16 event (Seager et al., 2015) however questions the relationship between extreme El Niño and increased Californian precipitation (Lee et al., 2018), suggesting the need for further studies. My working hypothesis is that the eastward shift of the PNA into a TNH-like pattern specifically occurs for extreme El Niño events. To my knowledge, no studies have so far explored the specificity of the extreme El Niño events winter teleconnections over North America. Therefore, it is pertinent to investigate whether some seasonal climate impacts over North America and, more generally, the PNA/TNH teleconnection diversity can specifically be linked to extreme El Niño events. The

observed teleconnection diversity in previous studies (El Niño vs. La Niña, EP vs CP El Niño, convective vs non-convective EP El Niño) may in fact solely be attributable to the extreme El Niño events sub-category.

The second main objective of this chapter is to quantify the respective contributions of the SST pattern diversity and atmospheric nonlinearities to the teleconnection diversity. To that end, I will use a methodology established by [Srinivas et al. \(2024\)](#), based on ensemble sensitivity experiments performed with the CNRM-CM6.1 AMIP model. Two ensemble simulations forced by observed SST anomalies and their mirror image (i.e. climatological minus rather than plus SST anomalies) were run from 1979 to 2019. This approach allows separating the atmospheric response to SST into a linear and nonlinear contribution [Srinivas et al. \(2022, 2024\)](#). [Srinivas et al. \(2024\)](#) used this approach to demonstrate that atmospheric nonlinearities strongly contribute to extreme El Niño events in the eastern Pacific, but did not extend their analysis to the extratropical ENSO signals. To my knowledge, only [Frauen et al. \(2014\)](#) did explicitly examine the relative contributions of the SST pattern diversity and atmospheric nonlinearities to teleconnection diversity, but in the context of CP versus EP events, not specifically for extreme El Niño events. They concluded that the SST pattern diversity and atmospheric nonlinearities both contribute to ENSO teleconnections.

Finally, as underlined by [Brands \(2017\)](#), ENSO teleconnections may not be robust in the extratropics, due to large atmospheric internal variability. The last objective of this chapter will be to investigate the reproducibility of ENSO seasonal anomalies over North America, depending on the type of ENSO event (and more specifically, whether that reproducibility is larger for extreme events, for which the signal should be largest).

Questions addressed :

1. Previous studies suggested that an eastward-shifted (TNH-like) teleconnection pattern occurs either for El Niño relative to La Niña, EP vs CP El Niño events, or more specifically for EP events that generate convective anomalies in the central Eastern Pacific. Here, we want to test the hypothesis that this eastward-shifted pattern only specifically occurs for extreme El Niño events such as 1982-83, 1997-98 or 2015-16, i.e. for a subcategory of all the above mentioned types of El Niño events.
2. What are the respective contributions of the ENSO SST pattern diversity and atmospheric nonlinearities to the eastward shift of the TNH relative to the PNA teleconnection pattern ?

- 3. Are climate impacts over North America more robust and reproducible for some ENSO-types (more specifically for extreme El Niño events) ?**

III.2 Article published in Scientific Reports

Supplementary material can be found in appendix [A](#).

scientific reports



OPEN

A distinct and reproducible teleconnection pattern over North America during extreme El Niño events

Margot Beniche^{1✉}, Jérôme Vialard², Matthieu Lengaigne³, Aurore Voldoire⁴, Gangiredla Srinivas⁵ & Nicholas M. J. Hall¹

El Niño–Southern Oscillation (ENSO) teleconnections are an important predictability source for extratropical seasonal climate forecasts. Previous studies suggest that the ENSO teleconnection pattern depends on the ENSO phase (El Niño vs. La Niña) and/or Sea Surface Temperature (SST) pattern (central Pacific vs. eastern Pacific El Niño events). Observations and ensemble simulations with the CNRM-CM6.1 atmospheric general circulation model indicate that only extreme El Niño events (e.g. 1982–1983, 1997–1998, 2015–2016) display a statistically significant eastward shift relative to the well-known Pacific–North American teleconnection pattern that occurs during both central and eastern Pacific moderate El Niño or during La Niña. This specific teleconnection pattern emerges when equatorial SST anomalies are both eastward-shifted and sufficiently large to exceed the deep atmospheric convection threshold over most of the eastern Pacific, resulting in a basin-wide reorganization of tropospheric heat sources. It yields > 0.5 std wet conditions over Western United States (74% likelihood) as well as > 0.5 std warm anomalies over Canada and the Northern United States (71% likelihood), with more consistency across events and ensemble members than for any other El Niño or La Niña type. These findings hold important implications for the seasonal forecasting of El Niño’s impacts on the North American climate.

El Niño–Southern Oscillation (ENSO) is the dominant driver of year-to-year climate variability¹, with irregular warm (El Niño) and cool (La Niña) Sea Surface Temperatures (SST) anomalies occurring every 2 to 7 years in the equatorial central and/or eastern Pacific. These anomalies generate rainfall and tropospheric latent heat release, leading to the formation of Rossby waves² that induce seasonal precipitation, wind and surface temperature anomalies known as teleconnections along their path to the extratropics^{3,4}. As a result, ENSO affects the climate on a global scale, causing cold spells and heat waves, floods and droughts, with the attendant societal consequences⁵. ENSO teleconnections are a primary source of predictability for extratropical seasonal climate due to the improved accuracy of ENSO forecasts from dynamical models⁶.

The Pacific–North America (PNA) pattern⁷ is widely recognized as the dominant ENSO teleconnection pattern⁸. During El Niño events, a positive PNA pattern is usually observed. Its distinctive features include below-normal geopotential height south of the Aleutian Islands and the southeastern United States (US), while above-normal heights are observed over the US–Canadian border⁹ (Fig. 1a). This pattern provides abnormally warm winter temperatures to Northwestern North America and unusually wet, cool conditions in the southern US¹⁰. El Niño and La Niña exhibit notable asymmetries in their tropical Pacific oceanic characteristics and dynamics¹¹ and in their atmospheric teleconnections^{12,13}. Observed El Niño mid-level geopotential height composites anomalies (Fig. 1a) display stronger signals compared to those of La Niña and an above-normal geopotential height shifted eastward over Northern America by approximately 15° (Fig. 1b).

As a result, surface temperature and rainfall signals are not symmetrical (Fig. 1c) over North America between the two ENSO phases^{14,15}. This teleconnection asymmetry has been attributed to nonlinearities in the response of tropical convective precipitation to SST anomalies^{12,16,17}, as SSTs above 27°C–28°C are a critical prerequisite

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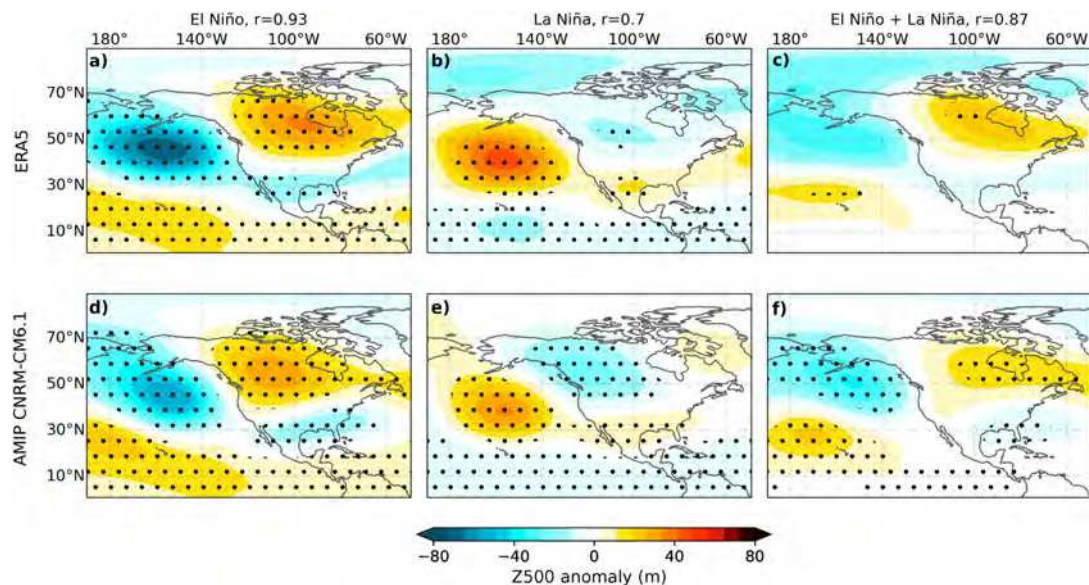


Figure 1. Composites of December–February (DJF) 500 hPa height anomaly (shaded, m) over the 1979–2019 period for El Niño (a,d), La Niña, (b,e) and El Niño+La Niña (c,f). The top row displays composites based on ERA5 data, while the bottom row illustrates composites from the CNRM-CM6.1 AMIP-type historical 6-member (CTL) ensemble mean. The composites are not normalized. r is the correlation coefficient between the observed and corresponding modelled composite. Dots indicate regions where anomalies exceed the 97.5% confidence level based on a bootstrap test (1000 resampling for observations, 10,000 for the model).

for initiating tropical convection^{18,19}. In the equatorial Pacific, the climatological SST increases towards the west, crossing this tropical convection threshold near the dateline. Positive anomalies in this area lead to increased rainfall east of the dateline, while negative anomalies suppress rainfall west of the dateline. This mechanism accounts for the larger and eastward-shifted rainfall anomalies and associated atmospheric response observed during El Niño¹².

The ENSO SST pattern itself also introduces a source of asymmetry in the teleconnection pattern. Notably, El Niño displays stronger SST anomalies that are shifted eastward relative to La Niña^{11,20}. In addition to this El Niño–La Niña asymmetry, the maximum SST anomaly location also varies between events, characterized by Central Pacific (CP, also known as “Modoki”, “Warm Pool” or “dateline”) and Eastern Pacific (EP, “Cold Tongue” or “Conventional”) events²¹. This inter-event variability is commonly referred to as ENSO diversity^{22–26} and is more pronounced for El Niño than for La Niña. EP and CP events have been suggested to trigger different teleconnection patterns^{27–31}. This leads to fundamental questions: Are El Niño and La Niña teleconnection patterns fundamentally different, or do most of the disparities between them stem from differences between CP and EP teleconnection patterns? Additionally, what are the SST pattern diversity and atmospheric nonlinearities relative contributions in the change of teleconnection patterns? To the best of our knowledge, only one study³² has investigated this last matter, concluding that SST pattern diversity and atmospheric nonlinearities both contribute to teleconnection patterns asymmetries.

A relationship exists between ENSO diversity and its amplitude, wherein extreme El Niño events are consistently EP events. However, it is important to highlight that not all EP events exhibit large amplitudes, there are also instances of moderate EP El Niño events³³ (e.g. 1986–1987, 1991–1992 or 2006–2007). Some studies have emphasized the amplitude of El Niño, rather than its diversity, as a primary driver of teleconnection diversity, and specifically that only extreme El Niño events (e.g., 1982–1983, 1997–1998 and 2015–2016, see “Methods” section for the definition of extreme El Niño events) increase the likelihood of wet conditions in California^{34,35}. To achieve this effect, SST anomalies must reach a sufficient magnitude to promote deep atmospheric convection in the eastern Pacific, thus reshaping the ENSO teleconnection pattern^{36–38}. Based on observational data, Chiodi and Harrison^{36,37} argued that El Niño events accompanied by convective perturbations in the eastern-central Pacific (160°W to 110°W) yield more statistically-significant teleconnections than other El Niño events. Johnson and Kosaka³⁸ refined these results using ensemble Atmospheric General Circulation Model (AGCM) experiments, identifying statistically significant differences in teleconnection patterns between El Niño events with and without convective perturbations in the eastern-central Pacific.

Previous studies have thus attributed the observed diversity in the ENSO teleconnection pattern to various factors, including El Niño–La Niña asymmetries^{12,16}, differences between the CP and EP El Niño SST patterns^{27–29}, the presence of convection in the eastern-central Pacific^{36–38} and, concerning Californian rainfall, the occurrence of an extreme El Niño^{34,35}. However, attributing ENSO teleconnection diversity to a specific event type in

observations is challenging due to the considerable uncertainties in the teleconnection pattern itself, stemming from the limited number of events and large mid-latitude internal atmospheric variability³⁹. This underscores the importance of complementing observational analyses with AGCM ensemble experiments, enabling a clear separation between the forced response and atmospheric noise^{39–41}. The signal-to-noise ratio can vary depending on the location and amplitude of the teleconnection pattern. A more reproducible teleconnection pattern, characterized by a higher signal-to-noise ratio, implies greater predictability potential. To our knowledge, no studies have investigated the reproducibility of the various ENSO (La Niña, El Niño, CP, EP, etc...) teleconnection patterns. This objective will also be a focus of this study.

This article uses a combination of observations and ensemble experiments performed with the atmospheric component of the CNRM-CM6.1 climate model (Srinivas et al., submitted⁴²) to investigate the factors contributing to the diversity of northern hemisphere ENSO teleconnections during boreal winter. The first section of our results highlights the distinctive nature of the teleconnection pattern associated with extreme El Niño events. Subsequently, we unravel how SST pattern diversity and atmospheric nonlinearities interact to produce this unique teleconnection pattern. In the last results section, we demonstrate that the extreme El Niño teleconnection pattern is more reproducible across events and ensemble members than any other type of ENSO event. In the “Discussion” section, we compare our results with previous studies, and discuss their implications for seasonal forecasting.

Results

Uniqueness of the extreme El Niño teleconnection pattern

We initiate our analysis by evaluating the ability of the CNRM-CM6.1 atmospheric component to replicate the observed El Niño and La Niña teleconnection patterns, including asymmetries outlined in the introduction (Fig. 1a–c). The composite geopotential height anomaly pattern for the model (Fig. 1d,e) is computed over the same time frame and for the same events as observations, using six ensemble members. The model reproduces the patterns and amplitudes of the observed La Niña and El Niño teleconnections reasonably well, achieving pattern correlations of 0.7 and 0.93, respectively. Notably, the model successfully captures the higher amplitude of El Niño teleconnections and replicates the eastward shift of the pattern over North America. Overall, the atmospheric component of the CNRM-CM6.1 model reasonably reproduces the El Niño–La Niña teleconnection asymmetries (Fig. 1c,f).

We now explore the factors contributing to the diversity of the teleconnection pattern. Figure 2 displays model composites of 500 hPa geopotential height (Z500), land surface temperature (Ts) and rainfall (Pr) anomalies for La Niña, moderate El Niño and extreme El Niño events (refer to the “Methods” for event category definitions) during December–February (DJF). Moderate El Niño composites (Fig. 2d–f) exhibit the canonical positive PNA pattern, featuring a strengthened Aleutian low, elevated pressure over western Canada, increased rainfall over the subtropical North Pacific (160°W; 35°N), decreased rainfall on the west American coast, warm anomalies over Alaska and western Canada and cold anomalies along the Gulf of Mexico coastline. The La Niña composite (Fig. 2a–c) closely mirrors the opposite of the moderate El Niño composite (Fig. 2d–f), both in terms of amplitude and pattern. To focus on pattern changes rather than amplitude changes, Fig. 3a–c depicts the sum of normalized composites for moderate El Niño and La Niña (see methods for details and justification of the normalization). It convincingly demonstrates that there are no statistically significant disparities between the teleconnection patterns associated with moderate El Niño and La Niña events, whether examining Z500, Ts or Pr. These findings are corroborated with observations for Z500 and Ts from ERA5 and Pr from GPCPv2.3 (Fig. S2). The striking similarity between the mirror-image teleconnection patterns for moderate El Niño and La Niña strongly suggests that El Niño–La Niña teleconnection asymmetries over North America, as depicted in Fig. 1, are primarily driven by extreme El Niño events.

Additional evidence in Fig. 2 underscores the distinctiveness of teleconnection patterns associated with extreme and moderate El Niño. Notably, the extreme El Niño patterns exhibit higher amplitude than the moderate El Niño composite across all variables, and a noticeable eastward shift of the entire teleconnection patterns. Specifically, the north Pacific negative Z500 anomaly is shifted approximately 20° eastwards, with negative anomalies touching the North American coast, while the positive Z500 anomaly over North America displays a more pronounced eastward shift of about 30°, extending all the way to the western North Atlantic (Fig. 2g). Accordingly, the surface warming over North America shifts southeastward, with the warmest anomalies over central and eastern Canada and the northern United States, as opposed to Alaska. The positive precipitation patch over the subtropical Pacific, typical during moderate events, also shifts eastwards during extreme El Niño, impacting the western US coast, including California, consistent with previous findings^{34,35}. Although noisier, the observed extreme El Niño teleconnection patterns from ERA5 (Fig. S2g–i) aligns with our simulation results. Additionally, Fig. 3d presents the composite teleconnection difference between extreme and moderate El Niño, with the normalization allowing a focus on the pattern rather than the amplitude. While no statistically significant asymmetries were found between moderate El Niño and La Niña (Fig. 3a–c), there are statistically significant differences between extreme and moderate El Niño for all variables (Fig. 3d–i), including the eastward shift of the Z500 signal, the warming of eastern North America, and the eastward shift of the rainfall towards the US west coast.

The ENSO teleconnection pattern displays notable differences solely for extreme El Niño events, i.e. the three strongest Eastern Pacific (EP) events since 1982. This suggests that the different teleconnection patterns between CP and EP events discussed in earlier research^{27–31} primarily stems from extreme events, and that there are no differences between moderate EP and CP events teleconnections. To investigate this aspect, Fig. 3g–i illustrates the differences in teleconnection patterns between moderate EP and CP events. Although some statistically significant differences emerge (e.g., Z500 over the North Pacific, over the western North Atlantic and Ts over

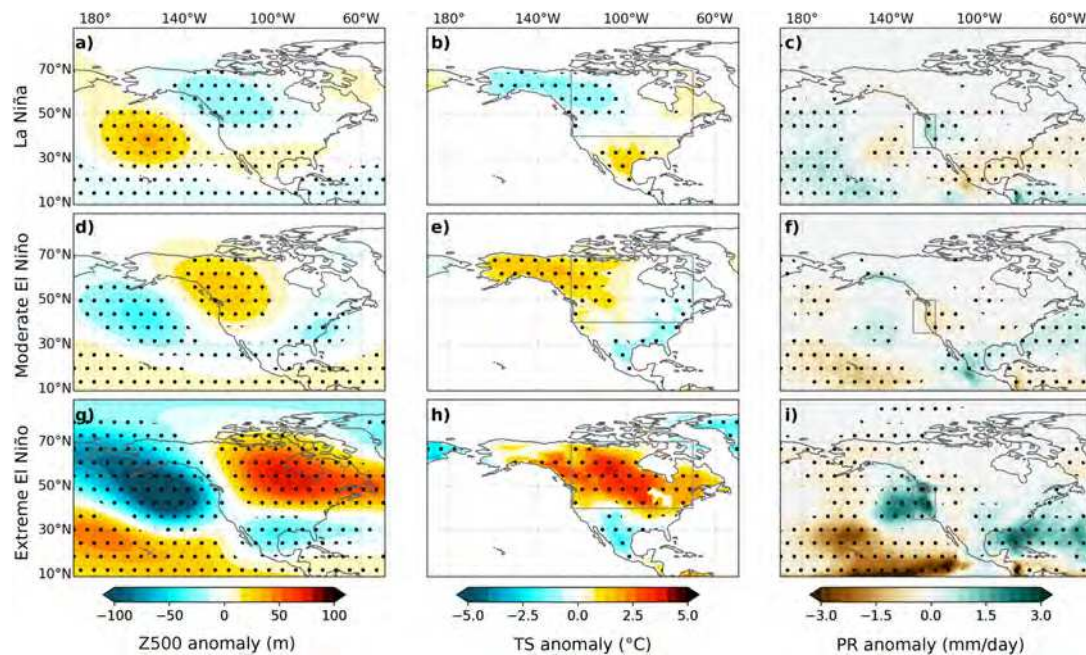


Figure 2. Composites of (left column) 500 hPa height (shaded, m), (middle column) land surface temperature (shaded, °C) and (right column) rainfall (shaded, mm/day) December–February (DJF) anomalies from the ensemble-mean CTL experiment over the 1979–2019 period for (top row) La Niña, (middle row) moderate El Niño and (bottom row) Extreme El Niño events. The composites are not normalized. The North American box (40–70°N, 125–80°W) used in Fig. 6c is marked in the middle column, and the Western United States box (35–50°N, 130–120°W) used in Fig. 6b in the right column. Dots indicate regions where anomalies exceed the 97.5% confidence level based on a bootstrap test with 10,000 resamples.

Mexico; see “Discussion” section), there is no statistically significant eastward shift for moderate EP events teleconnections over North America, as is evident for extreme El Niño events. This confirms that the change in teleconnection pattern, as identified in the aforementioned studies, are predominantly associated with extreme El Niño events. In the “Discussion” section, we will emphasize that our classification of “EP events” closely aligns with what some studies^{36–38} have defined as “convective eastern Pacific” events, i.e. that only the strongest convective perturbations corresponding to extreme El Niño events induce a shift in the teleconnection pattern.

This section demonstrated that both La Niña and moderate El Niño, whether of CP or EP types, consistently exhibit the well-established PNA teleconnection pattern in observations and the CNRM-CM6.1 atmospheric component. Our findings point to the occurrence of an extreme event as the key driver of a change in the ENSO teleconnection pattern, rather than the ENSO phase, diversity or the occurrence of convection in the eastern-central Pacific. This peculiar pattern resembles the negative phase of the Tropical/Northern Hemisphere (TNH) pattern^{43,44}.

Eastward-shifted SST forcing and atmospheric nonlinearities joint contributions to the extreme El Niño teleconnection pattern

In this section, we investigate the relative roles of the SST pattern and atmospheric nonlinearities in establishing the specific extreme El Niño teleconnection pattern. As discussed in the introduction, the nonlinear part of the atmospheric response can induce teleconnection asymmetries in response to a symmetrical SST forcing. But the linear atmospheric response to the ENSO asymmetrical SST forcing will also induce teleconnection asymmetries. We will thus estimate the relative roles of the linear and nonlinear atmospheric response to SST in establishing teleconnection asymmetries, and more specifically the extreme El Niño teleconnection pattern. We adopt the approach outlined by Srinivas et al. (in revision)⁴². It involves conducting two 6-member ensemble experiments: one follows the standard AMIP-style ensemble experiment, where the atmospheric response is driven by observed SST anomalies, while the other experiment involves reversing the sign of SST anomalies. By doing so, it allows diagnosing the linear and nonlinear parts of the atmospheric response to SST (see “Methods” section for details). Despite different localization of the equatorial SST anomalies, CP and moderate EP events exhibit similar teleconnection patterns, while only extreme EP events display a distinct teleconnection pattern. To understand the reasons underlying this feature, Fig. 4 displays the SST patterns (contours on middle column),

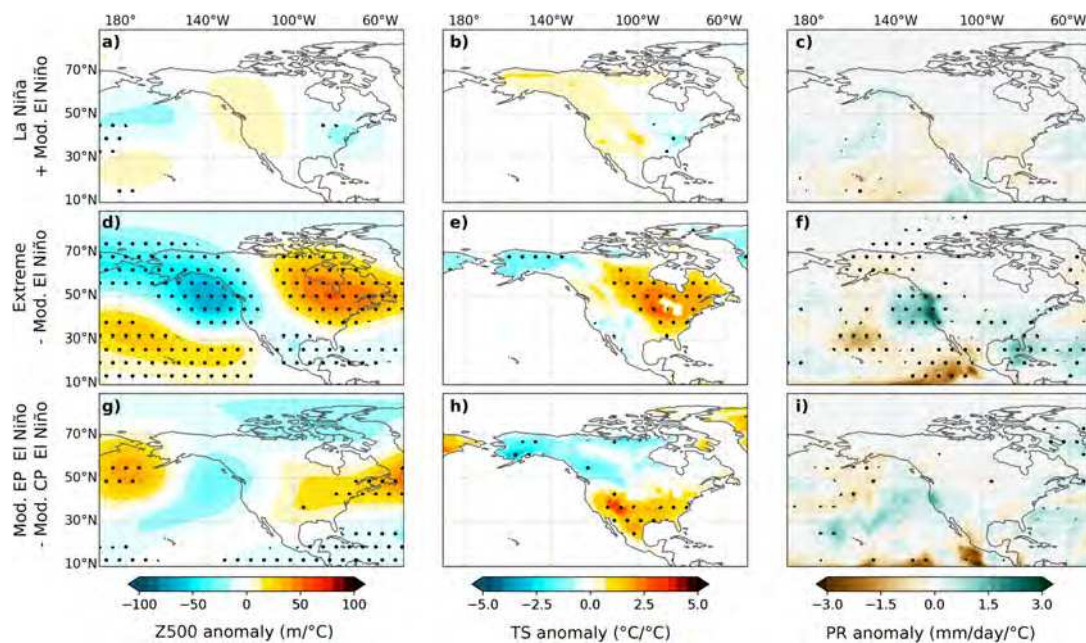


Figure 3. Composites sum/differences of (left column) 500 hPa height (shaded, m/°C), (middle column) land surface temperature (shaded, °C/°C) and (right column) rainfall (shaded, mm/day/°C) December–February (DJF) anomalies from the ensemble mean CTL experiment over the 1979–2019 period for (top row) La Niña plus El Niño, (middle row) Extreme minus moderate El Niño and (bottom) moderate Eastern Pacific (EP) minus moderate Central Pacific (CP) events. Each composite is obtained after normalizing by SST anomalies in the forcing region ([5°N/S, 170°E–130°W], see “Methods” section) in order to emphasize pattern rather than amplitude differences. Dots indicate areas where anomalies exceeded the 97.5% confidence level based on a bootstrap test with 10,000 resamples.

tropical rainfall response (left column) and its linear and nonlinear contributions (middle and right columns, respectively) for CP, moderate EP and extreme El Niño events.

The SST pattern associated with moderate CP events (Fig. 4b, red contours) features warm anomalies over the Niño3.4 and Niño4 regions, with maximum rainfall anomalies occurring over Niño4 (Fig. 4a). During moderate EP events, the SST anomalies are slightly shifted eastwards, with a peak in Niño3.4, and become stronger in the eastern Pacific, as expected (Fig. 4e, red contours). Despite this distinct SST pattern, the maximum rainfall anomalies location during moderate EP event does not greatly differ from that of moderate CP events (Fig. 4a,d). Figure 4b,e indicates a relatively linear rainfall response during moderate CP and EP events, in agreement with Srinivas et al. (in revision)⁴². The larger eastern Pacific SST anomalies during moderate EP events (contours in Fig. 4e) are indeed insufficient to trigger deep convection (hatching on Fig. 4c,f) over the climatology cool Niño3 region, thus resulting in a relatively small nonlinear contribution to rainfall there (shading in Fig. 4f). Conversely, extreme El Niño events are characterized by a much larger warming over Niño3 (contours on Fig. 4h). During these events, the maximum rainfall response shifts eastward to 160°W, and positive rainfall anomalies extend along the equator all the way to the South American coast (Fig. 4g). The linear and nonlinear components contribute roughly equally to rainfall anomalies over Niño3. This can be attributed to the SST threshold required to initiate deep atmospheric convection. The Niño3 SST anomalies are much larger for extreme than for moderate El Niño events (contours in Fig. 4e,h), now exceeding the convective threshold and yielding a large nonlinear rainfall response over Niño3 (hatching and shading on Fig. 4i, respectively). In summary, Fig. 4 demonstrates that only extreme El Niño events exhibit sufficiently large SST anomalies over Niño3 to exceed the convective threshold and induce a large eastward shift of the tropospheric heat source.

Figure 5 provides a similar analysis to Fig. 4, but for the mid-latitude response to moderate CP, moderate EP and extreme El Niño events, allowing us to explore how the aforementioned shifts in tropical precipitation influence mid-latitude teleconnection patterns. The mid-latitude response to moderate CP and EP El Niño is largely linear, resembling the PNA pattern (Fig. 5a–f). On the other hand, the extreme El Niño teleconnection pattern is primarily determined by the linear response to the eastward-shifted SST pattern (Fig. 5h vs. 5i, 0.91/0.69 pattern correlation of the linear/nonlinear contribution to total). However, as expected from the tropical rainfall response discussed earlier, the mid-latitude teleconnections associated with extreme El Niño events involve a significantly larger contribution from nonlinearities, with the intensified nonlinear rainfall in the eastern Pacific during extreme El Niño (Fig. 4i) driving an additional nonlinear response that strengthens

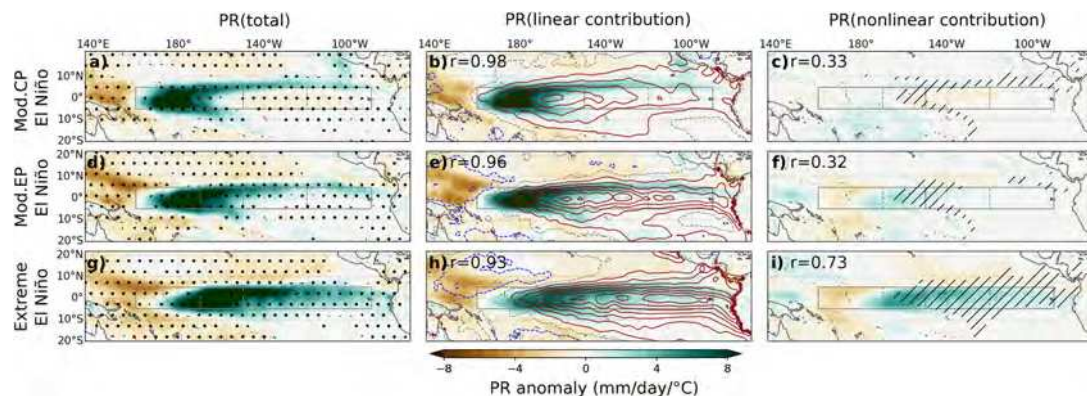


Figure 4. Composites of December–February (DJF) tropical Pacific rainfall anomalies (shading, mm/day/°C) from the ensemble mean CTL experiment over the 1979–2019 period for: (top row) moderate Central Pacific (CP), (middle row) moderate Eastern Pacific (EP) and (bottom row) Extreme El Niño events. Composites (shading, mm/day/°C) have been obtained after normalizing fields by the average [5°N/S, 170°E–130°W] SST anomalies (considered the main forcing region, see “Methods” section), in order to highlight the pattern rather than the amplitude differences. The left column displays the total anomaly from our 6-member ensemble simulation, while the middle and right column respectively display the linear and nonlinear response to SST contributions (see “Methods” section for details). Dots in the left column indicate areas where anomalies exceed the 97.5% confidence level based on a bootstrap test with 10,000 resamples. On middle panels, contours (red for positive, blue for negative, with a 0.2 °C contour interval) indicate the corresponding SST composites. Hatching in the right column indicates when the SST anomaly brings total SST from below to above the deep convection threshold (27.5 °C). On the middle (right) column, r indicates the pattern correlation between the total anomaly and the linear (nonlinear) SST contribution to the rainfall anomaly. Black continuous boxes encompass the Niño3 and Niño4 regions. The black dashed box highlights the Niño3.4 region.

the eastward-shifted response due to the linear contribution (Fig. 5i), almost matching the magnitude of the linear component (Fig. 5h).

In this section, we have explained why a distinct, eastward-shifted teleconnection pattern arises solely during extreme El Niño events. The SST pattern shifts eastwards during moderate EP events, but the Niño3 anomalies are still not strong enough to cross the convective threshold in the climatologically cool eastern Pacific. However, during the strongest EP events (i.e. extreme El Niño), eastward-shifted SST anomalies are strong enough to exceed the threshold for deep atmospheric convection in the Niño3 region, and atmospheric nonlinearities reinforce the eastward shift of the tropospheric heat source and of the associated mid-latitude Z500 response.

Reproducibility of ENSO teleconnection patterns

Extratropical seasonal forecasts rely on two factors: the ability to predict ENSO and the associated tropical heat source or sink; and the reproducibility of the extratropical teleconnection pattern. The reproducibility depends on the teleconnection pattern signal to atmospheric internal variability noise ratio. In this section, we investigate the reproducibility of the teleconnection pattern we have identified for extreme El Niño against that of the PNA pattern associated with other types of ENSO events (La Niña, CP, moderate EP). As outlined in the Methods section, we have expanded the 6-member reference ensemble for the common period (1979–2014) by incorporating an additional 10 members from AMIP CMIP6 simulations, resulting in a total of 16 members for all ENSO events, except for the 2015/2016 extreme El Niño, 2016/2017 and 2017/2018 moderate La Niña events, for which only 6 members are available.

We first assess the reproducibility of the Z500 patterns over the Pacific–North America region. In Fig. 6a, whiskers display the distribution of pattern correlations within 20–70°N, 180–60°W between each member and the composite ensemble mean for each specific ENSO phase. The circles display the same diagnostic for individual events in ERA5 correlated to the corresponding ENSO composite from the ensemble simulation. Hereafter, we refer to these quantities as the reproducibility score. First, we note that the median of the observed reproducibility reasonably matches that of the model, while its distribution falls within that of the model. This indicates that, considering the range of internal variability, the modeled teleconnection patterns satisfyingly reproduce those in observations. Secondly, the model and observed reproducibility scores exhibit a marked shift towards higher values for the extreme El Niño category (90% of modeled values, and 3 out of 3 observed values above 0.75), and a smaller spread than any other category of ENSO events. This indicates that the spatial pattern of Z500 anomalies for individual realizations is very similar to the composite extreme El Niño teleconnection in both models and observations. The Supplementary Figure S5 indicates that the extreme El Niño Z500 anomalies are both reproducible across members in the model, and across the three extreme events in both the model and observations. This enhanced reproducibility of North American Z500 anomalies during extreme El Niño events

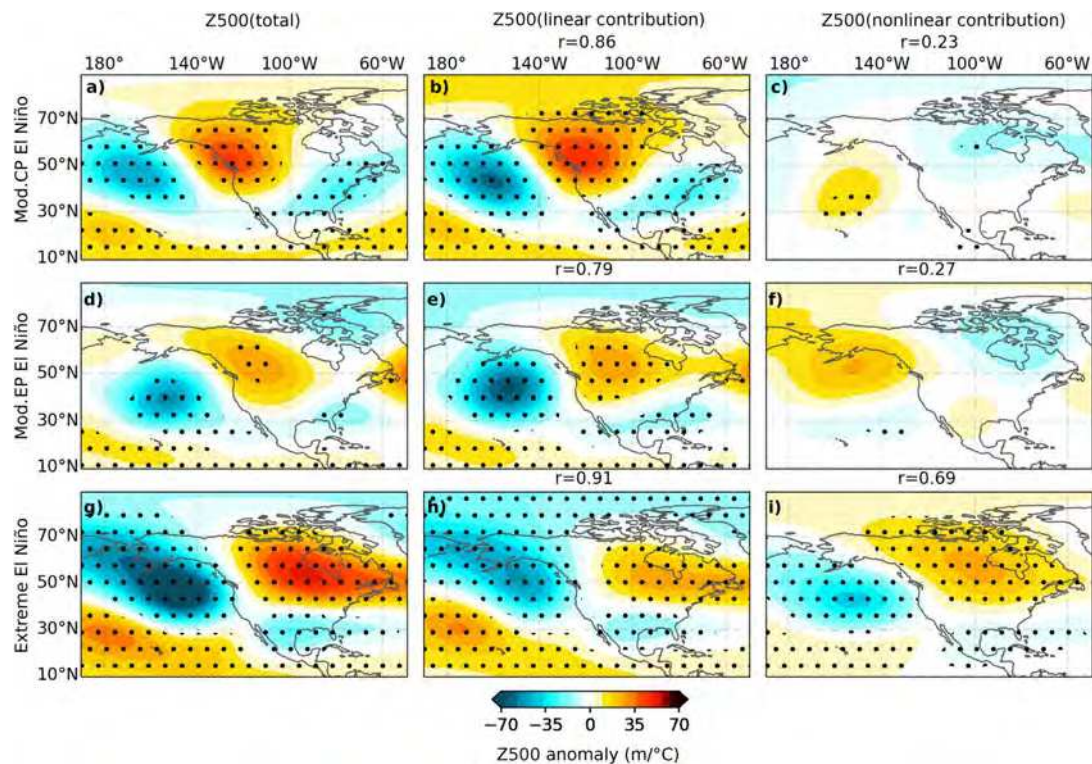


Figure 5. Composites of December–February (DJF) 500 hPa height anomaly from the ensemble mean CTL experiment over the 1979–2019 period for (top row) moderate Central Pacific (CP), (middle row) moderate Eastern Pacific (EP), and (bottom row) extreme El Niño events. Composites have been obtained after normalizing fields by the average [5°N/S, 170°E–130°W] SST anomalies (considered the main forcing region, see “Methods” section), in order to highlight the pattern rather than the amplitude differences (shading, m/°C). Each row consists of three panels: (left column) total anomaly, (middle column) linear response to the SST forcing and (right column) contribution from atmospheric nonlinearities. Dots indicate areas where anomalies exceed the 97.5% confidence level based on a bootstrap test with 10,000 resamples. On the middle (right) column, r indicates the pattern correlation between the total anomaly and the linear (nonlinear) SST contribution to the Z500 anomaly.

could be due to the fact that the larger amplitude, eastward-shifted response is less affected by internal atmospheric variability or other sources of external forcing, favoring a higher signal-to-noise ratio.

As mentioned in the introduction, recent studies have highlighted the association of wet conditions in California and the strongest El Niño events^{34,35}. Figure 6b presents the observed and ensemble distribution of the average rainfall anomalies in the West Coast of the United States (35–50°N; 130–120°W, including the states of Washington, Oregon and California) for each ENSO composite phase (whisker box for the 16 model realizations distribution, and circles for observed events). Despite the limited number of realizations (3 to 9 depending on the ENSO type), the observed distributions are generally reasonably consistent with the observed ones. Extreme El Niño years display the most pronounced shift in the rainfall probability distribution over the Western United States, with a wet anomaly (defined based on 0.5 standard deviation threshold) in 74% (see Fig. 6b) of the 38 extreme El Niño ensemble members. The 3 observed extreme El Niño events also correspond to wet anomalies, further underlining the consistent impact of extreme El Niño on Californian rainfall in observations. Figure 6c presents the same diagnostic for Ts anomalies over North America (within 40–70°N, 125–80°W) and leads to similar conclusions. The North American warming during extreme El Niño is robust, with 71% of the members exhibiting warm anomalies that exceed 0.5 standard deviation in our simulation, and a warm anomaly for 2 of the 3 observed events. One can however note that the 3 moderate EP events also correspond to warm anomalies in observations, unlike in the model.

In this section, we have shown that the boreal winter Z500 anomalies are more alike the composite teleconnection patterns for extreme El Niño than for any other type of ENSO event (La Niña, CP, moderate EP). In particular, this specific teleconnection pattern leads to more consistent wet anomalies over Western United States and warm anomalies over North America. The implications of these findings for seasonal forecasts will be discussed below.

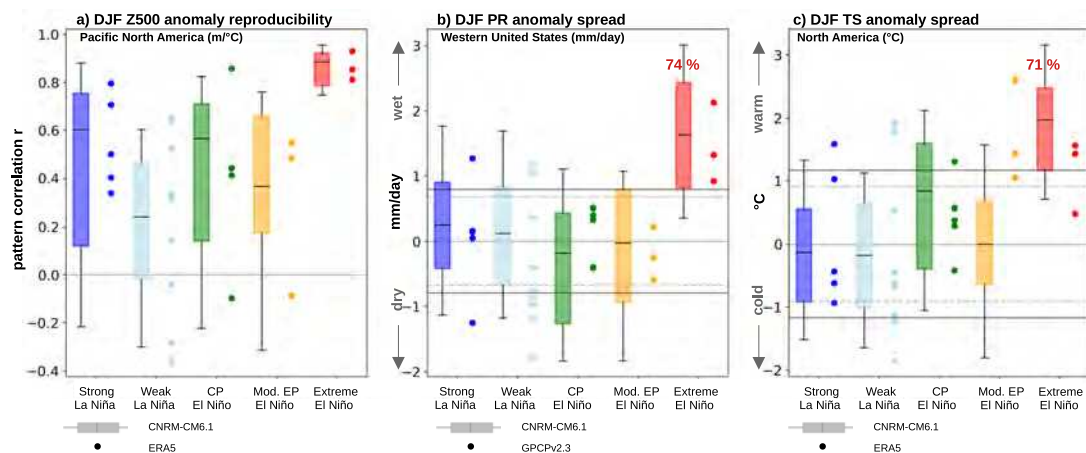


Figure 6. (a) Reproducibility of the DJF 500 hPa height pattern during ENSO events from the ensemble mean CTL experiment (whisker boxes) and ERA5 (circles), as a function of the type of ENSO event (strong La Niña, weak La Niña, CP El Niño, moderate EP El Niño, extreme EP El Niño). Whisker boxes (circles) represent the distribution of pattern correlations between individual members (individual years for ERA5) and the corresponding CTL ENSO composite, over the 20–70°N, 180–60°W region. Anomalies are normalized by the average [5°N/S, 170°E–130°W] SST anomalies (considered the main forcing region, see “Methods” section), although the normalization method does not significantly affect the findings. (b) Distribution of the DJF rainfall anomaly average (mm/day) over the 35–50°N, 130–120°W region encompassing Western United States. Anomalies are not normalized. (c) same as (b) but for land surface temperature (°C) over North America (40–70°N, 125–80°W). The whiskers, box boundaries and middle marker respectively indicate the 10th and 90th percentiles, 25th and 75th percentiles and median for the CTL ensemble, while circles indicate values for individual events in observations (ERA5 for surface temperature, GPCP v2.3 for rainfall). On panels b,c the solid/dashed grey lines indicate CTL ensemble / observed $\pm 0.5 \times$ standard deviation threshold used to characterize wet/dry or warm/cold anomalies. Percentages indicate wet/dry (panel b) or warm/cold (panel c) anomalies, based on the 0.5 std threshold across all years and ensemble members (CTL ensemble). The distributions are based on 16-member ensembles except for 2015–2017 for which only 6 members are available (see “Methods” section).

Discussion

In this study, we use observations and AMIP-type ensemble integrations with the CNRM-CM6.1 ARPEGE-Climate v6.3 atmospheric general circulation model to explore the diversity of DJF ENSO teleconnection patterns over the North Pacific and North America. Previous studies have explored differences in teleconnection patterns between El Niño and La Niña¹², between central and eastern Pacific El Niño events^{27–29}, or between El Niño events with and without convective anomalies in the eastern-central Pacific^{36–38}. This last category is closest to our extreme El Niño definition, but also retains moderate EP events that do not involve as large eastern Pacific rainfall anomalies as extreme El Niño events do. We show that the differences in teleconnection pattern discussed in previous studies are in fact solely due to extreme El Niño events (see Supplementary Figure S3). These events display a unique eastward shift relative to the well-known PNA pattern, resulting in a pattern that closely resembles the TNH teleconnection pattern^{43,44}. On the other hand, asymmetries between the La Niña and moderate El Niño teleconnection patterns are not statistically significant. Similarly, differences between the moderate CP and moderate EP teleconnection patterns are much less significant than those between extreme El Niño events and any other category. Our results however suggests statistically significant differences between the moderate CP and moderate EP teleconnection patterns over the North Pacific and western North Atlantic regions. This would need to be investigated in a larger ensemble, as we only have three moderate EP events in our sample, and a large sampling size is needed to reach statistical robustness^{15,45}. Investigating moderate CP/EP teleconnection diversity in large AMIP ensembles would be a pertinent perspective for accurately evaluate changes in teleconnections between these two specific phases.

Our record being quite short (only 3 extreme El Niño events), it is difficult to definitively conclude that the north American ENSO teleconnection distribution is bimodal, with the eastward shift only occurring during extreme El Niño events. There may be a more continuous eastward shift of the teleconnection pattern as SST and precipitation anomalies in the east progressively increase, aligning with the ideas of some previous publications^{36–38}. However, because we cannot detect it based on last 40 years record, the idea that the ENSO teleconnection pattern only changes for extreme El Niño events can serve as a good null hypothesis.

Several studies^{12,17} have emphasized the role of atmospheric nonlinearities related to the threshold for atmospheric convection, as opposed to the influence of the different SST patterns during La Niña, CP or EP events. Our methodology allows us to disentangle the respective contributions of these two factors. As a previous study³²,

we find that the SST pattern and atmospheric nonlinearities both influence changes in ENSO teleconnection patterns. For moderate EP El Niño events, the eastward-shifted SST anomalies do not exceed the convective threshold over the Niño3 region. Conversely, during extreme El Niño events, the SST anomaly is both eastward-shifted and sufficiently large to cross the convective threshold over much of the Niño3 region. Consequently, atmospheric nonlinearities combine with the linear response to SST to produce a tropospheric heat source shift from the central to the eastern Pacific, leading to an eastward shift in the North American teleconnection pattern.

Our study contributed to better understand the mechanisms behind the tropospheric heat source change, but did not investigate the Rossby wave pathway between this eastward-shifted heat source and the mid-latitudes. A previous study using an idealised atmospheric model⁴⁶ found a sensitivity of the mid-latitude teleconnection pattern to the longitude of the equatorial heat source that is reminiscent of that we highlighted during extreme El Niño events. Following this perspective, sensitivity experiments with atmospheric GCMs forced with various SST patterns such as the Green's Function Model Intercomparison Project (GFMIP⁴⁷) or Rossby wave tracing analysis could provide valuable insights into the mechanisms involved in the teleconnection change during extreme El Niño events.

Finally, we examined the reproducibility of North American 500 hPa geopotential height anomalies for various ENSO event categories, and found they were more reproducible during extreme El events than during any other type (La Niña, CP, moderate EP). This is attributable to a more favorable signal-to-noise ratio due to the larger amplitude forcing in the tropics, although this hypothesis will have to be investigated. This finding carries important implications for seasonal climate predictability over North America. The consistently higher risks of wet conditions over Western United States and warm conditions over Canada and Northern US during extreme El Niño are potentially predictable, provided that an extreme El Niño can be skillfully forecasted. A recent study indicates that the amplitude of extreme El Niño events is strongly affected by the semi-random occurrence of Westerly Wind Events during summer and fall in the equatorial Pacific⁴⁸. An investigation of the lead-time at which extreme El Niño conditions can confidently be predicted is thus necessary to evaluate the potential skill gain from considering the unique extreme El Niño teleconnection pattern.

Our results also have implications for the future evolution of ENSO impacts. Recent studies suggested an eastward shift of the ENSO-related tropical rainfall and extratropical teleconnections⁴⁹, as well as more frequent extreme El Niño events⁵⁰ under warmer climates. Our results imply that this should be associated with more frequent wet conditions over Western United States including California, and heat waves over Northern US and Canada. In the future, we will explore whether CMIP6 models reproduce the specific extreme El Niño teleconnection pattern discussed in the present study, and the consequences for the future projections of ENSO events impacts over North America.

Methods

We use AMIP ensembles designed by Srinivas et al. (in revision)⁴² with the atmospheric component of the Centre National de Recherches Météorologiques (CNRM) - CERFACS climate model CNRM-CM6.1, ARPEGE-Climate v6.3⁵¹. It is a global spectral model with a T127 triangular truncation which is equivalent to a spatial resolution of about 150 km. The vertical coordinate is progressive hybrid sigma-pressure, from 0.01 hPa to the surface over 91 levels. This model is able to reproduce the ENSO observed sea level pressure and air temperature teleconnections to the North Pacific⁵².

Our control simulation (abbreviated as CTL) is the AMIP-type 6-member ensemble experiment run over 1979–2019 by Srinivas et al. (in revision)⁴². Initial conditions are selected as in Voldoire et al. (2019)⁵², following Rhoerig et al. (2020)⁵¹. Figures 1, 2, 3, 4 and 5 use 6-members ensemble. This ensemble was too small to assess the reproducibility of the teleconnection patterns (Fig. 6) and we increased the size of the ensemble by using the 1979–2014 10-member AMIP experiment of Voldoire et al. (2019)⁵². Figure 6 hence uses 16 members for all events except for 2015–2016, for which only 10 members are available. Figure S6 illustrates that the Figs. 1, 2, 3 are robust when using 16 instead of 6 members. We did however stick to 6 members in the main text so that the linear/nonlinear decomposition of Figs. 4 and 5 is comparable to Figs. 1, 2 and 3.

For 500 hPa geopotential height and surface temperature, we used the monthly averaged ERA5 on pressure levels⁵³ as a reference dataset. Our monthly precipitation reference dataset is the Global Precipitation Climatology Project v2.3⁵⁴. All model and observed anomalies are obtained after linearly detrending and removing the 1979–2019 climatology. In this manuscript, we only discuss boreal winter (December–January–February, DJF) average anomalies, as ENSO SST anomalies peak in boreal winter⁵⁵ and the PNA teleconnection pattern in February⁸.

We estimate the linear and nonlinear components of the atmospheric response to SST anomalies following the methodology of Srinivas et al. (in revision)⁴². The CTL ensemble mean is our estimate of the forced response to the SST anomaly T' , noted $M(T')$. Observed interannual SST anomalies relative to the 1979–2019 climatology are subtracted from the climatology, and used to force a second 6-member ensemble experiment over 1979–2019, and the resulting ensemble-mean forced response is noted $M(-T')$. By calculating the half-difference $\frac{1}{2}(M(T') - M(-T'))$, Srinivas et al. (in revision)⁴² effectively isolates the odd terms of the Taylor series (i.e. linear term, plus all non-symmetry-breaking nonlinearities). Conversely, the half-sum $\frac{1}{2}(M(T') + M(-T'))$ extracts all the even terms (symmetry-breaking nonlinearities). As demonstrated by Srinivas et al. (in revision)⁴², $\frac{1}{2}(M(T') - M(-T'))$ is dominated by the first order linear term, and $\frac{1}{2}(M(T') + M(-T'))$ by the second-order quadratic term. In the paper, we simply refer to these as the linear and nonlinear contributions, respectively.

ENSO events are defined according to the NOAA oceanic Niño index (ONI⁵⁶), when the 3-month running mean of mean ERSST.v5 SST anomalies over the Niño-3.4 region (5°N–5°S, 120°–170°W) exceeds 0.5°C (El Niño) or falls below -0.5°C (La Niña). To compute the SST anomalies for a consecutive 5-year periods, a 30-year base periods is employed as climatology⁵⁷. The CP/EP classification follows the “Cold Tongue/Warm Pool” classification method³³, based on coordinate transformation of the Niño3/Niño4 phase space to calculate the

CT/WP indices. Extreme El Niño events are defined as events with DJF ONI above $+2^{\circ}\text{C}$, according to recent studies^{58,59}. Strong La Niña events are defined as events with DJF ONI below -1.5°C , according to the Climate.gov ENSO Blog⁶⁰. Supplementary Figure S4 lists the events in each category, and summarizes how some categories are subset of some others (e.g. extreme El Niño are included in EP).

We use composites to isolate the tropical rainfall response and extratropical teleconnections associated with various event categories (La Niña, El Niño, CP, moderate EP, extreme El Niño). We identify composite anomalies that are different from zero at a 97.5% confidence level based on a bootstrap method. Multiple composites are built by randomly resampling (10,000 times for the model, 1000 for observations) the sample (one sample per event for observations, as many samples as ensemble members per type for the model). The lower (upper) 2.5% of the distribution allow to determine whether the mean is significantly above (below) from 0.

Figures 3, 4 and 5 display differences between composites. They aim at identifying differences in spatial pattern rather than differences in amplitude of the atmospheric response. The events have thus been normalized by the amplitude of the SST forcing prior to computing the composites and their difference. We have chosen to normalize based on average SST anomalies over the $[5^{\circ}\text{N/S}, 170^{\circ}\text{E}-130^{\circ}\text{W}]$ region, that covers most of the more conventional Niño3.4 and Niño4 boxes (except the most eastward and westward 10°). We chose this region because it encompasses both the regions of maximum La Niña and El Niño precipitation anomalies, and hence broadly the region where SST anomalies force the atmosphere. Note, however, that the results are not sensitive to using, e.g., the more conventional Niño3.4 box for normalizing.

Accession codes

Figures are prepared in Python, codes are available on request from MB. The simulations are available on request from GS.

Received: 22 September 2023; Accepted: 20 January 2024

Published online: 30 January 2024

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Acknowledgements

This work was supported by the French Agence Nationale pour la Recherche (ANR) ARISE Grant (ANR-18-CE01-0012). MB has been partially supported through the Grant EUR TESS N°ANR-18-EURE-0018 in the framework of the Programme des Investissements d'Avenir.

Author contributions

M.B. did all the analyses and wrote the first draft of the manuscript, with the help of J.V. and M.L. J.V. and M.L. designed the study. S.G. performed some of the numerical experiments used in that study, with the help of A.V.

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N.H. contributed to literature about studying ENSO teleconnections with simple atmospheric models. All authors contributed to the writing and interpretation of the results.

Competing interests

The authors declare no competing interests.

Additional information

Supplementary Information The online version contains supplementary material available at <https://doi.org/10.1038/s41598-024-52580-9>.

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III.3 Conclusions and way forward

In this chapter, I examined the diversity of the DJF ENSO teleconnection pattern over North America, using observations and AMIP-type ensemble simulations with the CNRM-CM6.1 model atmospheric component.

- Based on a 16 member ensemble, I find that La Niña, Moderate CP and Moderate EP El Niño events are all associated with a PNA pattern. In contrast, extreme El Niño events uniquely induce an eastward-shifted mid-level geopotential height anomaly, i.e. a TNH-like pattern. In other words, I find no statistically significant differences between the moderate CP and moderate EP El Niño events teleconnections.
- I also find that the extreme El Niño events result in specific impacts, characterized by a robust increase of precipitation anomalies (74% likelihood) along the USA west coast and warm anomalies (71% likelihood) over Canada and northern USA. Other ENSO categories do not produce statistically significant seasonal anomalies in those regions.
- The specific, eastward shifted and large-amplitude SST anomalies during extreme El Niño events and atmospheric nonlinearities associated with the tropical convective response to SST contribute equally to the teleconnections eastward shift during extreme El Niño events. Other ENSO categories have negligible contributions from atmospheric nonlinearities. In other words, the PNA-type teleconnection pattern responds linearly to the ENSO SST anomalies during La Niña and moderate El Niño events.

The main limitation of the analyses in this chapter is the limited sampling size (3 observed extreme El Niño events, 16 members in the CNRM-CM6.1.AMIP ensemble). A second limitation is linked to the use of a single model. This model may be heavily influenced by model error, and there is no easy way to verify whether this is the case, knowing that the extreme El Niño teleconnection pattern obtained from the 3 observed samples is most likely heavily contaminated by sampling error. An immediate next step to ascertain my results is therefore to investigate the specificity and robustness of the extreme El Niño TNH-like teleconnection pattern, in a larger multi-model sample. The broad AMIP6 database is an ideal resource for conducting this analysis: that will be the starting point of Chapter IV.

Chapter IV

Robustness of extreme El Niño teleconnections to North America in AMIP6/CMIP6 models

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IV.1 Preamble

This chapter has two main objectives. First, examining the robustness of chapter III key findings about extreme El Niño teleconnections in the face of sampling and model error. Second, evaluate whether coupled ocean-atmosphere models of the CMIP6 database reproduce the specific extreme El Niño teleconnections as well as AGCMs. This chapter is presented under the form of an article, submitted to *JGR-Atmospheres* in June 2024, untitled "How well do AMIP6 and CMIP6 reproduce the specific extreme El Niño teleconnections to North America?".

In chapter III, I established that only extreme El Niño events yield the a specific TNH-like teleconnection pattern (eastward-shifted relative to the PNA pattern), with highly reproducible seasonal impacts over North America. These results are largely based on a sixteen-members ensemble with a single AGCM. However, two main factors can contribute to uncertainties in the teleconnection patterns established in chapter 3: sampling and model error.

Variability unrelated to ENSO is primary source of sampling error. First, the PNA is also externally forced by other phenomenons, for instance by MJO-related convective activity in the Indian Ocean (Seo & Lee, 2017). Second, the PNA pattern has a large amplitude internal variability, associated with the modulation of the intensity and direction of the Asian-Pacific jet (Yang et al., 2000; Lau & Boyle, 1987). More generally, variability unrelated to ENSO forcing, and in particular the large internal extratropical variability (Deser et al., 2017) will alias the ENSO signal, giving rise to large sampling error (Deser et al., 2012; Garfinkel et al., 2018). This is even more an issue when examining the extreme El Niño teleconnection pattern, for which only three events have occurred since the beginning of the satellite SST record.

Deriving teleconnection patterns from a single model, as we did in chapter 3, is also a source of concern. AGCMs are indeed subject to systematic model errors (Xiang et al., 2017; Hardiman et al., 2022). Errors in the representation of ENSO rainfall anomalies and in the mid-latitude atmospheric mean state will indeed result in errors in the teleconnection pattern, as they respectively control its forcing and propagation pathway. Therefore, the first objective of this chapter is to investigate the robustness of Chapter III results in a wider database, with both more members (to address sampling error) and more models (to address model error). We will use ensemble simulations from 23 models from the AMIP6 database (a total of 135 members over 1979-2014. This much broader ensemble will in addition allow us to understand why the extreme El Niño impacts are more reproducible than for other ENSO categories, through a signal-to-noise ratio (SNR) analysis.

The second main objective of this study is to evaluate how fully coupled state-of the art climate models from the CMIP6 database reproduce extreme El Niño teleconnections and the associated climate impacts. Coupled GCMs indeed have strong SST mean state biases, such as

the persistent equatorial SST “cold tongue” bias (Planton et al., 2021; Zhang et al., 2023). This cold tongue bias results in underestimated rainfall in the western Pacific and a tendency to have a too zonal South Pacific Convergence Zone (referred as the “double ITCZ bias”). This bias also degrades the representation of ENSO, for instance hindering the generation of extreme El Niño events, and degrading the representation of ENSO phase asymmetry (Bayr et al., 2024). Bayr et al. (2019) also demonstrated that this cold SST bias resulted in a misrepresentation of the teleconnection asymmetry between El Niño and La Niña. Overall, the SST biases that develop in coupled models introduce additional sources of errors relative to AMIP simulations, which use observed SST. There is thus a need to investigate the representation of ENSO teleconnections in CMIP models, and in particular of extreme El Niño events teleconnections. CMIP models are indeed used to perform future climate projections (IPCC AR6-WG1, 2021). Such projections indicate a robust projected increase of Extreme El Niño events frequency under global warming, in CMIP3-5 (Cai et al., 2014) and CMIP6 models (Cai et al., 2021; Heede & Fedorov, 2023) capable of reproducing these Extreme El Niño events. In view of the chapter III results, this may 1) contribute to an ENSO teleconnection pattern change in the future; 2) influence ENSO teleconnection pattern predictability (as extreme El Niño teleconnection patterns tend to be more reproducible). As a first step to examining their future evolution (chapter V), it is therefore crucial to investigate how well CMIP6 models reproduce the specific Extreme El Niño teleconnections (i.e. whether the SST biases in CMIP models induce a strong degradation of this pattern relative to that in AMIP models).

Overall, I will address the following questions using the extensive AMIP6 and CMIP6 multi-model databases :

Questions addressed :

1. Are results about the specificity of extreme El Niño teleconnections over North America obtained in chapter 3 robust in the wider AMIP6 database ?
2. Are Extreme El Niño teleconnection patterns also highly reproducible in the wider AMIP6 database ? Does this stronger reproducibility arise from stronger signal or reduced atmospheric internal variability?
3. How do CMIP6 models biases affect their ability to reproduce the extreme El Niño teleconnection pattern and the associated impacts?

IV.2 Article in revision in *JGR: Atmospheres*

Now published : Beniche et al. (2025)

How well do AMIP6 and CMIP6 reproduce the specific Extreme El Niño teleconnections to North America ?

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Key Points:

- 22 AMIP6 ensemble simulations confirm the specific, eastward-shifted teleconnection pattern over North America during extreme El Niño events
- The Extreme El Niño teleconnection pattern and its impacts (warm Northeast America, wet California and Florida) are very reproducible
- Most CMIP6 models that produce Extreme El Niño events reproduce their teleconnection pattern, but downplay wet California/Florida anomalies

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Abstract

Extreme El Niño events (e.g. 1982-83, 1997-98) are characterized by strong, eastward-shifted warm Sea Surface Temperature anomalies, and a southward migration of the eastern Pacific Intertropical convergence zone (ITCZ) to the equator. Using an ensemble simulation with a single AMIP6 model, Beniche et al. (2024) suggested that such events uniquely yield an eastward shift of the Pacific North America (PNA) teleconnection pattern, with specific impacts over North America. Here, we first examine the robustness of these results in 135 ensemble members from 23 AMIP6 models. The specific, eastward-shifted extreme El Niño teleconnection pattern is robust in all models but one. It is also highly reproducible across years and ensemble members, due to a stronger signal than the internal noise. This yields specific, predictable impacts (defined as > 0.5 std) such as warm conditions over Northeast America (69% chances), and wet anomalies over California (77%) and Florida (97%). We then show that 26 out of the 42 CMIP6 models we examined reproduce extreme El Niño events, defined as large eastern Pacific rainfall anomalies. These models tend to have a weaker cold tongue bias than the rest of CMIP6. Despite a degradation in performance from AMIP6 to CMIP6, 18 out of the 26 selected models capture the specific extreme El Niño teleconnections, albeit with some underestimation of wet anomalies over California and Florida. We end by discussing implications for future north American climate projections based on CMIP6.

Plain Language Summary

The El Niño-Southern Oscillation (ENSO) alternates between a warm and wet (El Niño) or cold and dry (La Niña) equatorial Pacific. ENSO events modify the atmospheric circulation, leading to climate impacts over remote regions, including North America. This is known as ENSO teleconnections. Occasionally, El Niño escalate into extreme events, characterized by strong and eastward-shifted equatorial Pacific warm anomalies compared to weaker events. By analysing a large database of atmospheric models forced by observed Sea Surface Temperature, we demonstrate that these extreme El Niño events produce North American teleconnection pattern and impacts that are distinct from those of milder events, and more reproducible. Extreme El Niño in particular result in high probability of warm anomalies over Northeast America and wet anomalies over California and Florida. Not all coupled ocean-atmosphere climate models can simulate extreme El Niño events, but most of those that do reproduce their specific teleconnection pattern, albeit with underestimations of wet conditions over California and Florida. We discuss the implications of our results for future projections of the North American Climate.

1 Introduction

The El Niño-Southern Oscillation (ENSO) is the primary driver of interannual climate variability (McPhaden et al., 2006; Taschetto et al., 2020). ENSO is characterized by alternating warm (El Niño) and cold (La Niña) Sea Surface Temperature (SST) anomalies in the central and eastern equatorial Pacific. These anomalies trigger changes in tropical atmospheric convection, setting off extratropical atmospheric responses known as teleconnections (Hoskins & Karoly, 1981; Horel & Wallace, 1981). With ENSO predictability extending several seasons in advance (L’Heureux et al., 2020), those teleconnections are crucial in accurately forecasting seasonal rainfall and surface temperature across North America during boreal winter (J. Yu et al., 2012; Kumar & Hoerling, 1995, 1998). ENSO teleconnections are mostly associated with the Pacific-North American (PNA) pattern (Wallace & Gutzler, 1981; Horel & Wallace, 1981), whose positive (negative) phase is associated with El Niño (La Niña) events (Livezey & Mo, 1987). The PNA features centers of action over the Aleutian Islands and western Canada, facilitating the northward advection of warmer air over Northwest US and Canada (Ropelewski & Halpert, 1986).

ENSO is also linked to another teleconnection pattern known as the Tropical North Hemisphere (TNH) pattern (Mo & Livezey, 1986; Livezey & Mo, 1987), which exhibits an eastward shift and a phase quadrature relative to the PNA pattern (Barnston & Livezey, 1987). Early studies suggested that the nonlinear response of the tropical convection to Sea Surface Temperature (SST) resulted in eastward-shifted rainfall anomalies during El Niño relative to La Niña, triggering the TNH pattern (Hoerling et al., 1997; Peng & Kumar, 2005). ENSO diversity (Capotondi et al., 2015) distinguishes El Niño events with peak SST anomalies in the Central Pacific (CP, dateline or Modoki) and Eastern Pacific (EP) events (Ashok et al., 2007; Takahashi et al., 2011; Kug et al., 2009). Hoerling and Kumar (2002); J. Yu et al. (2012); B. Yu et al. (2015) suggested that only EP events trigger the TNH teleconnection and associated impacts (Mo, 2010; Feng et al., 2016). Chiodi and Harrison (2013, 2015); Johnson and Kosaka (2016) pointed out the necessity of deep convective anomalies over the central-eastern Pacific to induce impacts over North America, noting that only sufficiently large EP events could trigger anomalies over this climatological cold region.

Some EP El Niño events, such as in 1982-83 and 1997-98 reach much larger SST anomalies magnitude than CP events, leading to classify them as extreme El Niño events. These extreme ENSO events play a pivotal role in shaping the SST and rainfall asymmetry between El Niño and La Niña (Bayr et al., 2023), Liu et al, in rev, (Srinivas et al., n.d., 2024). Their large SST anomalies exceed the convective threshold over the eastern Pacific, inducing large eastern Pacific rainfall anomalies (Srinivas et al., n.d., 2024; Bayr et al., 2023). Consequently, only extreme El Niño events are found to drive rainfall anomalies over California (Hong Lee et al., 2023; Lee et al., 2018; Hoell et al., 2016). Building on these studies, (Beniche et al., 2024) used Atmospheric General Circulation model (AGCM) experiments to demonstrate that such extreme El Niño events are the sole contributor to the diversity of winter ENSO teleconnection over North America. In other words, they demonstrate that while both La Niña and moderate El Niño events (EP and CP alike) induce a PNA response (positive for El Niño, and negative for La Niña), only extreme El Niño events can trigger a TNH response and wet anomalies over the western US coast.

However, Beniche et al. (2024) only considered a single 16-members ensemble with the CNRM-CM6.1 atmospheric component (Roehrig et al., 2020), whereas fifty-five atmospheric models simulations forced by observed SST and sea-ice are available in the Atmospheric model Intercomparison Project (AMIP) database. At first, AGCM suffer from various biases, attributable to imperfect parameterizations (Zhang et al., 2024; Xiang et al., 2017), raising doubts about the robustness of the teleconnection patterns derived from a single model. Secondly, extratropical atmospheric internal variability is substantial (Kumar & Hoerling, 1995), with some studies suggesting that, in addition to being SST-forced, the PNA may also reflect internal atmospheric variability (Straus & Shukla, 2002, 2000). This large internal noise can obscure the ENSO-driven signal, leading to large sampling errors on ENSO teleconnections patterns in both observations (Garfinkel et al., 2012) and models (O'Reilly, 2018; Sardeshmukh et al., 2000). Addressing this issue requires large sample sizes (Garfinkel et al., 2018; Deser et al., 2018), which can be achieved from large ensemble simulations. The first objective of this study is therefore to ascertain the robustness of Beniche et al. (2024) results using a broader database (see Table 1), encompassing a total of 135 ensemble members from 23 different AMIP6 models, focusing on the 1982/83 and 1997/98 Extreme El Niño events. This approach will both address the sampling issue, and assess robustness of the Beniche et al. (2024) results in other AGCMs. Moreover, Beniche et al. (2024) emphasized that the larger reproducibility of extreme El Niño teleconnections and impacts over North America were much more reproducible compared to those of moderate El Niño or La Niña events. Therefore, our second objective is to investigate the extreme El Niño teleconnection reproducibility within the extensive AMIP6 database and explore whether this reproducibility arises from stronger signals and/or reduced internal variability.

Finally, projections from the Coupled model Intercomparison Project (CMIP) database, particularly CMIP6 (Eyring et al., 2016), indicate an increase of extreme El Niño frequency (Cai et al., 2021; Heede & Fedorov, 2023b) and larger El Niño EP events (Shin et al., 2022) in warmer climates. The results of Beniche et al. (2024) consequently imply more frequent ENSO impacts over North America in a warmer climate. CMIP models however are known to suffer from large systematic biases that can affect their representation of ENSO teleconnections. Notably, CMIP models display a persistent “cold tongue” bias in the equatorial Pacific SST climatology, associated with a dry bias, which has been observed across multiple CMIP generations (Bellenger et al., 2013; Planton et al., 2021). This bias can prevent the initiation of deep convection, even in presence of large, eastward-shifted SST anomalies characteristic of extreme El Niño events, potentially preventing the occurrence of large eastern Pacific rainfall anomalies (Cai et al., 2014) that trigger the TNH response (Beniche et al., 2024). Additionally, CMIP atmospheric mean state biases can affect the Rossby wave pattern that underpins teleconnections to the Pacific-North American sector (Li et al., 2020). These systematic biases may compromise the CMIP6 model ability to accurately reproduce the distinctive TNH-like teleconnection pattern associated with Extreme El Niños in the present climate. Therefore, our third objective is to investigate whether CMIP6 models can reproduce the specific teleconnection pattern of extreme El Niño diagnosed from the AMIP6 simulations.

This paper is organized as follows. Section 2 present our observational, AMIP6 and CMIP6 datasets and methods. In section 3, we demonstrate that the specific extreme El Niño teleconnection pattern discussed by Beniche et al. (2024) is robust and across 22 out of 23 examined AMIP simulations, and investigate the cause of its strong reproducibility. In section 4, we assess the performance of CMIP6 models in simulating extreme El Niño events, with 26 out of 42 models which are able to simulate strong eastern Pacific rainfall anomalies during such events. These models reproduce the AMIP6 extreme El Niño teleconnection pattern reasonably well, despite an underestimation of extreme El Niño wet anomalies over California and Florida. In section 5, we summarize our results, and discuss them with an emphasis on perspectives regarding using CMIP models to investigate future ENSO teleconnections over North America.

2 Methods and Data

We implement a standardized data processing methodology to ensure consistency across all datasets. Monthly values are first linearly detrended and then averaged over the boreal winter season (December-January-February, DJF), aligning with the peak activity periods of both ENSO-related tropical SST anomalies and the PNA/TNH teleconnections patterns (Rasmusson & Carpenter, 1982; Barnston & Livezey, 1987). Anomalies are computed relatively to a 1979-2014 DJF climatology for AMIP6 and observed datasets, and 1850-2014 DJF for CMIP6. All datasets are bi-linearly interpolated to a standard $1^\circ \times 1^\circ$ grid. Normalized composites refer to composites built from individual years divided by the DJF average N3.4 SST anomaly. When no mention of normalisation is made, a classical composite is displayed.

We use HadISST SST (Rayner, 2003), Global Precipitation Climatology Project v2.3 rainfall (Adler et al., 2018) and ERA5 reanalysis (Hersbach et al., 2020) 2m height Temperature (T2m) and 500 hPa geopotential height.

We consider 23 AMIP6 models 1, selecting models with a minimum of 3 ensemble members covering the 1979-2014 period. The variants selected are ilp1f1, except for the AMIP6.CNRM-CM6.1 and AMIP6.MIROC-ES2L models, which are ilp1f2. Forcing Sea surface temperature (SST) is prescribed based on observations Eyring et al. (2016). Prior to computing the composites of Multi model Ensemble Mean (MEM), ensemble-means (EMs) for individual models are computed to avoid giving more weight to models with large ensembles (up to 22 members for AMIP6.ISPL-CM6A-LR). We followed the same

methodology as Beniche et al. (2024) to define ENSO phases using the NOAA Oceanic Niño Index (ONI, (*Oceanic Niño Index (ONI)*, n.d.): mean SST anomalies over the 5N-5S, 120-170W Niño-3.4 region, computed from ERSSTv5) over the boreal winter season. Moderate El Niño over the 1979-2014 period are categorized by ONI values ranging from $+0.5^{\circ}\text{C}$ and 2°C , La Niña by ONI values lower than -0.5°C and extreme El Niño events by ONI values exceeding $+2^{\circ}\text{C}$. Moderate El Niño events are further divided into Central Pacific (CP) and Eastern Pacific (EP) events following the Cold Tongue (CT)/Warm Pool (WP) classification method of Ren and Jin (2011).

Table 1. List of the 23 AMIP6 models with at least 3 ensemble members available, analyzed over the period 1979-2014. The center column indicates the number of members M , and the left column indicates the forcing variant of the model.

model	M members	Variant
ACCESS-CM2	4	f1
ACCESS-ESM1-5	10	f1
BCC-CSM2-MR	3	f1
BCC-ESM1	3	f1
CAMS-CSM1-0	3	f1
CAS-ESM2-0	4	f1
CESM2	10	f1
CESM2-FV2	3	f1
CESM2-WACCM	3	f1
CNRM-CM6-1	16	f2
E3SM-1-0	3	f1
E3SM-2-0	3	f1
FGOALS-f3-L	3	f1
GISS-E2-1-G	5	f1
IPSL-CM6A-LR	22	f1
MIROC6	10	f1
MIROC-ES2L	3	f2
MPI-ESM-1-2-HAM	3	f1
MPI-ESM1-2-HR	3	f1
MPI-ESM1-2-LR	3	f1
MRI-ESM2-0	3	f1
NESM3	5	f1
NorCPM1	10	f1
Total members	135	

We also analyse historical simulations (1850-2014) from 42 CMIP6 models (see Table 2). For model selection, we exclusively consider the first variant, namely r1i1p1-f1, f2 or f3, depending on availability (we only consider one member per CMIP6 model, even if multiple members are available). To select models able to produce extreme El Niño events, we follow the same procedure as in (Cai et al., 2014): we select models exhibiting a DJF Niño 3 rainfall anomaly skewness exceeding 1 (the observed 1979-2014 Niño3 rainfall anomaly skewness is 3.7mm/day) and producing at least one Extreme El Niño events defined by both a N3.4 DJF SSA exceeding 0.5 STD and DJF Niño3 rainfall anomalies greater than 5 mm/day. This method ensures that we only select events associated with a massive reorganisation of the eastern pacific tropical deep convection, a characteristic observed during extreme El Niño events (Lengaigne & Vecchi, 2009; Cai et al., 2014). The extreme El Niño event detection and model selection will be illustrated by Figures 6 and 7 at the beginning of section 4. We tested an alternative method based on the non-linear relation between the equatorial Pacific rainfall PC1 and PC2, with similar results, and therefore only presented

results with the established methodology outlined by (Lengaigne & Vecchi, 2009; Cai et al., 2014).

Table 2. List of the 42 CMIP6 first variant used (one member per model) considered for the analysis over 1850-2014. The symbol *a* indicates models capable of simulating Extreme El Niños and the symbol *b* indicates such models that possess an AMIP6 equivalent ensemble presented in Table1.

CMIP6 model first variant	(r1i1p1f1 or r2i1p1f2)
ACCESS-CM2 ^{a,b}	HadGEM3-GC31-LL
ACCESS-ESM1-5	HadGEM3-GC31-MM ^a
BCC-CSM2-MR	INM-CM4-8
BCC-ESM1	INM-CM5-0
CAMS-CSM1-0 ^{a,b}	IPSL-CM6A-LR
CanESM5	KACE-1-0-G ^a
CESM2 ^{a,b}	KIOST-ESM ^a
CESM2-FV2 ^{a,b}	MIROC6 ^a
CESM2-WACCM ^{a,b}	MIROC-ES2L ^a
CMCC-CM2-HR4 ^a	MPI-ESM-1-2-HAM
CMCC-CM2-SR5 ^a	MPI-ESM1-2-HR
CNRM-CM6-1 ^{a,b}	MPI-ESM1-2-LR
CNRM-CM6-1-HR	MRI-ESM2-0 ^{a,b}
CNRM-ESM2-1 ^a	NESM3
E3SM-1-0	NorCPM1 ^{a,b}
E3SM-1-1	NorESM2-LM ^a
FGOALS-f3-L ^{a,b}	NorESM2-MM ^a
GFDL-CM4	SAM0-UNICON ^a
GFDL-ESM4	TaiESM1 ^a
GISS-E2-1-G ^{a,b}	UKESM1-0-LL ^a
GISS-E2-1-G-CC	
GISS-E2-1-H	

We used the following method to define anomalous DJF climate (e.g. cold or wet) over North America in AMIP6. For each model, we derive average time series of anomalous DJF temperature or rainfall in selected regions (see Figure 2c,d). The standard deviation (STD) is computed in each model over 1979-2014 and across ensemble members to ensure statistical robustness. An anomalous event in a given model is identified when the value exceeds the 0.5 STD threshold (e.g. below -0.5 STD for a dry event). For each ENSO category, the percentage of a given event is computed for each model (across years and ensemble members), and then averaged across models. This ensures that each model's contribution receives equal weight in the MMM analysis. Note that for a normal distribution, an almost equal probability of about 1/3 for each event (e.g. cold, normal, warm) would be expected.

We test whether composites are different from zero at the 97.5% confidence level using a bootstrap resampling (10000 resampling for models, 1000 for observations). The lower or upper 2.5% of the distribution allow to determine whether the composite mean is significantly above or below 0.

Finally, we use a signal-to-Noise ratio (SNR) computation to investigate the causes of the enhanced extreme El Niño reproducibility in AMIP6. SNR is computed following the Kumar and Hoerling (1995) procedure. This allows the separation of the noise into a SST-dependent part (i.e. attributable to the interannual SST diversity within a given ENSO class) and a (dominant) internal variability part. Assume there are M different realizations

(years) of a given type of ENSO event (e.g. La Niña) and N ensemble members, internal variability is defined as :

$$\sigma_I^2 = \frac{1}{M * N} \sum_{i=1}^N \sum_{\alpha=1}^M (A_{i\alpha} - \overline{A_\alpha})^2 \quad (1)$$

with $\overline{A_\alpha}$ being the ensemble mean for a specific year. External variability (atmospheric variability due to changes in SST forcing) is defined as :

$$\sigma_E^2 = \frac{1}{M} \sum_{\alpha=1}^M (\overline{A_\alpha} - \overline{A})^2 \quad (2)$$

with $\overline{A}$ being the ensemble-mean composite for the considered ENSO event type. Total noise is defined as the square root $\sqrt{\sigma_I^2 + \sigma_E^2}$. Finally, SNR is defined as the ratio $\frac{\text{signal}}{\text{total noise}}$, where the signal is $\overline{A}$.

3 Extreme El Niño teleconnection pattern in AMIP6

In this section, we examine the ability of an ensemble simulations from 23 AMIP6 models to reproduce extreme El Niño teleconnection patterns, in order to generalize the results of Beniche et al. (2024) obtained from the CNRM-CM6.1 atmospheric component to the AMIP6 database. We describe the extreme El Niño teleconnection pattern in section 3.1 and evaluate its reproducibility in section 3.2.

3.1 Extreme El Niño TNH teleconnection pattern across 23 AMIP6 models

Fig. 1a-h displays AMIP6 Multi-model Ensemble Mean (MMEM) composites of tropical Pacific anomalies and North-American teleconnections for La Niña and moderate CP El Niño events. The rainfall (PR) anomalies associated with La Niña and moderate CP events have almost the same pattern with opposite sign (Fig. 1 a,e), with either dry or wet anomalies west of the dateline. This antisymmetric forcing therefore produces an equally antisymmetric PNA-like response over the North Pacific and North America (Fig. 1b,f). Consequently, the patterns of rainfall and surface temperature (TS) are mostly antisymmetric during La Niña and moderated CP El Niño events. It is noteworthy that the results presented on Fig. 1 are robust when the composites are normalized by the mean Niño 3.4 SST anomaly forcing amplitude.

The positive SST anomalies extend further east during moderate EP than during moderate CP events (Fig. 1e,i). However, the SST anomalies during moderate EP events are not sufficient to cross the deep atmospheric convective threshold in the eastern Pacific (Srinivas et al., 2024; Beniche et al., 2024). Consequently, the moderate CP and moderate EP equatorial Pacific rainfall anomalies are similar. This comparable zonal distribution of the tropospheric latent heat release gives rise to similar PNA-positive teleconnection patterns over North America (Fig. 1f,j). The rainfall and surface temperature patterns are also almost similar during moderate CP and EP events (Fig. 1g,h and k,l), with wet anomalies confined offshore of the western coast of the USA.

During extreme El Niño events, the SST anomalies are sufficiently large to exceed the deep atmospheric convective threshold over a large portion of the eastern Pacific (Fig. 1m). Thus, equatorial Pacific rainfall anomalies extend further east than during La Niña and moderate CP and EP El Niño events (Fig. 1a,e,f). This substantial and eastward-shifted tropospheric latent heat release during extreme El Niño events results in a similarly substantial and eastward-shifted Z500 response over North America (compare Fig. 1n,o,p with panels above). Consequently, the poleward advection of warm anomalies extends further east over North America, now influencing northeastern America (Fig. 1o). Similarly, wet anomalies are no longer offshore, as during moderate El Niño events, but over the western US coast, including California. Finally, wet anomalies over the Caribbean and Florida become

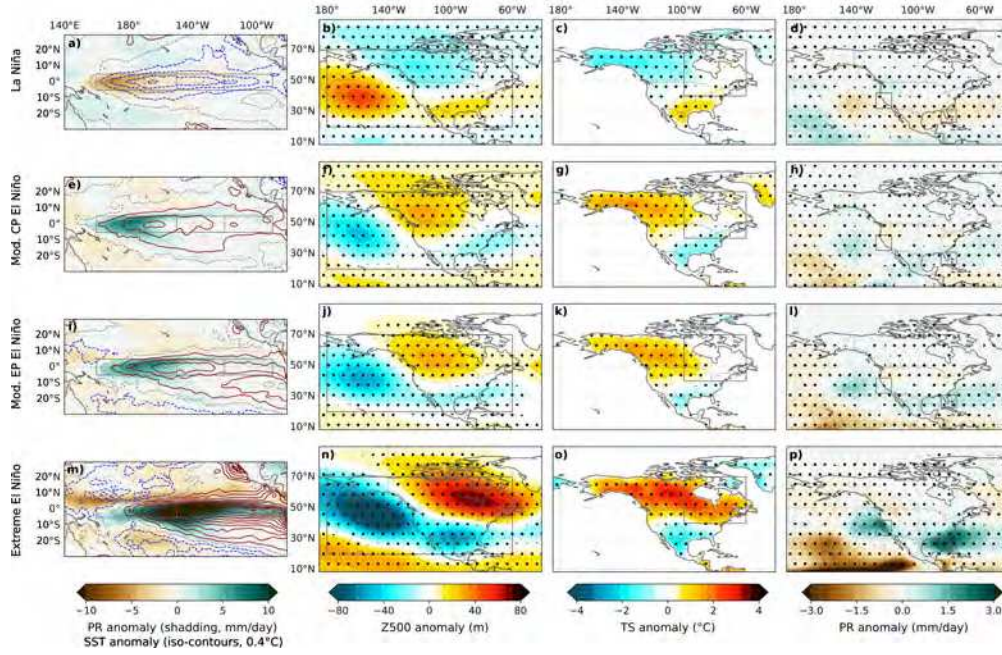


Figure 1. 1979-2014 AMIP6 multi model ensemble-mean (MMEM) winter (DJF) composites for (a-d) La Niña, (e-h) Mod. CP El Niño, (i-l) Mod. EP El Niño and (m-p) Extreme El Niño, for (left) tropical Pacific rainfall (PR) anomaly (shading, mm/day) and HadISST anomaly (contours, 0.4°C, dotted contours for negative values), and North Pacific-North American (middle left) 500hPa height (Z500) anomaly (m), (middle right) land surface temperature (TS) anomaly (°C) and (right) rainfall (PR) anomaly (mm/day). The composites are not normalized. Dots indicate regions where anomalies are significantly different of zero at the 97.5% confidence level based on a bootstrap test with 10,000 resamples. See Table 1 for the list of the 23 AMIP6 ensemble simulations, and the number of members available for each.

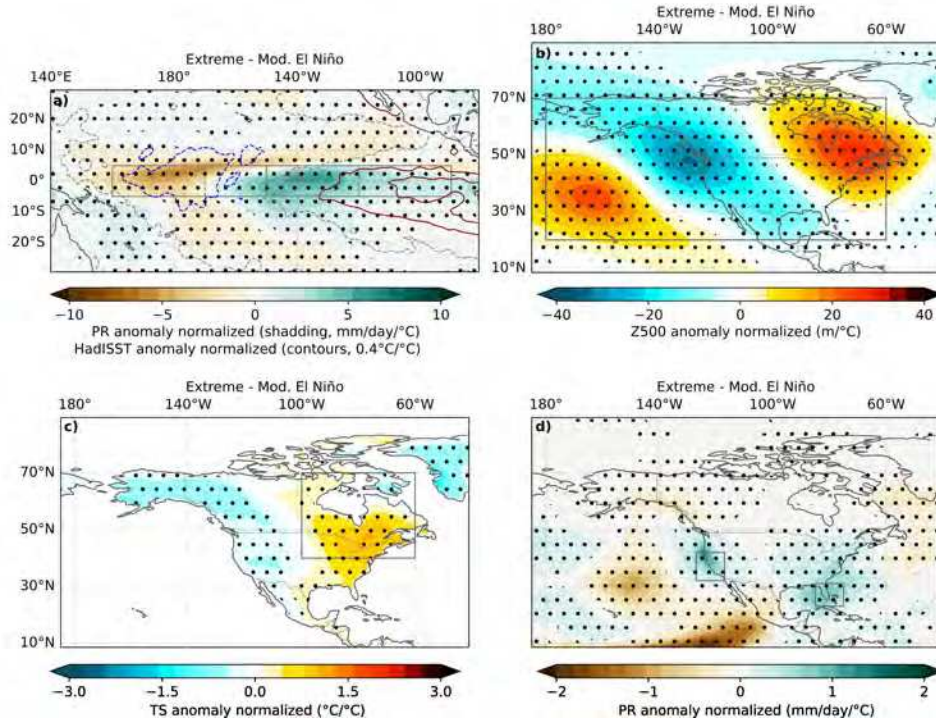


Figure 2. Extreme minus moderate El Niño MMEM winter (DJF) composites, for (a) tropical rainfall (shaded, mm/day/°C) and SST anomalies (contours, red for positive and blue for negative, 0.4°C/°C), and North Pacific-North American (b) 500 hPa height (m/°C), (c) land surface temperature (°C/°C) and (d) rainfall anomalies (mm/day/°C). Each composite is obtained after normalizing by the N3.4 SST anomaly, in order to emphasize the pattern rather than the amplitude differences (see methods for details). Dots indicate areas where anomalies are significantly different from zero at the 97.5% confidence level based on a bootstrap test with 10,000 resamples.

significantly stronger than during moderate El Niño events. In summary, the MMEM from 23 AMIP6 models is very similar to the Extreme El Niño specific teleconnections pattern identified in the AMIP6-CNRM.CM6-1 by Beniche et al. (2024).

Fig 2 finally examines the differences in teleconnection pattern between extreme and moderate El Niño events. In this instance, anomalies have been normalized by the amplitude of the mean N3.4 SST anomaly forcing prior to compositing, with the objective of focusing on differences in patterns rather than differences in amplitude. However, the results remain robust if this normalization is not performed. The eastward shift of the equatorial Pacific tropospheric heat source, the resulting eastward shift of the North American Z500 PNA response toward the TNH pattern of Wallace and Gutzler (1981); Mo and Livezey (1986); Livezey and Mo (1987), the occurrence of extra wet anomalies over California and Florida, and extra warm anomalies over the Northeast US are all statistically significant in the AMIP6 MMEM (and in observations, see Supp Info Fig S1).

As previously demonstrated, the eastward shift and distinctive teleconnections over North America during extreme El Niño events discussed in (Beniche et al., 2024) are robust in the AMIP6 MMEM. We now investigate whether these features are similarly robust across individual AMIP6 model ensemble means. Figure 3 displays the normalized extreme minus moderate El Niño ensemble mean composites (i.e. Fig 2b) but for each of the 23 AMIP6

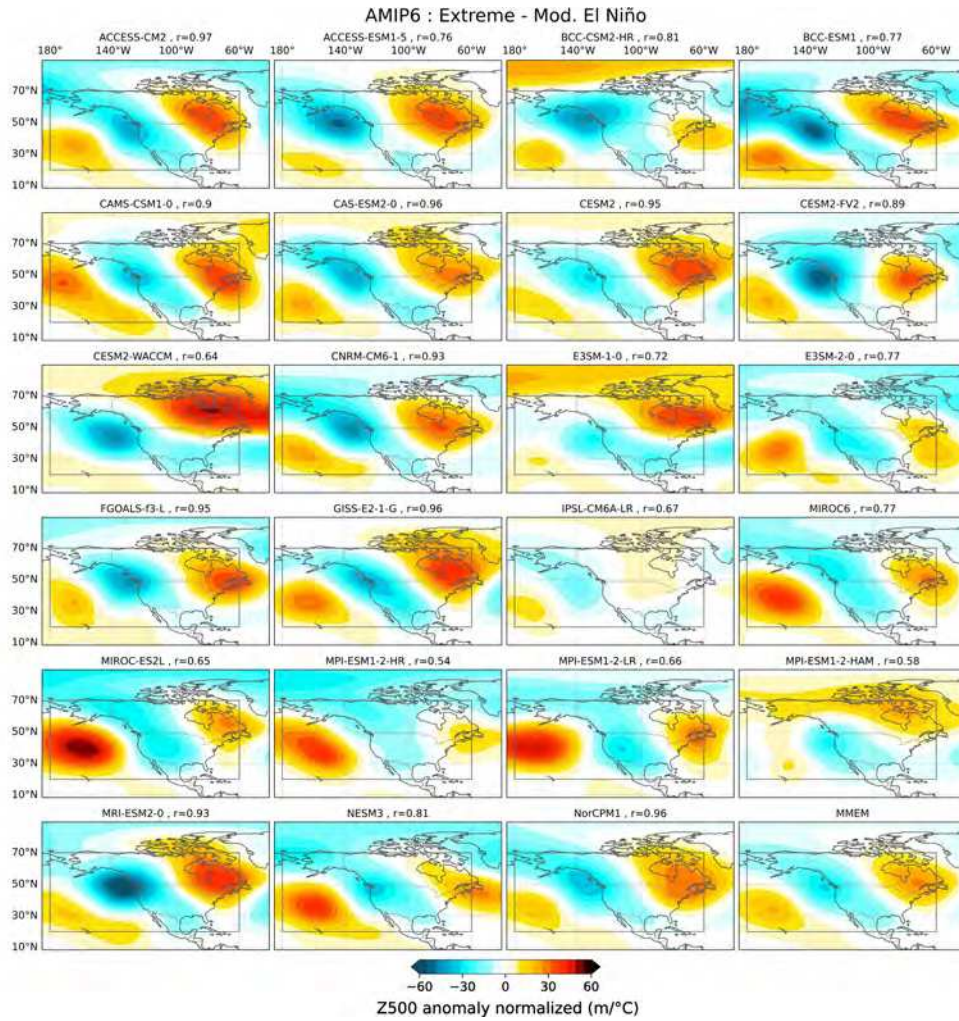


Figure 3. Extreme minus moderate El Niño ensemble-mean winter (DJF) 500 hPa anomalies ($\text{m}/^\circ\text{C}$) composites for AMIP6 individual models, and for the multi-model ensemble mean (MMEM) in the lower right panel. Each composite is obtained after normalizing by the N3.4 SST anomaly (see method for details). The name of the model, and the pattern correlation to the MMEM are indicated above each panel.

models. All models exhibit a pattern correlation to the MMEM AMIP6 difference greater than 0.5. However, one fails to present the eastward shift over eastern Canada despite presenting the eastward shift of the Aleutian Low. Overall, more than half (12) of the models exhibit a pattern correlation above 0.8. This indicates a high degree of agreement with the MMM, by showing the tripole that is indicative of an eastward shift of extreme El Niño teleconnections relative to those of moderate El Niño (except for one out of 23 models). The distinctive TNH-like teleconnection pattern of extreme El Niño relative to the PNA-like teleconnection pattern of moderate El Niño events is thus a robust feature in 22 out of 23 AMIP6 ensemble simulations.

3.2 Extreme El Niño teleconnections reproducibility in AMIP6

Beniche et al. (2024) demonstrate that the extreme El Niño teleconnection pattern to North America is reproducible across events and ensemble members in their CNRM-CM6.1 atmospheric component 16-members ensemble. They assumed the high reproducibility of the Z500 pattern and associated PR and TS anomalies were due to a higher signal-to-noise ratio during extreme El Niño events. In this subsection, we examine the robustness of the extreme El Niño teleconnection pattern reproducibility in the larger AMIP6 ensemble, and investigate the reason behind it.

Fig 4a displays the distributions of the pattern correlation of Z500 anomalies across the North Pacific-North America in each member to the multi-model ensemble for La Niña, moderate El Niño and extreme El Niño MMEM composites, respectively. For La Niña and moderate El Niño, the median pattern correlation is only 0.5, indicating that anomalies in an individual ensemble member are a mixture of the ENSO signal and noise associated with internal atmospheric variability (e.g. (Deser et al., 2017)). This explains why pattern correlations range from negative values (might be due to strong internal variability signature) to values above 0.9 (weak internal variability signature). In contrast, for Extreme El Niño, the median pattern correlation is approximately 0.85, with 90% of values exceeding 0.6. This implies that the North American Z500 realization in each member of each model during each analysed extreme El Niño (1982-83 and 1997-98) is highly similar to the MMEM composite pattern displayed on Fig. 1n. This therefore confirms that the considerably greater reproducibility of extreme El Niño teleconnections in comparison to other ENSO categories (La Niña, moderate El Niño) in the AMIP CNRM-CM6.1 ensemble is a robust finding within the broader AMIP6 database.

Figure 4b-d illustrates the La Niña, moderate and extreme El Niño MMEM Z500 teleconnection signal-to-noise ratios (SNR) as defined in the Method section. In agreement with previous studies (Horel & Wallace, 1981; Kumar & Hoerling, 1995), our analysis points to regions of SNR exceeding 0.5 in the vicinity of the PNA extrema during La Niña and moderate El Niño, indicating that this teleconnection pattern is associated with a satisfying potential for predictability over North America. The SNR values are considerably higher (1 to 2.5) during extreme El Niño events, which explains the high reproducibility of North American Z500 anomalies during those events. Fig 4e further compares the signal and noise amplitudes around two regions of high SNR during moderate and extreme El Niño events. The stronger signal is the primary factor contributing to the favourable SNR during extreme events : the amplitude of the mean Z500 anomaly signal is more than doubled, while noise only decreases by about 20% from a moderate to an extreme El Niño. Fig 4f further indicates that the noise is mostly dominated by atmospheric internal variability, with a smaller contribution of SST pattern diversity within a given ENSO category.

Figure 5a-c illustrates the reproducibility of wet anomalies over California and Florida, and warm anomalies over Northeast America during extreme El Niño events. It should be noted that the averaging regions have been modified from Beniche et al. (2024)) to focus on the specific extreme El Niño signature observed in AMIP6. However, our results remain robust to both area selections. In addition, a new region around Florida has been introduced (see frames on Fig. 2cd). There is no discernible shift in the probability distribution for the Californian rainfall and Northeast American surface temperature during La Niña or moderate El Niño events. In both cases, the median remains close to zero, and positive and negative anomalies are equally probable. The situation is markedly different for extreme El Niño events, with a pronounced shift of the distribution and 69% / 77% chances of warm / wet anomalies (defined as exceeding the 0.5 std threshold, see Methods). The situation is somewhat different for Florida, where a minor shift towards dry anomalies occurs during La Niña and towards wet anomalies during moderate El Niño events. The shift to wet anomalies is, however, much more pronounced and systematic during extreme El Niño events, with a 97% probability of wet anomalies. These reproducible signals during extreme El Niño events are due to high SNR values (greater than 1, Fig. 5de). The

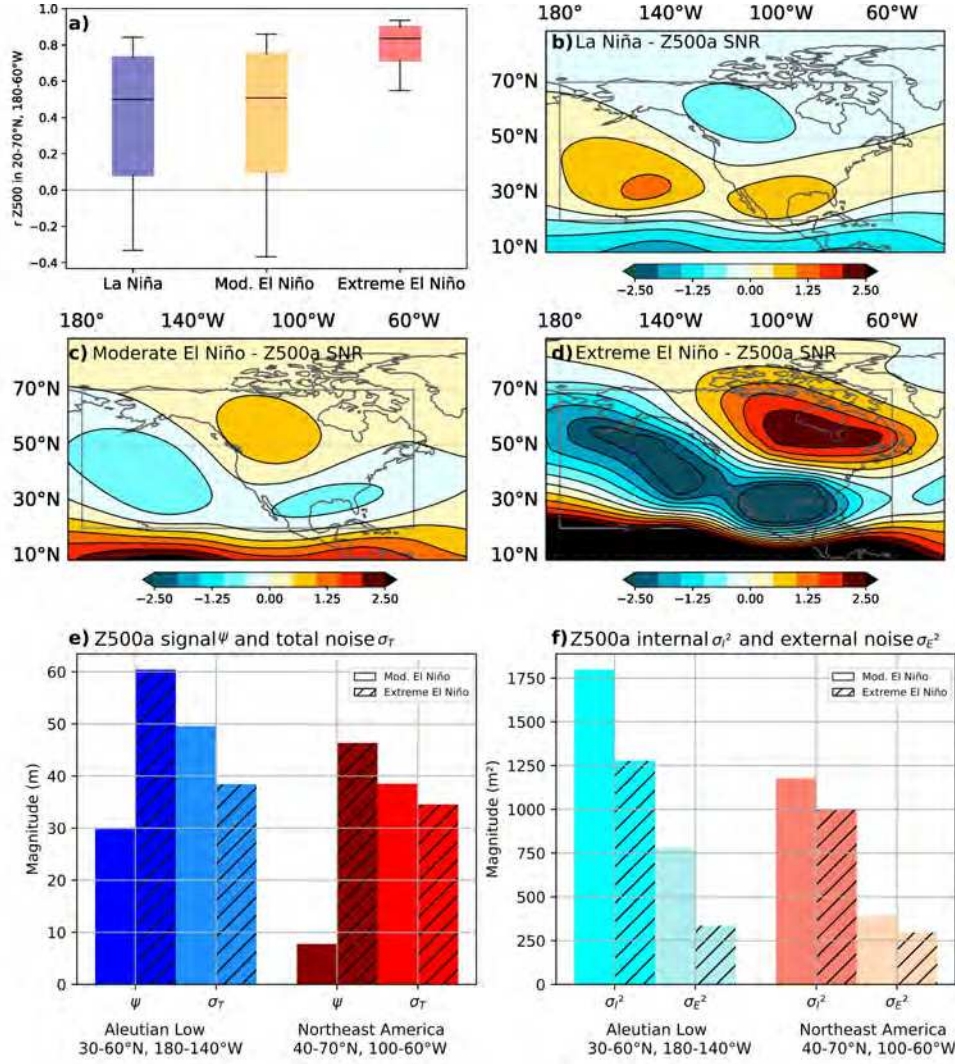


Figure 4. (a) Reproducibility of the DJF 500hPa height anomalies during La Niña (blue), moderate (yellow) and Extreme (red) El Niño events. The whiskers indicate the 10th and 90th percentiles and boxes the 25th, 50th (horizontal line) and 75th percentiles of the pattern correlation between the Z500 anomalies from each member, model, and event to the MMEM composite of the corresponding ENSO phase. The pattern correlation is computed within the box on panels (b-d): 20-70°N, 180-60°W. 500hPa height anomalies MMEM signal-to-noise ratio (SNR) for (b) La Niña, (c) Moderate El Niño and (d) Extreme El Niño events. The signal to noise ratio represents the ratio of the MMEM signal for a given event to the spread associated to both the internal variability, and inter-event SST-driven variability (diversity of SST patterns within a given ENSO type class, see Methods for details). (e) AMIP6 MMEM moderate (plain) and Extreme (hatching) El Niño Aleutian Low region (shades of blue, [30-60°N, 180-140°W]) and Northeast America (shades of red, [40-70°N, 100-60°W]) DJF 500hPa height anomaly signal Ψ and total atmospheric noise σ_T . (f) Decomposition of total noise σ_T^2 into internal atmospheric variability σ_I^2 and inter-event SST-forcing diversity σ_E^2 contributions.

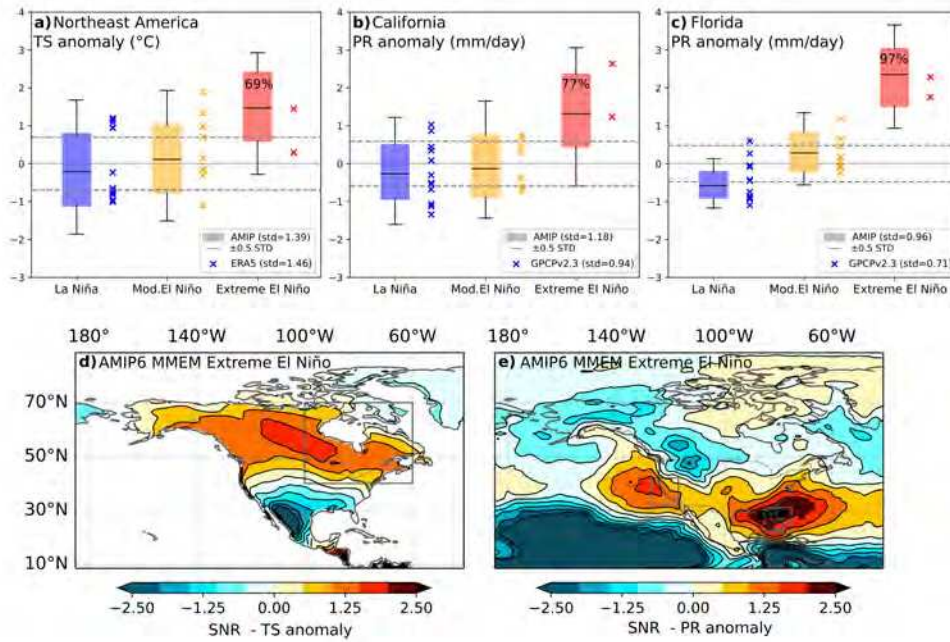


Figure 5. (a) Distribution of mean Northeast American (40-70°N, 100-60°W) DJF land surface temperature anomalies (°C) in the entire AMIP6 multi model ensemble for La Niña (blue), Moderate El Niño (orange) and Extreme El Niño (red) events. The whiskers indicate the 10th and 90th percentiles and boxes the 25th, 50th (horizontal line) and 75th percentiles. The crosses indicate observed ERA5 surface temperature anomalies for each event in a given category. The AMIP6 MMEM and ERA5 anomalies standard deviation are indicated in the inset. Dotted lines mark ± 0.5 STD (from the MMEM value). (b) Same as (a) but for California (32-42°N, 133-123°W) rainfall anomalies. (c) Same as (a) but for Florida (23-30°N, 85-75°W) rainfall anomalies. (d) MMEM composite signal-to-noise ratio (SNR) for Extreme El Niño land surface temperature anomalies. The Northeast American box used in (a) is plotted. (e) Same as (d) but for rainfall anomalies SNR, with the California and Florida boxes plotted.

enhanced reproducibility observed during extreme El Niño events and over Florida compared to California is a consequence of the stronger signals (see SNR decomposition in Figure S2).

This section presents evidence that extreme El Niño events are associated with a distinct teleconnection pattern over Northern America. This pattern is shifted eastward relative to the typical PNA pattern, and associated with higher probabilities of rainfall over California, Florida, and warm anomalies over Northeast America. This pattern is highly reproducible across the 270 realisations of the 1982/83 and 1997/98 extreme El Niño realisations (i.e. 135 ensemble members) from 23 AMIP6 models, a result largely attributable to larger signals than those observed during moderate El Niño or La Niña events.

4 Do CMIP6 models reproduce the specific extreme El Niño teleconnections?

4.1 Selecting models that produce extreme El Niño events

This section examines the influence of the SST equatorial cold bias in CMIP6 models on the reproduction of extreme El Niño teleconnection pattern relatively to AMIP6. CMIP6 models are selected based on their ability to reproduce the large observed eastern Pacific rainfall anomalies during extreme El Niño events, which is essential to generating their specific teleconnection (Beniche et al., 2024). We show that those models are generally characterized by a weaker cold tongue bias than other CMIP6 models. We will then compare the extreme El Niño teleconnection pattern and North American impacts in those models with those in AMIP6.

Here, we briefly illustrate our method for detecting extreme El Niño events in CMIP6 (see section 2). In order to trigger the specific TNH pattern, extreme El Niño events must be associated with large eastern Pacific rainfall anomalies (Beniche et al., 2024). We therefore use the criteria proposed by Cai et al. (2014), which defines extreme El Niño based on their ability to generate such anomalies. Fig. 6 illustrates this extreme El Niño detection method for observations and one CMIP6 model example (here, CMIP6.CNRM-CM6.1). In observations and AMIP6, the two extreme El Niño events during the 1979-2014 period (1982/83 and 1997/98, both with Niño3.4 SSTa above 2 STD) meet such criteria, with Niño3 rainfall anomalies exceeding 5 mm/day. For the CMIP6.CNRM-CM6.1 164-years historical simulation (1850-2014), two extreme El Niño events are identified (Niño3.4 SSTa greater than 0.5 std and Niño3 PRa greater than 5mm/day), one of them being displayed on Fig. 6c,d. Due to the limitation of rainfall and SST records before the satellite era (before the 1980s), and the modulation of the tropical SST variability by tropical decadal variability (Latif et al., 1997; Power et al., 2021), there is a considerable uncertainty in the number of observed extreme El Niño events using this criteria (over the satellite era, 7 to 8 events per century if we include the 2015/16, 5 to 6 if only 1979-2014 is considered).

A total of 42 CMIP6 models, as listed in 2, are analyzed. Fig 7 displays the their DJF Niño3-average rainfall anomalies skewness (SKW) computed over 164 years (1850-2014). The MMM SKW is underestimated (2.2) in comparison to observations (3.7) and AMIP6 (3.3) over recent decades (1979-2014) and the majority of models exhibit such underestimation (33 out of 42 models below 3). Six models exhibit a Niño3 rainfall anomaly SKW below 1, thus failing to meet the SKW criterion (red bars). These models consistently fail to produce extreme rainfall in association with El Niño events (see the extreme El Niño frequency above each bar). In addition, ten models with a Niño3 rainfall anomaly skewness above 1 are rejected, as they are unable to produce El Niño events with Niño3 rainfall anomalies exceeding 5mm/day (orange bars). Consequently, we select 26 out of 42 CMIP6 models that verify the rainfall-based extreme El Niño detection criteria of Cai et al. (2014), with a mean Extreme El Niño frequency of 4 events per century, against 5 to 6 over the satellite era in observations and the AMIP6 ensemble (Fig 7b). Among the 26 selected models, corresponding AMIP6 simulations are available for 11 of them, which allows for a comparison of extreme El Niño teleconnection patterns between AMIP6 and CMIP6 in those models.

Bayr et al. (2023) have related the ability of CMIP6 models to produce large eastern Pacific rainfall anomalies to the amplitude of their cold tongue bias. Fig 8a compares the equatorial RSST bias in the selected and rejected (i.e. those that fail to produce extreme rainfall in the eastern Pacific) CMIP6 models. The RSST proxy is employed here because it is a reliable indicator of atmospheric stability ((Izumo et al., 2020; Xie et al., 2010)) and it effectively removes tropical average biases, that do not influence the convective threshold (Johnson & Xie, 2010). The selected models exhibit a MMM cold bias over the Niño3 and Niño4 regions of about -0.25°C , while the rejected models exhibit a stronger MMM cold bias of about -0.75°C . Furthermore, the central Pacific bias distributions do not overlap. Consistent with the reduced cold bias, the selected models display a reduced western-central

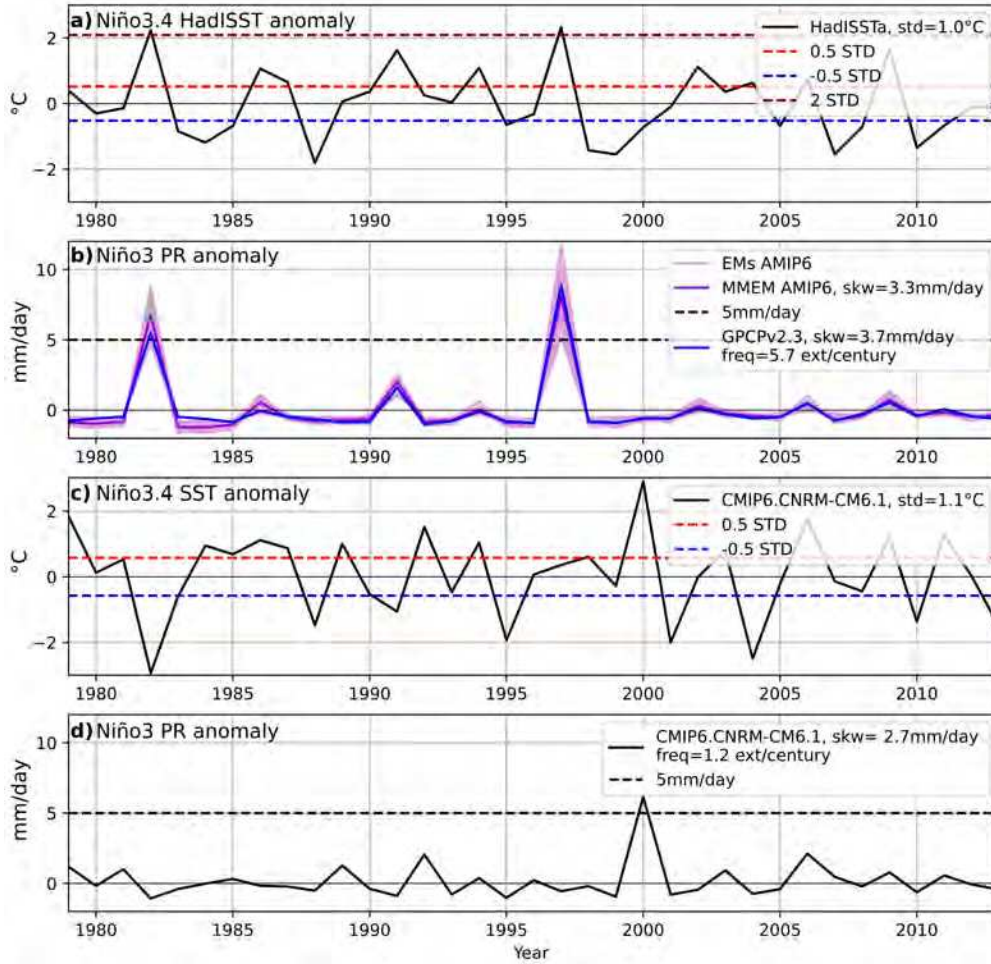


Figure 6. (a) 1979-2014 time series of DJF mean N3.4 HadISST SST anomalies. Dashed lines indicate the -0.5, +0.5 and +2 STD thresholds. (b) 1979-2014 time series of DJF mean N3 rainfall anomalies from individual AMIP6 ensemble-means (pink), the AMIP6 MMEM (purple) and GPCPv2.3 observations (blue). The dashed line indicates the +5mm/day threshold. (c) 1979-2014 time series of DJF mean N3.4 SST anomalies from the CMIP6.CNRM-CM6.1 historical simulation. Dashed lines indicate the -0.5, +0.5 STD threshold. (d) Same as (c) but for the mean Niño3 PR anomaly. Dashed line indicates the +5mm/day threshold. This figure illustrates our method for detecting extreme El Niño events in CMIP6 (defined as El Niño events - i.e. that exceed the Niño3.4 SSTA 0.5 STD threshold - with Niño3 average rainfall anomalies above 5 mm/day).

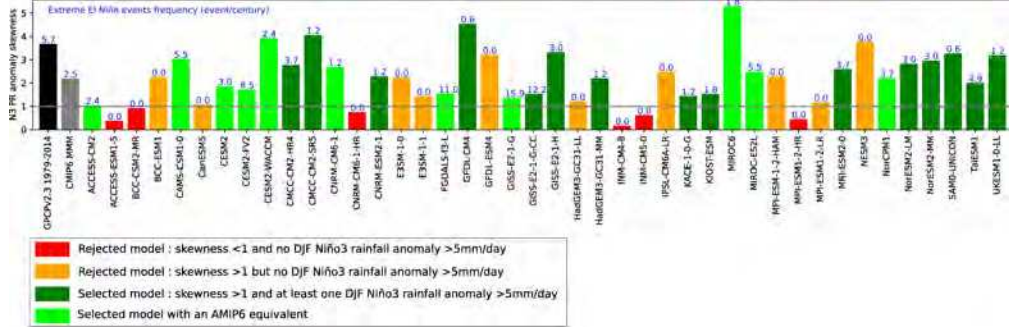


Figure 7. (a) Bar plot of the Niño3 rainfall anomaly skewness (SKW) for GPCPv2.3 (1979-2014 period) and the 42 considered CMIP6 models (1850-2014 period). The extreme El Niño occurrence frequency (event/century, with extreme El Niño events defined as N3.4 SSTA exceeding 0.5 STD and N3 rainfall anomalies exceeding 5 mm/day) is indicated above each bar. Red bars indicate rejected models because their N3 rainfall skewness is below 1. Orange bar indicate rejected models because they do not produce any extreme El Niño event. Dark green bars indicate selected models for which no corresponding AMIP6 simulation is available. Light green bars indicate selected models for which an AMIP6 simulation is available. Within 42 examined CMIP6 models, 16 are rejected, and 26 selected (11 of which have an AMIP6 equivalent).

equatorial Pacific dry bias, with non-overlapping distributions (Fig 8b). While the rejected models produce positive SST anomalies in Niño3, their cold RSST bias results in absolute RSST that never exceed zero, thus preventing deep atmospheric convection and rainfall above 5 mm/day in Niño3 (Fig 8c). Figure 7d illustrates the number of extreme eastern Pacific rainfall event per century as a function of the RSST bias. A positive RSST bias is not a sufficient condition to produce extreme eastern Pacific rainfall, as seven models with positive RSST bias do not produce them. However, it is a necessary condition to produce more than two events per century (the observed value over the satellite period being 7-8). In summary, our findings corroborate the relation between the cold tongue bias and ability to generate large wet eastern Pacific events, as previously proposed by Bayr et al. (2023).

4.2 CMIP6 reproduce the teleconnection shift between moderate and extreme El Niño events

Figure 9 provides the MMM of the moderate and extreme El Niño teleconnection patterns for the 26 selected CMIP6 models. In general, the CMIP6 teleconnection pattern are relatively similar to those in AMIP6 (pattern correlation with the AMIP6 MMEM above 0.9 for Z500, 0.7 for surface temperature and 0.8 rainfall, Figure 9). The CMIP6 MMM reproduces the eastward shift of the AMIP6 extreme El Niño teleconnection pattern relative to that of moderate events (shown in Fig 1). In particular, the Z500 anomaly for moderate El Niño events displays a typical PNA pattern, while extreme El Niño events exhibit a TNH-like pattern, with positive Z500 anomalies shifted eastward to over the Hudson bay (Figure 9a,d). The warm anomalies similarly shift from Alaska and western Canada to central and eastern Canada. The rainfall response also strengthens and shifts eastward, as in AMIP6, the only difference being that California also experiences mild rainfall anomalies during moderate El Niño events in the CMIP6 MMM. In summary, the MMM of CMIP6 models that are capable of simulating extreme El Niño events also captures the distinct TNH-like teleconnection pattern of extreme El Niño events, shifted eastward relative to that of moderate events. The MMM CMIP6 La Niña teleconnection pattern is similar to that in AMIP6, also corresponding to a negative PNA pattern (not shown).

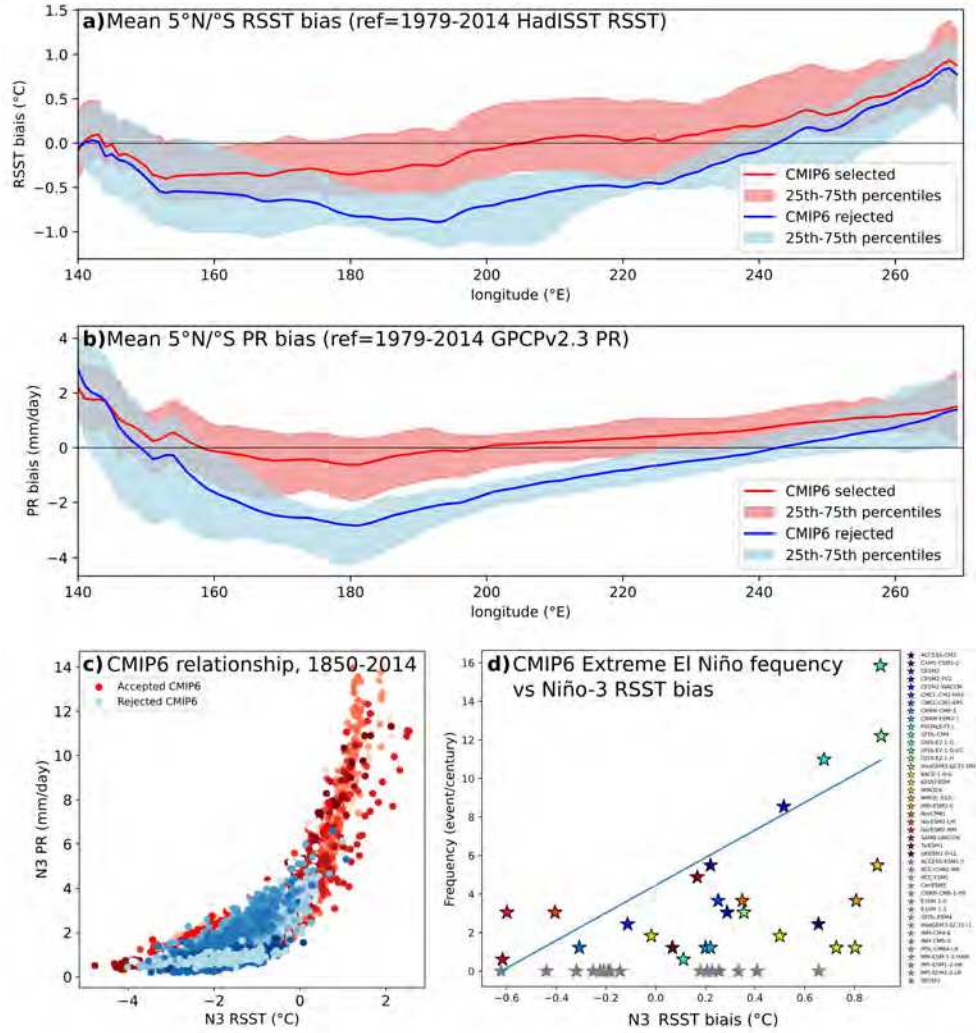


Figure 8. (a) 5°N-5°S average RSST bias (°C) for the 26 selected (red) and 16 rejected (blue) CMIP6 models. The line indicates the MMM, shading the 25th-75th percentile based on a bootstrap test with 10,000 resampling. The bias is calculated with respect to 1870-2014 average HadISST data. (b) Same as (a), but for precipitation (mm/day) and 1979-2014 average GPCPv2.3 data. (c) Scatterplot of Niño3 average rainfall (mm/day) against the Niño3 RSST bias (RSST correspond to Niño3 SST minus the 20°N-20°S average SST for each model). Selected models are in red, and rejected in blue, with different shades of red/blue indicating different models in each group. (d) Extreme El Niño occurrence frequency (event/century) as a function of the Niño3 RSST bias (°C) for the 42 CMIP6 models (rejected models are in grey).

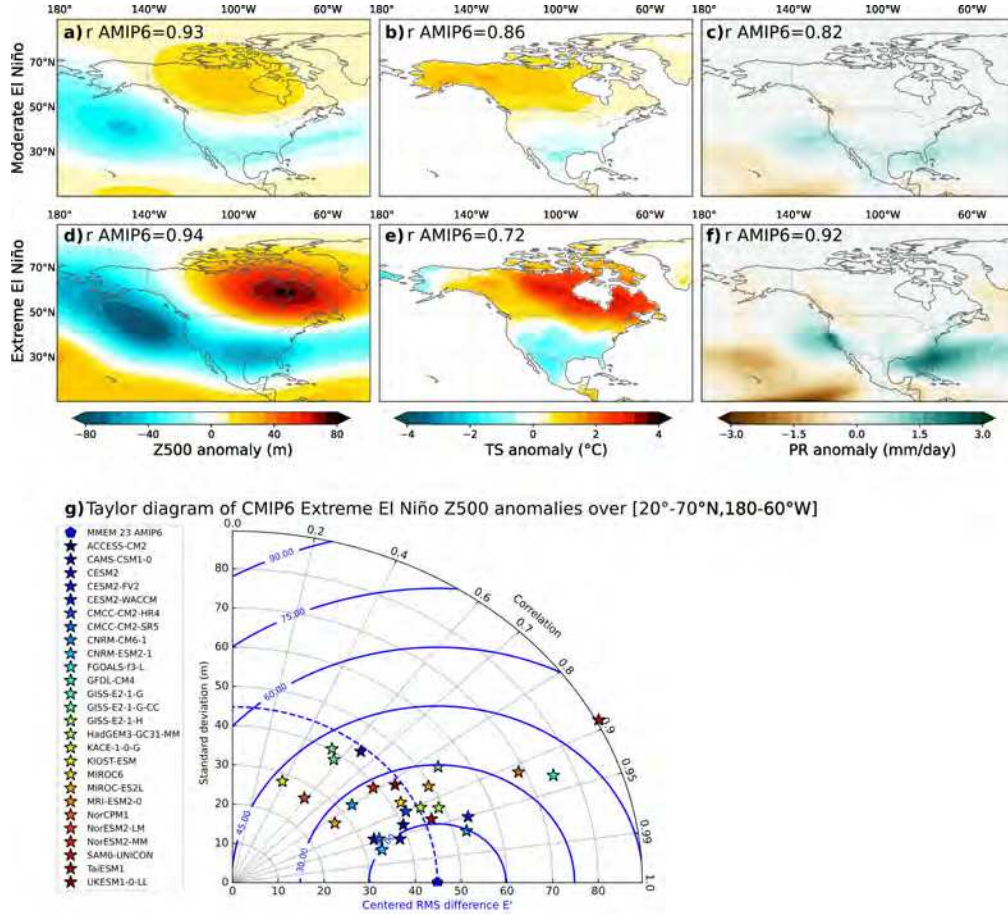


Figure 9. Multi model Mean 500 hPa height anomaly composites from all 26 CMIP6 models (able to perform Extreme El Niño events), for Moderate El Niño (a) DJF GPH 500hPa anomaly (m), (b) land surface temperature anomaly ($^{\circ}\text{C}$) and rainfall anomaly (mm/day), and Extreme El Niño (e,f,g). R_{AMIP6} indicates the pattern correlation over the entire plotted area with the composite and its corresponding AMIP6 MMEM from Figure 1. (g) Taylor Diagram for the North Pacific-North American Z500 anomalies extreme El Niño teleconnection pattern for the 26 individual selected CMIP6 models. The reference dataset (black pentagon on the x-axis) is the Z500 Extreme El Niño composite from the AMIP6 MMEM.

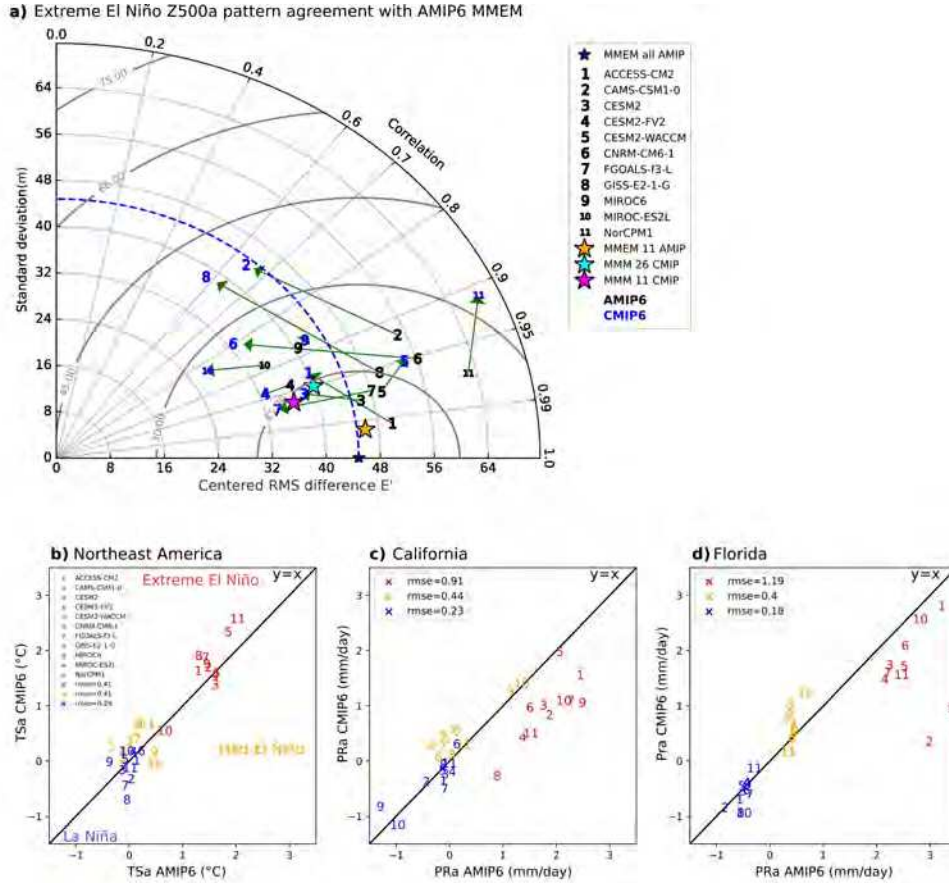


Figure 10. (a) Taylor diagram of North Pacific-North American Extreme El Niño 500 hPa height anomaly for the 11 common AMIP6 (black numbers) and CMIP6 (blue numbers) ensemble-mean composite. Direction of the green arrows indicate for each AMIP6/CMIP6 model, how the pattern and amplitude is modified from the AMIP6 to the CMIP6 version (radius is STD, angle is pattern correlation). (b) model means of land surface temperature anomaly composites average over the Northeast America box (40-70°N, 100-60°W) from the 11 AMIP6 and CMIP6 commun models, for La Niña (blue), Mod. El Niño (orange) and Extreme El Niño (red). Anomalies are not normalized. (c) Same as (b) but for rainfall anomalies averaged over California. (d) Same as (b) but for rainfall anomalies averaged over Florida.

Let us now investigate how individual CMIP6 models reproduce the AMIP6 MMEM, eastward-shifted teleconnection pattern. Figure 9g displays a Taylor diagram (Taylor, 2001) evaluating each selected CMIP6 model Z500 extreme El Niño composite against that of the AMIP6 MMEM. 18 out of 26 models lie within the 30 m RMS error contour, and have pattern correlations with the AMIP6 MMEM pattern above 0.8 and a pattern amplitude within $\pm 30\%$ of the observed value, i.e. have similar extreme El Niño teleconnections to our AMIP6 MMEM reference. On the other hand, 8 CMIP6 models have really degraded extreme EN teleconnection patterns relative to the AMIP6 MMEM, with pattern correlations as low as 0.3 and over or underestimated magnitudes by a factor 2. In summary, 18 of the 26 models that reproduce extreme El Niño events have a very comparable extreme El Niño teleconnection pattern to that from the AMIP6 MMEM.

Above, we have compared the AMIP6 MMEM to all the CMIP6 models that produce extreme eastern Pacific rainfall anomalies (26 models). The specificity of the extreme El Niño teleconnection pattern remains robust when only considering the subset of selected CMIP6 models for which an AMIP6 simulation is available (11 models, see Figure S3). Within this subset, we can investigate how CMIP6 models SST biases, including the equatorial Pacific "cold tongue bias", affect extreme El Niño teleconnections. Figure 10a presents a Taylor diagram of the MMM Z500 extreme El Niño teleconnection pattern over the North Pacific-North American box for these 11 AMIP6 models and their CMIP6 counterparts (the reference being the AMIP6 MMEM). The MMM for these common models (yellow and purple stars) indicate a slight extreme El Niño teleconnection pattern degradation (0.99 to 0.96 pattern correlation) and amplitude decay (45 to 36 m) from AMIP6 to CMIP6. Let us now consider individual models. Green arrows link each CMIP6 score to that of its corresponding AMIP6 model, allowing to gauge the impact of SST biases in each model. For all models, arrows point to a region with a lower pattern correlation with the reference pattern. More specifically, all AMIP6 models have a pattern correlation above 0.85 while 4 of the corresponding CMIP6 models drop to between 0.55 and 0.85. All models except 3 also display a teleconnection with a weaker amplitude than that of the reference AMIP6 MMEM, with amplitude underestimations of up to 40% in CMIP6. Overall, the MMM AMIP6 extreme El Niño teleconnection pattern is quite well reproduced by the CMIP6 ensemble mean. The CMIP6 extreme El Niño teleconnection pattern remains reasonable in 18 individual CMIP6 models, but is degraded relative to its AMIP6 counterpart in some.

We now compare the surface temperature and rainfall impacts of ENSO between the CMIP6 and AMIP6, for the 11 selected CMIP6 models that have AMIP6 counterparts, and for the three regions already discussed on Figure 5 (Northeast America, California, Florida). CMIP6 models display a comparable surface temperature response over Northeast America to their AMIP6 counterpart across ENSO phases. All the models but one display a pronounced warming over North America during extreme El Niño, in both AMIP6 and CMIP6. Over California and Florida, CMIP6 and AMIP6 models tend to agree during La Niña and moderate El Niño events. In contrast, the California and Florida CMIP6 rainfall response to extreme El Niño events is notably reduced relatively to its AMIP6 counterpart (57%/40% reduction for the MMM over California/Florida, with a much more severe reduction in some models and even the wrong sign in one model).

In this section, we have demonstrated that 16 out of the 42 CMIP6 models considered are unable to simulate extreme El Niño events (defined from eastern Pacific rainfall anomalies above 5 mm/day). These models are associated with large equatorial cold tongue bias. The MMM of the 26 CMIP6 models capable of simulating extreme El Niño events reproduces the distinct eastward shift from a Pacific-North American (PNA) towards a Tropical Northern Hemisphere (TNH) teleconnection pattern during these events, in a consistent manner with AMIP6. However, the teleconnection pattern is generally degraded in CMIP6 models relative to their AMIP6 counterparts, very degraded in 8 of the 26 selected CMIP6 models, and CMIP6 models tend to underestimate the extreme El Niño wet anomalies over California and Florida.

5 Summary and discussion

5.1 Summary

Beniche et al. (2024) found that La Niña and moderate El Niño share the same Pacific North-American (PNA) boreal winter teleconnection pattern, and that only extreme El Niño events such as in 1982-83, 1997-98 and 2015-16 lead to a significant eastward shift of that teleconnection pattern toward a Tropical North-Hemisphere (TNH) pattern, associated with strong and reproducible surface temperature and rainfall anomalies over North America. Their results were however obtained from a 16-member ensemble with a single AMIP6 model (namely, the CNRM-CM6.1 atmospheric component), and hence both subject to

model error and noise from internal variability. Here, we first investigate the robustness of their results using a broader AMIP6 dataset (23 different models, and a total 135 members covering 1979-2014, i.e. a total of 270 realisations for two extreme El Niño events: 1982-83 and 1997-98). Our analysis confirms that the PNA teleconnection during moderate ENSO events only shifts to the specific TNH teleconnection pattern during extreme El Niño events. It also confirms that the associated climate impacts are very reproducible, with 69% chances of warm (> 0.5 std) anomalies over northeastern America, and 77%/97% of wet anomalies over California/Florida states across the entire AMIP6 database. We attribute those more systematic impacts than those during moderate El Niño or La Niña events to a much more reproducible Z500 teleconnection pattern during extreme El Niño events. Our large database permitted a signal to noise ratio analysis that was not possible from the Beniche et al. (2024) limited ensemble, confirming that this increased reproducibility stems from a large signal relative to the atmospheric internal variability.

Our second objective was to examine if the SST biases that develop in CMIP6 models impact their ability to produce a distinct teleconnection pattern during extreme El Niño events. Among the 42 examined CMIP6 models, 16 fail to produce extreme El Niño events, defined based on their ability to produce large (> 5 mm/day) eastern Pacific rainfall anomalies during a warm event, as in Cai et al. (2014); Lengaigne and Vecchi (2009). These models tend to have a strong cold tongue bias, as already noted by Bayr et al. (2023), which inhibits deep atmospheric convection development in the eastern Pacific. A near-zero or positive RSST bias is necessary (but not sufficient) for CMIP6 models to be able to develop strong eastern Pacific wet anomalies. The MMM teleconnection patterns from the 26 CMIP6 models that produce such strong eastern Pacific wet anomalies successfully reproduce PNA-like teleconnection for Moderate El Niño (and La Niña) and TNH-like teleconnections exclusively for Extreme El Niño events, in agreement with AMIP6. While reasonable in 18 of those 26 models, the CMIP6 teleconnection pattern is however degraded relatively to its AMIP6 counterpart, with a lower pattern correlation to and generally weaker amplitude than the AMIP6 MMEM reference pattern. CMIP6 models underestimate wet anomalies over California and Florida during extreme El Niño events, while they generally reproduce the AMIP6 Moderate El Niño and La Niña weaker signals.

5.2 Discussion and perspectives

Previous studies have discussed the sources of diversity in the ENSO teleconnection patterns, with some studies identifying a different teleconnection pattern between CP and EP events (Ashok et al., 2007; Garfinkel et al., 2012), and others concluding that a convective anomaly is necessary in the eastern-central Pacific (Chiodi & Harrison, 2015; Johnson & Kosaka, 2016). Consistent with other work (Jong et al., 2016; Hoell et al., 2016) our study shows that, as far as Northern America is concerned, only extreme El Niño events (i.e. EP events that have both large SST and convective anomalies in the eastern Pacific) really induce a major change in the teleconnection pattern. The moderate CP and EP events composites of Figure 1 take advantage of the large AMIP6 database (675 moderate CP events and 405 moderate EP events realisations). Although this large database reveals significant differences between the moderate CP and EP events normalised patterns, such as an enhanced warming over eastern United States of America and slightly stronger wet anomalies over Florida (SI Figure S5), these differences are very weak compared to those between Extreme and Moderate El Niño events. The observed composites for moderate CP and EP events are more different than those in AMIP6 (SI Figure S6), although less significant and noisier. The observed teleconnection patterns for moderate EP events closely resemble the canonical PNA pattern and associated anomalies, while those for moderate CP El Niño events are somewhat different. Previous studies have however warned that such observed patterns are highly subject to modification from internal atmospheric variability (Deser et al., 2017). In addition, our record only contains 3 moderate EP events, implying that the observed (and AMIP6 MMEM) patterns may also contain signatures from SST anomalies that are not related to ENSO. We suggest, in line with previous studies, e.g. (Brands, 2017),

that the observed differences between Moderate CP and EP events are mainly associated with those ENSO-independent SST anomalies and internal atmospheric variability. In summary, we think that the strong inter-model agreement and large number of realisation in AMIP6 strongly supports the view that the main source of ENSO teleconnection diversity over Northern America is associated with extreme El Niño events.

The recent 2015/16 extreme El Niño event was associated with prolonged drought over California, with significant societal impacts (Seager et al., 2015). The seasonal forecasts on the other hand projected wet anomalies (Lee et al., 2018; Paek et al., 2017), possibly due to overestimated eastern Pacific warm and convective anomalies (Jong et al., 2018; Paek et al., 2017)). The study of Beniche et al. (2024) also included the 2015-16 event (and concluded to 74% chances of wet anomalies), while our study only covers the 1982-83 and 1997-98 events (with a similar probability of wet conditions of 77%). One possibility for this mismatch may be due to the weaker prolonged eastern Pacific warming after the 2015-16 El Niño peak Lee et al. (2018), or to internal variability as the observed anomalies do fall within the range of possible forecast outcomes (Jong et al., 2018; Kumar & Chen, 2016). Finally, our AMIP6 ensemble still indicates a 10% chance of dry anomalies over California during the 1982-83 and 1997-98 extreme El Niño events (Fig. 5b). Our results are thus also consistent with the observed dry anomalies over California in 2015-16, if we consider a probabilistic rather than deterministic approach.

Climate projections from CMIP models suggest an enhanced eastern and central Pacific warming in response to climate change, or "El Niño-like" warming (e.g. Power et al. (2021)). Notwithstanding recent observations of subdued warming in the eastern and central Equatorial Pacific (e.g. Heede and Fedorov (2023a); Power et al. (2021)), this "El Niño" like warming reduces the barrier to deep-atmospheric convection in the eastern Pacific, with a strong influence on ENSO projections. CMIP6 models indeed project both more frequent extreme eastern Pacific rainfall response to ENSO, and more frequent extreme eastern Pacific SST anomalies ((Cai et al., 2021; Heede & Fedorov, 2023c; Shin et al., 2022)). A promising avenue for future research is to investigate the consequence of our results for future projections. Our results indeed indicate that 18 CMIP6 models reproduce extreme El Niño events and their specific, eastward-shifted teleconnection pattern. The reinforced and eastward shift ENSO teleconnection pattern seen in some studies (e.g. (Drouard & Cassou, 2019; McGregor et al., 2022; Zhou et al., 2014)) could thus be partly interpreted as an increased frequency of the TNH-like pattern associated with extreme El Niño events, rather than a change in the teleconnection pathway. In addition, it will also be valuable to assess the impact of the biases in the CMIP6 ENSO teleconnection patterns on future projections, especially over California where CMIP6 already tends to underestimate extreme El Niño rainfall anomalies in the current climate.

6 Open Research

The ECMWF Reanalysis v5 (ERA5) monthly averaged is available from Copernicus at <https://cds.climate.copernicus.eu/cdsapp#!/dataset/reanalysis-era5-pressure-levels-monthly-means?tab=form>. The Global Precipitation Climatology Project (GPCP) v2.3 dataset is available from <https://www.ncei.noaa.gov/data/global-precipitation-climatology-project-gpcp-monthly/>. The HadISST version 1.1 monthly reanalysis data are available from <https://www.metoffice.gov.uk/hadobs/hadisst/data/download.html>. The AMIP6 and CMIP6 from the Coupled Model Intercomparison Project Phase 6 archives are freely available from <https://esgf-node.ipsl.upmc.fr/search/cmip6-ipsl/>.

Acknowledgments

Margot Beniche's PhD grant was funded under the French Agence Nationale pour la Recherche (ANR) ARISE project (ANR-18-CE01-0012) and partially supported through the grant EUR TESS N°ANR-18-EURE-0018 in the framework of the Programme des Investissements d'Avenir. We thank the X anonymous reviewers for their comments, which helped to improve the manuscript.

7 Competing interests

The authors declare no competing interests.

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IV.3 Conclusions and way forward

In this chapter, I did ascertain the robustness of Chapter III key findings in the large AMIP6 and CMIP6 databases.

- 22 out of 23 AMIP6 model reproduce a specific, TNH-like teleconnection pattern for extreme El Niño events, with La Niña and moderate El Niño events respectively associated with with negative and positive phases of the PNA pattern. In other words, almost all AMIP6 models indicate that extreme El Niño events are the main driver of the North Hemisphere boreal winter ENSO teleconnection diversity.
- The specific climate North American impacts associated with extreme El Niño events over North America are also highly reproducible in the AMIP6 database: warm anomalies over Northeastern America (69% probability), and wet anomalies over California (77%) and Florida (97%). Those robust impacts arise from a favorable signal to noise ratio (>1.5) due to large signals exceeding the internal atmospheric noise - rather than by a reduction of internal noise - during extreme El Niño events.
- 16 of the 42 CMIP6 models we examined were not able to produce extreme El Niño events (defined as large rainfall over the eastern equatorial Pacific). These models tend to have a particularly strong cold tongue bias compared to models capable of producing extreme Niño events.
- The 26 models that produce extreme El Niño events reproduce their specific TNH-like teleconnection pattern and PNA-like teleconnections for La Niña and moderate El Niño events. However, some models depict degraded TNH patterns and amplitudes in comparison to those in AMIP6. CMIP6 models also tend to underestimate the wet anomalies over California and Florida during extreme El Niño events.

This chapter demonstrates that 18 CMIP6 models are capable of reproducing extreme El Niño teleconnections to North America (and, more generally, ENSO teleconnections) quite well (relative to our AMIP6 multi-model-mean reference). An immediate perspective is therefore to assess how this teleconnection pattern is projected to change under global warming. Previous studies have examined changes in the ENSO teleconnection climate already, but those studies did not consider specificities in the extreme ENSO teleconnection pattern. Some studies indeed simply obtained an overall ENSO teleconnection pattern through regression on an ENSO index, some distinguished El Niño from La Niña events and some EP vs CP events. However, the question of how extreme El Niño teleconnections specifically change under global warming scenarios, and how these potential changes might contribute to overall changes in the ENSO teleconnection pattern has to my knowledge not been investigated so far. I will therefore explore this open question in chapter V.

Chapter V

Extreme El Niño teleconnections in a warmer world

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This last result chapter investigates future changes in ENSO teleconnections in the context of global warming, with a more specific focus on extreme El Niño events. To that end, we will use the large CMIP6 historical and ScenarioMIP databases, focusing on models that are able to produce extreme El Niño events (cf chapter [IV](#)).

V.1 Introduction

I have already summarized studies that investigated future changes in ENSO teleconnections in section [I.3.3](#). I will only briefly summarize the main findings here. In general, studies that did investigate future ENSO teleconnection changes found a broad eastward shift of these teleconnections. More precisely, an eastward shift of the Pacific-South American (PSA) pattern in the Southern Hemisphere, an eastward shift of the geopotential height anomalies that occur over the Aleutians, and a strengthening of teleconnections to the northern Atlantic sector. Those studies also document an eastward shift of tropical ENSO convective source in the Pacific.

However, to my knowledge, no studies have explicitly investigated the projected changes specifically for extreme El Niño events. Previous studies simply investigated the overall ENSO teleconnection change, obtained from a regression to the ONI index (Drouard & Cassou, 2019), distinguished El Niño from La Niña (Johnson et al., 2022), or CP from EP (Cai et al., 2021) teleconnections. The only study that separated strong ENSO events is that from Yeh et al. (2022), but it only investigated surface temperature teleconnections. This study also only considered 7 CMIP6 models (i.e. a relatively small subset of the CMIP6 database). More importantly, this study defines "strong El Niño events" based on Niño 3.4 SST anomalies that exceed 1.5 standard deviation. Such a criterion would retain more warm events than the three extreme events of 1982, 1997, and 2015 if applied to the observational dataset. In other words, it corresponds to relatively strong El Niño events, but not necessarily extreme ones for which large rainfall anomalies are triggered over the eastern Pacific, and for which I find a specific teleconnection pattern. Below, I will define extreme El Niño using a rainfall criterion, in order to make sure they capture the large, eastward shifted tropospheric heat source that only occurs during extreme El Niño events. The specific added value of this chapter is therefore to specifically examine teleconnection changes for extreme El Niño events, and if those changes differ from those associated with La Niña or moderate El Niño events.

V.2 Methods

V.2.1 CMIP6 datasets

In this chapter, I use numerous realizations of the CMIP6 ScenarioMIP database covering the 2015-2100 period, under different levels of radiative forcing, resulting in different levels of global warming by the end of the 21st century. In the previous chapter, I established a list of CMIP6 models based on their capacity to produce at least one extreme El Niño events (26 models), I also showed that 18 models of those were able to reproduce correct extreme El Niño Z500 anomaly teleconnections patterns over North America, based on the selection methodology described in chapter IV. As a reminder, I select models for which the first member of the historical simulation produces at least one extreme El Niño event over 1850-2014. Extreme events were defined based on average DJF Niño 3 region precipitation anomalies exceeding 5 mm/day, as in Lengaigne and Vecchi (2009); Cai et al. (2014). 26 models passed this selection test (see table II.2). In the following study, in order to maximize samplings, I considered all of the models that were able to produce at least one extreme El Niño event and for which a SSP simulation was available, i.e. 17 models. Within the 17 models under consideration, four were identified as having an deteriorated representation of extreme El Niño teleconnections (GFDL-CM4, GISS-E2-1-H, GISS-E2-1-G and NordESM2-LM), but were included in the present analysis. I intend to repeat the analysis after excluding these "bad" models, see Perspectives. For each of these 17 models, I downloaded every available SSP (SSP1-2.6, 2-4.6, 3-7.0 and 5-8.5) and historical ensemble

member, with a limit of 10 members per SSP per model to avoid over-representation. All data were bi-linearly interpolated to a $1^\circ \times 1^\circ$ resolution regular grid, as in previous chapters. The list of the 17 CMIP6 models (296 realizations, spread across 4 SSPs, corresponding to a total of about 74000 DJF realizations) that could be downloaded is detailed in Table II.3. Models for which SSP simulations were not available were not considered in the historical sample.

V.2.2 Estimation of the Climate Change signal

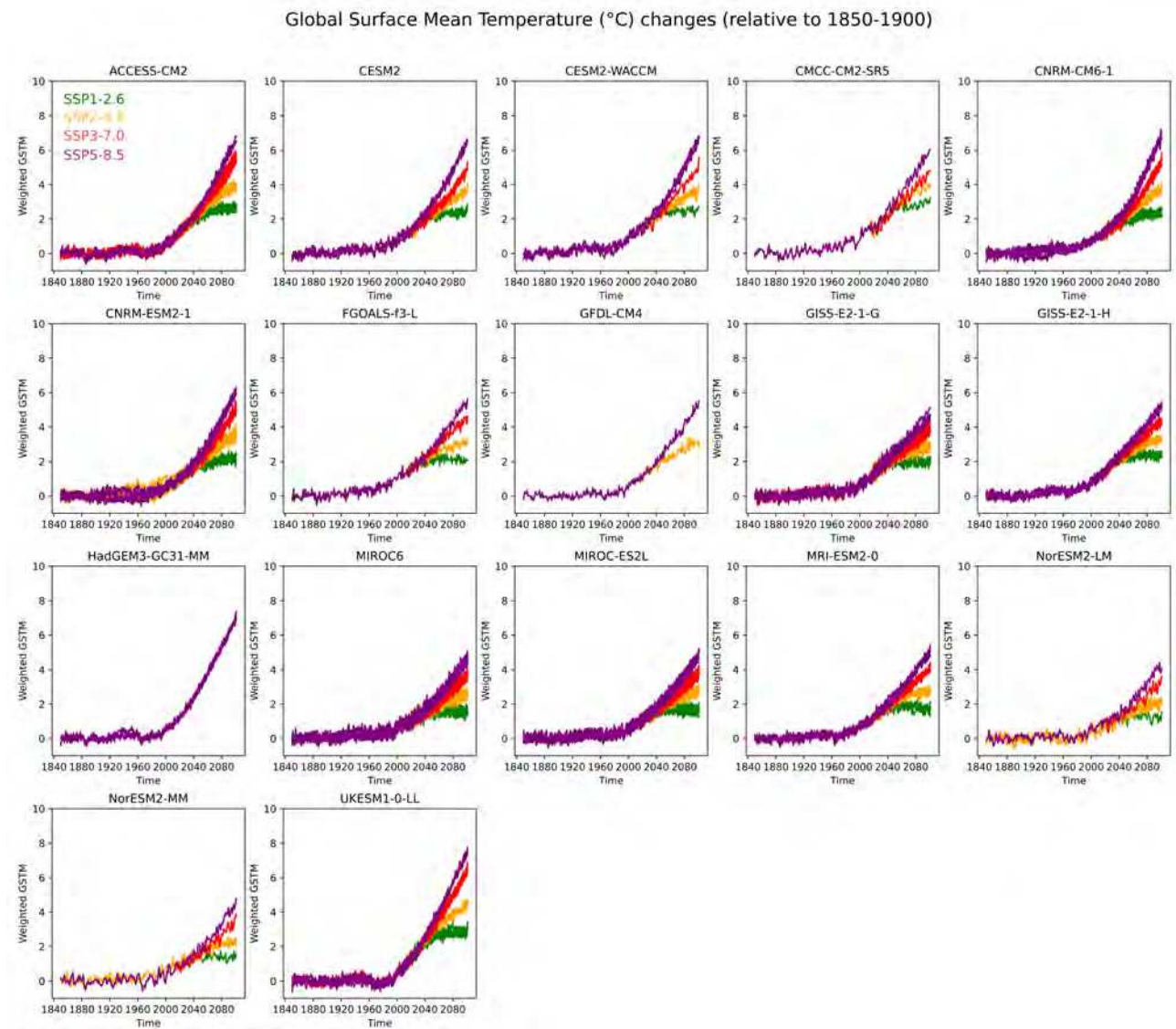


Figure V.1: DJF Global Mean Surface Temperature ($^\circ\text{C}$) changes relative to 1850-1900, for individual SSPs CMIP6 realizations investigated in Chapter V.

Under global warming, changes in Global Mean Surface Temperature (GMST) from 1850 to 2100 exhibit a non-linear trend, with a clear increase in the warming rate after 1980s (Figure

V.1). The linear detrending applied in Chapters III and IV is therefore inadequate for separating the climate change signal from that of the natural background climate variability (Hawkins & Sutton, 2012; Gopika et al., 2024). Following those two studies, I construct a global warming index $\tilde{T}_{\text{global}}(t)$ for each individual model, scenario and ensemble member from a 4th order polynomial fit to the 1850-2100 GMST (concatenated historical and SSP data, with GMST set to 0°C over 1850-1920 to ensure a near-zero warming index during this period, following Gopika et al. (2024)). Following Hawkins and Sutton (2012); van Oldenborgh et al. (2009), we assume that local signals of a given variable $T(x, y, t)$ can be decomposed into a climate change signal that is proportional to the warming index plus a residual internal variability term noted $\epsilon(x, y, t)$:

$$T(x, y, t) = \alpha(x, y) \cdot \tilde{T}_{\text{global}}(t) + \beta(x, y) + \epsilon(x, y, t)$$

where $\alpha(x, y)$ and $\beta(x, y)$ are obtained through a linear regressions, and the above approach allows separating the space and time-dependent climate change signal ($\alpha(x, y) \cdot \tilde{T}_{\text{global}}(t) + \beta(x, y)$) from that associated with internal variability ($\epsilon(x, y, t)$, including ENSO variability).

V.2.3 Global Warming Levels approach

The globally averaged warming level in our database is very variable (Figure V.1), depending on time (low in historical simulations, with increasing levels as decades go by), SSP scenario (highest for SSP5-8.5) and model (depending on the model climate sensitivity). The 2100 globally averaged surface warming relative to 1850-1900 for example spans +1.2 to 5.7°C in CMIP6 (see IPCC AR6-WG1 (2021) Table SMP1). The last IPCC report has proposed to consolidate climate change effects by grouping periods, models and SSPs into consistent globally-averaged warming levels (Lee et al., 2021; Schleussner et al., 2016; King et al., 2017). I use decadal averages (e.g., 2015–2025, 2025–2035, etc.) of the global warming index $\tilde{T}_{\text{global}}(t)$ to group each decade of each ensemble members of each SSP scenario of each model into consistent Global Warming Level (GWL) bins centered on (+1.5°C, +2°C, +2.5°C, +3°C, +3.5°C, +4°C, +4.5°C). I use [−0.2°C, +0.3°C] bin edges to avoid overlap¹. I use a 0°C anomaly reference for the 1860–1920 baseline period, but using an alternative baseline period before 1960 yields similar results (note that I will discuss some of the methodological choices at the end of this chapter.) Figure V.2 shows the number of DJF realizations (one per year) for each model, for the historical and 'global warming levels' samples (corresponding table C.1 in Appendix C). Depending on the model, the baseline historical period features from 165 (1 single member) to 1650 years (10 members, the maximum number I set), with a total of nearly 15000 years. By construction, the number of years in the sample decreases with the global warming level, with only 395 years for the 4.5°C

¹ Note that this choice of bin edges need adjustment, I will further test the sensitivity of the results to using larger bin sizes.

GWL bin. This implies that the sampling error will be larger at higher GWL. I will come back to this point in the following section.

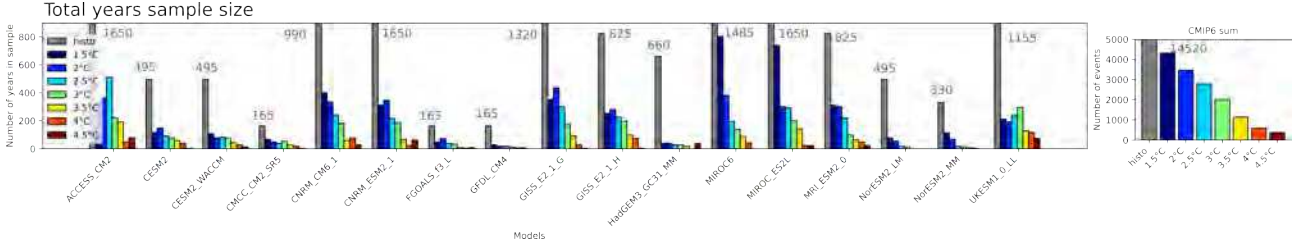


Figure V.2: Number of DJF realizations (i.e. years) in historical (grey) and for each Global Warming Level (colored) bin, for each of the 17 models considered. The vertical axis has been truncated to enhance readability, with the total number of years in historical samples noted as grey digits near corresponding bars. The right panel indicates the total number of years across the 17 available CMIP6 models.

V.2.4 Coherence with the Chapter IV model selection

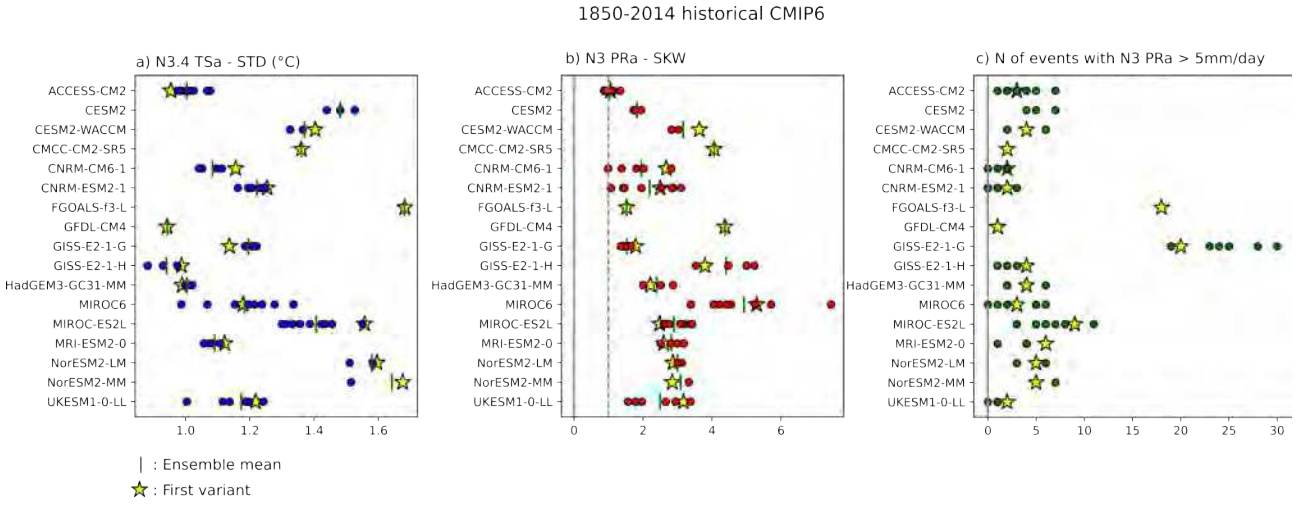


Figure V.3: Historical (1850-2014) ENSO properties of members used in the chapter. (a) Niño 3.4 SST anomalies standard deviation (STD, °C) for individual members (dots), the member used in chapter IV (star) and ensemble mean (green marker). (b) same as (a) but for the Niño 4 PR anomalies skewness (SKW), (c) same as (a) but for the number of extreme El Niño events detected within the historical period.

Before describing the methodology to detect extreme El Niño events, I briefly discuss the consistency of the database used in chapter IV over the historical (1 single member per model) with that used here (up to 10 members per model). Previous studies have indeed showed that some ENSO properties could significantly differ across ensemble members of the same model, even for 165 years long historical simulations (e.g [Planton et al. \(2021\)](#); [Bayr et al. \(2024\)](#); [Maher et al. \(2018\)](#)). Figure V.3 compares the statistics discussed in chapter IV (standard

deviation of Niño 3.4 SST anomalies, skewness of Niño 3 PR anomalies, and number of extreme Niño events defined as in [Lengaigne and Vecchi \(2009\)](#); [Cai et al. \(2014\)](#)) in the single member considered in chapter [IV](#) (star) and in the up to 9 additional members considered in the present chapter (circles), with the green bar indicating the ensemble mean. The grey line in panel b marks the skewness=1 threshold, below which models were excluded. Overall, this analysis confirms that the ENSO SST amplitude, asymmetry and number of extreme events can vary significantly from one ensemble member to another. Yet, only a small number of the 18 models would not have been considered in chapter [IV](#) by selecting a different ensemble member (e.g. only one single member in each of the CNRM-CM6.1, CNRM-ESM2-1, MIROC6 and UKESM1-0-LL ensembles does not produce an extreme El Niño over its historical period). Selecting a different member in Chapter [IV](#) would have yielded similar results.

V.2.5 ENSO categories determination

ENSO events within these historical and GWL bins are detected and categorized as follows. I compute DJF Niño 3.4 SST anomaly standard deviation (STD) over the historical period (1850-2014) for each model, and isolate La Niña events as Niño 3.4 SSTa < -0.5 STD, and El Niño events as Niño 3.4 SSTa > 0.5 STD. El Niño events with Niño 3 PR anomalies > 5 mm/day are categorized as extreme El Niño events, consistently with the extreme El Niño definition used throughout this thesis [Cai et al. \(2014\)](#); [Lengaigne and Vecchi \(2009\)](#). Conversely, moderate El Niños are defined as El Niño events with Niño 3 PR anomalies < 5 mm/day. Figure [V.4](#) displays histograms of the number of DJF realizations for each ENSO category in the historical and GWL bins (see [C](#) for the corresponding tables C.2 to C.4). As expected, the number of samples is lower for extreme El Niño events, and for the highest GWL. The historical reference period is extremely well sampled (5110 La Niña, 3628 moderate El Niño and 457 extreme El Niño events), even for extreme El Niño events. The 4.5°C GWL still has a reasonable number of La Niña and moderate El Niño events (about 100, i.e. a tenfold reduction of sampling error), but only 29 extreme El Niño events are available for this GWL and for only about half of the models. We will still show extreme El Niño composites for 4.5°C GWL, but we will interpret them carefully because of the larger sampling errors compared to other warming categories. We will therefore also show composites for the 3.5°C GWL (127 extreme El Niño events for 15 out of 17 models), which should be much less subject to sampling error. The last GWL we will illustrate (2°C) will be less influenced by sampling error (379 extreme El Niño cases across the 17 models). Note that the confidence intervals that were computed using a Monte Carlo method in previous chapters were computationally too demanding to be performed over the large CMIP6 database, but they will be performed in the coming months (see discussion in the perspectives).

Previous literature describes a consistent increase in the frequency of extreme El Niño events under global warming ([Cai et al., 2018, 2022](#); [Heede & Fedorov, 2023](#); [Shin et al., 2022](#);

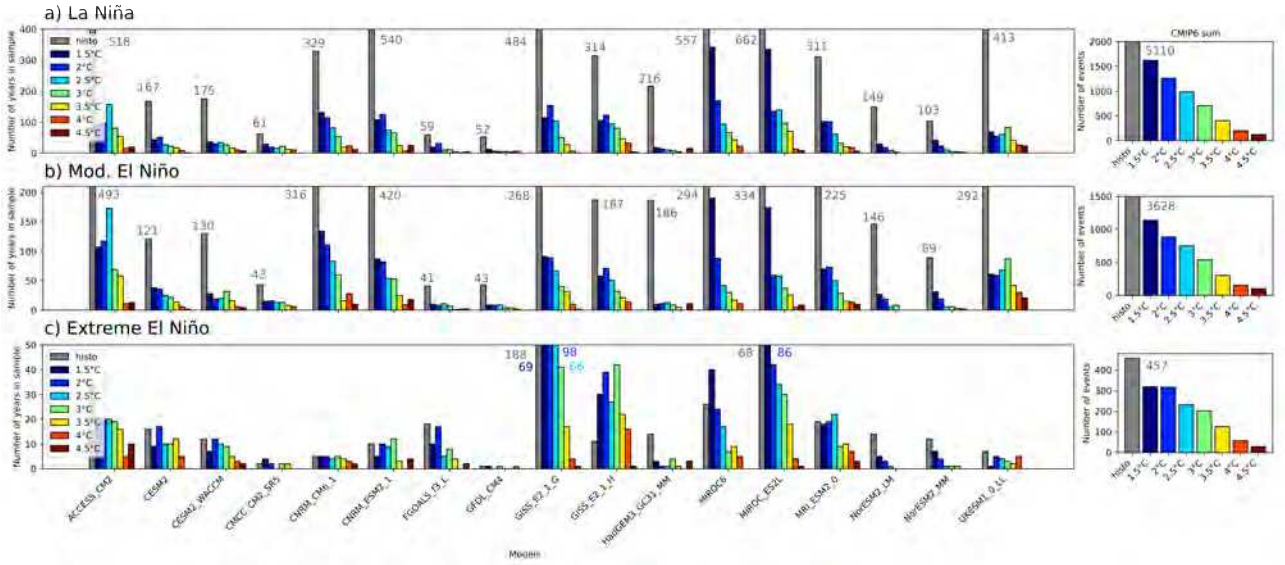


Figure V.4: As figure V.2, but for (a) La Niña events, (b) Mod. El Niño events and (c) extreme El Niño events.

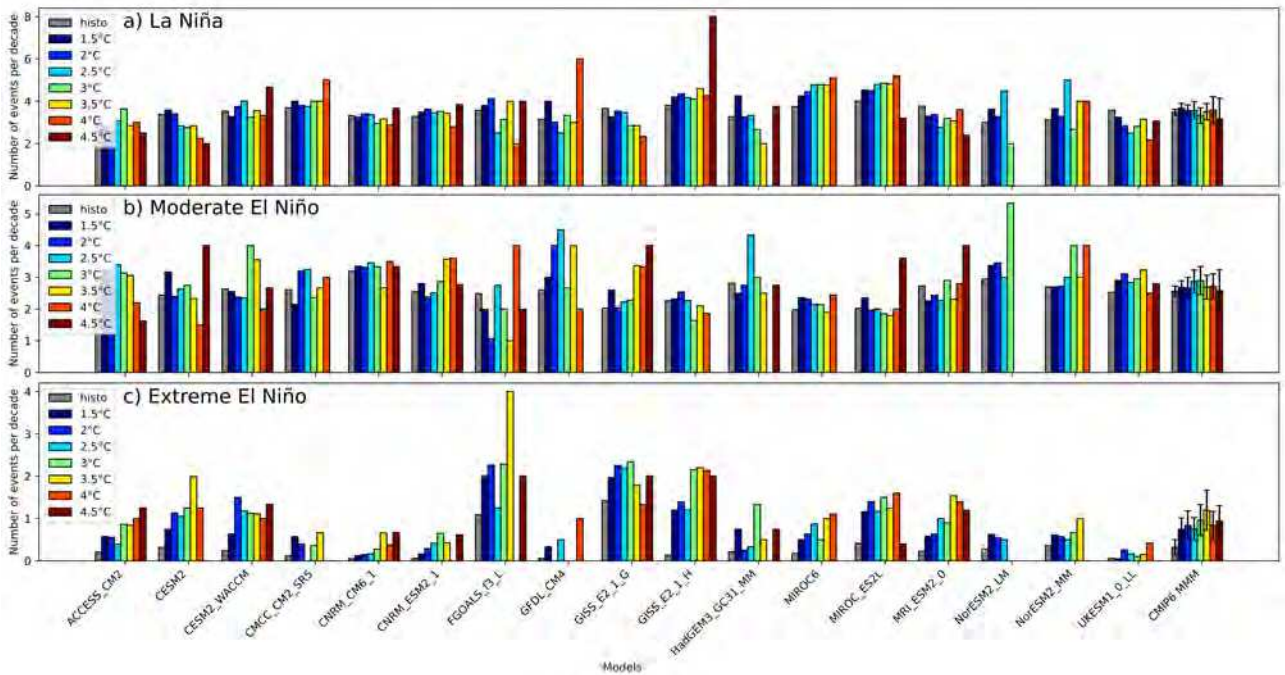


Figure V.5: Frequency of events per decade for (a) La Niña, (b) moderate El Niño, and (c) extreme El Niño over historical period (grey) and future GWL bins (colors). Error bars represent ± 0.5 standard deviations (STD). Level of warming not reached by models are ignored from the multi-model mean (MMM) calculation, this latter being computed over Ensemble-Mean (EM) to give equal weight to models.

Fredriksen et al., 2020). Let us examine if we find consistent results with our database and methods. Figure V.5 displays the number of ENSO events per decade. The frequency of La Niña and moderate El Niño events only modestly changes in warmer worlds (compare the colored

bars with the grey ones on panels a and b). On the other hand, there is a considerable increase in the frequency of extreme El Niño events relative to historical simulations in most models (panel c). The multi-model mean (MMM) indicates a increase of +130% to + 270%, with more modest increase at the highest +4.0°C to +4.5°C GWL. This smaller increase at highest warming levels may be related to the sampling issues discussed in the previous section for these very high GWL. Some studies however suggest that the "El Niño like warming" pattern (with enhanced eastern Pacific warming) inhibits El Niño variability at very high GWL (Callahan et al., 2021; Geng et al., 2024). In other words, an El Niño (a weakening of the climatological cold tongue) cannot develop if there is no longer a Cold Tongue. In any case, we detect a clear increase in the frequency of extreme El Niño events across a wide GWL range (1.5 to 4.5°C) compared to the historical period in our database, in agreement with published literature (Cai et al., 2014; Heede & Fedorov, 2023).

V.3 Results

V.3.1 Future changes in the overall ENSO teleconnection pattern

The main objective of this chapter is to specifically assess extreme El Niño events teleconnection pattern changes in future climates. Let us first examine the overall changes in the ENSO teleconnection pattern during boreal winter (DJF), i.e. for all ENSO phases taken together. This will allow us verifying that we find consistent results with the previously-published literature on this topic. To that end, Figure V.6 illustrates the linear regression of Z500, PR, and TS anomalies onto the normalized Niño 3.4 SST anomaly index, comparing historical and warmer climates. To emphasize future changes in those teleconnection patterns, we also show Figure V.7, that displays the future minus historical patterns. In the following, unless otherwise indicated, I will present CMIP6 multi-model mean composites, which are calculated by first computing the ensemble mean for each model, in order to give the same weight to each model.

Figure V.6a first confirms that our CMIP6 historical database capture reasonably well typical ENSO signatures and teleconnection patterns in current climate, starting in the tropical Pacific with warm surface temperature and wet rainfall anomalies over the equatorial Pacific. In the northern extratropics, Z500 anomalies reflect the PNA pattern over North America, with warm anomalies over western Canada and Alaska and wet anomalies off the western US coastline and over Florida. In the southern extratropics, ENSO teleconnection resembles the Pacific–South American (PSA) wave train characterized by alternating pressure centers near New Zealand and near the Amundsen Sea, highly impacting the depth of the Amundsen Sea Low, in agreement with the literature (Karoly, 1989; Mo & Higgins, 1998; Schneider et al., 2012). Tropical anomalies also reveal well-known ENSO impacts (e.g. Taschetto et al. (2020); Perry et al. (2017)), such as

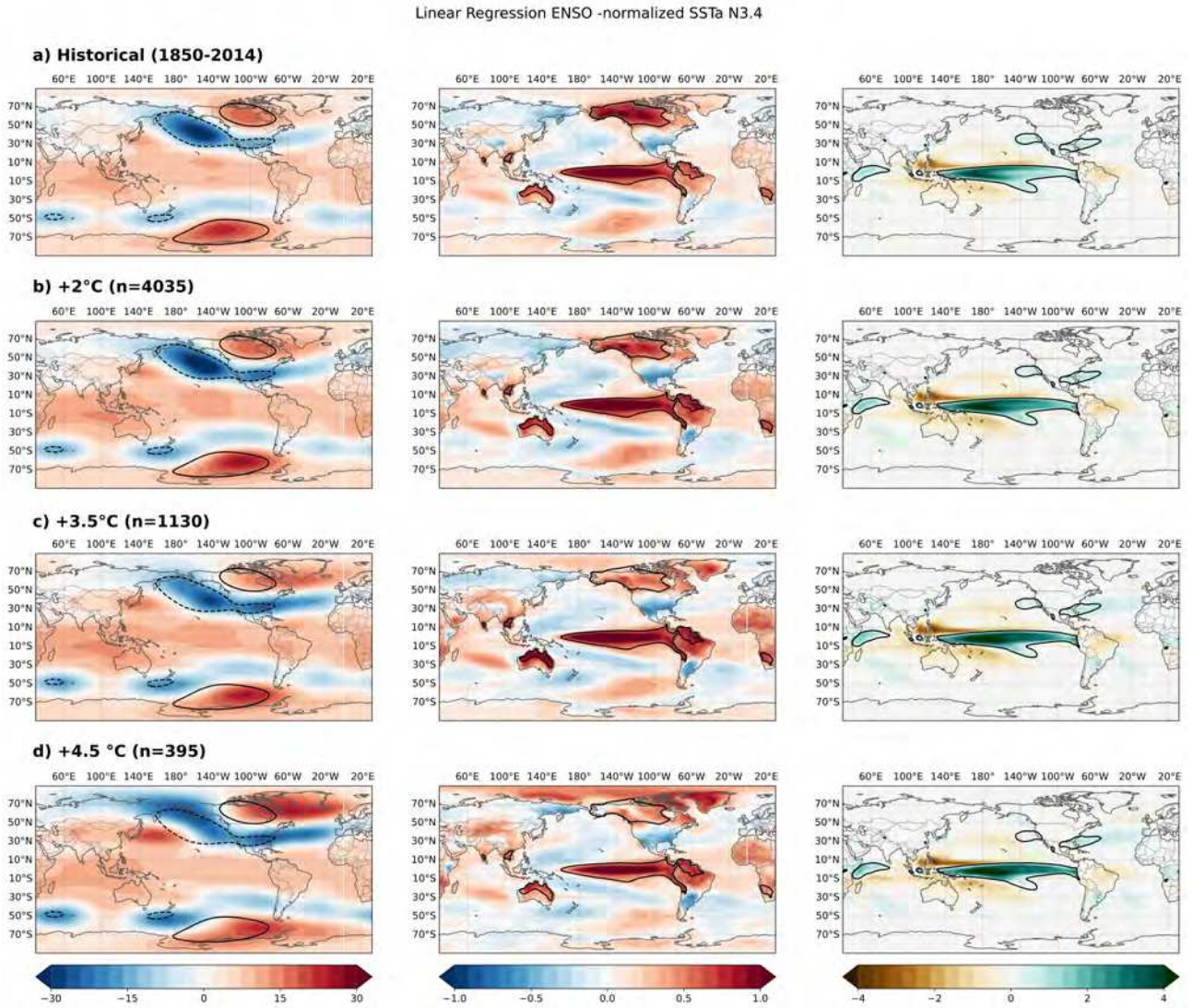


Figure V.6: MMM regression of DJF Z500 (left), TS (middle) and PR (right) anomalies onto the corresponding normalized Niño 3.4 SST anomalies for (a) historical climate and (b) 2°C, (c) +3.5°C and (d) +4.5°C GWL. Black contours indicate prominent historical signals for reference : $\pm 12\text{m}$ (left column), $+0.5^\circ\text{C}$ (middle column) and $+0.4\text{mm/day}$ (right column).

warm anomalies over northern Australia, warm and dry anomalies over northern South America.

As climate warms (Figure V.6b-d), extratropical ENSO teleconnection patterns in both hemispheres are shifted eastward, as documented in previous studies (see sections I.3 and V.1). This agreement with previous literature increases the confidence in our methodology (e.g. climate change / internal signals separation). In the northern extratropics, ENSO teleconnection pattern remains relatively similar to that in historical simulations at +2°C GWL (hereafter, GWL: global warming level), although the PNA pattern begin to shift eastward toward a more TNH-like teleconnection pattern. At +3.5°C, the PNA pattern fades (the negative PNA Z500

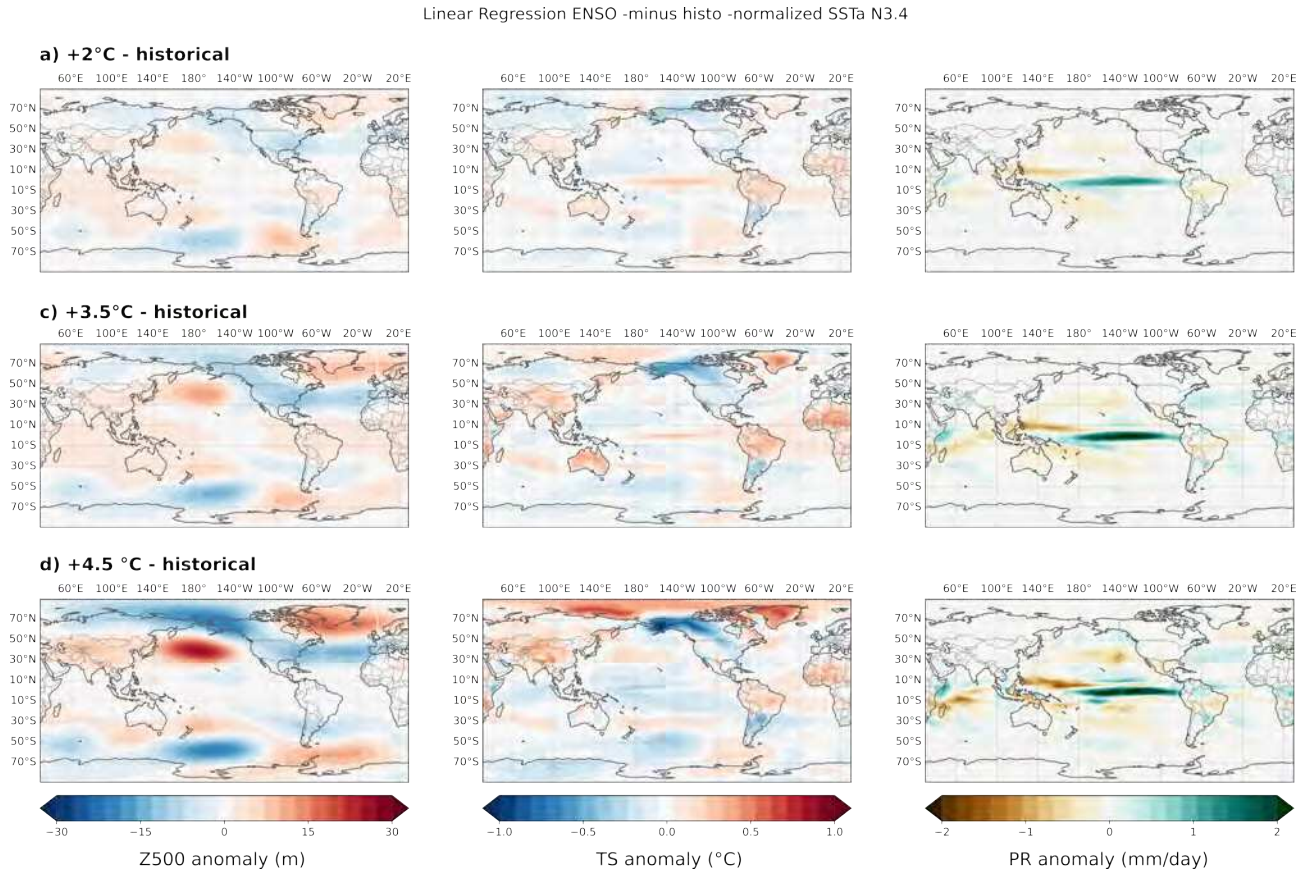


Figure V.7: Difference of regressed DJF Z500 anomalies onto the corresponding Niño 3.4 SST anomalies between future climates (2°C, 3.5°C and 4.5°C) and historical climate.

anomalies over the north Pacific weaken) and shifts eastward (in particular the positive Z500 anomalies over central-west North America). Further east, we can also note a strengthening of ENSO teleconnections to the North Atlantic, as also noted by [Geng et al. \(2024\)](#); [Johnson et al. \(2022\)](#); [Drouard and Cassou \(2019\)](#); [Fereday et al. \(2020\)](#). At +4.5°C GLW, the center of action of the Aleutian Low becomes significantly weaker, and both PNA and TNH structures are fading on the western-central North America, while the ENSO-NAO-like teleconnection pattern becomes significantly stronger, becoming the main new ENSO teleconnection pattern. In the North Pacific, a teleconnection structure similar to the Western Pacific (WP) pattern² emerges gradually with increasing GWL. Finally, in the Southern Hemisphere, a progressive eastward shift of the Pacific South America PSA is also noted, maximum at the highest GWL, in agreement with ([Cai et al., 2020a](#); [Wang et al., 2022](#)). Concurrently, in the tropical Pacific, there is a robust strengthening of the equatorial Pacific rainfall response, with enhanced wettening in the central and eastern Pacific and enhanced drying in the western consistent with the results

² Initially described by [Wallace and Gutzler \(1981\)](#); [Barnston and Livezey \(1987\)](#), the Western Pacific (WP) pattern is the mid-to-upper level geopotential height manifestation of the North Pacific Oscillation (NPO), with its signature observable in the Sea Level Pressure field ([Linkin & Nigam, 2008](#)).

of (Power & Delage, 2018; Cai et al., 2012).

In terms of impacts, the eastward shift of the teleconnection patterns leads to reduced ENSO influence on temperatures over northwestern Canada and Alaska, as well as decreased offshore precipitation anomalies offshore the western U.S. coast (around 140°W). This shift also results in wet anomalies during El Niño events being more confined to the western U.S. coast, consistent with findings by McGregor et al. (2022) and Beverley et al. (2021). In the subtropical North Atlantic, the development of a NAO-like teleconnection pattern is associated with increased precipitation anomalies that extend from Florida up to the Azores and the Iberian Peninsula, in line with Drouard and Cassou (2019) and Brown et al. (2020).

Overall, under future climate conditions, we detect a global eastward shift of the extratropical ENSO teleconnections, as well as a strengthening of the ENSO-NAO teleconnections. These changes imply reduced impacts over North America but increased impacts over the North Atlantic.

V.3.2 Future changes in extreme El Niño teleconnection patterns

Above, I have confirmed that changes in the overall ENSO teleconnections in warmer worlds obtained through our methodology and model sample are consistent with those documented in the literature. I can therefore now specifically investigate changes in extreme El Niño teleconnections in future climates. To that end, I present composites of extreme El Niño in historical and future climates in Figure V.8, and their changes (future-historical) in Figure V.9. The historical composites in this figure are very similar to those obtained using a single ensemble member by model in chapter IV. This confirms that conclusions from chapter IV would have been similar if another member would have been used to conduct the analysis.

Under warmer climates, precipitation anomalies associated with extreme El Niño events in the equatorial Pacific are projected to shift eastward (i.e. intensify in the eastern Pacific and weaken in the central Pacific, Figure V.9). The extreme El Niño tropical SST anomaly pattern is projected to weaken in the central-eastern Pacific for all GWL (Figure V.9). This $\approx 0.25^\circ\text{C}/^\circ\text{C}$ reduction in amplitude of extreme El Niño SST anomalies under global warming is relatively weak, and may not be statistically significant. It could be physically based, however, and linked to our detection method for isolating extreme El Niño events. We indeed select "extreme El Niño events" based on large eastern Pacific rainfall anomalies, not large SST anomalies. Since most CMIP6 models produce an enhanced warming in the eastern Pacific, which reduces the barrier to deep convection in this region (e.g. Watanabe et al. (2024)), smaller SST anomalies are probably required in that region to trigger a $> 5\text{mm/day}$ deep convective response.

Extreme El Nino

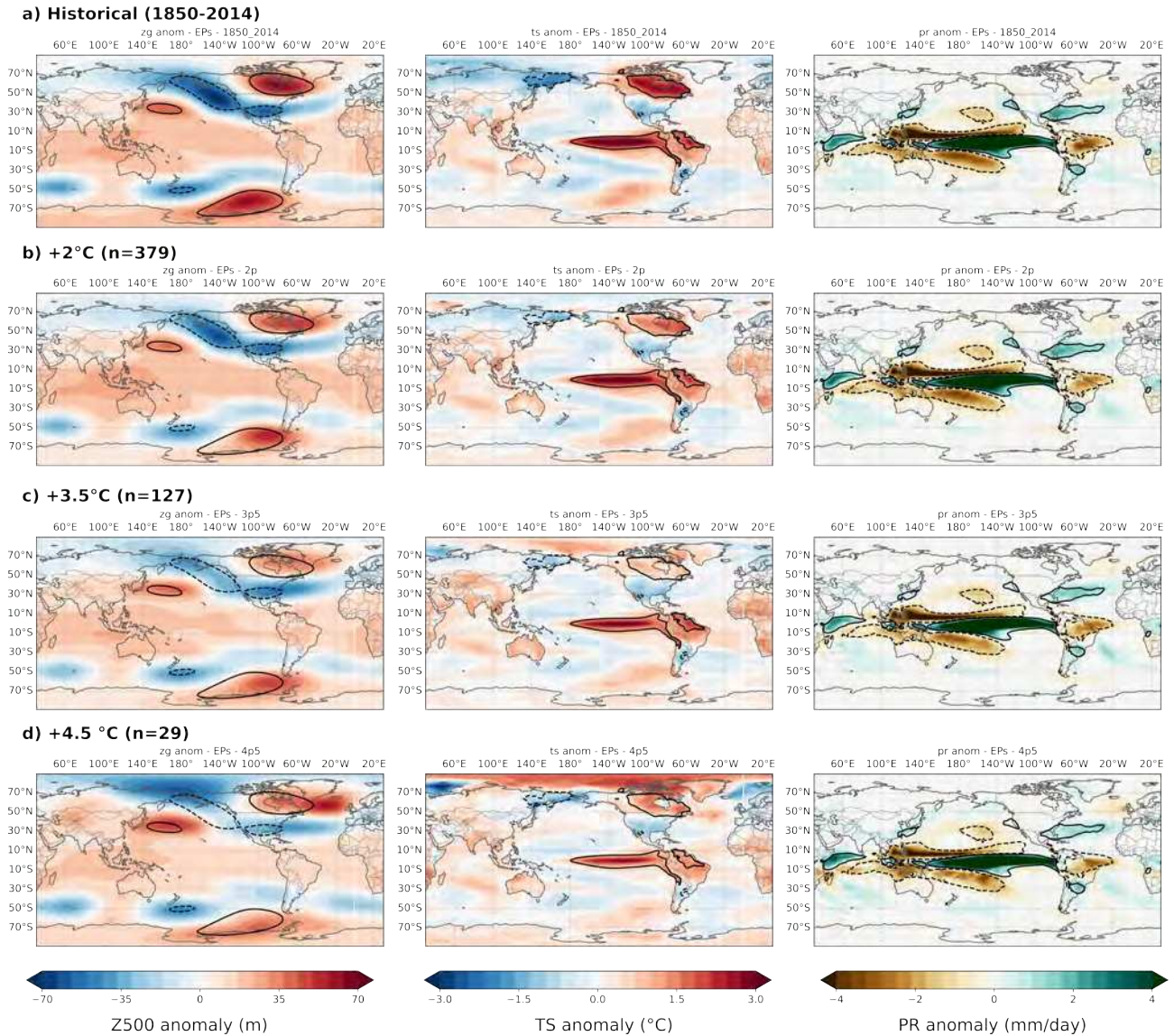


Figure V.8: Composites of DJF extreme El Niño for the Z500 (left) TS (middle) and PR (right) anomalies for (a) historical climate and (b) 2°C, (c) +3.5°C and (d) +4.5°C GWL, n indicating the number of total composite realizations. Black contours indicate prominent historical signals for reference : -45/+35m (left column), $\pm 1^\circ\text{C}$ (middle column) and $\pm 1.5\text{mm/day}$ (right column).

Over northern Pacific and America, there is a progressive eastward shift and weakening of the TNH-like teleconnection pattern. On the contrary, a negative NAO signal emerges over the northern Atlantic as climate warms is particularly clear. Over the Amundsen Sea in the southern hemisphere, the positive Z500 signal progressively shifts eastward as climate warms. All these features result in an apparent eastward shift of extreme El Niño teleconnections under warmer climates in the extratropics.

Extreme El Niño

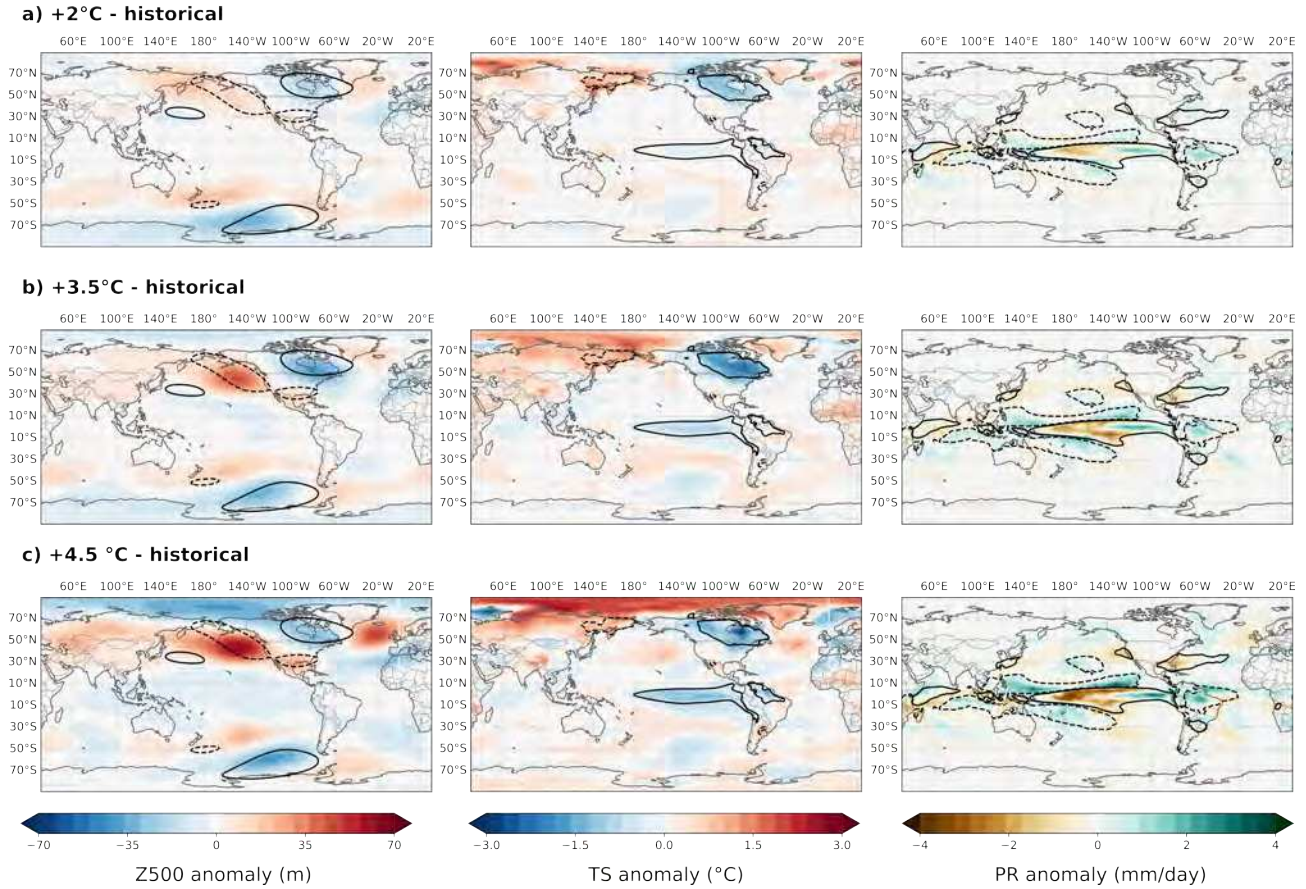


Figure V.9: Composites of changes in DJF extreme El Niño Z500 (left) TS (middle) and PR (right) anomalies, for (a) +2°C minus historical, (b) +3°C minus historical (middle), and (c) +4.5°C minus historical MMM composites. Black contours indicate prominent historical signals for reference: -45/+35m (left column), ±1°C (middle column) and ±1.5mm/day (right column).

In terms of impacts, the most striking signal is a considerable reduction of the northeast American warming specific to extreme El Niño events, in relation to the TNH-like teleconnection weakening. The wet anomalies along the western US coast associated with the TNH in current climate are also reduced at higher warming level (Figure V.9), probably because as the anomalously deep Aleutian Low is no longer present, there is a reduced northward advection toward the western US coast of moist tropical air. The wet anomalies over Florida are also reduced at increasing GWLs. Another interesting change is evident over the Amazon basin and northeastern South America. The warm and dry anomalies over this region seen during extreme El Niño reduces as climate warms. If robust, this would have important implications for the region, as El Niño events are typically associated with boreal winter droughts (Kay et al., 2022; Cai et al., 2020a).

Most extreme El Niño teleconnection changes discussed in Figure V.8 are reminiscent of those seen in overall ENSO composite (Figure V.6). This raises the question of whether teleconnection

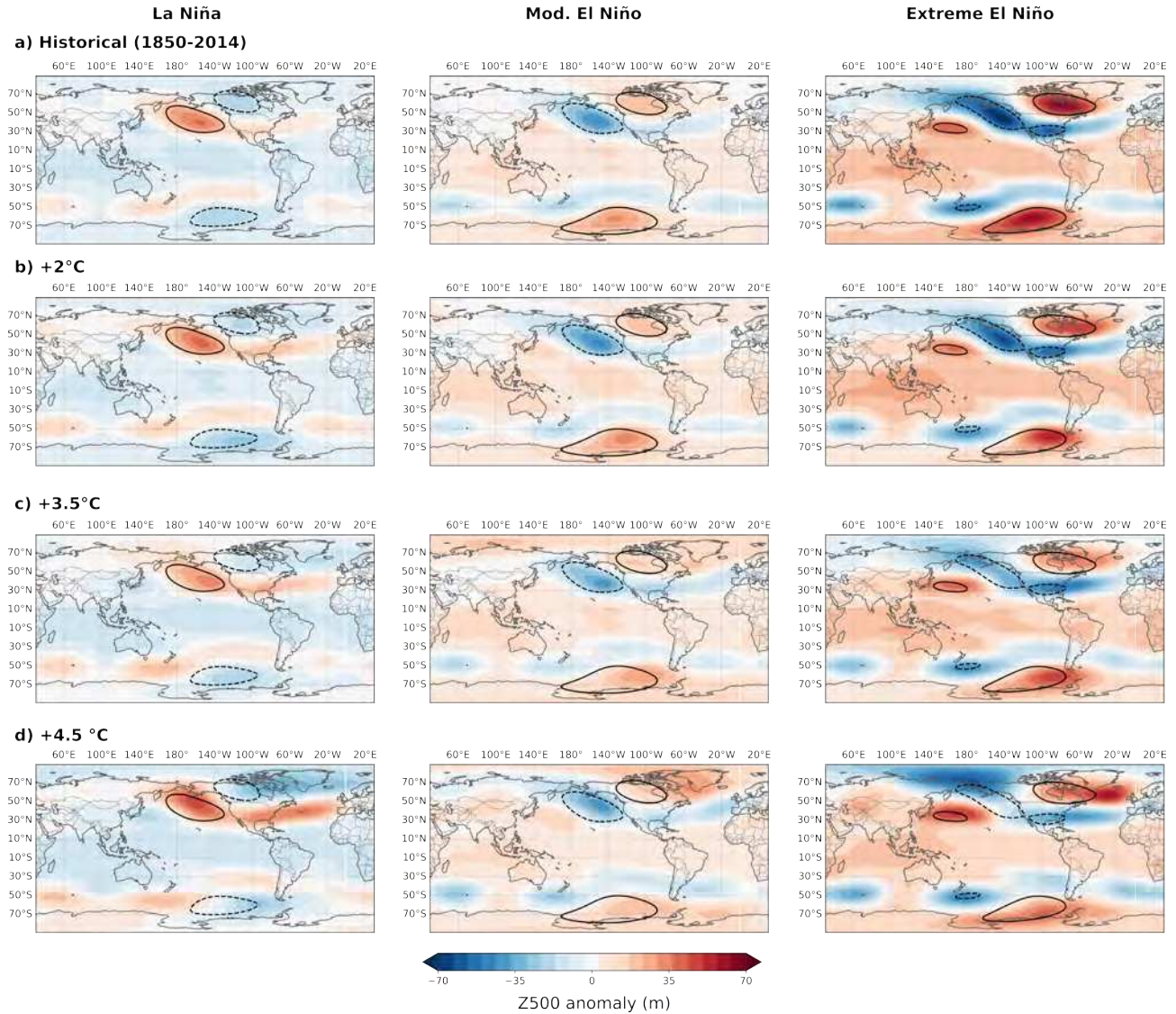


Figure V.10: Multi model mean DJF composites of Z500 anomaly for La Niña (left), Moderate El Niño (middle) and extreme El Niño (right), for (a) historical period, (b) +2°C, (c) +3.5°C and (d) +4.5°C GWLs. Black contours indicate prominent corresponding historical signals for reference : -15/+20m (left column), -20/+15m (middle column) and -45/+35m (left column).

changes are similar across ENSO events categories, or specific to some. To address this question, let us briefly examine the projected teleconnection changes for moderate El Niño and La Niña events and compare them with those of extreme El Niño events (see Figure V.10, note that composites for La Niña and Moderate El Niño are available in Annex C Figures C.I and C.III).

At first glance, both La Niña and moderate El Niño teleconnections changes appear considerably smaller than those of extreme El Niño impacts. Although the weakening of the northern Pacific and America teleconnection signal is less prominent, the positive and negative PNA response to moderate El Niño and La Niña events tends to slightly shift eastward

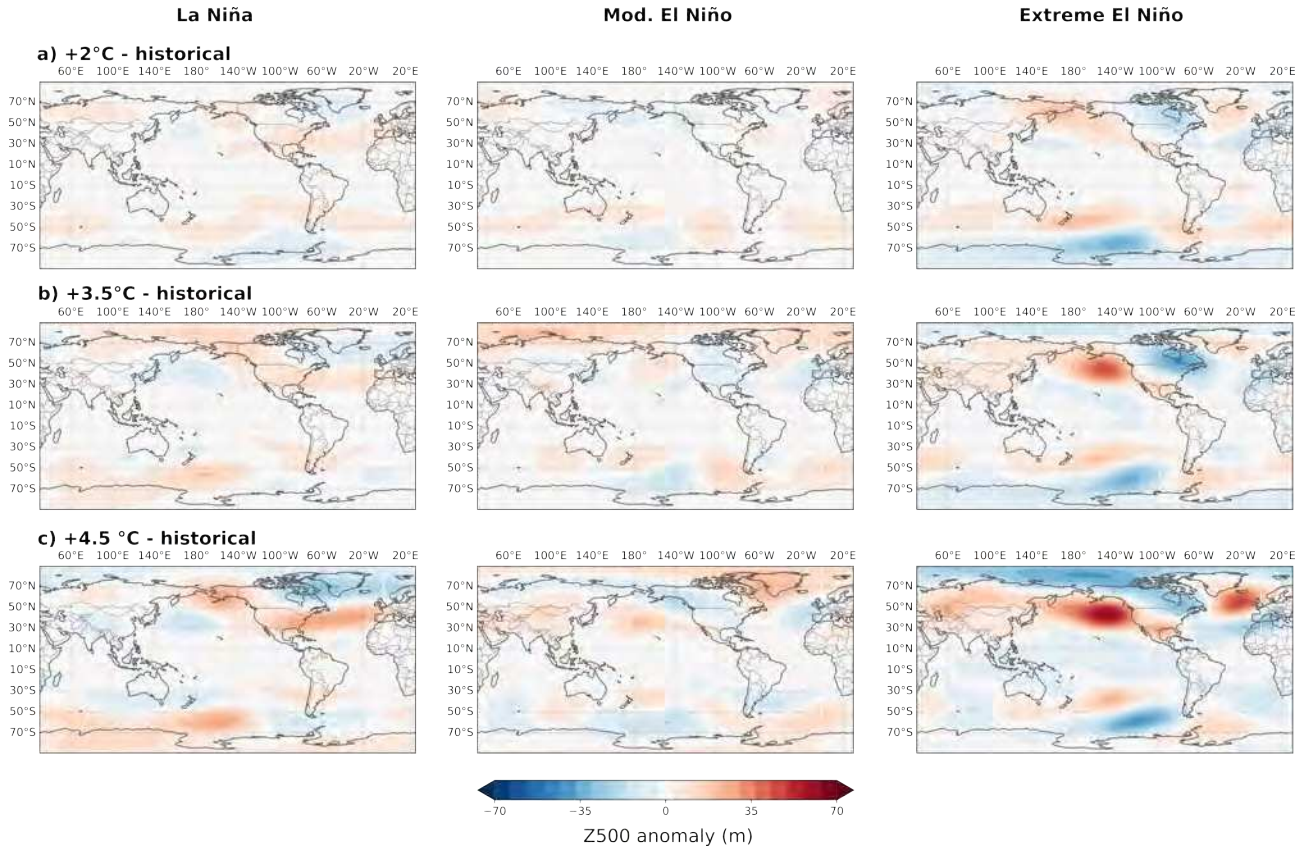


Figure V.11: Multi model mean DJF composites of Z500 anomaly for La Niña (left), Moderate El Niño (middle) and extreme El Niño (right), for the +2°C minus historical MMM composite (top), +3°C minus historical (middle), and +4.5°C minus historical (bottom).

under future climates (becoming more TNH-like), as is the case for extreme El Niño events in current climate. Over Northwest Canada/Alaska, the dampening of negative/positive La Niña/Mod. El Niño TS anomalies seems to occur. In Z500 anomalies, a stronger response is found over the northern Atlantic, where the NAO-like response increases strongly as climate warms, especially for La Niña events. Finally, as for extreme El Niño events, the southern hemisphere PSA response to moderate El Niño and La Niña events also shift eastward under warmer climate. Overall, future changes in ENSO Z500 teleconnections under warmer climates, are characterized by a eastward shift of the PNA, strengthening of a NAO-like teleconnection response and an eastward shift of the PSA teleconnection across ENSO categories, though generally more pronounced for extreme El Niño. Because equatorial Pacific rainfall changes are considerably weaker for La Niña and moderate El Niño than for extreme El Niño events (not shown), this suggests that changes in the mid-latitude atmospheric circulation that determines the pathway of Rossby waves should contribute to teleconnection changes, as suggested by the study of [Lee and Jin \(2024\)](#).

V.3.3 Inter-realization consistency of extreme El Niño-driven regional impacts

Finally, I show the distributions of seasonal anomalies during ENSO events in regions of North America, where I found reproducible impacts in chapter IV. I indeed found that only extreme El Niño events drive a robust warming over the Northeast America and increased rainfall over California and Florida compared to other type of events.

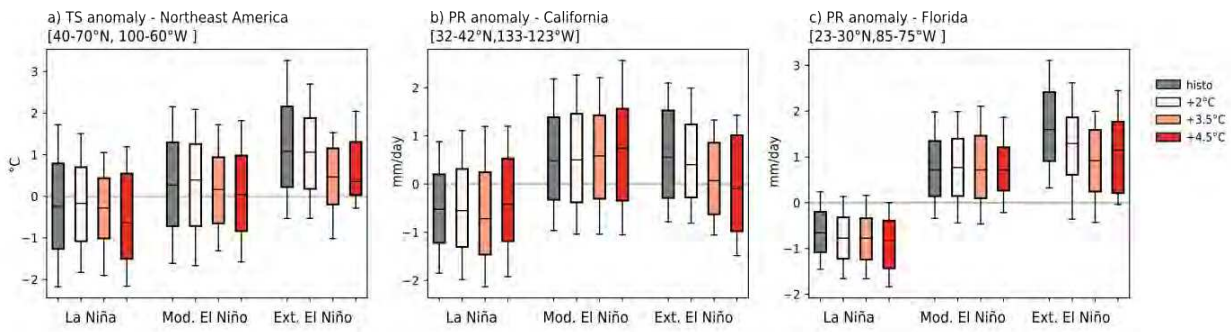


Figure V.12: Distribution of mean DJF (a) land surface temperature anomaly (°C) over Northeast America for each La Niña, Mod. El Niño and extreme El Niño CMIP6 realizations, for the historical (grey), +2°C (white), +3.5°C (pink) and +4.5°C (red) samples. (b) Same as (a), but for precipitation anomalies (mm/day) over the California region. (c) Same as (a) but for precipitation anomalies (mm/day) over the Florida region. The latitude/longitude of the boxes is given above the corresponding subplots. Boxes are identical to those used in Figure 5 of chapter IV for consistency. The median is indicated in black, box edges indicates the 25th/75th percentiles and whiskers the 10/90th percentiles. Outliers are not shown.

Figure V.12a show the spread of mean Surface Land Temperature anomalies over northeastern America under historical (grey) and increasingly warmer climates (shades of red) for La Niña, moderate El Niño and extreme El Niño. In broad agreement with IV, only extreme El Niño are associated with robust warm anomalies over the historical period in this region. As climate warms, this extreme El Niño warming signal consistently decreases, while the distribution only changes marginally for La Niña and moderate El Niño events. Panel b displays a similar analysis but for precipitation anomalies over California. As indicated in chapter IV, CMIP6 models tend to yield similar wet impacts of moderate and extreme El Niño events over California, by underestimating wet precipitation anomalies extreme El Niño over the region, unlike what we found in the AMIP6 database (compare the grey bars for the moderate and extreme El Niño distributions). Again, there is a clear decrease of the wet anomalies over California during extreme El Niño events as climate warms, while La Niña and moderate El Niño events do not exhibit any substantial changes. Finally, wet anomalies over Florida during extreme El Niño events also weaken as climate warms. In contrast, precipitation distribution changes over Florida remain modest for La Niña and moderate El Niño events. Overall, the typical impacts of extreme El Niño over North America weaken under warmer climates.

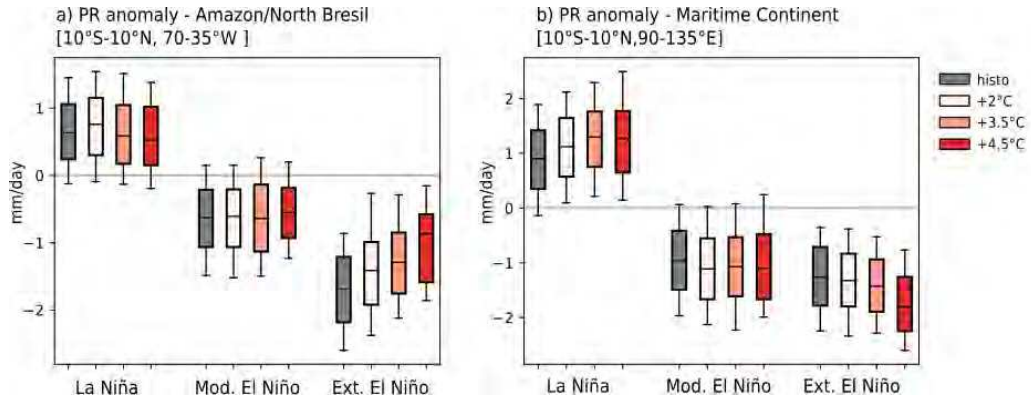


Figure V.13: Distribution of mean DJF (a) precipitation anomaly (mm/day) over Amazon/Northeast Brasil for each La Niña, Mod. El Niño and extreme El Niño CMIP6 realizations, for the historical (grey), +2°C (white), +3.5°C (pink) and +4.5°C (red) samples. (b) Same as (a), but over the Maritime Continent. The latitude/longitude of the boxes is given above the corresponding subplots. Boxes are identical to those used in Figure 5 of chapter IV for consistency. The median is indicated in black, box edges indicates the 25th/75th percentiles and whiskers the 10/90th percentiles. Outliers are not shown.

As discussed above, regions other than those discussed in chapter IV may be affected by ENSO teleconnection changes in the future, at least for extreme El Niño events. Figure V.13 display a similar analysis to that in figure V.12, but for precipitation anomalies over two other interesting regions that experience droughts during extreme El Niño years (Figure V.8): the Northeast Brazil and the Maritime Continent. Being located in the tropics, the first striking result is that rainfall anomalies in these two regions display reproducible signals for all ENSO classes, in contrast to mid-latitudes where noise is considerably larger. Over Northeast Brasil, La Niña events tend to induce wet years over the historical period while this region tends to experience drought during El Niño events. These droughts are however larger and more systematic during extreme El Niño events than during moderate ones. As climate warms, the amplitude of these droughts hardly change for La Niña and moderate El Niño events, while they becomes less severe during extreme El Niño. For the Maritime Continent, results are different. This region is unusually wet during La Niña and dry during El Niño. The dry signal during extreme El Niño is not really larger than that associated with moderate El Niño events under the current climate. There is no clear change of the El Niño dry anomalies under warmer climates. On the other hand, there is a clear increase of the La Niña wet and extreme El Niño dry anomalies under warmer climates. These results agree with (Chen et al., 2023) that also found an increase in dry (wet) anomalies during El Niño (La Niña) under CMIP6-SSP5-8.5. Overall, this Maritime Continent box is the only region where I found a clear increase in extreme El Niño (and La Niña) impacts under warmer climate. Since the teleconnection pattern changes seem to suggest more systematic ENSO impacts over Europe, I also investigated a couple of average response in this sector, but found no very robust future changes. Looking more systematically

for regions where there is a robust future change in ENSO impacts is one of my perspectives.

In conclusion, this preliminary analysis shows that the specific impacts of extreme El Niño impacts over North America in the current climate (wet California and Florida, warm Northeast America), are projected to weaken under warmer climates. Extreme El Niño dry anomalies over Northeast Brazil also become weaker, and more similar to those of moderate events under warmer climates. The only region where I could find a clear future increase of extreme El Niño (and La Niña) under warmer climates is the maritime continent with larger dry (wet) anomalies in future.

V.4 Conclusions and way forward

V.4.1 Conclusions

The aim of the preliminary analyses in this chapter was to establish a methodology for exploring future changes in ENSO teleconnection patterns, with a specific focus on extreme El Niño events, which are a primary focus of this thesis.

I do not estimate those teleconnection changes on a SSP-scenario basis, because a single scenario can give rise to various levels of warming depending on the model climate sensitivity and the target period ([Hawkins & Sutton, 2009](#)). Instead, I grouped decades between 2015 and 2100 based on their surface global warming levels (GWL), relative to the 1850-1920 period. In line with the literature ([Heede & Fedorov, 2023](#); [Cai et al., 2014](#); [Shin et al., 2022](#)), I first show a significant increase in the frequency of extreme El Niño events (defined on the basis of strong wet anomalies over the Niño 3 region) relative to the historical period, for warming levels between $+2^{\circ}\text{C}$ to $+4.5^{\circ}\text{C}$. There is on the other hand no clear change in the frequency of moderate El Niño or La Niña events.

Second, projected changes in the overall ENSO teleconnection pattern (regressions to the normalized Niño 3.4 SSTa) are consistent with those mentioned in previous studies ([McGregor et al., 2022](#)). I indeed show that the tropical sources (precipitation) of ENSO shift eastwards. The overall extratropical ENSO teleconnections also changes: there is an eastward shift of the PNA teleconnection pattern over the Northern Pacific and PSA pattern over the South Pacific. On the other hand, NAO-like teleconnections becomes stronger over the North Atlantic (NAO+ for La Niña, NAO- for El Niño), in agreement with ([Johnson et al., 2022](#); [Drouard & Cassou, 2019](#); [Beverley et al., 2024](#)). I find that the ENSO teleconnection eastward shift and ENSO-NAO link strengthening increases proportionally to the GWL. As a result, in the main ENSO impacts, northwestern Canada/Alaska temperature signals gradually weaken as climate

warms, and precipitation anomalies seems to be more confined toward the western US coastline.

Changes in extreme El Niño events teleconnection feature a clear eastward shift of the tropical Pacific rainfall anomalies, with wet anomalies that are more confined to the eastern equatorial Pacific. Extratropical changes can broadly be described as a weakening of the TNH teleconnection signal over the north Pacific and north America, and a strengthening of a NAO-like teleconnection pattern over the north Atlantic, as well as the weakening of warm anomalies over Northeast America, and those of wet anomalies over California and Florida. Likewise, droughts over Northeast Brazil seems to become less intense in association with extreme El Niño in future climates. The only region where we find a future increase of the current climate-extreme El Niño (and La Niña) impacts is the Maritime continent, where dry (wet) anomalies become more severe under warmer climates.

Thus, extreme El Niño events display much larger changes in their future teleconnection patterns than other ENSO categories (La Niña, moderate El Niño, Figure V.11). Yet, the changes in teleconnection pattern identified for extreme El Niño events share several common features with other ENSO categories (weakening of teleconnection patterns over the North America, strengthening of the NAO-like teleconnection to the Northern Atlantic, eastward shift of the south Pacific PSA teleconnection pattern). This has some implications about the possible mechanisms for these changes in teleconnections: I will come back to this discussion in Chapter V.4.2. Overall, extreme El Niño tend to have less specific impacts relative to other ENSO categories under warmer climates over North America.

V.4.2 Way forward

Results in chapter V are still preliminary, and several methodological caveats still need being addressed. I detail these methodological perspectives below, and will come back to the broader scientific perspectives in chapter V.4.2.

The large number of samples in the CMIP6 database I work with made the statistical significance method I used in previous chapters impractical to work with. Improving its implementation will allow me to perform statistical significance tests on the teleconnection and teleconnection change patterns I discussed in chapter V, similarly to what has been done in chapter III for instance.

I retained all the CMIP6 models that could produce extreme El Niño events for which both historical and scenario simulations were available in our analyses. Yet, we know from chapter IV that some of these models do not produce a very accurate extreme ENSO teleconnection

pattern (compared to the AMIP6 ensemble mean): such models (4 models out of 17, with a total ≈ 50 members) could be excluded from our analyses, to test its robustness.

My method for separating anthropogenically forced signals from internal climate variability assumes that local changes scale with global mean surface temperature changes, implying that all regions warm at the same rate. This assumption does not hold in polar regions, where observed trends show significantly faster warming, particularly in the Arctic ([Rantanen et al., 2022](#)). Some of our analyses feature a similar Arctic signal across all ENSO categories. This caveat prevents us from investigating ENSO teleconnection changes in interesting regions such as the Arctic or Greenland. I will investigate alternative methods for separating climate change signals from internal climate variability (for instance using models with large pre-industrial control and scenario ensembles). I do not expect this to change my results a lot in most regions.

The choice of global warming level (GWL) bins I made are clearly not optimal. The bins are small, and the most extreme bins ($+4^{\circ}\text{C}$, $+4.5^{\circ}\text{C}$ GWL) has a reduced number of samples, especially for extreme El Niño events. I will investigate how I can gather the existing categories into broader bins (maybe 3 for historical, moderate warming up to 2°C , and strong warming above 2.5°C ?) in order to strengthen the significance of the composite changes in teleconnection patterns.

These are a few of the methodological challenges I need to tackle for chapter [V](#). I will verify that the results obtained so far are robust when addressing all those methodological issues. Once this is done, I will also investigate more systematically in which regions ENSO teleconnections are projected to change in the future, separately for La Niña, moderate El Niño and extreme El Niño events. I will come back to the broader scientific perspectives in chapter [V.4.2](#).

General conclusion (EN)

The main objective of this doctoral thesis was to investigate the diversity of ENSO winter atmospheric teleconnections over North America, with a specific focus on the contribution of Extreme El Niño events to the present-day and future teleconnection diversity. Results of this thesis are supported by analyses of atmosphere-only and coupled ocean-atmosphere simulations from the AMIP6 and CMIP6 databases, observational datasets, as well as dedicated sensitivity experiments performed by [Srinivas et al. \(2024\)](#) with the AMIP version of the CNRM-CM6.1 model. Hereafter, I revisit the scientific questions addressed in this thesis, summarize the key results, and present potential avenues for future investigations.

V.5 Conclusions

Chapter III : What are the drivers and mechanisms of the winter ENSO teleconnection diversity over North America?

1) Previous studies suggested that an eastward-shifted (TNH-like) teleconnection pattern occurs either specific ally during El Niño (relative to La Niña) events, for EP (relative to CP) El Niño events, or even more specifically for EP events that generate convective anomalies in the central Eastern Pacific. Here, I test the null hypothesis that this eastward-shifted pattern only specifically occurs for extreme El Niño events such as 1982-83, 1997-98 or 2015-16, i.e. for a subcategory of all the above-mentioned types of El Niño events.

I begin my investigation by examining ENSO teleconnection diversity over North America during the boreal winter (DJF) period in observations (1979-2019) and an AMIP type 16 ensemble from the CNRM-CM6.1 AGCM (6 members from [Srinivas et al. \(2024\)](#) covering 1979-2019, 10 members from AMIP6 [Voldoire et al. \(2019\)](#) covering 1979-2014). I find that La Niña teleconnections are associated with a negative phase of the Pacific North America (PNA) pattern, associated with cold surface temperature anomalies over western Canada and Alaska. Moderate central (CP) and eastern (EP) Pacific El Niño events are associated a positive PNA pattern and warm anomalies over the same region. Finally, I demonstrate that only extreme El Niño events, defined as intense SST anomalies in the eastern equatorial Pacific leading to large rainfall anomalies there, exhibit teleconnection patterns that are shifted by about 30° eastward relative to the PNA pattern. These patterns resemble the Tropical North Hemisphere (TNH) pattern. While previous literature attributed such shifted teleconnection patterns to El Niño/La Niña asymmetry ([Hoerling et al., 1997](#)) or ENSO diversity (i.e. EP/CP events, see ([Ashok et al., 2007](#))), I show that only extreme El Niño events lead to the TNH teleconnection pattern. In other words, there are no significant differences in teleconnections between Moderate

El Niño and La Niña, and between Moderate CP and Moderate EP El Niño teleconnection patterns to the North Pacific-North America region. Finally, I demonstrate that only extreme El Niño events lead to warm surface temperature anomalies over Northeast America. While some studies associated central-eastern convective El Niño events ([Johnson & Kosaka, 2016](#); [Chiodi & Harrison, 2015](#)) or EP events ([Larkin, 2005](#); [Ashok et al., 2007](#)) with wet anomalies over California, my results agree with those of ([Jong et al., 2016](#); [Hoell et al., 2016](#)) in specifically linking wet anomalies over California are to extreme El Niño events.

2) What are the respective contributions of the ENSO SST pattern diversity and atmospheric nonlinearities to the eastward shift of the teleconnection patterns, the TNH relative to the PNA teleconnection pattern ?

To address this question, I used sensitivity experiments conducted by [Srinivas et al. \(2024\)](#) with the CNRM-CM6.1 model. Their methodology involves two AMIP-type 6-member ensemble experiments, with one forced by observed SST anomalies and one by their mirror image (i.e. climatology minus SST anomalies). A linear combination of these two ensembles allows for disentangling the effects of atmospheric tropical nonlinearities (i.e. nonlinearities in the SSTs-deep convection response) from the effect of ENSO SST diversity (differences in the linear response to moderate vs extreme El Niño events SST patterns) on the teleconnection shift. My analysis reveals that during moderate CP or EP El Niño events, SST anomalies are insufficiently large to trigger nonlinear convective response in the eastern Pacific. As a result, the PNA pattern observed during these events is mostly a linear atmospheric response to the ENSO SST pattern. Conversely, during Extreme El Niño events, large eastern Pacific SSTA lead to a substantial nonlinear convective response, roughly equal in magnitude to the linear response. In other words, only extreme El Niño events are associated with substantial atmospheric convective nonlinearities, which combines with the linear response to the eastward-shifted SST pattern to induce a basin-wide reorganization of tropical heat sources, large convective anomalies in the eastern equatorial Pacific, and the eastward-shifted TNH pattern.

3) Are the extreme El Niño specific climate impacts over North America more robust and reproducible than for other ENSO-types ?

Finally, using the 16 ensemble members from the AMIP6 CNRM-CM6.1 model, I investigated the reproducibility of seasonal anomalies over North America during La Niña, Moderate El Niño and Extreme El Niño events. I found that impacts associated with extreme El Niño events (i.e. the TNH teleconnection pattern) are much more reproducible across events and ensemble members than those associated with moderate El Niño or La Niña events. For instance, there is a 71 % likelihood of warm anomalies over Canada and northern U.S, and 74 % likelihood of wet anomalies along the western U.S coast region during extreme El Niño events. No other type of ENSO events is associated with such high inter-realizations consistency. However, the conclusions in this chapter are somewhat limited by the substantial contamination of ENSO teleconnection

estimates by extratropical internal aliasing variability (Deser et al., 2017; Garfinkel et al., 2018) in the relatively small (16-member) ensemble I analyzed, as well as potential biases in the CNRM-CM6 atmospheric component. I will therefore examine the robustness of these results in the larger AMIP6 and CMIP6 databases in chapter IV.

Chapter IV : Robustness of Extreme El Niño teleconnections to North America in AMIP6/CMIP6 models

1) Is the specific extreme El Niño TNH teleconnection pattern obtained in chapter III robust in the wider AMIP6 database ?

In this chapter, I expanded the analysis of the boreal winter ENSO teleconnection pattern diversity using a broader dataset: 135 ensemble members from 23 AMIP6 models, covering the 1979-2014 period. This period includes two Extreme El Niño events (1982/83 and 1997/98), yielding a total of 270 extreme El Niño realizations. My analysis confirms Chapter 3 results: La Niña and moderate El Niño events induce a PNA response, while the TNH teleconnection pattern specifically arises for Extreme El Niño events for 22 out of 23 models.

2) Are Extreme El Niño teleconnection patterns also highly reproducible in the wider AMIP6 database ? Does this stronger reproducibility arise from stronger signal and/or reduced atmospheric internal variability?

The large number of realizations in the AMIP6 ensemble also allowed a more robust assessment of the reproducibility of the extreme El Niño impacts over North America. My analysis of the AMIP6 multi-model ensemble shows very diverse Z500 seasonal anomalies during a Niña and Moderate El Niño, but much more robust inter-event and inter-member anomaly maps during extreme El Niño events. As a result, the Northeast American warming and wet anomalies over California and Florida are more reproducible (69%, 77% and 96% probabilities, respectively) during Extreme El Niño events. This increased reproducibility mainly arises from a stronger ENSO signal during extreme El Niño events.

3) How does the SST cold tongue bias inherent to most CMIP6 models affect their ability to reproduce the extreme El Niño teleconnection pattern and associated impacts?

After examining extreme El Niño teleconnections in AMIP6, I turned to CMIP6 coupled models to assess how they reproduce extreme El Niño teleconnections and impacts in the current climate, using the AMIP6 multi-model ensemble mean as a reference. This step is crucial before investigating extreme El Niño teleconnections in future climates. CMIP6 models are known to exhibit large SST biases, particularly a cold equatorial Pacific bias, often referred to as the "cold tongue bias" (Planton et al., 2021). This bias degrades their simulated climate relative to

that in AMIP simulations, affecting various ENSO properties, including teleconnection diversity, as highlighted in CMIP5 by [Bayr et al. \(2017\)](#). For this analysis, I considered the first available historical member from 42 CMIP6 models over the 1850-2014 period. I previously demonstrated that the large eastern Pacific rainfall anomalies during extreme El Niño events play a critical role in establishing their specific TNH teleconnection pattern. Following [Cai et al. \(2014\)](#); [Lengaigne and Vecchi \(2009\)](#), I therefore define extreme El Niño events as those with large eastern equatorial Pacific precipitation events (Niño 3 anomalies $> 5\text{mm/day}$). 16 out of 42 models fail to produce Extreme El Niño events, partly because of their large cold tongue bias, in line with ([Bayr et al., 2024](#)). The remaining 26 CMIP6 models are able to simulate at least one Extreme El Niño event over the historical period. Among these, 18 models successfully reproduced the specific TNH pattern during extreme El Niño, aligning well with the AMIP6 ensemble mean. In these models, the TNH teleconnection pattern emerged exclusively during extreme El Niño events, as in AMIP6. Additionally, I compared impacts simulated by AMIP6 and CMIP6 using data from 11 models that had both simulations available. I found that CMIP6 models tend to underestimate precipitation anomalies over California and Florida during extreme El Niño events, whereas no significant biases were detected for moderate El Niño or La Niña-related winter surface temperature and precipitation anomalies.

Chapter V : Extreme El Niño teleconnections in a warmer world

1) How are teleconnections associated with different ENSO categories (La Niña, moderate El Niño, extreme El Niño) projected to change under future climate conditions?

In this chapter, I did analyze historical (1850-2014) and future (2015-2100) simulations from 17 CMIP6 models that are able to produce extreme El Niño events. This database (4 different SSPs with up to 10 members per model, with a total of 296 members, and about 74000 DJF realizations) was analyzed based on globally-averaged surface warming level (global warming level, GWL), as recommended by the IPCC AR6 report. I separated ENSO events into La Niña, moderate and extreme El Niño categories to detect how their teleconnection evolves in the future. Consistent with ([McGregor et al., 2022](#)), I found that changes in teleconnection pattern scale with the degree of GWL: the warmer the atmosphere, the more pronounced the changes. For moderate El Niño and La Niña events, I observed small shifts that align with existing literature. These include an eastward shift of teleconnection patterns over North America, which I interpret as a transition from a PNA-like to a more TNH-like pattern. Additionally, there is a strengthening of an NAO-like teleconnection pattern over the North Atlantic, with a negative phase for moderate El Niño and a positive phase for La Niña, in agreement with e.g. ([Johnson et al., 2022](#)). However, the most significant changes occur for extreme El Niño events. The eastward shift of TNH-like teleconnection patterns of extreme El Niño events as climate warms is considerably more pronounced than for other ENSO categories. This leads to a weakening of

the specific extreme El Niño impacts over northeastern America, i.e. weaker warm anomalies over Northeast America and wet anomalies over California and Florida during extreme El Niño events than under current conditions. Similarly, dry anomalies over Northeast Brazil during extreme El Niño events will become weaker under future climates (no significant changes for La Niña and moderate El Niño). The only regions where we found increased climate anomalies under future climates is the maritime continent where dry anomalies during extreme El Niño (and wet anomalies during La Niña) are projected to become more severe. These findings call for further investigation into the potential future changes in extreme El Niño teleconnections worldwide.

2) What is the contribution of extreme El Niño events frequency and teleconnection patterns changes to the overall ENSO teleconnection pattern ?

This question remains open and requires further investigation. The stronger teleconnection pattern changes I found were for the extreme ENSO than for other ENSO categories, and the future increase of the extreme ENSO frequency however suggest that extreme ENSO may contribute non-negligibly to future changes in ENSO teleconnections.

V.6 Perspectives

In addition to the methodological and further analyses suggested in the continuity of Chapter V, several others avenues for future work are provided here :

- **Mechanisms behind the shift from PNA to TNH-like patterns** : Chapter III demonstrates that ENSO teleconnections only shift from a PNA-like toward a TNH-like pattern during Extreme El Niño events. While the contribution of the SST patterns and atmospheric nonlinearities to this shift were identified, the mechanisms behind it remain unexplored. Dedicated sensitivity experiments, like those performed with intermediate complexity AGCM models, could help clarify this. For instance, the SPEEDY model (Kucharski et al., 2013) could be used to perform experiments modulating SST anomaly (SSTa) positions and amplitudes separately. Studies like Taschetto et al. (2015) used similar approaches with the NCAR-CAM3 atmospheric model. Additionally, forcing the model with different convective heating anomalies could shed light on nonlinearities in the atmospheric response to tropical diabatic heating. The Green's Function Model Intercomparison Project (Bloch-Johnson et al., 2024) (GFMIP) for instance proposes a common multi-model protocol for exploring the sensitivity of the atmospheric response to the SST pattern, by allowing to force AGCMs with patches of SST anomalies to systematically test sensitivity to position and intensity of idealized SST anomalies.
- **Influence of other modes of natural variability on ENSO teleconnections** : Another perspective is to consider the influence of other modes of natural variability on modulating

ENSO teleconnections to North America. For instance, the Pacific Decadal Oscillation has been shown to modulate ENSO's influence on North America. For example, [Maher et al. \(2022\)](#); [Dong et al. \(2018\)](#) found that the PDO affects El Niño's impact over Alaska and California, while [Dong et al. \(2021\)](#) noted similar modulations by the InterDecadal Pacific Oscillation. Additionally, the MJO-ENSO relationship has also been shown to modulate the Northern Hemisphere ENSO teleconnections ([Hoell et al., 2014](#)). It is currently not clear if this "modulation" of the ENSO teleconnection is symptomatic of a real change in the teleconnection pattern, in response to nonlinear interactions between two climate modes, or if it simply translates sampling errors associated with the aliasing of the ENSO signal by that of another mode of variability. To my knowledge, no study has explored the potential modulation of extreme El Niño teleconnections by the MJO or the PDO under this perspective. The large databases I used in chapters 3 and 4 are invaluable tools to investigate those potential ENSO teleconnection interactions, particularly under future warming scenarios.

- Changes in ENSO regional impacts :** Aside from North America, the preliminary analysis in chapter V suggests that other regions may be affected by changes in ENSO teleconnections in the future, including a more consistent influence of ENSO over the North Atlantic, Europe and North Africa. A more thorough investigation into these regions is needed. For example, [King et al. \(2020\)](#) show that Extreme El Niño, as opposed to Strong El Niño events (both ENSO types selected on usual SST metrics), resulted in opposite hydro-climate response over the European region, while ([Zhou et al., 2020b](#)) show that the impact of Extreme El Niño on Eurasian surface temperature can persist through spring due to a weaker stratospheric vortex, whereas this is not the case for Moderate El Niño. Overall, these studies suggest that the European climate response to ENSO is non-linear, with a significant contribution from extreme El Niño. I will investigate the regions and seasons for which there are future changes in the ENSO impacts more systematically once the methodological caveats discussed at the end of Chapter V have been addressed.
- Contribution of extreme El Niño events to future ENSO teleconnection changes:** Another important perspective of this work is to assess how extreme El Niño events contribute to future ENSO teleconnection changes. The projected increase in extreme El Niño frequency and their large-amplitude teleconnection changes (relative to other ENSO categories) implies that they could contribute non-negligibly to future changes in the overall ENSO teleconnection. It would be interesting to quantify whether the increase in the frequency of extreme El Niño has an impact on the tropical precipitation or extratropical mean state, or results in changes in the occurrence of extremes weather events, as suggested by the recent study of [Lieber et al. \(2024\)](#), who demonstrated a strengthening of extreme rainfall events in relation with ENSO teleconnections.

- **Contribution of extreme El Niño events to stronger future heat waves?** Chapter V reveals a weakening of the warm anomalies over the North east America during Extreme El Niño. However, this anomalous warming during extreme ENSO events will combine with the mean climate change to produce higher absolute temperatures. This effect is further amplified at high latitude, as polar regions such as the Arctic experience the fastest warming rate (Rantanen et al., 2022; IPCC AR6-WG1, 2021). Therefore, it would be interesting to examine how the effects of Extreme El Niño superimposed to the climate change signal affects extremes events such as heat waves over the North America.
- **What implications for North American seasonal forecasts ?** Chapter IV highlights a quite systematic anomalous warming over Northeast America, along with wet anomalies over California and Florida during the peak of extreme El Niño events. Warnings can therefore be issued as soon as an extreme El Niño can reliably be predicted. This raises an important question regarding the capability of seasonal forecast systems to accurately simulate extreme El Niño events and their associated impacts. This is especially relevant given that current forecast systems have been shown to underestimate ENSO teleconnections over the North Pacific-North America region (Williams et al., 2023). In evaluating the ability of forecast models to capture extreme El Niño events, it is crucial to address the factors limiting the predictability of their genesis. For instance, Puy et al. (2017) suggest that the peak amplitude of extreme El Niño is strongly constrained by unpredictable synoptic atmospheric variability until late summer, but becomes more predictable after august. Analyzing ensemble forecasts from systems such as the North American Multi-Model Ensemble (NMME) multi-model seasonal forecast database (Barnston et al., 2017) could provide insight into whether reliable warnings of extreme El Niño impacts can be issued from early September onward. This would also allow for an assessment of the potential skill improvement in predicting the effects of extreme El Niño on North American winter climate.
- **A methodological venue for investigating future IOD-ENSO teleconnections ?** Finally, our results about the specificity of extreme El Niño teleconnection patterns opens avenues for determining teleconnections of other climate modes more reliably. Several other climate modes such as the IOD (the main mode of climate variability intrinsic to the Indian Ocean) are not completely independent from ENSO, so that the ENSO signal has to be removed prior to computing their intrinsic teleconnections. The present thesis implies that doing so properly involves separately considering signal associated with extreme El Niño events. More generally, the use of the large ensemble databases considered in the present PhD would further allow to reduce the effect of sampling and model error on the teleconnection estimate. It would allow a better assessment of how state-of-the-art AMIP6/CMIP6 models represent IOD teleconnections and how these teleconnections are

projected to change in a warmer climate. While I will not personally pursue this line of inquiry, future studies are expected to address this important topic.

Conclusion générale (FR)

L'objectif principal de cette thèse doctorale était d'examiner la diversité des téléconnexions atmosphériques hivernales d'ENSO sur l'Amérique du Nord, en se concentrant spécifiquement sur la contribution des événements El Niño extrêmes à la diversité actuelle et future des téléconnexions. Les résultats de cette thèse s'appuient sur des analyses de simulations atmosphériques seules et couplées océan-atmosphère issues des bases de données AMIP6 et CMIP6, des ensembles de données d'observation, ainsi que sur des expériences de sensibilité dédiées réalisées par [Srinivas et al. \(2024\)](#) avec la version AMIP du modèle CNRM-CM6.1. Ci-dessous, je revisite les questions scientifiques abordées dans cette thèse, résume les résultats clés et présente des pistes potentielles pour des investigations futures.

V.7 Conclusions

Chapter [III](#) : Quels sont les moteurs et mécanismes de la diversité des téléconnexions d'ENSO en hiver boréal sur l'Amérique du Nord ?

1) Des études précédentes ont suggéré qu'un pattern de téléconnexion décalé vers l'est (de type TNH) se produit soit pour El Niño par rapport à La Niña, soit pour les événements El Niño EP vs CP, ou plus spécifiquement pour les événements EP générant des anomalies convectives dans le Pacifique central. Ici, je teste l'hypothèse nulle que ce pattern décalé vers l'est se manifeste **uniquement** pour les événements El Niño extrêmes (1982-83, 1997-98, 2015-16), c'est-à-dire **une sous-catégorie des types mentionnés**. Je commence mon investigation en examinant la diversité des téléconnexions d'ENSO sur l'Amérique du Nord durant l'hiver boréal (période DJF) à partir des observations (1979-2019) et d'un ensemble AMIP de 16 membres du modèle AGCM CNRM-CM6.1 (6 membres de ([Srinivas et al., 2024](#)) couvrant la période 1979-2019, 10 membres de l'AMIP6 ([Voldoire et al., 2019](#)) couvrant la période 1979-2014). Je constate que les téléconnexions de La Niña sont associées à une phase négative du schéma Pacific North America (PNA), caractérisée par des anomalies de température froide à la surface sur l'ouest du Canada et l'Alaska. Les événements modérés d'El Niño du Pacifique central (CP) et du Pacifique oriental (EP) sont associés à une phase positive du schéma PNA et à des anomalies chaudes sur la même région. Enfin, je démontre que seuls les événements El Niño extrêmes, définis par des anomalies intenses de SST dans l'est de l'océan Pacifique équatorial entraînant d'importantes anomalies de précipitations, présentent des schémas de téléconnexions déplacés d'environ 30° vers l'est par rapport au schéma PNA. Ces schémas ressemblent au schéma Tropical North Hemisphere (TNH). Alors que la littérature précédente attribuait de tels schémas de téléconnexions décalés à l'asymétrie El Niño/La Niña ([Hoerling et al., 1997](#)) ou à la diversité d'ENSO (c'est-à-dire

les événements EP/CP, voir (Ashok et al., 2007)), je montre que seuls les événements El Niño extrêmes conduisent au schéma de téléconnexion TNH. En d'autres termes, il n'y a pas de différences significatives entre les téléconnexions des événements El Niño modérés et de La Niña, ni entre les téléconnexions modérées CP et EP d'El Niño dans la région Pacifique Nord-Amérique du Nord. Enfin, je démontre que seuls les événements El Niño extrêmes entraînent des anomalies de température de surface chaude sur le nord-est de l'Amérique. Alors que certaines études ont associé les événements El Niño centraux-orientaux convectifs (Johnson & Kosaka, 2016; Chiodi & Harrison, 2015) ou les événements EP (Larkin, 2005; Ashok et al., 2007) à des anomalies humides sur la Californie, mes résultats concordent avec ceux de (Jong et al., 2016; Hoell et al., 2016) en liant spécifiquement les anomalies humides sur la Californie aux événements El Niño extrêmes.

2) Quelles sont les contributions relative de la diversité des patterns de SST d'ENSO et des non-linéarités atmosphériques au décalage vers l'est du pattern de téléconnexions, soit le basculement du PNA vers le TNH ?

Pour répondre à cette question, j'ai utilisé les expériences de sensibilité réalisées par Srinivas et al. (2024) avec le modèle CNRM-CM6.1. Leur méthodologie comprend deux expériences d'ensemble AMIP de 6 membres, l'une forcée par les anomalies de SST observées et l'autre par leur image miroir (c'est-à-dire la climatologie moins les anomalies de SST). Une combinaison linéaire de ces deux ensembles permet de séparer les effets des non-linéarités atmosphériques tropicales (c'est-à-dire les non-linéarités dans la réponse des SST à la convection profonde) de l'effet de la diversité des SST d'ENSO (les différences dans la réponse linéaire aux schémas de SST des événements El Niño modérés contre extrêmes) sur le décalage des téléconnexions. Mon analyse révèle que durant les événements El Niño modérés CP ou EP, les anomalies de SST ne sont pas suffisamment grandes pour déclencher une réponse convective non linéaire dans le Pacifique oriental. En conséquence, le schéma PNA observé pendant ces événements est principalement une réponse atmosphérique linéaire au schéma de SST d'ENSO. En revanche, pendant les événements El Niño extrêmes, les grandes anomalies de SST du Pacifique oriental entraînent une réponse convective non linéaire substantielle, à peu près égale en magnitude à la réponse linéaire. En d'autres termes, seuls les El Niño extrêmes sont associés à des non-linéarités convectives atmosphériques substantielles, qui se combinent avec la réponse linéaire au schéma de SST décalé vers l'est pour induire une réorganisation à l'échelle du bassin des sources de chaleur tropicales, de grandes anomalies convectives dans le Pacifique équatorial oriental, et le schéma TNH décalé vers l'est.

3) Les impacts climatiques spécifiques des événements El Niño extrêmes sur l'Amérique du Nord sont-ils plus robustes et reproductibles que ceux des autres types d'ENSO ?

Enfin, en utilisant les 16 membres de l'ensemble du modèle CNRM-CM6.1 AMIP6, j'ai étudié la reproductibilité des anomalies saisonnières sur l'Amérique du Nord pendant les événements de La Niña, d'El Niño modéré et d'El Niño extrême. J'ai constaté que les impacts associés aux

événements El Niño extrêmes (c'est-à-dire le schéma de téléconnexion TNH) sont beaucoup plus reproductibles d'un événement à l'autre et entre les membres de l'ensemble que ceux associés aux événements El Niño modérés ou à La Niña. Par exemple, il y a une probabilité de 71% d'anomalies chaudes sur le Canada et le nord des États-Unis, et une probabilité de 74% d'anomalies humides le long de la côte ouest des États-Unis pendant les événements El Niño extrêmes. Aucun autre type d'événement d'ENSO n'est associé à une telle cohérence inter-réalisation. Cependant, les conclusions de ce chapitre sont quelque peu limitées par la contamination substantielle des estimations des téléconnexions d'ENSO par la variabilité interne extratropicale d'alias (Deser et al., 2017; Garfinkel et al., 2018) dans l'ensemble relativement petit (16 membres) que j'ai analysé, ainsi que par les biais potentiels dans le composant atmosphérique du CNRM-CM6.1. J'examinerai donc la robustesse de ces résultats dans les bases de données plus larges AMIP6 et CMIP6 au chapitre IV.

Chapitre IV : Robustesse des téléconnexions des événements El Niño extrêmes en Amérique du Nord dans les modèles AMIP6/CMIP6

textbf1) Le schéma de téléconnexion TNH spécifique aux El Niño extrêmes obtenu au chapitre III est-il robuste dans la base de données plus large d'AMIP6 ?

Dans ce chapitre, j'ai élargi l'analyse de la diversité des schémas de téléconnexion d'ENSO pour l'hiver boréal en utilisant un ensemble de données plus vaste : 135 membres d'ensemble provenant de 23 modèles AMIP6, couvrant la période 1979-2014. Cette période inclut deux événements El Niño extrêmes (1982/83 et 1997/98), ce qui donne un total de 270 réalisations d'El Niño extrêmes. Mon analyse confirme les résultats du chapitre 3 : les événements La Niña et les El Niño modérés induisent une réponse PNA, tandis que le schéma de téléconnexion TNH apparaît spécifiquement pour les événements El Niño extrêmes dans 22 des 23 modèles.

2) Les patterns de téléconnexion des événements El Niño extrêmes sont-ils également hautement reproductibles dans AMIP6 ? Cette plus grande reproductibilité découle-t-elle d'un signal plus fort et/ou d'une variabilité interne atmosphérique réduite ?

Le grand nombre de réalisations dans l'ensemble AMIP6 a également permis une évaluation plus robuste de la reproductibilité des impacts des El Niño extrêmes sur l'Amérique du Nord. Mon analyse de l'ensemble multi-modèles AMIP6 montre des anomalies saisonnières Z500 très diverses pendant les événements La Niña et El Niño modéré, mais des cartes d'anomalies beaucoup plus robustes d'un événement à l'autre et entre les membres de l'ensemble pendant les événements El Niño extrêmes. En conséquence, le réchauffement du nord-est de l'Amérique et les anomalies humides sur la Californie et la Floride sont plus reproductibles (69 %, 77 % et 96 % de probabilités, respectivement) pendant les événements El Niño extrêmes. Cette reproductibilité accrue provient principalement d'un signal d'ENSO plus fort pendant les événements El Niño

extrêmes.

3) Comment le biais de la langue froide des SST, inhérent à la plupart des modèles CMIP6, affecte-t-il leur capacité à reproduire le schéma de téléconnexion des El Niño extrêmes et les impacts associés ?

Après avoir examiné les téléconnexions des El Niño extrêmes dans les simulations AMIP6, je me suis tourné vers les modèles couplés CMIP6 pour évaluer comment ils reproduisent les téléconnexions et les impacts des El Niño extrêmes dans le climat actuel, en utilisant la moyenne de l'ensemble multi-modèles AMIP6 comme référence. Cette étape est cruciale avant d'examiner les téléconnexions des El Niño extrêmes dans les climats futurs. Les modèles CMIP6 sont connus pour présenter de grands biais de SST, en particulier un biais de refroidissement dans le Pacifique équatorial, souvent appelé le "biais de langue froide" ([Planton et al., 2021](#)). Ce biais dégrade leur climat simulé par rapport à celui des simulations AMIP, affectant diverses propriétés d'ENSO, y compris la diversité des téléconnexions, comme souligné dans CMIP5 par [Bayr et al. \(2017\)](#). Pour cette analyse, j'ai considéré le premier membre historique disponible parmi 42 modèles CMIP6 pour la période 1850-2014. J'ai précédemment démontré que les grandes anomalies de précipitations dans le Pacifique oriental pendant les événements El Niño extrêmes jouent un rôle crucial dans l'établissement de leur schéma de téléconnexion TNH spécifique. Suivant [Cai et al. \(2014\)](#); [Lengaigne and Vecchi \(2009\)](#), je définis donc les événements El Niño extrêmes comme ceux avec de grandes anomalies de précipitations dans le Pacifique équatorial oriental (anomalies Niño3 > 5 mm/jour). 16 des 42 modèles ne parviennent pas à produire des événements El Niño extrêmes, en partie en raison de leur grand biais de langue froide, conformément à ([Bayr et al., 2024](#)). Les 26 modèles CMIP6 restants sont capables de simuler au moins un événement El Niño extrême pendant la période historique. Parmi ceux-ci, 18 modèles ont reproduit avec succès le schéma TNH spécifique pendant les El Niño extrêmes, en accord avec la moyenne de l'ensemble AMIP6. Dans ces modèles, le schéma de téléconnexion TNH est apparu exclusivement pendant les événements El Niño extrêmes, comme dans AMIP6. De plus, j'ai comparé les impacts simulés par AMIP6 et CMIP6 en utilisant les données de 11 modèles ayant les deux simulations disponibles. J'ai constaté que les modèles CMIP6 tendent à sous-estimer les anomalies de précipitations sur la Californie et la Floride pendant les événements El Niño extrêmes, tandis qu'aucun biais significatif n'a été détecté pour les anomalies de température de surface et de précipitations hivernales associées aux El Niño modérés ou à La Niña.

Chapitre V : Téléconnexions des El Niño extrêmes dans un monde plus chaud

1) Comment les téléconnexions associées aux différentes catégories d'ENSO (La Niña, El Niño modéré, El Niño extrême) sont-elles projetées à évoluer sous les conditions climatiques futures ?

Dans ce chapitre, j'ai analysé les simulations historiques (1850-2014) et futures (2015-2100) de 17 modèles CMIP6 capables de produire des événements El Niño extrêmes. Cette base de données (4 SSP différentes avec jusqu'à 10 membres par modèle, soit un total de 296 membres, et environ 74 000 réalisations DJF) a été analysée en fonction du niveau moyen de réchauffement global (global warming level, GWL), comme recommandé par le rapport AR6 du GIEC. J'ai séparé les événements ENSO en catégories La Niña, El Niño modéré et El Niño extrême pour détecter comment leurs téléconnexions évoluent dans le futur. En accord avec (McGregor et al., 2022), j'ai constaté que les changements dans le schéma de téléconnexion sont proportionnels au degré de GWL : plus l'atmosphère se réchauffe, plus les changements sont prononcés. Pour les événements El Niño modéré et La Niña, j'ai observé de petits déplacements qui s'alignent avec la littérature existante. Ceux-ci incluent un déplacement vers l'est des schémas de téléconnexion sur l'Amérique du Nord, que j'interprète comme une transition d'un schéma de type PNA à un schéma plus proche de TNH. De plus, il y a un renforcement d'un schéma de téléconnexion de type NAO sur l'Atlantique Nord, avec une phase négative pour El Niño modéré et une phase positive pour La Niña, en accord avec par exemple (Johnson et al., 2022). Cependant, les changements les plus significatifs se produisent pour les événements El Niño extrêmes. Le déplacement vers l'est des schémas de téléconnexion de type TNH pour les El Niño extrêmes avec le réchauffement climatique est considérablement plus prononcé que pour les autres catégories d'ENSO. Cela conduit à un affaiblissement des impacts spécifiques des El Niño extrêmes sur le nord-est de l'Amérique, c'est-à-dire à des anomalies de chaleur plus faibles sur le nord-est de l'Amérique et à des anomalies de précipitations plus faibles en Californie et en Floride pendant les événements El Niño extrêmes par rapport aux conditions actuelles. De même, les anomalies sèches sur le nord-est du Brésil pendant les événements El Niño extrêmes deviendront plus faibles sous les climats futurs (aucun changement significatif pour La Niña et El Niño modéré). Les seules régions où nous avons trouvé des anomalies climatiques accrues sous les climats futurs sont le continent maritime, où les anomalies sèches pendant les El Niño extrêmes (et les anomalies humides pendant La Niña) devraient devenir plus sévères. Ces résultats appellent à une enquête plus approfondie sur les changements futurs potentiels des téléconnexions des El Niño extrêmes à l'échelle mondiale.

2) Quelle est la contribution des événements El Niño extrêmes en termes de fréquence et de changements de schémas de téléconnexion au schéma global des téléconnexions de l'ENSO ?

Cette question reste ouverte et nécessite des recherches supplémentaires. Les changements de schémas de téléconnexion plus prononcés que j'ai observés pour les événements ENSO extrêmes par rapport aux autres catégories d'ENSO, ainsi que l'augmentation future de la fréquence des ENSO extrêmes, suggèrent toutefois que les ENSO extrêmes pourraient contribuer de manière non négligeable aux changements futurs des téléconnexions d'ENSO.

V.8 Perspectives

Outre les analyses méthodologiques et complémentaires proposées dans la continuité du chapitre V, plusieurs autres pistes de travail futures sont proposées ici :

Mécanismes derrière la transition des régimes PNA vers des régimes similaires à TNH : Le chapitre III démontre que les téléconnexions de l'ENSO ne passent d'un régime similaire à PNA à un régime similaire à TNH que lors des événements El Niño extrêmes. Bien que la contribution des motifs de SST et des non-linéarités atmosphériques à cette transition ait été identifiée, les mécanismes sous-jacents restent inexplorés. Des expériences de sensibilité dédiées, comme celles réalisées avec des modèles AGCM de complexité intermédiaire, pourraient aider à clarifier ce point. Par exemple, le modèle SPEEDY (Kucharski et al., 2013) pourrait être utilisé pour réaliser des expériences modulant séparément les positions et les amplitudes des anomalies de SST (SSTa). Des études comme celle de Taschetto et al. (2015) ont utilisé des approches similaires avec le modèle atmosphérique NCAR-CAM3. De plus, forcer le modèle avec différentes anomalies de chauffage convectif pourrait apporter des éclaircissements sur les non-linéarités de la réponse atmosphérique au chauffage diabatique tropical. Le Green's Function Model Intercomparison Project (Bloch-Johnson et al., 2024) (GFMIP) propose par exemple un protocole multi-modèle commun pour explorer la sensibilité de la réponse atmosphérique au motif de SST, en permettant de forcer les AGCMs avec des patchs d'anomalies de SST afin de tester systématiquement la sensibilité à la position et à l'intensité des anomalies idéalisées de SST.

Influence d'autres modes de variabilité naturelle sur les téléconnexions de l'ENSO : Une autre perspective consiste à considérer l'influence d'autres modes de variabilité naturelle sur la modulation des téléconnexions de l'ENSO en Amérique du Nord. Par exemple, il a été démontré que l'Oscillation Décennale du Pacifique module l'influence de l'ENSO sur l'Amérique du Nord. Maher et al. (2022); Dong et al. (2018) ont montré que la PDO affecte l'impact d'El Niño sur l'Alaska et la Californie, tandis que Dong et al. (2021) a noté des modulations similaires par l'Oscillation Pacifique Inter-Décennale. De plus, la relation MJO-ENSO a également été démontrée comme modulant les téléconnexions de l'ENSO dans l'hémisphère Nord (Hoell et al., 2014). Il n'est actuellement pas clair si cette "modulation" des téléconnexions de l'ENSO est symptomatique d'un véritable changement dans le motif de téléconnexion, en réponse à des interactions non linéaires entre deux modes climatiques, ou si cela traduit simplement des

erreurs d'échantillonnage associées à l'aliasing du signal de l'ENSO par celui d'un autre mode de variabilité. À ma connaissance, aucune étude n'a exploré la modulation potentielle des téléconnexions d'El Niño extrême par la MJO ou la PDO sous cette perspective. Les grandes bases de données que j'ai utilisées dans les chapitres 3 et 4 sont des outils précieux pour étudier ces interactions potentielles de téléconnexions de l'ENSO, notamment dans le cadre de scénarios de réchauffement futur.

Changements dans les impacts régionaux d'ENSO : En dehors de l'Amérique du Nord, l'analyse préliminaire du chapitre V suggère que d'autres régions pourraient être affectées par des changements dans les téléconnexions d'ENSO à l'avenir, notamment une influence plus marquée d'ENSO sur l'Atlantique Nord, l'Europe et l'Afrique du Nord. Une investigation plus approfondie de ces régions est nécessaire. Par exemple, [King et al. \(2020\)](#) montre que les événements El Niño extrêmes, contrairement aux événements El Niño forts (les deux types d'ENSO sélectionnés selon les métriques usuelles de SST), entraînent une réponse hydroclimatique opposée sur la région européenne, tandis que ([Zhou et al., 2020b](#)) démontre que l'impact d'El Niño extrême sur la température de surface en Eurasie peut persister jusqu'au printemps en raison d'un vortex stratosphérique affaibli, ce qui n'est pas le cas pour les événements El Niño modérés. Globalement, ces études suggèrent que la réponse climatique de l'Europe à l'ENSO est non linéaire, avec une contribution significative des événements El Niño extrêmes. J'examinerai de manière plus systématique les régions et saisons pour lesquelles il existe des changements futurs dans les impacts d'ENSO, une fois que les limites méthodologiques discutées à la fin du chapitre V auront été résolues.

Contribution des événements El Niño extrêmes aux futurs changements des téléconnexions de l'ENSO : Une autre perspective importante de ce travail est d'évaluer comment les événements El Niño extrêmes contribuent aux futurs changements des téléconnexions de l'ENSO. L'augmentation projetée de la fréquence des événements El Niño extrêmes et leurs changements de téléconnexions de grande amplitude (par rapport aux autres catégories d'ENSO) implique qu'ils pourraient contribuer de manière non négligeable aux futurs changements des téléconnexions globales d'ENSO. Il serait intéressant de quantifier si l'augmentation de la fréquence des événements El Niño extrêmes a un impact sur les précipitations tropicales ou l'état moyen extratropical, ou entraîne des changements dans la fréquence des événements météorologiques extrêmes, comme le suggère l'étude récente de [Lieber et al. \(2024\)](#), qui a démontré un renforcement des événements de précipitations extrêmes en lien avec les téléconnexions d'ENSO.

Contribution des événements El Niño extrêmes à des vagues de chaleur plus intenses à l'avenir ? Les résultats du chapitre V révèlent un affaiblissement des anomalies chaudes sur le nord-est de l'Amérique lors des événements El Niño extrêmes. Cependant, ce réchauffement anormal durant les événements ENSO extrêmes se combinera avec le changement climatique moyen pour produire des températures absolues plus élevées. Cet effet est encore amplifié à haute latitude, car les régions polaires, telles que l'Arctique, connaissent le taux de réchauffement le plus rapide

([Rantanen et al., 2022](#); [IPCC AR6-WG1, 2021](#)). Il serait donc intéressant d'examiner comment les effets des événements El Niño extrêmes, superposés au signal du changement climatique, influencent les événements extrêmes tels que les vagues de chaleur en Amérique du Nord.

Quelles implications pour les prévisions saisonnières en Amérique du Nord ? Le chapitre [IV](#) met en évidence un réchauffement anormal assez systématique sur le nord-est de l'Amérique, ainsi que des anomalies humides sur la Californie et la Floride lors du pic des événements El Niño extrêmes. Des avertissements peuvent donc être émis dès qu'un El Niño extrême peut être prédit de manière fiable. Cela soulève une question importante concernant la capacité des systèmes de prévision saisonnière à simuler avec précision les événements El Niño extrêmes et leurs impacts associés. Cela est particulièrement pertinent étant donné que les systèmes de prévision actuels sous-estiment les téléconnexions de l'ENSO sur la région Pacifique Nord-Amérique du Nord ([Williams et al., 2023](#)). Lors de l'évaluation de la capacité des modèles de prévision à capturer les événements El Niño extrêmes, il est crucial de prendre en compte les facteurs limitant la prévisibilité de leur genèse. Par exemple, ([Puy et al., 2017](#)) suggèrent que l'amplitude maximale des événements El Niño extrêmes est fortement contrainte par la variabilité atmosphérique synoptique imprévisible jusqu'à la fin de l'été, mais devient plus prévisible après le mois d'août. L'analyse des prévisions d'ensemble issues de systèmes comme la base de données de prévision saisonnière multi-modèle NMME ([Barnston et al., 2017](#)) pourrait fournir des informations sur la possibilité d'émettre des avertissements fiables concernant les impacts des événements El Niño extrêmes à partir du début septembre. Cela permettrait également d'évaluer l'amélioration potentielle de la compétence prédictive concernant les effets des El Niño extrêmes sur le climat hivernal nord-américain.

Une approche méthodologique pour explorer les téléconnexions futures IOD-ENSO ? Enfin, nos résultats sur la spécificité des schémas de téléconnexions des événements El Niño extrêmes ouvrent des perspectives pour déterminer de manière plus fiable les téléconnexions d'autres modes climatiques. Plusieurs autres modes climatiques, tels que l'IOD (le principal mode de variabilité climatique intrinsèque à l'océan Indien), ne sont pas complètement indépendants de l'ENSO, ce qui signifie que le signal de l'ENSO doit être retiré avant de calculer leurs téléconnexions intrinsèques. La présente thèse implique que pour le faire correctement, il est nécessaire de considérer séparément le signal associé aux événements El Niño extrêmes. Plus généralement, l'utilisation des grandes bases de données d'ensemble considérées dans cette thèse permettrait de réduire l'effet de l'échantillonnage et des erreurs de modèle sur l'estimation des téléconnexions. Cela permettrait une meilleure évaluation de la manière dont les modèles AMIP6/CMIP6 de pointe représentent les téléconnexions de l'IOD et de la façon dont ces téléconnexions sont projetées pour évoluer dans un climat plus chaud. Bien que je ne poursuivrai pas personnellement cette voie de recherche, des études futures devraient aborder ce sujet important.

Appendix A

Supplementary Information for Chapter **III**

Supplementary Information for:

A distinct and reproducible teleconnection pattern over North America during
extreme El Niño events

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Submitted to Scientific Reports

22 September 2023

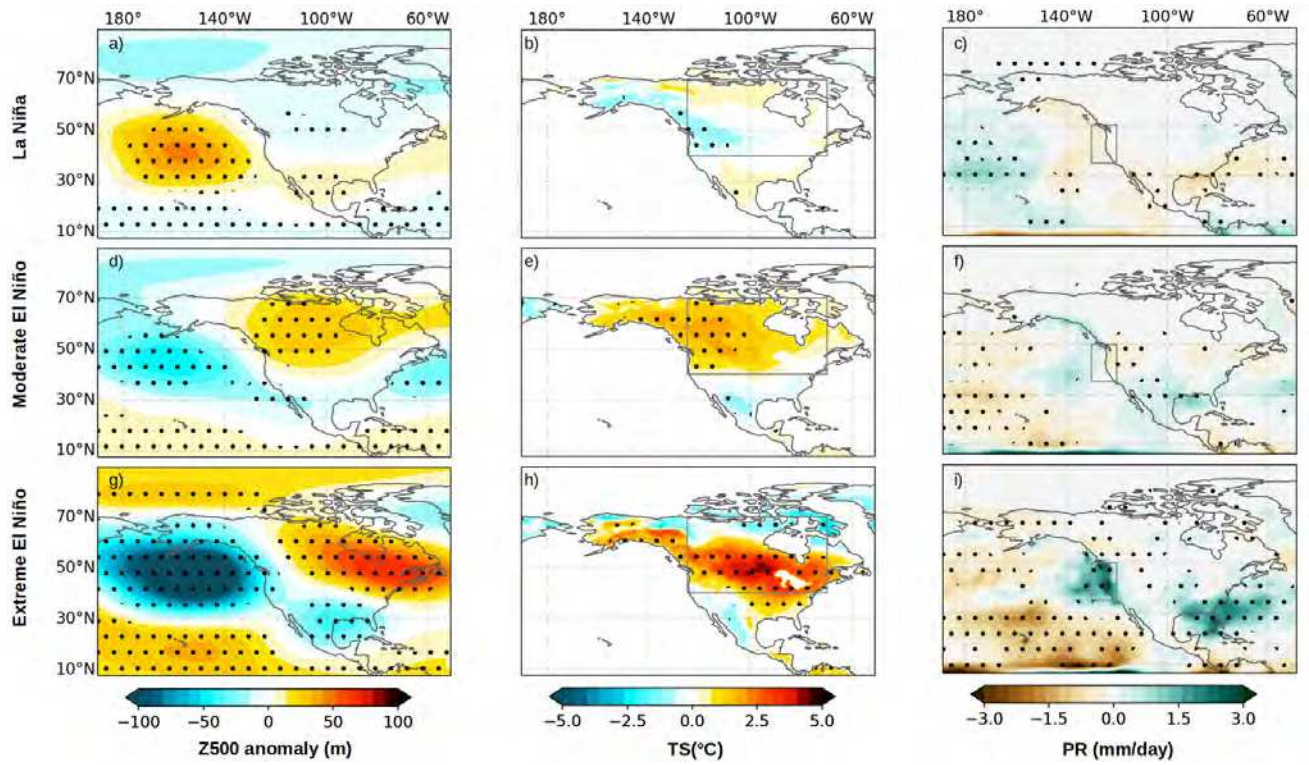
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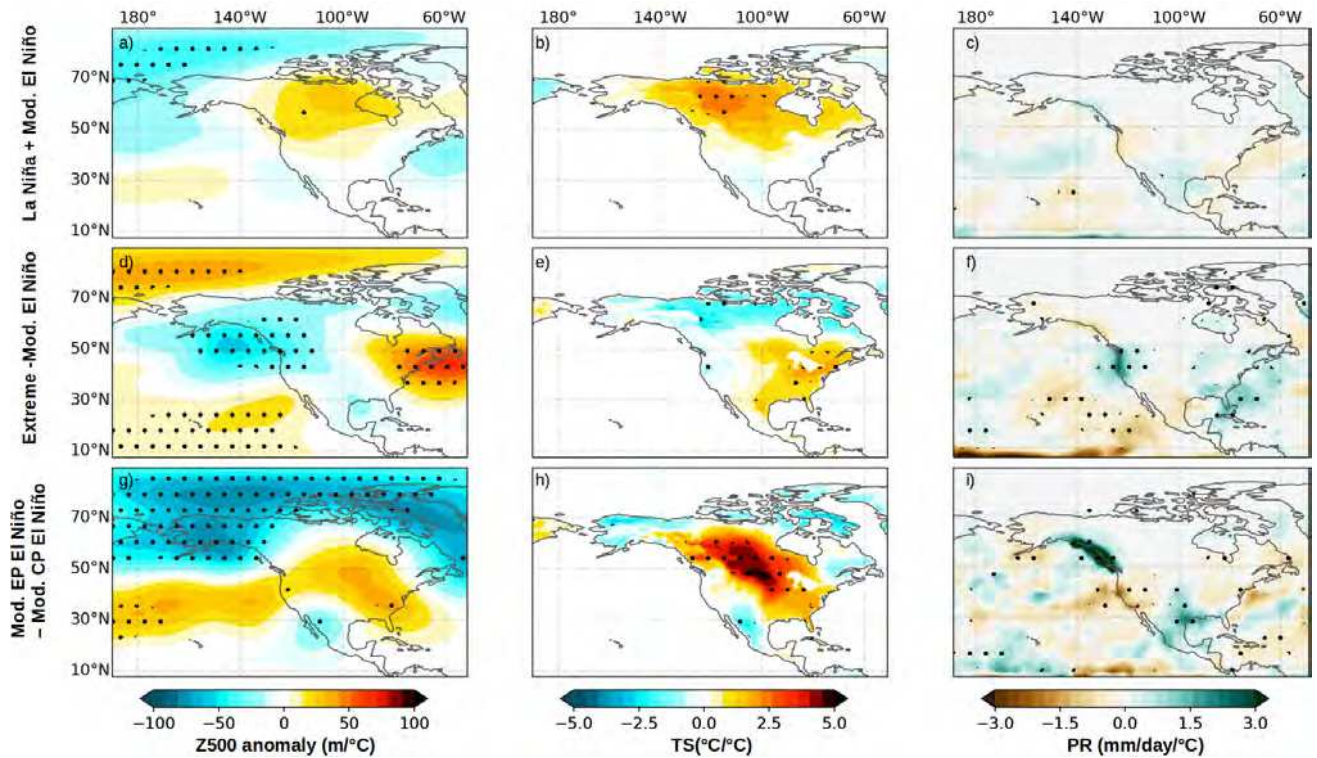
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This supplementary material contains six figures (S1 to S6) and their caption. Below each figure, a short text in *italics* summarizes the main take-home message from this figure and how it relates to the figures in the article.



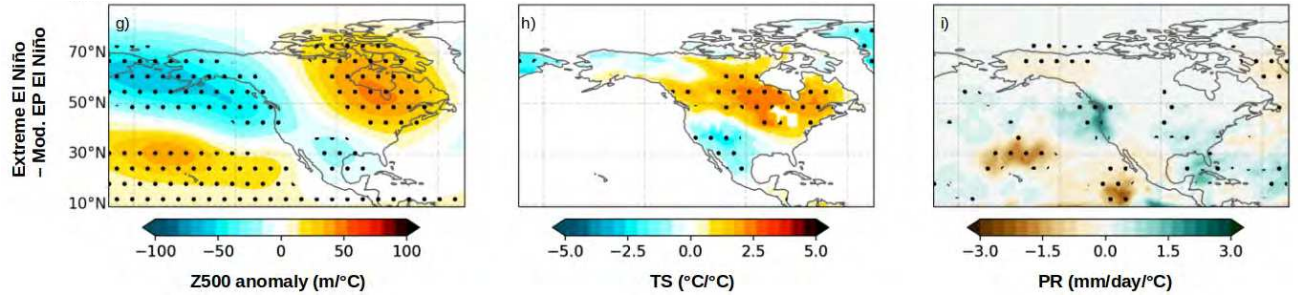
Supplementary Figure S1 : Composites of (left column) 500 hPa height (shaded, m), (middle column) land surface temperature (shaded, °C) and (right column) rainfall (shaded, mm/day) December-February (DJF) anomalies from ERA5 (left and center) and GPCP V2.3 (right) over the 1979-2019 period for (top row) La Niña, (middle row) moderate El Niño and (bottom row) Extreme El Niño events. The composites are not normalized. Dots indicate regions where anomalies exceed the 97.5% confidence level based on a bootstrap test with 1,000 resamples. Boxes in the middle column indicate the North-east America box (30-60°N, 100-60°W) used in Fig6c. Boxes in the right column indicate the Western United State box (35-50°N, 130-120°W) in Fig6b.

To compare with model (Fig2). We can note the good performance of the model to reproduce observed teleconnection for different variables. It should however be noted that the observed composites are less statistically significant, since they are not based on an ensemble average (16 members over 1979-2015 and 6 over 2015-2019) as for the model.



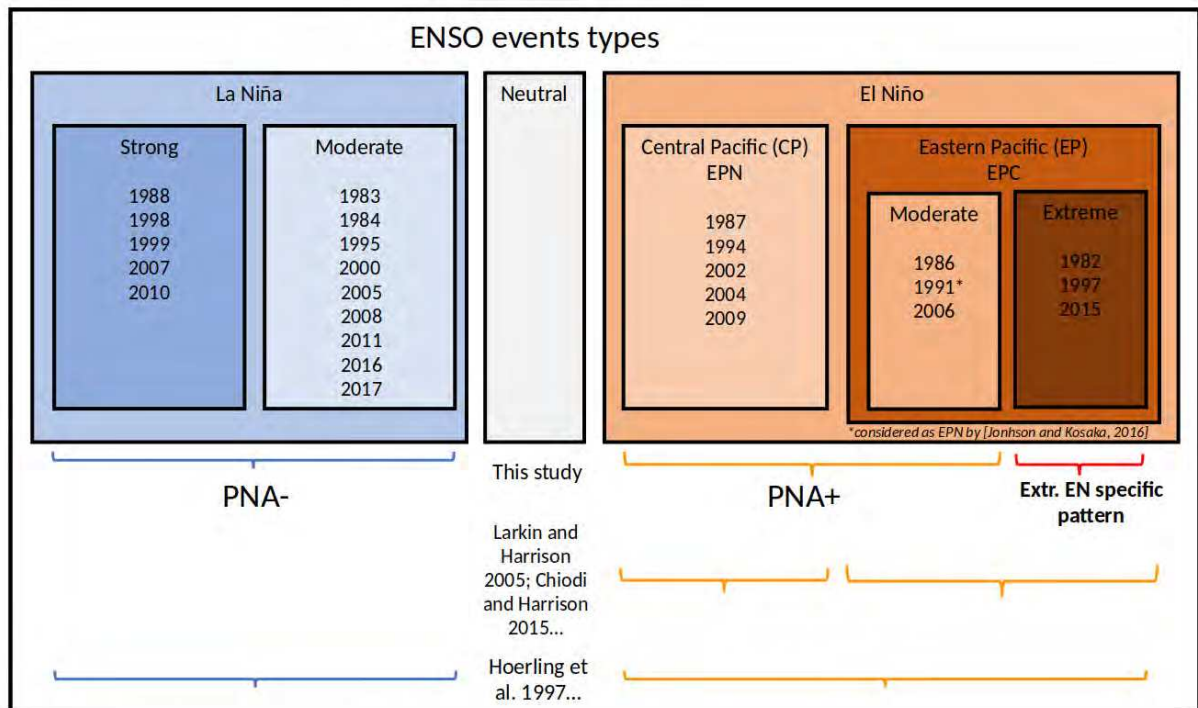
Supplementary Figure S2 : Composites sum/differences of (left column) 500 hPa height (shaded, m/°C), (middle column) land surface temperature (shaded, °C/°C) and (right column) rainfall (shaded, mm/day/°C) December-February (DJF) anomalies from ERA5 (left and center) and GPCP V2.3 (right) over the 1979-2019 period for (top row) La Niña plus El Niño, (middle row) Extreme minus Moderate El Niño and (bottom) Moderate Eastern Pacific minus Central Pacific. Each composite is obtained after normalizing by SST anomalies in the forcing region ([5°N/S, 170°E-130°W], see Methods) in order to emphasize pattern rather than amplitude differences. Dots indicate areas where anomalies exceed the 97.5% confidence level based on a bootstrap test with 1,000 resamples.

To compare with model (Fig3). Unlike the model, observations present noisier composites due to extratropical internal variability and the difference between composites that are displayed here are less statistically significant. The significant difference anomalies plotted in the Mod. EP El Niño minus Mod. CP El Niño are found to not be linked to ENSO-related activity, and year by year observed composites seems to display a strong NAO-related activity over North Atlantic, absent in the model. Despite those differences, there is generally a qualitative agreement between the model and observed composites.



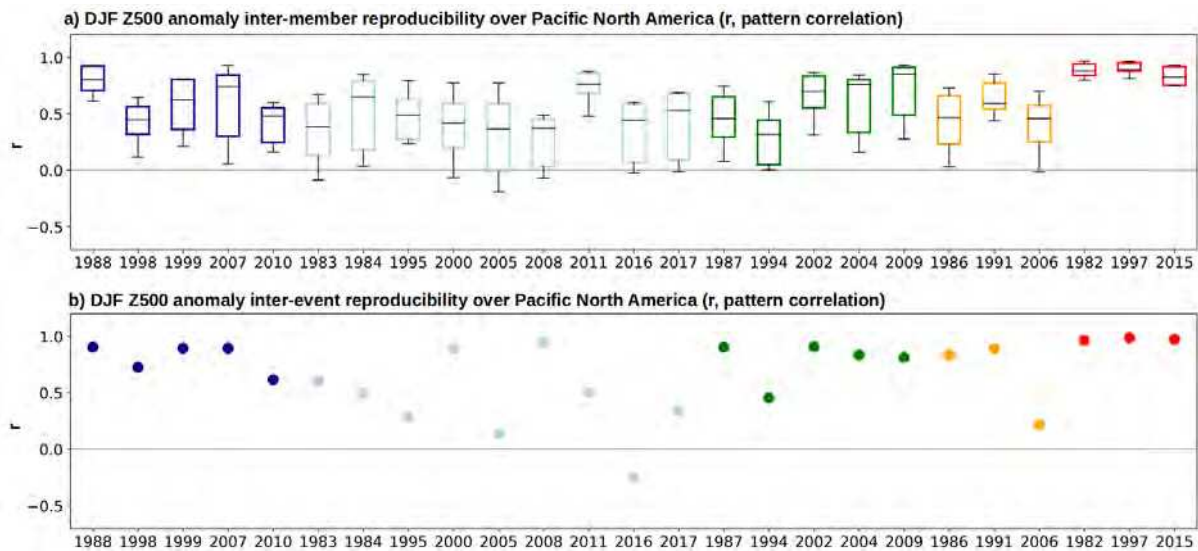
Supplementary Figure S3 : Composites sum/differences of (left column) 500 hPa height (shaded, m/°C), (middle column) land surface temperature (shaded, °C/°C) and (right column) rainfall (shaded, mm/day/°C) December-February (DJF) anomalies from the ensemble mean CTL experiment over the 1979-2019 period for Extreme minus Moderate Eastern Pacific El Niño. Each composite is obtained after normalizing by SST anomalies in the forcing region ([5°N/S, 170°E-130°W], see Methods) in order to emphasize pattern rather than amplitude differences. Dots indicate areas where anomalies exceed the 97.5% confidence level based on a bootstrap test with 10,000 resamples.

This figure complements Fig3, by showing Extreme EP minus Moderate EP composites (Figure 3 displays Extreme EP minus all moderate El Niño events). It demonstrates that the eastward shift of the SST pattern alone during moderate Eastern Pacific events is not sufficient to trigger distinct teleconnection patterns.



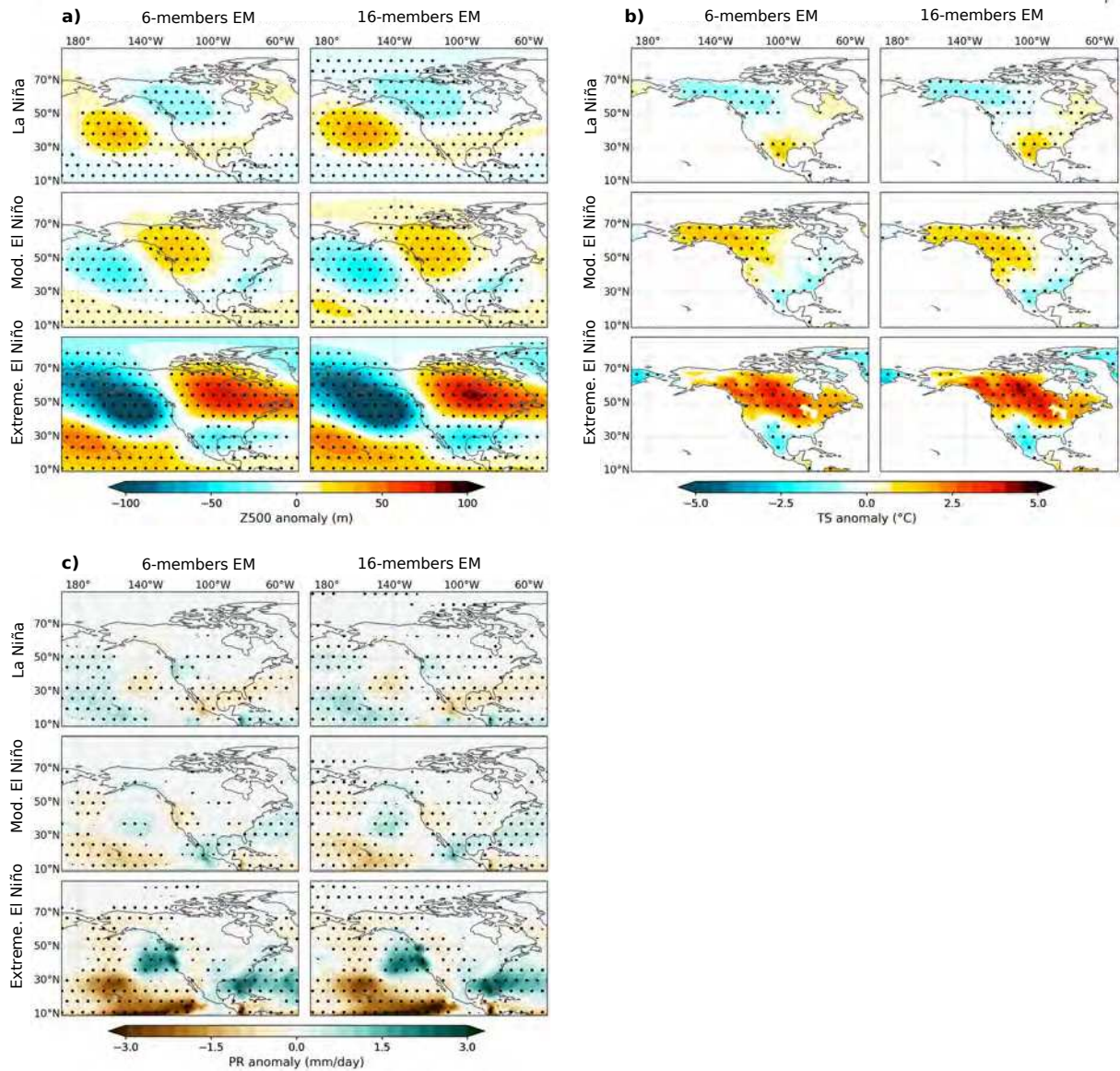
Supplementary Figure S4: List of ENSO events categories over the 1979-2019 period used in this paper (the year indicate the onset year, e.g. 1997 for 1997-98). See the methods section for the references of the method used to obtain each category: La Niña (strong and moderate La Niña categories are only distinguished on Fig 6), Neutral, and El Niño including: Central Pacific (CP) and Eastern Pacific (EP). The CP and EP categories respectively match the non-convective (EPN) and convective (EPC) categories used in [Jonhson and Kosaka, 2016], except for 1991 (considered as non-convective by [Jonhson and Kosaka, 2016] and EP here). We also distinguish extreme El Niño events, which are a subset of the EP events for the period we consider.

The bottom part of the sketch summarizes how differences in teleconnection patterns previously attributed to the ENSO phase (El Niño vs La Niña, e.g. Hoerling et al. 1997) or ENSO diversity (CP vs EP, e.g. Larkin and Harrison 2005, etc...) are in fact largely attributable to the specific extreme El Niño teleconnection pattern. Potential differences between EP and CP teleconnection patterns appear to be much weaker and not detectable from observations or our ensemble simulation dataset.



Supplementary Figure S5 : (a) Inter-member reproducibility of the DJF 500 hPa height pattern amongst ensemble members. Whisker boxes represent the distribution of pattern correlations between individual members and the corresponding ensemble mean for that year, over the 20-70°N, 180-60°W region. (b) Inter-event DJF 500 hPa pattern reproducibility. The circle represents the pattern correlation (20-70°N, 180-60°W region) between each event ensemble mean and the corresponding CTL ENSO composite. All values are normalized by the mean SST anomaly in region [5°N/S, 170°E-130°W], although the normalization method does not significantly affect the findings. The whiskers, box boundaries and middle marker respectively indicate the 10th and 90th percentiles, 25th and 75th percentiles and median. The distributions are based on 16-member ensembles except for 2015-2019 for which only 6 members are available (see Methods).

This figure complements figure 6a. Figure 6a indicates that the 500 hPa height anomalies over North America in any member is very similar to the extreme El Niño composite teleconnection pattern. The figure S4 illustrates that this strong reproducibility both results from a strong inter-member reproducibility during a given extreme El Niño (panel a) and from the similarity of the North American anomaly pattern during the three extreme El Niño which were considered (panel b).



Supplementary Figure S6 : Composites of (a) 500 hPa height (shaded, m), (b) land surface temperature (shaded, °C) and (c) rainfall (shaded, mm/day) December-February (DJF) anomalies from the ensemble-means 6-member ensemble CTL experiment (right) and extended 16-member ensemble experiment (left) over the 1979-2019 period for (top row) La Niña, (middle row) moderate El Niño and (bottom row) Extreme El Niño events. The composites are not normalized. Dots indicate regions where anomalies exceed the 97.5% confidence level based on a bootstrap test with 10,000 resamples.

This figure demonstrates that the composites of Figure 2 of the main text, obtained with 6 members, are robust when recomputed using 16 members (see Methods).

Appendix B

Supplementary Information for Chapter **IV**

Supporting Information for "How well do AMIP6 and CMIP6 reproduce the specific Extreme El Niño teleconnections to North America ?"

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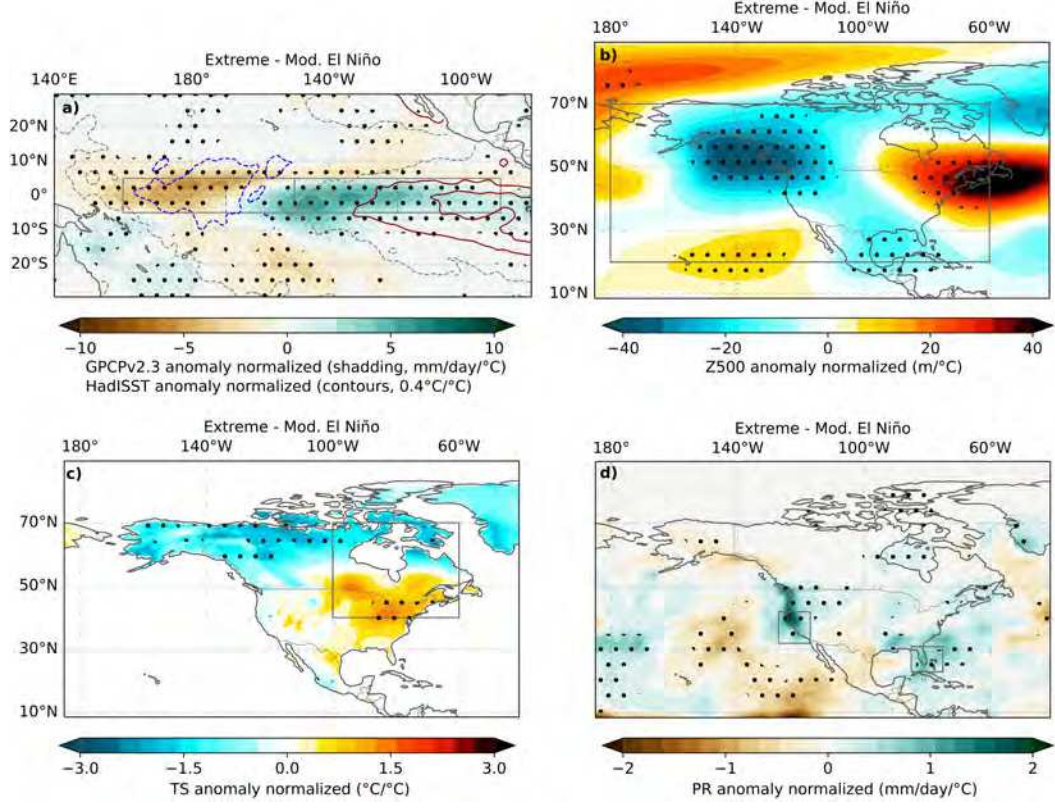


Figure S1: Extreme El Niño minus Moderate El Niño observed composites, for (a) GPCPv2.3 tropical rainfall (shaded, mm/day/°C) and HadISST anomalies (contours, 0.4°C/°C), North Pacific-North American (b) ERA5 500 hPa height (m/°C), (c) ERA5 land surface temperature (°C/°C) and (d) GPCPv2.3 rainfall anomalies (mm/day/°C). Each composite is obtained after normalizing by N3.4 mean SST anomaly. Dots indicate areas where anomalies exceed the 97.5% confidence level based on a bootstrap test with 1,000 resamples.

To be compared with Figure 2. Although noisier due to the very limited observed sampling size (two Extreme El Niño observed over 1979-2014), it appears their extratropical patterns are significantly eastward shifted compared to the height observed Moderate El Niño.

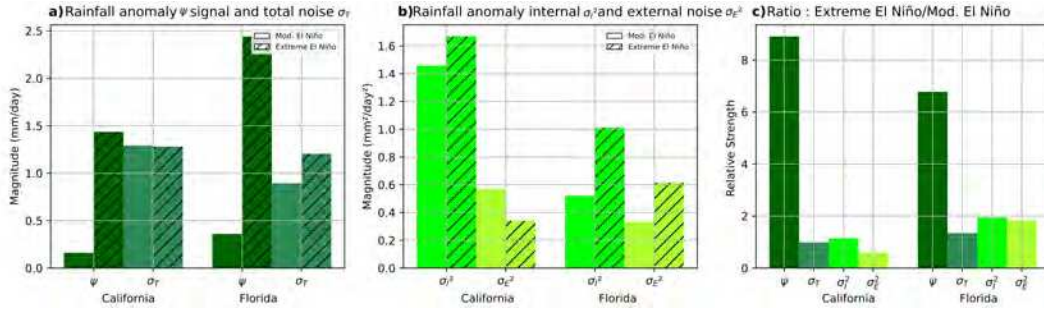


Figure S2: (a) AMIP MMEM Moderate El Niño (plain color) and Extreme El Niño (hatching) averaged in the California region (left, (32-42°N, 133-123°W)) and Florida region (right, (23-30°N, 85-75°W)) for DJF rainfall anomaly Ψ and total atmospheric noise, and (b) its decomposition into internal atmospheric variability (σ_I^2) and external inter-event SST-forced atmospheric variability (σ_E^2). (c) Ratio of Extreme El Niño over Moderate El Niño rainfall anomaly signal, total noise, internal noise and external noise for California and Florida.

This figures completes Figure 5 and is similar to Figure 4ef, but adapted to rainfall anomalies. It illustrates well that over California and Florida, the gain in reproducibility of Extreme El Niño signals, in comparison to Moderate El Niño signals, is well due to the strong Extreme Niño signals, rather than a reduced internal variability.

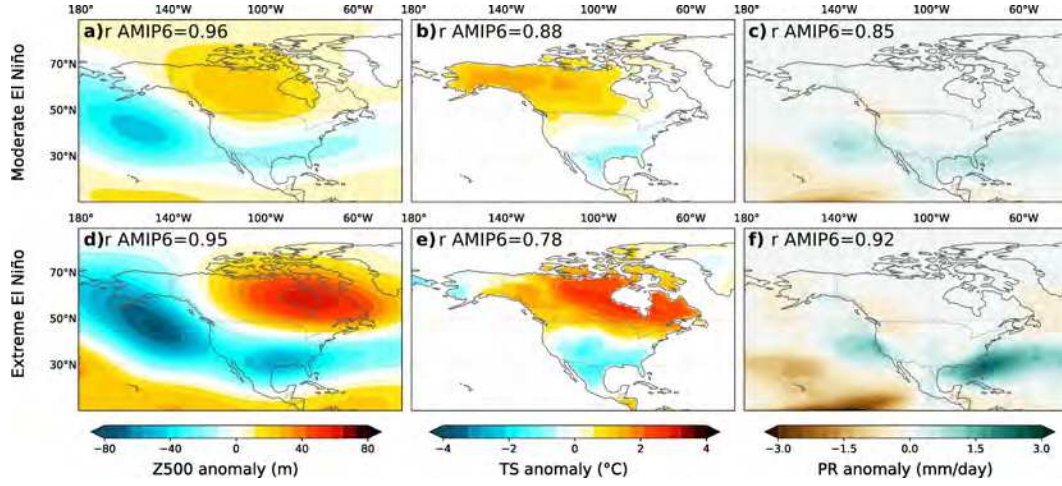


Figure S3: Multi Model Mean 500 hPa height anomaly composites, from the 11 CMIP6 models that pass the selection and possess an AMIP6 analog, of Mod. El Niño for (a) DJF GPH 500hPa anomaly (m), (b) land surface temperature anomaly ($^{\circ}\text{C}$) and rainfall anomaly (mm/day). (e,f,g) same as (a,b,c) but for Extreme El Niño. R AMIP6 indicates the pattern correlation over the entire plotted area with the composite and its corresponding AMIP6 MMEM from Figure 1.

This figures show that the Multi Model Mean from the subselection of the 11 CMIP6 that can perform Extreme El Niño and possess an AMIP6 analog closely resembles the 23 AMIP6 MMEM (to compares with main Figure 1) and the 26 CMIP6 MMM (from Figure 9).

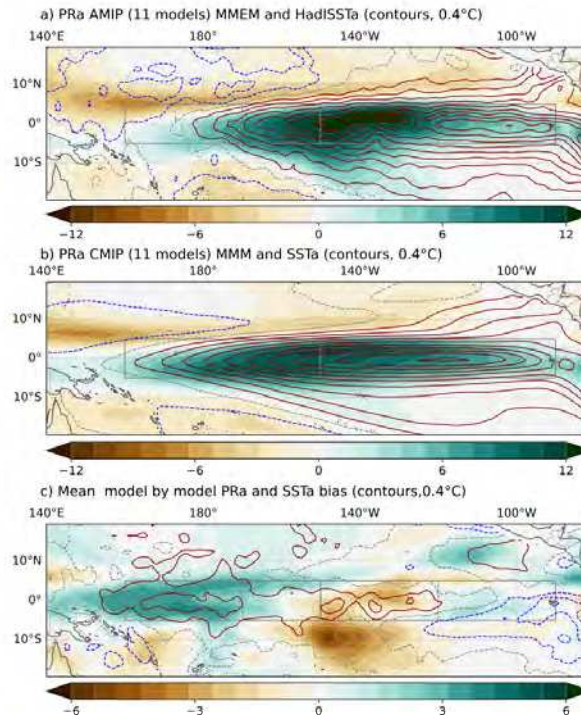


Figure S4: Extreme El Niño composites of (a) HadISST anomaly(contours, 0.4°C) and MMEM 11 AMIP PR anomaly (color), (b) 11 CMIP MMM SST anomaly and PR anomaly, (c) and the mean of the difference model by model CMIP-AMIP.

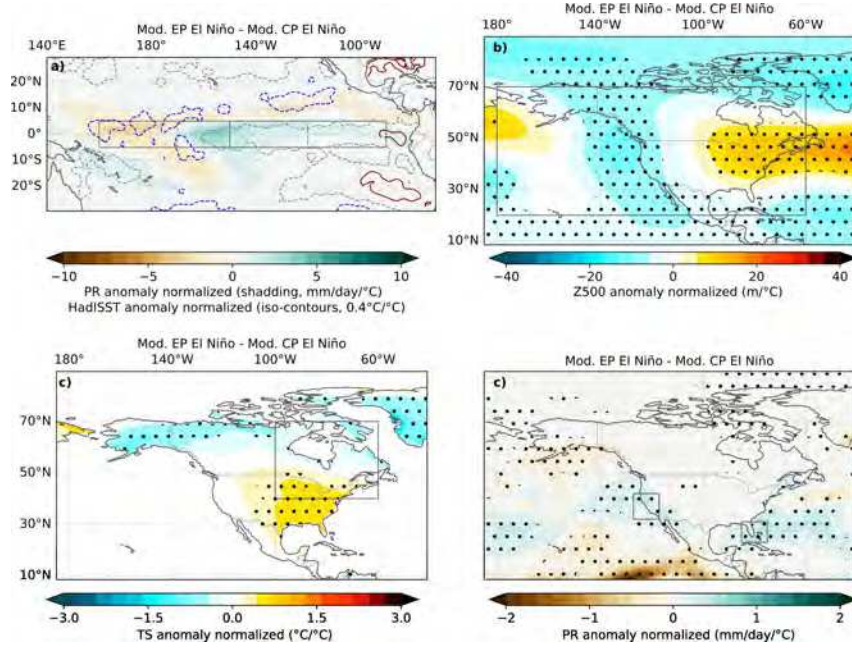


Figure S5: Moderate Eastern Pacific (EP) El Niño minus moderate Central Pacific (CP) El Niño AMIP6 MMEM winter (DJF) composites, for (a) tropical rainfall (shaded, mm/day/°C) and HadISST anomalies (contours, red for positive and blue for negative, 0.4°C/°C), and North Pacific-North American (b) 500 hPa height (m/°C), (c) land surface temperature (°C/°C) and (d) rainfall anomalies (mm/day/°C). Each composite is obtained after normalizing by the N3.4 SST anomaly. Dots indicate areas where anomalies are significantly different from zero at the 97.5% confidence level based on a bootstrap test with 10,000 resamples.

To compares with main Figure 2. Although the patterns of differences might be significant due to the large sampling we considered (675 AMIP6 realisations for Mod. CP El Niño, 405 for Mod. EP El Niño), the amplitude of the differences are of order half of those from the Extreme minus Mod. El Niño. This analysis does not indicate whether the normalised difference is significant with respect to the total composites and the very similar AMIP6 composites of Figure 1 indicates caution when discussing Mod. CP and EP El Niño teleconnection asymmetry in AMIP6.

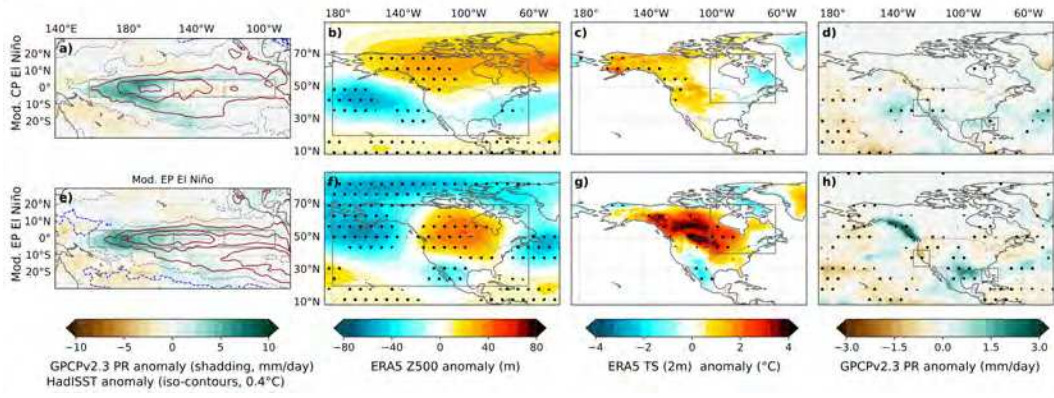


Figure S6: 1979-2014 observed winter (DJF) composites for (a-d) Mod. CP El Niño and (e-h) Mod. EP El Niño, for (left) GPCPv2.3 tropical Pacific rainfall (PR) anomaly (shading, mm/day) and HadISST anomaly (contours, 0.4°C, dotted contours for negative values), and ERA5 North Pacific-North American (middle left) 500hPa height (Z500) anomaly (m), (middle right) ERA5 land surface temperature (TS 2m) anomaly (°C) and (right) GPCP2.V3 rainfall (PR) anomaly (mm/day). The composites are not normalized. Dots indicate regions where anomalies are significantly different of zero at the 97.5% confidence level based on a bootstrap test with 1,000 resamples.

This figures is discussed in the Discussion, supports Supp Info Fig S5 and illustrates how a reduced sampling in observations might contributes to the debat of whether Mod. CP and Mod. EP El Niño have distinct teleconnection patterns, that is not represented in AMIP6.

Table S1: List of ENSO events used in the AMIP6 analysis over 1979-2014 (total realisations indicate the total number of ensemble-members available multiplied by the events).

<i>ENSO type</i>	DJF-event	Total realisations
La Niña	1983/84, 1984/85, 1988/89, 1995/96, 1998/99, 1999/2000, 2000/01, 2005/06, 2007/08, 2008/09, 2010/11, 2011/12	1620
Mod. CP El Niño	1987/88, 1994/95, 2002/03, 2004/05, 2009/10	675
Mod. EP El Niño	1986/87, 1991/92, 2006/07	405
Extreme El Niño	1982/83, 1997/98	270

Appendix C

Supplementary Information for Chapter V

Model	Historical	+1.5°C	+2°C	+2.5°C	+3°C	+3.5°C	+4°C	+4.5°C
ACCESS_CM2	1650	330	360	510	220	190	50	80
CESM2	495	120	150	95	80	60	40	5
CESM2_WACCM	495	110	80	85	80	45	30	15
CMCC_CM2_SR5	165	70	50	40	55	30	20	5
CNRM_CM6_1	990	400	335	240	180	60	80	30
CNRM_ESM2_1	1650	310	345	215	185	70	25	65
FGOALS_f3_L	165	50	75	40	35	10	5	10
GFDL_CM4	165	30	20	20	15	10	10	10
GISS_E2_1_G	1320	350	435	300	175	95	30	5
GISS_E2_1_H	825	250	280	225	195	100	75	5
HadGEM3_GC31_MM	660	40	40	30	30	20	-	40
MIROC6	1485	805	380	195	140	90	45	-
MIROC_ES2L	1650	740	300	290	200	145	25	25
MRI_ESM2_0	825	310	300	220	100	65	50	25
NorESM2_LM	495	80	55	20	15	-	-	-
NorESM2_MM	330	115	70	20	15	10	5	-
UKESM1_0_LL	1155	210	190	240	295	130	120	75
Total	14520	4910	4035	2865	2035	1130	630	395

Table C.1: Number of DJF realizations (total, climate, or anomalies) resampled by model, with bins representing historical (1850-2014) or resampled events from different levels of warming (extracted from 2015-2100 SSPs)

Model	Historical	+1.5°C	+2°C	+2.5°C	+3°C	+3.5°C	+4°C	+4.5°C
ACCESS_CM2	34	19	20	20	19	16	5	10
CESM2	16	9	17	10	10	12	5	0
CESM2_WACCM	12	7	12	10	9	5	3	2
CMCC_CM2_SR5	2	4	2	0	2	2	0	0
CNRM_CM6_1	5	5	5	4	5	4	3	2
CNRM_ESM2_1	10	5	10	9	12	3	0	4
FGOALS_f3_L	18	10	17	5	8	4	0	2
GFDL_CM4	1	1	0	1	0	0	1	-
GISS_E2_1_G	188	69	98	66	41	17	4	1
GISS_E2_1_H	11	30	39	27	42	22	16	1
HadGEM3_GC31_MM	14	3	1	1	4	1	-	3
MIROC6	26	40	24	17	7	9	5	-
MIROC_ES2L	68	86	42	34	30	18	4	1
MRI_ESM2_0	19	18	19	22	9	10	7	3
NorESM2_LM	14	5	3	1	0	-	-	-
NorESM2_MM	12	7	4	1	1	1	0	-
UKESM1_0_LL	7	1	5	4	3	2	5	0
Sum	457	388	379	273	222	127	53	29

Table C.2: As Table C.1 but for the number of Extreme El Niño events.

Model	Historical	+1.5°C	+2°C	+2.5°C	+3°C	+3.5°C	+4°C	+4.5°C
ACCESS_CM2	493	107	117	173	69	58	11	13
CESM2	121	38	36	25	22	14	6	2
CESM2_WACCM	130	28	19	20	32	16	6	4
CMCC_CM2_SR5	43	15	16	13	13	8	6	-
CNRM_CM6_1	316	134	111	83	60	16	28	10
CNRM_ESM2_1	420	87	82	54	53	25	9	18
FGOALS_f3_L	41	10	8	11	7	1	2	2
GFDL_CM4	43	9	8	9	4	4	2	2
GISS_E2_1_G	268	91	89	67	40	32	10	2
GISS_E2_1_H	187	58	71	51	32	21	14	-
HadGEM3_GC31_MM	186	10	11	13	9	5	-	11
MIROC6	294	190	88	42	30	17	11	-
MIROC_ES2L	334	174	59	58	37	26	5	9
MRI_ESM2_0	225	70	73	50	29	15	14	10
NorESM2_LM	146	27	19	6	8	-	-	-
NorESM2_MM	89	31	19	6	6	3	2	-
UKESM1_0_LL	292	61	59	68	87	42	30	21
Sum	3628	1240	936	814	546	318	180	119

Table C.3: As Table C.1 but for the number of Moderate El Niño events.

Model	Historical	+1.5°C	+2°C	+2.5°C	+3°C	+3.5°C	+4°C	+4.5°C
ACCESS_CM2	518	94	98	157	80	54	15	20
CESM2	167	43	51	27	22	17	9	1
CESM2_WACCM	175	36	30	34	26	16	10	7
CMCC_CM2_SR5	61	28	19	15	22	12	10	0
CNRM_CM6_1	329	130	114	81	53	19	23	11
CNRM_ESM2_1	540	108	125	74	65	24	7	25
FGOALS_f3_L	59	19	31	10	11	4	1	4
GFDL_CM4	52	12	6	5	5	3	6	-
GISS_E2_1_G	484	114	154	104	50	27	7	0
GISS_E2_1_H	314	105	122	94	80	46	32	4
HadGEM3_GC31_MM	216	17	13	10	8	4	-	15
MIROC6	557	342	169	93	67	43	23	-
MIROC_ES2L	662	335	135	139	97	70	13	8
MRI_ESM2_0	311	102	101	61	32	20	18	6
NorESM2_LM	149	29	18	9	3	-	-	-
NorESM2_MM	103	42	23	10	4	4	2	-
UKESM1_0_LL	413	68	54	60	83	41	26	23
Sum	5110	1684	1233	1057	768	420	227	128

Table C.4: As Table C.1 but for the number of La Niña events.

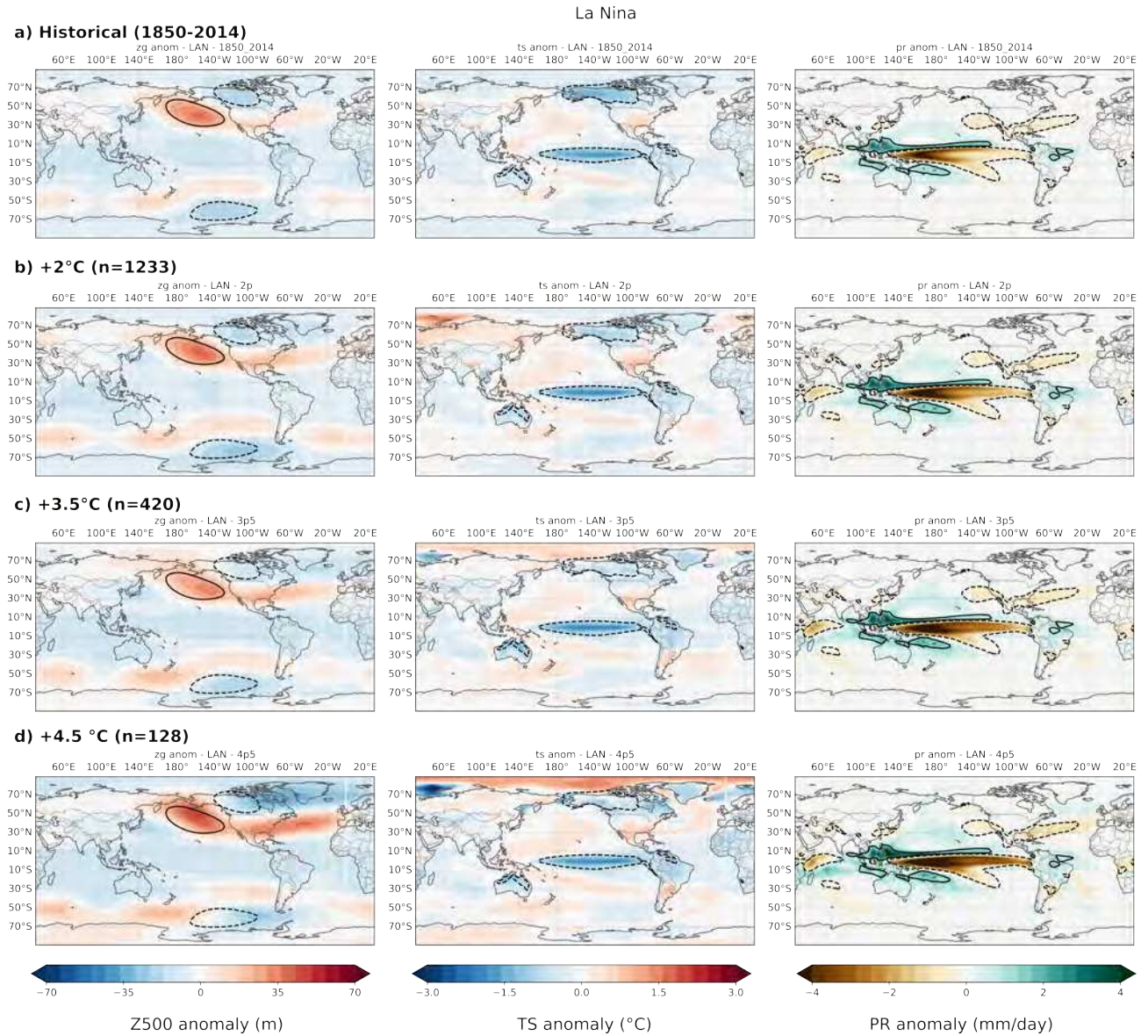


Figure C.1: Composites of DJF La Niña for the Z500 (left) TS (middle) and PR (right) anomalies for (a) historical climate and (b) 2°C, (c) +3.5°C and (d) +4.5°C GWL, n indicating the number of total composite realizations. Black contours indicate prominent corresponding historical signals for reference : -15/+20m (left column), -0.5°C (middle column) and -0.25/+1mm/day (left column).

La Nina

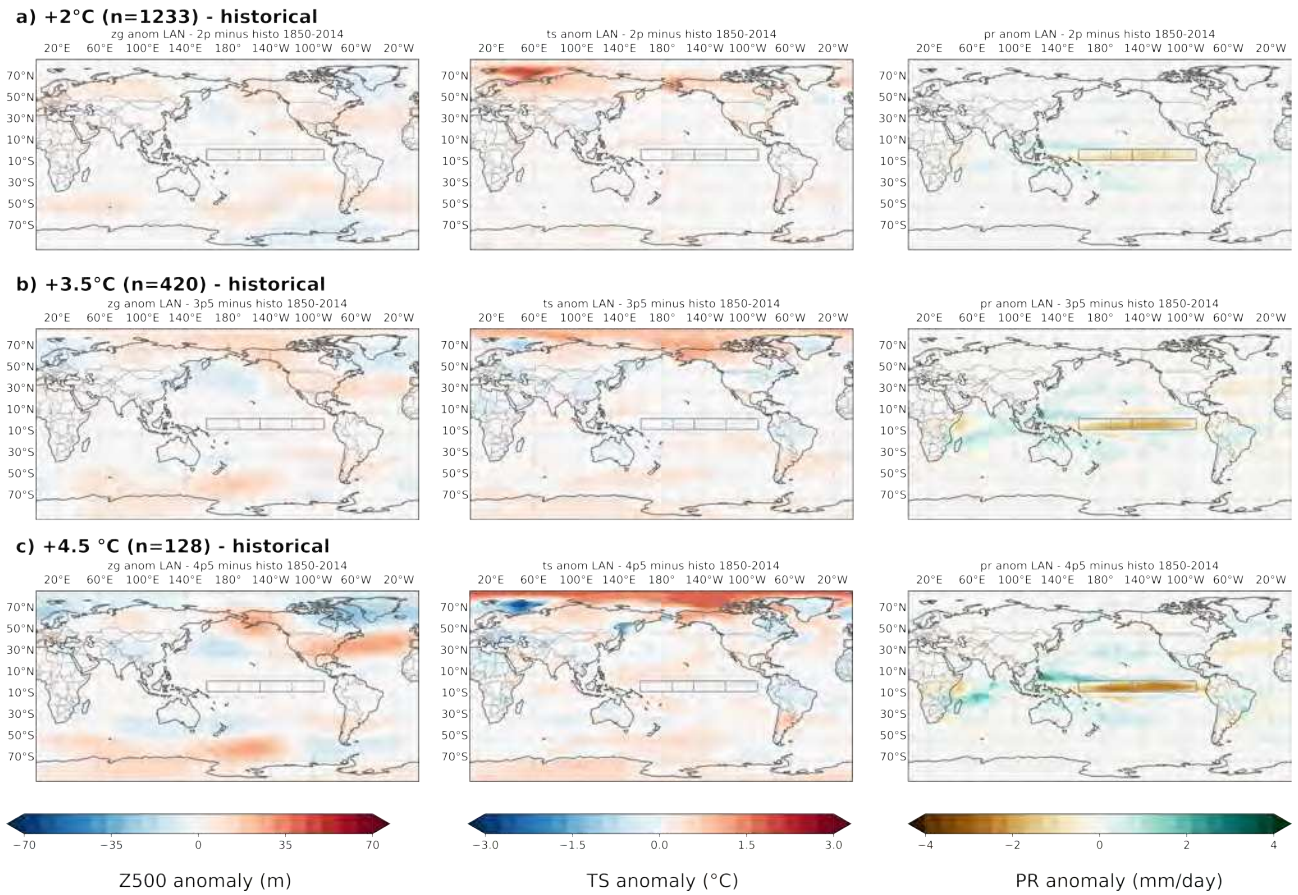


Figure C.2: Composites of changes in DJF La Niña Z500 (left) TS (middle) and PR (right) anomalies, for (a) +2°C minus historical, (b) +3°C minus historical (middle), and (c) +4.5°C minus historical MMM composites. Boxes indicate key regions Niño 3, Niño 3.4 and Niño 4.

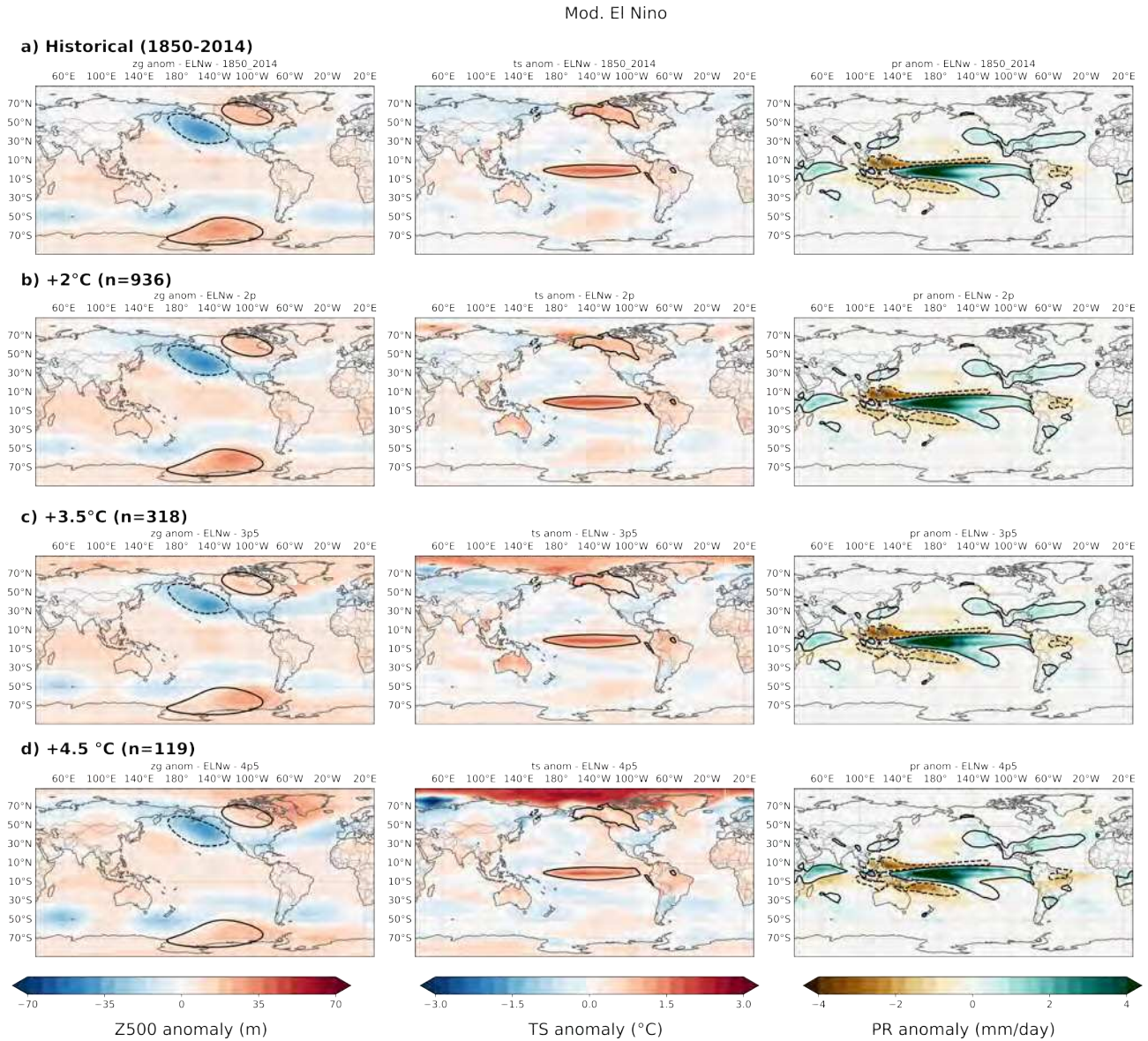


Figure C.3: Composites of DJF Moderate El Niño for the Z500 (left) TS (middle) and PR (right) anomalies for (a) historical climate, (b) +2°C, (c) +3.5°C and (d) +4.5°C GWL, n indicating the number of total composite realizations. Black contours indicate prominent corresponding historical signals for reference : -20/+15m (left column), +0.75°C (middle column) and -1/+0.25mm/day (left column).

Moderate El Niño

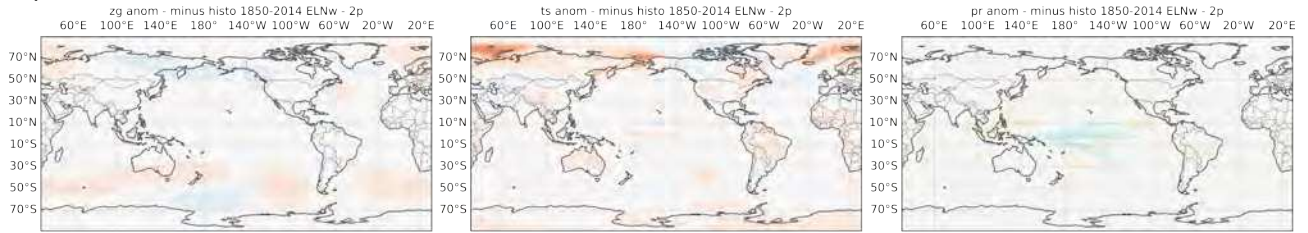
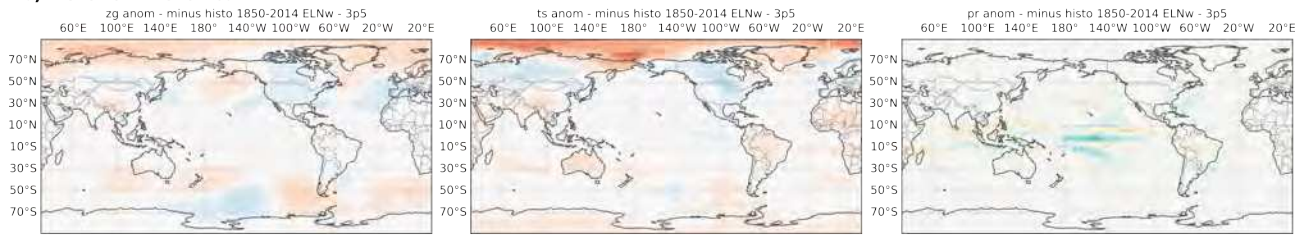
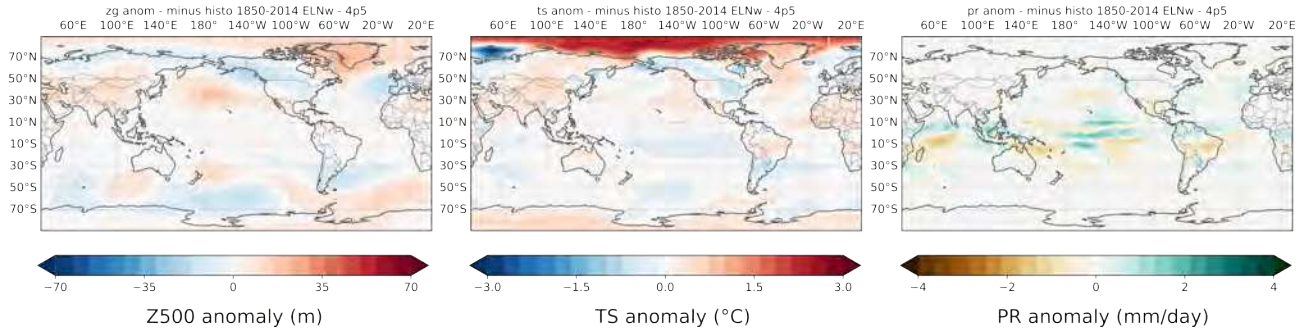
a) +2°C - historical**b) +3.5°C - historical****c) +4.5°C - historical**

Figure C.4: Composites of changes in DJF Moderate El Niño Z500 (left) TS (middle) and PR (right) anomalies, for (a) +2°C minus historical, (b) +3°C minus historical (middle), and (c) +4.5°C minus historical MMM composites. Boxes indicate key regions Niño 3, Niño 3.4 and Niño 4.

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Titre : Spécificité des téléconnexions atmosphériques des El Niño extrêmes dans les climats actuels et futurs

Mots clés : El Niño - Oscillation Australe(ENSO), téléconnexions atmosphériques, El Niño extrêmes, Climat nord Américain, Changement climatique, Variabilité interne atmosphérique

Résumé : ENSO (El Niño-Oscillation Australe) se développe grâce aux interactions océan-atmosphère du Pacifique tropical et constitue la principale source de variabilité climatique interannuelle. ENSO influence le climat saisonnier à l'échelle mondiale via ses téléconnexions atmosphériques, et représente une source majeure de prévisibilité climatique. La téléconnexion principale d'ENSO dans l'hémisphère nord est le pattern Pacific-North American (PNA). Il n'y a actuellement pas de consensus sur ce qui contrôle la diversité des téléconnexions d'ENSO. Certaines études soulignent des patterns différents pour El Niño et La Niña, alors que d'autres pointent la diversité d'ENSO (c.-à-d. la localisation des anomalies de SST: dans le Pacifique central -événement CP- ou dans le Pacifique est-événement EP), ou encore l'amplitude des anomalies (certains événements EP donnant lieu à des El Niño "extrêmes"). Notre connaissance des téléconnexions d'ENSO est en outre limitée par la variabilité interne de l'atmosphère. Enfin, des études récentes suggèrent une modification des téléconnexions d'ENSO en réponse au réchauffement climatique. Une meilleure compréhension de la diversité des téléconnexions d'ENSO dans le climat actuel et futur est cruciale pour exploiter pleinement le potentiel de prévisibilité offert par ENSO. Cette thèse examine les téléconnexions d'ENSO pendant l'hiver en Amérique du Nord. Comment le pattern de téléconnexion d'ENSO varie-t-il selon le type et l'amplitude des événements ENSO ? Certains types d'ENSO sont-ils associés à des téléconnexions plus reproductibles ? Les téléconnexions d'ENSO sont-elles fidèlement reproduites par les modèles climatiques ? Le changement futur du pattern de téléconnexion d'ENSO dépend-il du type d'ENSO ? Ces questions sont explorées à travers l'analyse de simulations de modèles climatiques AMIP6-CMIP6, avec un focus sur les téléconnexions des El Niño extrêmes. Je montre que les La Niña et El Niño modérés sont associés à un pattern de téléconnexion de type PNA, mais que seuls les El Niño extrêmes (1982-83, 1997-98 et 2015-16) affichent un pattern de téléconnexion décalé vers l'est dit "Tropical-North Hemisphere" (TNH). Ce pattern s'active en réponse aux fortes pluies dans le Pacifique équatorial est pendant El Niño extrême. Les non-linéarités atmosphériques associées au seuil de convection profonde atmosphérique jouent un rôle clé dans l'activation du TNH. Les El Niño extrêmes sont associés à des impacts hivernaux spécifiques et fortement reproductibles sur l'Amérique du Nord: réchauffement sur le nord-est de l'Amérique (~70% de chances), et anomalies humides sur la Californie (~80%) et la Floride (97%). Les impacts associés au PNA sont moins reproductibles en raison d'un rapport signal sur bruit défavorable que pour les forts signaux TNH lors des El Niño extrêmes. Ces résultats sont robustes dans 22 simulations d'ensemble de modèles AMIP6 (sur 23 examinés). 16 des 42 modèles couplés océan-atmosphère CMIP6 que j'ai examinés ne produisent pas d'El Niño extrêmes. Malgré une dégradation (i.e.sous-estimation des anomalies humides sur la Californie) par rapport à leur version atmosphère-seule, 18 des 26 modèles CMIP6 restants capturent raisonnablement les téléconnexions spécifiques associées aux El Niño extrêmes. Ces modèles indiquent un affaiblissement de la téléconnexion TNH au-dessus du Pacifique Nord et de l'Amérique ainsi que le développement d'une téléconnexion de type NAO au-dessus de l'Atlantique lors des événements El Niño extrêmes sous un réchauffement global moyen fort (> +3,5 °C). Ces changements sont qualitativement similaires, mais d'amplitude beaucoup plus importante que les changements de téléconnexion associés à La Niña et aux El Niño modérés. Les impacts typiques d'un El Niño extrême (nord-est de l'Amérique chaud, Californie et Floride humides, nord-est du Brésil sec) s'affaiblissent sous des climats plus chauds et deviennent moins distincts de ceux des événements El Niño modérés.

Title: Specificity of extreme El Niño atmospheric teleconnections in present and future climates

Key words: El Niño - Southern Oscillation (ENSO), atmospheric teleconnections, Extremes El Niño, North American climate, Climate Change, Atmospheric internal variability

Abstract: El Niño-Southern Oscillation (ENSO) originates from ocean-atmosphere interactions in the tropical Pacific. It is the main driver of interannual climate variability, and influences seasonal climate globally through atmospheric teleconnections. ENSO is therefore an important source of seasonal climate predictability. The dominant ENSO teleconnection is the Pacific-North American (PNA) pattern. While previous studies underline different teleconnection patterns between warm (El Niño) and cold (La Niña) ENSO phases, others argue that it is rather the ENSO "flavour" (i.e. whether ENSO anomalies peak in the eastern or central Pacific, CP or EP events) or amplitude (some EP events escalate into extreme warm anomalies) that determines its teleconnection pattern. The ENSO teleconnection pattern knowledge is in addition limited by its large aliasing by internal atmospheric variability. Finally, recent studies indicate that the ENSO teleconnection pattern changes in our warming world. A better understanding of how the ENSO teleconnection pattern changes depending on the type of ENSO, and in response to global change is needed to fully tap in the associated predictability potential. This PhD examines these questions for boreal winter teleconnections over North America. How does the ENSO teleconnection pattern depends on the ENSO event type and amplitude? Are some ENSO types associated with more reproducible teleconnection patterns? Are ENSO teleconnection patterns faithfully reproduced by climate models? Does the future ENSO teleconnection pattern change depend on the ENSO type? I examine these questions through the analysis of numerous climate model AMIP6-CMIP6 simulations, with a focus on extreme El Niño teleconnections. I show that La Niña, moderate CP El Niño and moderate EP El Niño events are all associated with a PNA teleconnection pattern. Only extreme El Niño events - such as in 1982-83, 1997-98 and 2015-16 - display different, eastward-shifted anomalies similar to the Tropical North Hemisphere (TNH) pattern, in response to large rainfall anomalies over the central/eastern equatorial Pacific. Atmospheric nonlinearities associated with the threshold for deep atmospheric tropical convection play a key role in this pattern formation. Extreme El Niño events yield highly reproducible impacts such as warm conditions over Northeast America (~70% chances), wet anomalies over California (~80%) and Florida (97%). Impacts associated with the PNA are less reproducible, due to a less favourable signal to noise ratio than that associated with stronger TNH-like signals during extreme El Niño events. Such findings are robust in 22 out of 23 atmospheric ensemble simulations from the AMIP6 database. 16 out of the 42 coupled ocean-atmosphere models (CMIP6 database) I examined do not produce extreme El Niño events. Despite a degradation (e.g. underestimation of wet anomalies for California and Florida) relative to their atmospheric-only counterpart, 18 out of the remaining 26 CMIP6 models capture the specific extreme El Niño TNH-like teleconnections. These models indicate a weakening of the TNH teleconnection over North Pacific and America and development of a NAO-like teleconnection over the Atlantic during extreme El Niño events under strong globally-averaged warming (> +3.5 °C). Those changes are qualitatively similar, but of much larger amplitudes than La Niña and moderate El Niño teleconnection changes under warmer climate discussed by previous studies. The extreme El Niño typical impacts (warm Northeast America, wet California and Florida, dry northeast Brazil) weaken under warmer climates, and become less distinct from those of moderate El Niño events.