Arctic Climate Change and Extreme Midlatitude Events:

Observational Analysis and Modeling Investigation

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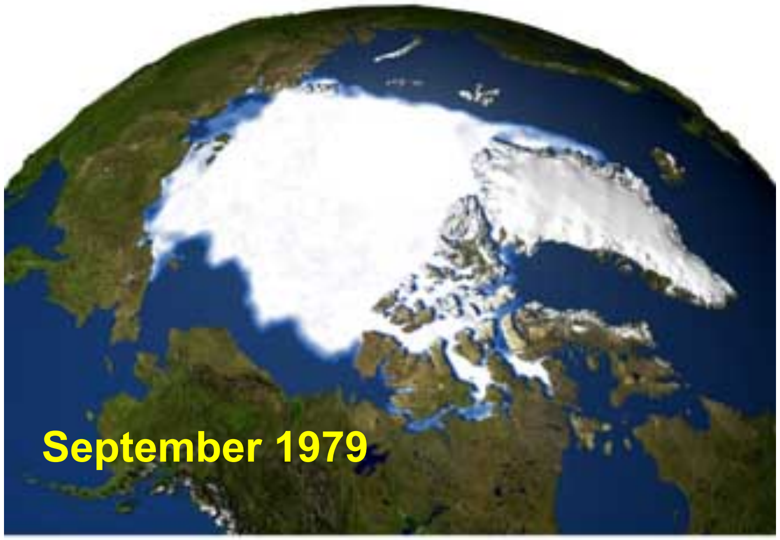
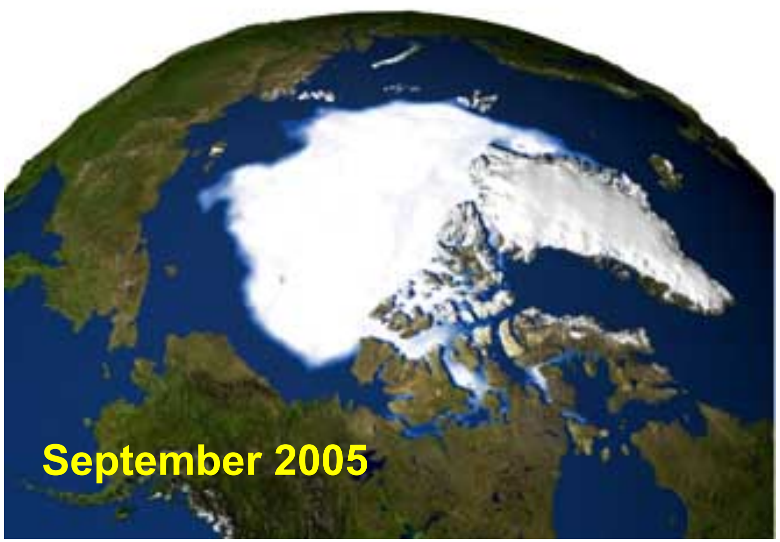
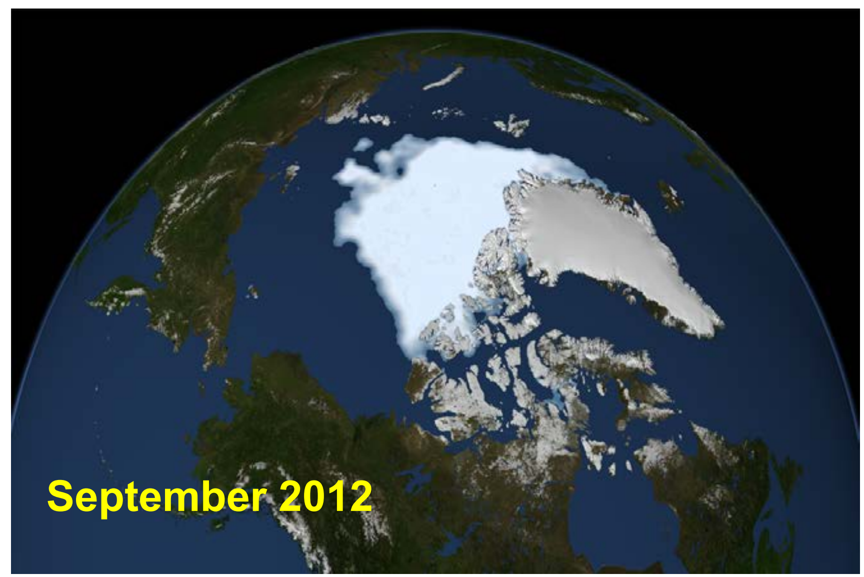
• Record lows of sea ice extent have consecutively occurred



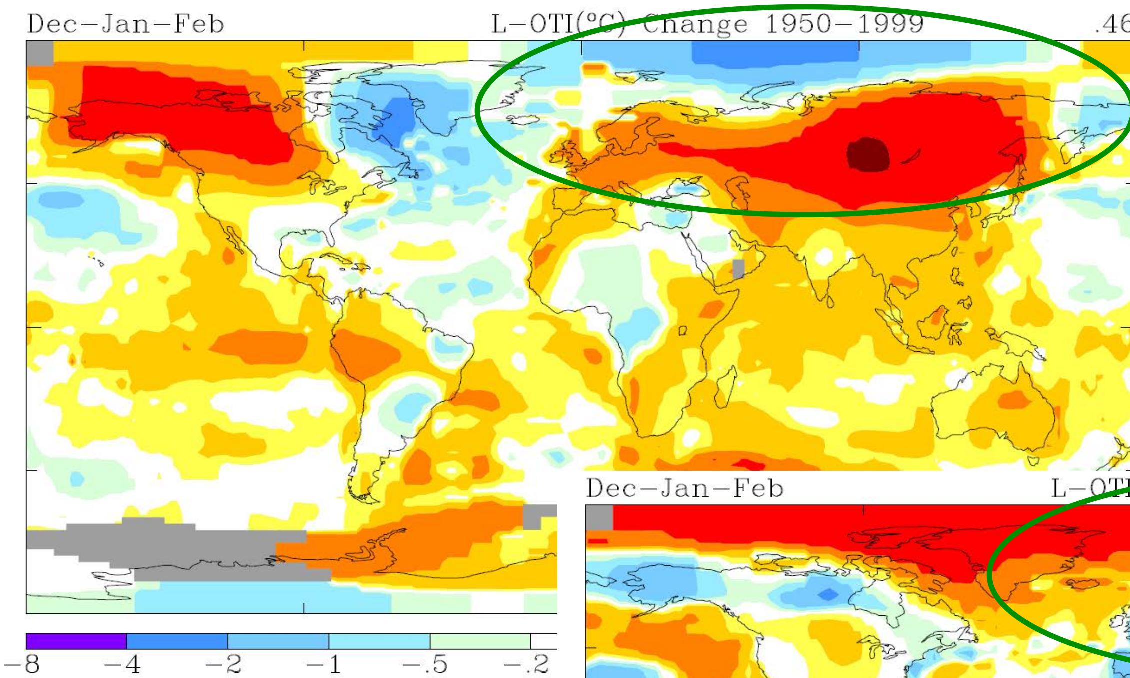


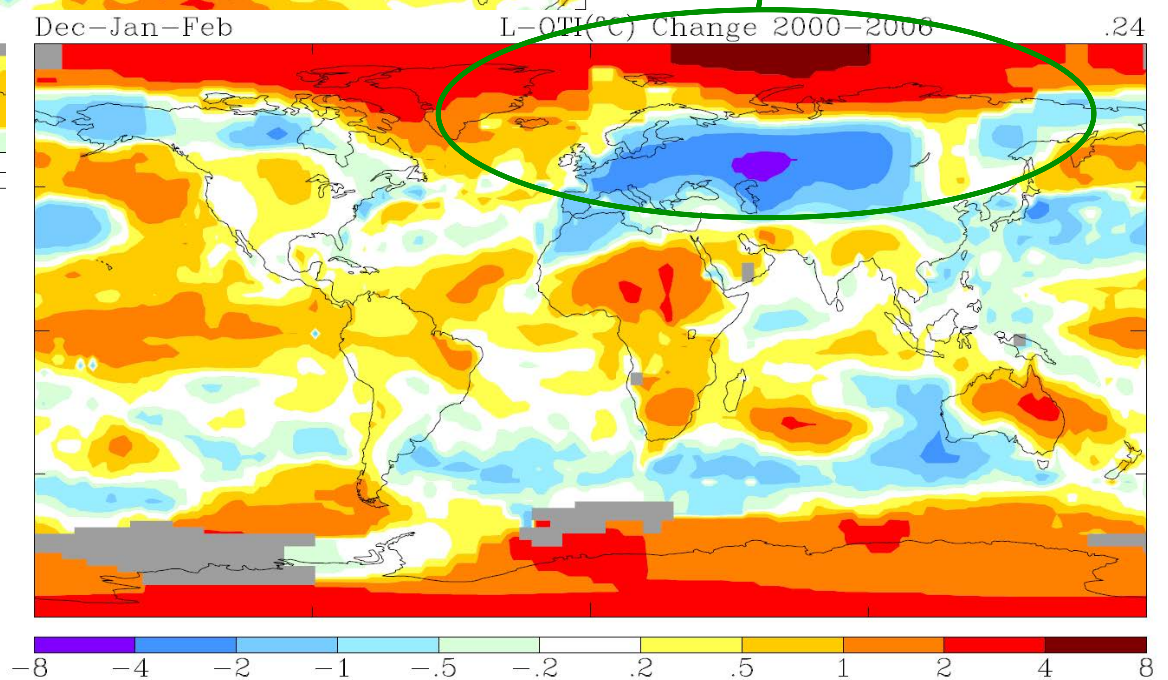


NASA

• Surface temperature increase has been further amplified over Arctic

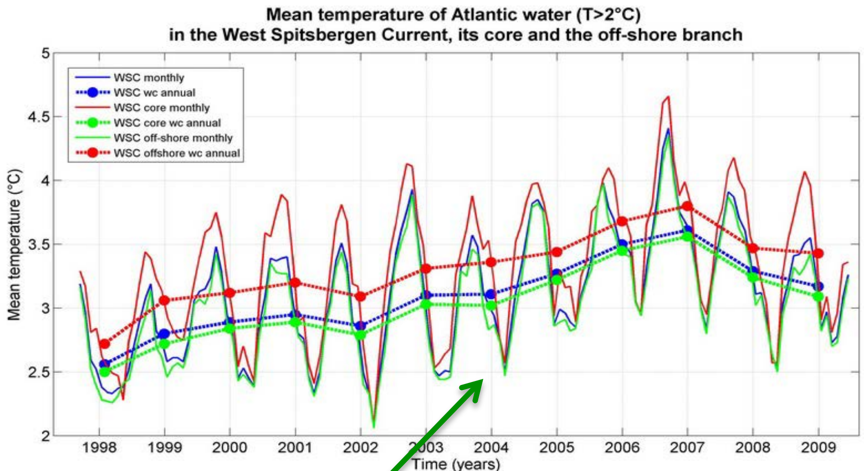
Shift of SAT trend pattern



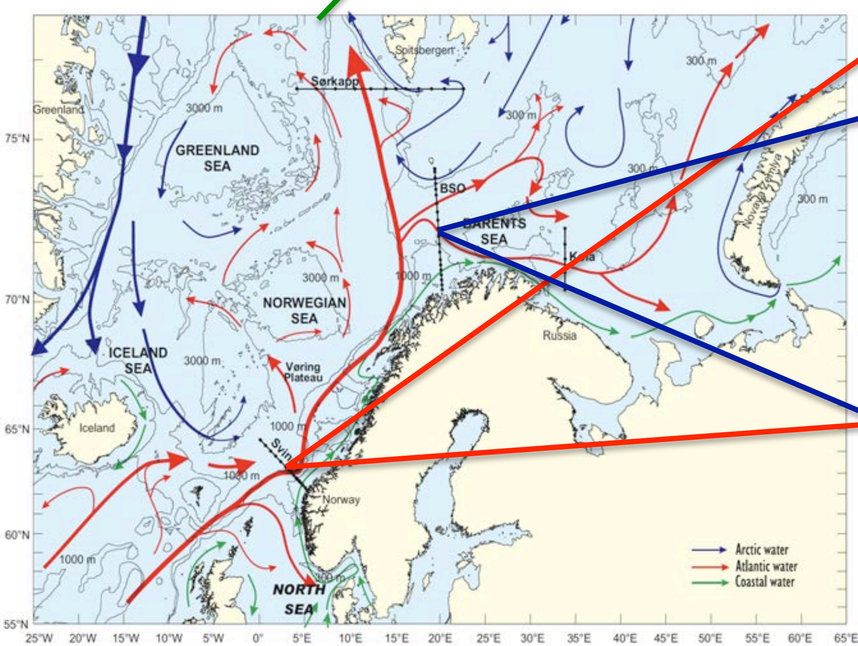


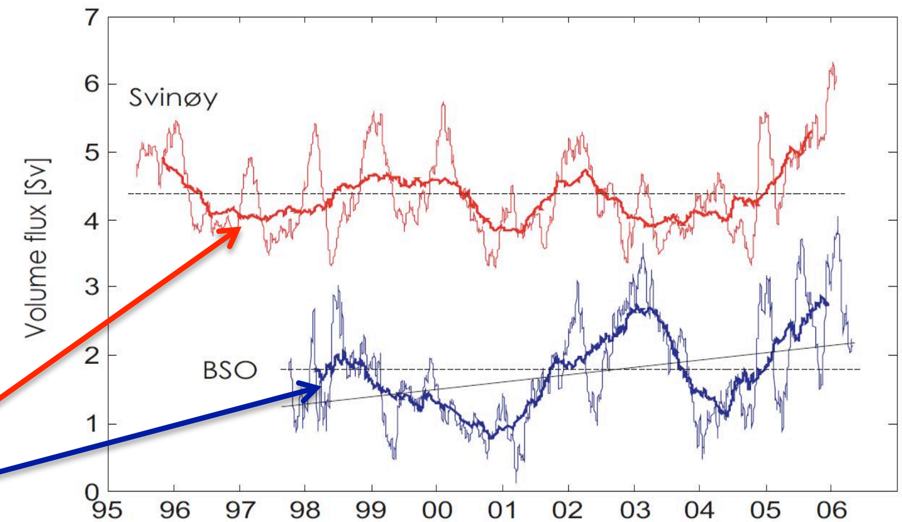
Note:
Winter: No sea ice retreat induced albedo feedback

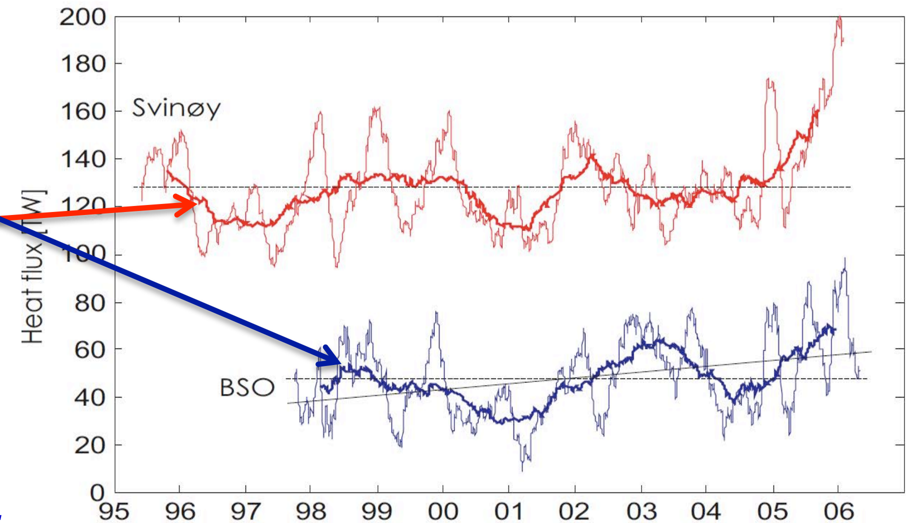
• **Atlantic warm water intrusion has been enhanced**



Beszczynska-Möller et al.







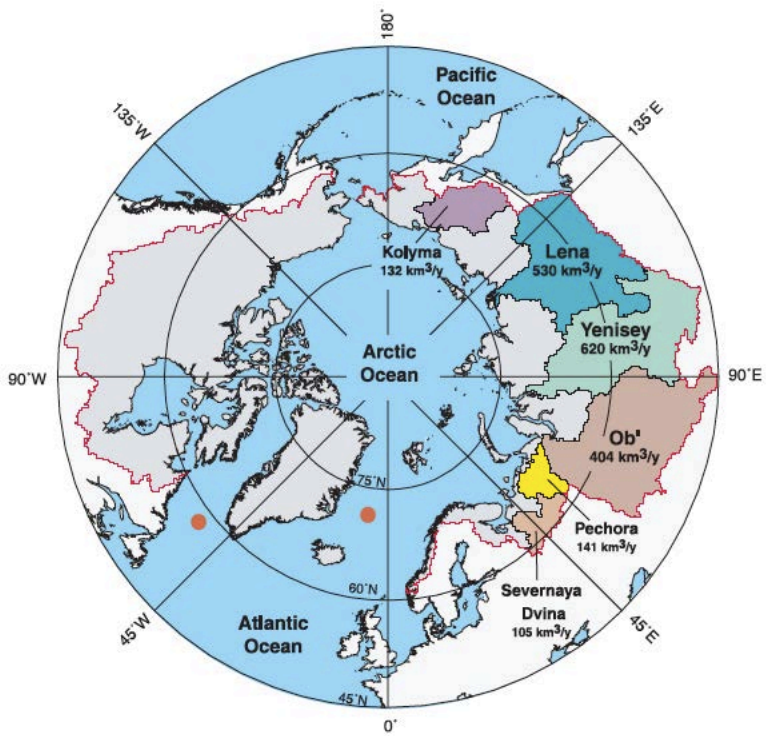
Skagseth et al.

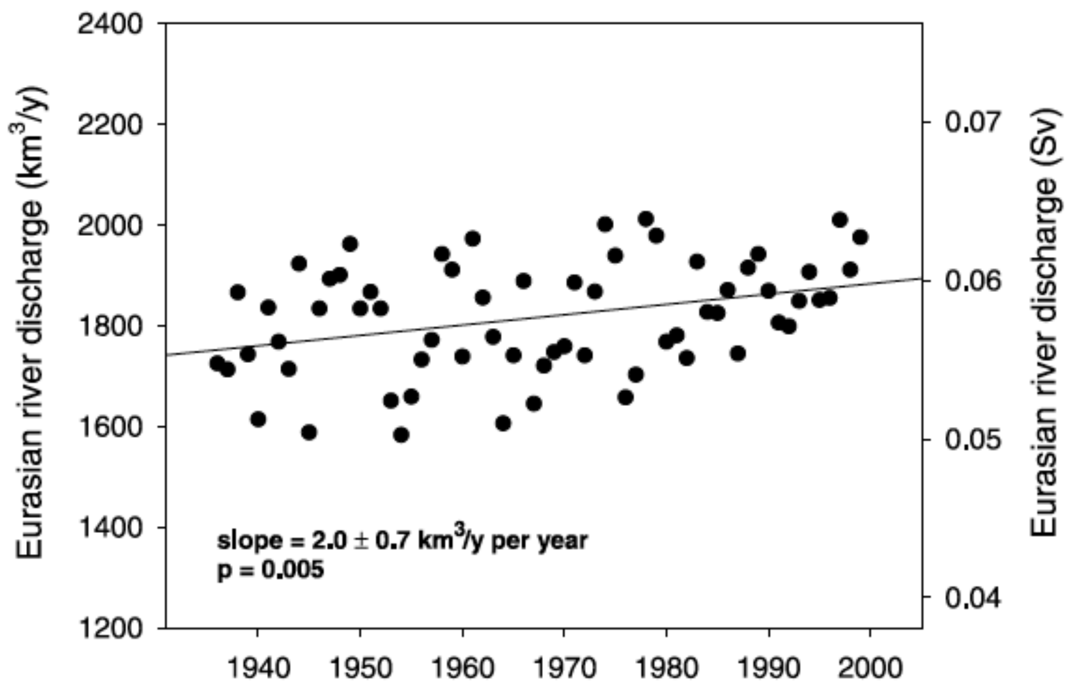
Science
AAAS

Science **298**, 2171 (2002);
DOI: 10.1126/science.1077445

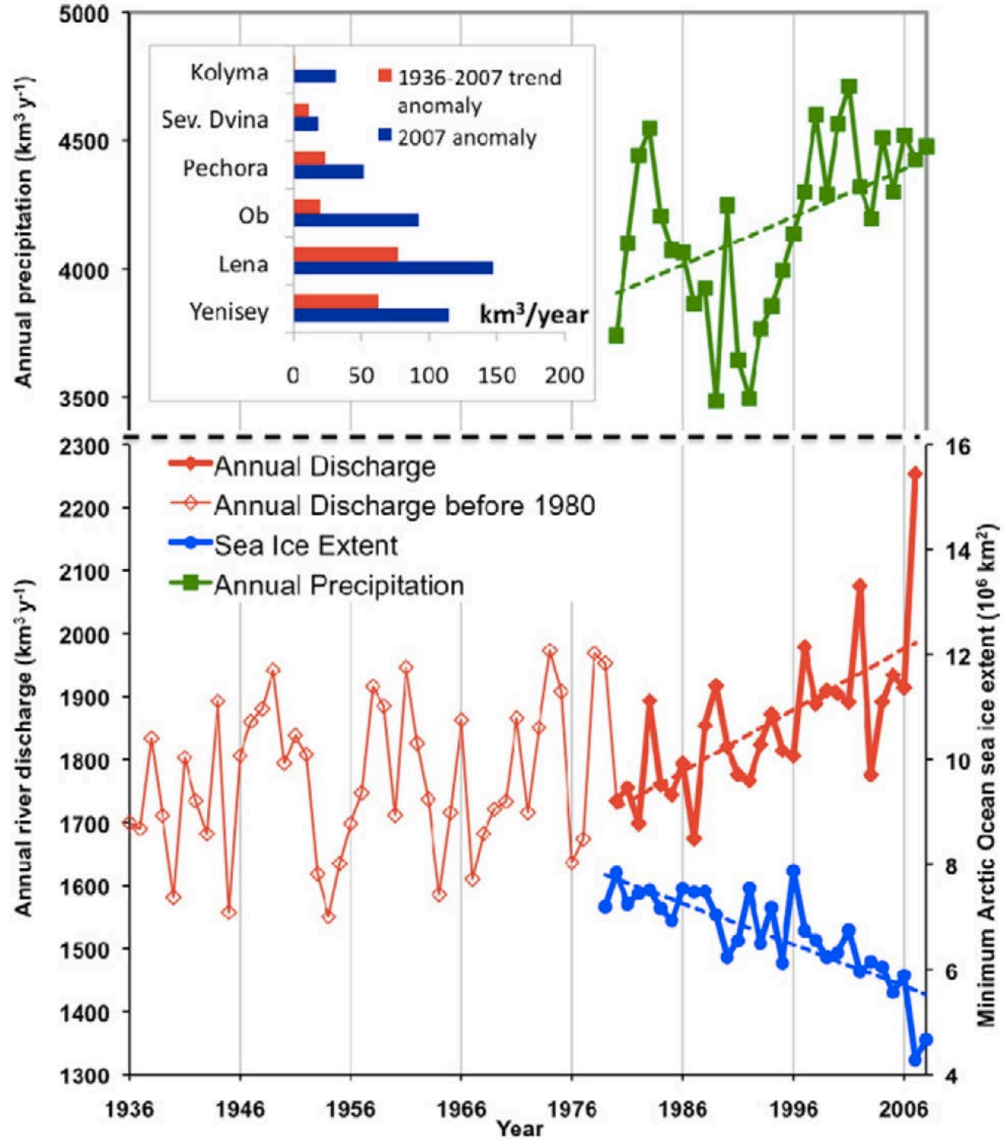
Increasing River Discharge to the Arctic Ocean

Bruce J. Peterson,[1*] Robert M. Holmes,[1] James W. McClelland,[1] Charles J. Vörösmarty,[2] Richard B. Lammers,[2] Alexander I. Shiklomanov,[2] Igor A. Shiklomanov,[3] Stefan Rahmstorf[4]





- **Increase in the Eurasian Arctic river discharge has accelerated and a record high occurred in summer 2007**



Shiklomanov and Lammers, 2009

- ***Scientific Question: What has driven the increase in the Eurasian river discharge into the Arctic Ocean?***

A large amount of research efforts towards answering this question:

1. **Increase in local Precipitation – Evaporation;**

   winter precipitation error ~ 50 – 100%

   evaporation ~ empirical

2. **Thawing permafrost;**

   lack of temporally and spatially well covered observations

3. **Decrease in vegetation transpiration.**

   lack of direct observations

Large uncertainties exist! No agreement has been reached!

Zhang et al., Nature Clim. Change, 2013

- ***Atmospheric dynamics: How do changed atmospheric water content and wind contribute to the Eurasian river discharge?***

Atmospheric Moisture Transport (AMT) converged into the river basins:

$$\text{Net AMT} = \int_{\text{basin}} \left(\nabla \cdot \int_1^0 \frac{p_s q \mathbf{v}}{g} \, d\sigma \right) dS$$

Clausius-Clapeyron Equation: $\frac{de_s}{dT} = \frac{L_v(T)e_s}{R_v T^2}$

+

Observations

↓

An increase of ~7% K^{-1} in lower tropospheric moisture content

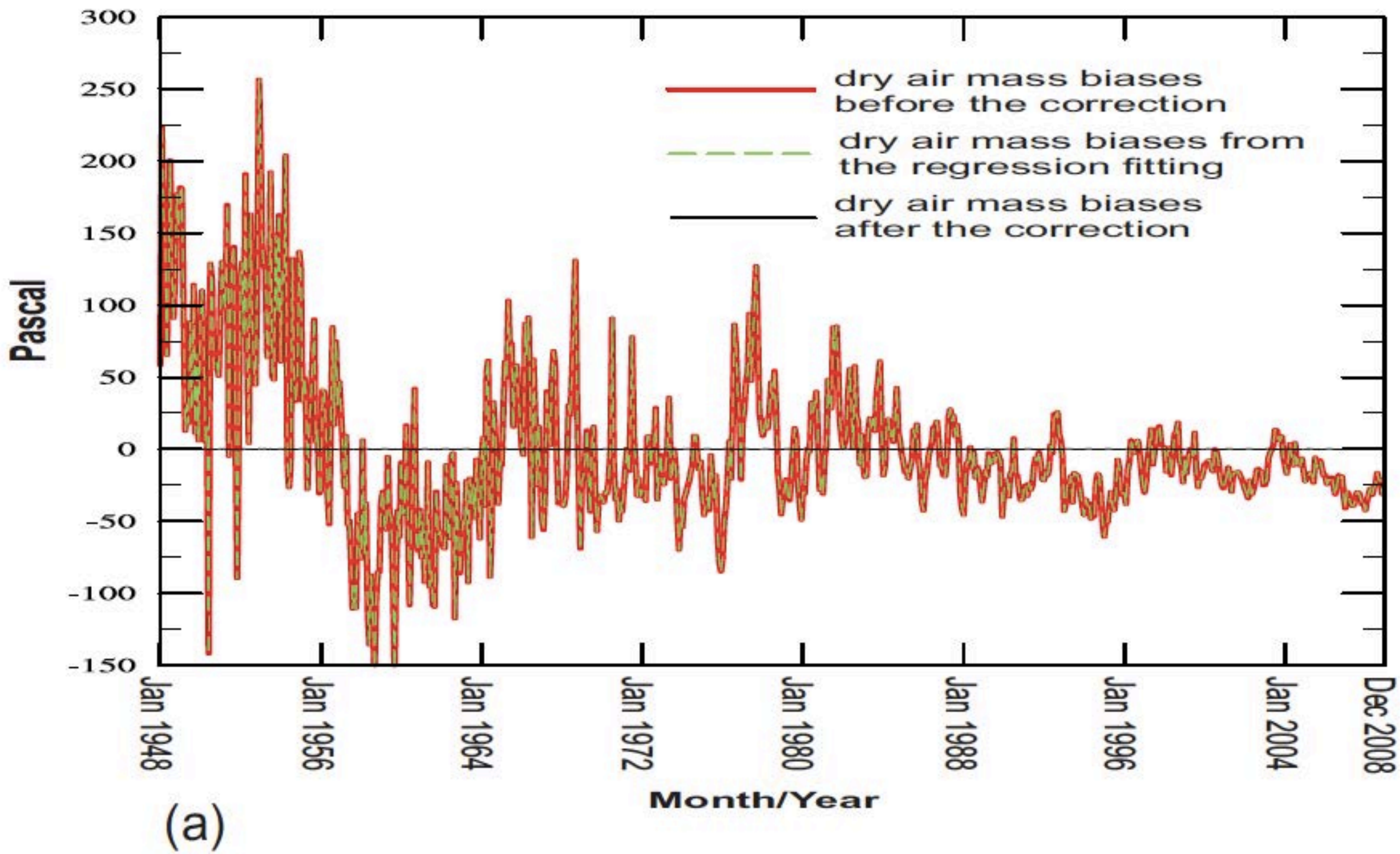
The specific humidity and wind are conventionally observed at met stations, assuming higher credibility than precipitation, evaporation, and …

Data set: NCAR-NCEP reanalysis from 1948-2008, 6-hourly.

Zhang et al., Nature Clim. Change, 2013

• ***Homogeneity of the data set throughout the study time period***

Global dry air mass is not conserved with time:



Zhang et al., Nature Clim. Change, 2013

Air Mass Correction: A critical step

- **Dry air mass correction:**

Dry air mass bias at each grid cell:
Linear regression analysis upon global dry air mass biases

$$P_d' = a\int_{globe} P_s\left(1-\int_1^0 q\,d\sigma\right)dS + b$$

Total air mass bias at each grid cell:

$$P_c = \frac{P_d'}{1-\int_1^0 q\,d\sigma}$$

The corrected surface pressure:

$$P_s^{new} = P_s - P_c$$

Zhang et al., Nature Clim. Change, 2013

Air Mass Correction: A critical step

- **Continuity Equation (in σ coordinate):**

$$\frac{\partial}{\partial t}\left[\frac{1}{g}\int_1^0 P_s^{new}\, d\sigma\right] + \nabla \bullet \left[\frac{1}{g}\int_1^0 P_s^{new}\vec{v}\, d\sigma\right] = E - P \qquad (1)$$

- **Water Vapor Balance Equation (in σ coordinate)**

$$\frac{\partial}{\partial t}\left[\frac{1}{g}\int_1^0 P_s^{new} q\, d\sigma\right] + \nabla \bullet \left[\frac{1}{g}\int_1^0 P_s^{new} q\vec{v}\, d\sigma\right] = E - P \qquad (2)$$

- **Theoretically, (1) = (2):**

$$\frac{\partial}{\partial t}\left[\frac{1}{g}\int_1^0 P_s^{new}(1-q)\, d\sigma\right] + \nabla \bullet \left[\frac{1}{g}\int_1^0 P_s^{new}(1-q)\vec{v}\, d\sigma\right] = 0 \qquad (3)$$

Zhang et al., Nature Clim. Change, 2013

Air Mass Correction: A critical step

- **However, in the reality:**

$$\frac{\partial}{\partial t}\left[\frac{1}{g}\int_1^0 P_s^{new}(1-q)\,d\sigma\right]+\nabla\bullet\left[\frac{1}{g}\int_1^0 P_s^{new}(1-q)\vec{v}\,d\sigma\right]\neq 0$$

- **Correct moisture transport/convergence:**

$$R=\frac{\partial}{\partial t}\left[\int_1^0 P_s^{new}(1-q)\,d\sigma\right]+\nabla\bullet\left[\int_1^0 P_s^{new}(1-q)\vec{v}\,d\sigma\right]$$

$\frac{\partial}{\partial t}\left[\int_1^0 P_s^{new}(1-q)\,d\sigma\right]$ is generally very small and can be neglected:

$$\nabla\cdot\left[P_s^{new}\int_1^0(1-q)\,d\sigma\right]\overrightarrow{v_c}=R$$

Poisson Equation:

$$\nabla^2\chi=R$$

Boundary condition (globally dry air mass is conserved):

$$\int_{globe}RdS=0$$

Zhang et al., Nature Clim. Change, 2013

Air Mass Correction: A critical step

- **Solution:**

$$\overrightarrow{v_c} = \frac{\nabla \chi}{P_s^{new} \int_1^0 (1-q)\, d\sigma}$$

$$u_c = \frac{\sum_{m=-N}^{N} \sum_{n=|m|}^{N} \frac{-imr}{n(n+1)} R_n^m P_n^m(\mu) e^{im\lambda}}{P_s^{new} \int_1^0 (1-q)\, d\sigma} \qquad v_c = \frac{\sum_{m=-N}^{N} \sum_{n=|m|}^{N} \frac{-r}{n(n+1)} R_n^m P_n^m(\mu) e^{im\lambda}}{P_s^{new} \int_1^0 (1-q)\, d\sigma}$$

P_n^m : the associated Legendre Polynomials; $\mu = \sin\theta$

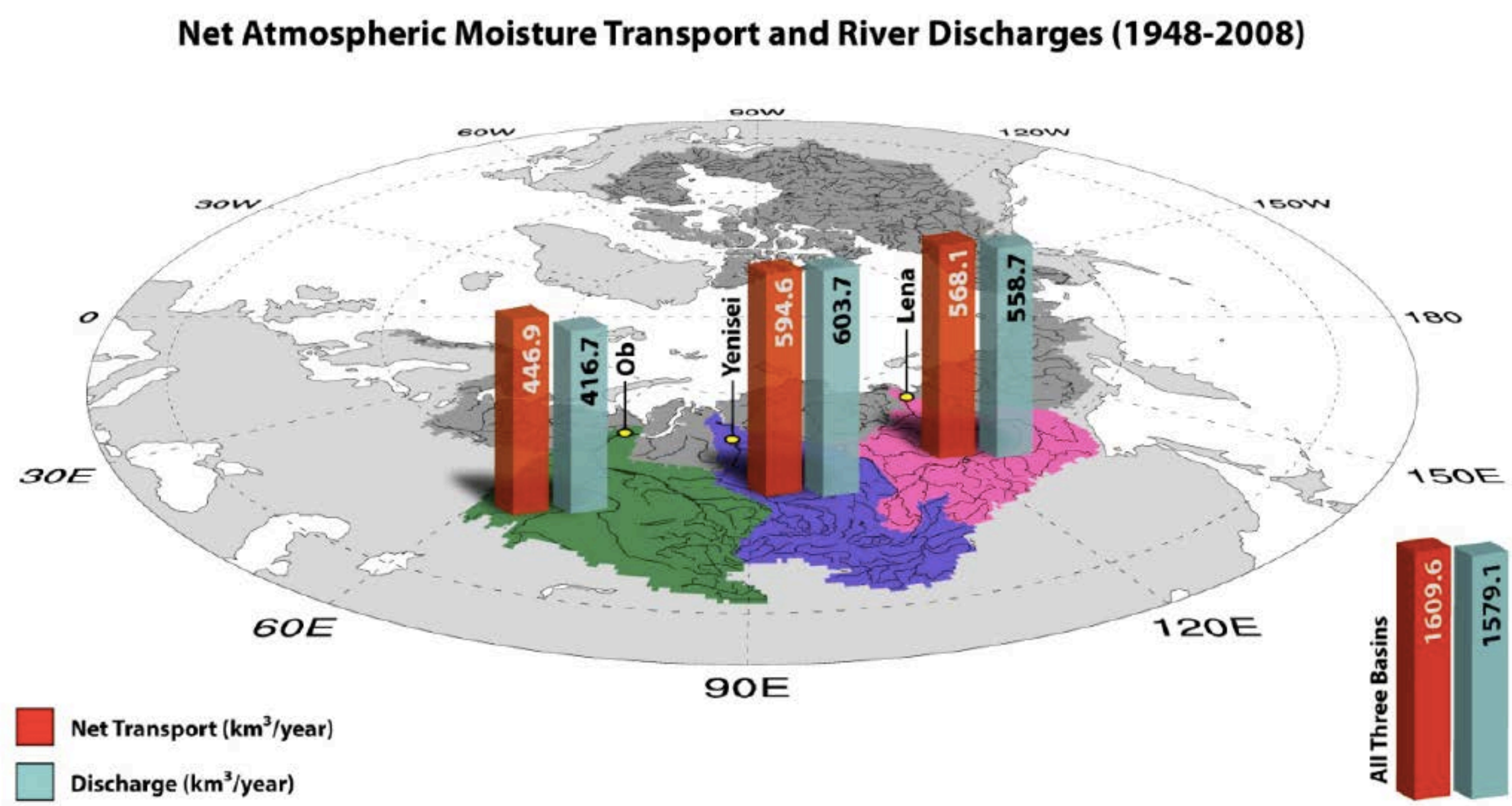
R_n^m : the coefficient of the spherical harmonic decomposition

- **Corrected wind field:**

$$\overrightarrow{v_{new}} = \overrightarrow{v_{old}} - \overrightarrow{v_c}$$

Zhang et al., Nature Clim. Change, 2013

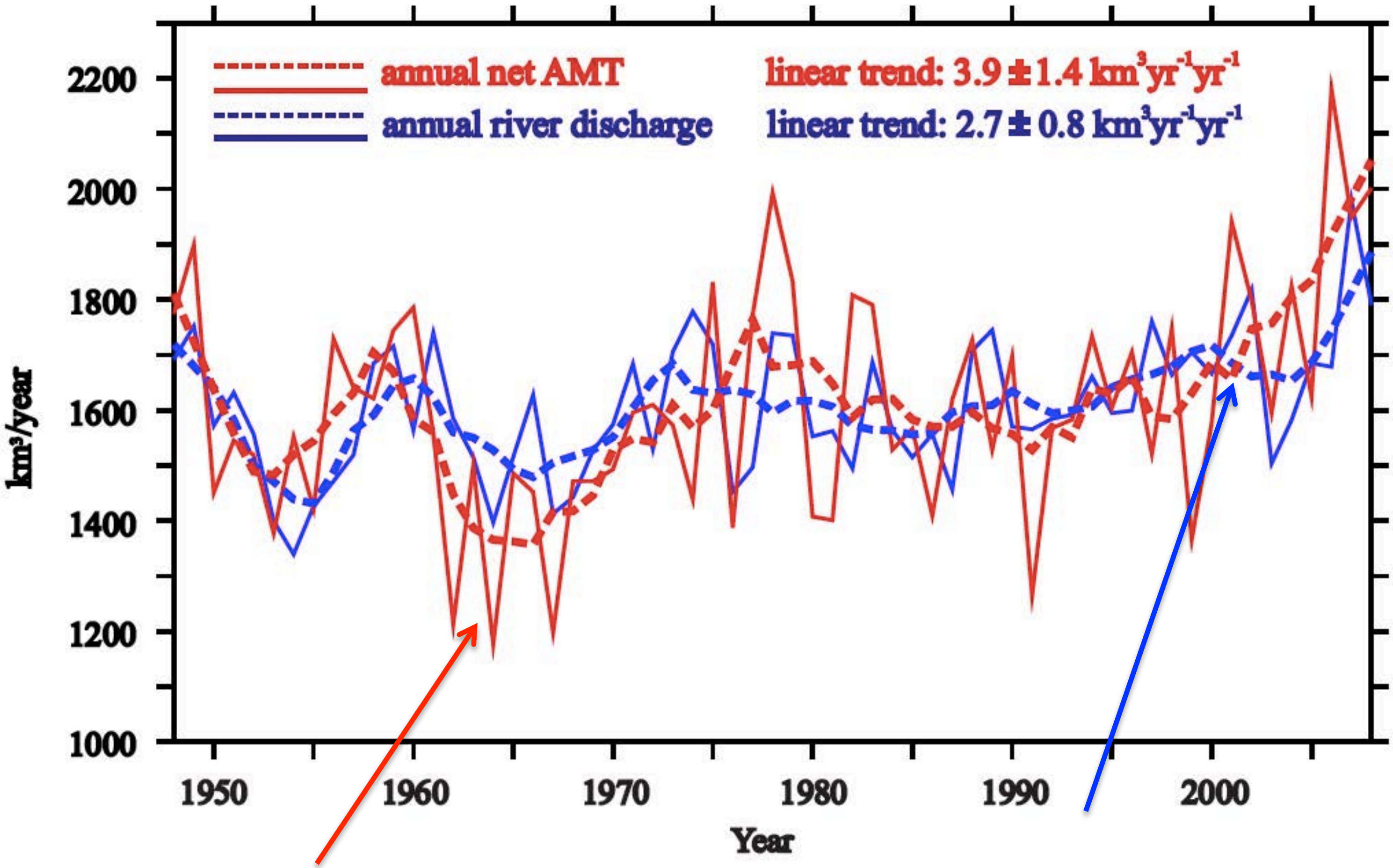
- ***Atmospheric moisture transport into the selected large Eurasian river basins captured ~98% of the gauged river discharges***



Suggest: atmospheric circulation dynamics plays a primary role in shaping climatology of Eurasian river discharges.

Zhang et al., Nature Clim. Change, 2013

• ***Atmospheric moisture transport into the selected large Eurasian river basins is a decisive driver of the river discharge increase***

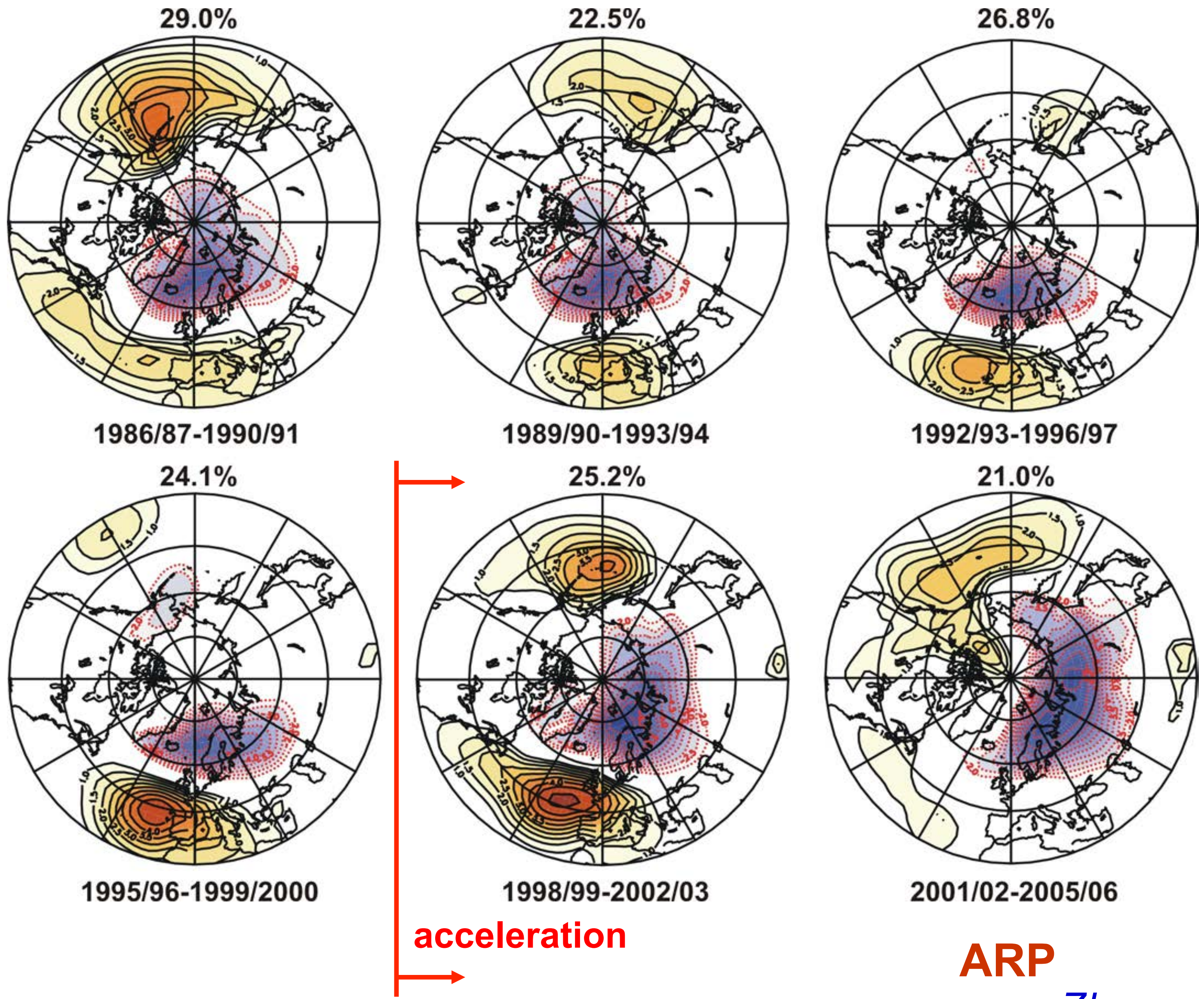


Correlation of interannual variability: 0.50 at a significance level of 99.9%.

Correlation of decadal variability: 0.75 at a significance level of 99.9%.

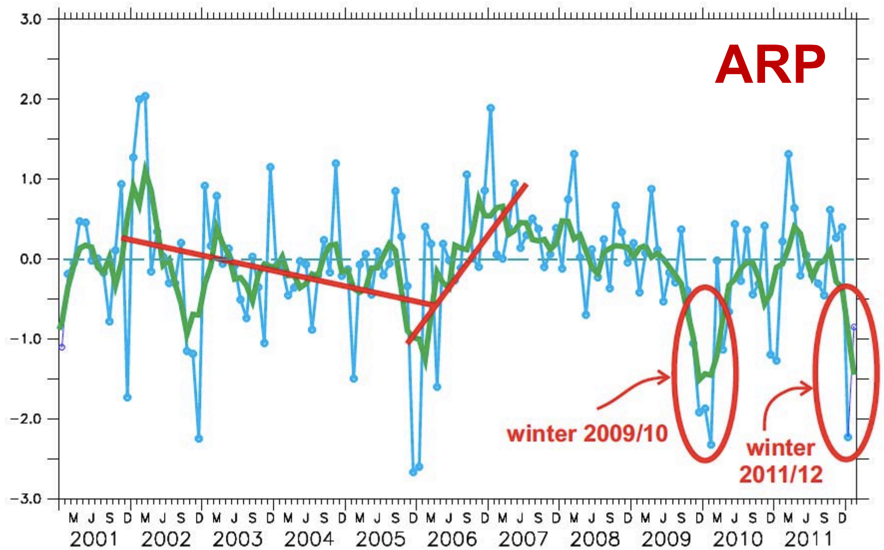
Zhang et al., Nature Clim. Change, 2013

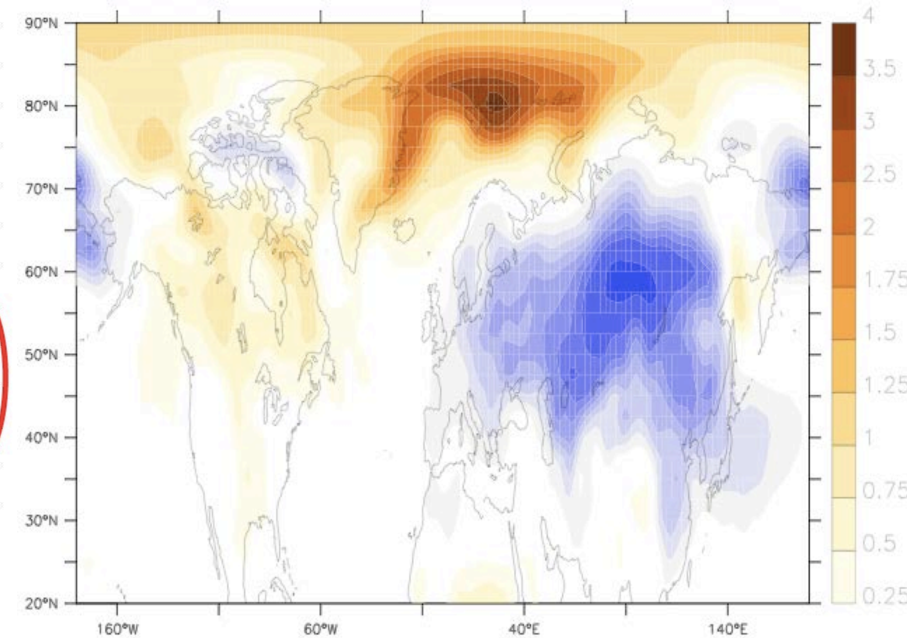
- <u>**Atmospheric circulation pattern shift and the Arctic Rapid change Pattern (ARP)**</u>

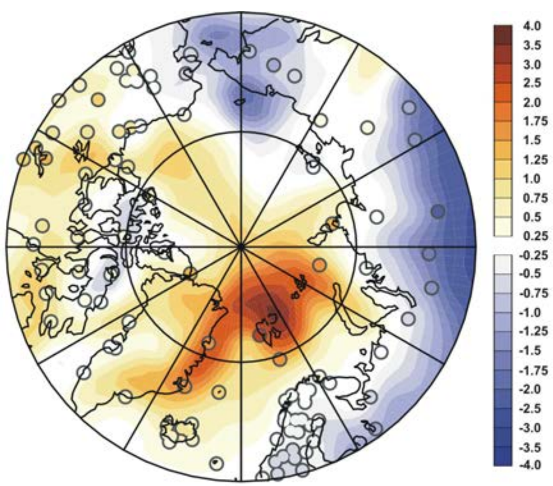


Zhang et al., GRL, 2008

• **ARP has not only orchestrated rapid changes in the Arctic climate system but also played driving role in midlatitude climate cold winters**





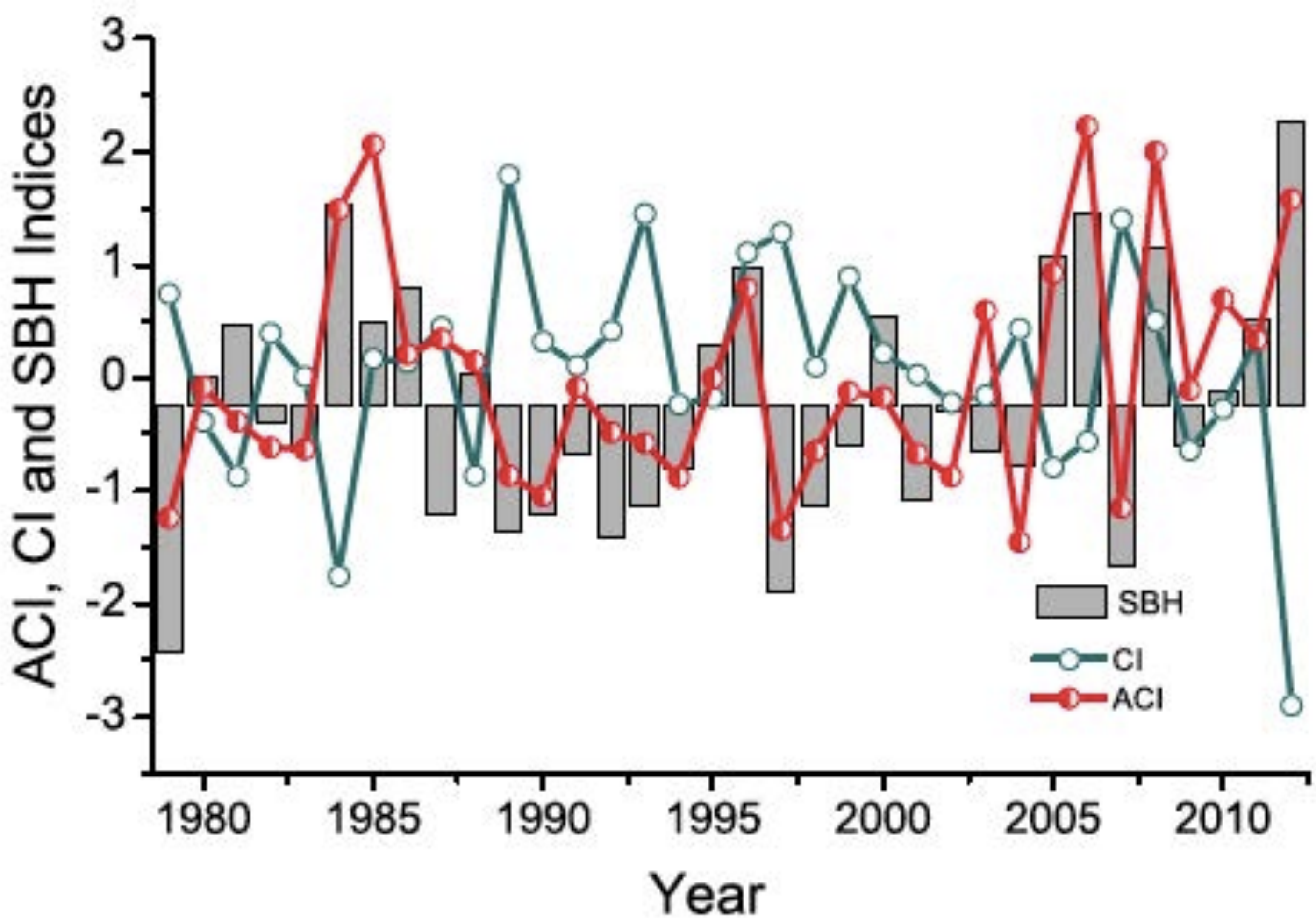


Winter Surface Air Temperature Regressed onto ARP Index

ARP driven surface air temperature Anomalies

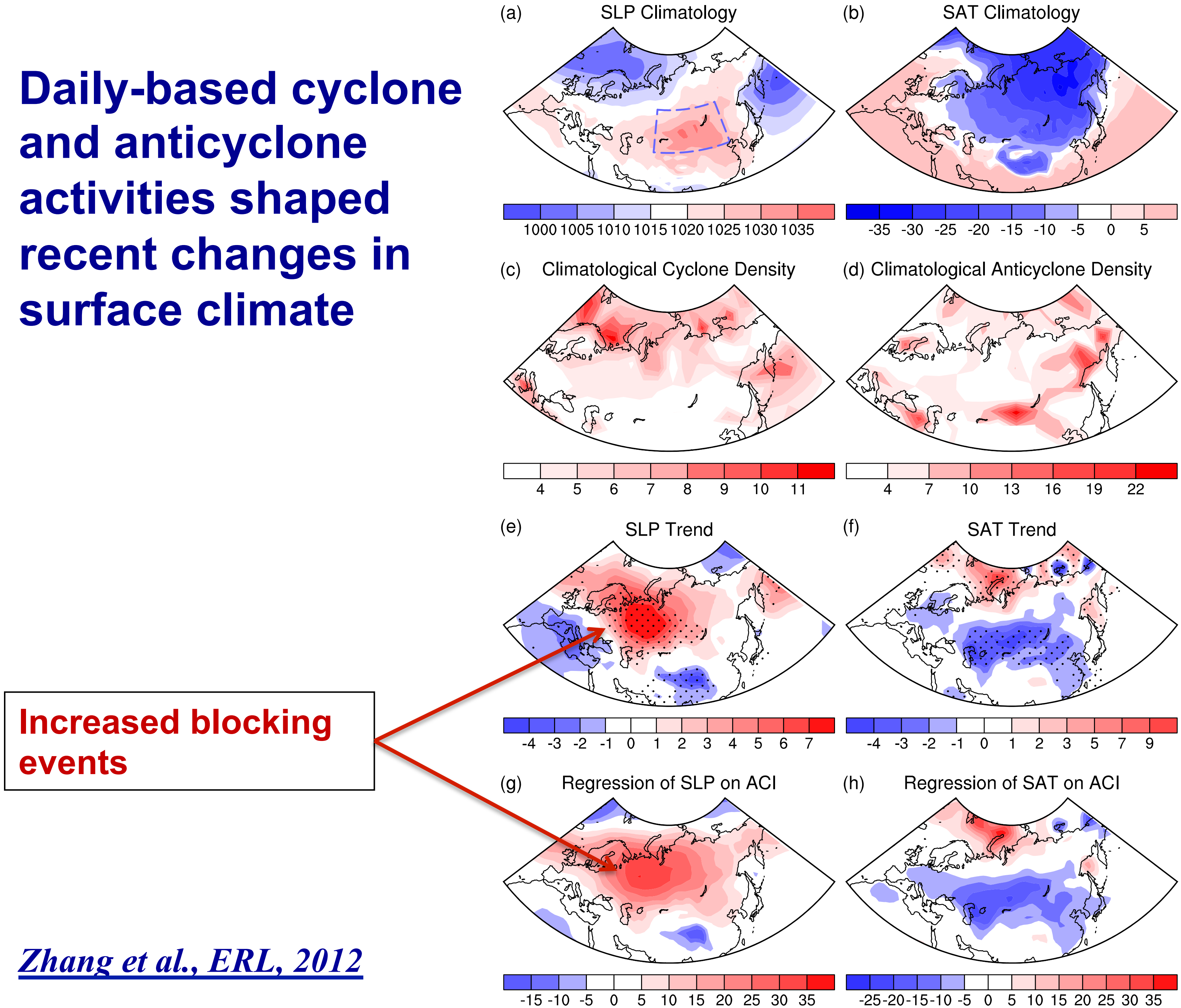
Zhang et al, 2008, 2012

• **Eurasian cyclones has weakened and anticyclones has intensified**



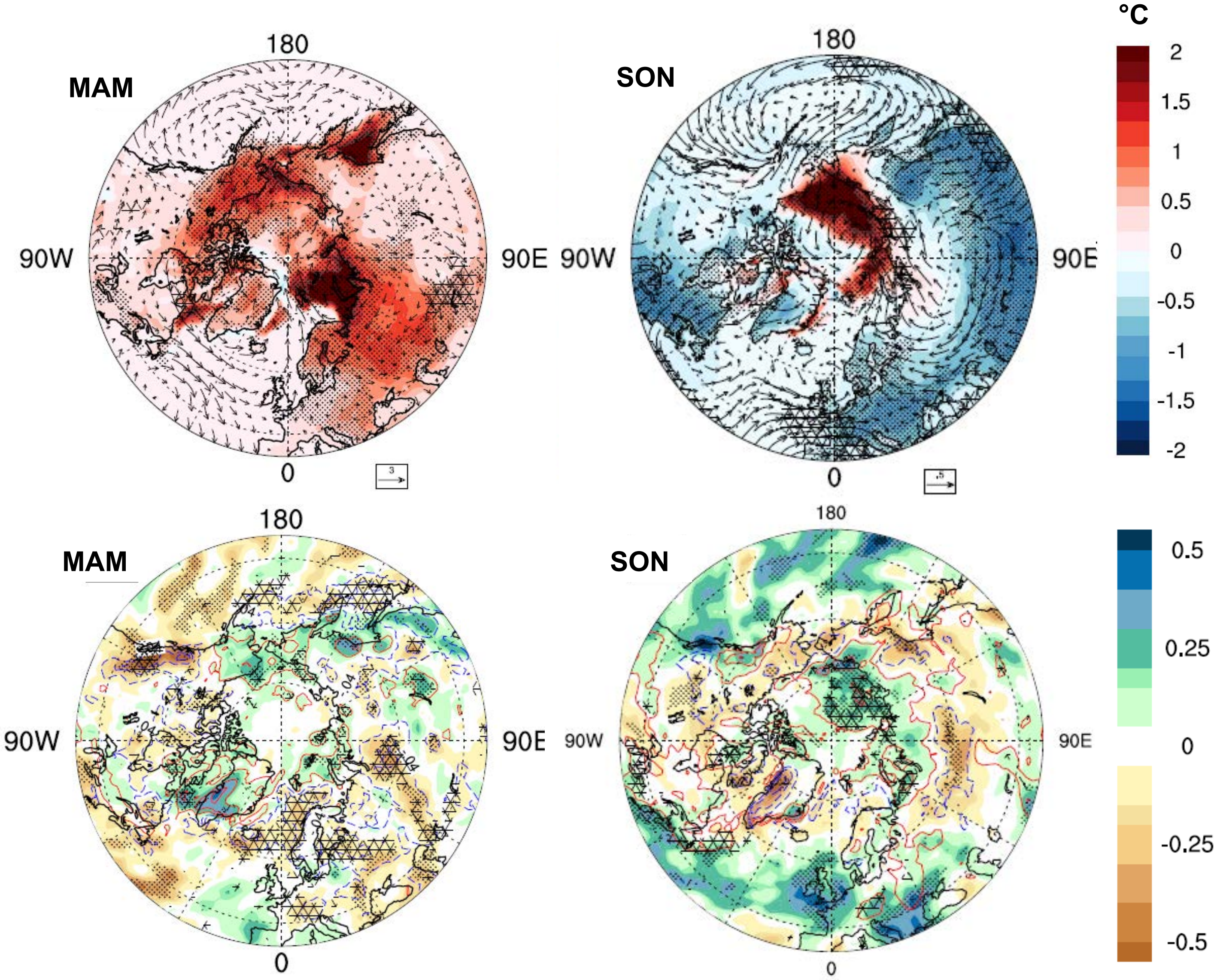
Zhang et al., ERL, 2012

Daily-based cyclone and anticyclone activities shaped recent changes in surface climate



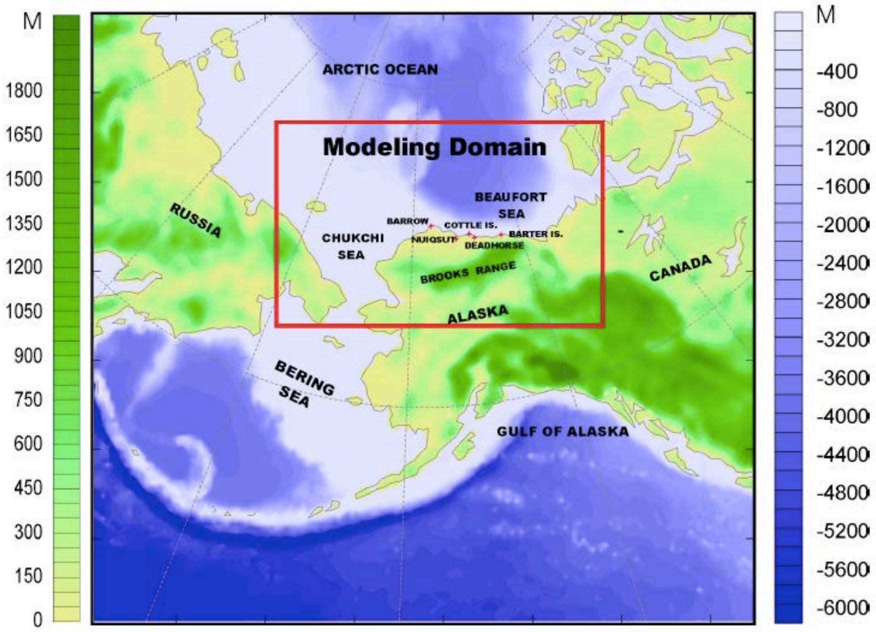
Zhang et al., ERL, 2012

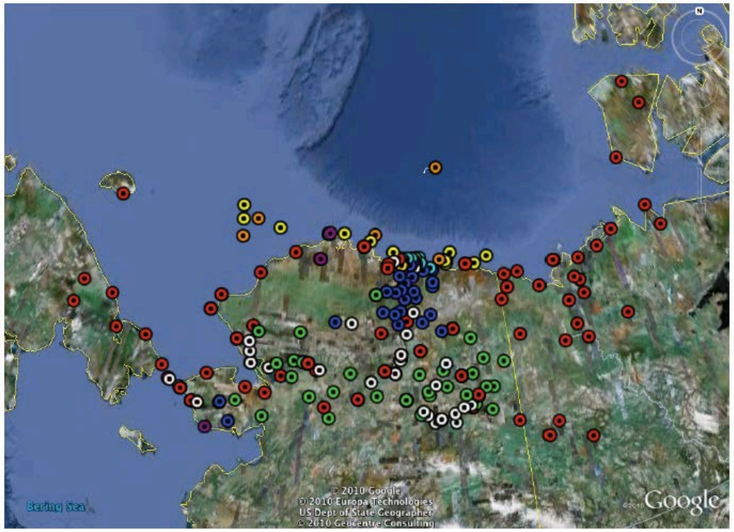
Atmospheric Modeling (CAM3) study of Arctic sea ice on storms and surface climate



Basu, S., and X. Zhang, 2014

- **The Chukchi-Beaufort seas High-resolution Atmospheric Reanalysis (CBHAR)**



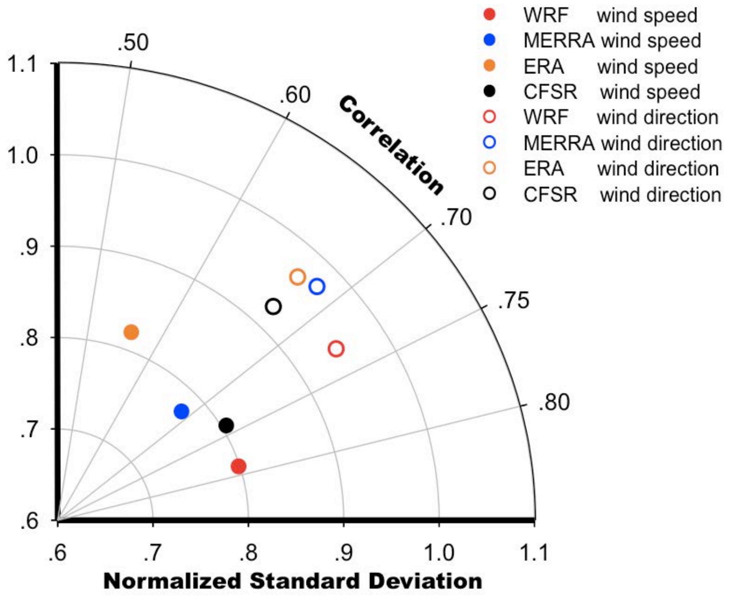


Model: WRF-ARW

Data product:

Spatial resolution: 10 km

Temporal resolution: 1 hour



Experiment Design

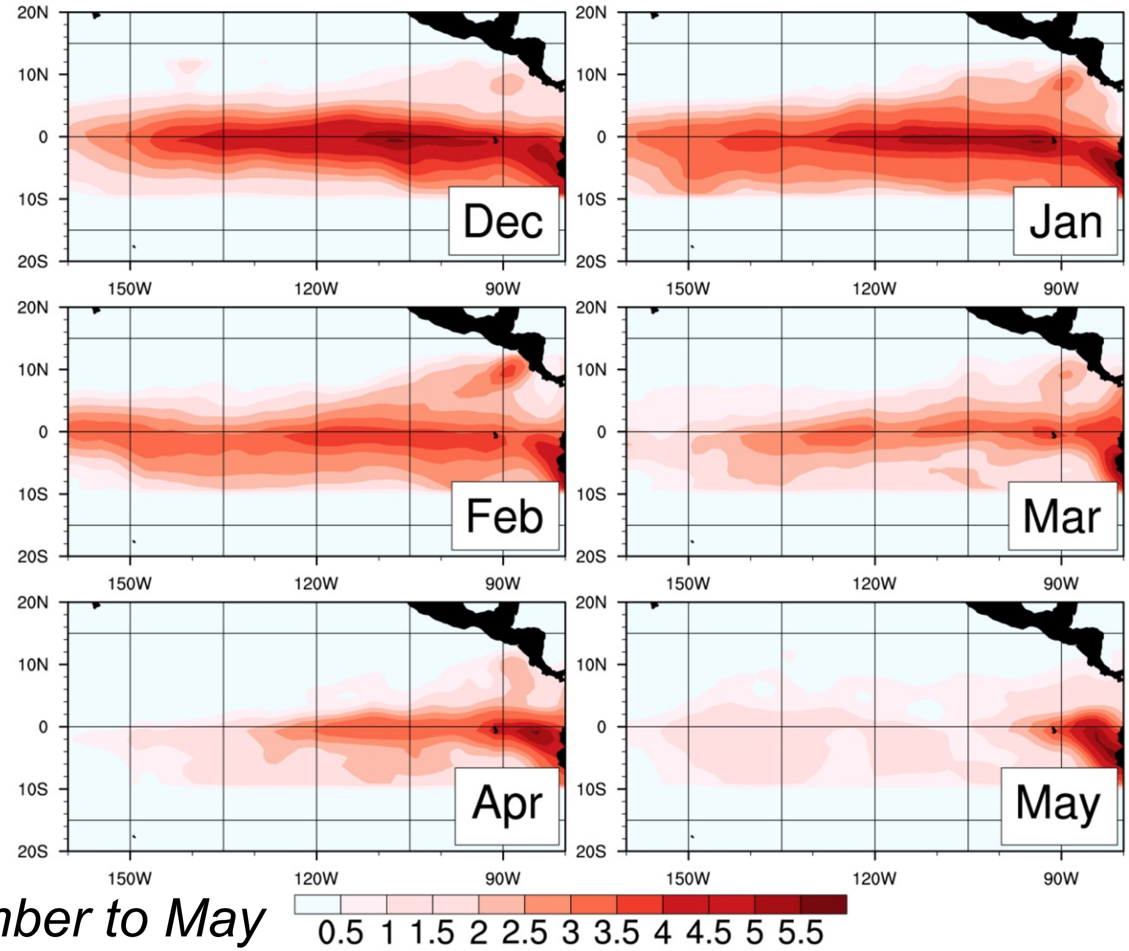
FORCING DATASETS

- ❑ Shea/Hurrell dataset
- ❑ Monthly SST anomalies calculated for the 1997-98 El Nino year
- ❑ Positive SST anomaly added to the tropical Pacific region 10°S - 10°N and165°W - 80°W for November to May

EXPERIMENTS

- ❑ **ConExp** – 60 members
- ❑ **SenExp** – 60 members
- ❑ **Simulation time** – *November to May*

SST Anomaly (Dec – May)



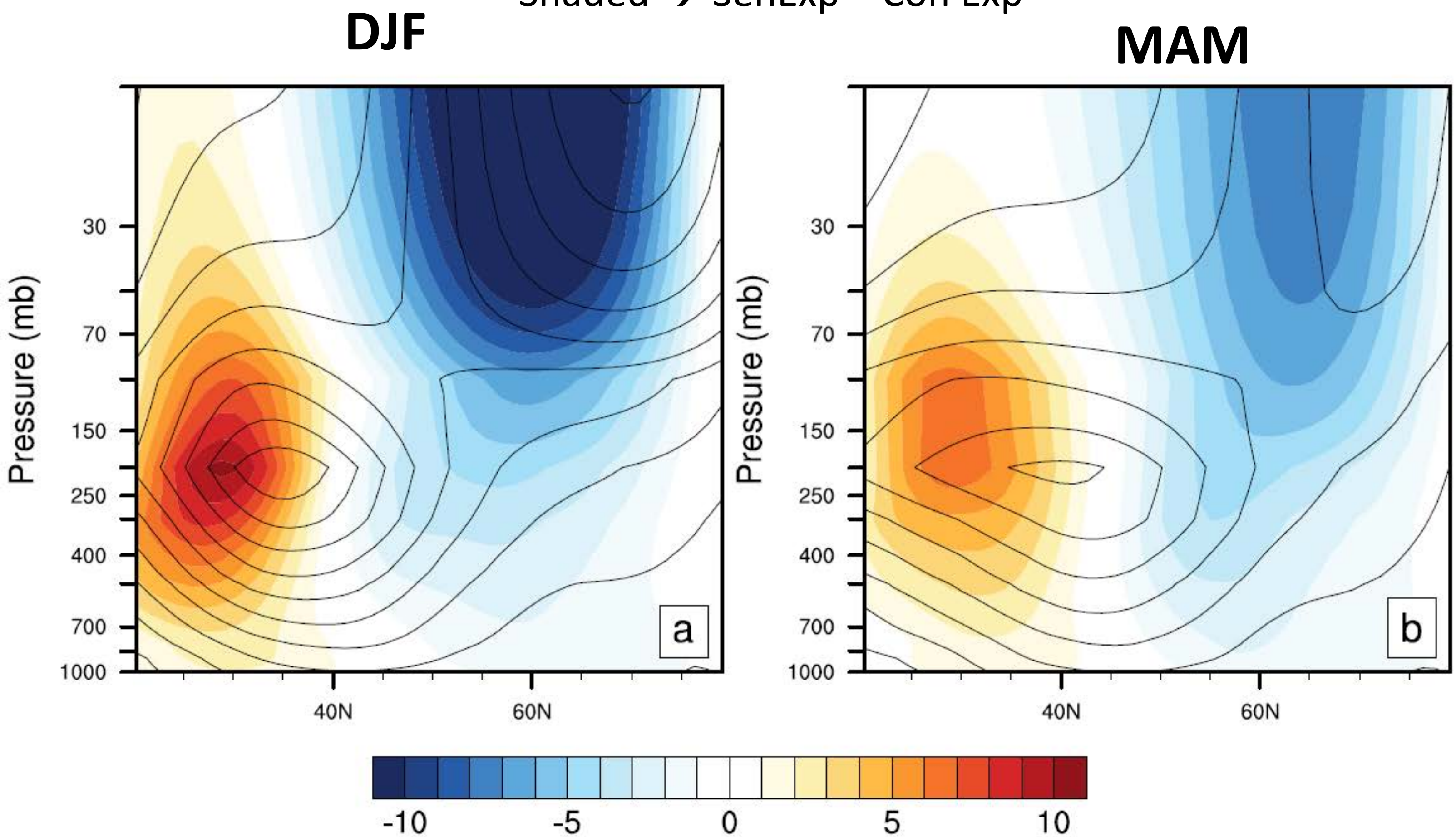
6 hourly output from the model

Basu et al., GRL, 2013

Vertical cross section of zonally averaged (between 180°-310° longitude) u-wind

Non shaded contours → zonal wind ConExp

Shaded → SenExp – Con Exp



Southwards shift of the jet stream → Enhanced baroclinicity

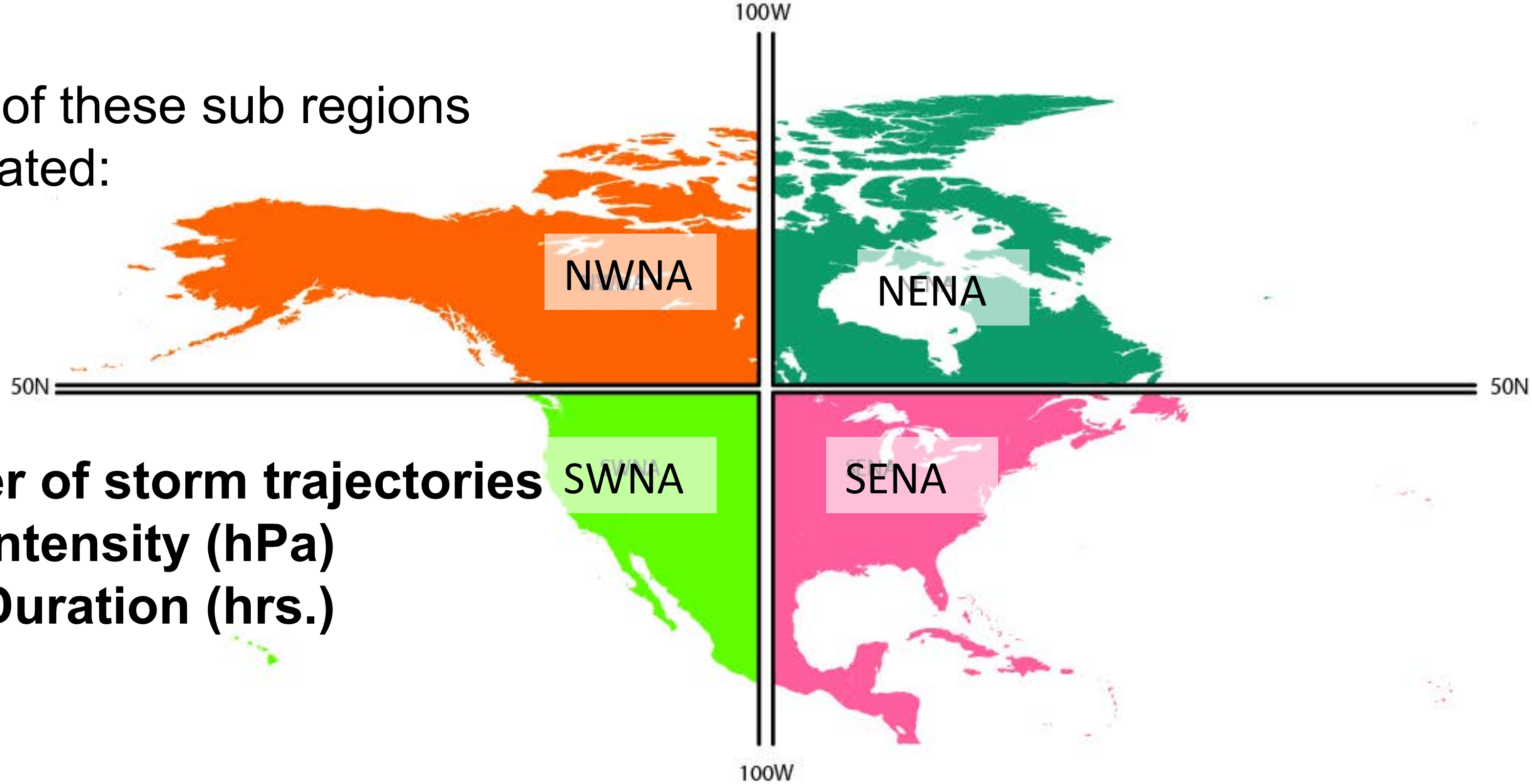
Basu et al., GRL, 2013

Identification and Tracking the storms (Lagrangian approach)

On 6- hourly SLP output we applied the storm identification and tracking algorithm (Zhang et. al, 2004)

For each of these sub regions we calculated:

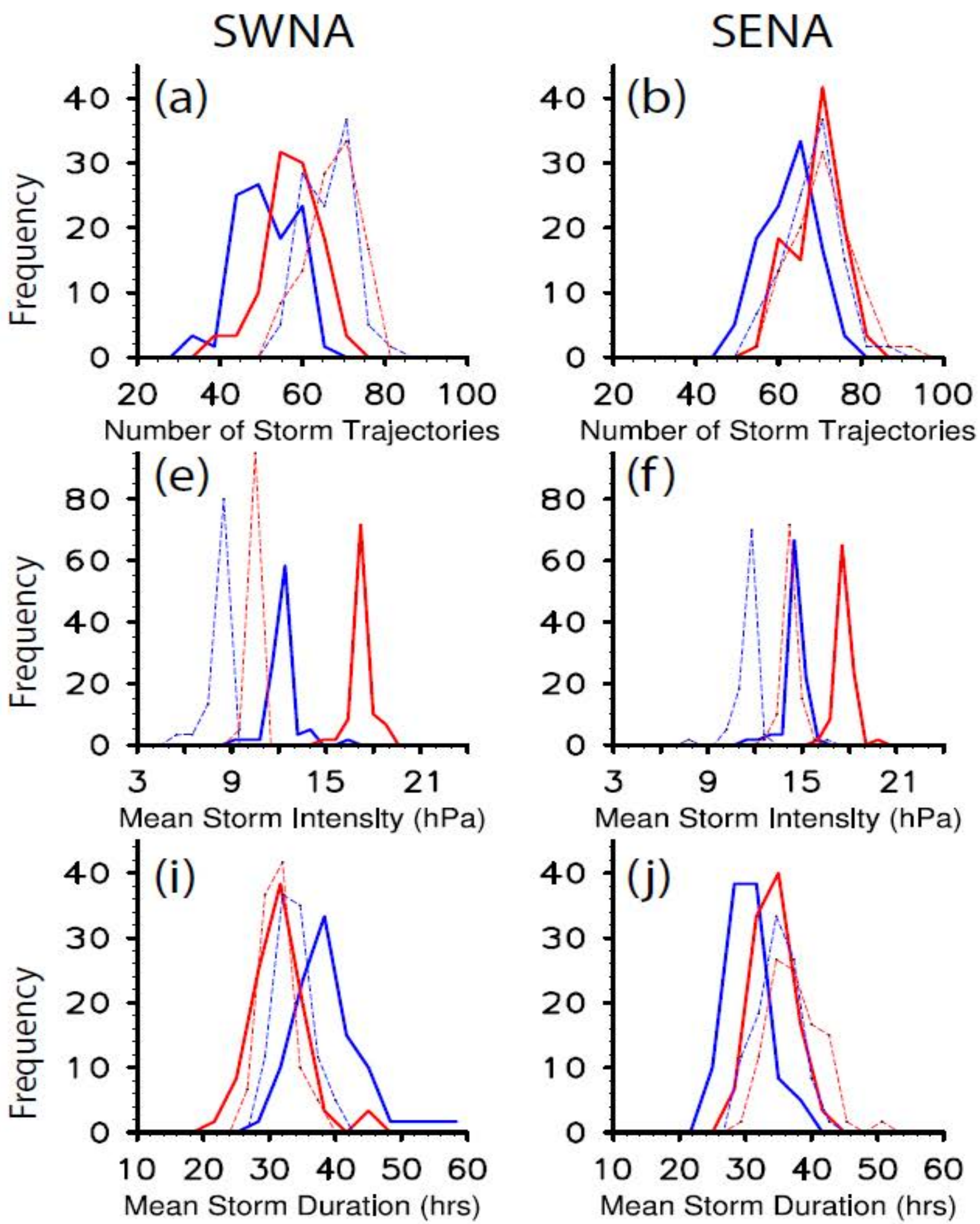
- **Number of storm trajectories**
- **Mean Intensity (hPa)**
- **Mean Duration (hrs.)**



We developed a statistics of these parameters for each of these sub regions.

Basu et al., GRL, 2013

Probability Density Function Analysis: SenExp(Red) and ConExp (Blue) for DJF (solid) and MAM (dotted)



More numerous and intense storms over SWNA and SENA

Basu et al., GRL, 2013

Polar Climate Discussion Points

Questions:

- What physical mechanisms/processes triggered/drove accelerated, systematic changes in the Arctic climate system?
- Why were synoptic-scale and meso-scale weather systems intensified over the Arctic?
- How does large-scale atmospheric circulation dynamics condition physical processes to cause accelerated Arctic warming and sea ice decrease?
- What is the relative role of local albedo feedback and poleward heat and moisture transport in the amplified warming of the Arctic Ocean?
- What role does the warmed Arctic play in the midlatitude weather extremes, such as cold winter weather events?
- How does the warmed Atlantic and Pacific ocean layers release heat to overlying sea ice and atmosphere?

Polar Climate Discussion Points

Observations needed or needed to improve:

- Long-term estimate of sea ice thickness covering the entire Arctic Ocean
- Spatially-well covered atmospheric observations, in particular vertical profile data
- Snow cover and depth data (recent publication showing some uncertainties across different data sets).
- Energy budgets from satellite data (consistence throughout the time)
- Improved data assimilation/reanalysis at higher resolutions