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

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Wicked problems\textsuperscript{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

\textsuperscript{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)

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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*)

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**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?)

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**AO PHASES**

- **Negative phase**
- **Positive phase**

**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
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.

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\textsuperscript{1}/AO\textsuperscript{2}/PNA\textsuperscript{3}.

\textsuperscript{1}Garfinkel et al. 2012; Cassou, 2018; Lin et al. 2009 \textsuperscript{2}Zhou & Miller, 2005; L’Heureux & Higgins, 2008 \textsuperscript{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)

**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)\(^1\)

**NH:** increased, more persistent, concurrent NH blocking during \(+\text{ENSO} /-\text{PDO}\)

**NH:** decreased blocking during \(+\text{ENSO}/+\text{PDO}\) but less robust.

**SH:** increased blocking during \(+\text{ENSO}\) in both PDO phases (not shown)

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\(^1\) [Lupo et al. 2019; Lupo, 2021]

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

<table>
<thead>
<tr>
<th></th>
<th>Occurrence</th>
<th>Duration (days)</th>
<th>Intensity (BI)</th>
<th>% Simultaneous</th>
</tr>
</thead>
<tbody>
<tr>
<td>(+\text{PDO})</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>El Niño (6)</td>
<td>23.5</td>
<td>8.1</td>
<td>3.06</td>
<td>7.6</td>
</tr>
<tr>
<td>Neutral (15)</td>
<td>24.2</td>
<td>8.2</td>
<td>3.26</td>
<td>8.9</td>
</tr>
<tr>
<td>La Niña (2)</td>
<td>30.5</td>
<td>8.3</td>
<td>3.11</td>
<td>12.7</td>
</tr>
<tr>
<td>Total (23)</td>
<td>24.7</td>
<td>8.2</td>
<td>3.20</td>
<td>8.9*</td>
</tr>
<tr>
<td>(-\text{PDO})</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>El Niño (8)</td>
<td>38.1</td>
<td>9.5</td>
<td>3.17</td>
<td>26.3</td>
</tr>
<tr>
<td>Neutral (12)</td>
<td>37.4</td>
<td>9.9</td>
<td>3.03</td>
<td>28.9</td>
</tr>
<tr>
<td>La Niña (9)</td>
<td>31.3</td>
<td>8.6</td>
<td>3.12</td>
<td>16.8</td>
</tr>
<tr>
<td>Total (29)</td>
<td>35.7</td>
<td>9.4</td>
<td>3.09</td>
<td>24.4*</td>
</tr>
</tbody>
</table>

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
ENSO diversity (AKA flavors) has distinct impacts

- 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.
• 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

- **climatological blocking**
- **simulating ENSO diversity**
- simulating the **tropical convection response to ENSO diversity**, and
- 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)

Karamperidou & Narinesingh, in prep: ENSO diversity impacts on wintertime atmospheric blocking: mechanisms and energetics
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)
- **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

Karamperidou & Narinesingh, in prep: ENSO diversity impacts on wintertime atmospheric blocking: mechanisms and energetics
• 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?

Karamperidou & Narinesingh, in prep: *ENSO diversity impacts on wintertime atmospheric blocking: mechanisms and energetics*
- 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**.
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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
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

**PaleoBlockNet**

MJJA surface temperature anomaly

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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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median pattern correlation in the test dataset (1414 years): 0.78
Extracting paleoweather from paleoclimate

**NTREND network:**

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

*King et al. 2021*

*Figures from 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

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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)

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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

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

Questions? Suggestions? Collaborations? Contact: ckaramp@hawaii.edu