Seasonal Weather and its Prediction*

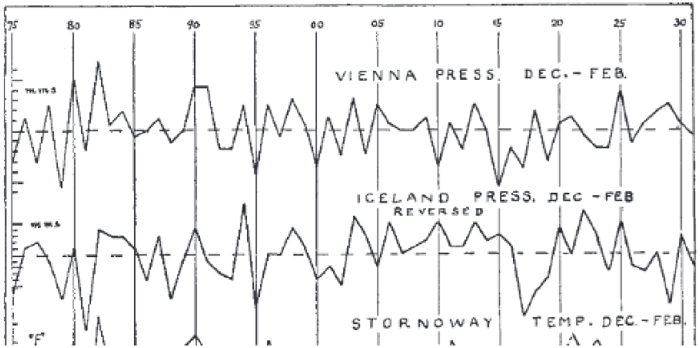
By SIR GILBERT T. WALKER, C.S.I., F.R.S.

THE economic importance of seasonal weather is obvious to most men who have lived in the tropics, and its scientific problems are full of interest. Unfortunately there is an additional motive for study, the threat of dangers ahead. For the difficulties of long-range forecasting are not in general adequately recognised, so that some of the most progressive countries in the world are inclined to make predictions on an insecure basis; their technical staff does not realise that though the prestige of meteorology may be raised for a few years by the issue of seasonal forecasts, the harm done to the science will inevitably outweigh the good if the prophecies are found unreliable.

In a country where conditions are so changeable from day to day as they are in England, it is natural that we should think in terms of wet or fine days rather than of wet or dry periods; but in the greater part of the British Empire the different seasons are much more sharply defined, and so their dominant features stand out more clearly. Also the vari-

of repute the artless remark of an author that if he were to limit his methods to those which would satisfy the criteria of reality, he would obtain few results of interest!

It will be convenient if I may here introduce a technical phrase. If we have series of values of two factors the variations of which are connected, there will be a certain proportion of the variations of each which are associated with those of the other, and this proportion is called the correlation coefficient between the series. If it is nearly unity the numbers vary closely together; if it is small



LECTURE 5:
Important climatic systems

ML-4430: Machine learning approaches in climate science

19 May 2021

El Niño Southern Oscillation

1

- What is the ENSO?
- Impacts
- Models of ENSO

North Atlantic Oscillation

2

- What is the NAO?
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- NAO in climate models

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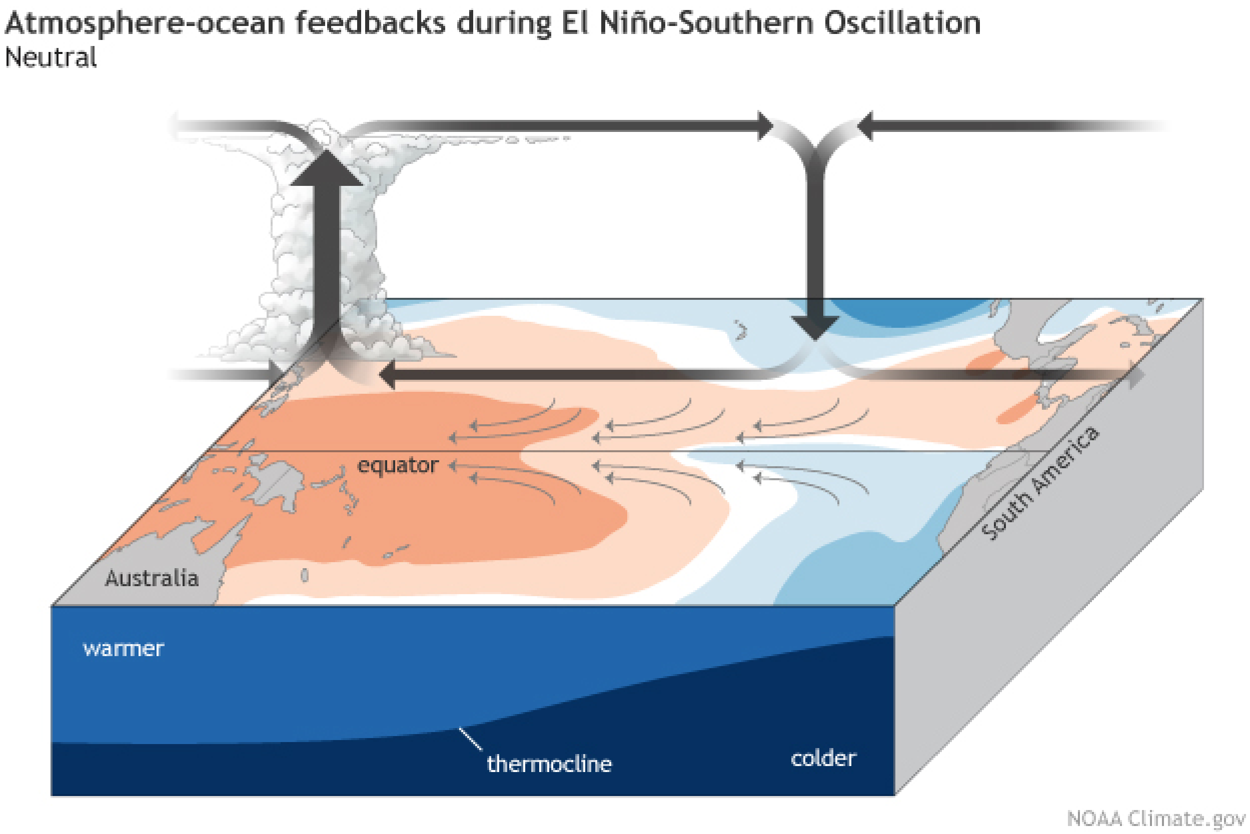
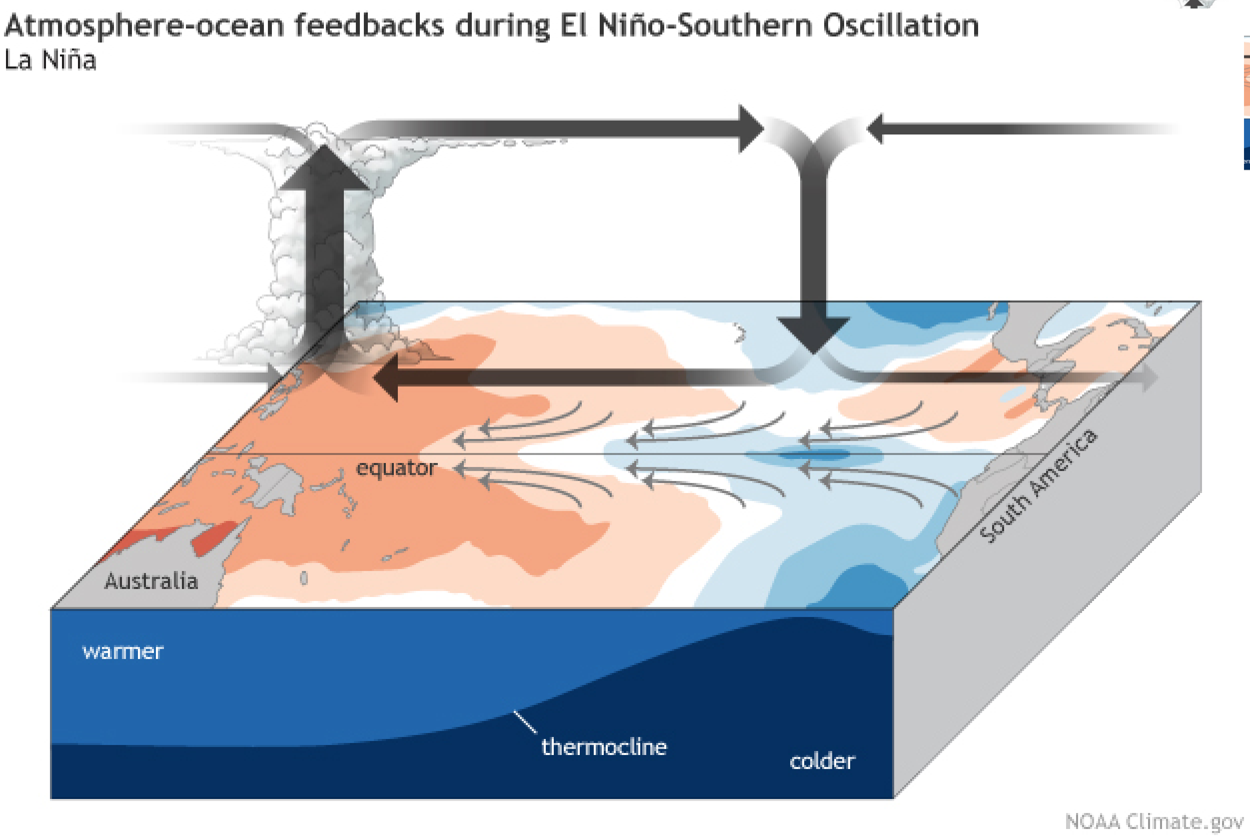
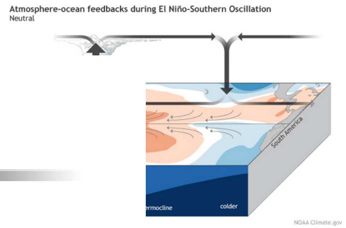


1. El Niño Southern Oscillation → What is ENSO?


Atmosphere-ocean feedbacks during El Niño-Southern Oscillation
La Niña
equator
Australia
South America
warmer
thermocline
colder
NOAA Climate.gov


Atmosphere-ocean feedbacks during El Niño-Southern Oscillation
Neutral
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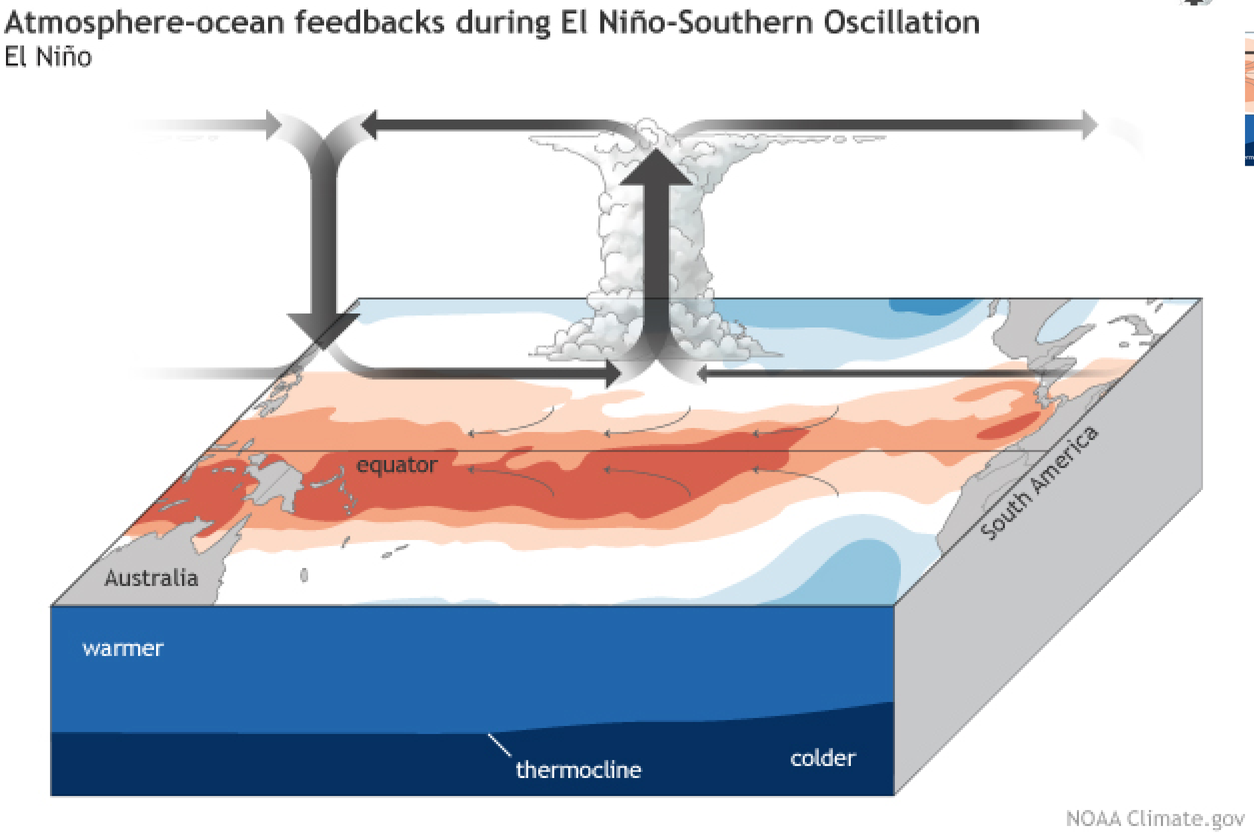

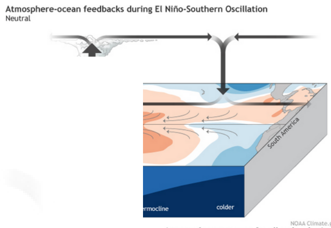

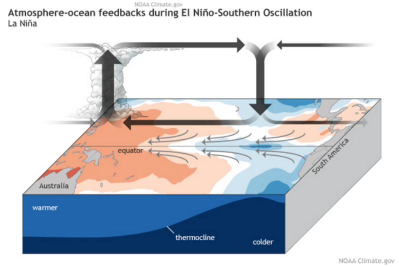

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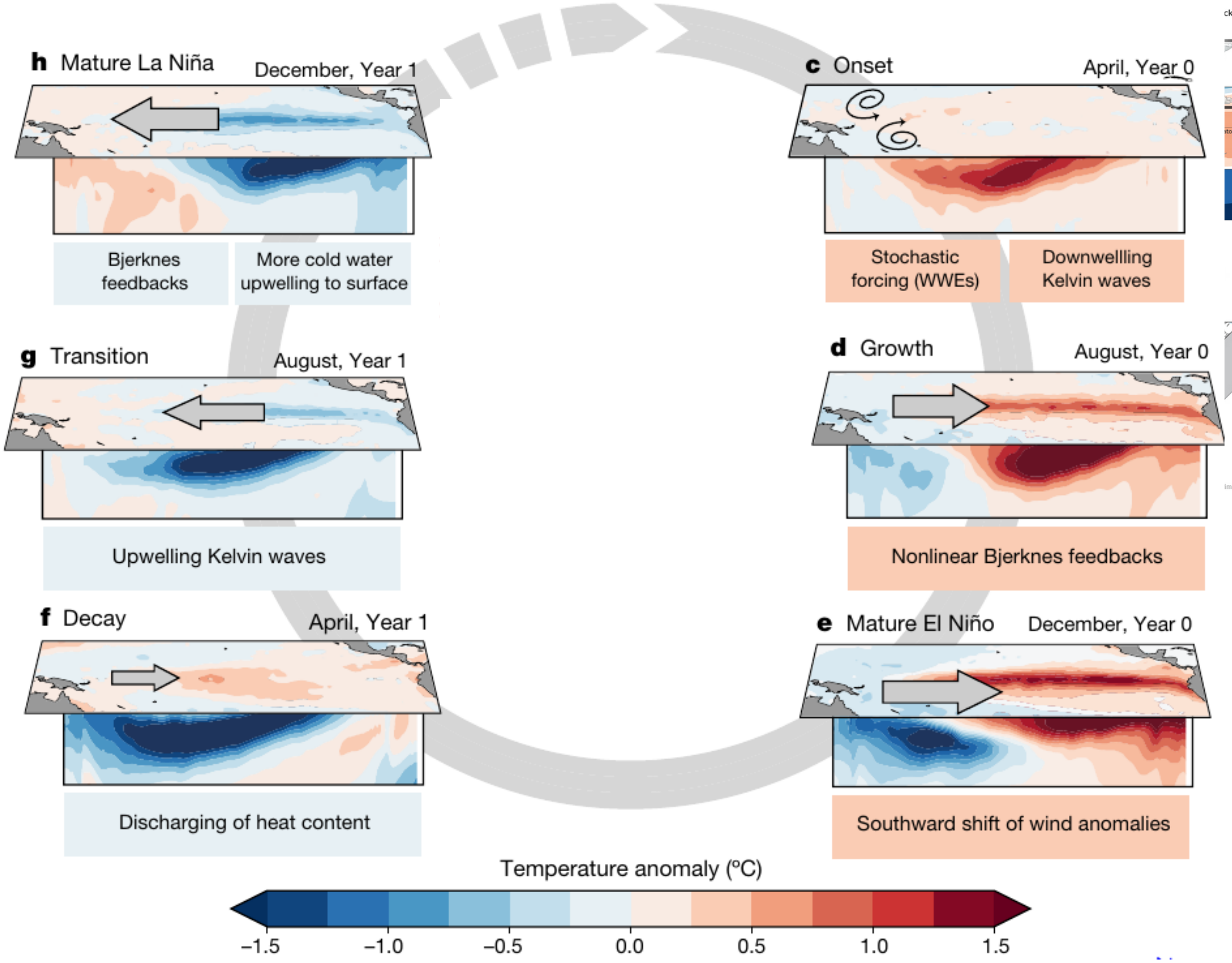

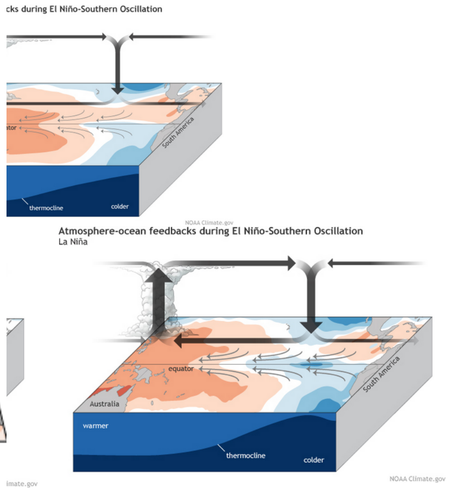

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1. El Niño Southern Oscillation → What is ENSO?

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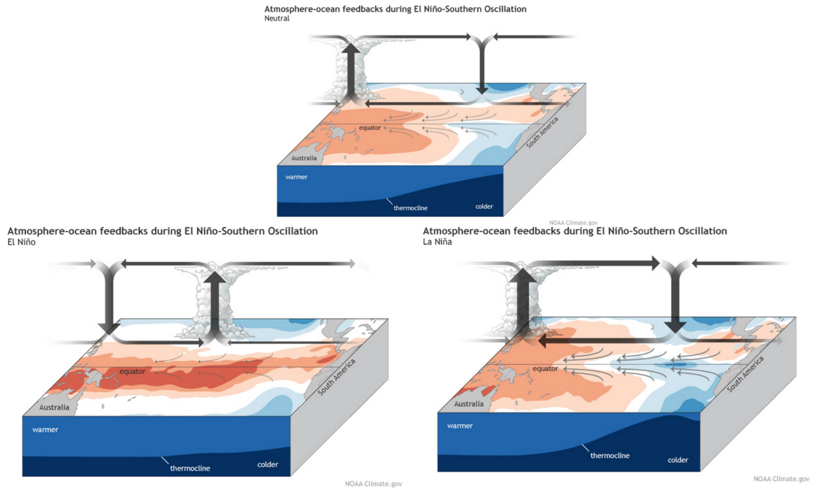
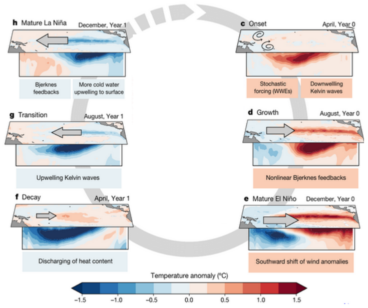
ENSO …

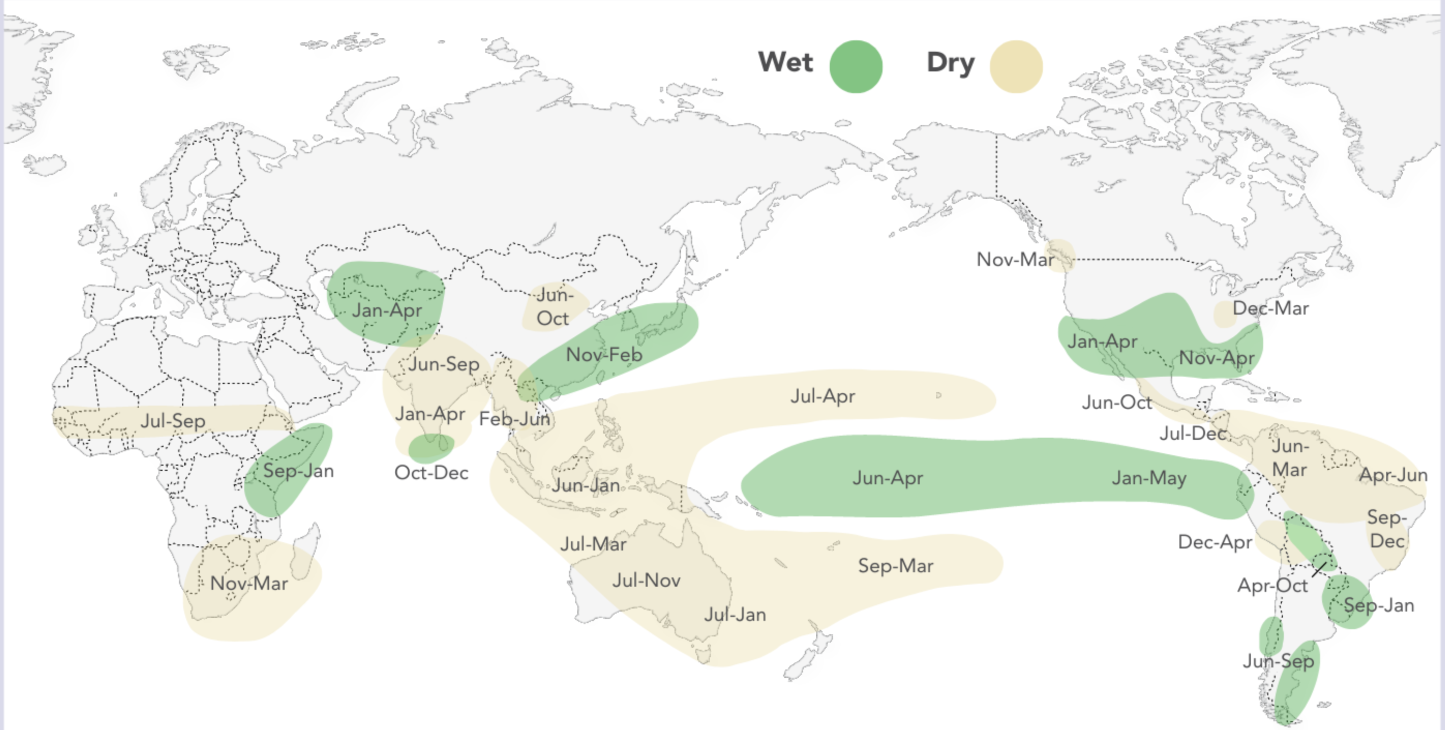
- Quasi-periodic oscillations of anomalously warm and cold waters in the equatorial Pacific
- Composed of El Niño (anomalous warm), La Niña (anomalous cold), and neutral (anomaly close to zero) phases
- El Niño (La Niña) is marked by a breakdown (intensification) of the Walker circulation
- Walker circulation is maintained by the Bjerknes feedback (between atmospheric winds and surface currents)





El Niño and Rainfall

El Niño conditions in the tropical Pacific are known to shift rainfall patterns in many different parts of the world. The regions and seasons shown on the map below indicate typical but not guaranteed impacts of La Niña. For further information, consult the probabilistic information* that the map is based on.



*http://iridl.ldeo.columbia.edu/expert/home/.lenssen/.ensoTeleconnections/
For more information on El Niño and La Niña: http://iri.columbia.edu/enso

Sources:
1. Lenssen, Goddard and Mason, 2020. Seasonal Forecast Skill of ENSO Teleconnection Maps. Weather Forecasting, 2387–2406
2. Mason and Goddard, 2001. Probabilistic precipitation anomalies associated with ENSO. Bull. Am. Meteorol. Soc. 82, 619-638

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https://iri.columbia.edu/our-expertise/climate/enso/

La Niña and Rainfall

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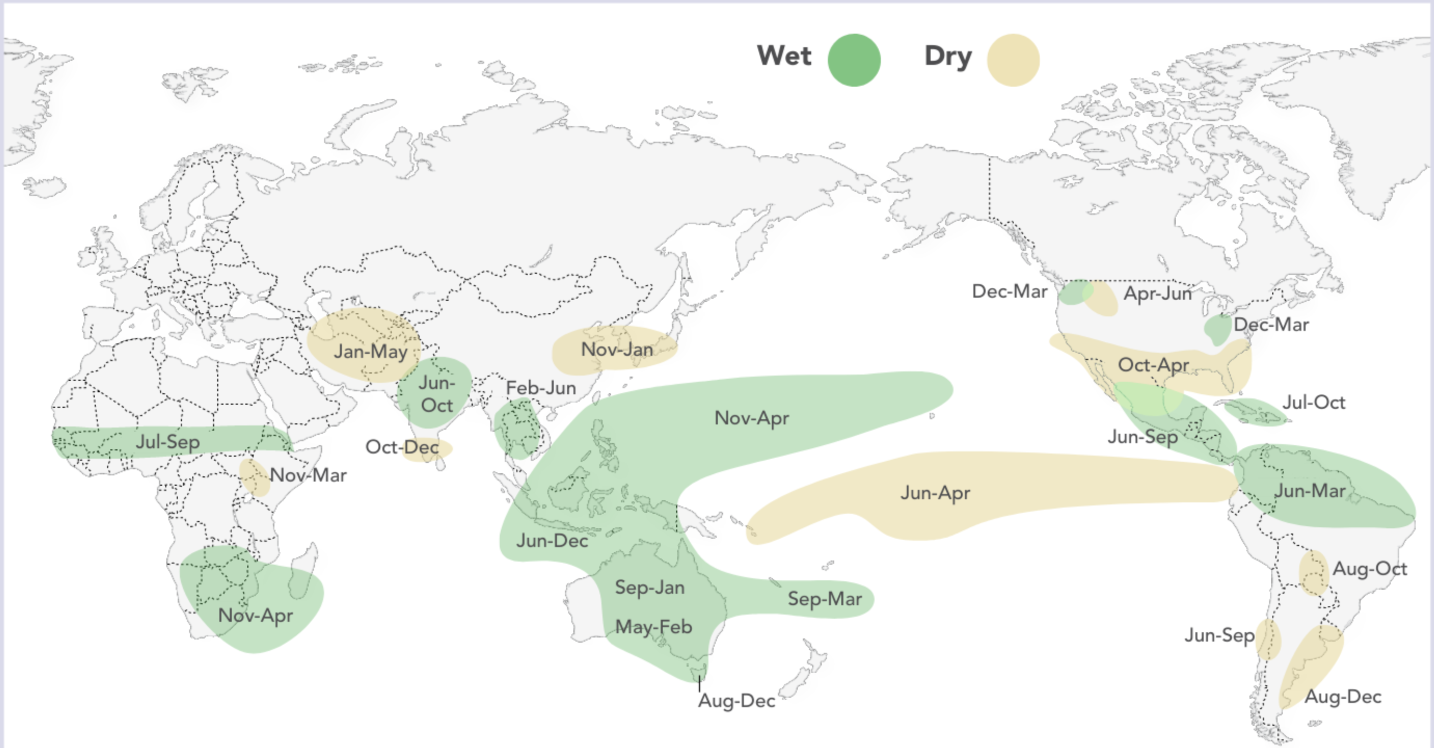

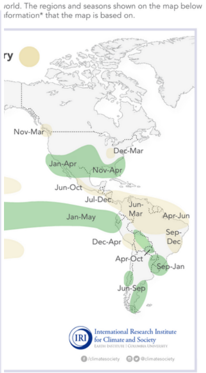

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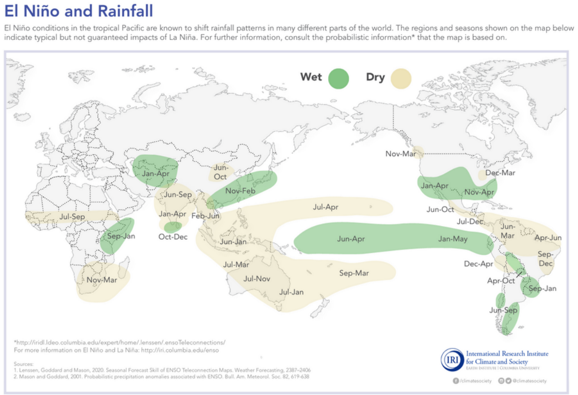
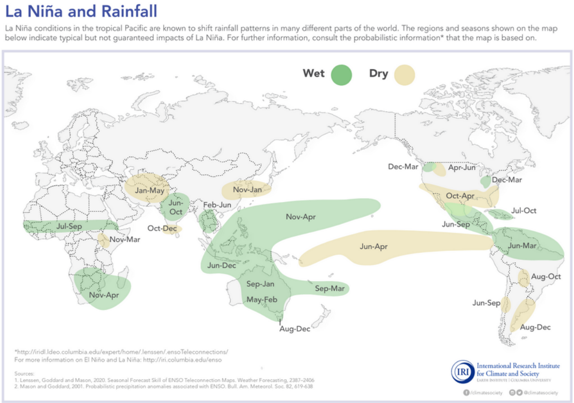
ENSO teleconnections

- The El Niño and La Niña phases are coincident with extreme weather around the globe
- El Niño is coincident with:
  - Dry conditions over South Asia, maritime continent, Australia, southern Africa, weatern Africa, and northern South America
  - Wet conditions over southern North America, south China sea region, eastern Africa, Arabia, and the central equatorial Pacific
- La Niña coincides with a reversal of El Niño effects (but not exactly)

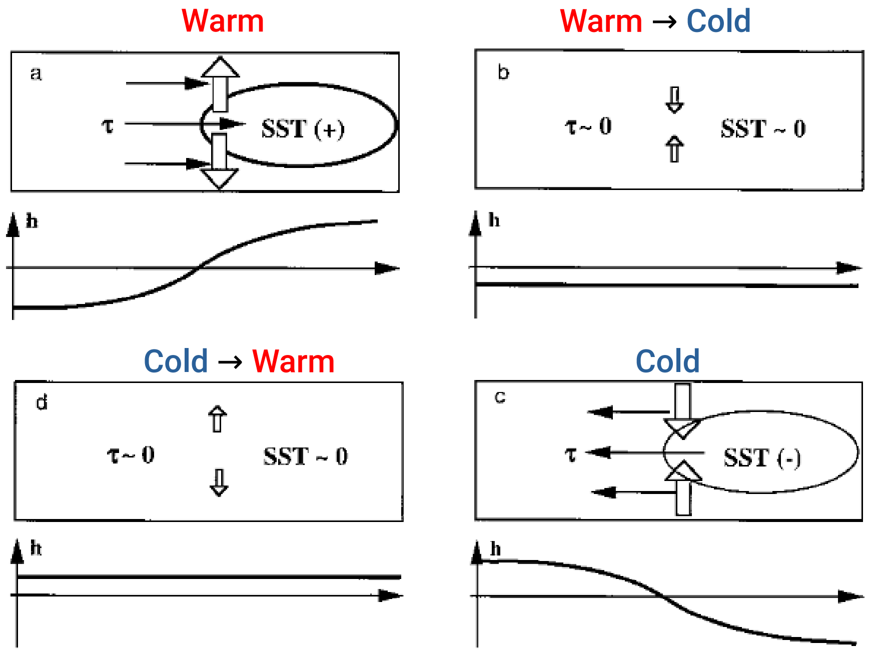




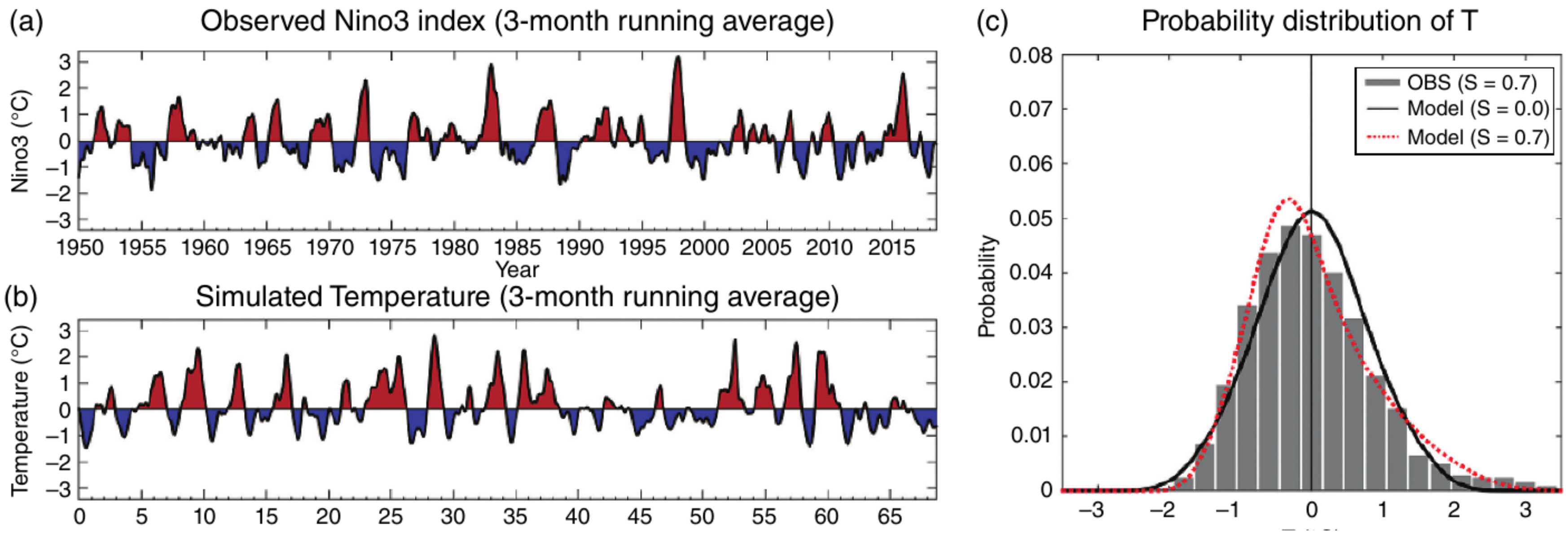
[4] The recharge oscillator of *Jin* [1997] is based on four equations for the western Pacific thermocline depth anomaly h_W, the eastern Pacific thermocline depth anomaly h_E, the central Pacific zonal wind stress anomaly τ, and the eastern Pacific SST anomaly T_E. There are two prognostic equations and two diagnostic equations:

$$
\begin{aligned}
\frac{d}{dt}h_W &= -r(h_W + \alpha\tau) \\
\frac{d}{dt}T_E &= -\epsilon_1(T_E - \gamma_h h_E) \qquad (1) \\
\tau &= bT_E \\
h_E &= h_W + \tau.
\end{aligned}
$$

Burgers, Jin, van Oldenburgh, Geophys. Res. Lett., 2005



Jin, J. Atmos. Sci., 1997



1. El Niño Southern Oscillation → Models of ENSO: Recharge Oscillator

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by the mean thermal structure of the ocean (in particular, the structure of the thermocline). These effects are important in determining the characteristic amplitude range of anomalies. Finally, due to the nature of the atmosphere–ocean coupling, there is a systematic, though somewhat variable, time delay between dynamical changes in the eastern ocean and associated large-scale fluctuations in equatorial wind stress. Due to the unique characteristics of equatorial ocean dynamics, this gives rise to a continuing succession of transitions between non–El Niño and El Niño states on interannual time scales. The transitions are a result of the linear shallow-water dynamics and not other, less familiar aspects of the model. The presence of nonlinear processes in the model additionally allows the possibility of aperiodicity.

If the model is correctly simulating the real ENSO cycle, then the results have a number of implications. First, a necessary precondition for the onset of a warm episode is above-normal equatorial heat content. This is not a sufficient condition, so it cannot take the place of a forecast model. However, it can identify favorable periods and can exclude others. Second, all the mechanisms essential to the ENSO cycle are contained within the tropical Pacific region alone. This does not preclude the possibility of teleconnections to other regions. Finally, we need not appeal to random forcing of unknown origin in order to account for the aperiodicity of ENSO; it can result from strictly deterministic processes. All of these bear favorably on the prospects for prediction of El Niño. Along these lines, we have found that the same model as presented here has skill in forecasting ENSO at lead times of 1–2 years (Cane et al., 1986). This, we believe, adds further weight to the argument that ENSO is largely controlled by deterministic processes in the tropical Pacific atmosphere–ocean system.

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APPENDIX

Governing Equations of the Coupled Model

The governing equations for the atmosphere (at iteration n) are as follows (see Zebiak, 1986):

$$+\epsilon u_a{}^n - \beta_0 y v_a{}^n = -(p^n/\rho_0)_x \tag{A1}$$

$$\epsilon v_a{}^n + \beta_0 y u_a{}^n = -(p^n/\rho_0)_y \tag{A2}$$

$$\epsilon(p^n/\rho_0) + c_a{}^2[(u_a{}^n)_x + (v_a{}^n)_y] = -\dot{Q}_s - \dot{Q}_1{}^{n-1} \tag{A3}$$

$$\dot{Q}_s = (\alpha T)\exp[\bar{T} - 30°\mathrm{C})/16.7°\mathrm{C}] \tag{A3a}$$

$$\dot{Q}_1{}^n = \beta[M(\bar{c} + c^n) - M(\bar{c})], \tag{A3b}$$

where

$$M(x) = \begin{cases} 0, & x \leqslant 0 \\ x, & x > 0. \end{cases} \tag{A3c}$$

In (A3a), $\bar{T}(x, y, t)$ is the prescribed monthly mean SST, and T is the anomalous SST. In (A3b), $\bar{c}(x, y, t)$ is the prescribed monthly mean surface wind convergence, and c^n is the anomalous convergence at iteration n, defined by

$$c^n \equiv -(u_a{}^n)_x - (v_a{}^n)_y. \tag{A3d}$$

The governing equations for the ocean (see Zebiak, 1984) are

$$u_t - \beta_0 y v = -g' h_x + \tau^{(x)}/\rho H - ru \tag{A4}$$

$$\beta_0 y u = -g' h_y + \tau^{(y)}/\rho H - rv \tag{A5}$$

$$h_t + H(u_x + v_y) = -rh, \tag{A6}$$

where

$$\mathbf{u} = H^{-1}(H_1 \mathbf{u}_1 + H_2 \mathbf{u}_2). \tag{A7}$$

The subscripts 1 and 2 refer to the surface layer and underlying layer, respectively.

The equations governing the shear between layers 1 and 2 are

$$r_s u_s - \beta_0 y v_s = \tau^{(x)}/\rho H_1 \tag{A8}$$

$$r_s v_s + \beta_0 y u_s = \tau^{(y)}/\rho H_1, \tag{A9}$$

where $\mathbf{u}_s \equiv \mathbf{u}_1 - \mathbf{u}_2$.

Equations (A4)–(A9) allow the surface current $\mathbf{u}_1$ to be determined. From this, the entrainment velocity is calculated:

$$w_s = H_1[(u_1)_x + (v_1)_y]. \tag{A10}$$

The temperature equation for the surface layer is, then,

$$\frac{\partial T}{\partial t} = -\mathbf{u}_1 \cdot \nabla(\bar{T} + T) - \bar{\mathbf{u}}_1 \cdot \nabla T - \{M(\bar{w}_s + w_s) - M(\bar{w})\} \times \bar{T}_z - M(\bar{w}_s + w_s)\frac{T - T_e}{H_1} - \alpha_s T, \tag{A11}$$

where $\bar{\mathbf{u}}_1(x, y, t)$ and $\bar{w}_s(x, y, t)$ are the mean horizontal currents and upwelling, respectively, $\bar{T}(x, y, t)$ is the prescribed mean SST, and $\bar{T}_z(x)$ is the prescribed mean vertical temperature gradient. The entrainment temperature anomaly, T_e, is defined by

$$T_e = \gamma T_{\mathrm{sub}} + (1 - \gamma)T. \tag{A12}$$

T_{sub} has the form

$$T_{\mathrm{sub}} = \begin{cases} T_1\{\tanh[b_1(\bar{h} + h)] - \tanh(b_1\bar{h})\}, & h > 0 \\ T_2\{\tanh[b_2(\bar{h} - h)] - \tanh(b_2\bar{h})\}, & h < 0, \end{cases} \tag{A13}$$

where $\bar{h}(x)$ is the prescribed mean upper layer depth.

Parameter values used for the coupled simulation are as follows:

$$\epsilon = (2\ \mathrm{days})^{-1}, \quad c_a = 60\ \mathrm{m\,s^{-1}}, \quad \alpha = 0.031\ \mathrm{m^2\,s^{-3}/°C},$$

$$\beta = 1.6 \times 10^4\ \mathrm{m^2\,s^{-2}},$$

$$r = (2.5\ \mathrm{years})^{-1},$$

$$c \equiv (g'H)^{1/2} = 2.9\ \mathrm{m\,s^{-1}}, \quad H = 150\ \mathrm{m},$$

$$H_1 = 50\ \mathrm{m},$$

$$r_s = (2\ \mathrm{days})^{-1}, \quad \alpha_s = (125\ \mathrm{days})^{-1},$$

$$\gamma = 0.75, \quad T_1 = 28°\mathrm{C}, \quad T_2 = -40°\mathrm{C},$$

$$b_1 = (80\ \mathrm{m})^{-1}, \quad b_2 = (33\ \mathrm{m})^{-1}.$$

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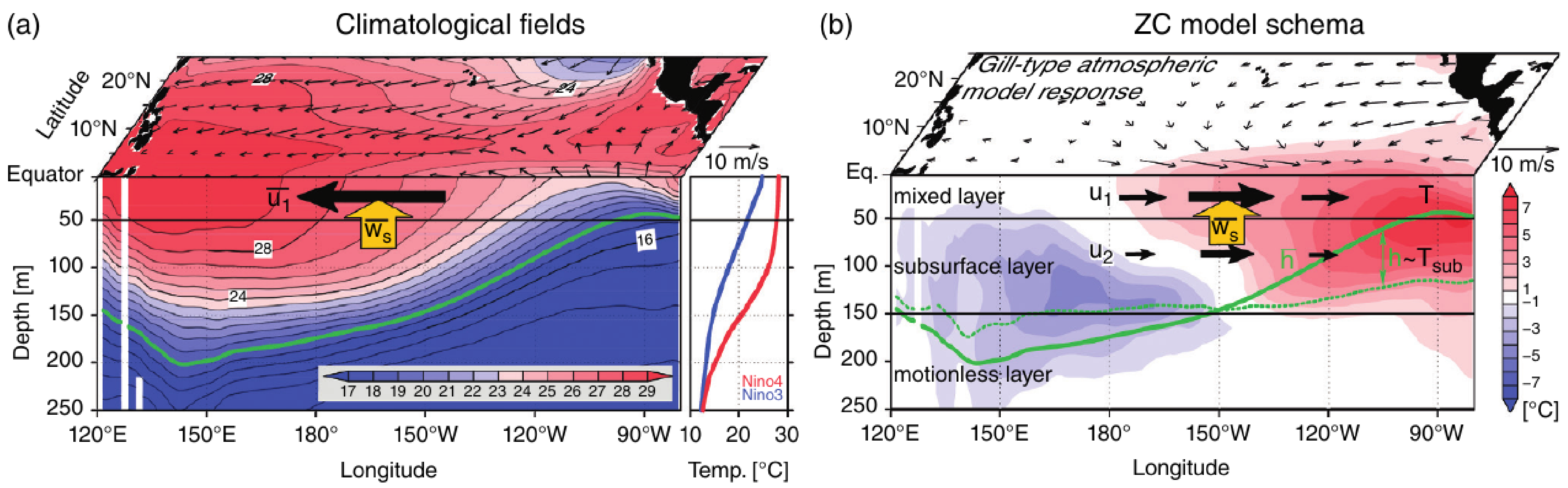
1. El Niño Southern Oscillation → Models of ENSO: Cane-Zebiak



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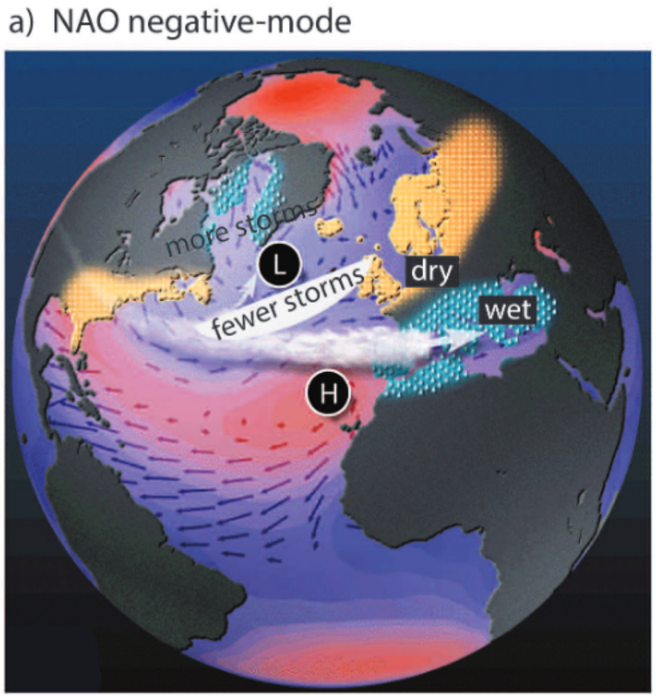
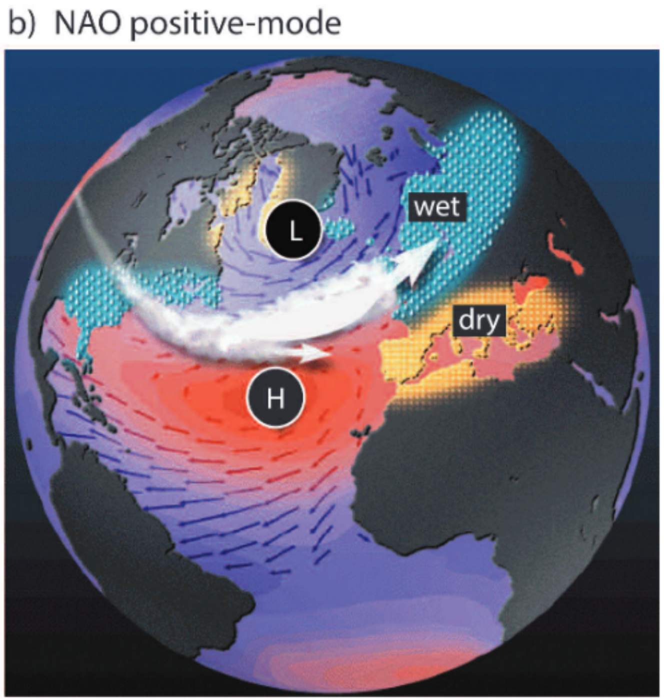
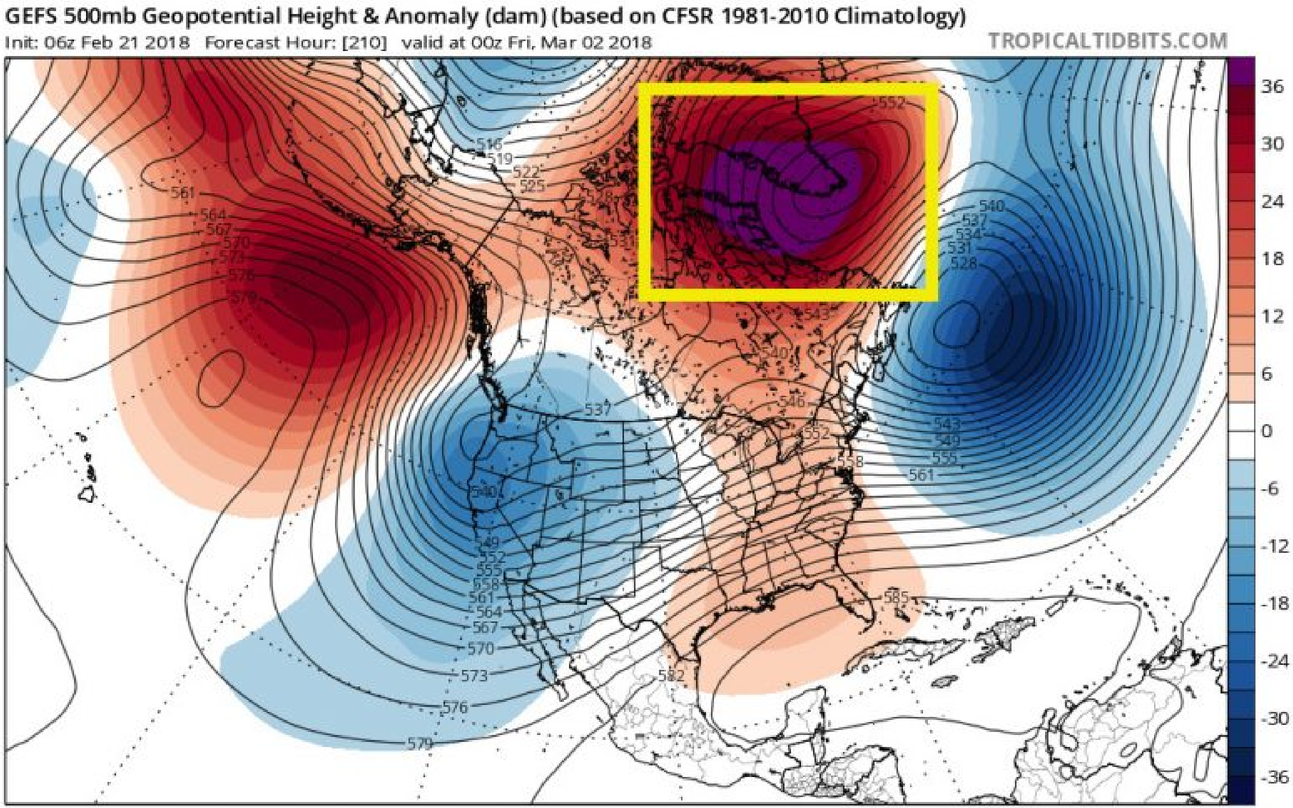
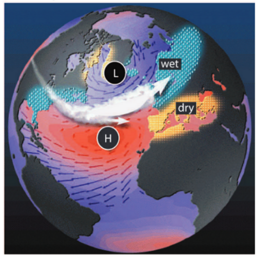




2. North Atlantic Oscillation → What is the NAO?



b) NAO positive-mode



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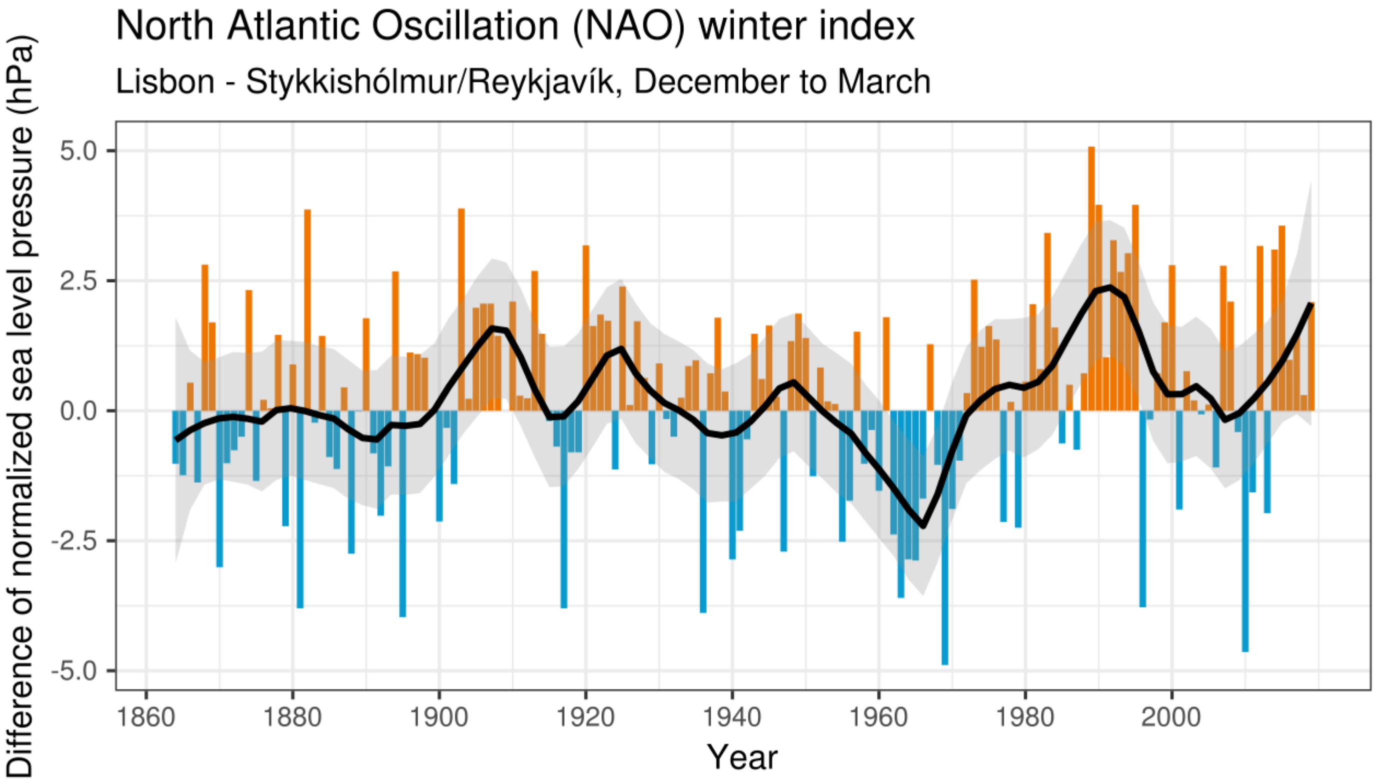
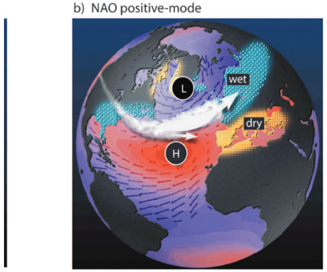
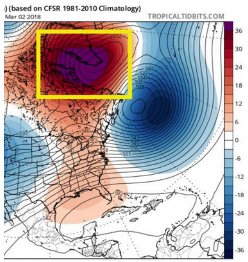


NAO Index Data provided by the Climate Analysis Section, NCAR, Boulder, USA, Hurrell (2003)
Updated regularly. Accessed 2020-11-01

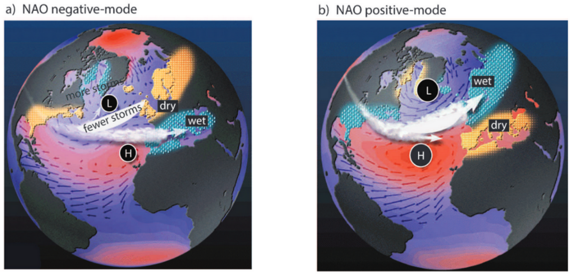


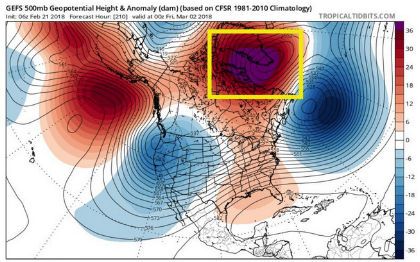


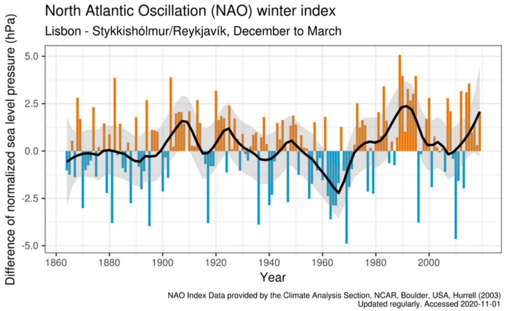
2. North Atlantic Oscillation → What is the NAO?

NAO

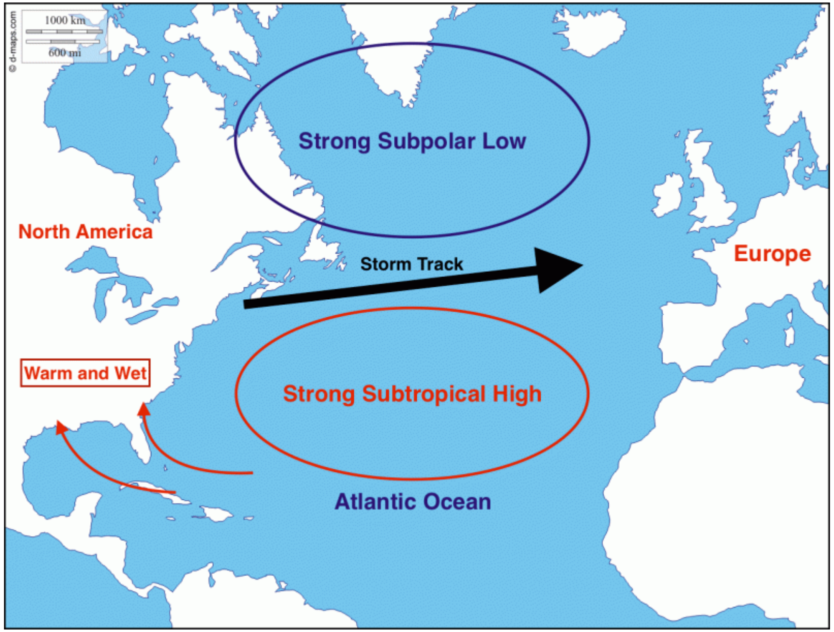
- Alternating pressure difference over the Atlantic between Iceland and Azores
- Caused due to shifting location of the Icelandic Low and the Azores High
- Influences North American and West European weather
- The oscillation is not obvious, and has complicated interdecadal variability

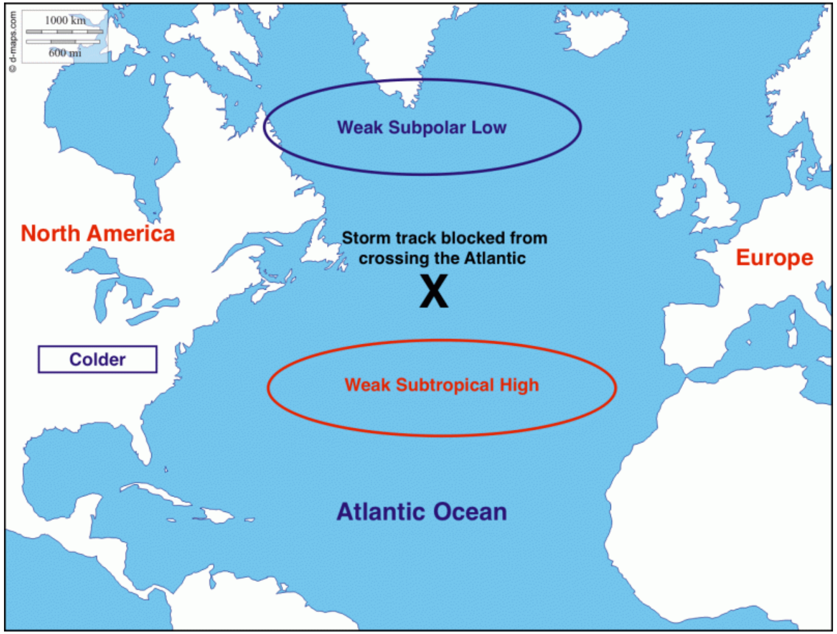




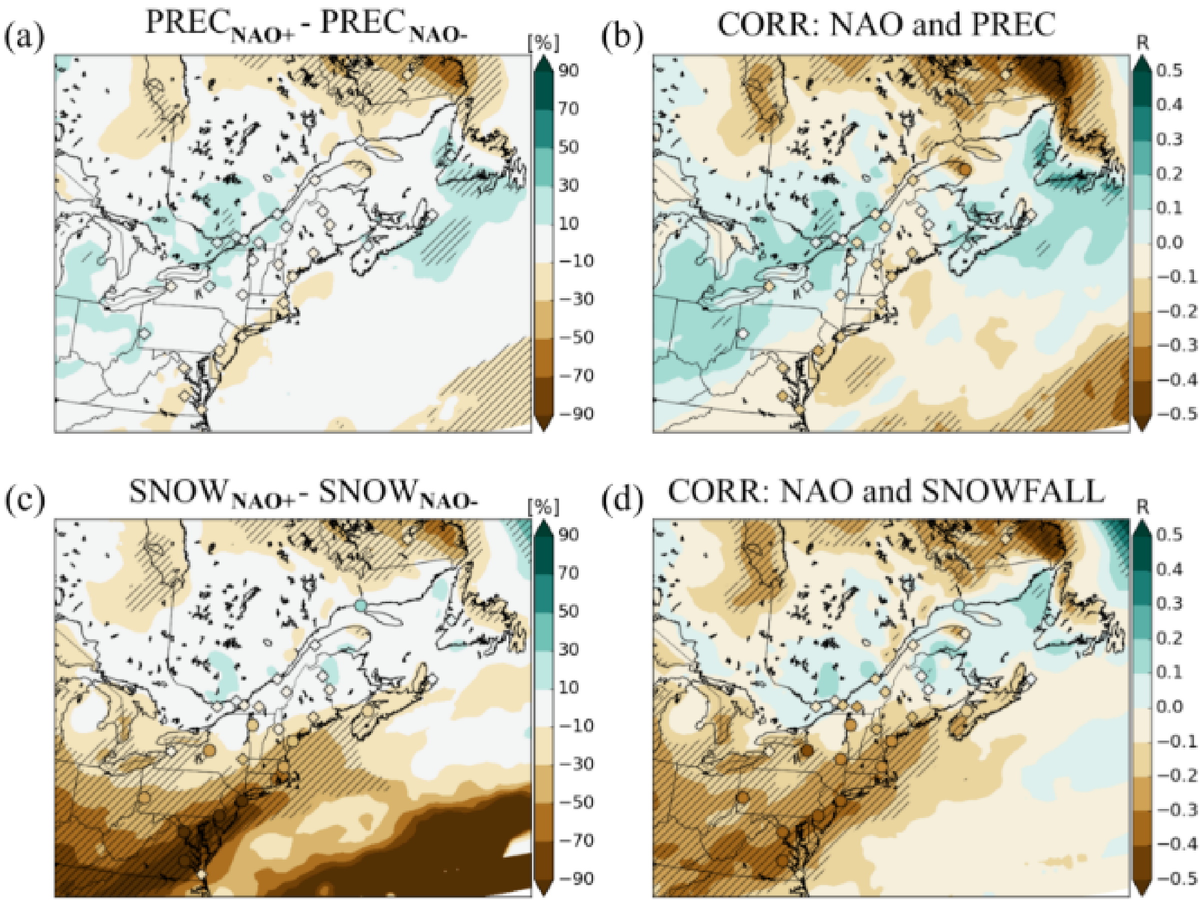


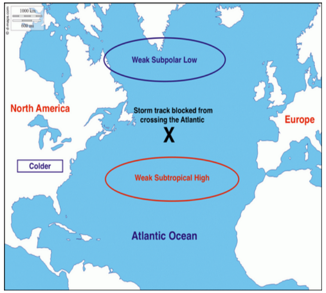
http://weather.umd.edu/2018/02/21/north-atlantic-oscillation-expected-plummet-means-us/





2. North Atlantic Oscillation → Impacts





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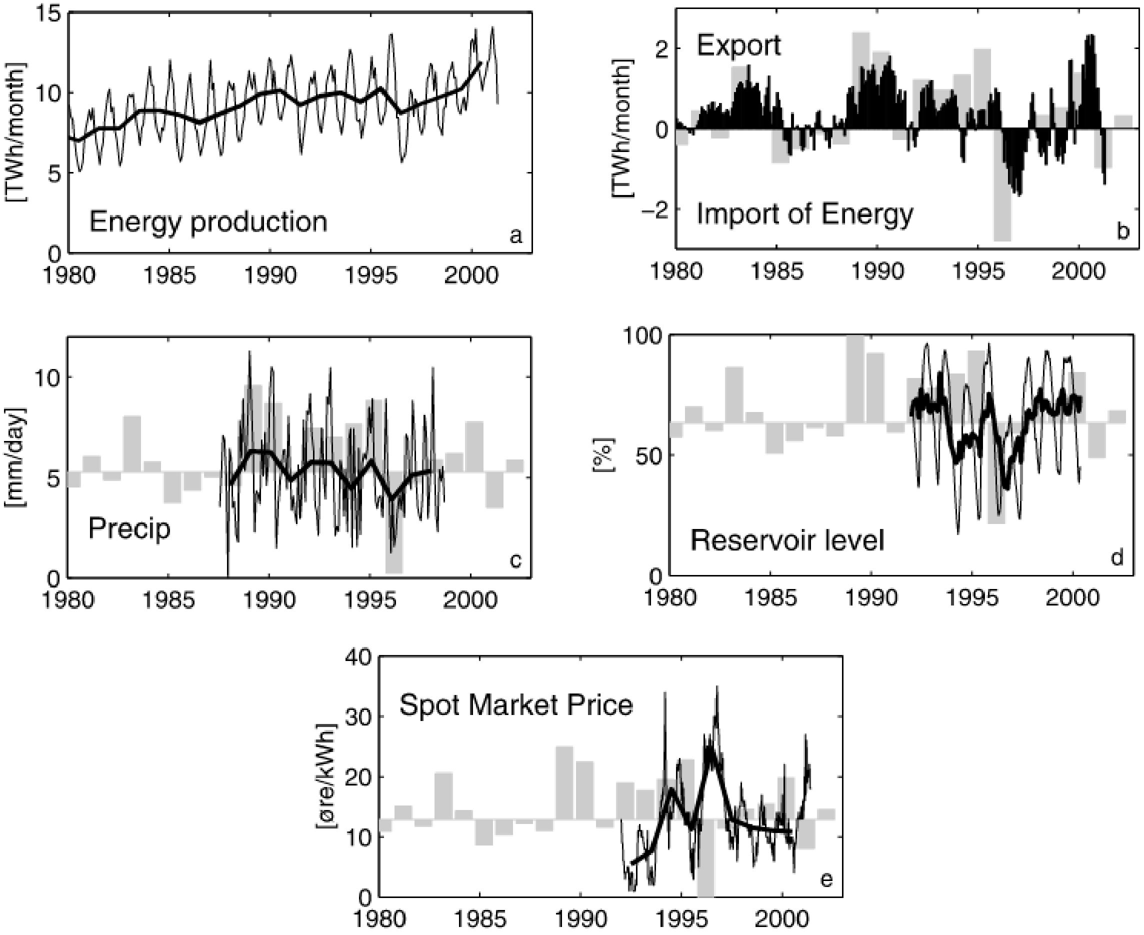

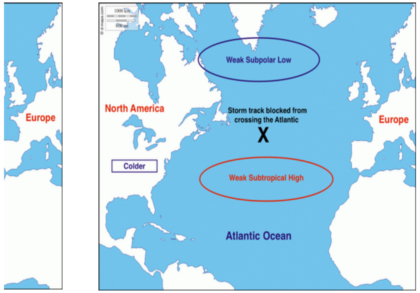

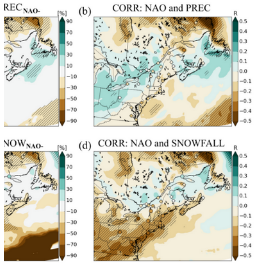

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2. North Atlantic Oscillation → Impacts

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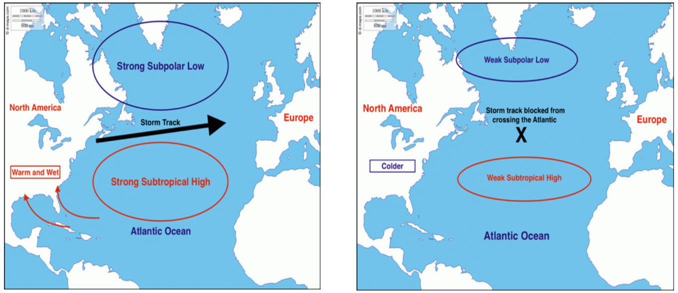
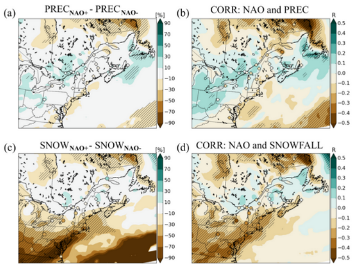
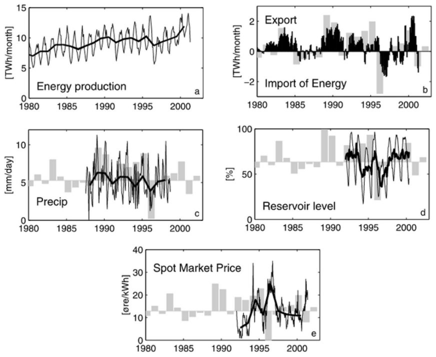
NAO impacts ...

- Storm tracks in the continental US
- Snowfall in the United States
- Heat waves over northwester Europe
- Storms over Southern Europe and the Mediterranean region
- Hydroelectric energy consumption in Norway exceeds consumption in NAO+ phases, enabling energy exports







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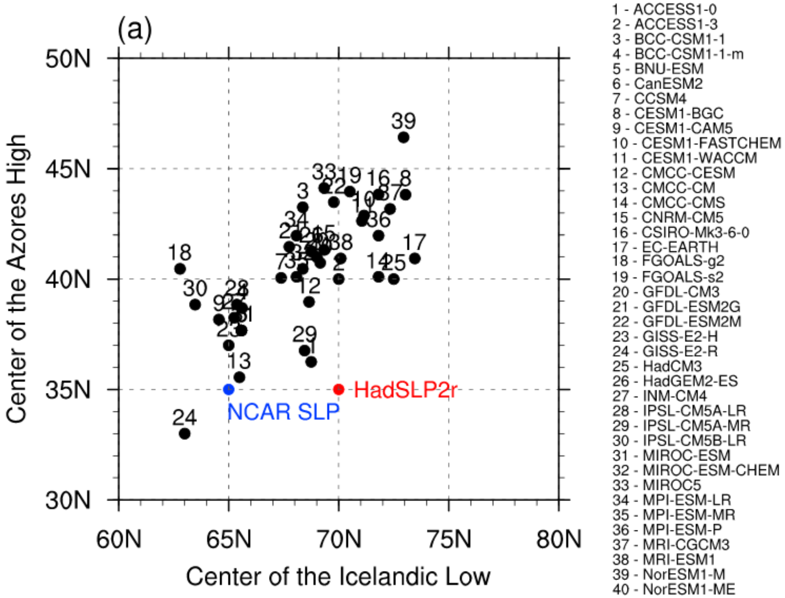
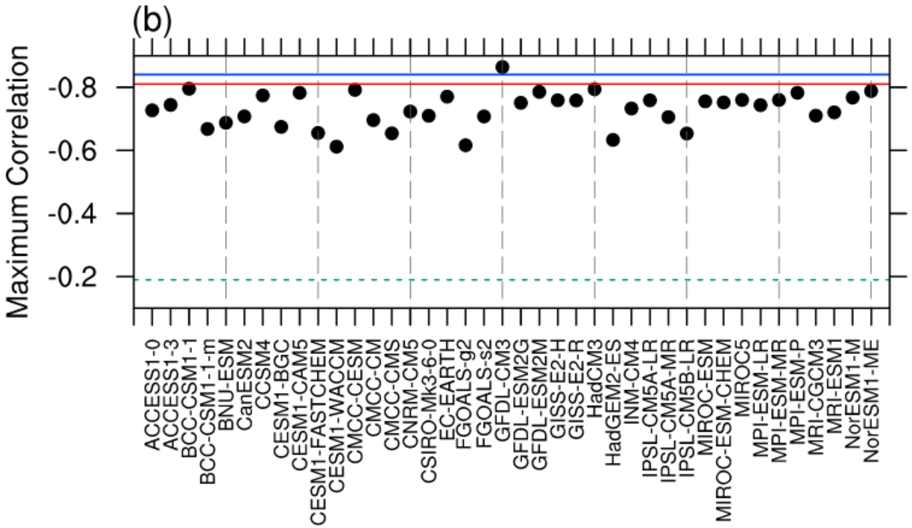
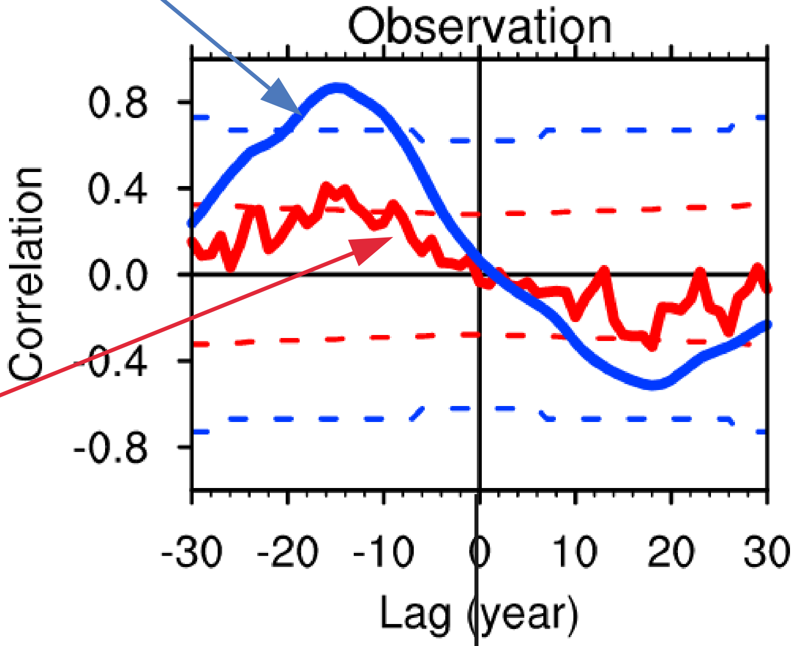
2. North Atlantic Oscillation → NAO in climate models





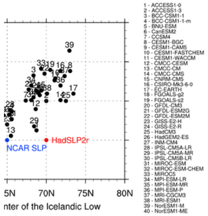
2. North Atlantic Oscillation → NAO in climate models

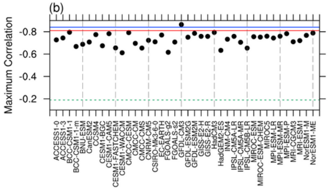
From 11 year averaged data



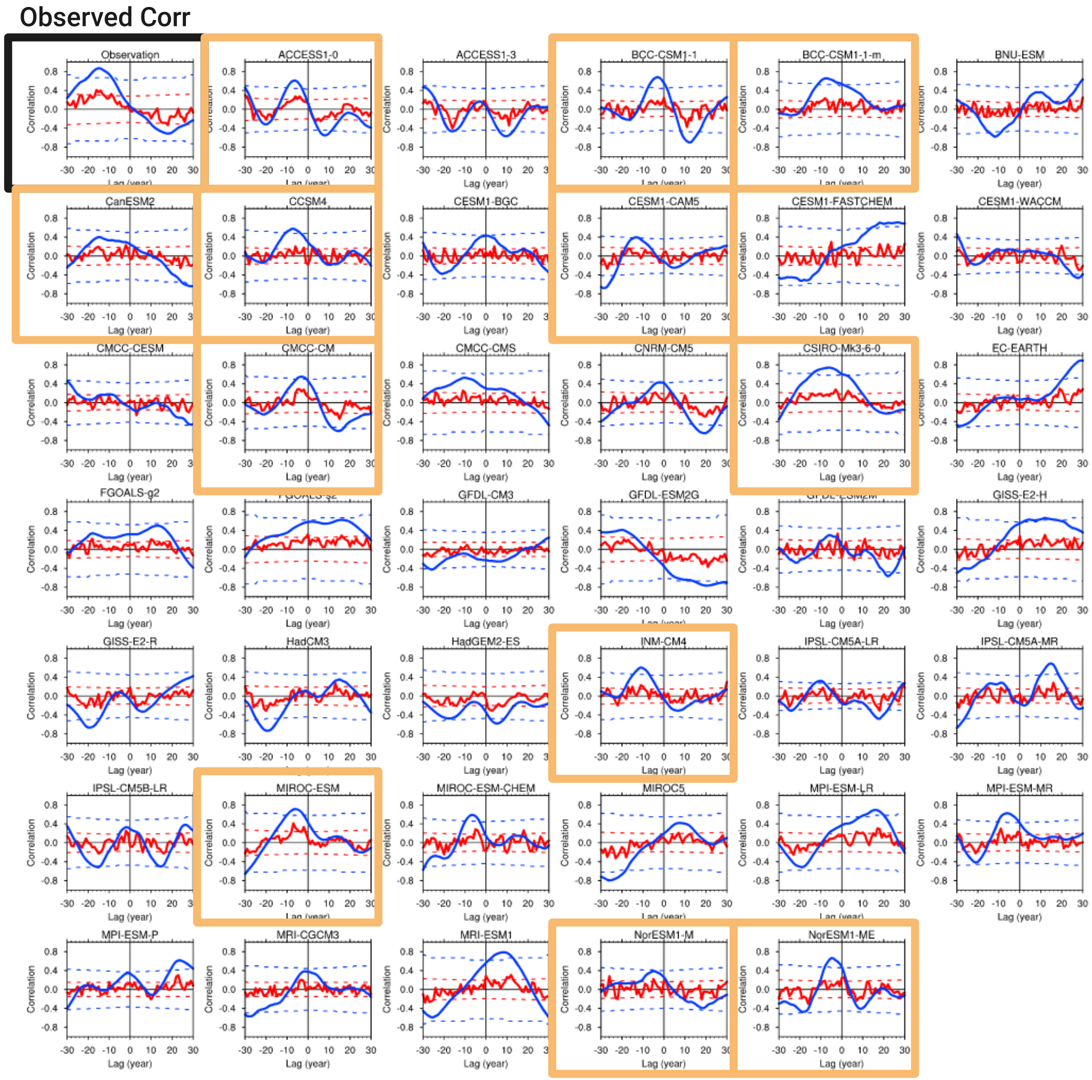
From annual data

NAO leads NHT ⟵⟶ NHT leads NAO





Wang et al., JGR Atmospheres, 2017



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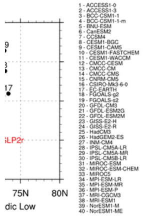

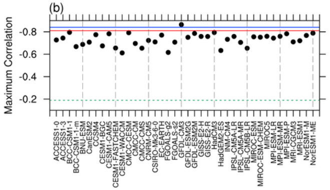

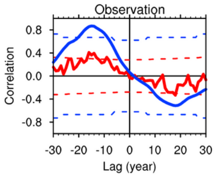

Bedartha Goswami

2. North Atlantic Oscillation → NAO in climate models

NAO in CMIP5 models …

- Has a nothward bias for the central location of the Azores High
- Underestimates correlation between SLPs at middle and high latitudes
- Only around 12 models of the CMIP5 show NAO leading NHT
- Inter-decadal variability of the NAO needs to be improved in GCMs

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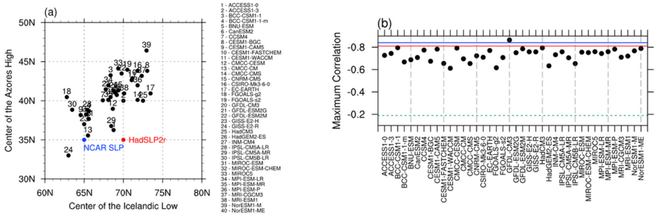
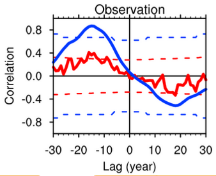
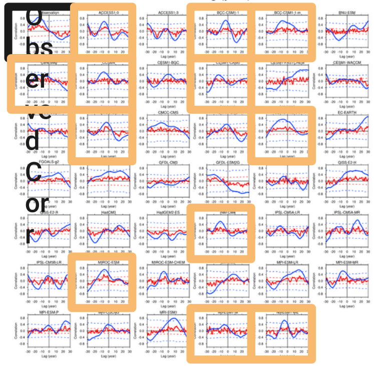






El Niño Southern Oscillation

1

- What is the ENSO?
- Impacts
- Models of ENSO

North Atlantic Oscillation

2

- What is the NAO?
- Impacts
- NAO in climate models

Arctic Oscillation

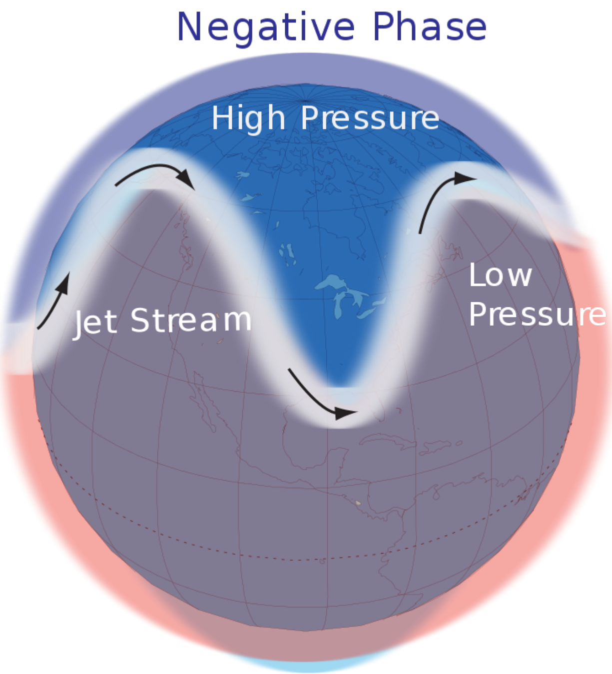
3

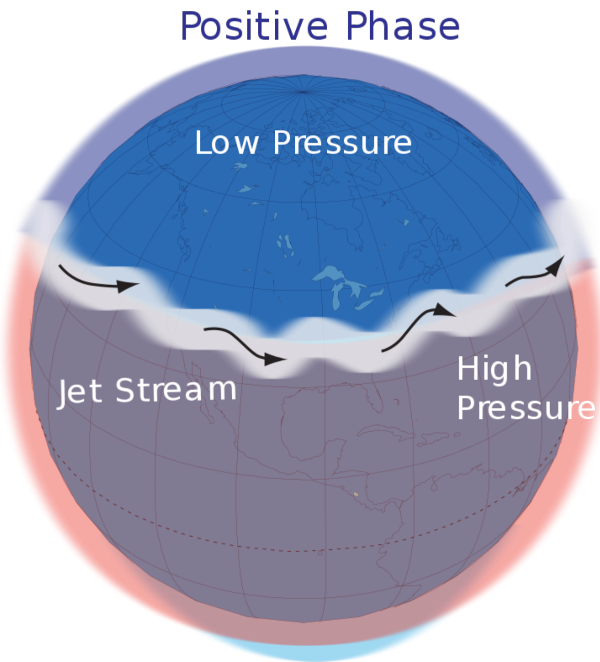
- What is the AO?
- Impacts
- AO in climate models

Indian Ocean Dipole

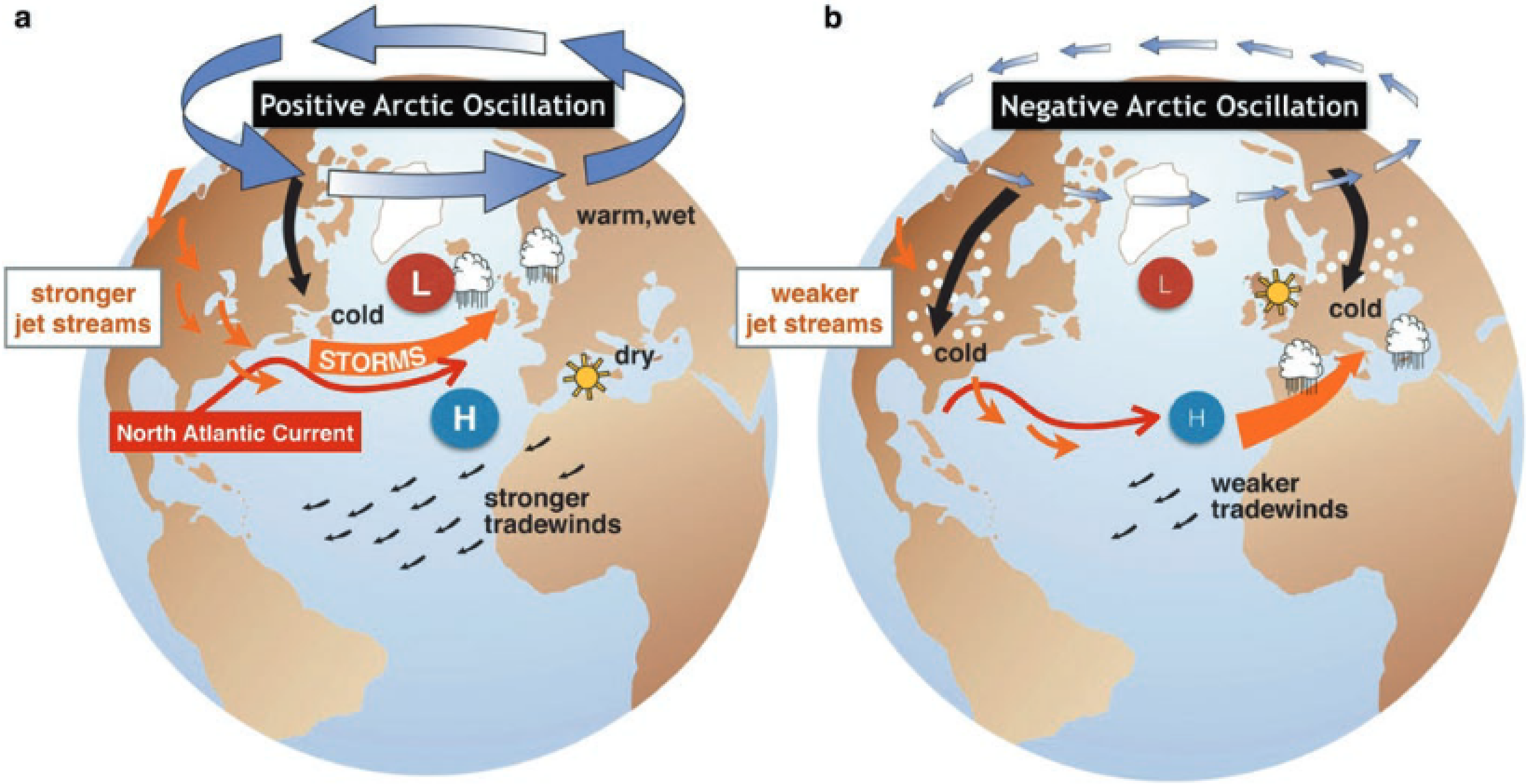
4

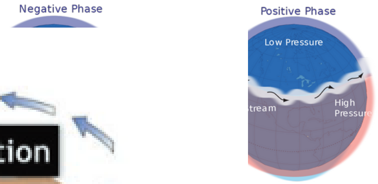
- What is the IOD?
- *Impacts*
- ~~IOD in climate models~~


Negative Phase
High Pressure
Jet Stream
Low Pressure

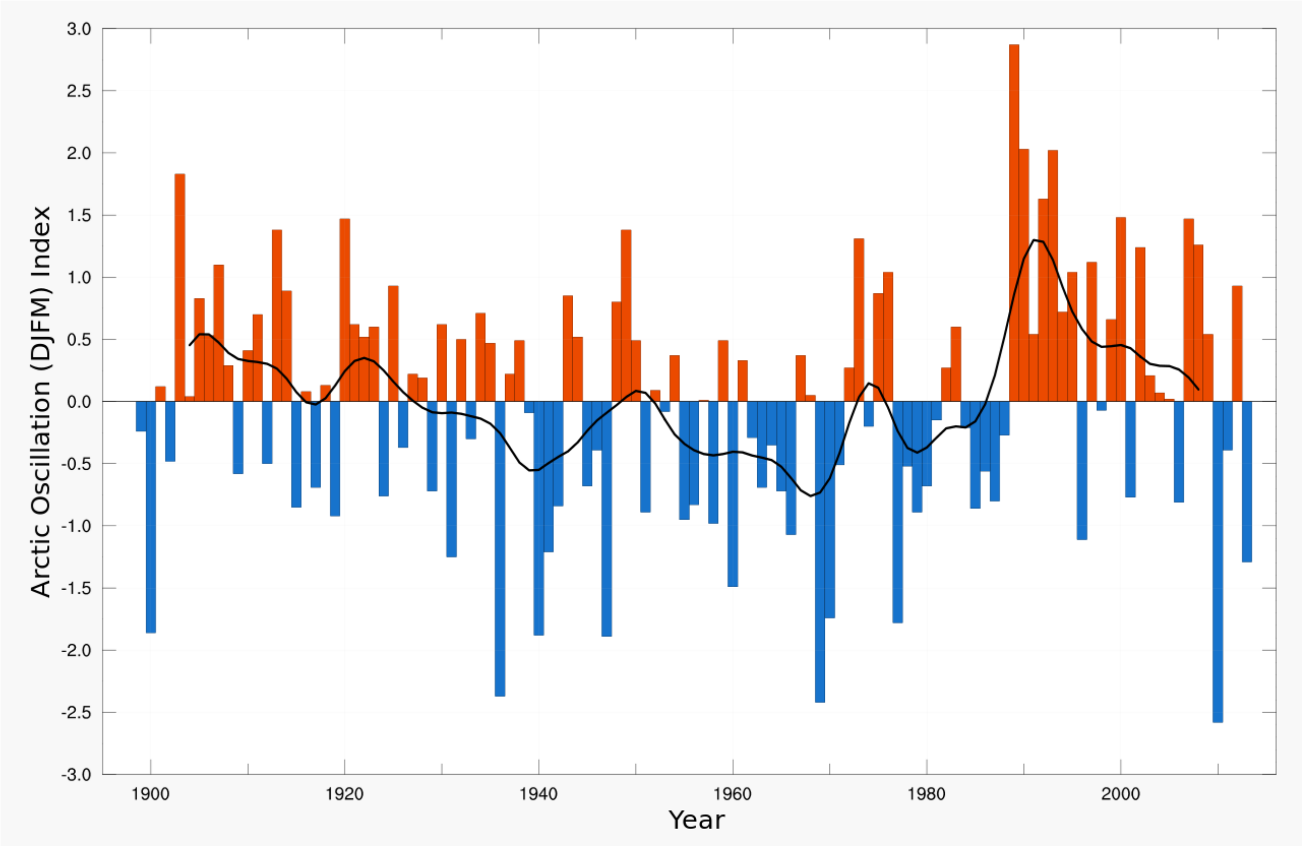

Positive Phase
Low Pressure
Jet Stream
High Pressure

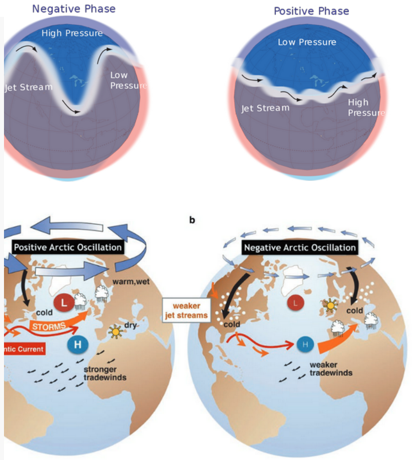
Campos & Horn, Oceans across boundaries, https://doi.org/10.1007/978-3-319-93284-2_3





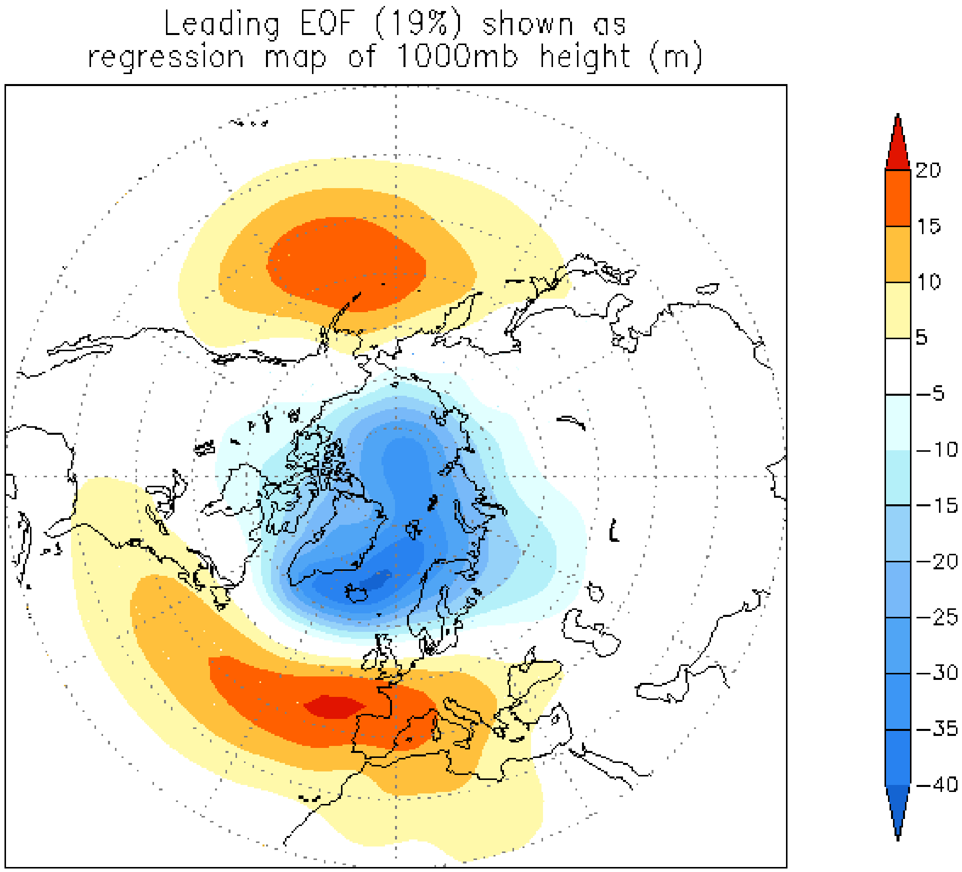
3. Arctic Oscillation → What is the AO?

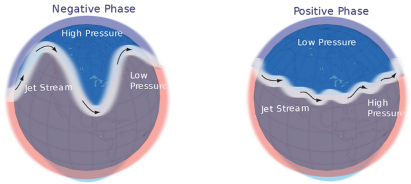


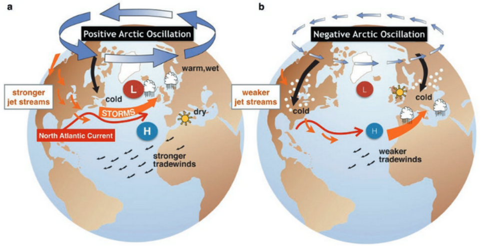


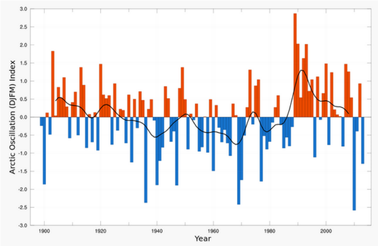
3. Arctic Oscillation → What is the AO?

https://en.wikipedia.org/wiki/Arctic_oscillation





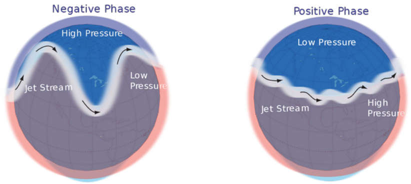


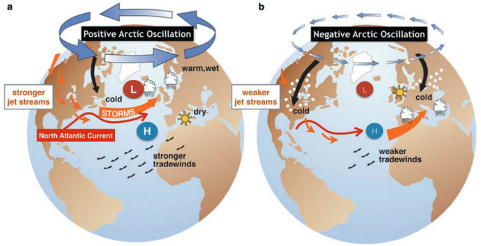


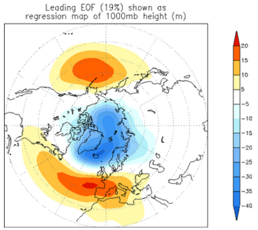
3. Arctic Oscillation → What is the AO?

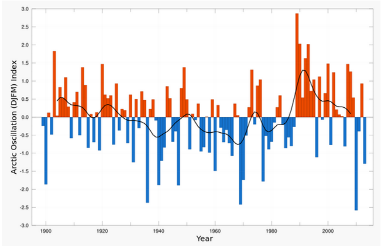
AO …

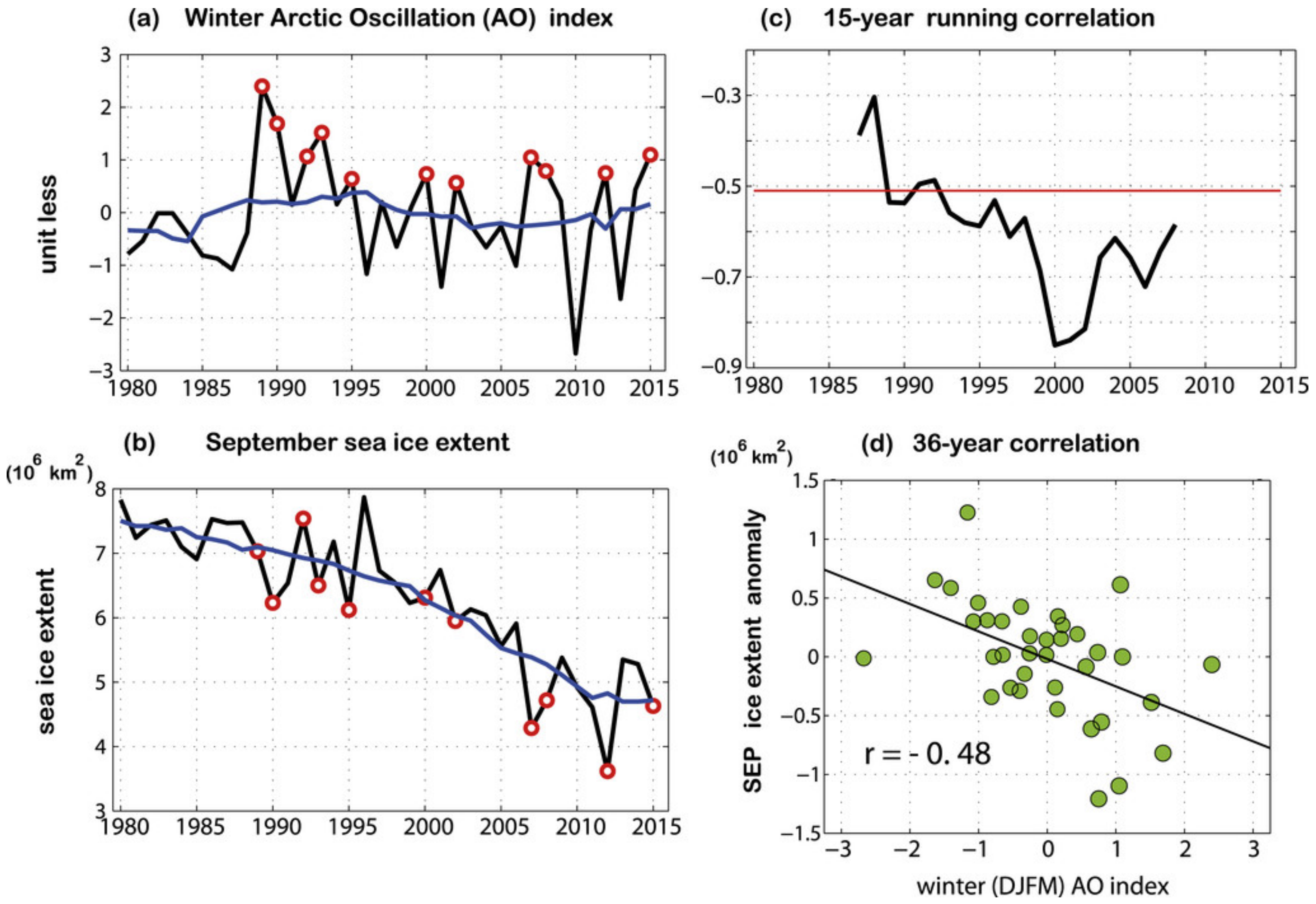
- Oscillating phenomenon of alternating high and low pressures over the Arctic
- Positive phase (high Arctic pressures) are related to a stronger polar jet
- Negative phase (low Arctic pressures) are related to a weaker polar jet
- Complicated interdecadal variability



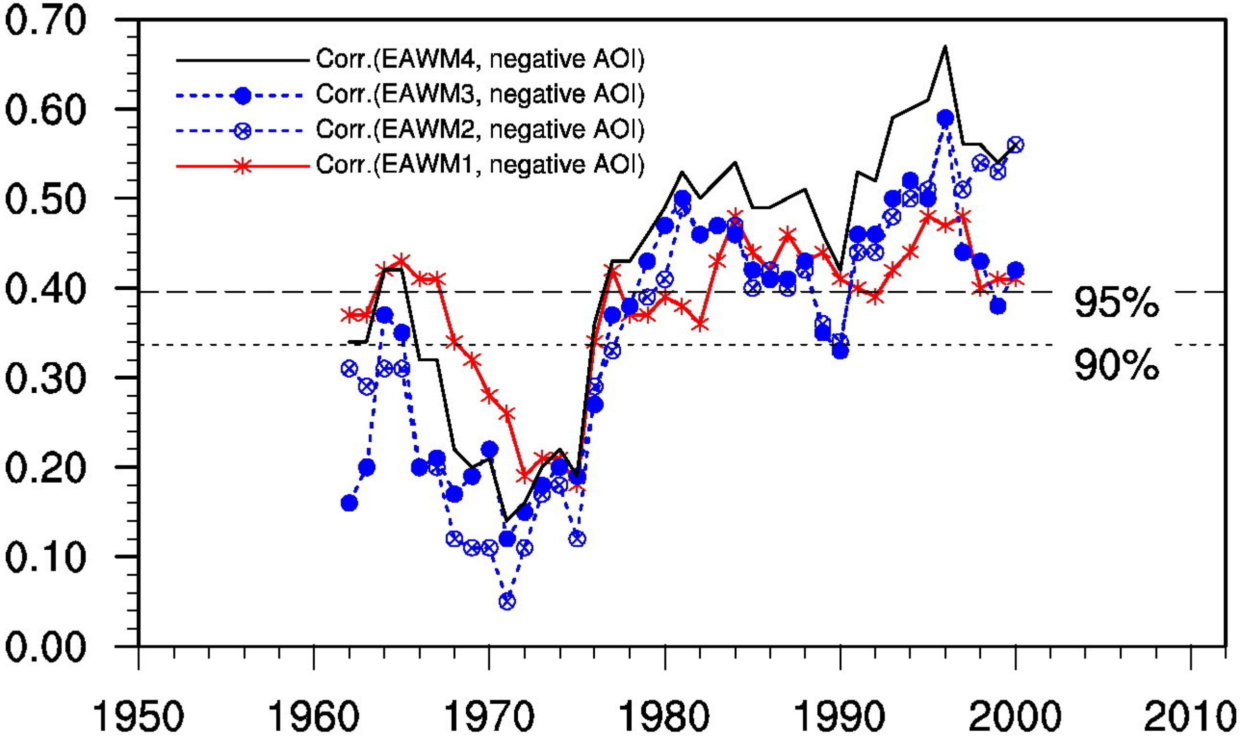


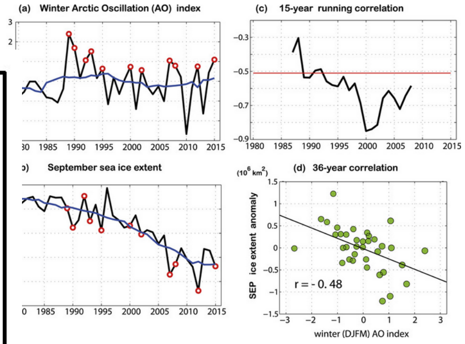






3. Arctic Oscillation → Impacts: Sea Ice Extent



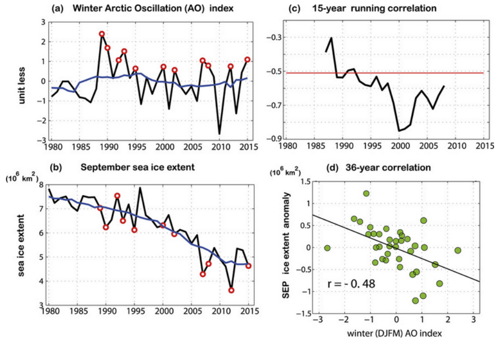


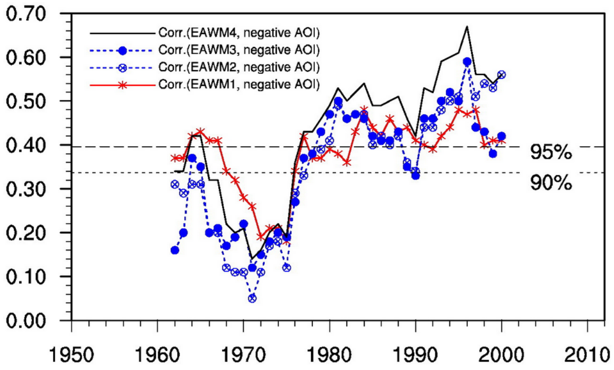
3. Arctic Oscillation → Impacts: East Asian Winter Monsoon

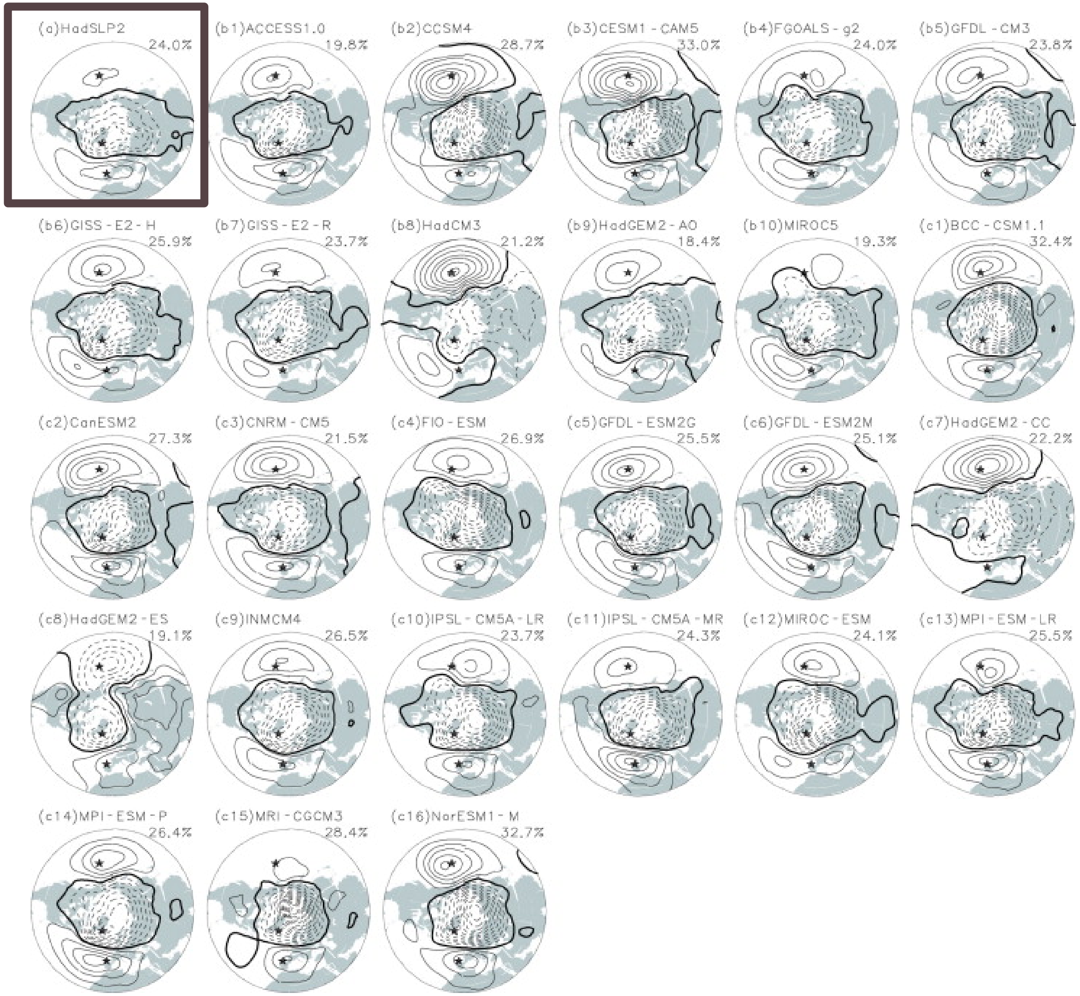
Bedartha Goswami

AO impacts …

- Crucially influences the strength of the polar jet, i.e., separation of cold Arctic air from mild temperature airs
  - Negative AO phase → weak polar jet → cold air outbreaks
- Also influences the sea ice extent
  - Especially on longer interdecadal timescales
- Positively correlated with East Asian Winter Monsoon
  - Non-stationary relation

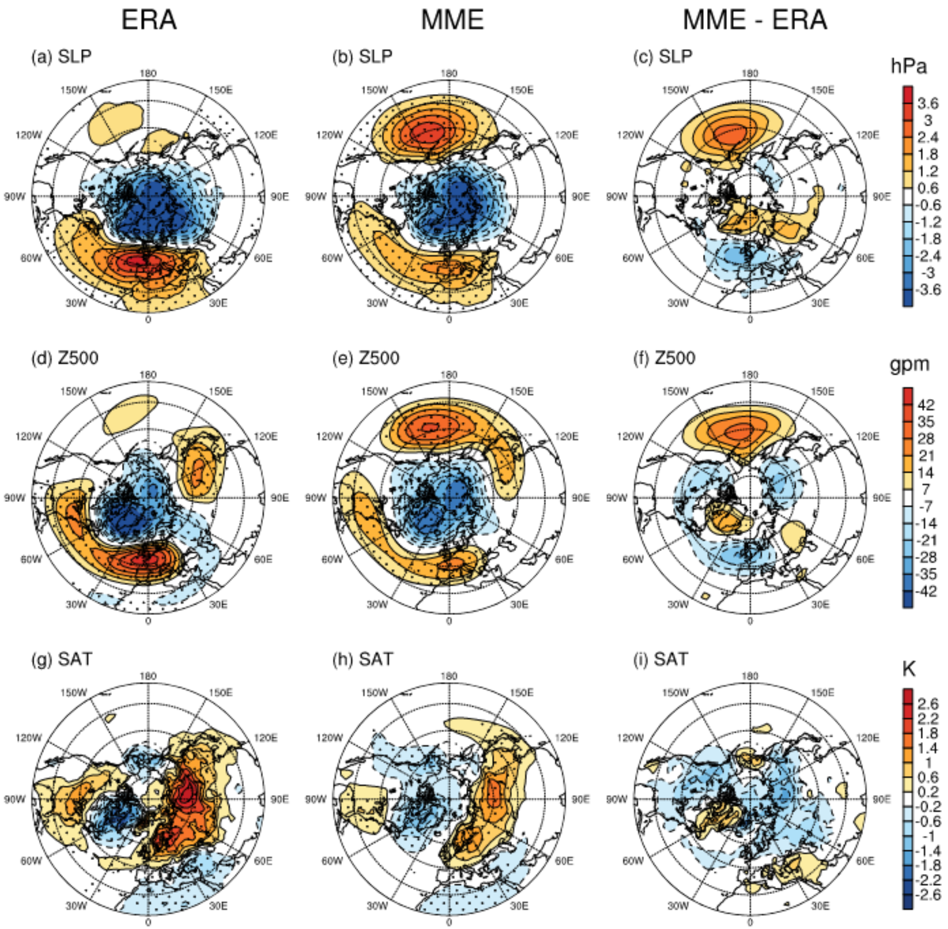


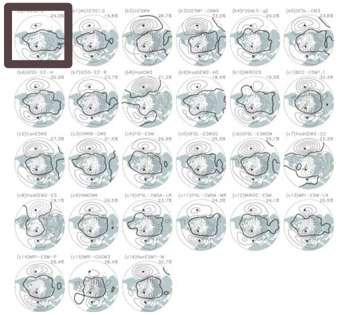




3. Arctic Oscillation → AO in climate models: Regression of SLP with AO Index

Gong et al., Env Res Lett., 2017

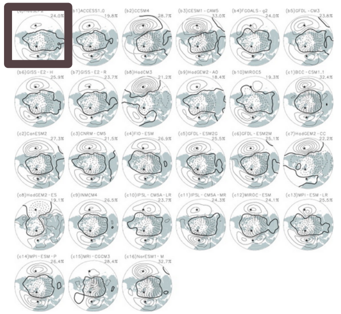


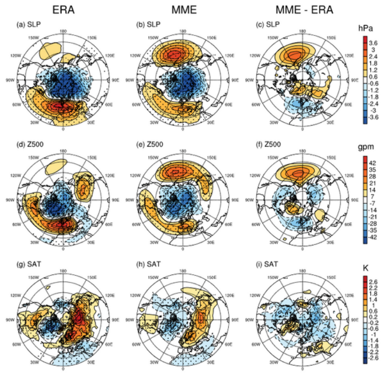


3. Arctic Oscillation → AO in climate models: Regression of Ensemble Mean w/ SLP/Z500/SAT with AO Index

AO in CMIP5 models …

- Large variability between ensemble members
  - Many model members do not capture the centers of action of the AO
- Strong bias in MME regressions with SLP and Z500
- Cold bias in regression of MME SAT field with AO index





El Niño Southern Oscillation

1

- What is the ENSO?
- Impacts
- Models of ENSO

North Atlantic Oscillation

2

- What is the NAO?
- Impacts
- NAO in climate models

Arctic Oscillation

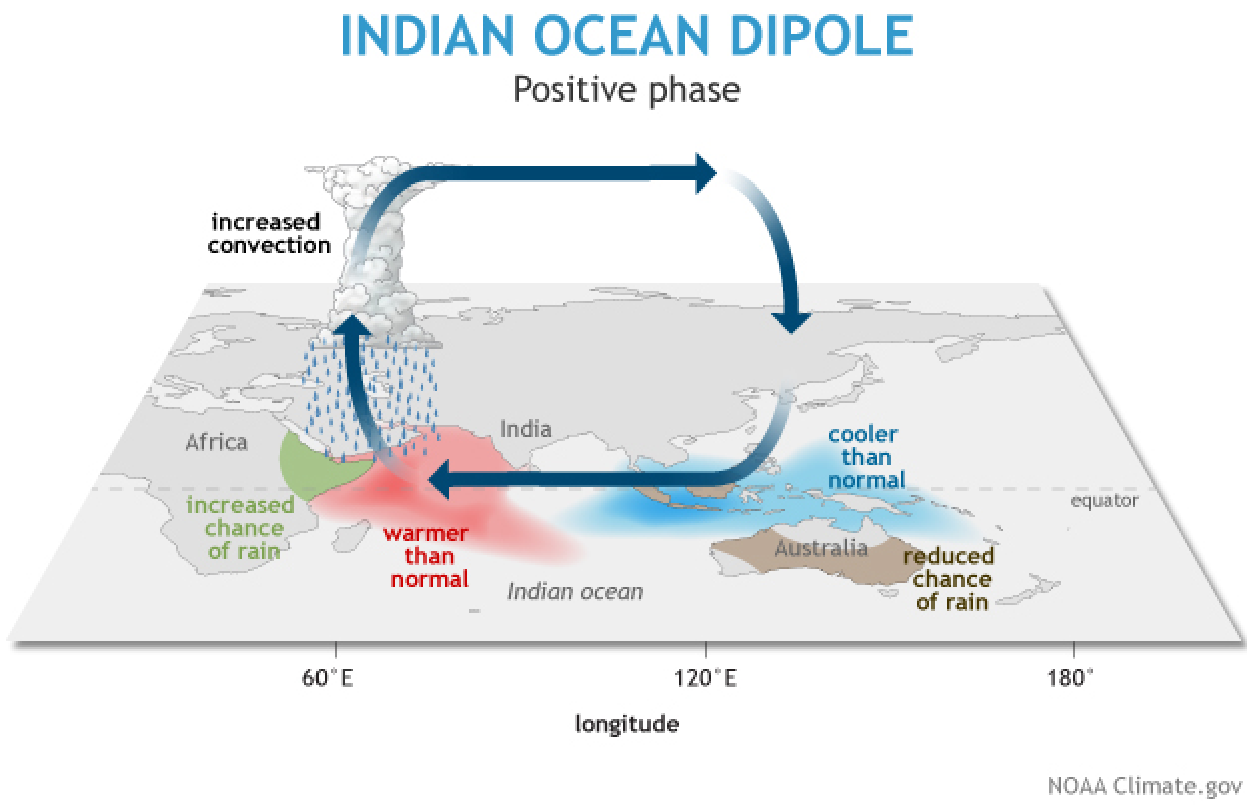
3

- What is the AO?
- Impacts
- AO in climate models

Indian Ocean Dipole

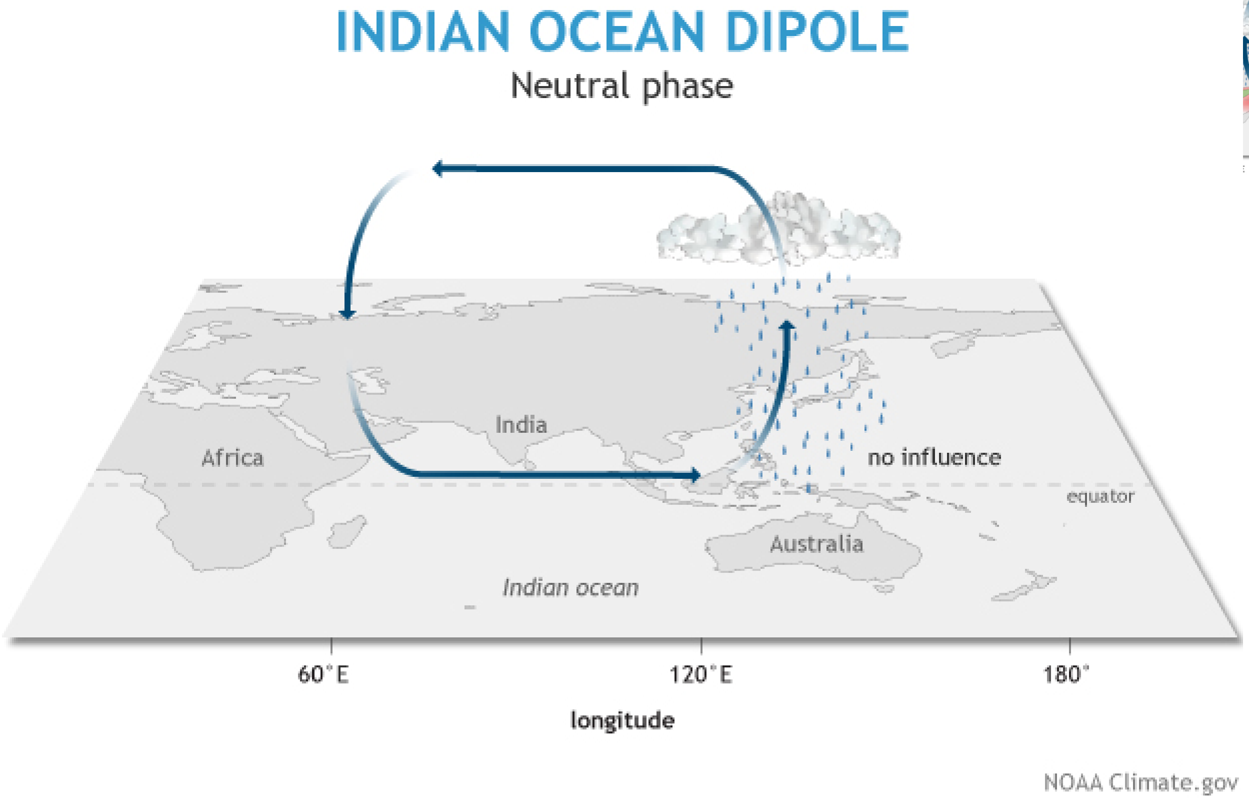
4

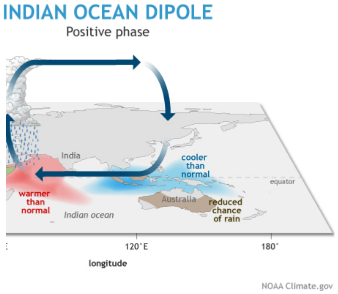
- What is the IOD?
- *Impacts*
- ~~IOD in climate models~~



4. Indian Ocean Dipole → What is the IOD?

Bedartha Goswami





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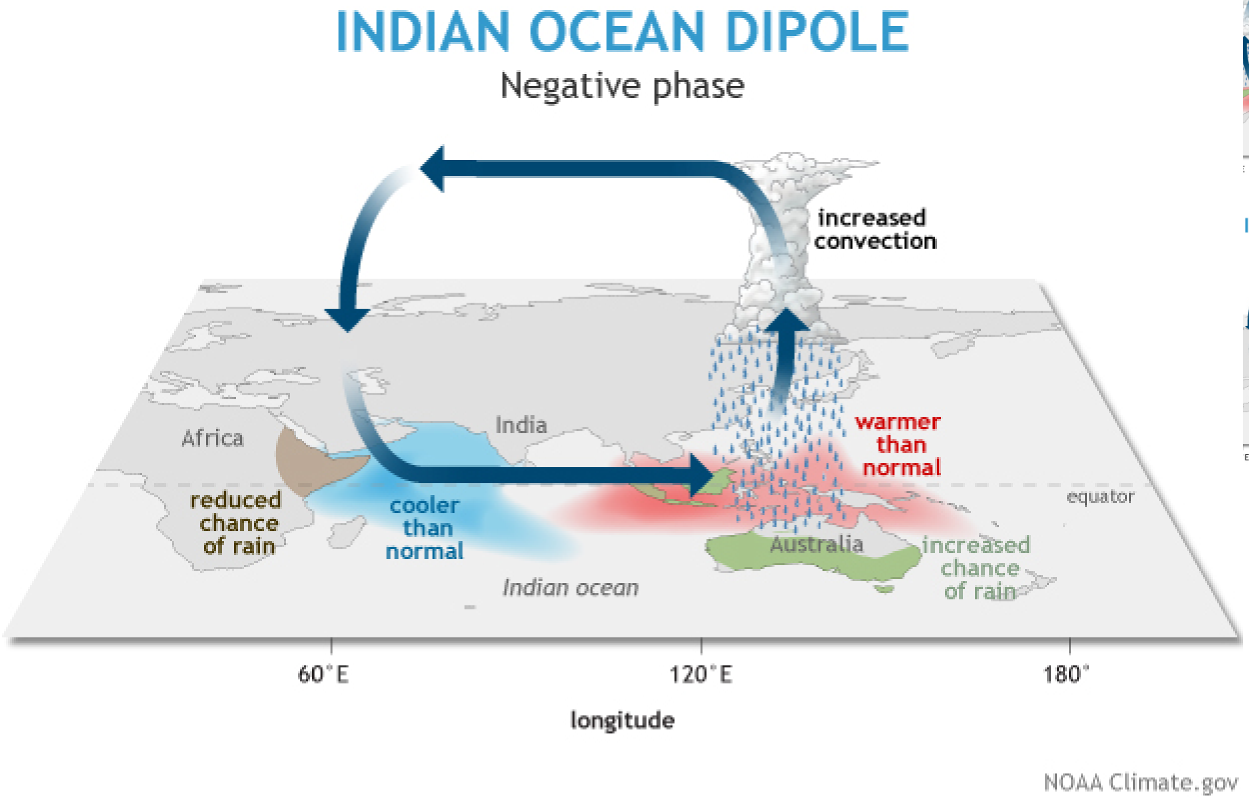
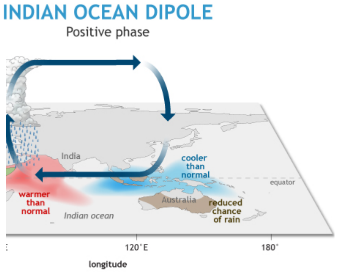
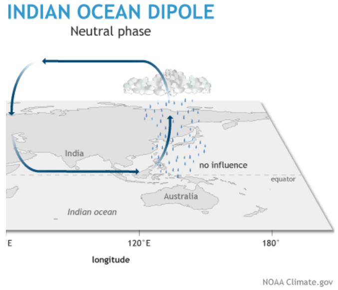


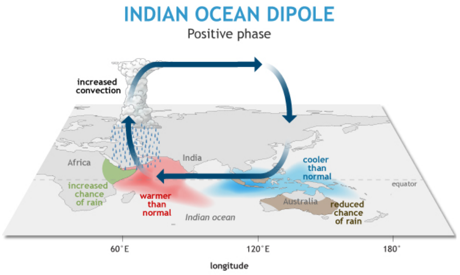


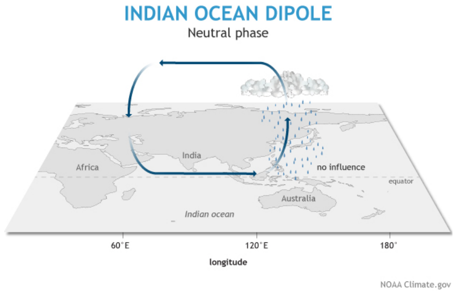


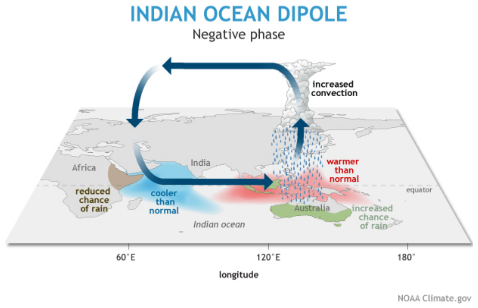
4. Indian Ocean Dipole → What is the IOD?

Indian Ocean Dipole ...

- Alternating anomalous warm and cold waters in western Indian Ocean
- Postive (negative) phase is associated with anomalously warmer (colder) western Indian Ocean
  - More than normal rainfall over the East African countries
  - Less than normal rainfall over the Maritime continent and over Australia
- In the negative phase the patterns are reversed
- Closely related to El Niño







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Q&A