UNIVERSITY of HAWAIʻI MĀNOA

Relationships between atmospheric blocking and large-scale modes of climate variability: the key role of the tropical Pacific

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Acknowledgments: M. McKenna[PhD], V. Narinesingh, U. Lall

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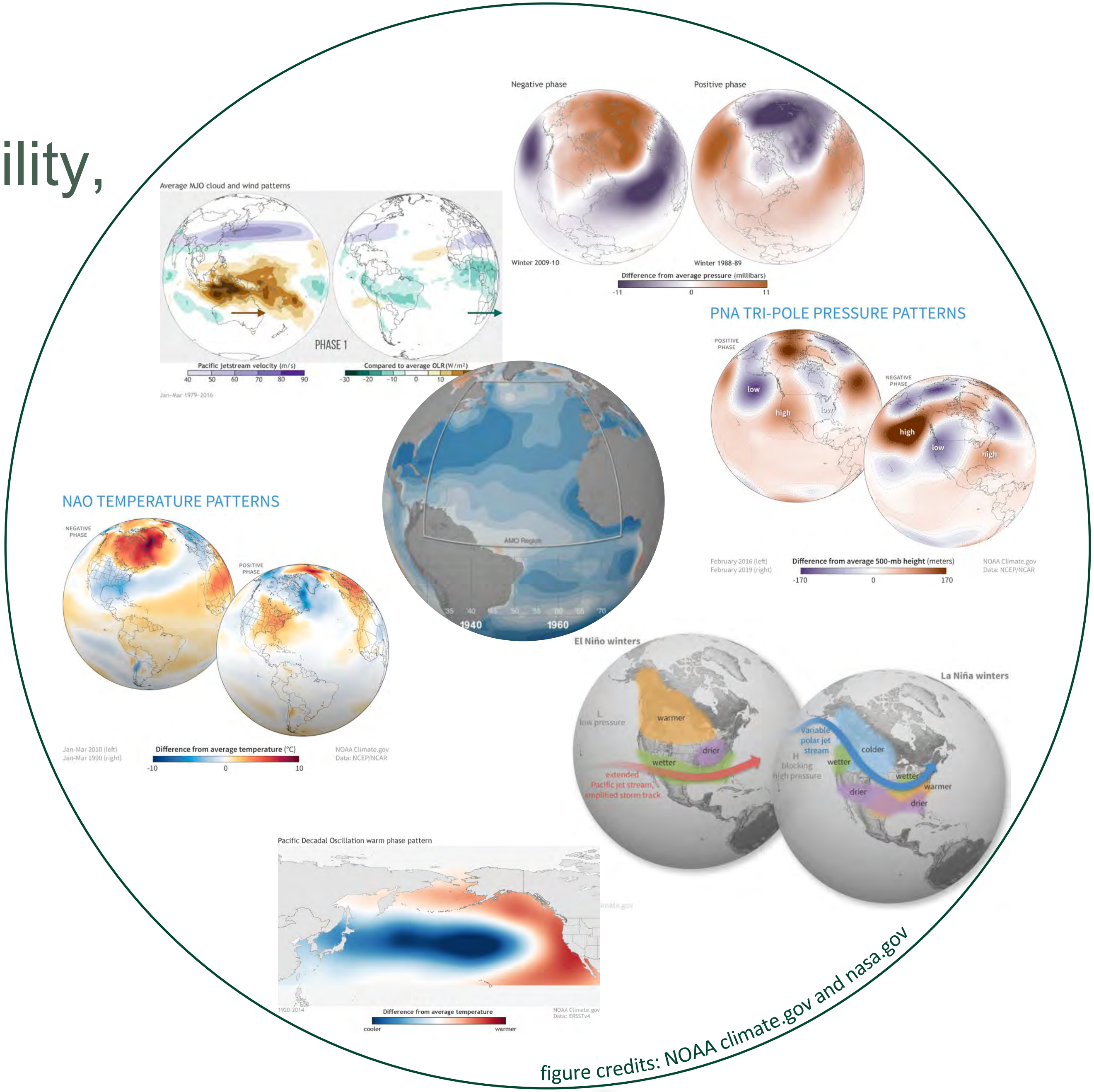
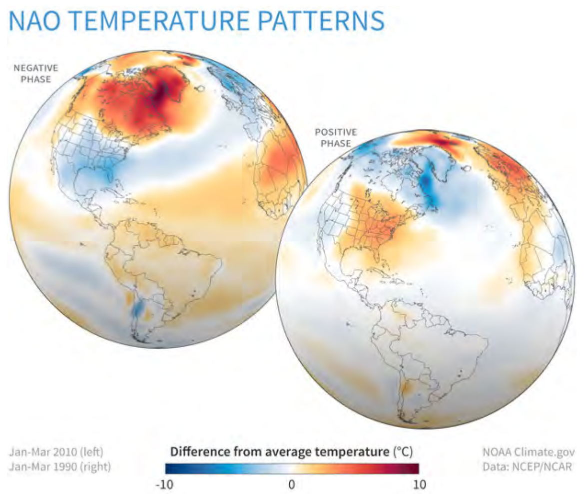
Wicked problems[1]:
Modes of large-scale climate variability, their interactions, and their impacts

- **Multiple time scales** (intraseasonal, interannual, multidecadal)
- **Causal inference** is challenging
- **Tropical vs. Extratropical** patterns
- **Opposing or concurring impacts** on midlatitude atmospheric circulation
- **Interactions** between modes
- Model **limitations and biases**
- **Predictability** opportunities and limits
- Potential **analogs** between climate variability & change



[1]complex, nonlinear, lack definitive formulation, accept multiple explanations, no stopping rules [Ritter & Webber, 1973; Conklin, 2016; U.S. Army CACD Training & Doctrine Command p525-5-500]

North Atlantic Oscillation



NAO+: favored European blocking[1] related to changes in the ocean-land contrast

NAO-: **increased Greenland blocking;** anticorrelation *(Woollings et al 2008)* has implications for predictability *(Athanasiadis et al. 2020)*

Similar spatiotemporal scale as blocking *(Yao & Luo, 2015)*

NAO variability **as a result** of variations in high-latitude blocking on interannual and longer time scales *(Woollings et al. 2010)*

Model biases in **NAO <-> blocking** *(Anstey et al. 2003; Masato et al. 2013; Davini & Cagnazzo, 2013)*

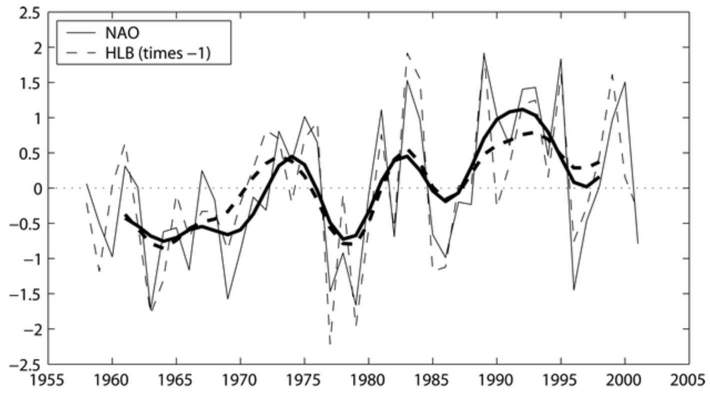


figure from Woollings et al. 2008

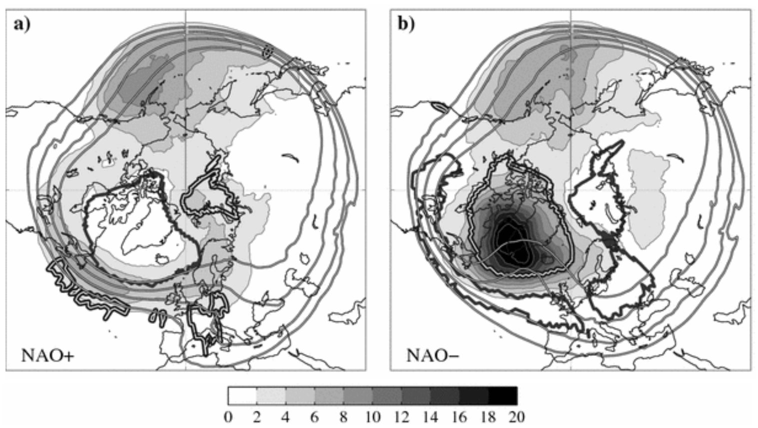


figure from Croci-Maspoli et al 2007

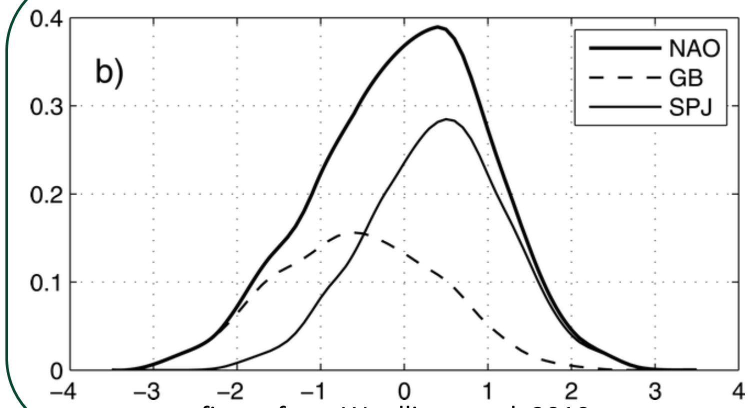
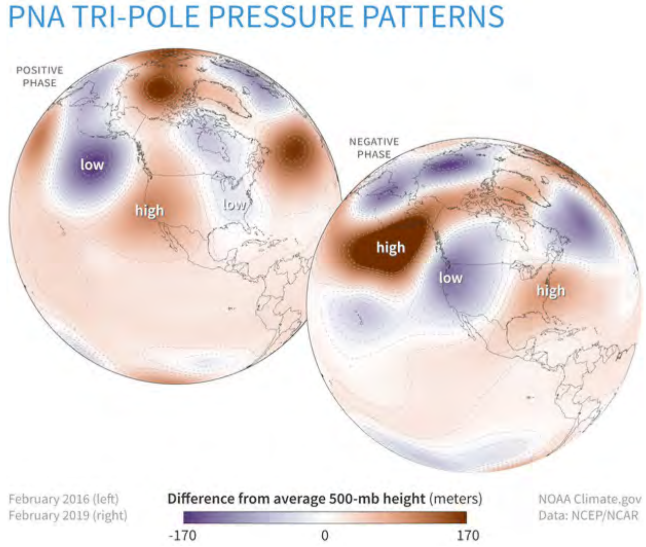


figure from Woollings et al. 2010

[1][Shabbar et al. 2001; Scherrer et al 2006; Croci-Maspoli et al 2007, Yao et al. 2016, Luo et al 2015; Pavan and Doblas-Reyes 2000; Barriopedro et al. 2006]

Pacific/North American Pattern (PNA)



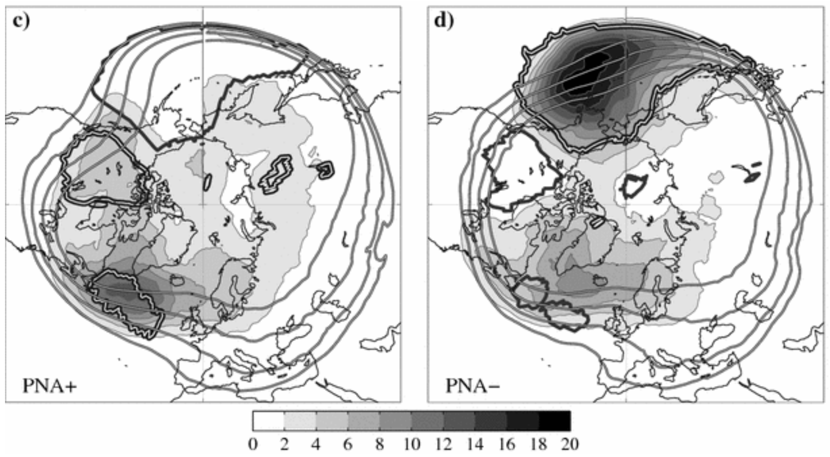


figure from Croci-Maspoli et al 2007

Temporally and spatially **correlated** mainly with Pacific blocking

ENSO modulation of PNA impacts *(Renwick & Wallace, 1996)*

Atmospheric blocking as a **major contributor** to PNA variability

Blocking can **sustain negative PNA from genesis to lysis**, and trigger a phase transition *(Croci-Maspoli et al. 2007)*

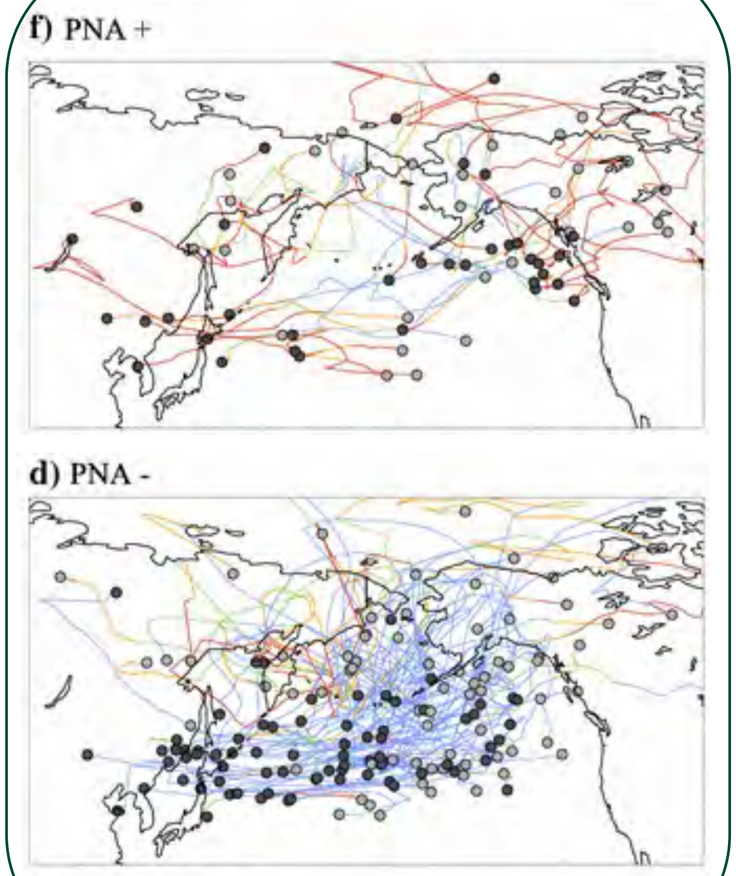
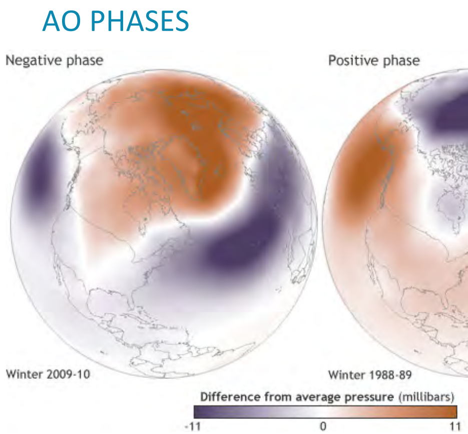


figure from Croci-Maspoli et al 2007

Arctic Oscillation/Northern Hemisphere Annular Mode



- **AO-:** increased blocking (x3), shifted poleward *(Hassanzadeh & Kuang, 2015; Overland et al. 2015, Thompson & Wallace 2001)*
- **AO/NAO/PNA-sea ice-blocking** interactions *(Hilmer & Jung, 2000; Vinje, 2001; Overland & Wang, 2010 inter alia)*
- Mechanisms, causality, and analogs **remain a challenging question** (also see NAO; equator-to-pole gradient? mean flow vs. eddy feedbacks? seasonality?)

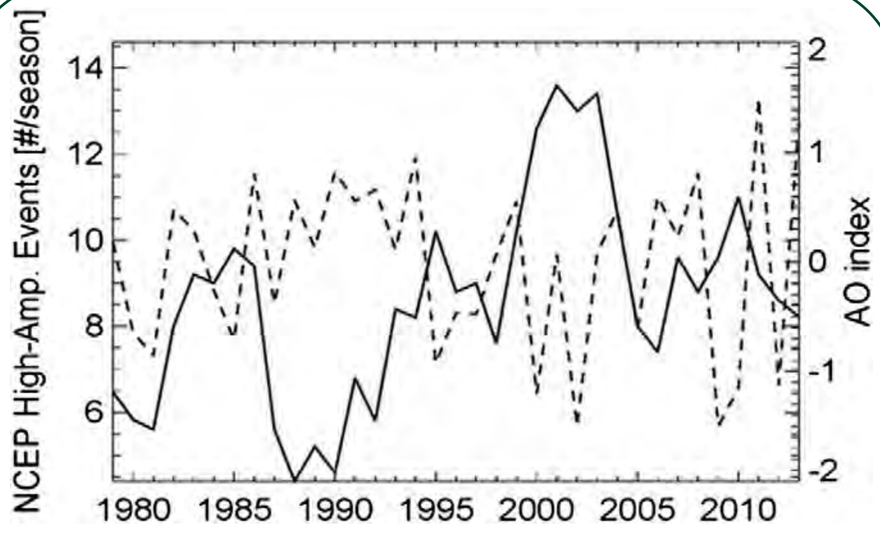


figure from Overland et al. 2015

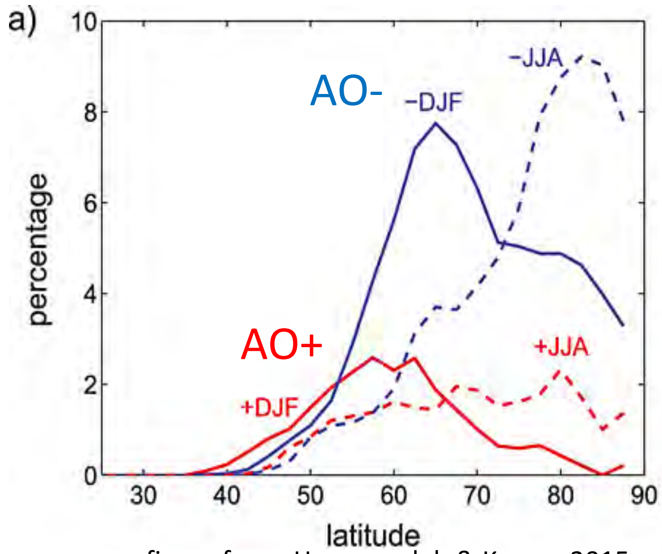
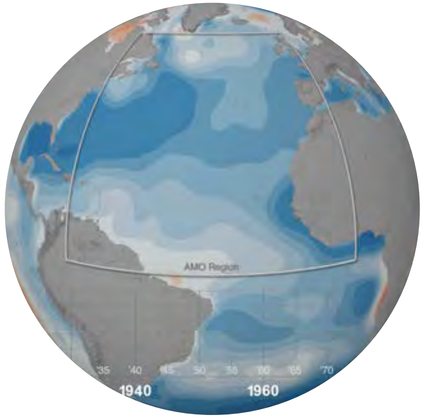


figure from Hassanzadeh & Kuang, 2015

Atlantic Multidecadal Oscillation (AMO/AMV)



AMO+: more frequent NAO- and Atlantic blocking *(Peings & Magnusdottir, 2014)*

The AMO–blocking relationship is stronger when the **AMO/V leads the NAO/blocking** *(Kwon et al. 2020)*

More frequent wintertime blocking corresponds to a **warmer, more saline subpolar ocean** *(Häkkinen et al. 2011)*

AMOC shifts can be triggered by blocking via changes in **sea ice export** through Fram Strait *(Ionita et al. 2016)*

Possible **two-way coupling** between AMO/V & blocking

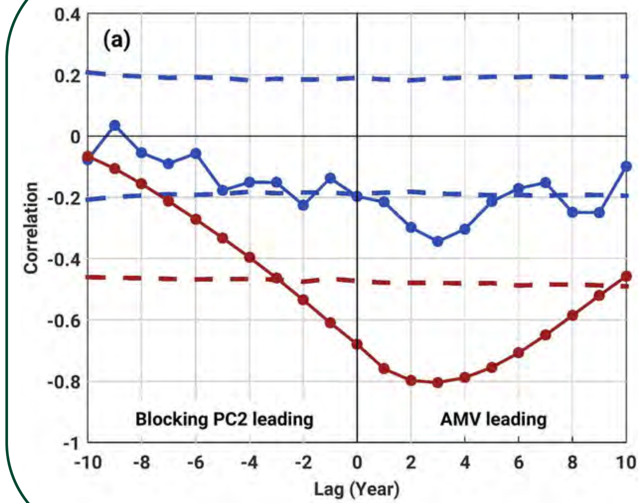


figure from Kwon et al. 2020

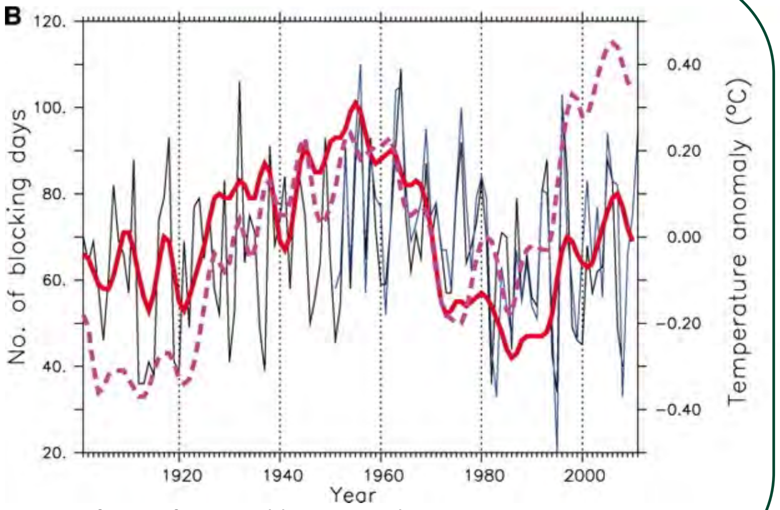


figure from Häkkinen et al. 2011

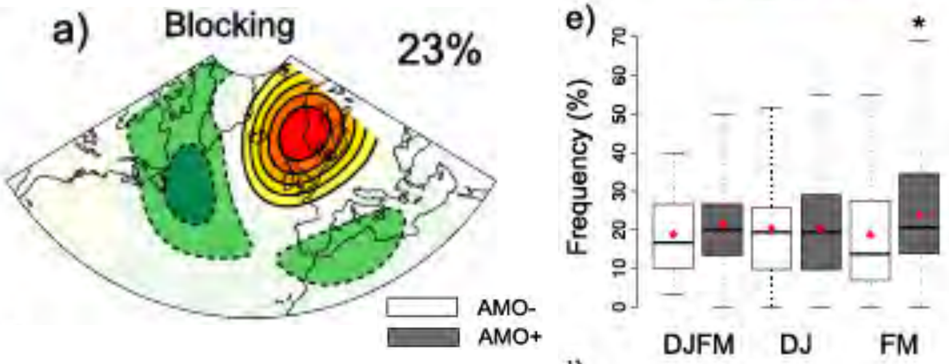
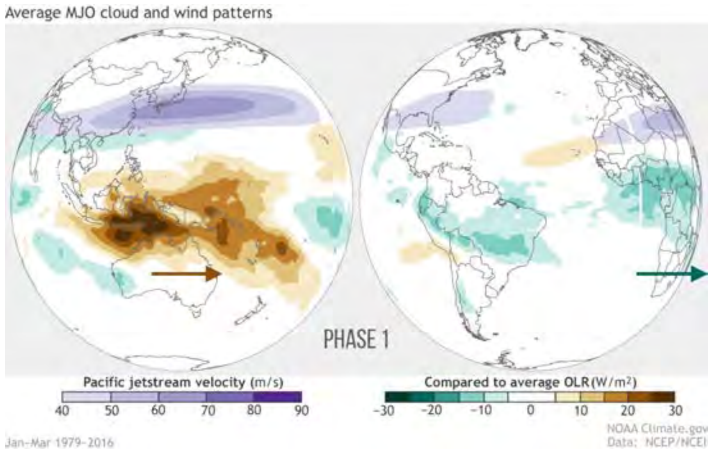


figure from Peings & Magnusdottir, 2014

Madden-Julian Oscillation (MJO)



Variations **in speed, intensity and structure** across MJO events *(Zheng & Chang, 2019)* and sensitivity to **initial state** *(Lin & Brunet, 2018)* lead to **uncertainties** in extratropical response

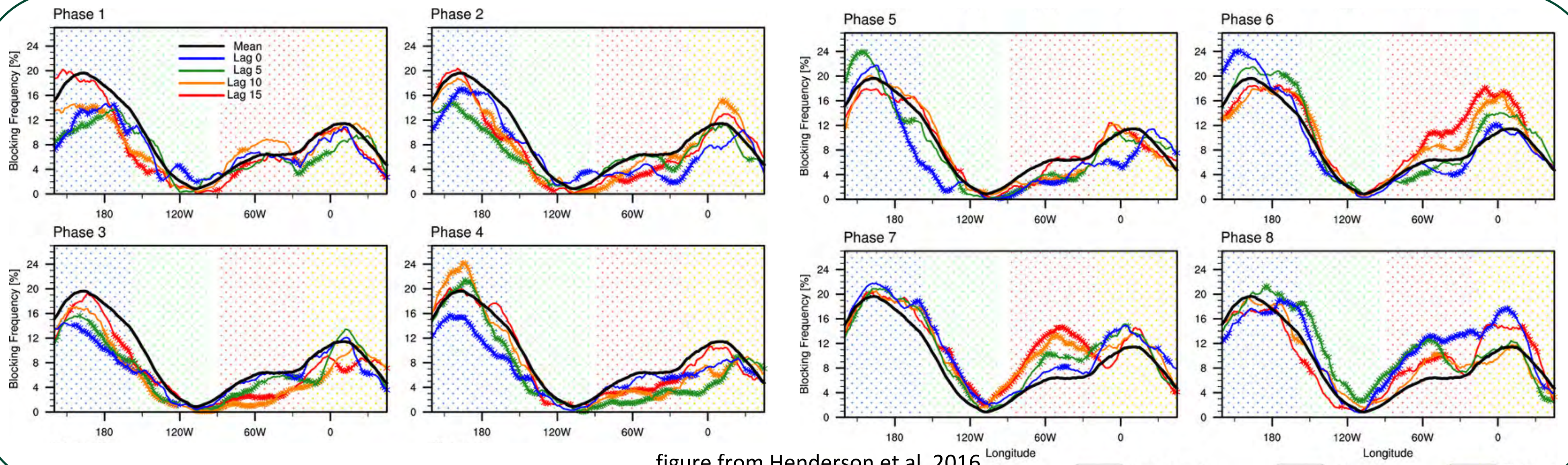


figure from Henderson et al. 2016

MJO impacts on blocking depend on the **phase** *(Henderson et al. 2016; Gollan & Greatbatch, 2017; Lee et al. 2020)* and are associated with its **impacts on NAO[1]/AO[2]/PNA[3]**

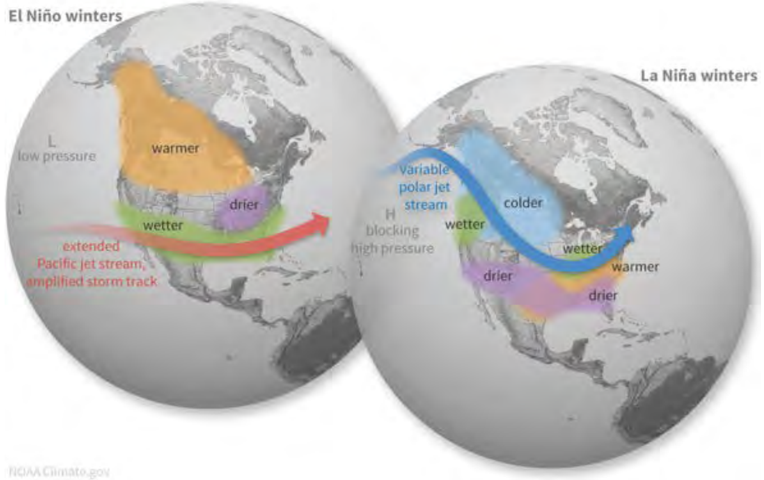
[1][Garfinkel et al. 2012; Cassou, 2018; Lin et al. 2009] [2][Zhou & Miller, 2005; L'Heureux & Higgins, 2008] [3][Seo & Lee, 2017; Seo & Son, 2012; Riddle et al. 2012; Goss & Feldstein, 2015]

ENSO influence on blocking

- **NH: fewer and weaker blocking** events over the Pacific during El Niño *(Renwick & Wallace, 1996; Wiedenmann et al., 2002)*

- **SH: increased blocking** during El Niño associated with SPCZ variability *(Renwick and Revell, 1999; Margues and Rao, 2000)*

- ENSO signal is often found to be **weak** and mostly applies to the preferred blocking formation locations, but not blocking occurrences (*Barriopedro et al., 2006; Davini et al., 2021; Lupo et al. 2019*)



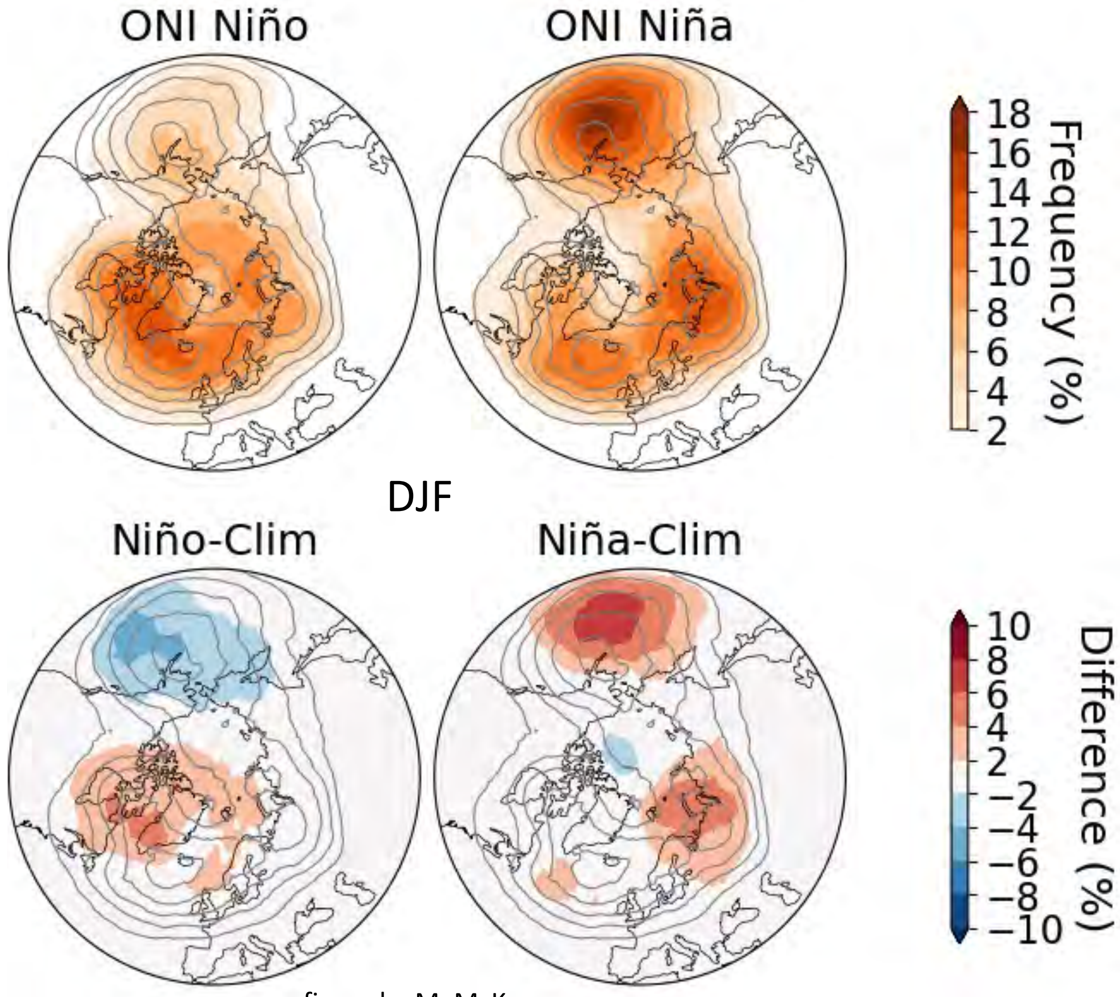


figure by M. McKenna

data: ERA5 (1940-2022)
detection method: anomaly

contours: DJF climatology (1961-2000)
shading: changes (significant at 90%)

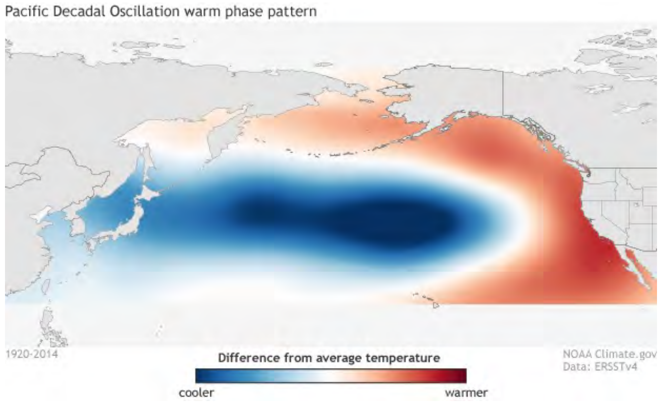
Modulation of ENSO impacts by the Pacific Decadal Oscillation (PDO)[1]

Table 1. The characteristics of Northern Hemisphere blocking events per year as a function of ENSO and PDO

+PDO	Occurrence	Duration (days)	Intensity (BI)	% Simultaneous
El Niño (6)	23.5	8.1	3.06	7.6
Neutral (15)	24.2	8.2	3.26	8.9
La Niña (2)	30.5	8.3	3.11	12.7
Total (23)	**24.7**	**8.2**	3.20	**8.9***
–PDO	**Occurrence**	**Duration (days)**	**Intensity (BI)**	**% Simultaneous**
El Niño (8)	**38.1**	9.5	3.17	26.3
Neutral (12)	37.4	9.9	3.03	28.9
La Niña (9)	**31.3**	8.6	3.12	16.8
Total (29)	**35.7**	**9.4**	3.09	**24.4***

Note: The number of years in each category is shown in parentheses. Bold numbers show a statistically significant difference at $P = 0.10$; $^*P = 0.05$. These data are taken from Ref. 25 and updated.

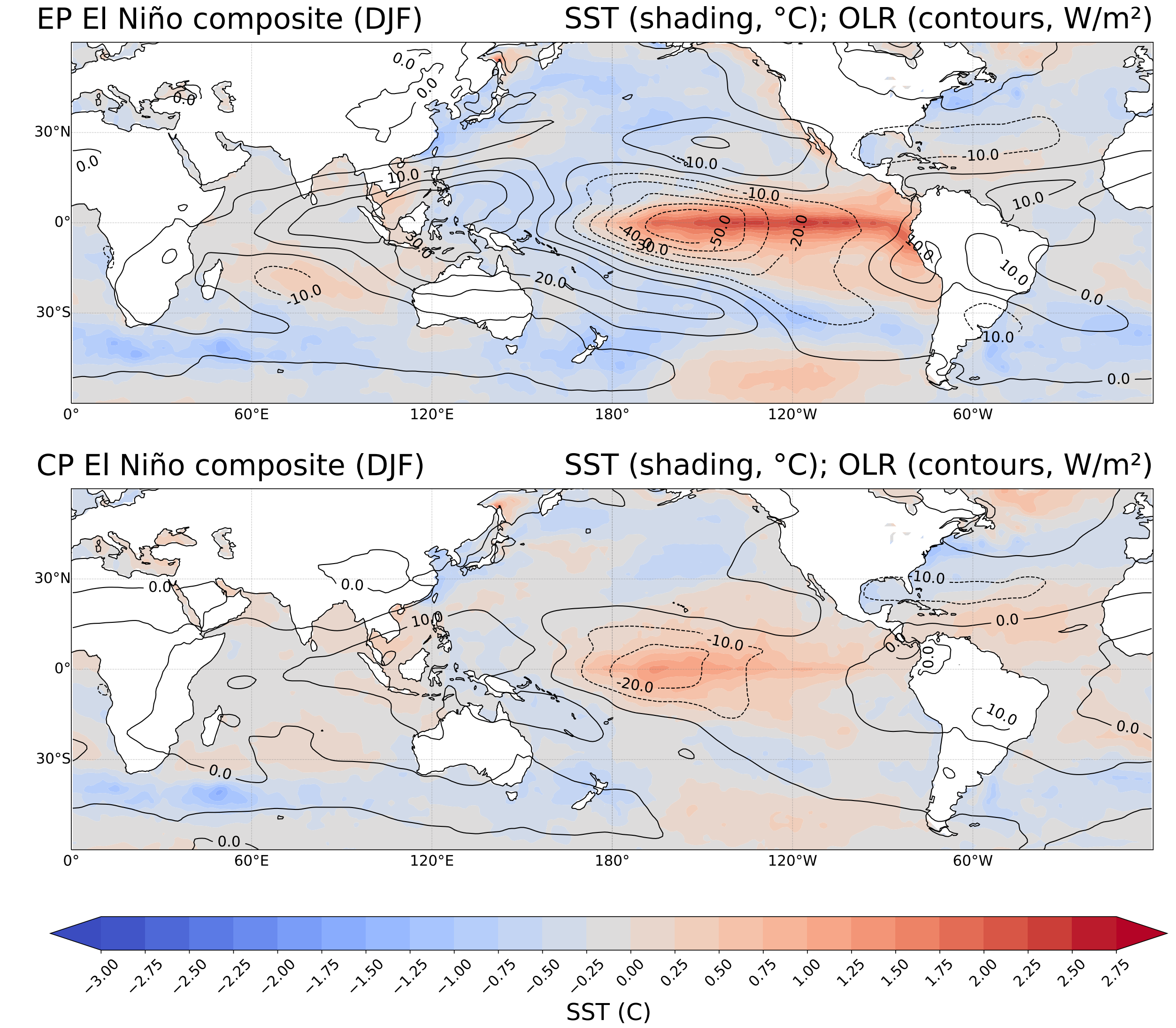
table from Lupo, 2021



- NH: **increased**, more persistent, concurrent NH blocking during **+ENSO /-PDO**
- NH: **decreased** blocking during **+ENSO/+PDO** but less robust.
- SH: **increased** blocking during +ENSO in **both PDO phases** (not shown)

[1] [Lupo et al. 2019; Lupo, 2021]

ENSO diversity (AKA flavors) has distinct impacts



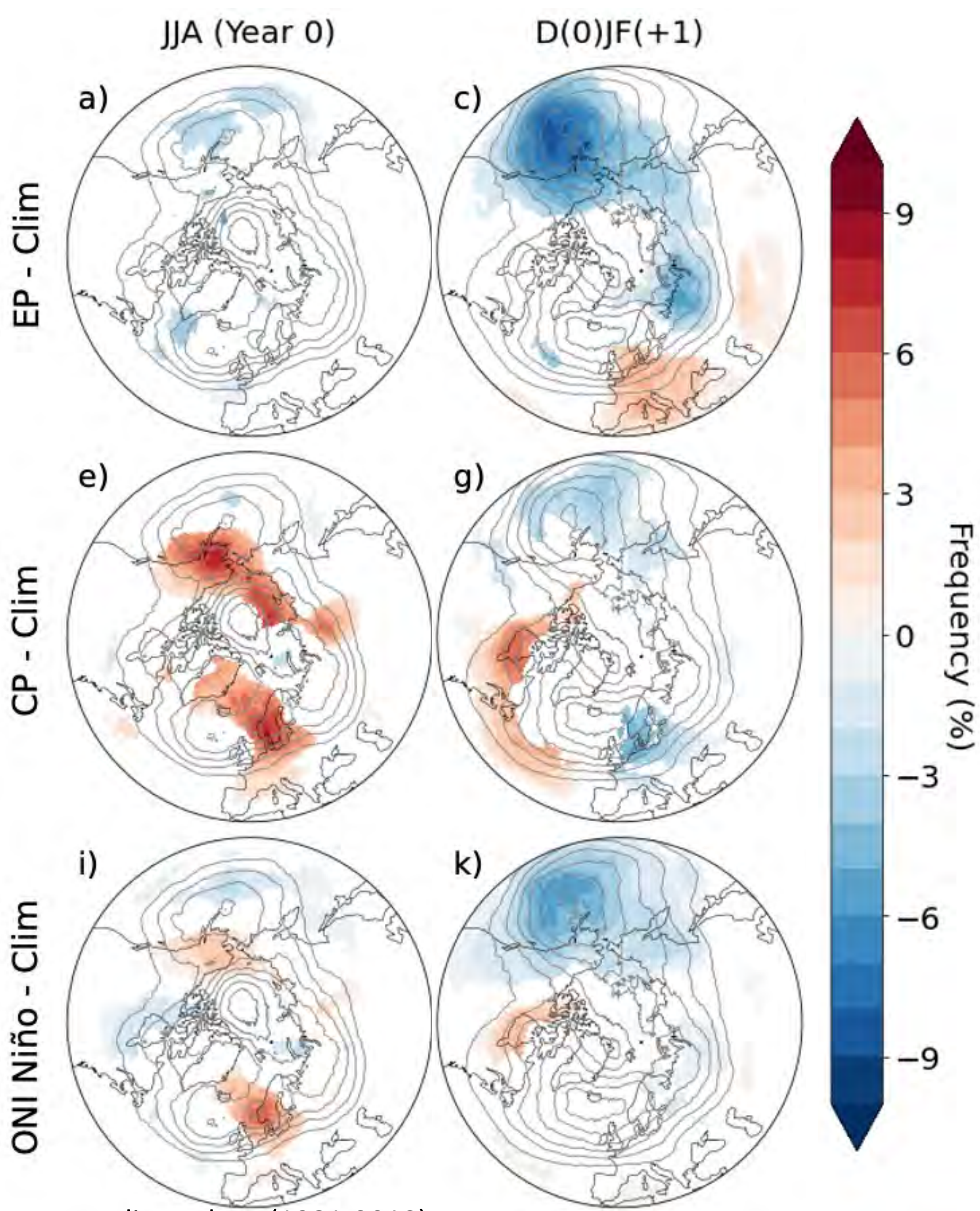
data: HadISST/20C Reanalysis V3

- Depending on the **season and location**, ENSO flavor teleconnections differ in **magnitude and sign** *(Ashok et al.,2007; Weng et al., 2007; Karamperidou & DiNezio, 2022)*

- Model spread in future blocking projections has been associated to **EP or CP-like** SST warming in the tropical Pacific (*Matsueda & Endo, 2017*)

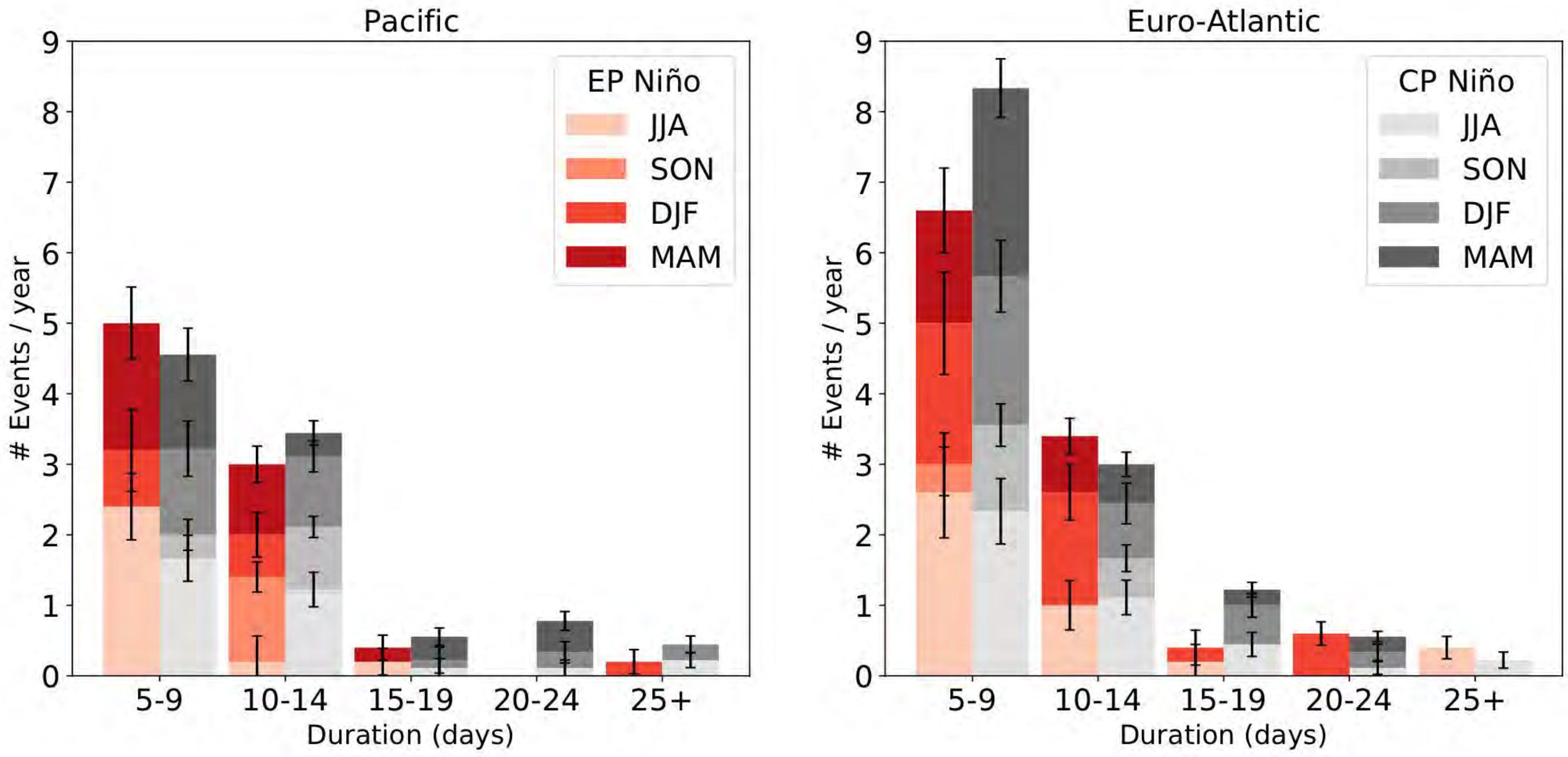
ENSO diversity impacts on blocking can be of opposite sign

- During the **peak of EP** events, blocking in the **North Pacific is decreased** by >10%, while blocking in **Central Europe is increased** by ~6%.
- **EP events** affect the **occurrence** of blocking the Pacific, and **location** of blocking in the EuroAtlantic sector.
- **CP events** primarily affect the **location** of blocking formation.
- Using a single ENSO index **conflates the EP/CP impacts**.



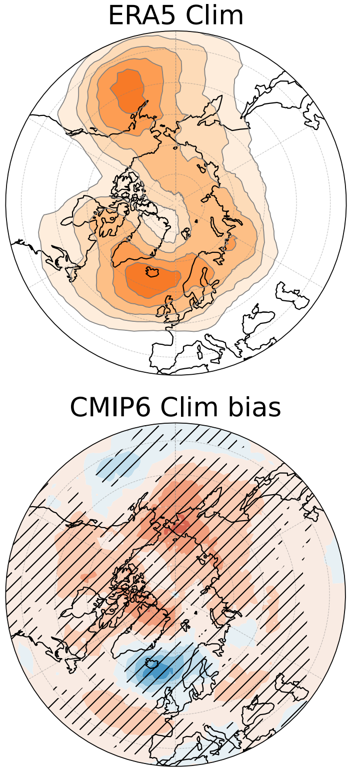
contours: climatology (1981-2010)
shading: changes (significant at 90%)

Data: ERA5 (1940-2022)



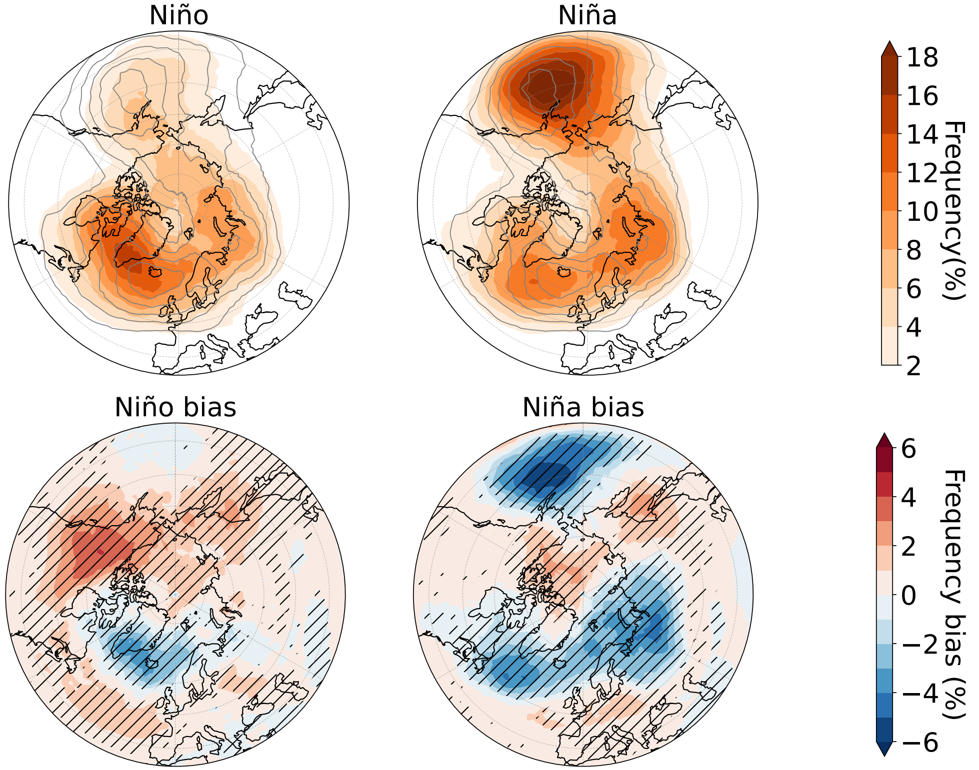
- In the Pacific, **long blocking events (>10 days) are primarily associated with CP events**, especially in JJA and DJF.
- In the EuroAtlantic sector, **CP years** are dominantly characterized by **short (5-9 days)** blocking events, while very **long (>20 days)** blocking events in DJF/JJA are primarily found in **EP years**.

Do coupled models simulate the impacts of **ENSO** on blocking?



Models **overestimate Pacific** blocking during **El Niño**, **underestimate Pacific** blocking during **La Niña**, **underestimate Greenland/Ural** blocking in both ENSO phases

ENSO-blocking bias patterns seem to **follow climatological bias (or contribute to it?)**.

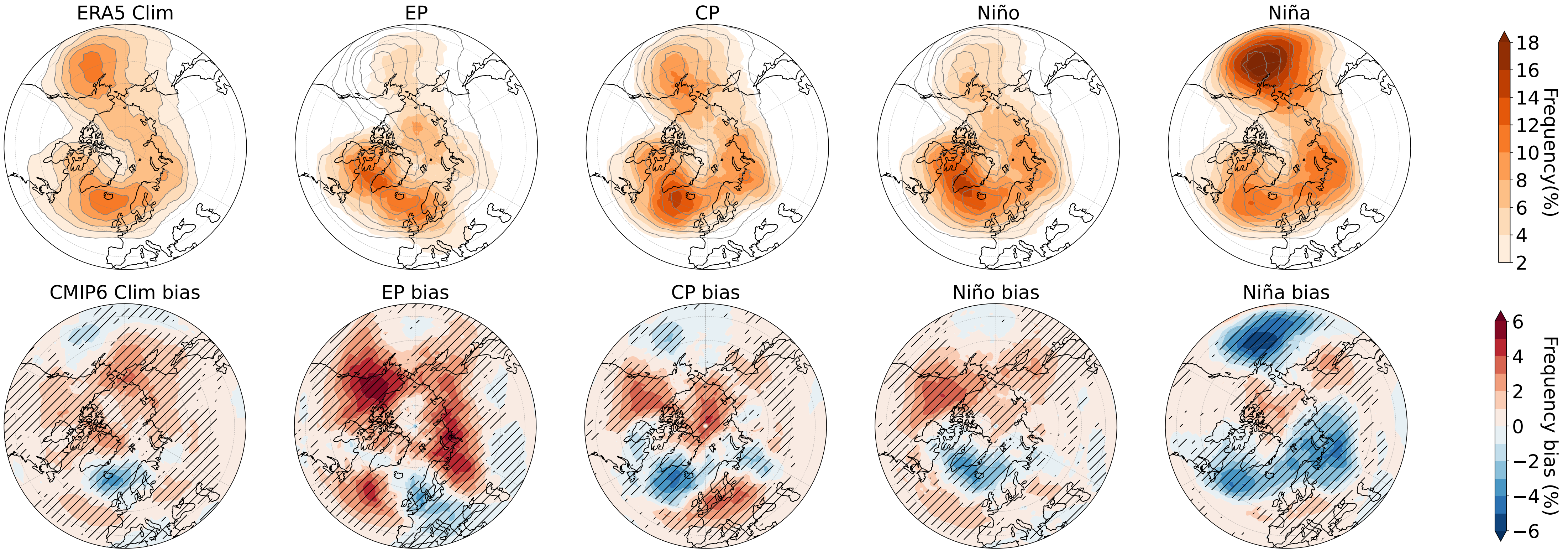


Depends on model biases in

a) **climatological** blocking
b) **simulating ENSO** (e.g. skewness, Dunn-Sigouin & Son, 2013)
c) simulating the **tropical convection response to ENSO**, and
d) simulating the **ENSO teleconnections**.

Data: ERA5 (1940-2022)
Contours: DJF climatology (1981-2010)
Hatching: >2/3 of models agree in sign

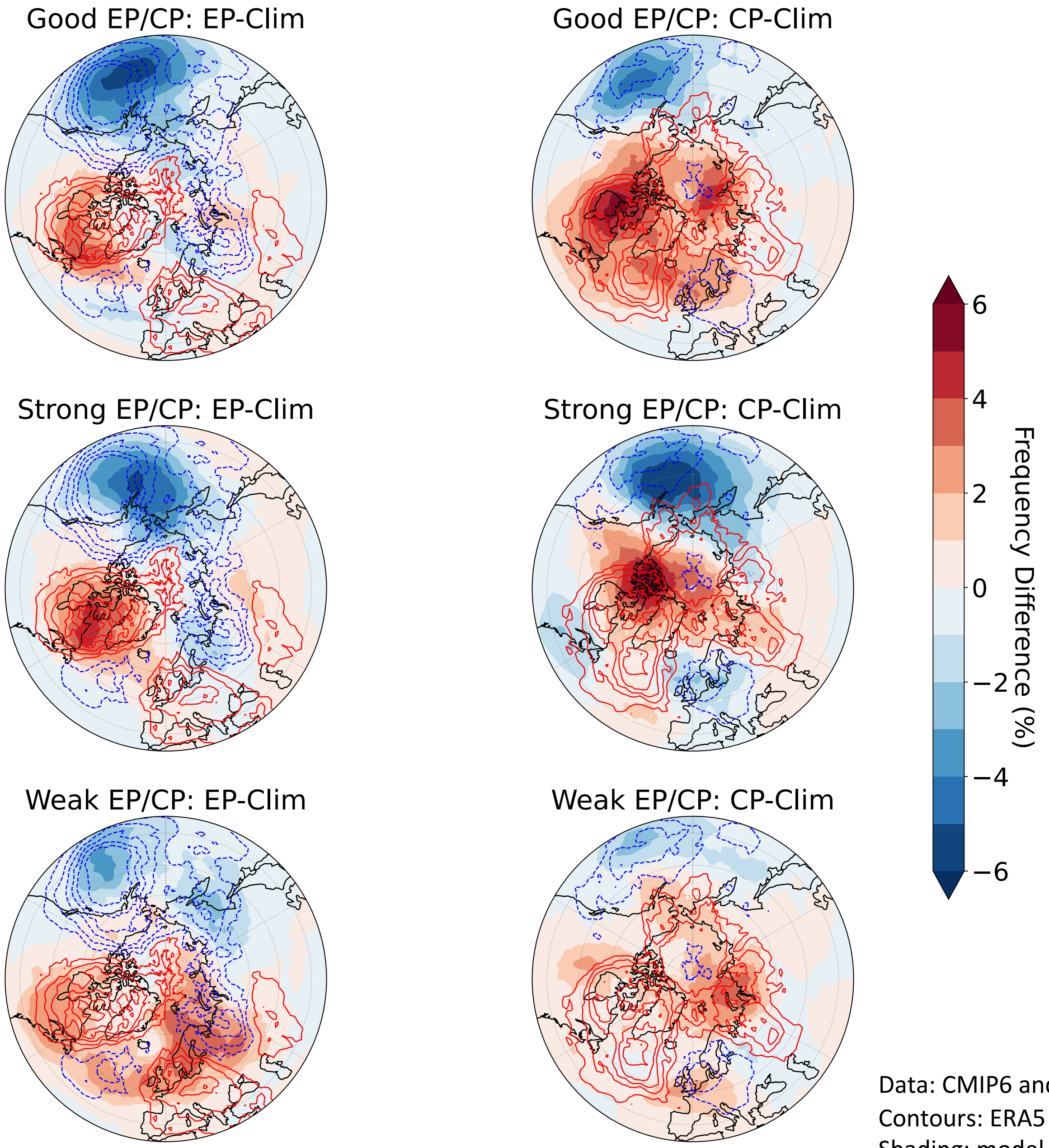
Do coupled models simulate the impacts of **ENSO** **diversity** on blocking?



Depends on model biases in

a) **climatological** blocking
b) **simulating ENSO diversity**
c) simulating the **tropical convection response to ENSO diversity**, and
d) simulating the **ENSO diversity teleconnections**.

Data: ERA5 (1940-2022)
Contours: DJF climatology (1981-2010)
Hatching: >2/3 of models agree in sign



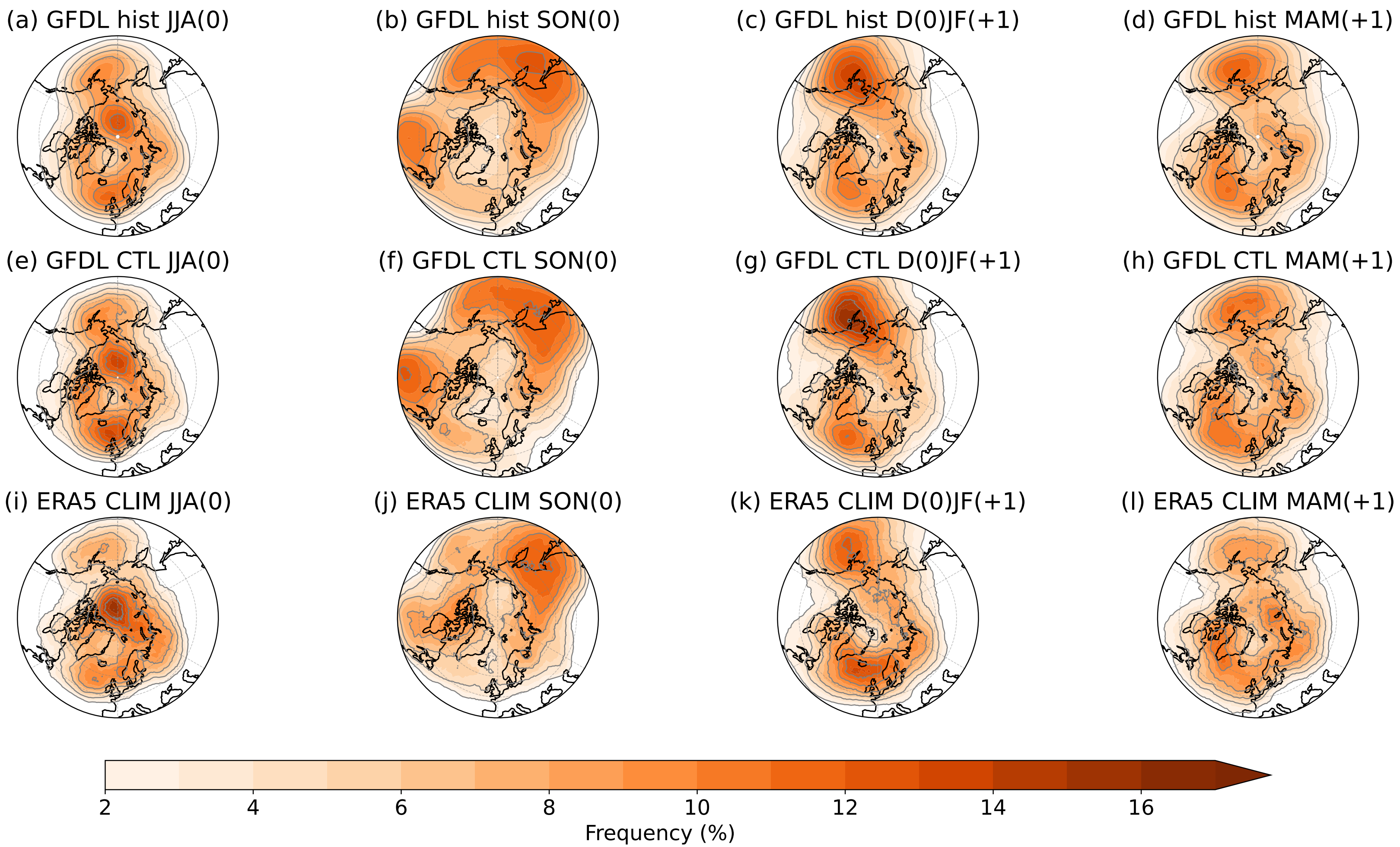
- Differences in the ratio of EP/CP events in coupled models are associated with shifted **Pacific and Greenland blocking**, and biases in the **Atlantic response** during CP events

- The **Europe/Ural dipole** is only captured in models that simulated strong EP/CP ratio

- These results indicate that the **simulation of ENSO diversity** in coupled models may **play a role** in simulating the **Pacific/Atlantic** blocking response; the connection to the **Europe/Ural bias** is unclear

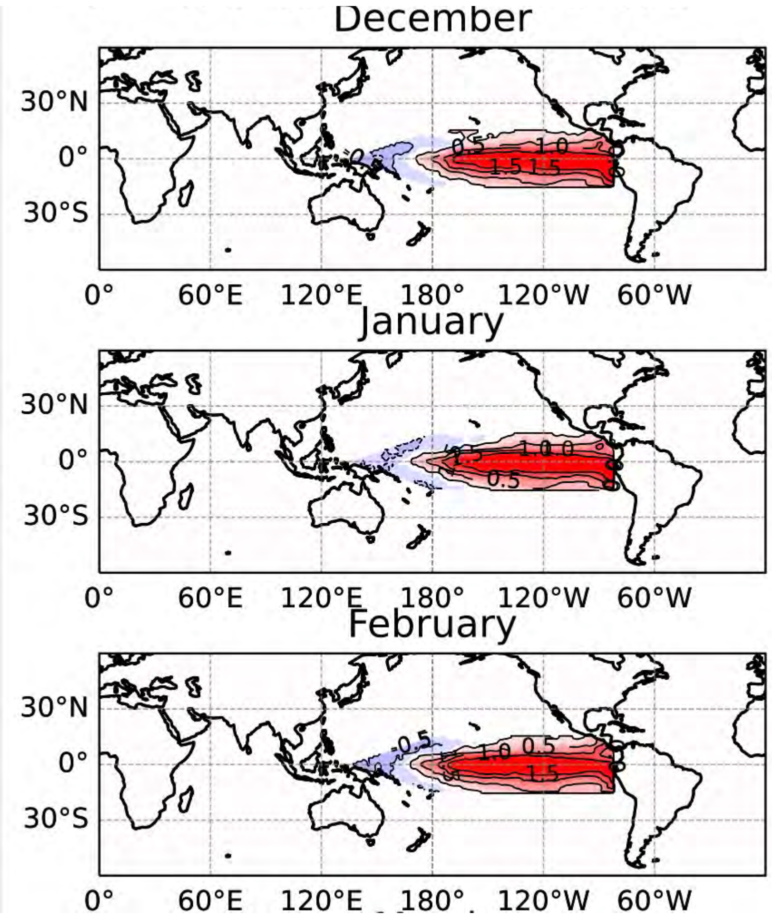
Data: CMIP6 and ERA5 (1940-2022)
Contours: ERA5 EP/CP response
Shading: model mean EP/CP response

Idealized and traditional POGA experiments

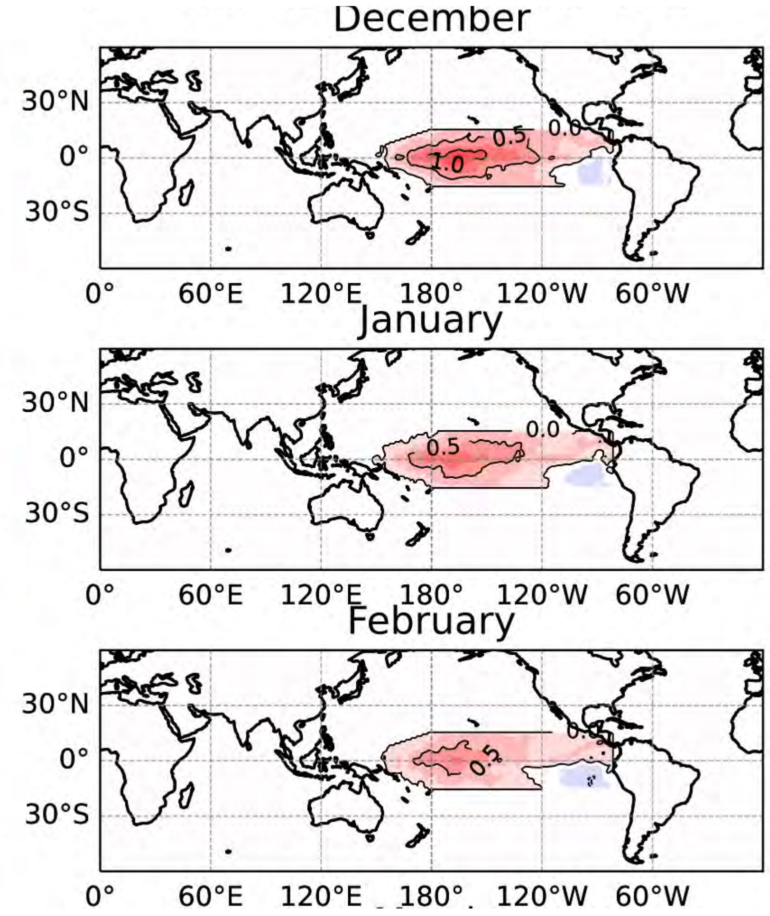


- Model : GFDL AM4.0 (Zhao et al. 2018)
- **CTL:** 50yr simulations forced by climatological SST
- **AM4 historical:** CMIP6 run, forced by historical SSTs (HadISST)

Idealized and traditional POGA experiments

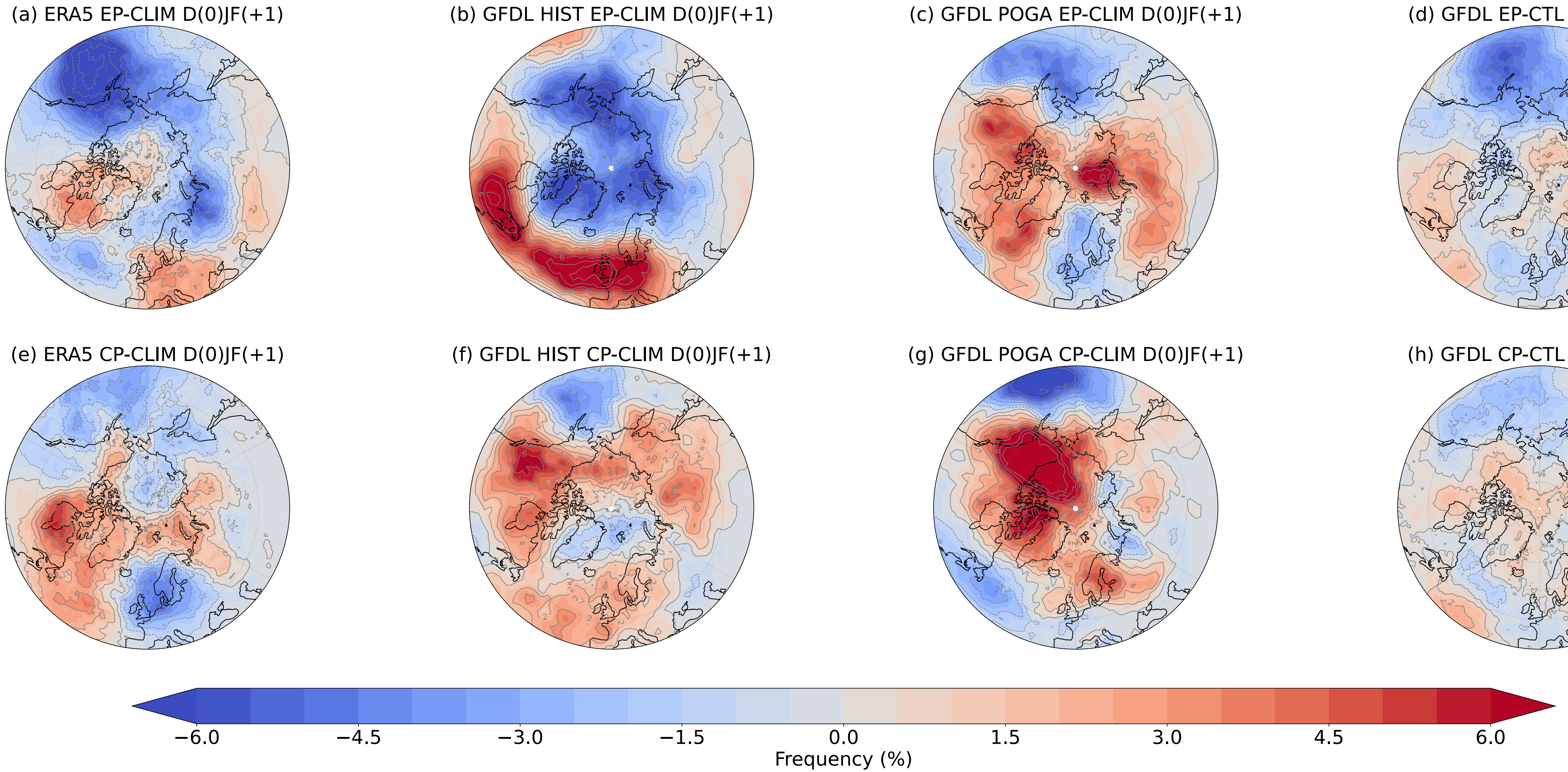


EP forcing



CP forcing

- Model : GFDL AM4.0 (Zhao et al. 2018)
- **CTL:** 50yr simulations forced by climatological SST
- **AM4 historical:** CMIP6 run, forced by historical SSTs (HadISST)
- **EP/CP experiments:** Imposed idealized EP and CP anomalies (June to May) in the tropical Pacific, recycled over 50 years
- **Traditional POGA:** forced with historical SST anomalies in the tropical Pacific, climatological SST everywhere else. *Rationale:* capture impacts of evolution/timing/strength of EP/CP events



- The **Pacific/N. America blocking** response is **driven by the tropical Pacific**
- EP: **non-Pacific drivers** of the **Europe-Ural** dipole
- CP: **possible Pacific drivers** of the **Europe-Ural** dipole
- The Atlantic response is likely not driven by the Pacific. Are interbasin relations playing a role?

- Modes of climate variability influence regional blocking at **multiple timescales**; the **strength** of the relationship **varies** and often depends on the **combination of mode phases** and possible **two-way interactions**.

- **Faithfull simulation** of the patterns of climate variability **remains a challenge** for models and may carry over to their simulation of blocking (e.g., ENSO biases)

- **Teleconnection biases** are a contributor: idealized and traditional POGA experiments suggest a **sensitivity** of EuroAtlantic blocking to tropical Pacific drivers

- The relationship between blocking and multiscale climate variability is important to decipher in order to **constrain** future blocking projections; **key limitation: the length of the record.**

- Modes of climate variability influence regional blocking at **multiple timescales**; the **strength** of the relationship **varies** and often depends on the **combination of mode phases** and possible **two-way interactions**.

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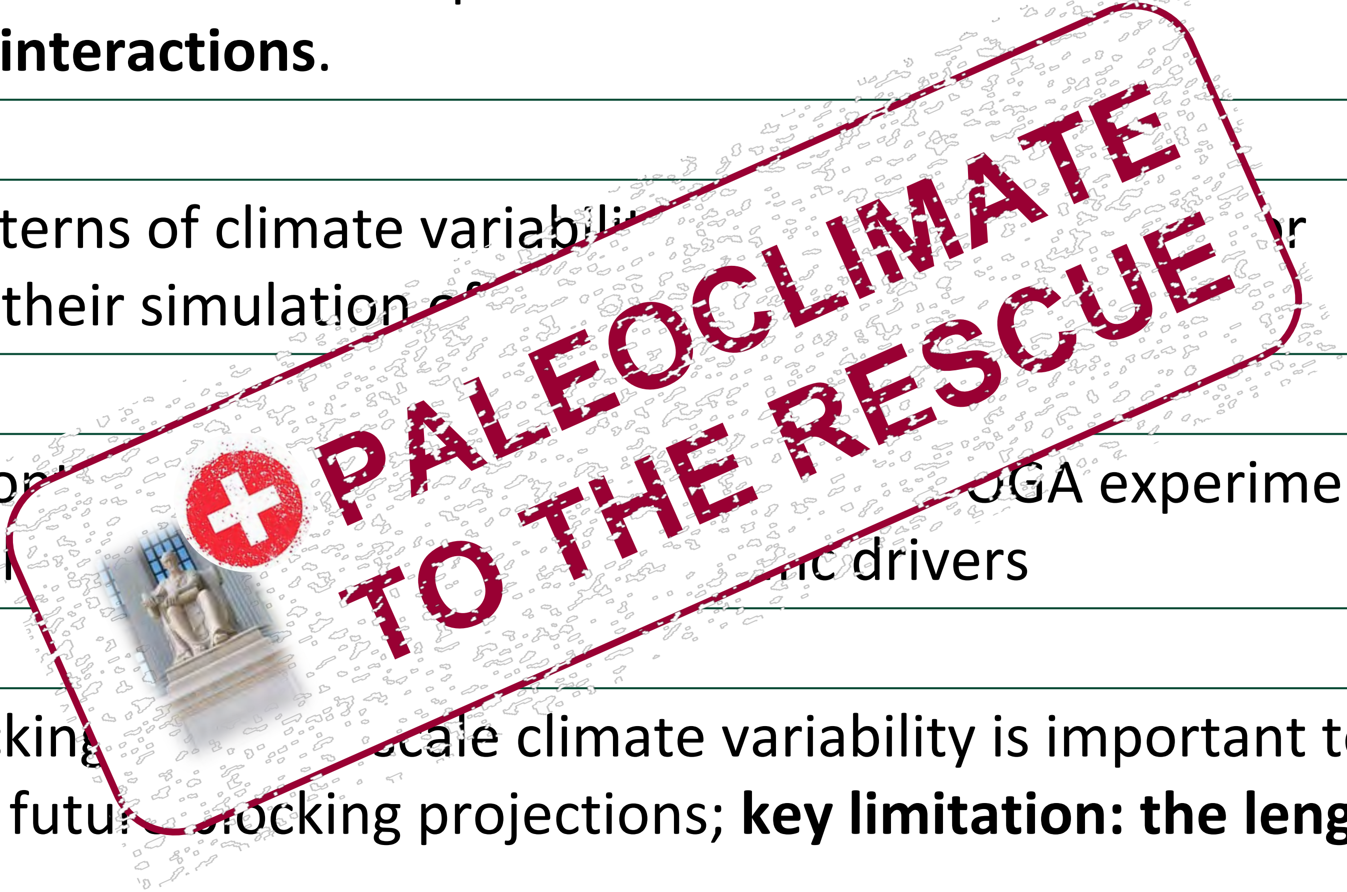


Paleoclimate proxy records suggest changes in blocking activity

- Tree-ring based reconstructions of **summer N. Atlantic Jet** have been linked to **increases in blocking activity** and temperature variability in Europe *(Trouet et al 2018)*
- European **megadroughts** associated with **persistent blocks** *(Persoiu et al 2019, Ionita et al 2021)*
- **Reduction in blocking in the 1400s** inferred by a reconstruction of Atlantic Multidecadal Variability *(Lapointe & Bradley, 2021)*
- **A temporal resolution problem**: Large-scale (quasi)stationary waves vs blocking activity

Figure from Trouet et al. (2018)

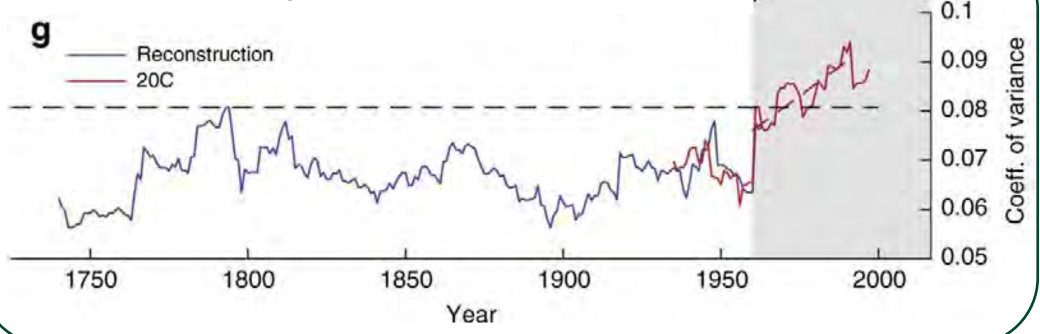
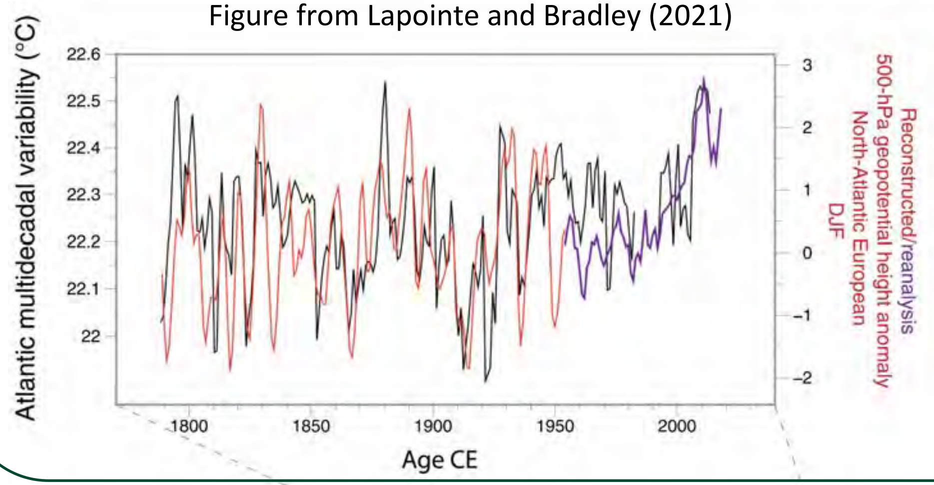
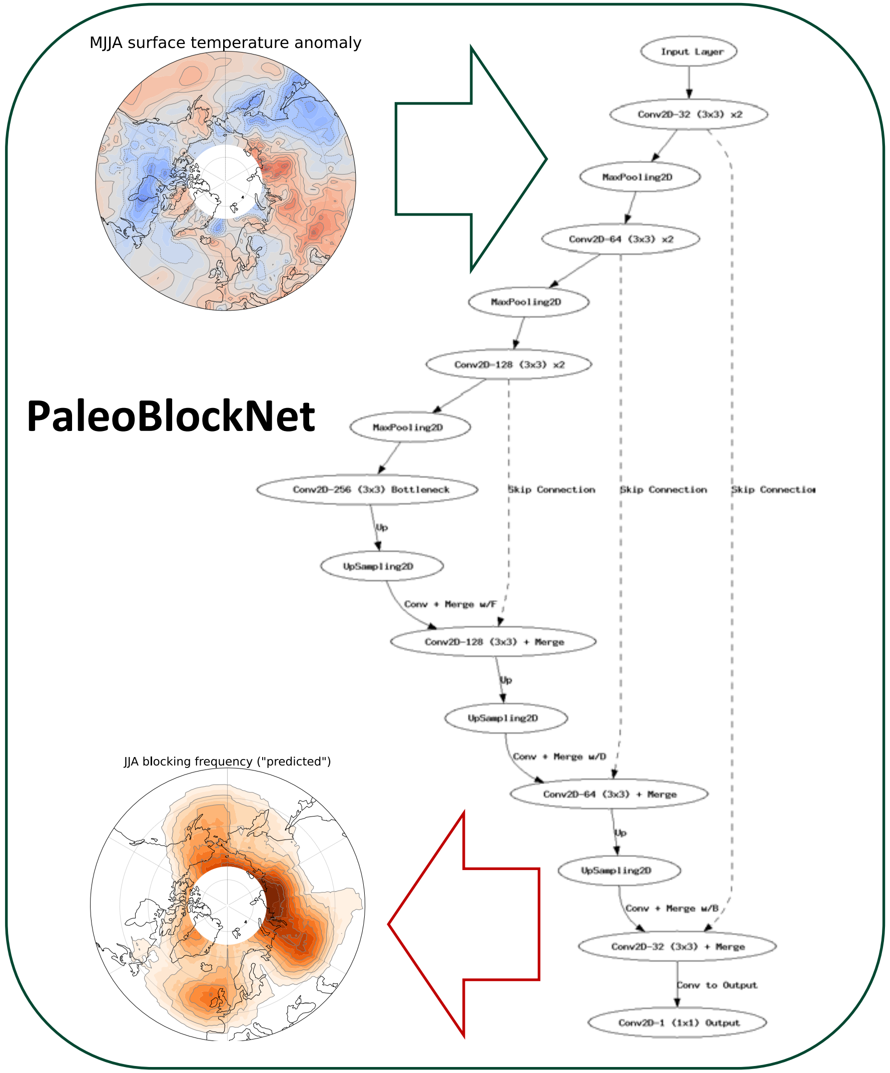


Figure from Lapointe and Bradley (2021)



Extracting paleoweather from paleoclimate

- **Deep Learning (DL)** model; Unet-based architecture
- **input:** MJJA surface temperature anomaly (30N-75N), 1951-1980 basis
- **output:** JJA blocking frequency



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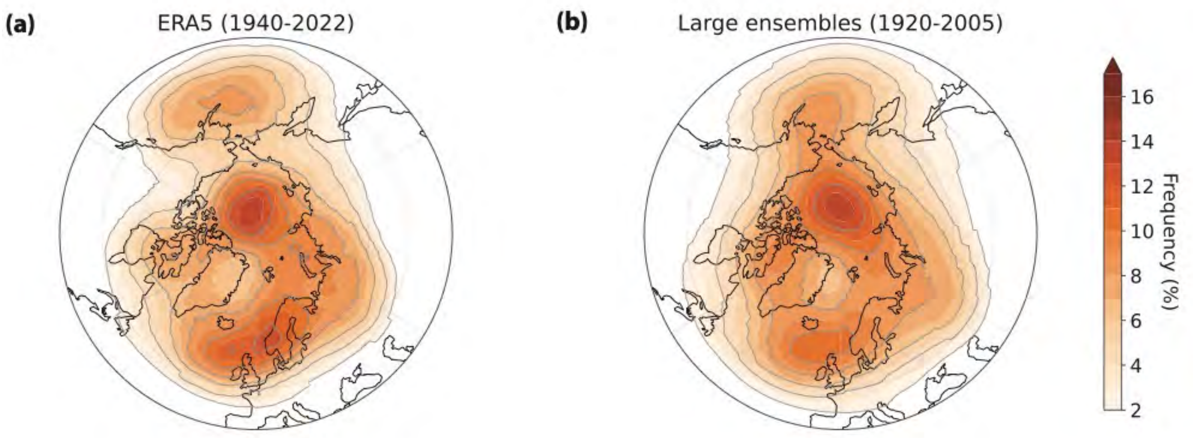
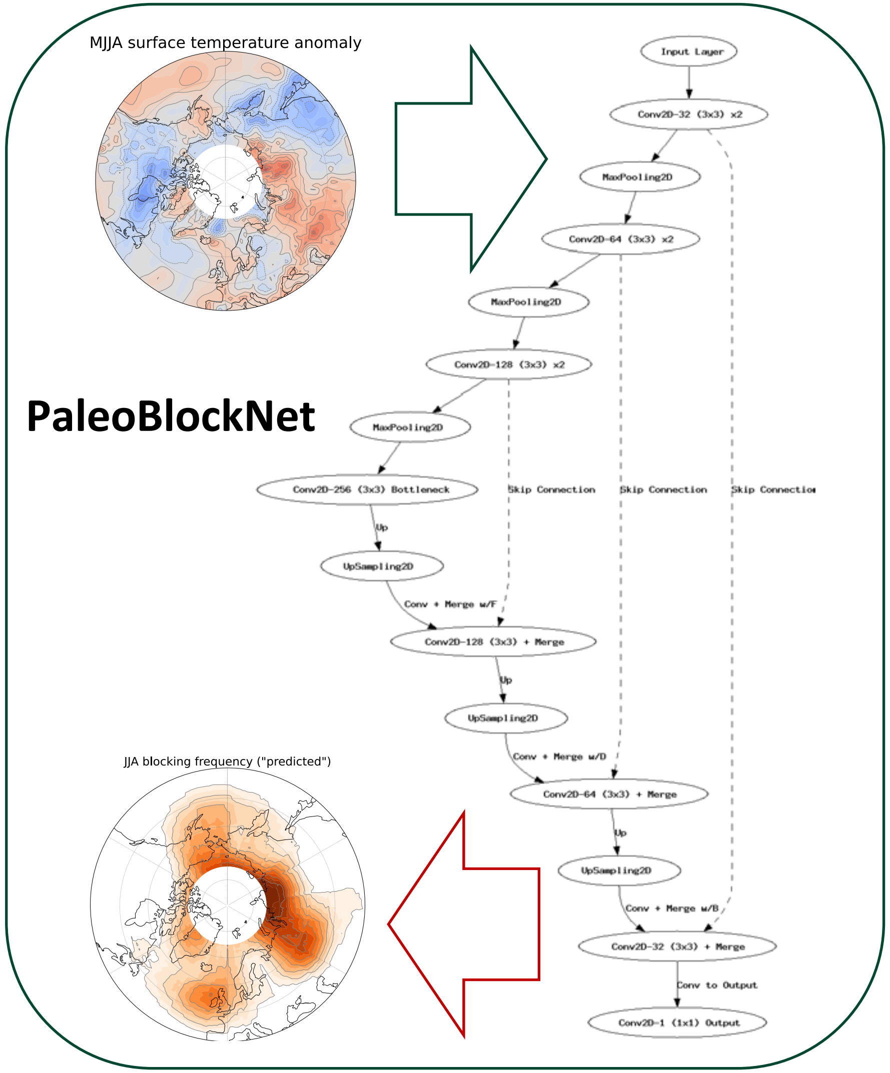
JJA blocking frequency





Karamperidou, 2024: *Extracting paleoweather from paleoclimate: A deep learning reconstruction of Northern Hemisphere summertime atmospheric blocking over the Last Millennium (submitted)*

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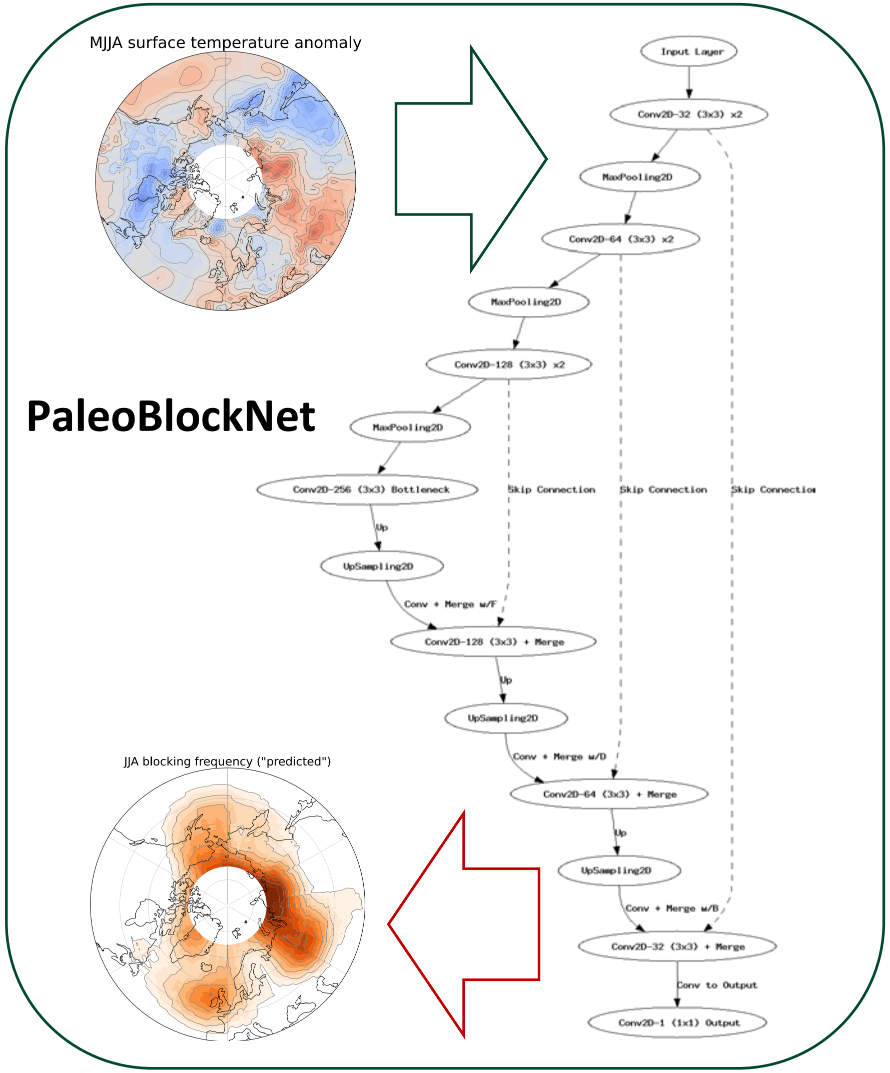
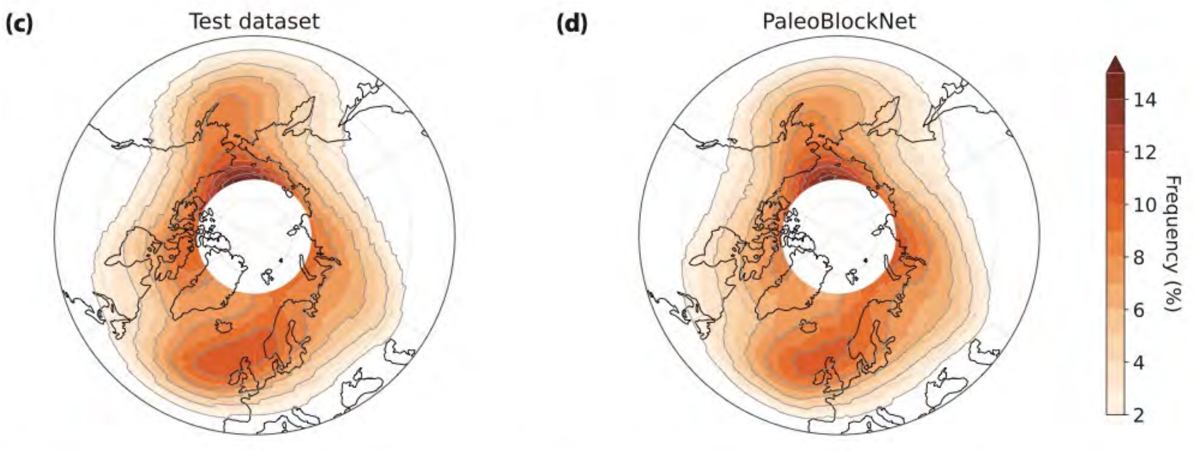
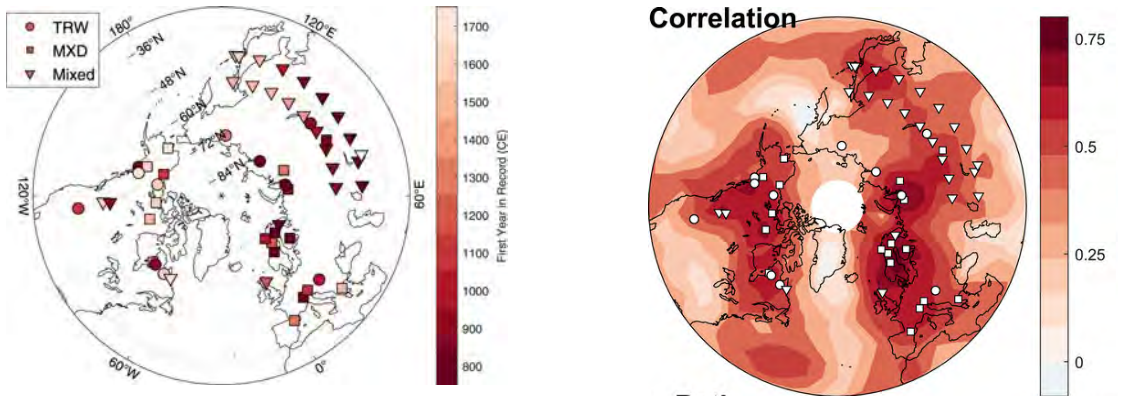


JJA blocking frequency



median pattern correlation in the test dataset (1414 years): 0.78

Extracting paleoweather from paleoclimate

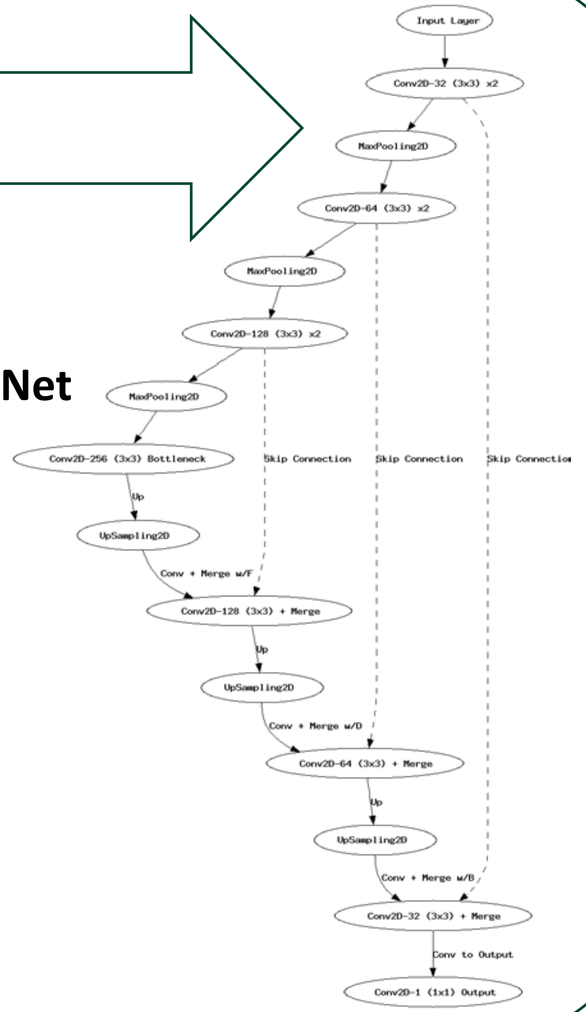


figures from King et al. 2021

NTREND network :
54 tree-ring based summer temperature proxy records (750-2000 CE; *Wilson et al. 2016; Anchukaitis et al. 2017*)

10-member NTREND-based reconstruction of MJJA surface temperature (30°–90°N) vs. Berkeley Earth instrumental dataset (1901–1988) (King et al. 2021)

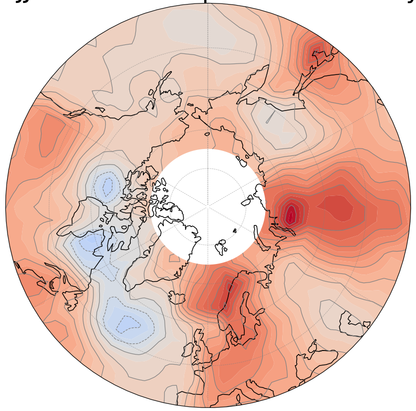
PaleoBlockNet



Extracting paleoweather from paleoclimate

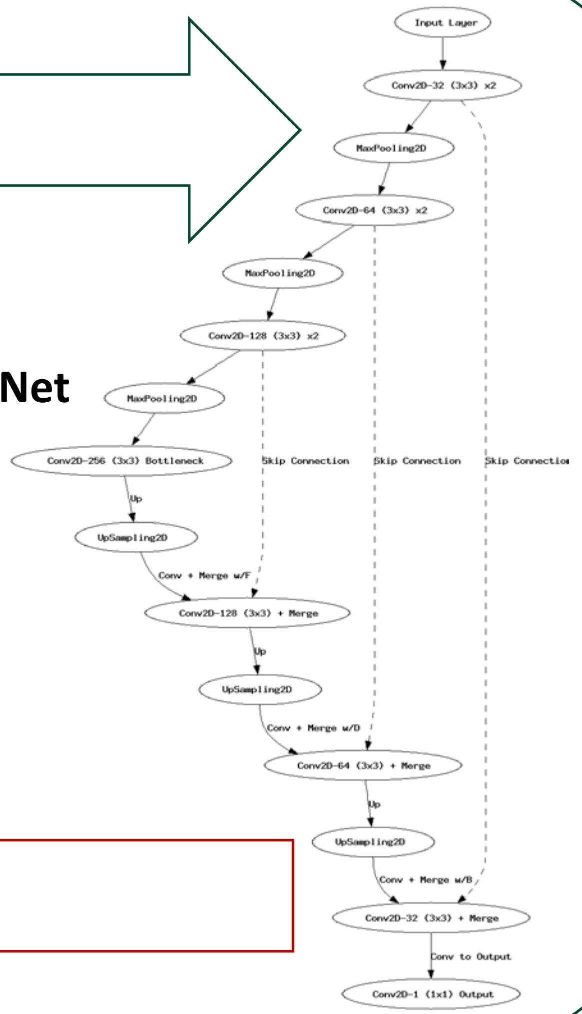
- DL reconstruction of JJA blocking frequencies **captures main blocking activity centers**
- Degree of separation of the centers depends on the model used for the temperature reconstruction

MJJA surface temperature anomaly

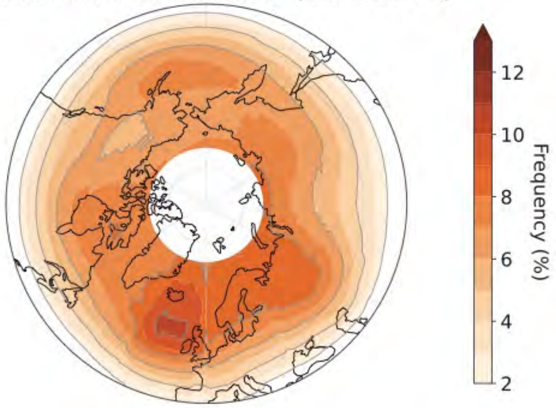


example input from NTREND-reconstruction

PaleoBlockNet

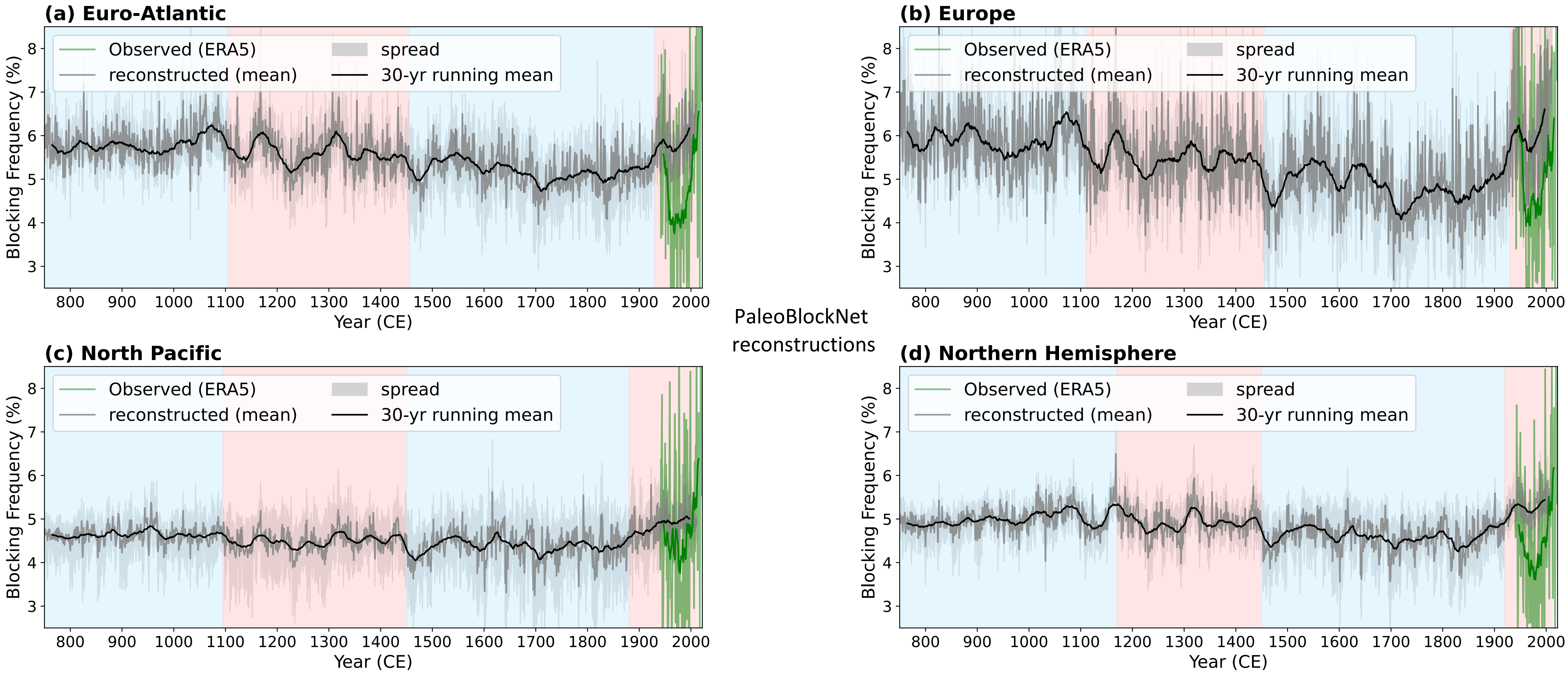


NTREND-based reconstruction (850-2005 CE)



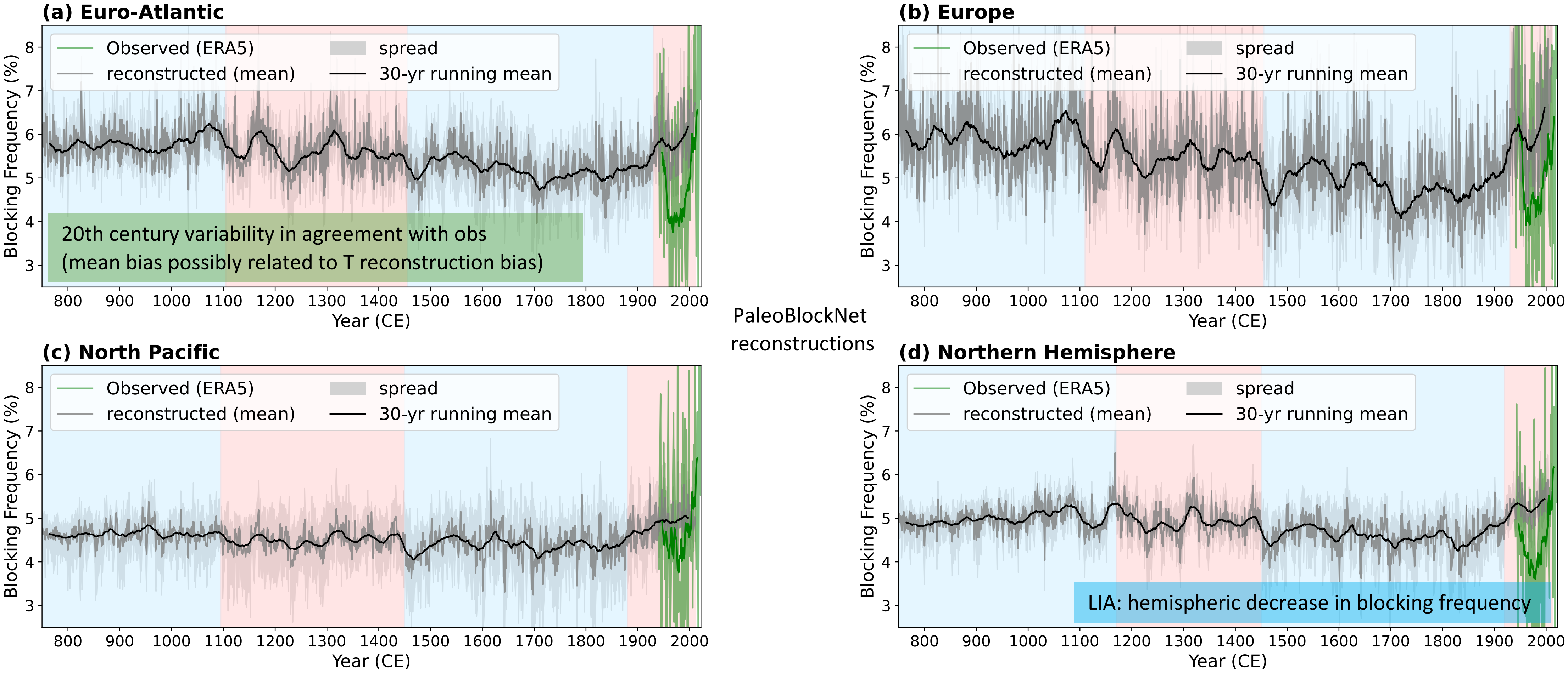
ensemble mean blocking frequency

Strong multidecadal variability in blocking frequency reflects known periods (LIA, MCA)



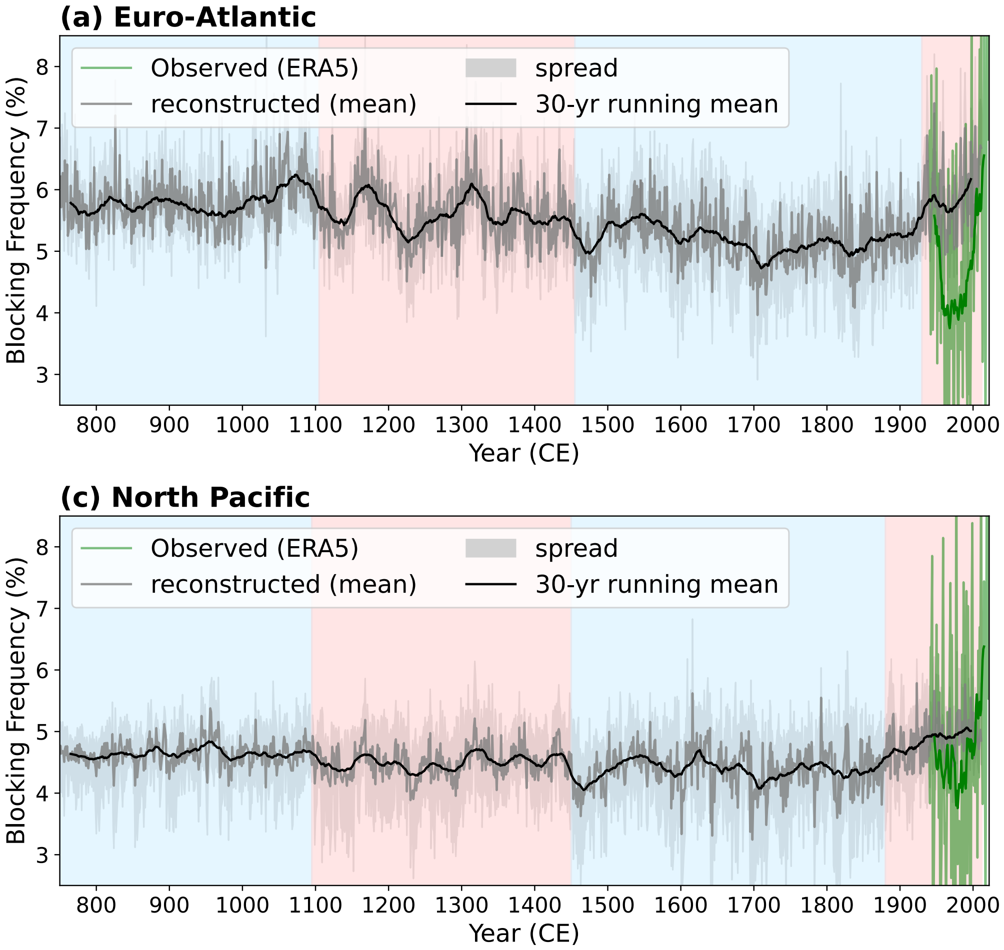
*shaded regimes identified by change-point detection and roughly coincide with the Medieval Climate Anomaly (MCA; 950-1250 CE) and Little Ice Age (LIA; 1450-1850 CE)

Strong multidecadal variability in blocking frequency reflects known periods (LIA, MCA)



*shaded regimes identified by change-point detection and roughly coincide with the Medieval Climate Anomaly (MCA; 950-1250 CE) and Little Ice Age (LIA; 1450-1850 CE)

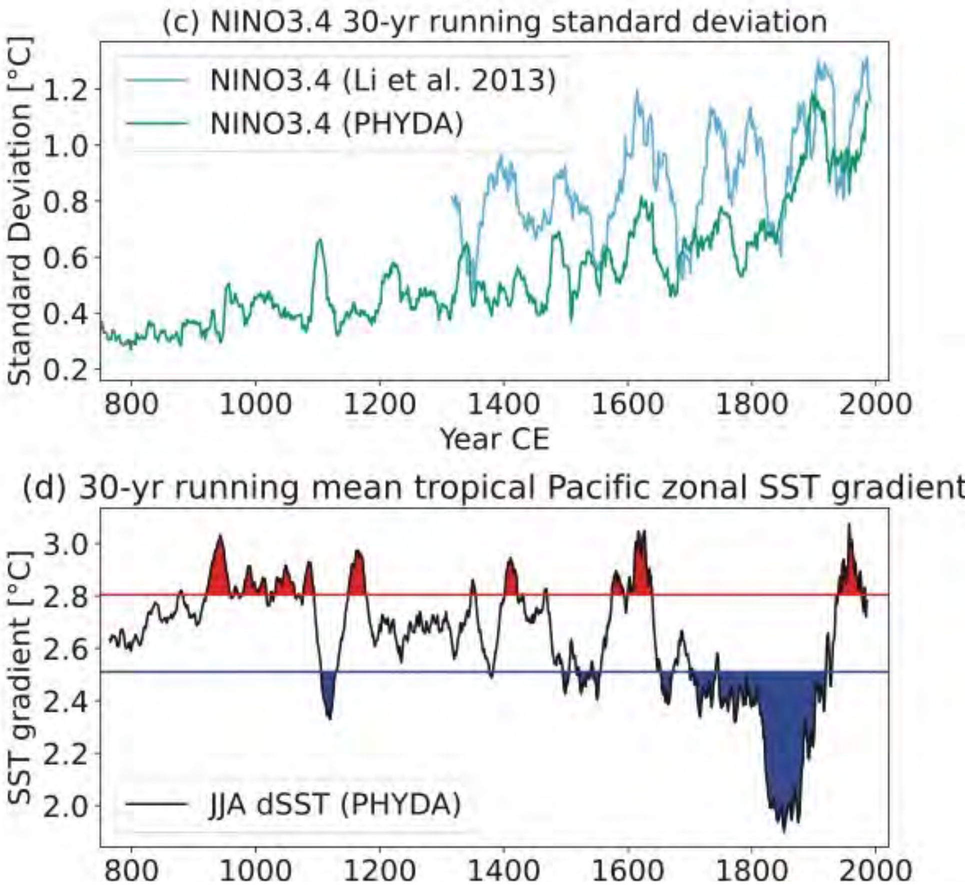
Blocking changes consistent with tropical Pacific variability



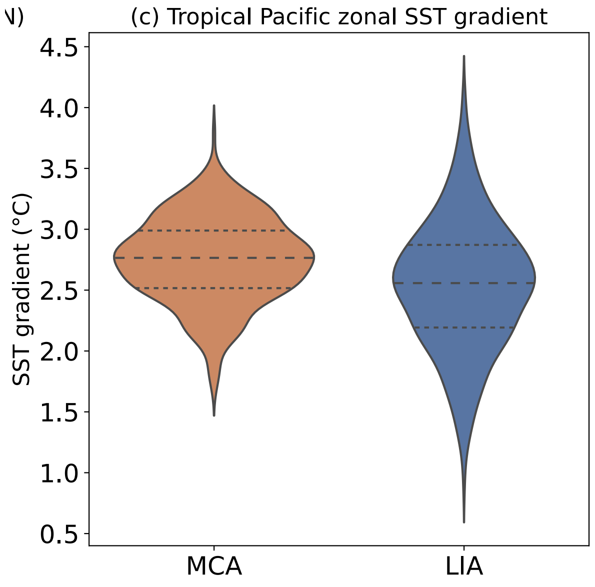
LIA blocking decrease is consistent with **weakened** tropical Pacific **zonal SST gradient** (Matsueda & Endo, 2017)

Increased ENSO-scale variability post 1600

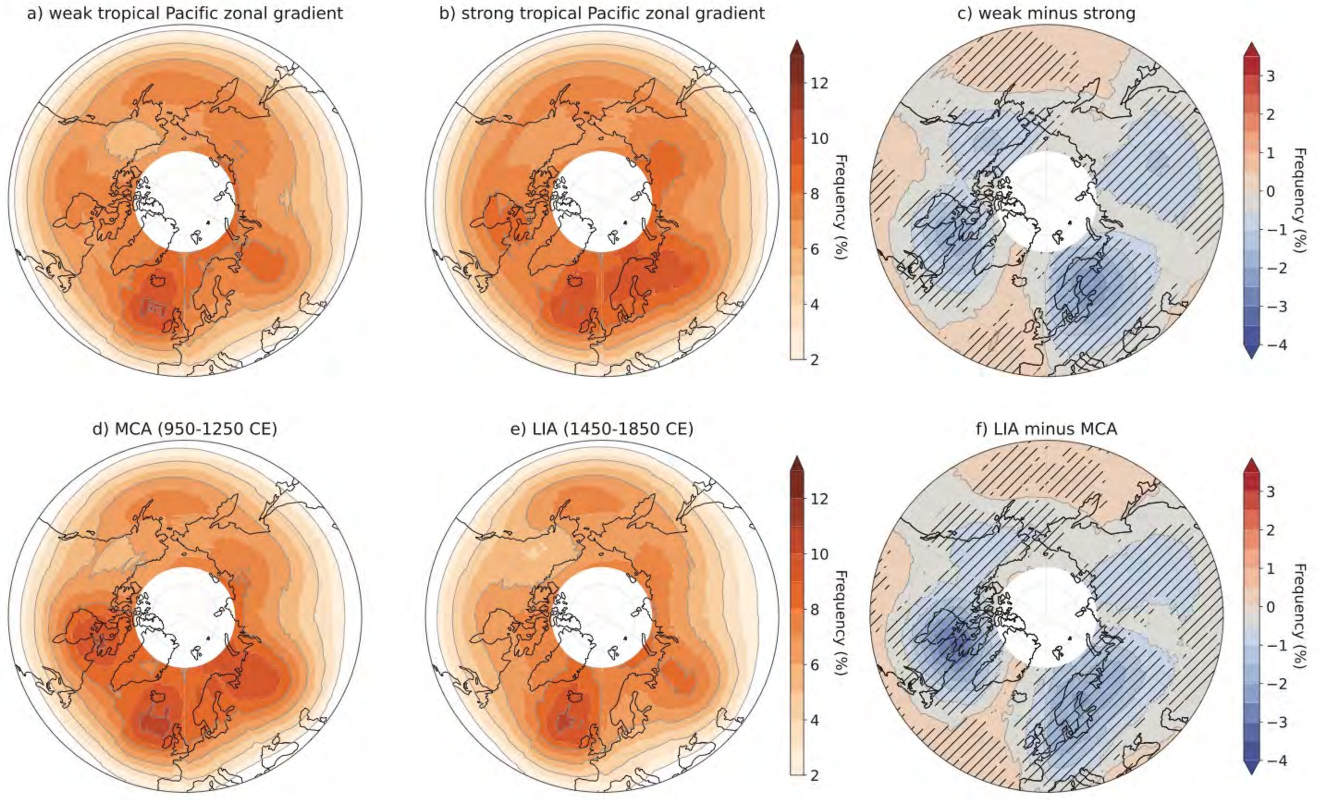
Recent increase possibly related **to La Nina-like** mean tropical Pacific state



Tropical Pacific drives Last Millennium changes in blocking frequency patterns



data: PHYDA reconstruction (Steiger et al. 2018)



Stronger eastern Pacific warming

→ stronger the JJA reduction in blocking in the EuroAtlantic sector (Matsueda & Endo, 2017)

→ small increase in Pacific blocking attributed to the changes in the ocean-land contrast in East Asia

Data: PaleoBlockNet reconstructions
Weak gradient: <25th %ile
Strong gradient: >75th %ile
Hatching: 2/3 of ensemble members agree in sign & significance

- The relationship between multiscale modes of climate variability and blocking **varies in strength** with season and location, depends on the **combination of mode phases**, and could be a **two-way interaction**

- **Faithfull simulation** of the patterns of climate variability and their relationship to blocking **remains a challenge**, but is important to consider for the next generation of models

- **Causality** is hard to establish, and **analogs** between past/future climate change and climate variability can be tricky

- **Extracting paleoweather signals from paleoclimate records** can help **constrain** the relationship between blocking and multiscale climate variability; e.g., DL-reconstructed Last Millennium Northern Hemisphere blocking variability highlights the **key role of the tropical Pacific**


PDO
image credit: DALL·E 3