A Decadal-scale Air-sea Interaction Theory for North Atlantic Multidecadal Variability: the NAT-NAO-AMOC-AMO Coupled Mode and Its Remote Influences

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Sun, Li and Jin, 2015, CD
Li, Sun and Jin, 2013, GRL
Sun et al., 2015, JC
Sun et al., 2015, Sci. Rep.
Sun et al., 2016, CD

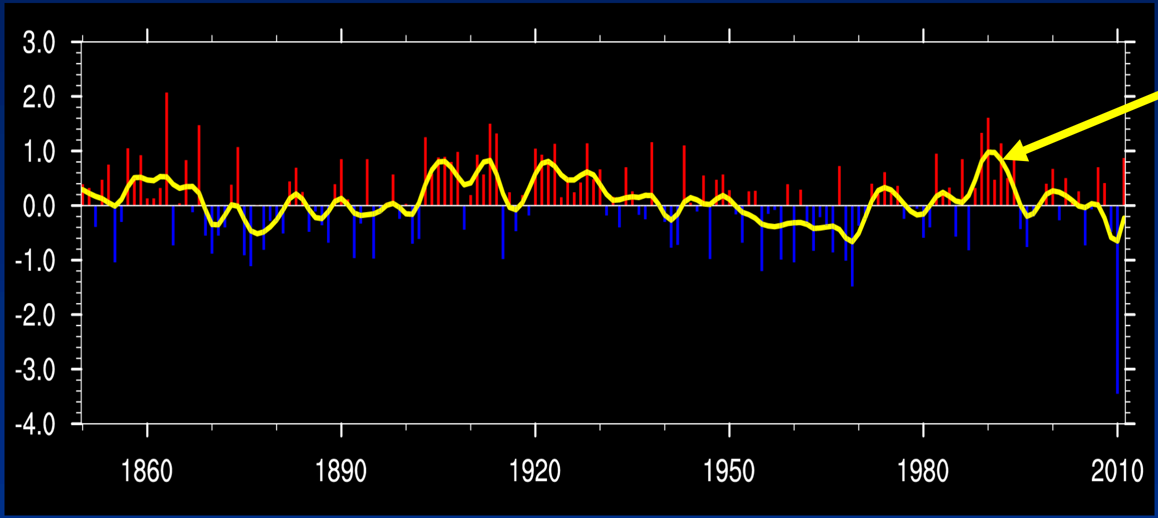
Outlines

- **Multidecadal variability in North Atlantic: a view from decadal-scale air-sea interaction**
- **Remote influences of North Atlantic multidecadal variability**

A delayed oscillator model for the quasi-periodic multidecadal variability of the NAO

Cheng Sun · Jianping Li · Fei-Fei Jin

(Sun, Li, & Jin, 2015, *Clim Dyn*)

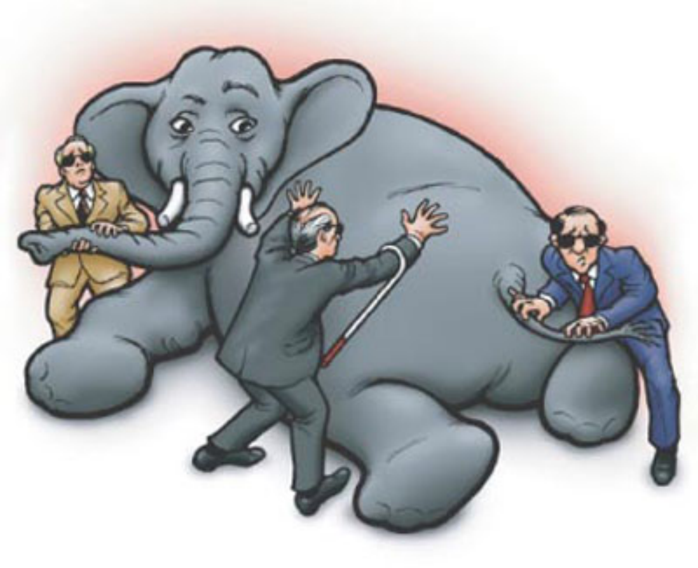


Multidecadal variability of the NAO and recently decadal weakening

(Li and Wang, 2003, *AAS*)

Decrease of Artic sea ice leads to strengthening of NAO (Deser et al. 2004)

Warming of Indo-Pacific warm pool enhances NAO (Hoerling et al. 2001)

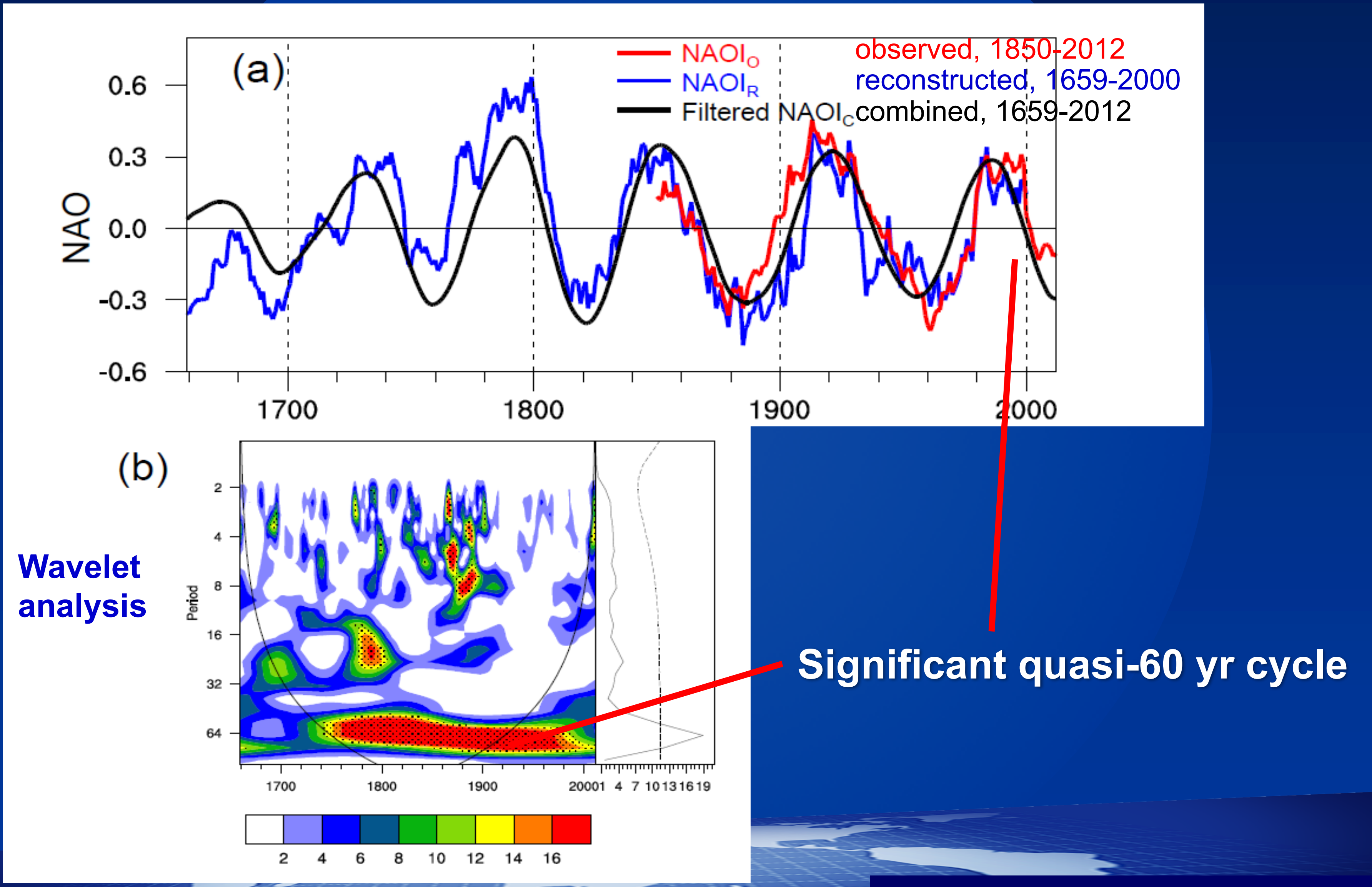


Greenhouse gas increase forces NAO upward trend (Shindell et al. 1999)

Questions:

- **Quasi-60 yr cycle**
- **The weakening trend over the past decades**

Reconstructed and Observed NAO Indices



(Sun, Li, & Jin, 2015, *Clim Dyn*)

Air-sea coupled model simulation

Historical observations of air-sea variables are relatively short. Climate models provide an alternative and useful approach to analyze multidecadal variability.

NCAR CCSM4 pre-industrial control simulation:

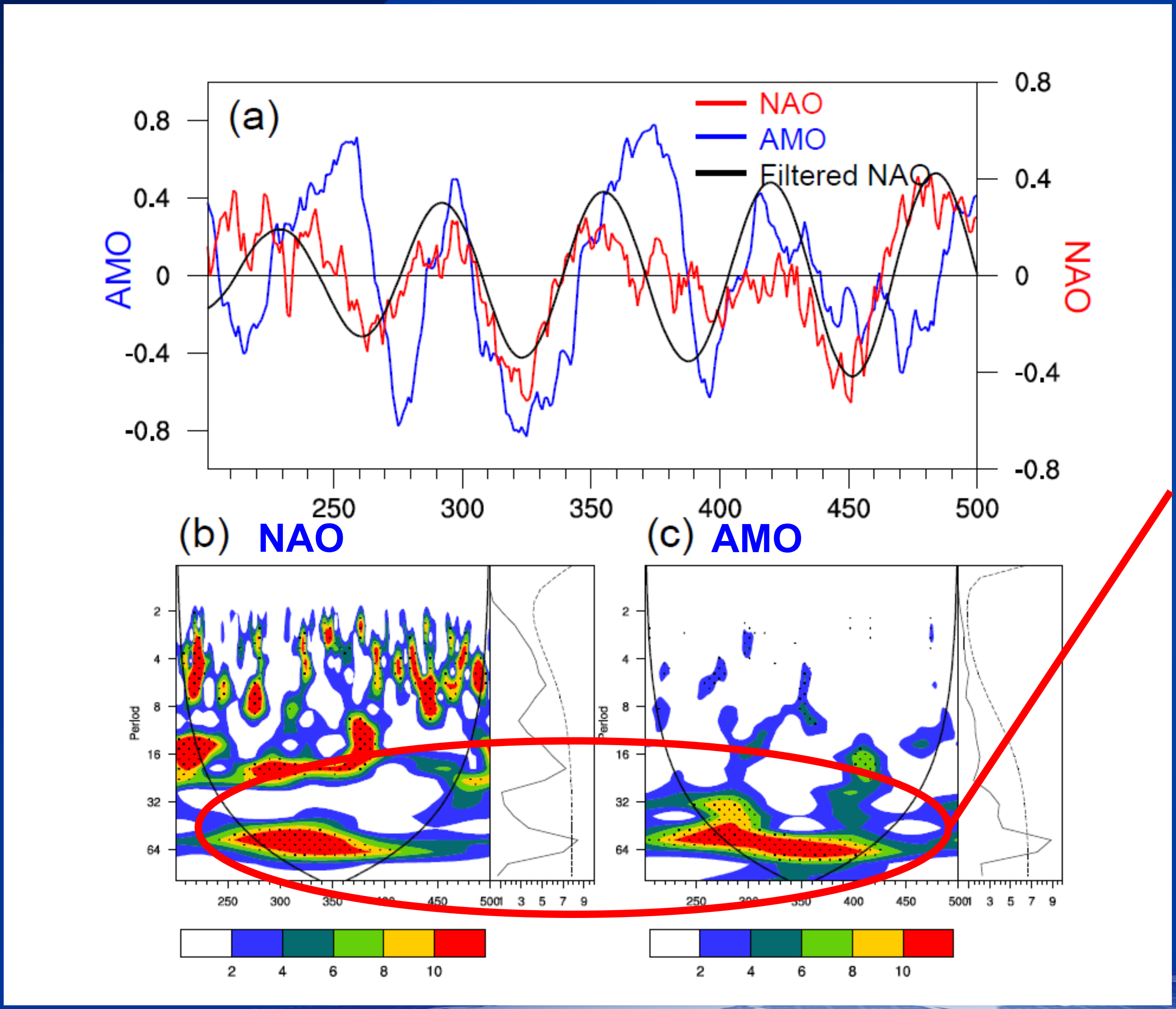
A long-term pre-industrial control simulation with constant external forcings

Several recent studies found that the model performs reasonably well in capturing the multidecadal variability (Danabasoglu et al. 2012; Zanchettin et al. 2013).

The control simulation was integrated over 1,300 model years, and a 300-year segment between model years 800 and 1,100 is used in the present analysis
1.To avoid the initial adjustment because of the model spin-up process
2.the multidecadal oscillation of the NAO in the 300-year segment is regular and very similar to the reconstruction

Variables at the air–sea interface (e.g. SLP and SST) and variables in the deep ocean (e.g. sea water temperature and meridional overturning circulation streamfunction).

NAO in the coupled model NCAR CCSM4

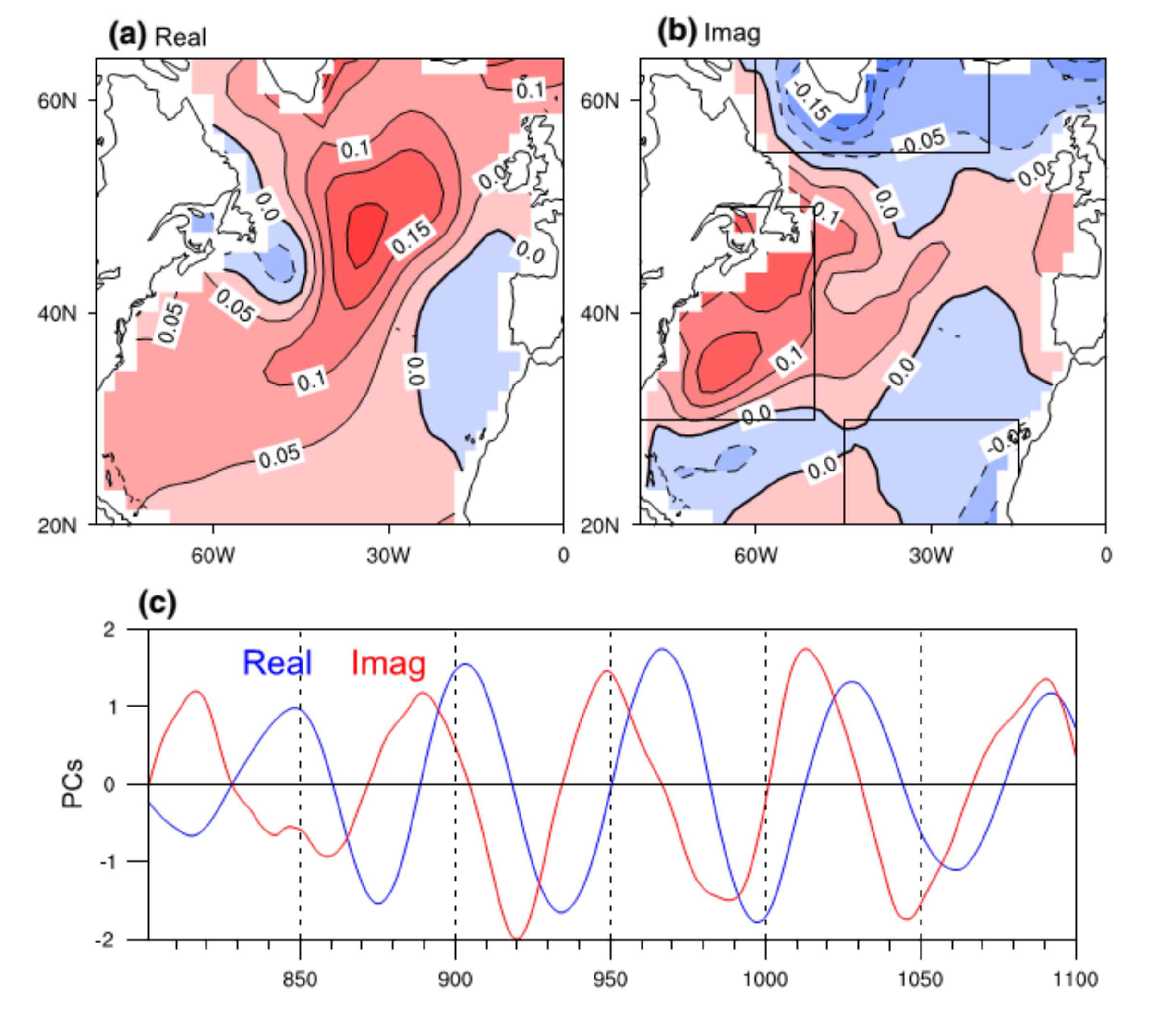


Significant quasi-60 yr cycle is reasonably well simulated

(Sun, Li, & Jin, 2015, *Clim Dyn*)

Dominant patterns of SST multidecadal variability

Principle oscillation pattern (POP) analysis:



AMO and North Atlantic Tripole (NAT)

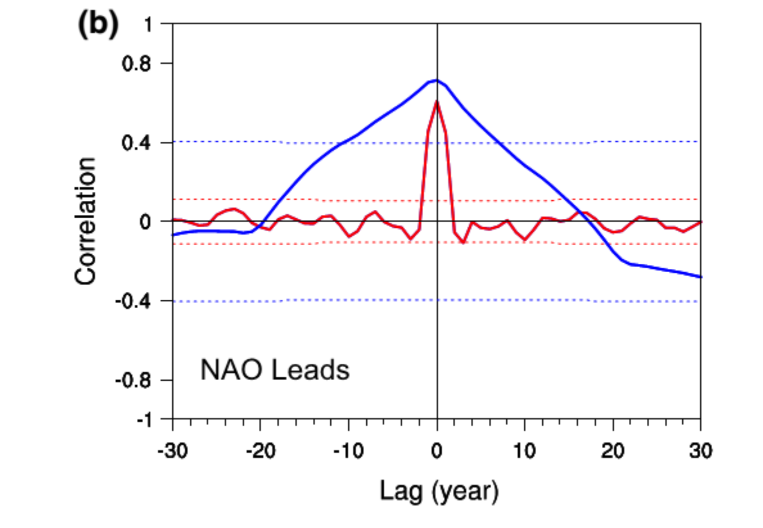
The oscillatory sequence of POPs

+NAT ➔+ AMO ➔–NAT

(Sun, Li, & Jin, 2015, *Clim Dyn*)

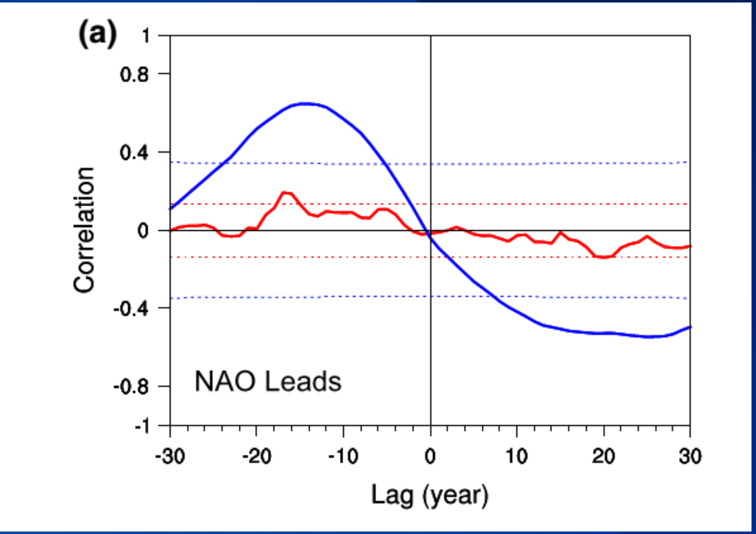
NAO vs. AMO and NAT

NAO vs. NAT



NAT is in phase with NAO

NAO vs. AMO



NAO leads AMO, while AMO has a negative feedback on NAO

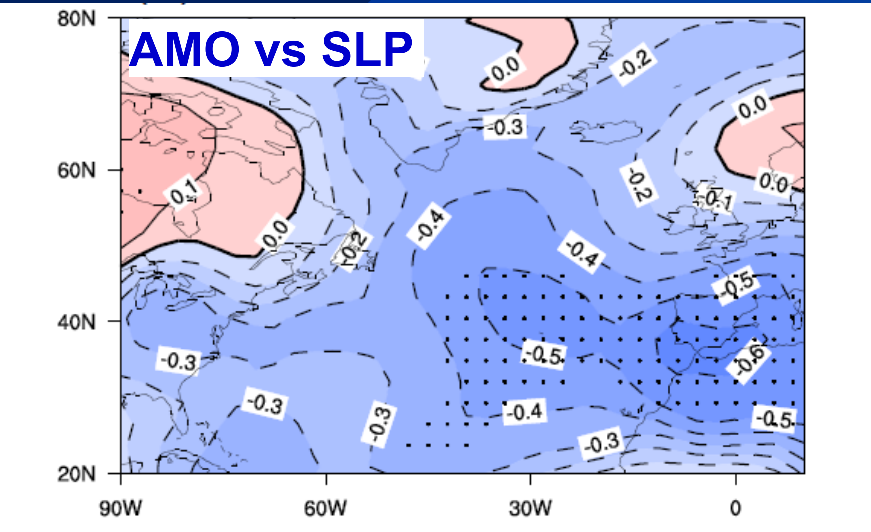
Hypothesize three possible mechanisms involved in the quasi-60-yr cycle

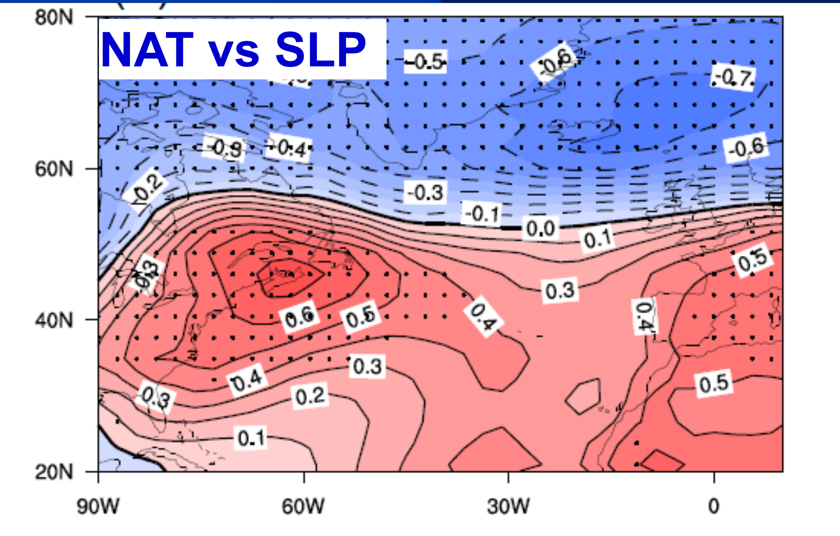
1. **NAT has a direct effect on the NAO；**
2. **NAO exerts some wind stress forcing on the AMO；**
3. **AMO in turn provides some negative feedback on NAT.**

(Sun, Li, & Jin, 2015, *Clim Dyn*)

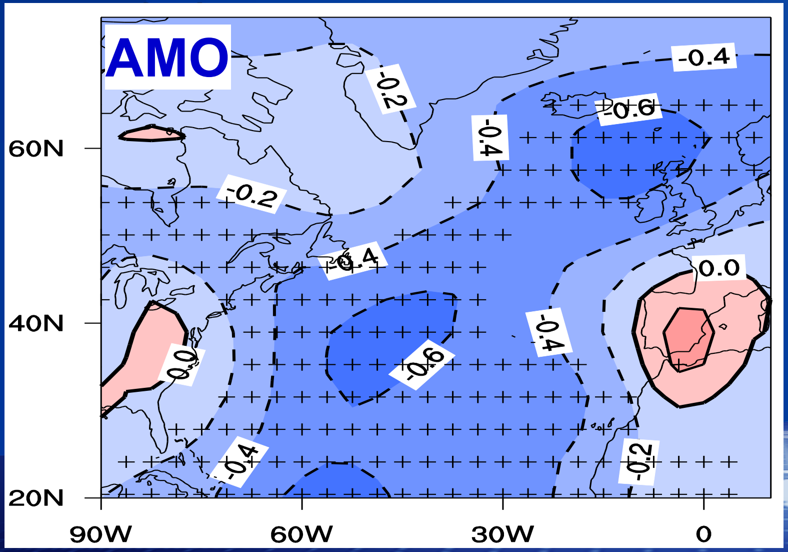
1. Direct effect of NAT on NAO

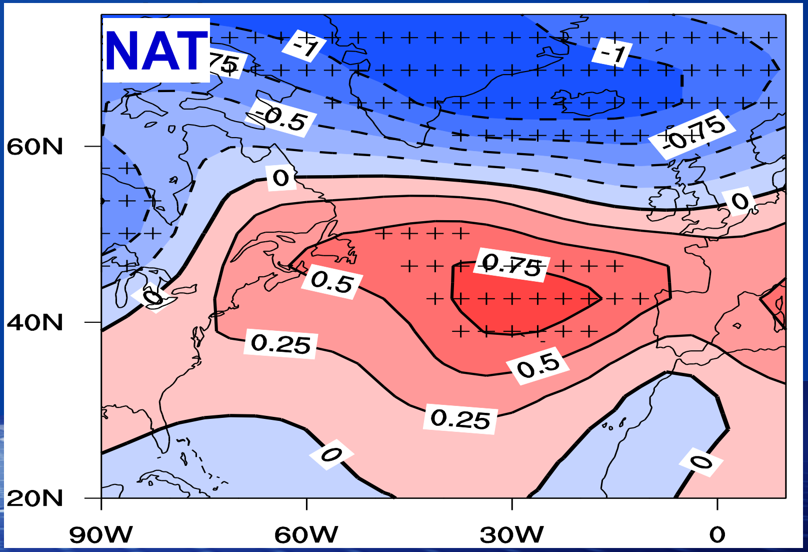
Atmospheric (SLP) responses to the AMO and NAT in CCSM4





SLP response in an AGCM (SPEEDY model) to the NAT and AMO

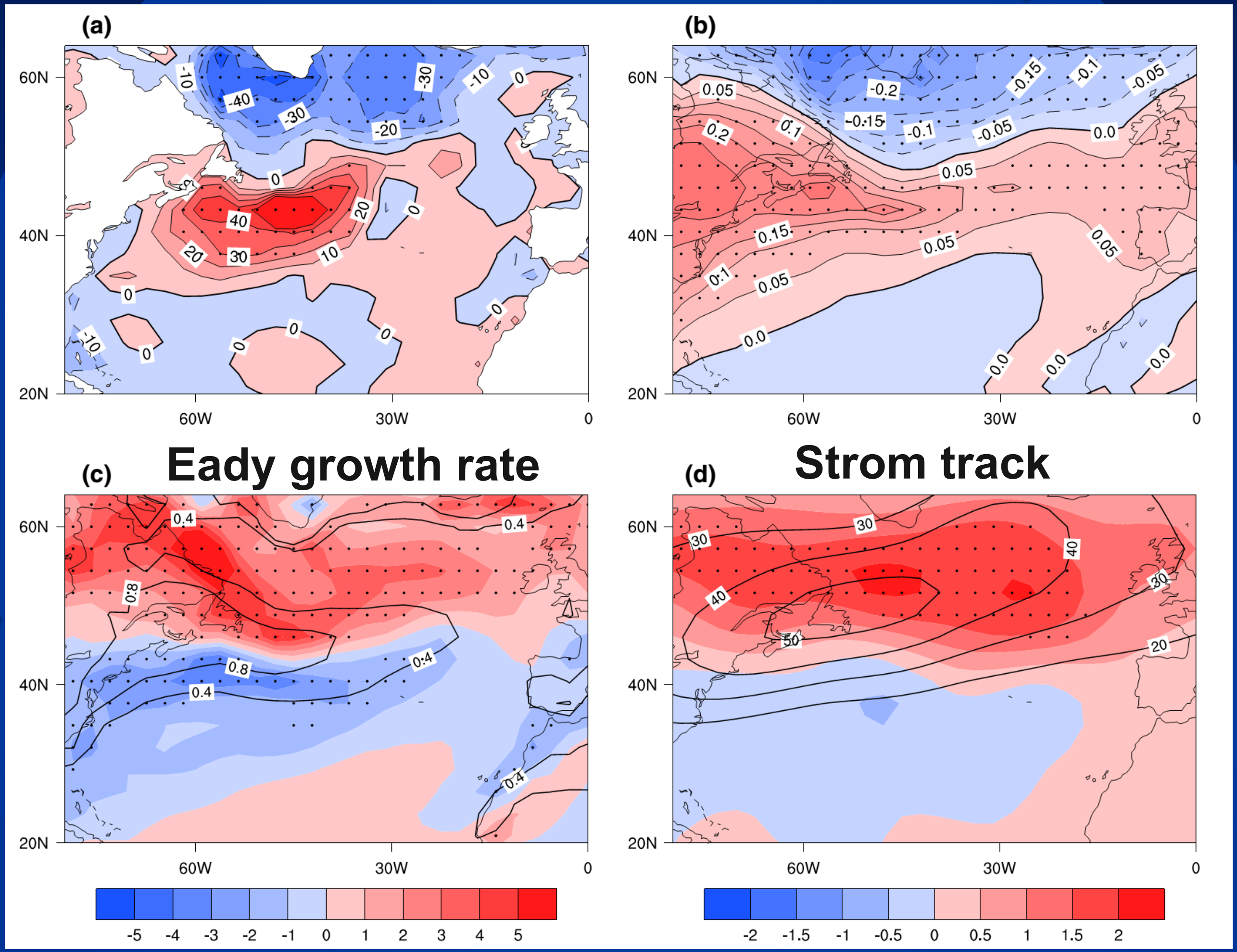




Physical processes for +NAT → +NAO

upward surface heat flux anomalies

850hPa air temperature



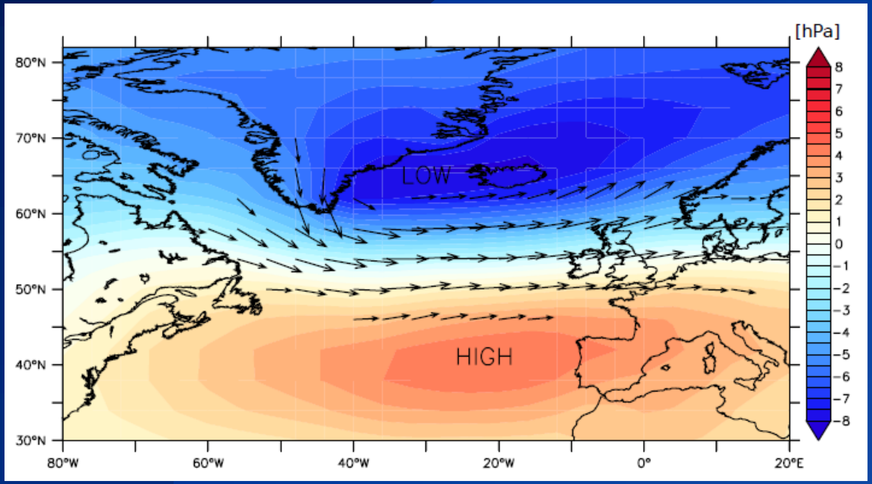
atmosphere acts to damp the SST anomalies

baroclinicity

increase storm track intensity and shift northward

NAT contributes to the increase of the storm track intensity and shifts the storm track northward, leading to a positive NAO phase.

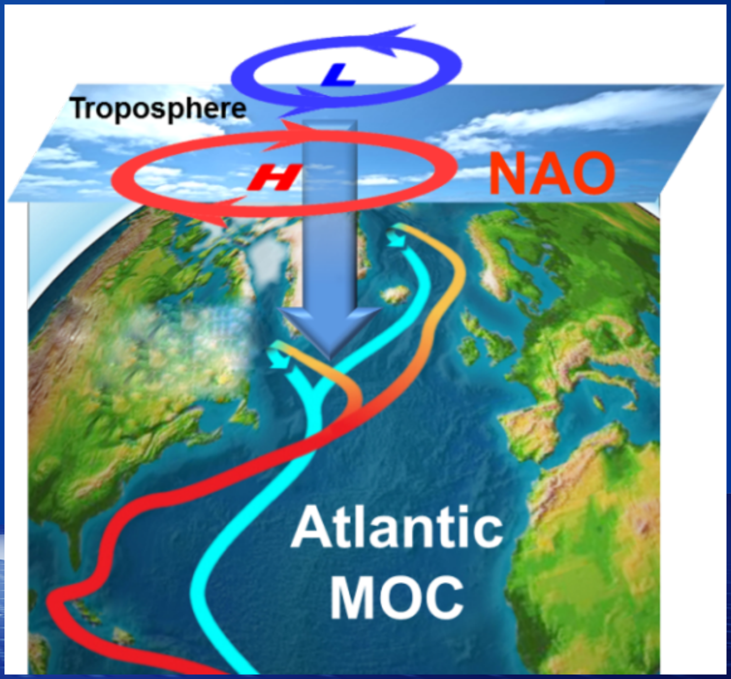
2. NAO forcing on the AMO, +NAO → +AMO



There is substantial modeling evidence that NAO-related wind stress anomaly can lead to multidecadal variations of the AMOC, which in turn produce the SST pattern of the AMO (Visbeck et al., 1998; Delworth and Greatbatch, 2000; Eden and Jung, 2001; Latif et al. 2006).

NAO
↓
Wind stress
↓
Deep convection
↓
Meridional Overturning Circulation
↓
Oceanic heat transport
↓
SST anomalies

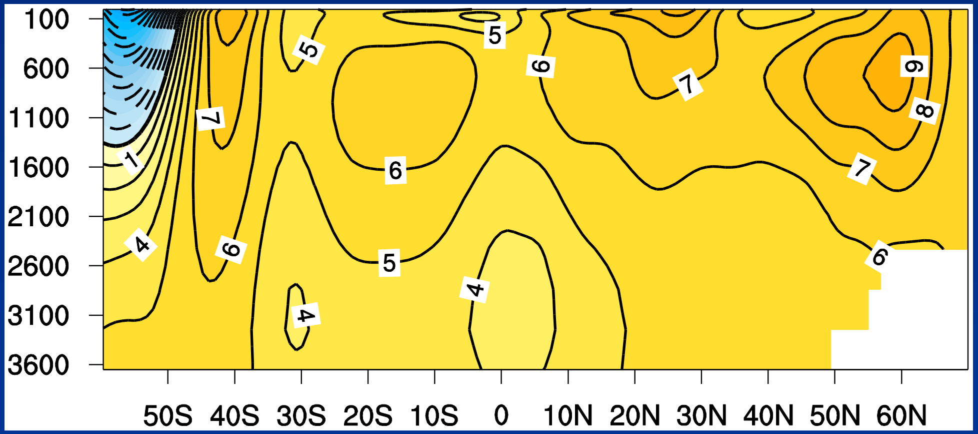
Slow oceanic process



The AMOC response simulated in the MOM5 model

The model is initialized by the steady state of a 200-yr-long control run. The control run is forced by climatological wind stress, heat flux, water flux and so on.

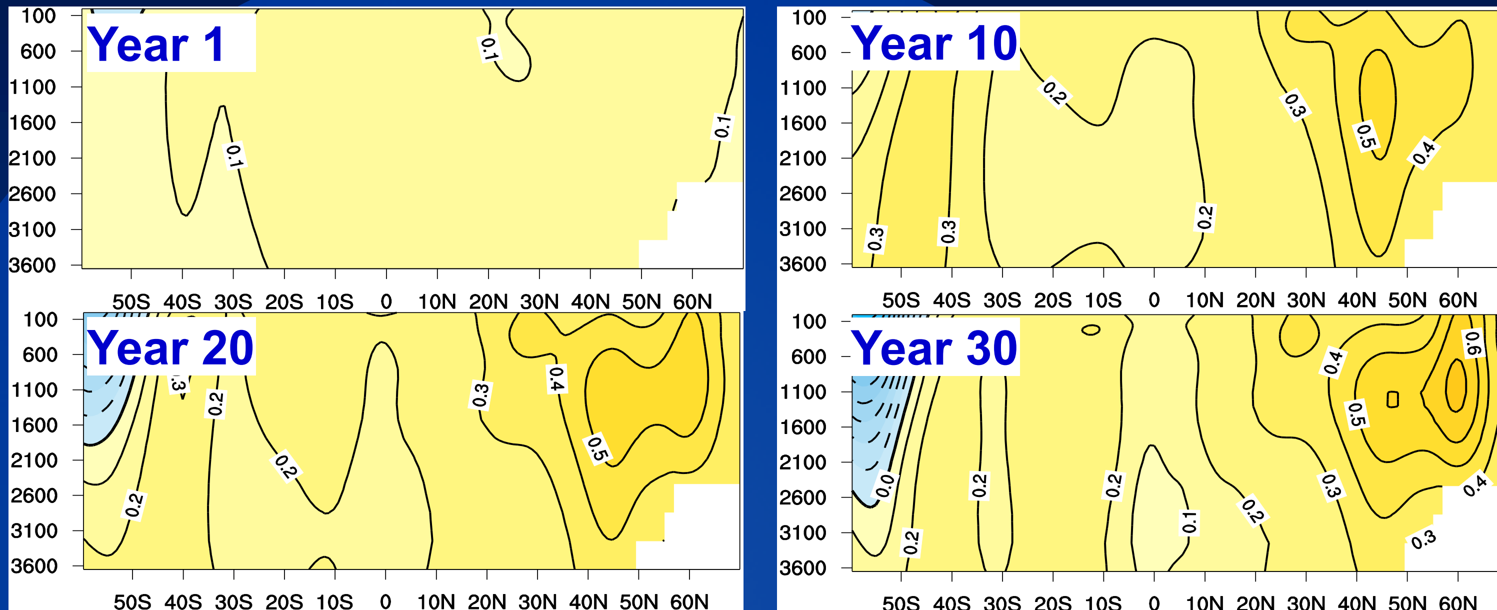
The model is driven by the NAO-type wind stress forcing (wind stress anomalies added to the climatological fields). The steady state is then subtracted from the results in order to examine the transient anomalous response to the NAO.



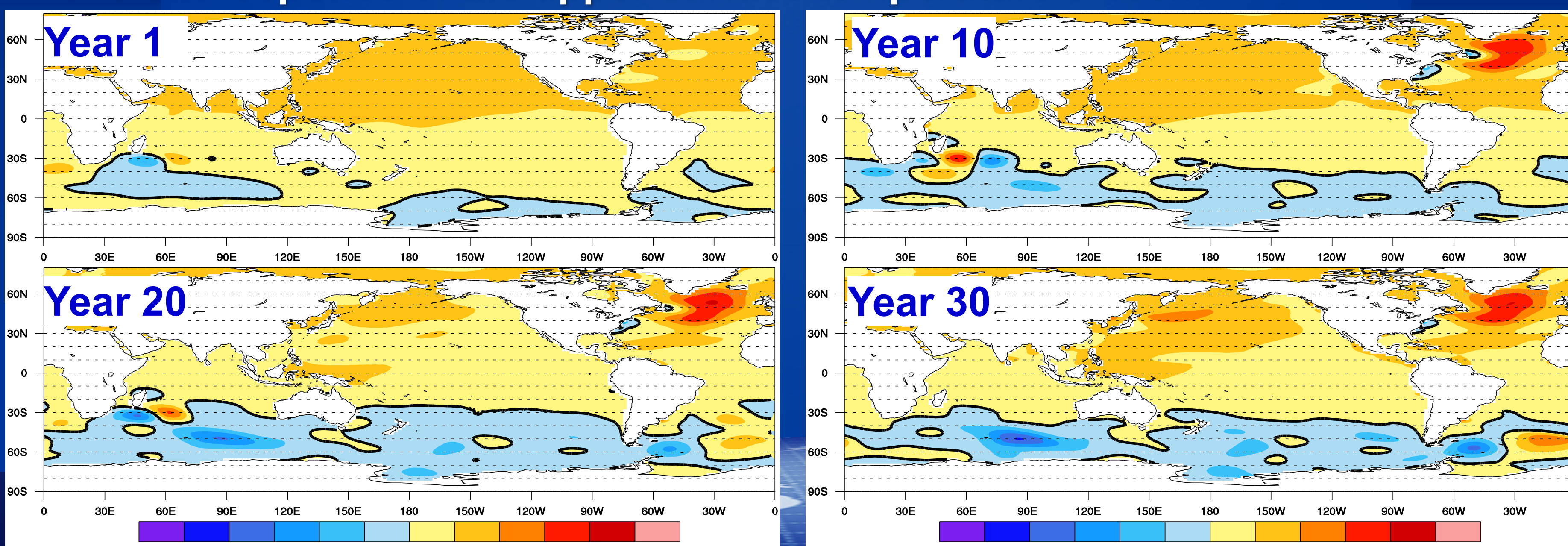
AMOC for the steady state

AMOC response to NAO in the MOM5 model

Transient response of the AMOC

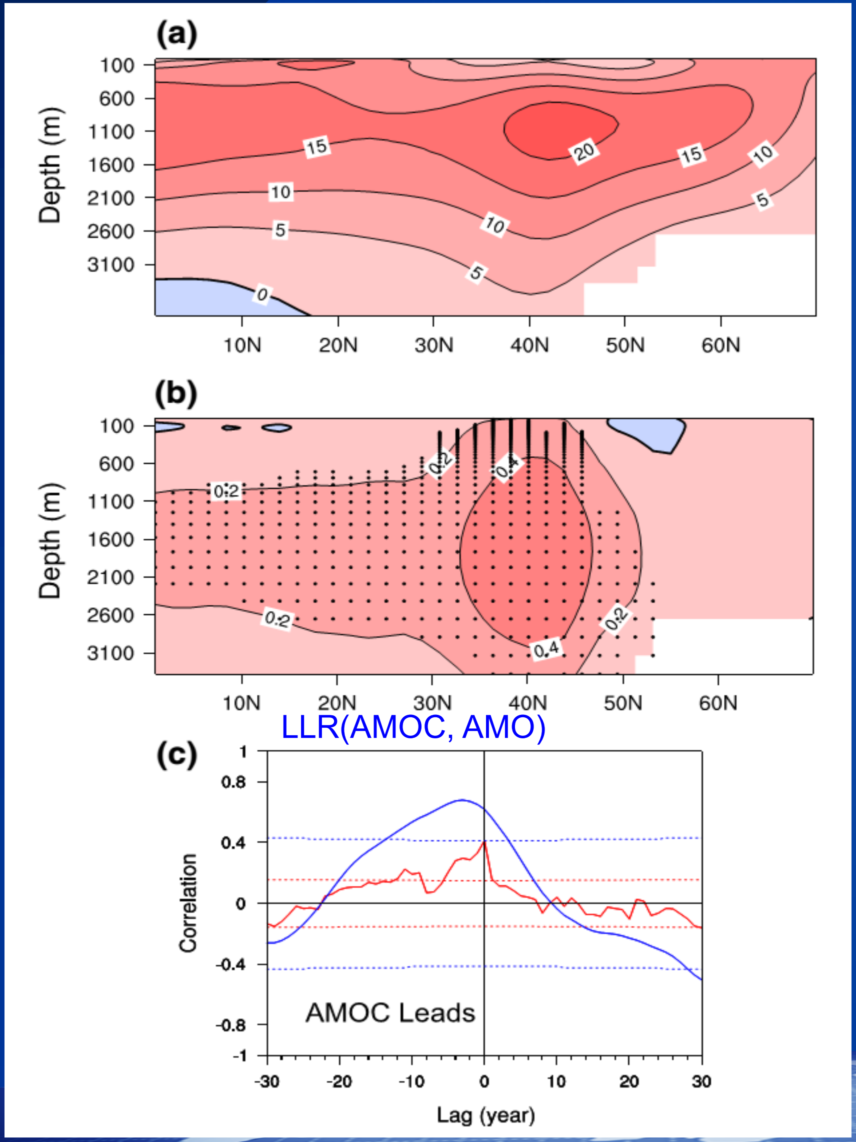


Transient response of the upper surface temperature 5-100m



NAO → AMO

CCSM4 simulation



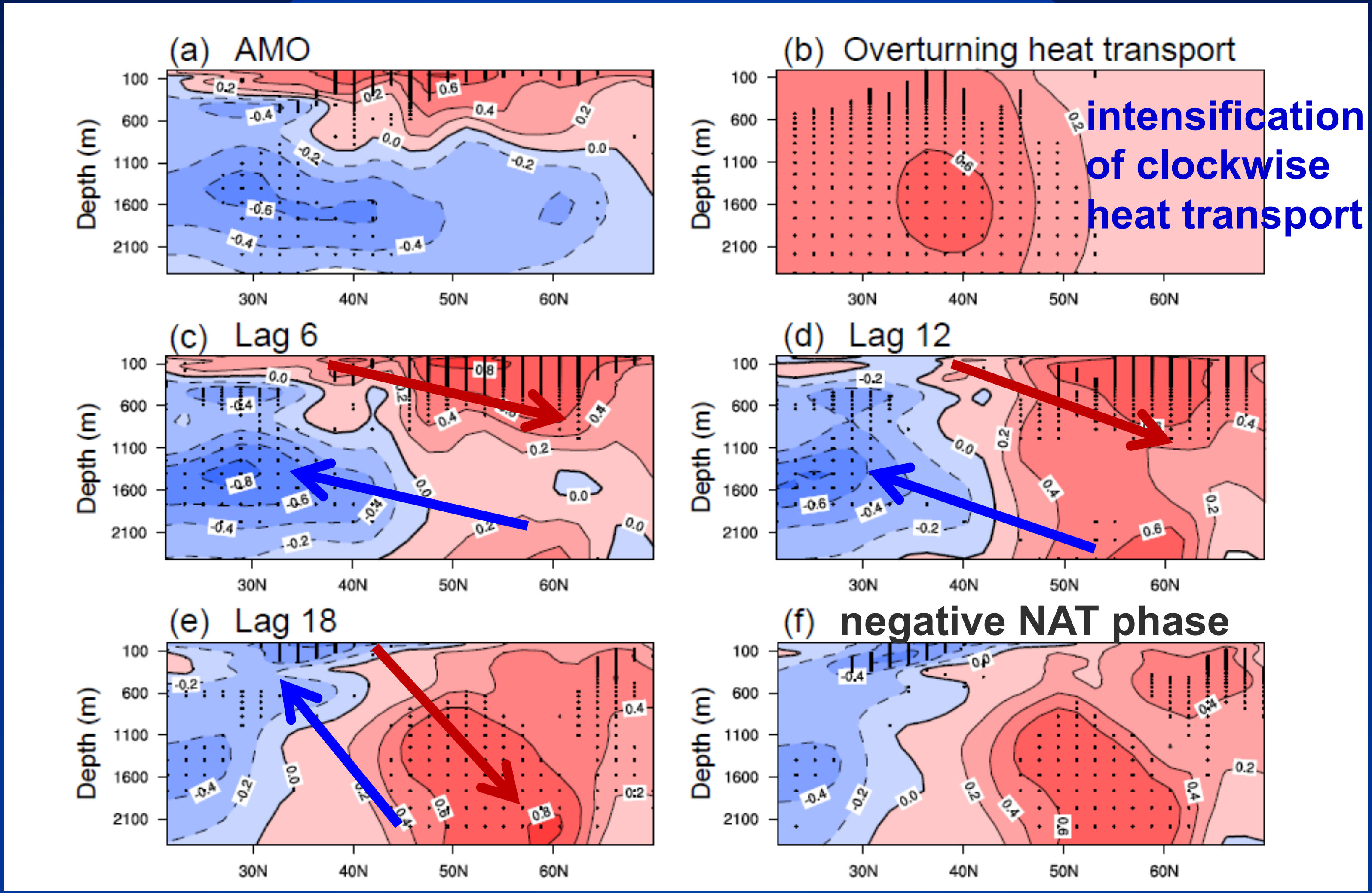
Simulated long-term mean AMOC

NAO leads the AMOC by 15 years
+NAO → AMOC strengthening
–NAO → AMOC weakening

AMOC in phase the AMO

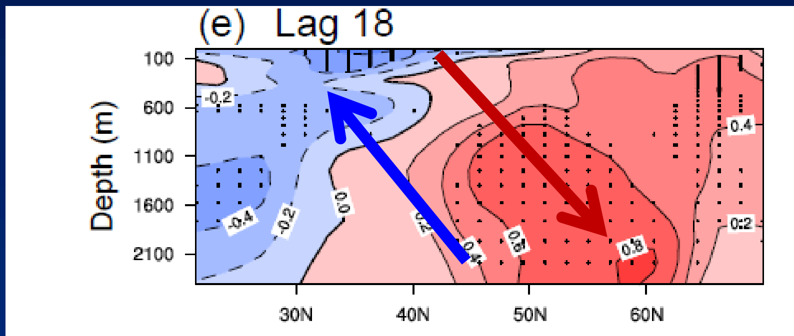
(Sun, Li, & Jin, 2015, *Clim Dyn*)

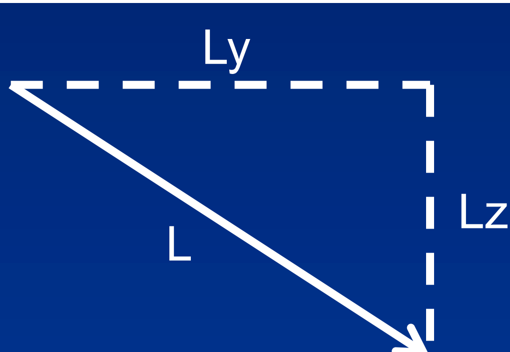
3. Negative feedback of AMO on NAT, +AMO → –NAT

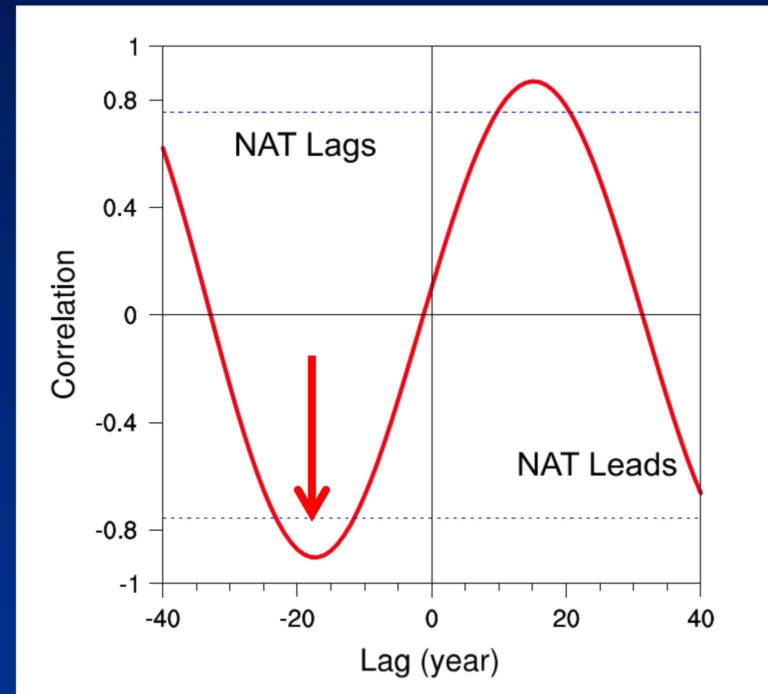


The positive correlations are at first located in the upper North Atlantic and then propagate into the subpolar region, expanding downward; the negative correlations are shifted southward.

Theoretical explanation for the time delay







Time it takes for transport along the OHT pathway $\frac{L}{V}$

$$\frac{L}{V} \approx \frac{L_y}{V_y} \approx \frac{L_z}{V_z}$$

$$Vy = \frac{\Psi}{W \cdot D}$$

$$\frac{L_y \cdot W \cdot D}{\Psi}$$

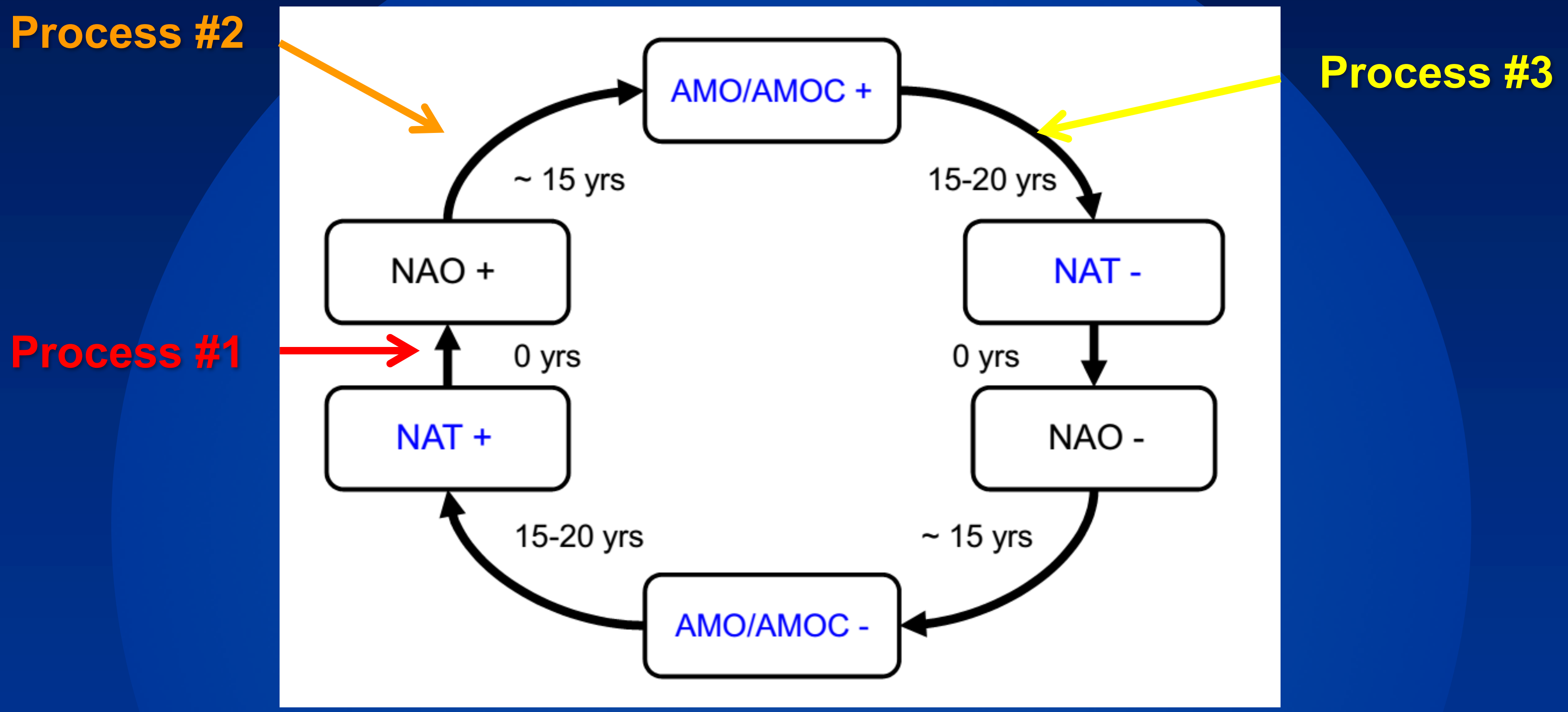
The theoretical time delay is ~16 years.

Very close to the time lag of the NAT relative to the AMO

The advection plays a key role in the SST evolution from positive AMO to negative NAT.

(Sun, Li, & Jin, 2015, *Clim Dyn*)

Summary of the mechanisms



The positive NAO forces the enhancement of the AMOC, and leads to the AMO positive phase. The forcing effect is delayed by about 15 years, possibly due to the large inertia associated with slow oceanic processes. The enhanced AMOC continues to affect the heat transport, and due to slow ocean adjustment, the North Atlantic Ocean shows a delayed response (after about 18 years) to the preceding enhanced AMOC with an SST pattern that resembles the NAT negative phase. The NAT negative phase coincides with the NAO negative phase in the atmosphere, and thus the cycle proceeds, but in the opposite sense. Blue (black) text indicates oceanic (atmospheric) phenomena.

(Sun, Li, & Jin, 2015, *Clim Dyn*)

Delayed oscillator model

$$\mathrm{NAO}(t) \approx \mathrm{NAT}(t), \quad \textbf{SST feedback to atmos.} \qquad (2)$$

$$C\frac{d\mathrm{AMO}}{dt} = \alpha\mathrm{NAO} - \frac{\mathrm{AMO}}{\beta}, \quad \textbf{atmos. forcing of ocean} \qquad (3)$$

$$-\mathrm{NAT}(t+\tau) \approx \mathrm{AMO}(t), \quad \textbf{ocean adjustment} \qquad (4)$$

$$\frac{d\mathrm{NAT}(t)}{dt} = -\frac{\alpha}{C}\mathrm{NAT}(t-\tau) - \frac{\mathrm{NAT}(t)}{\beta C}, \qquad (5)$$

$$\mathrm{NAO}(t) \approx \mathrm{NAT}(t).$$

Delayed oscillator model for NAO multidecadal variability

C is the estimated effective heat capacity of climate system, in the range of 13 to 35 W yr m^{-2} K^{-1} [Knutti et al., 2008];

β is linear damping coefficient, estimated in the range from 0.6 to 1.2 K (W $m^{-2})^{-1}$ [Knutti and Hegerl 2008];

The parameter α represent the magnitude of NAO effect;

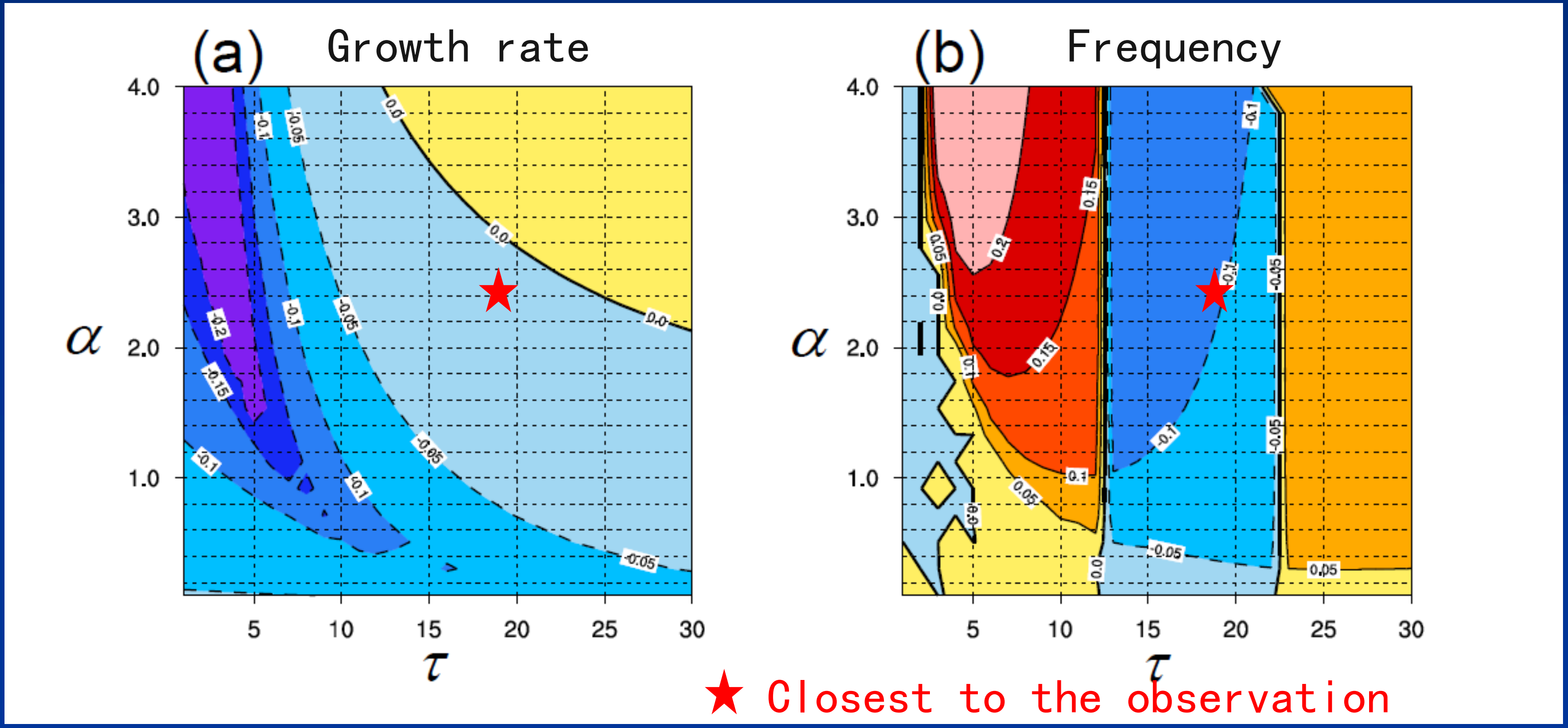
τ: the time delay for the AMO feedback

Normal mode analysis

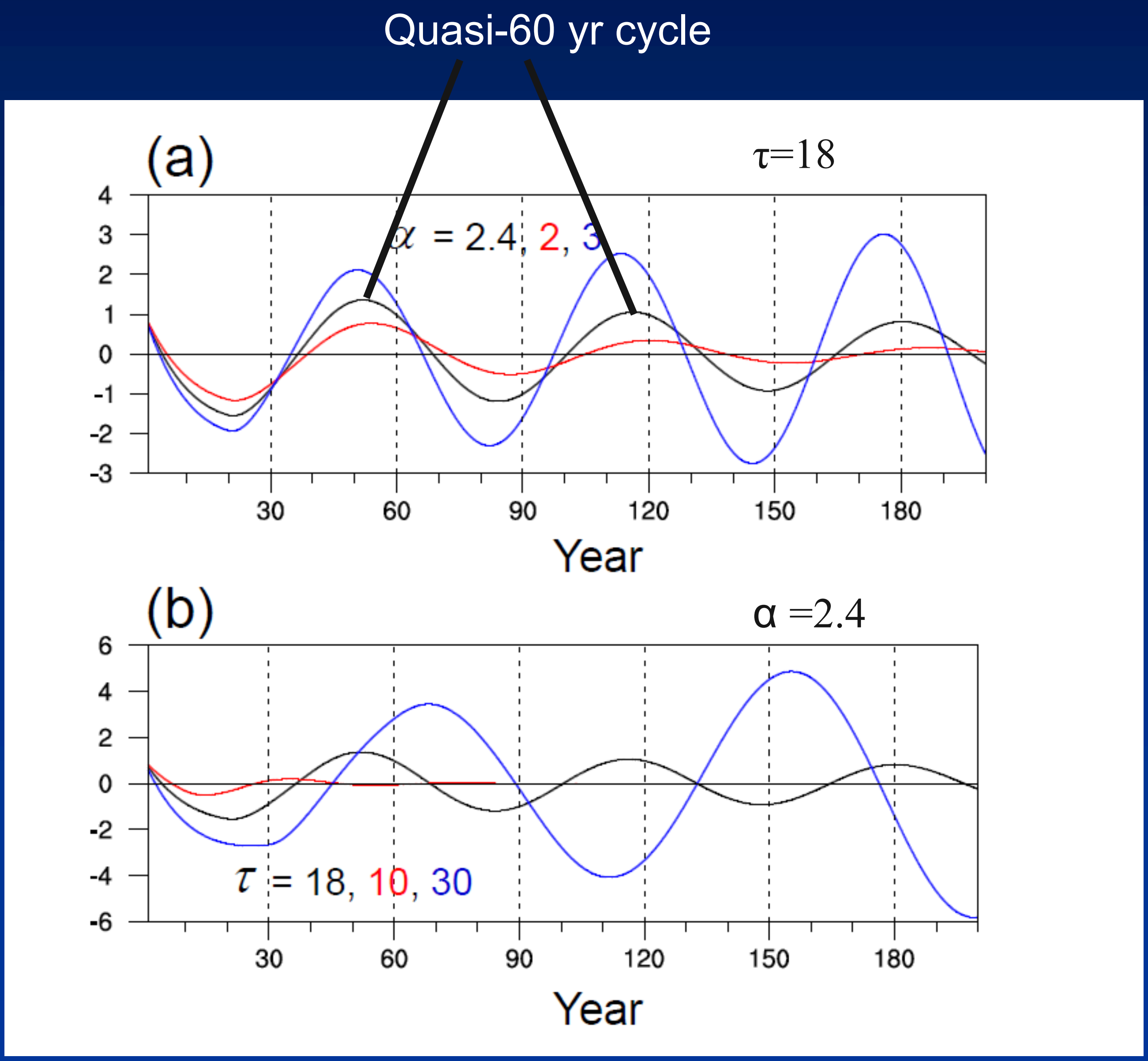
Frequency and growth rate

$$\sigma_R = -\frac{1}{\beta C} - \frac{\alpha}{C} e^{-\sigma_R \tau} \cos(\sigma_I \tau)\,, \qquad (6)$$

$$\sigma_I = \frac{\alpha}{C} e^{-\sigma_R \tau} \sin(\sigma_I \tau)\,. \qquad (7)$$



Numerical solution of the model



Given realistic parameter values, the model can reproduce stable quasi-60 yr cycle of the NAO

Outlines

- Multidecadal variability in North Atlantic: a view from decadal-scale air-sea interaction

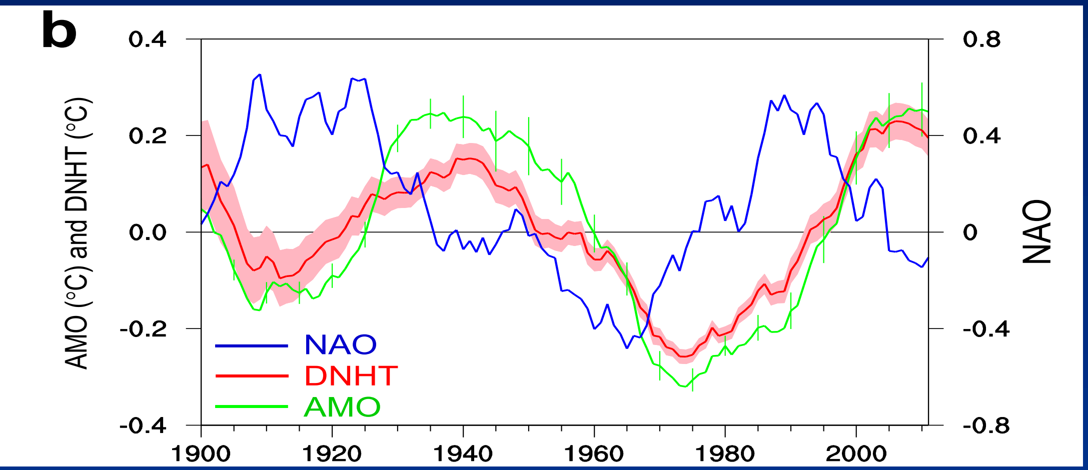
- Remote influences of North Atlantic multidecadal variability

NAO implicated as a predictor of Northern Hemisphere mean temperature multidecadal variability

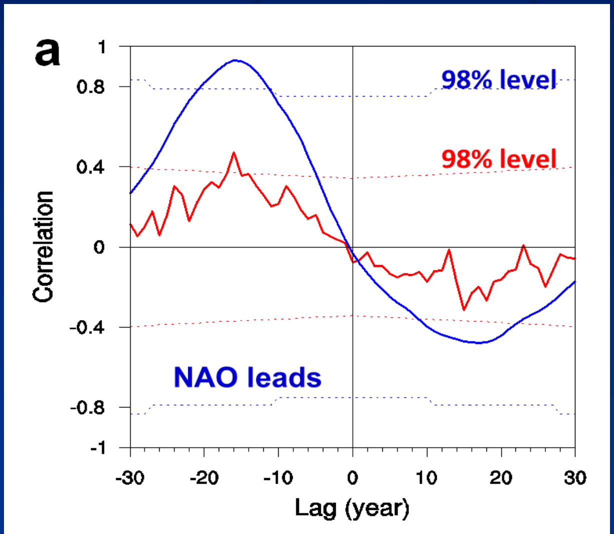
Jianping Li,[1] Cheng Sun,[1] and Fei-Fei Jin[2]

(Li, Sun, and Jin, 2013, *GRL*)

The above multidecadal dynamical theory can explain the observational fact that the NAO leads the DNHT (detrended NHT) by 1-2 decades

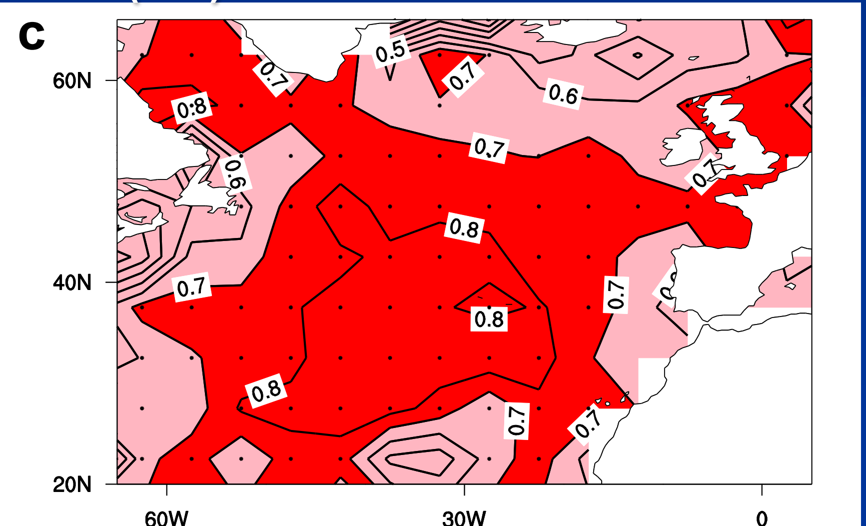


LLR (NAO, DNHT)



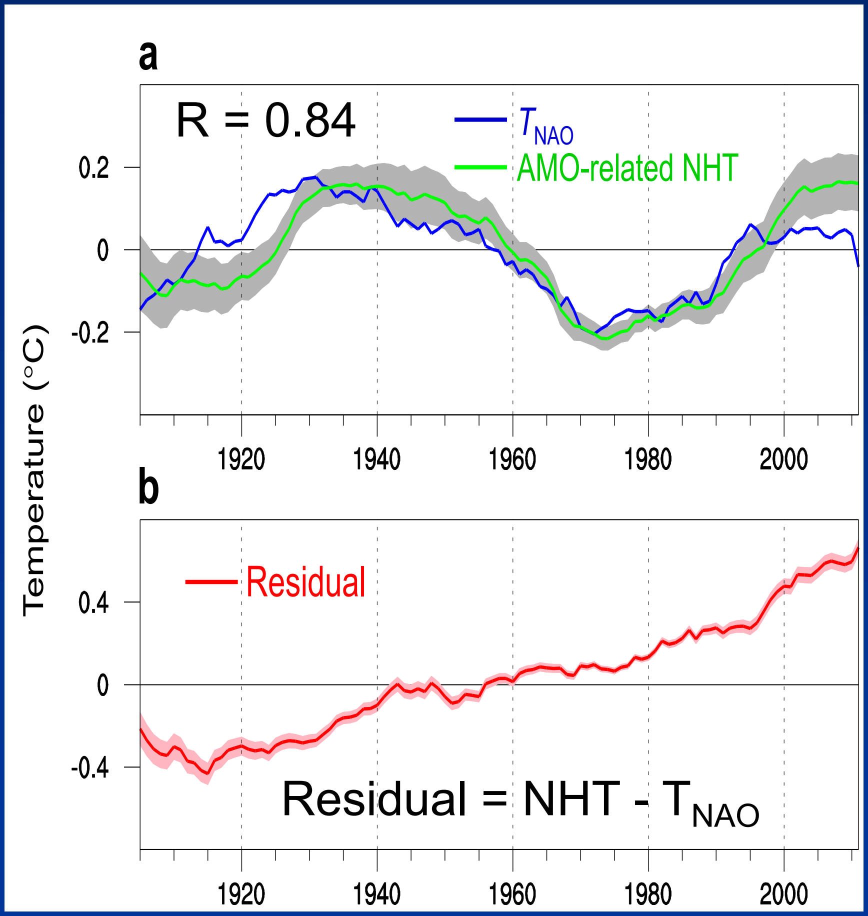
The maximum correlation coefficients occur at a lag of 16 years (NAO leading DNHT)
Red: unfiltered data
Blue: 11-yr running means

NAO (-16) vs. SST



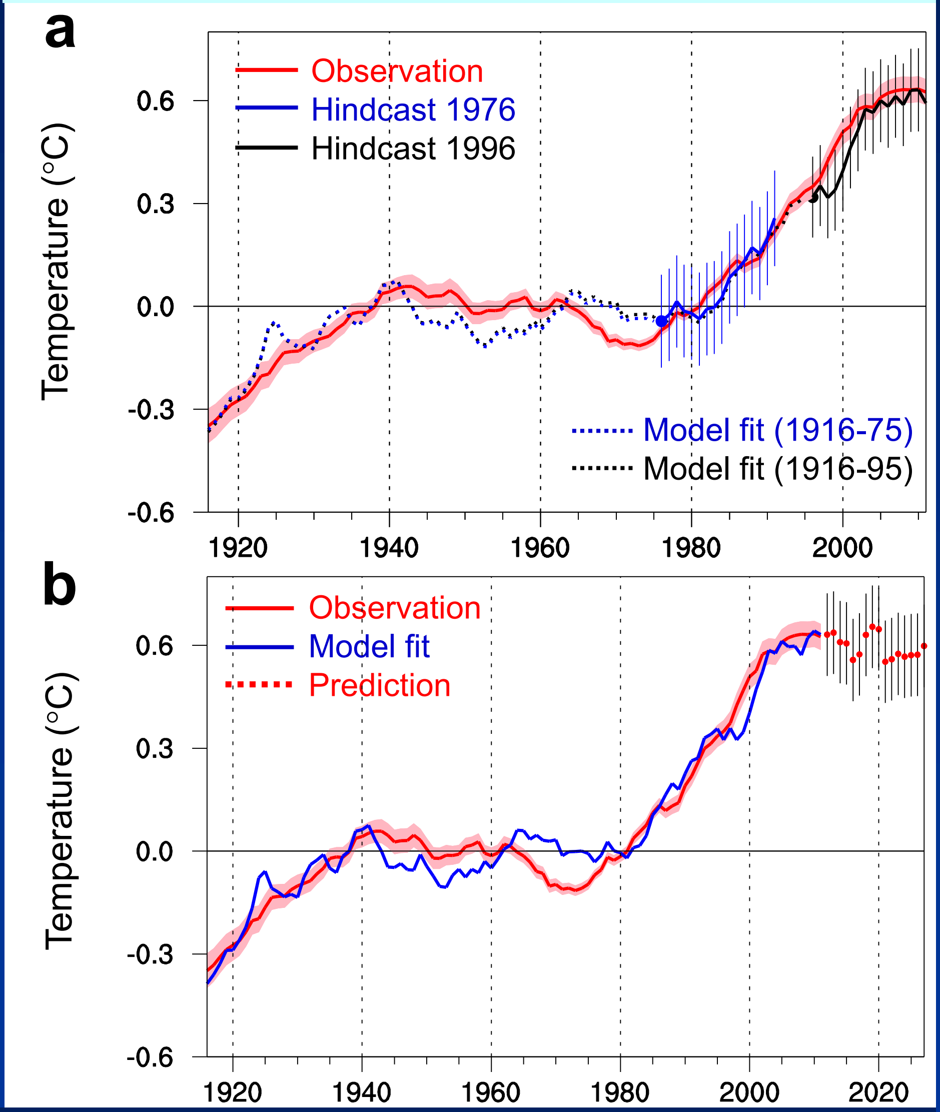
Modeling DNHT using NAO signal

$$C\frac{dT_{NAO}}{dt} = \alpha \mathrm{NAO} - \frac{T_{NAO}}{\beta}$$



NAO-based Prediction model

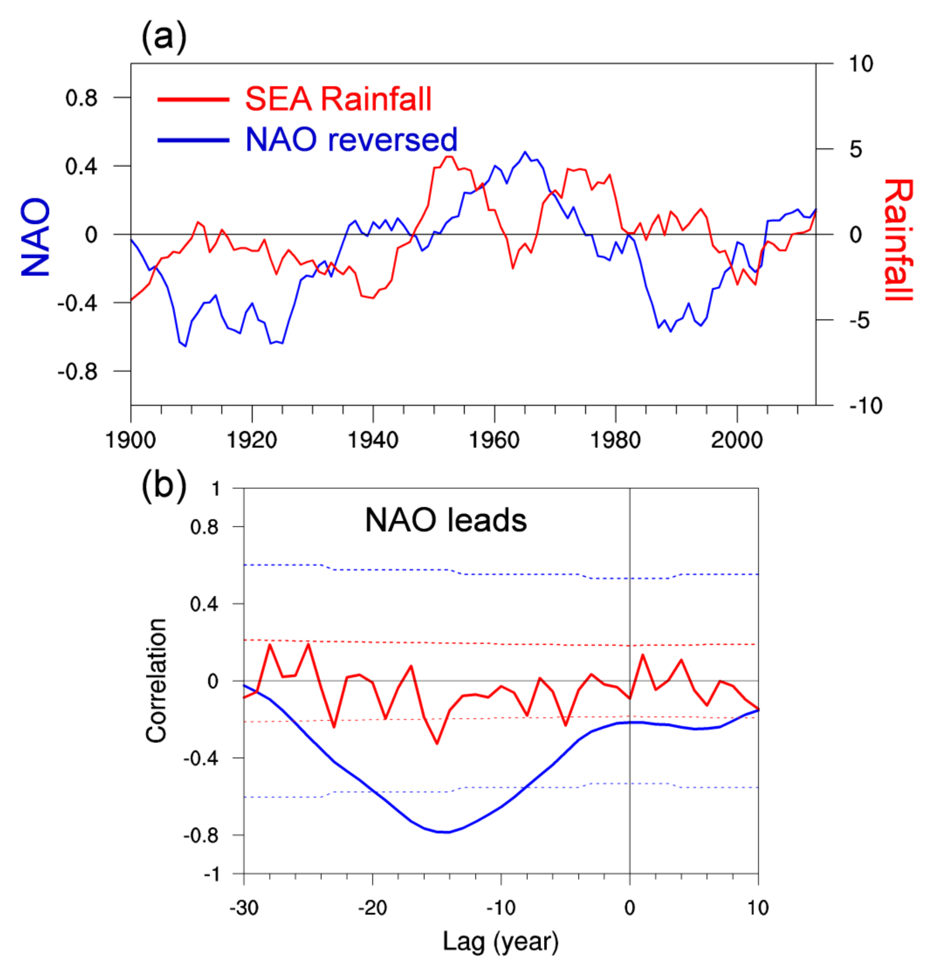
$$\mathrm{NHT}(t) = a\mathrm{NAO}(t-16) + bt + c$$

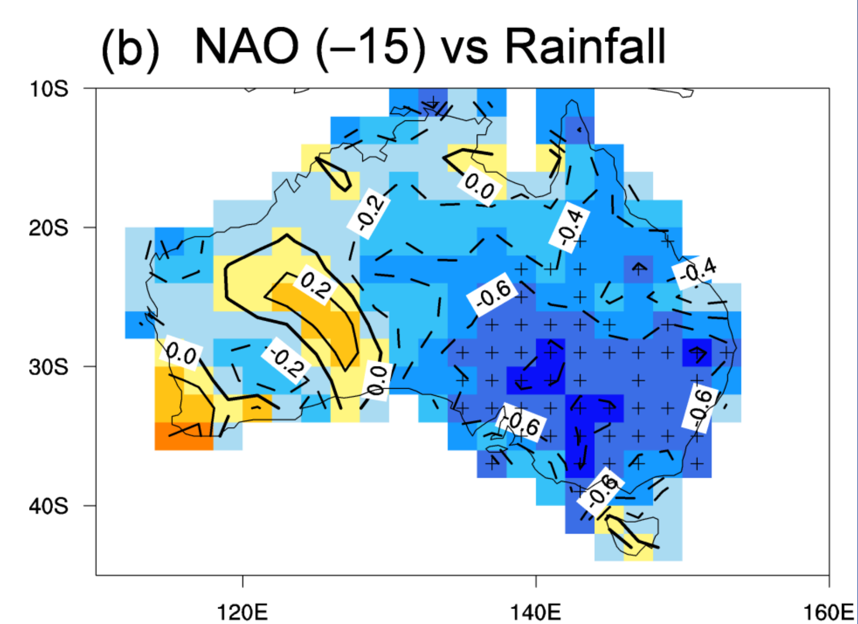


The prediction shows NHT will fall slightly over the next decade (2012-2027).

A Decadal-Scale Teleconnection between the North Atlantic Oscillation and Subtropical Eastern Australian Rainfall

(Sun et al., 2015, *JC*)

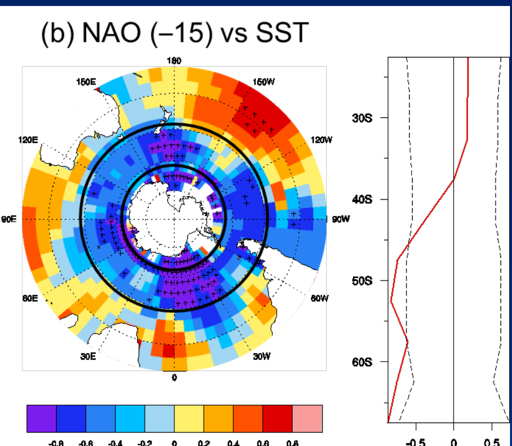


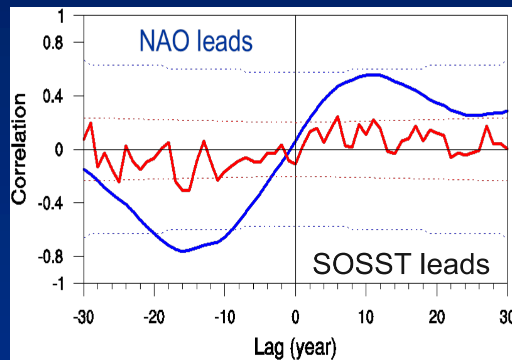


Based on observations, SEAR is connected with NAO, with NAO leading by ~15 years.

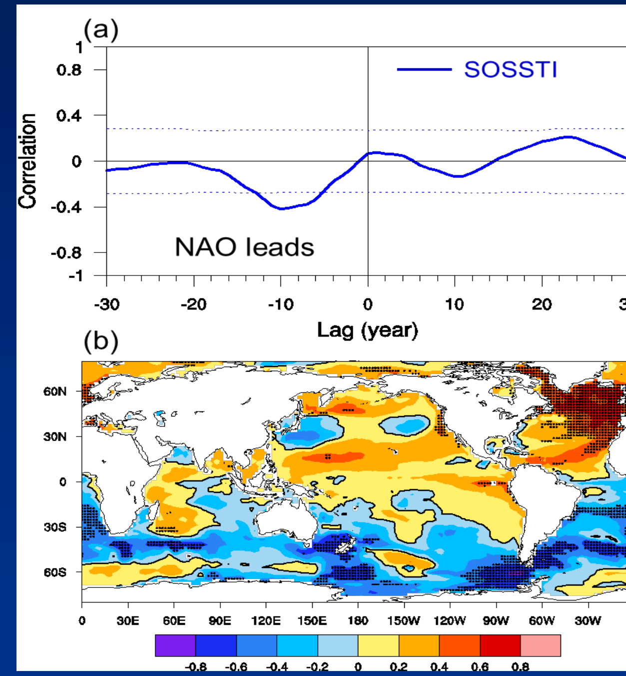
NAO → AMOC → SST Interhemispheric Dipole

Observation: NAO vs. SOSST



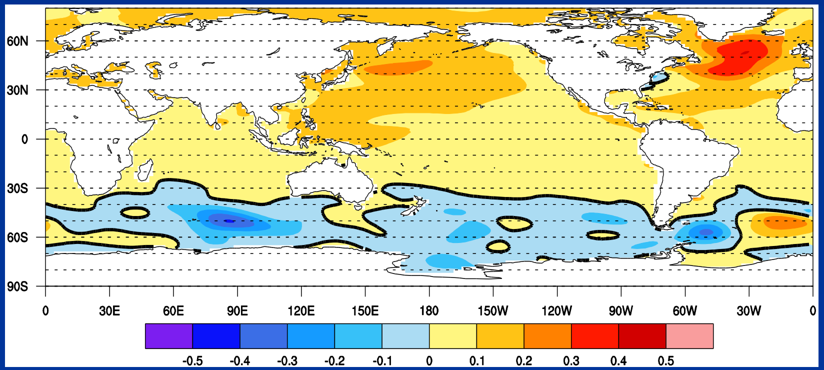


Fully coupled model: CCSM4

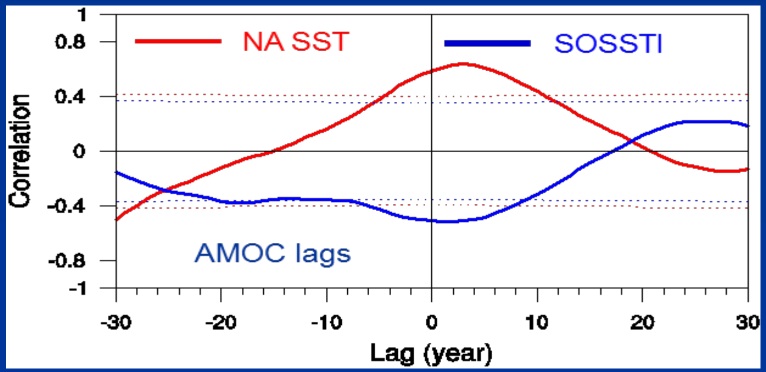


Ocean model: MOM5

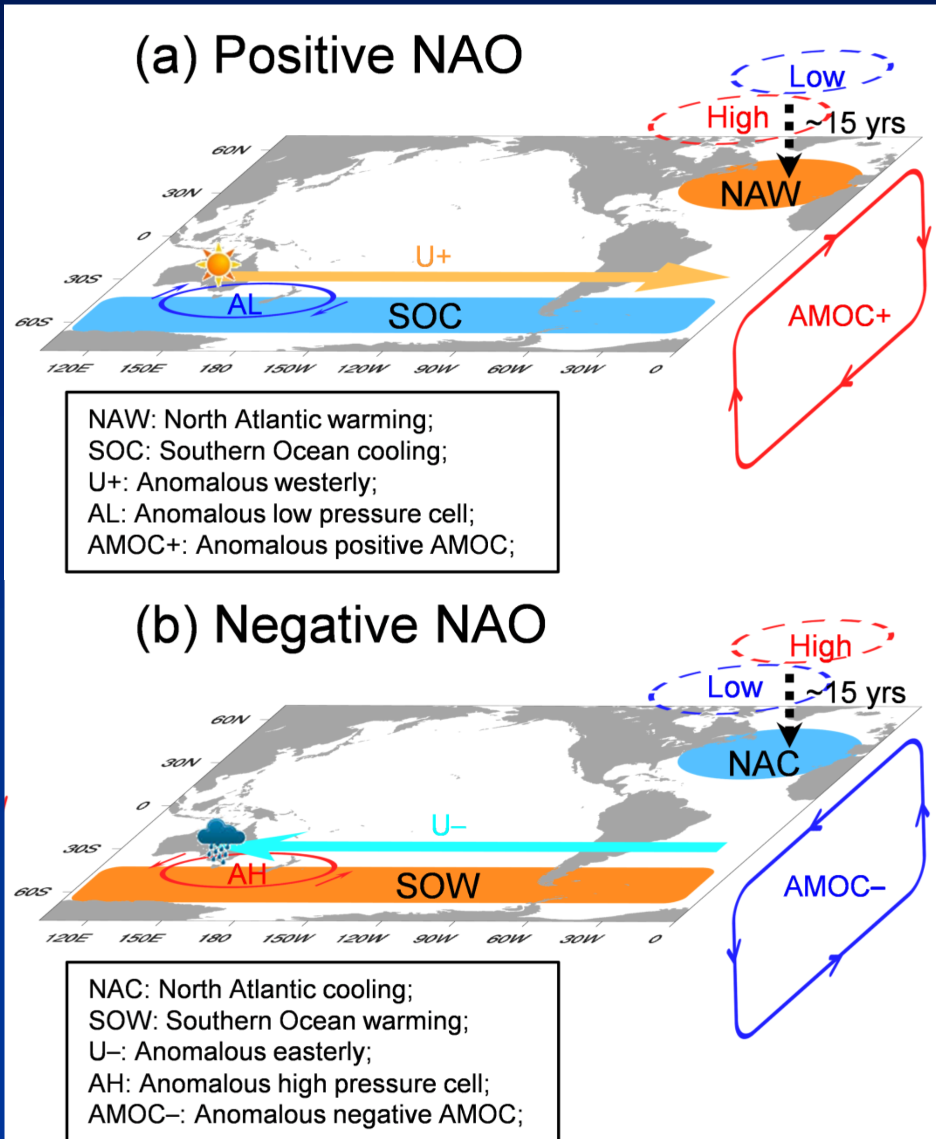
Upper temperature response to NAO forcing



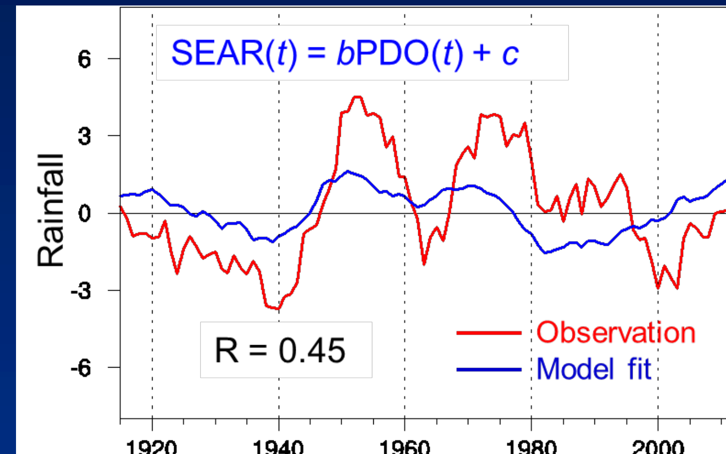
AMOC and SST interhemispheric dipole

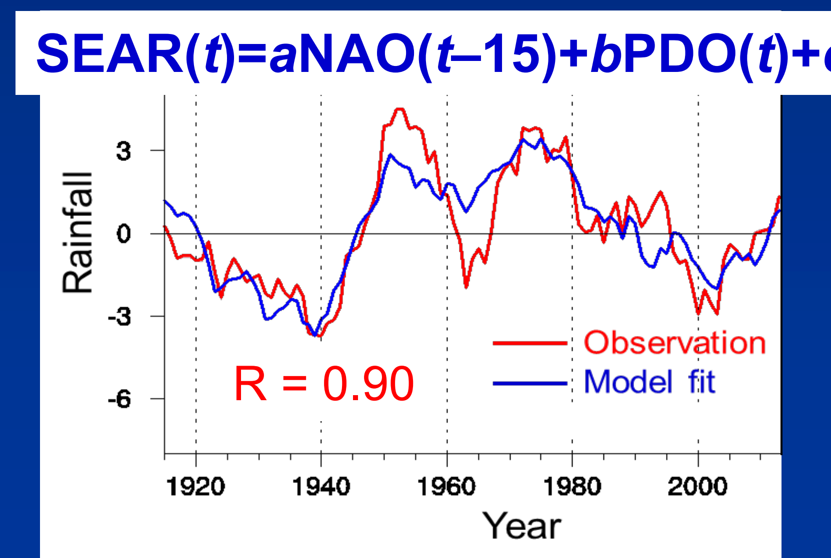


Mechanisms



Empirical model



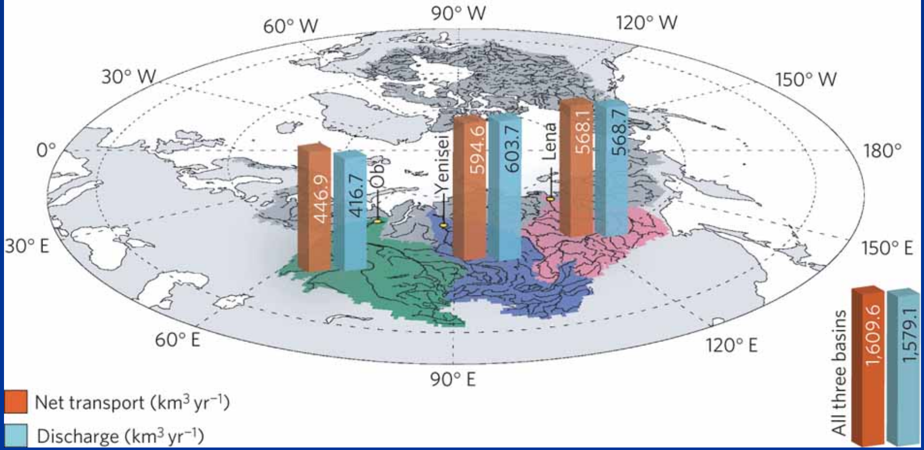


(Sun et al., 2015, *JC*)

Remote influence of Atlantic multidecadal variability on Siberian warm season precipitation

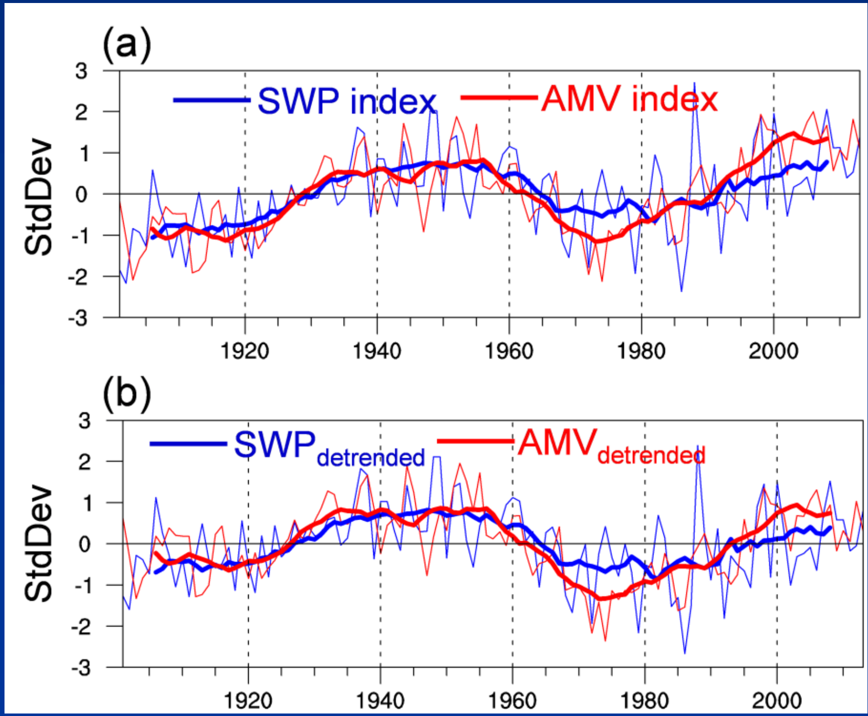
(Sun et al., 2015, *Sci. Rep.*)

Siberian precipitation peaks during the warm season (May to Oct.) and has important implications for Arctic hydrologic cycle, but our understanding of the Siberian warm season precipitation (SWP) decadal variability is still limited.



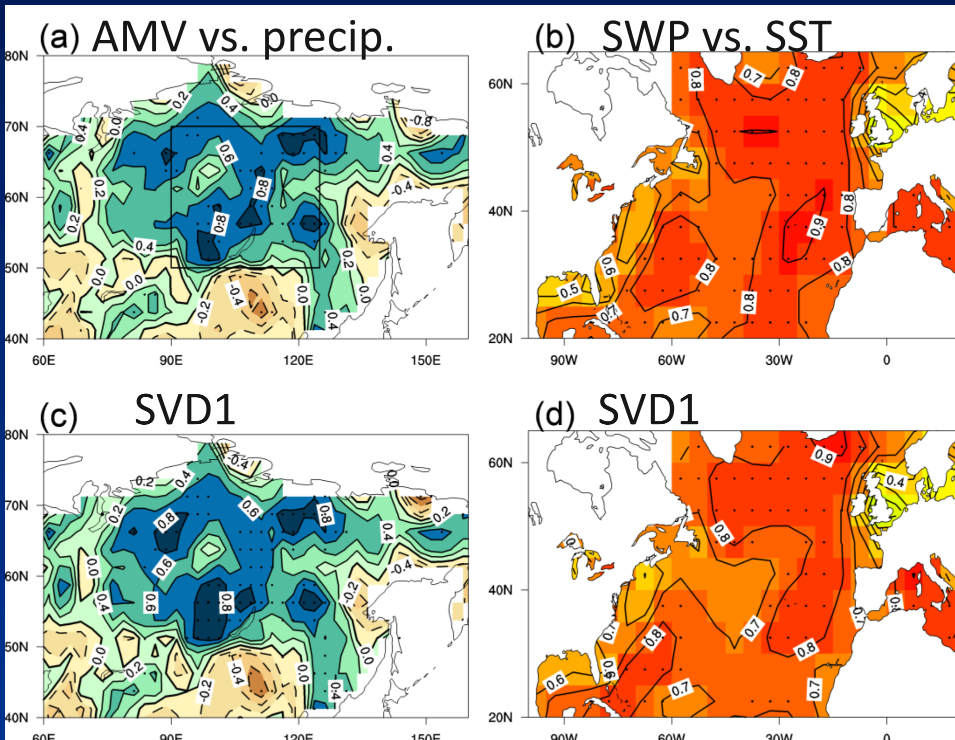
Zhang et al. 2012

Temporal covariability between SWP and AMV



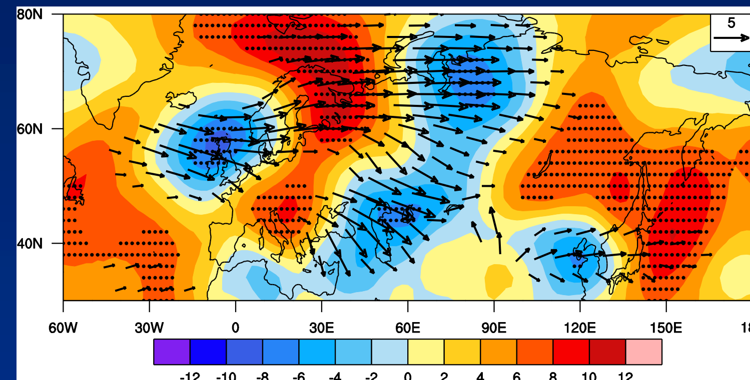
R = 0.91

Spatial patterns of covariability

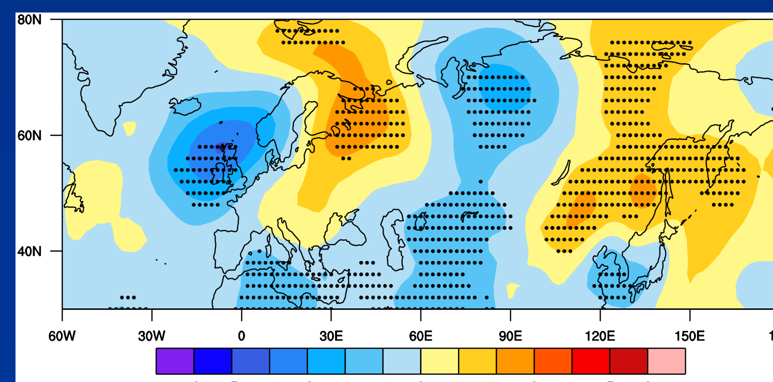


Large-scale atmospheric circulation pattern associated with AMV

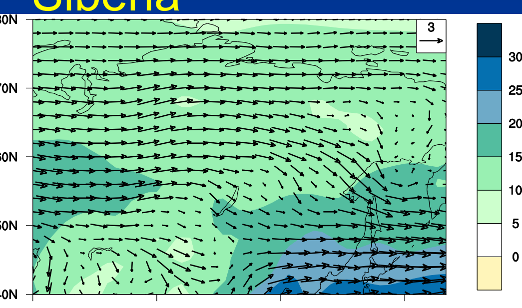
Z300 and stationary wave activity flux

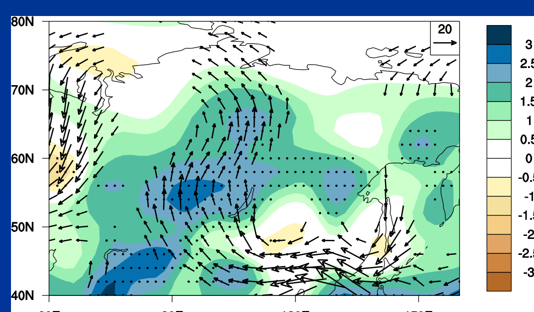


Z900



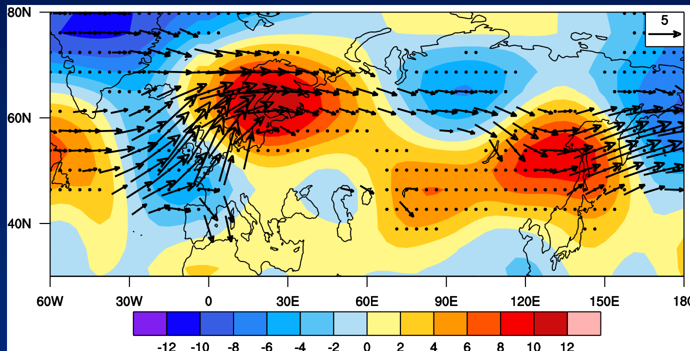
Southerly brings moisture northward to Siberia



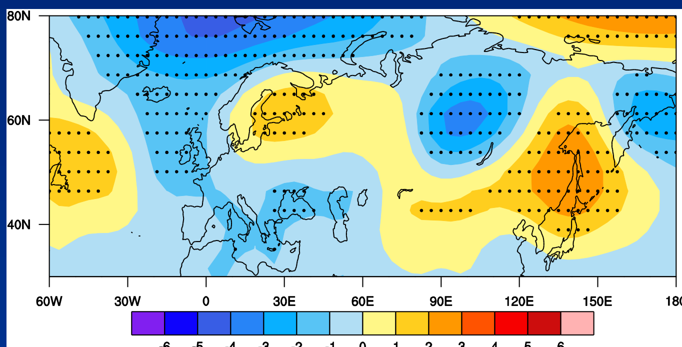


AGCM simulation using SPEEDY model

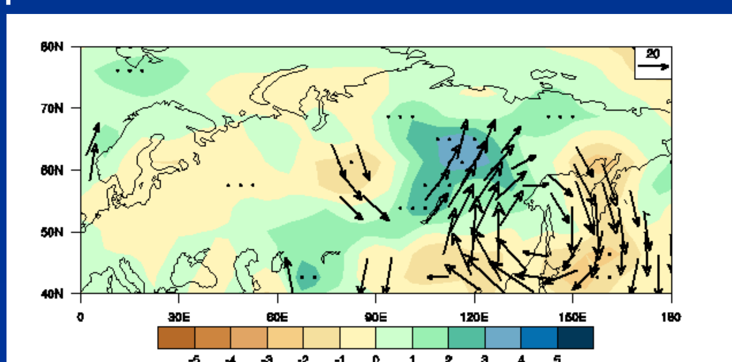
Z300



Z900

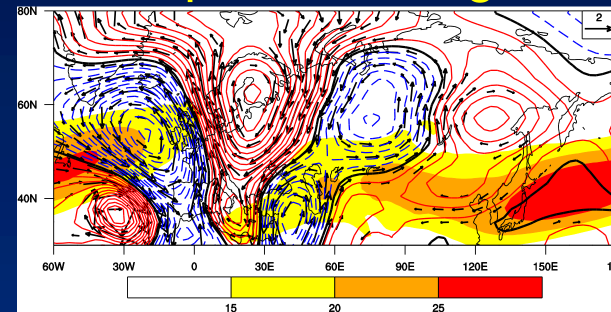


Precipitation and moisture flux



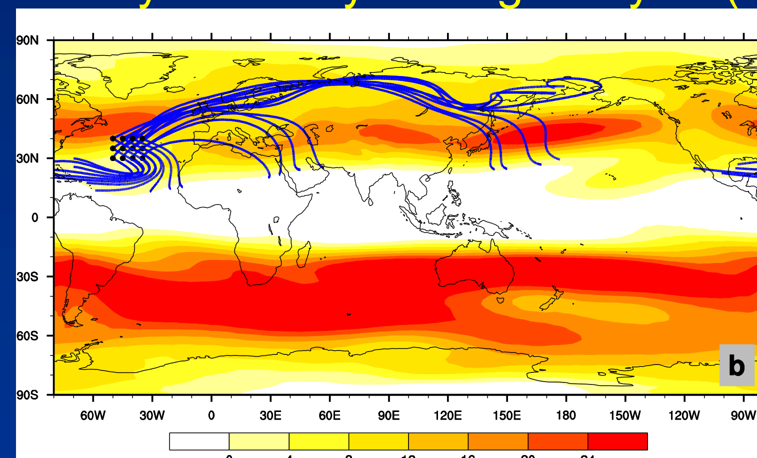
Rossby wave dynamics

Barotropic modelling

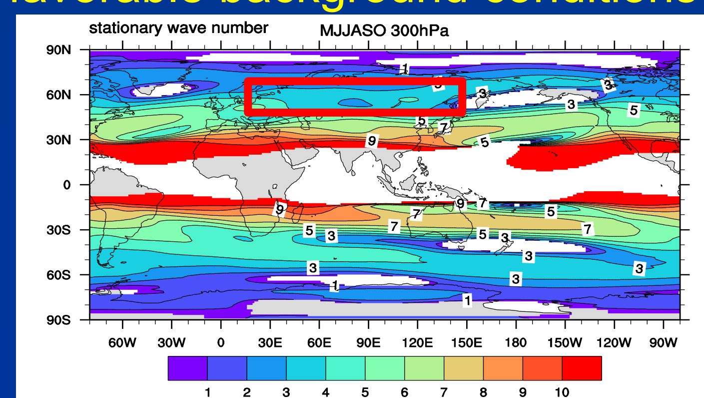


Z300

Rossby wave ray tracing analysis (k = 4)



favorable background conditions

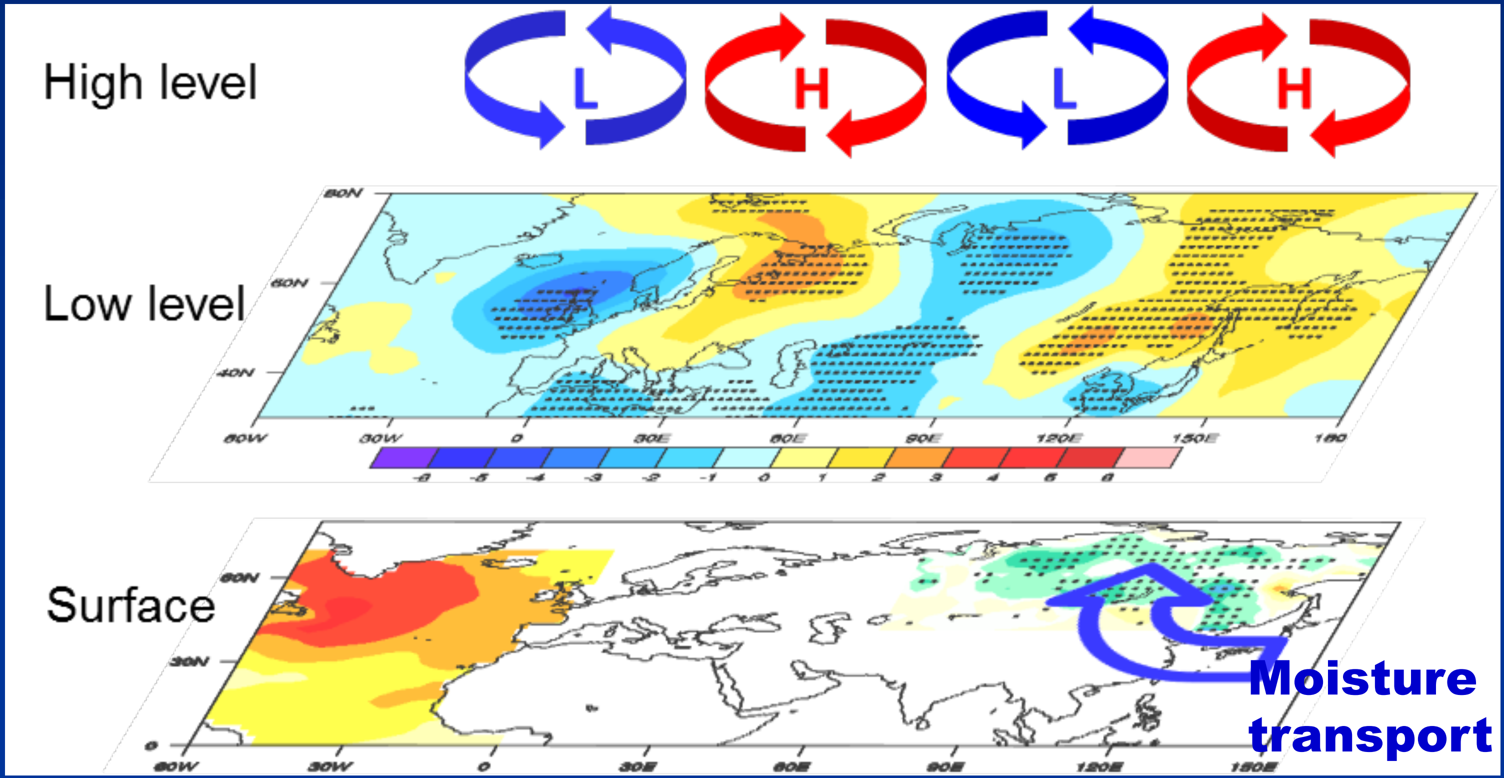


Remote influence of Atlantic multidecadal variability on Siberian warm season precipitation

(Sun et al., 2015, *Sci. Rep.*)

Mechanisms

SST anomaly excites a Rossby wave train

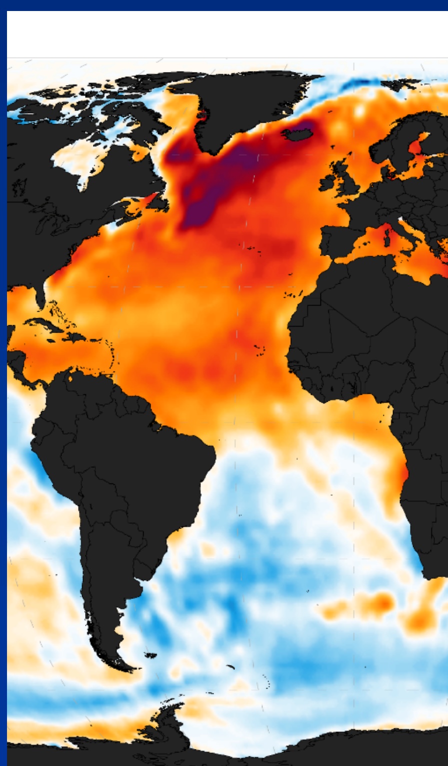


Cold season Africa–Asia multidecadal teleconnection pattern and its relation to the Atlantic multidecadal variability

(Sun et al., 2016, *CD*)

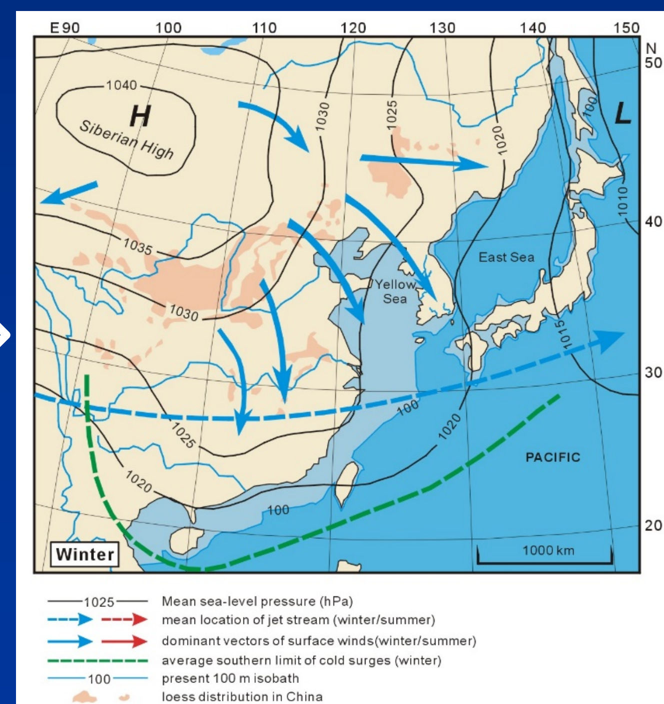
Observation and reconstruction studies have suggested a decadal-scale linkage between Atlantic multidecadal variability and East Asian winter climate, but the dynamical mechanism underlying this wintertime teleconnection is still unclear and the pathway remains to be elucidated

AMV



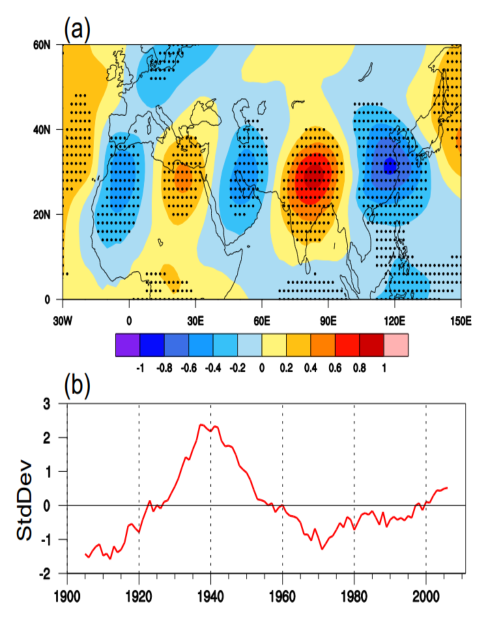
Teleconnection

East Asian winter climate

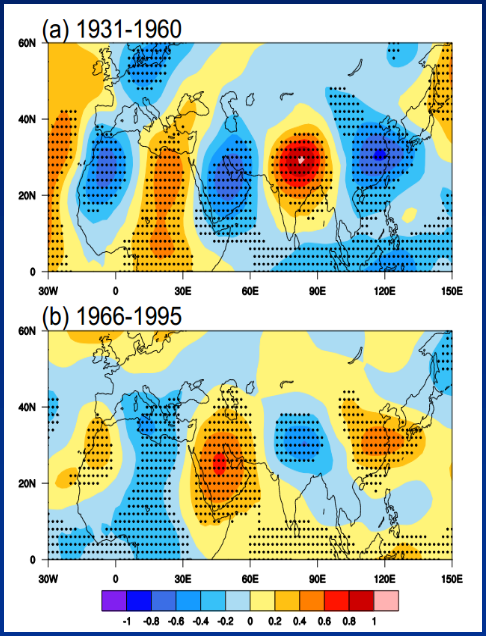


Identification of cold season AAMT

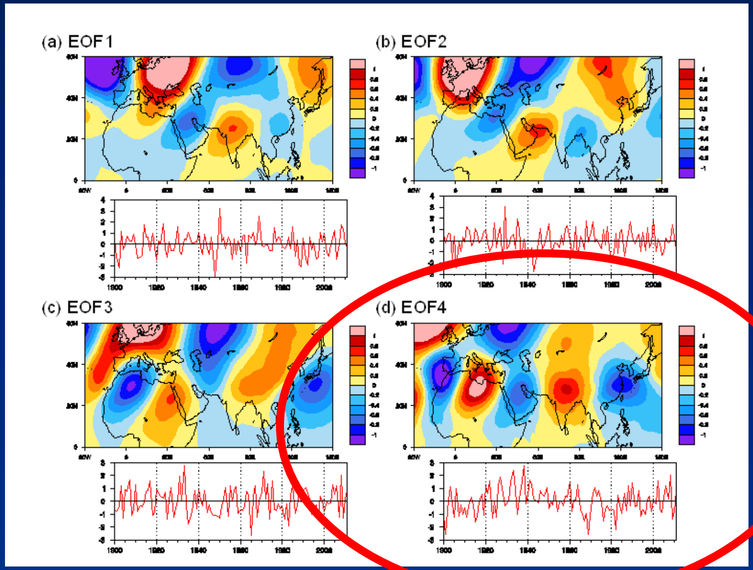
EOF1 of Eurasian cold season (Nov. to Apr.) V300 decadal variability



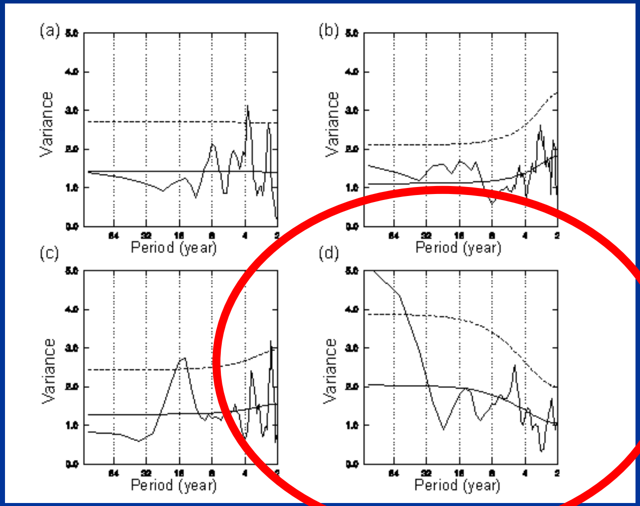
Multidecadal change in V300



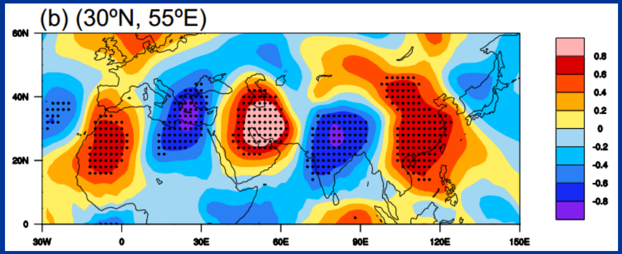
First four EOFs of Eurasian unfiltered V300 variability



Spectral analysis



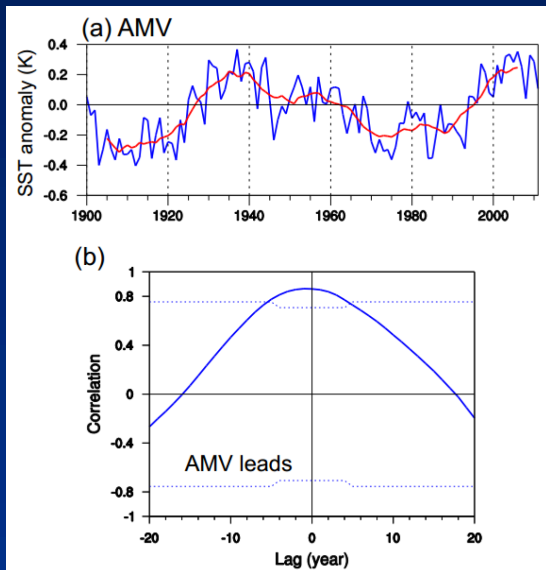
Strong teleconnectivity



Referred to as Africa-Asia multidecadal teleconnection pattern (AAMT)

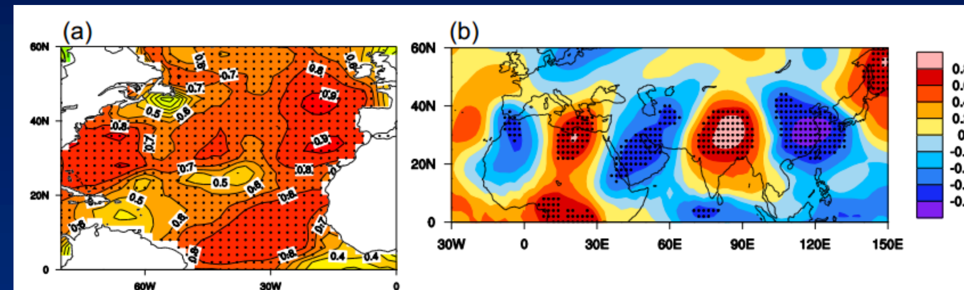
Connection between AAMT and AMV

Cold season AMV and lead-lag correlation

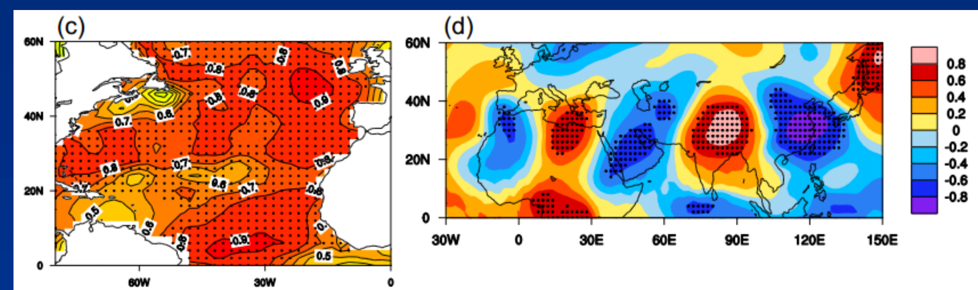


AAMT vs. SST

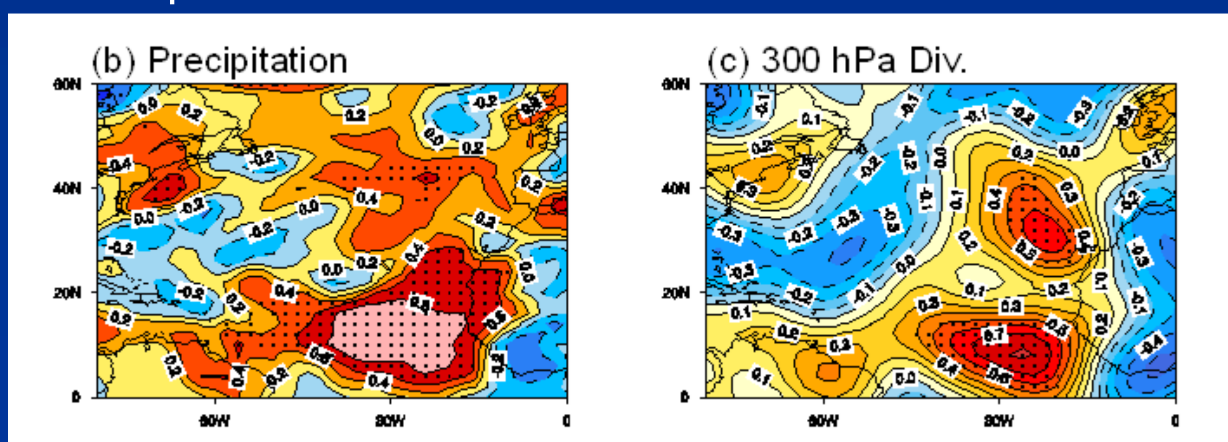
AMV vs. V300



First SVD coupled mode of decadal V300 and SST

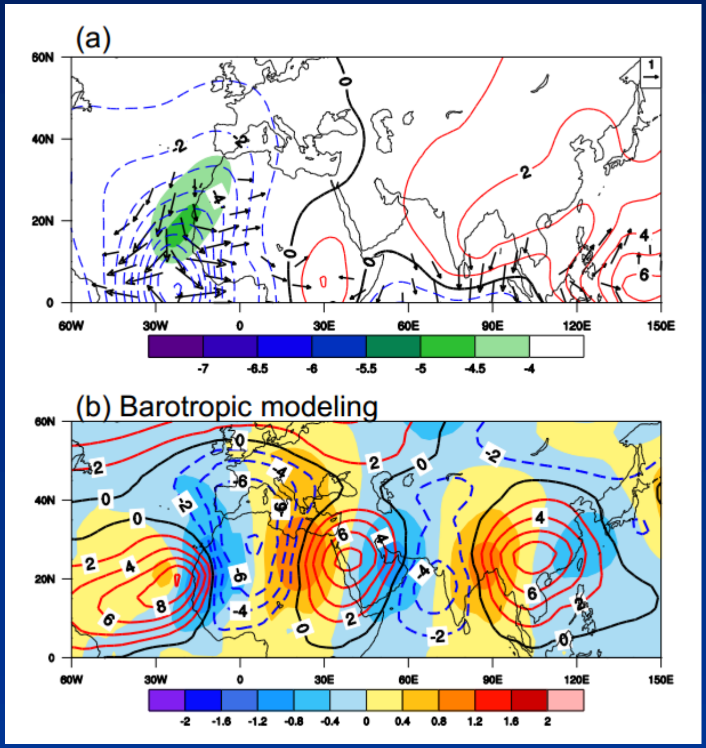


AMV and local atmospheric condition

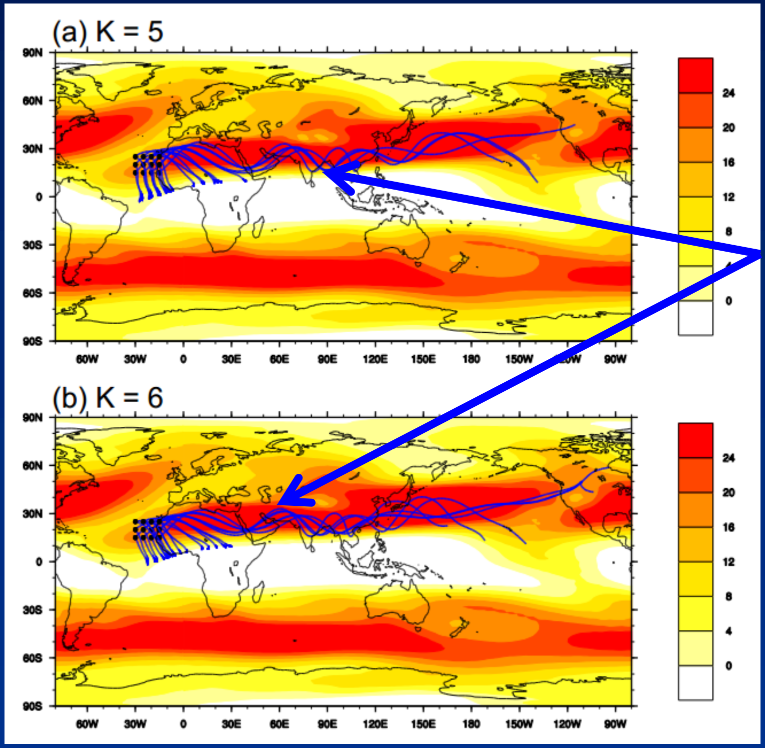


Rossby wave dynamics involved

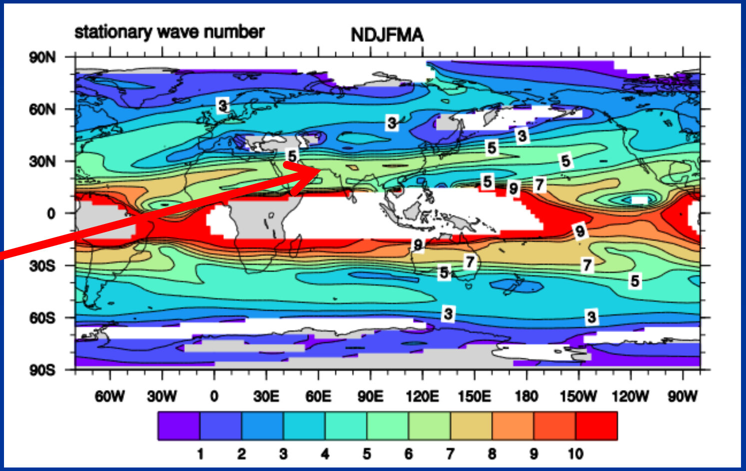
Steady response of a linear barotropic model to the AMV-induced RWS



Rossby wave ray tracing analysis (k = 5 and 6)

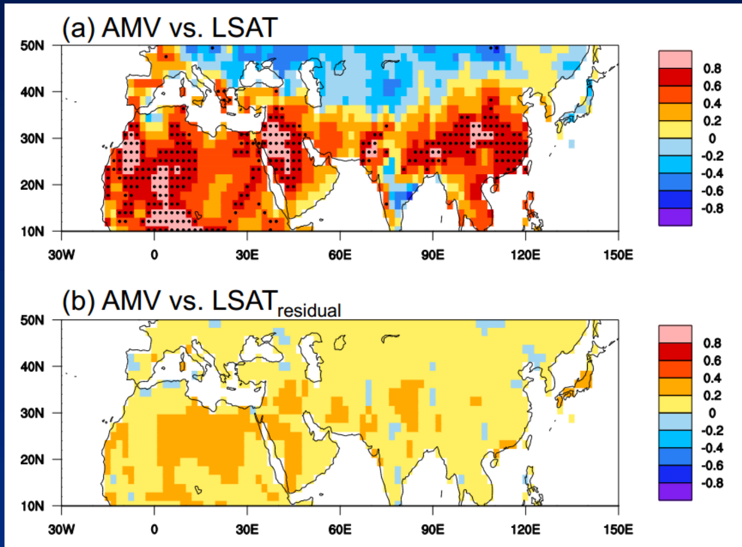


Asian jet stream waveguide

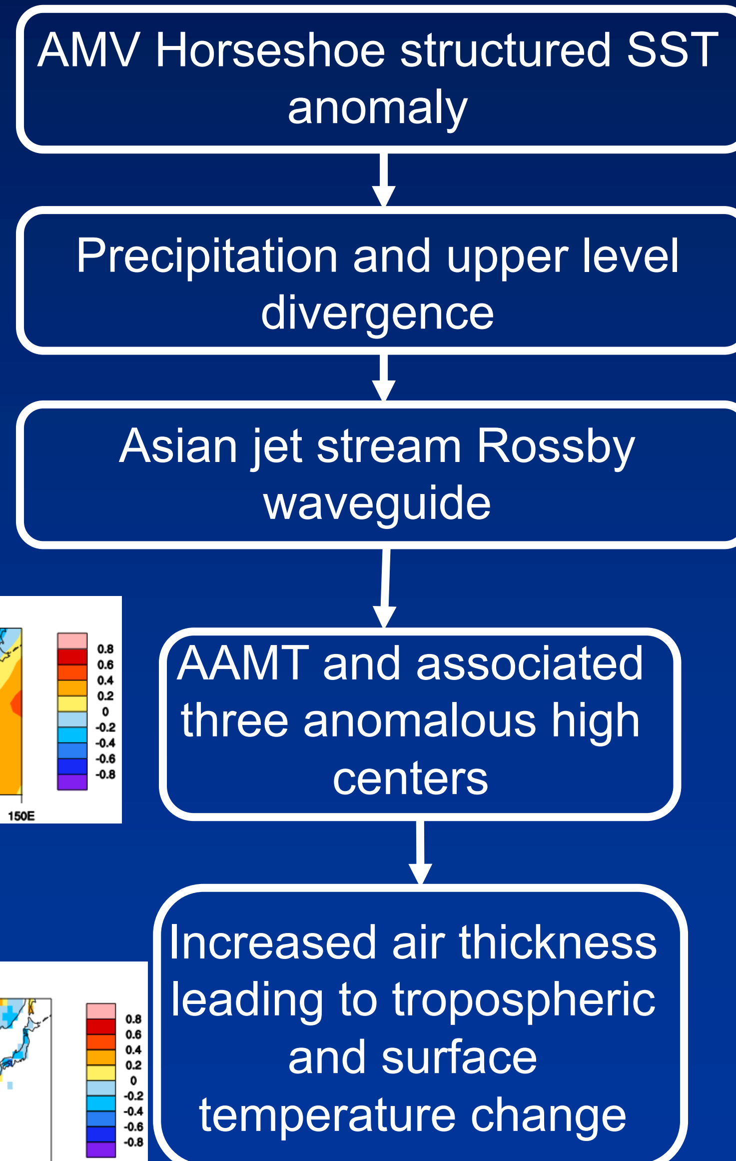


Large total wavenumbers (Ks ≥ 5) are observed along the Asian jet stream; stationary waves of higher wavenumber, like the AAMT, tend to be trapped

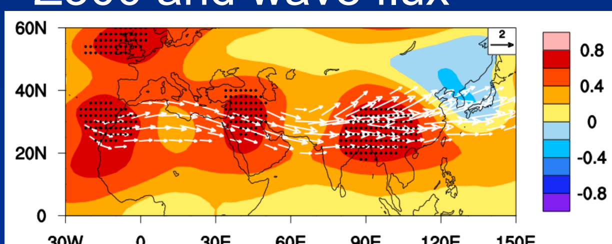
AAMT as an atmospheric bridge

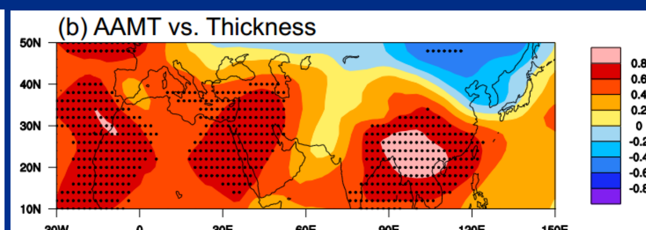


Schematic diagram



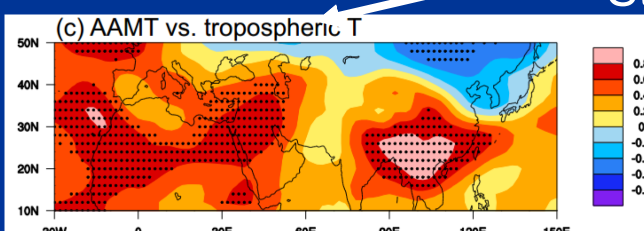
Z300 and wave flux

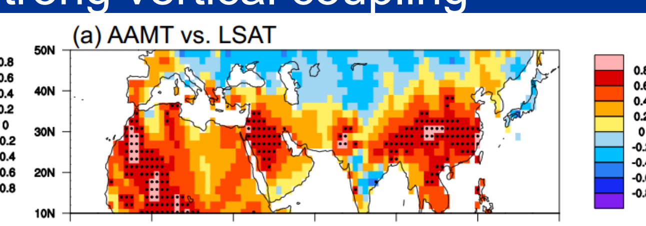




The hypsometric equation

Strong vertical coupling





Conclusions

- A coupled decadal-scale air-sea interaction theory: the NAT-NAO-AMOC-AMO coupled mode
  A delayed decadal oscillator model
- Hemispheric impacts: The coupled decadal mode leads to NHT multidecadal variability
- Inter-hemispheric impacts: The coupled decadal mode also exerts an influence on SH climate, esp. the Australian rainfall variations.
- Regional impacts: Remote influence on warm season Siberian climate and cold season Africa-Asia multidecadal teleconnection pattern (AAMT)

Thank You For Your Attention!