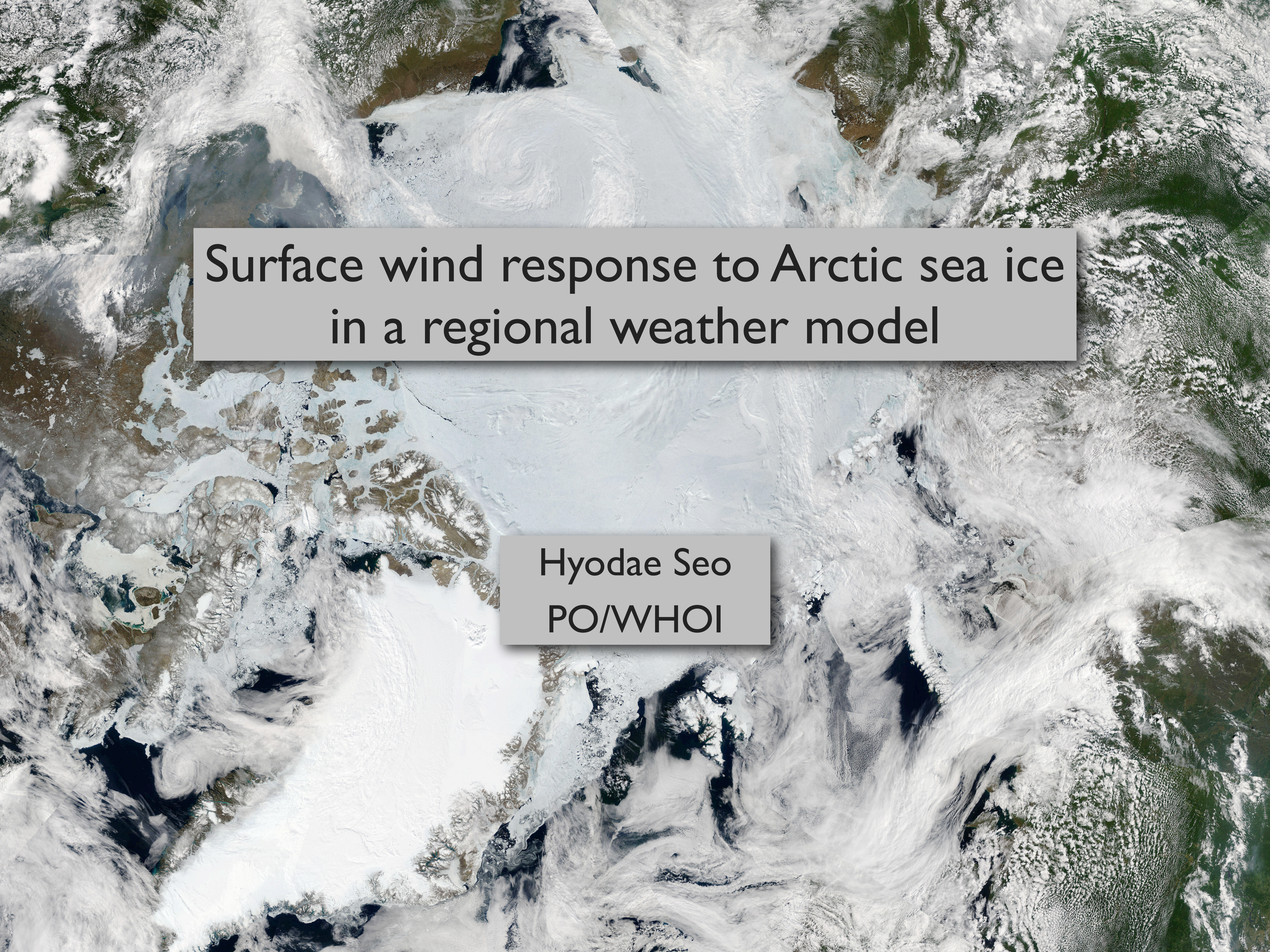


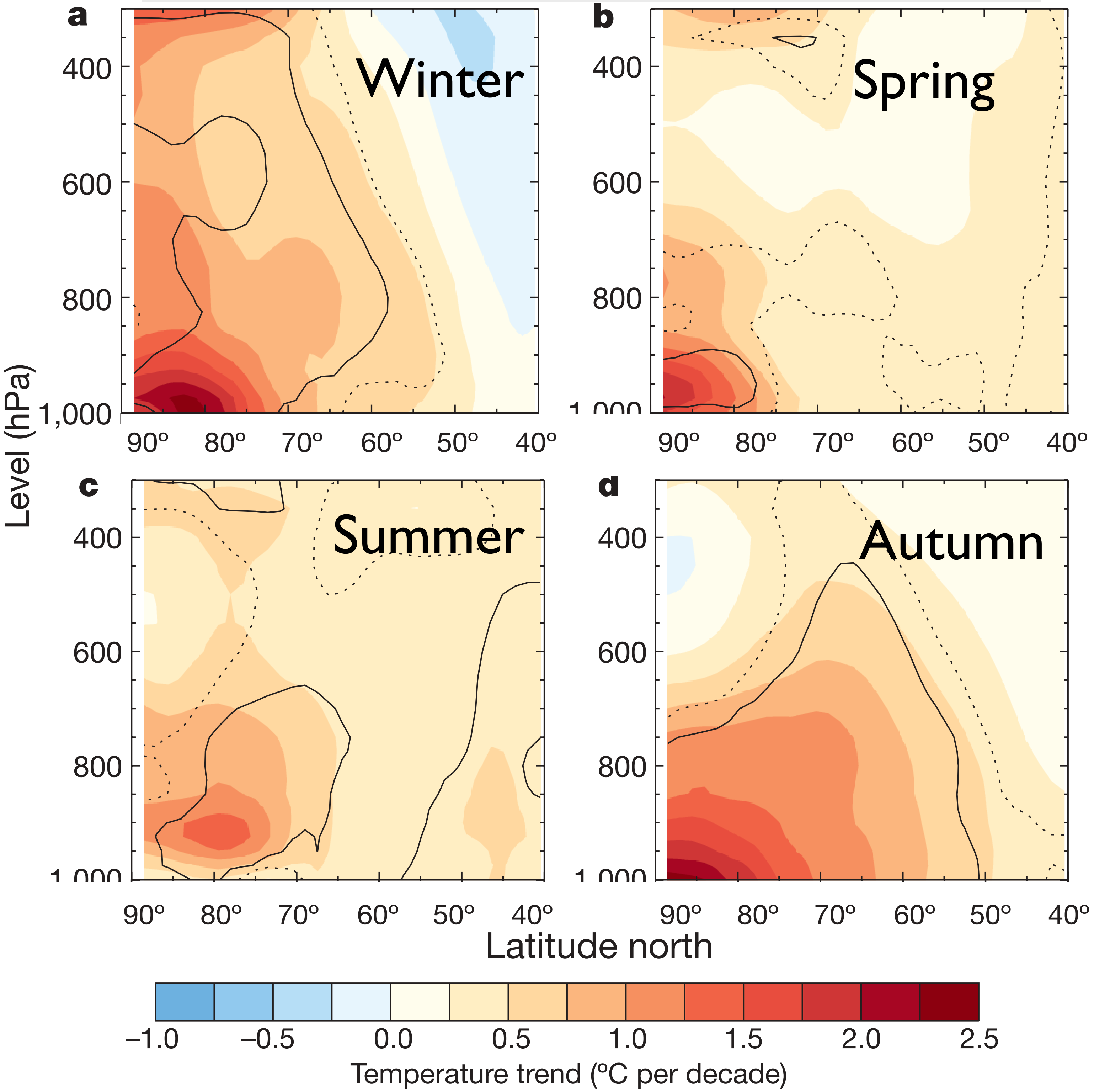
Surface wind response to Arctic sea ice in a regional weather model

Hyodae Seo
PO/WHOI

Surface intensified warming in the Arctic

- Arctic amplification
- Changes in atmospheric heat transport
- Reduction in sea ice and snow
- Warmer in the low-level
- Unstable atmosphere

Temperature trend in the ERA-Interim

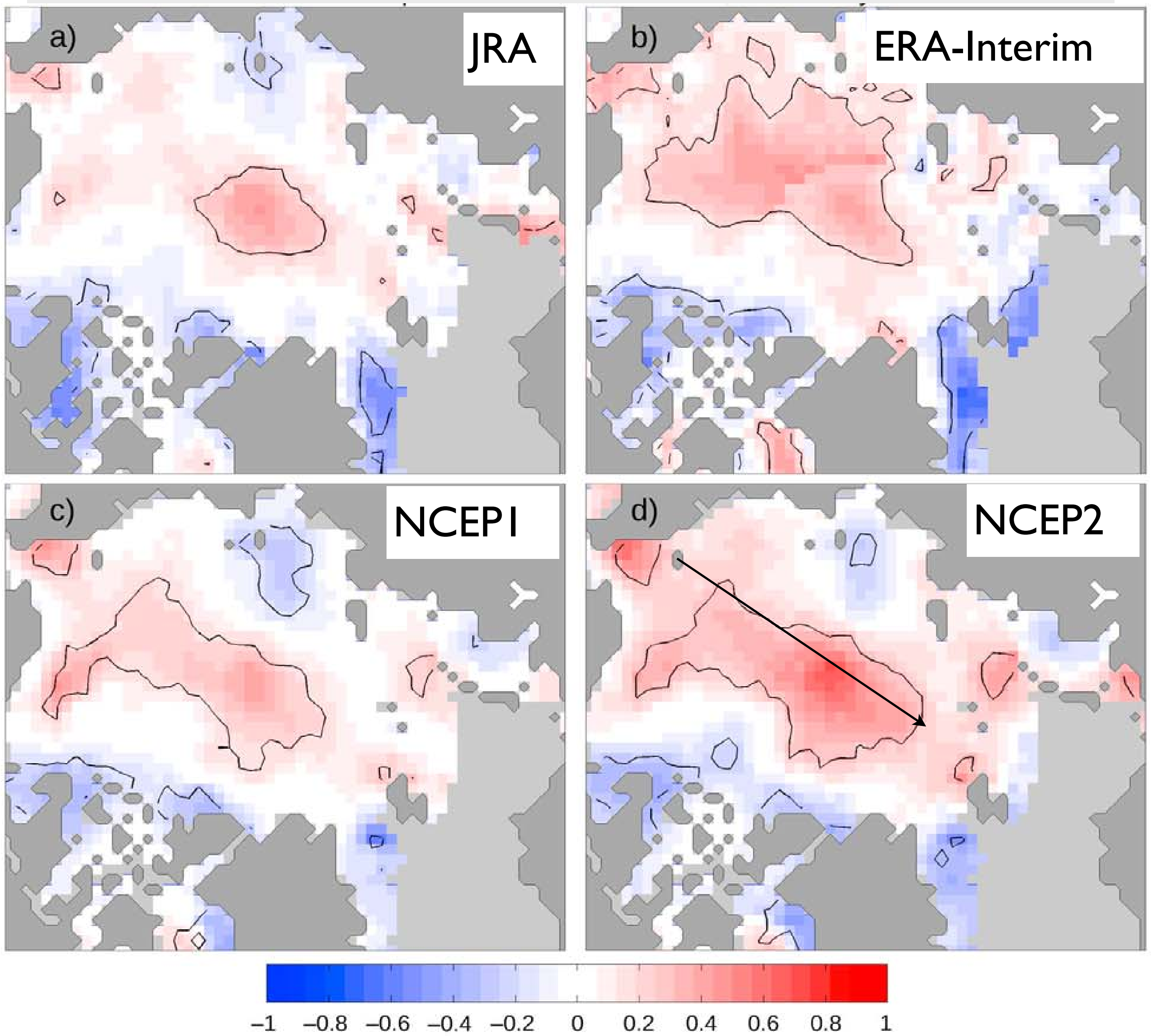


Screen et al. 2010

1989-2008

Increasing wind in the Arctic

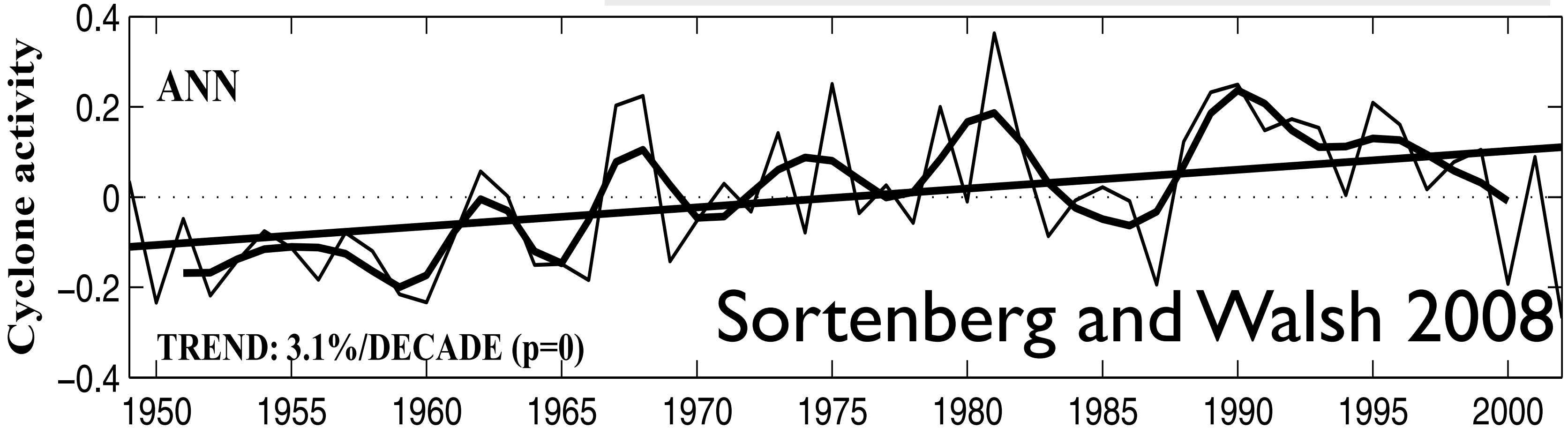
Trend in 10m wind speed 1993-2009 Oct-May



Atmospheric reanalyses show positive wind speed trend, especially along the transpolar drift stream

Spreen et al. 2011

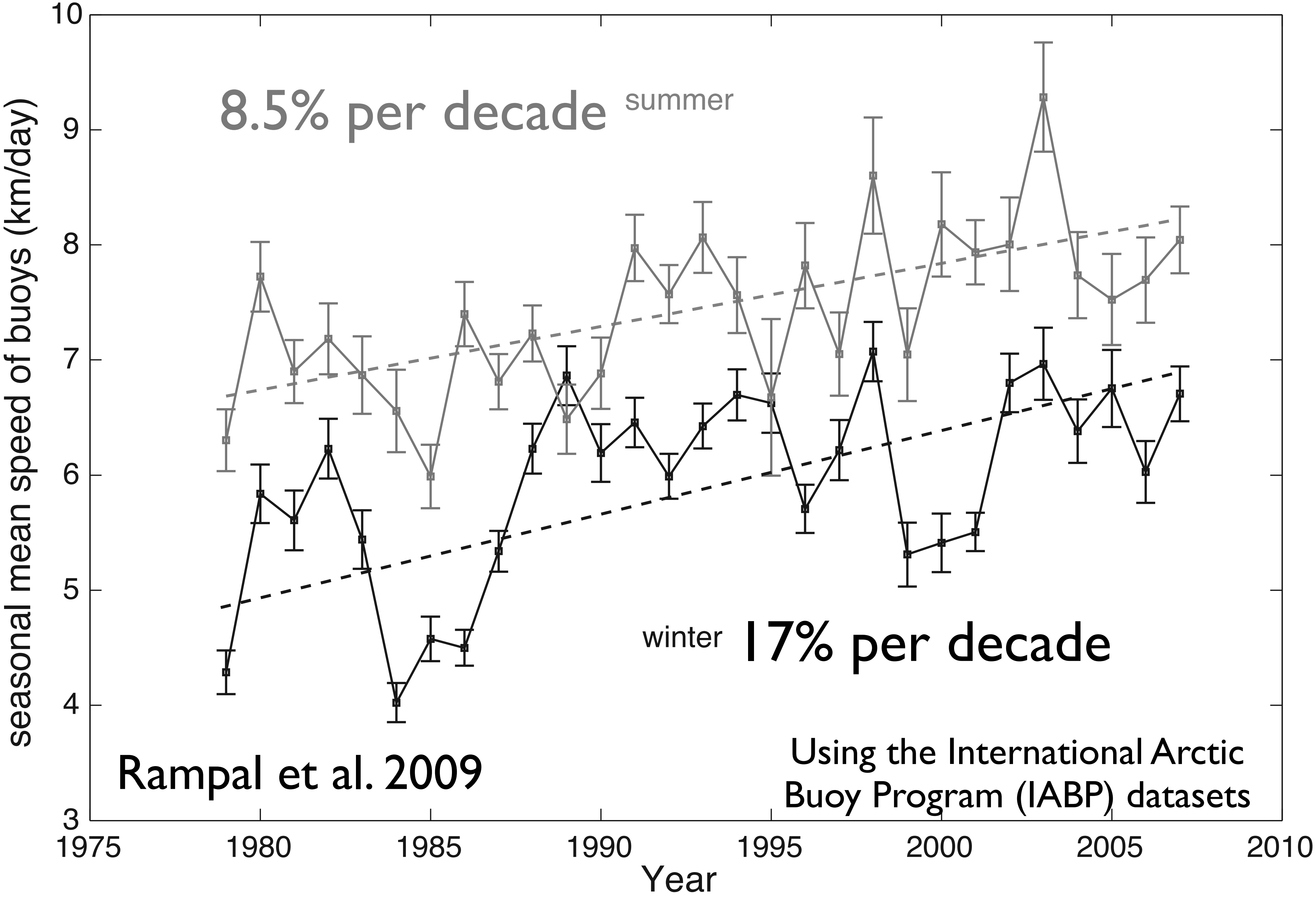
Trend in arctic cyclone activity



Sortenberg and Walsh 2008

Annually accumulated positive vorticity poleward 70N

Ice speed trend from buoys: 1978-2007



Ice speed is influenced by internal ice stress.
Increasing wind speed will contribute to the ice speed-up.

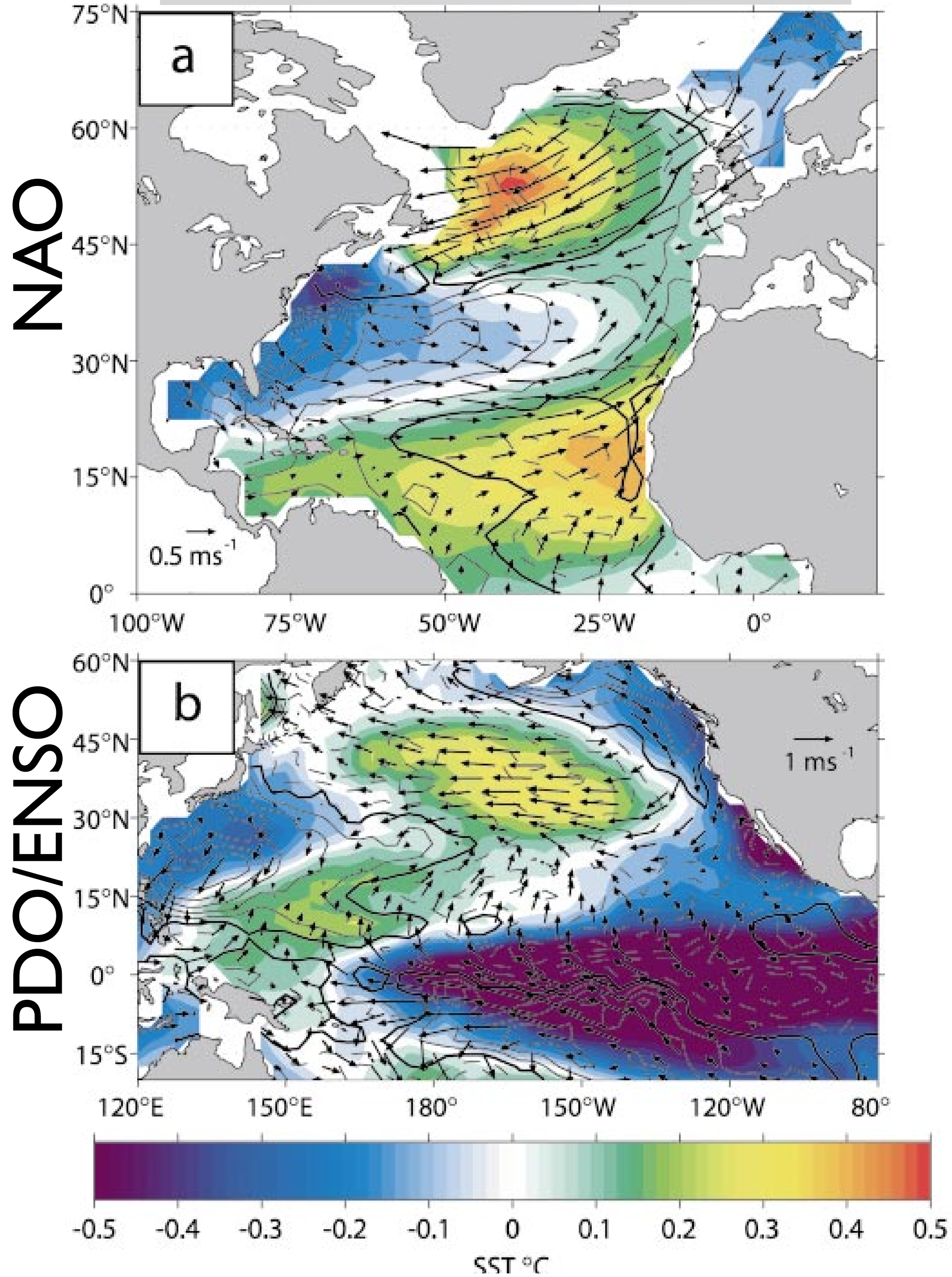
Warmer surface and more unstable ABL
⇆ Higher surface wind speed

→ Ice velocity and export...

Examine the relationship using air-sea boundary coupling processes that occur the lower latitudes

Air-sea interactions on different oceanic scales

basin/low-freq. scale

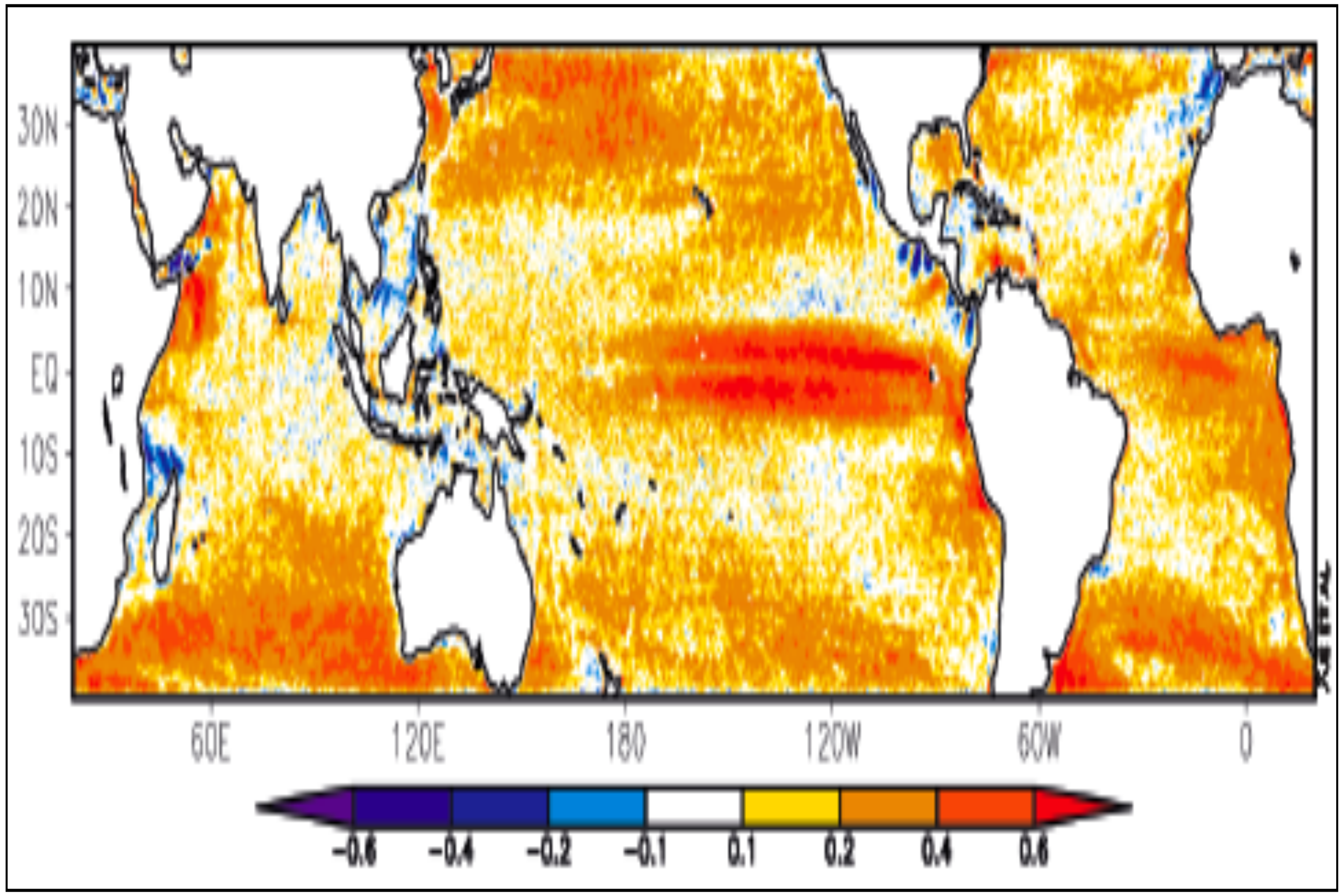


Stronger wind ➔ colder SST
(Negative correlation).

Kushnir et al. 2002

Oceanic mesoscale (<10°)

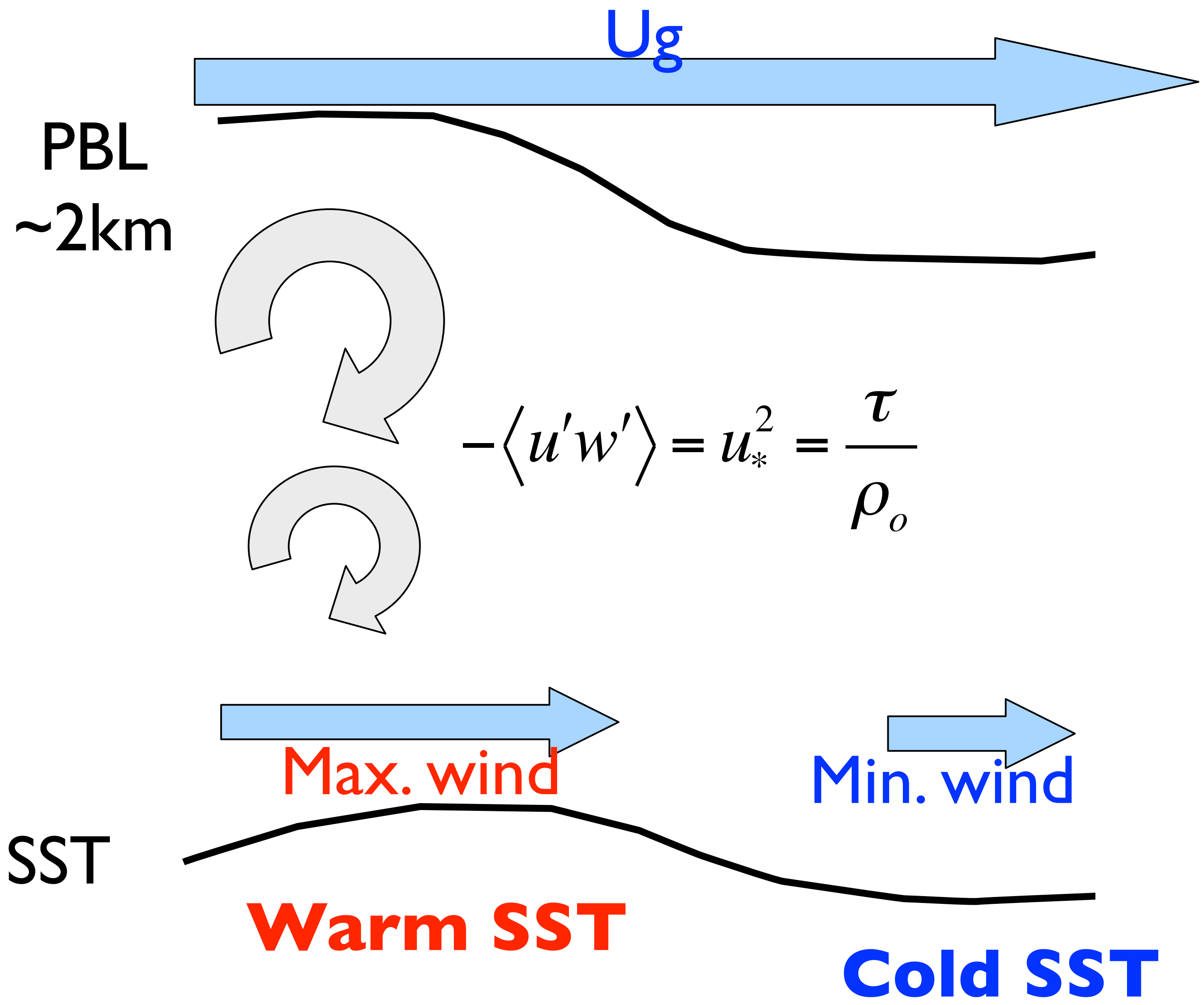
Correlation: high-passed WS and SST



Xie, 2004 Positive correlation
(Warm SST ➔ Stronger wind)

#1. Vertical momentum mixing
#2. Pressure adjustment

#1.Vertical momentum mixing: Wallace et al. 1989; Hayes et al. 1989



$$-\langle u'w'\rangle = u_*^2 = \frac{\tau}{\rho_o}$$

Stronger coupling between lower and upper layers

Decoupled stable boundary layer

Key features

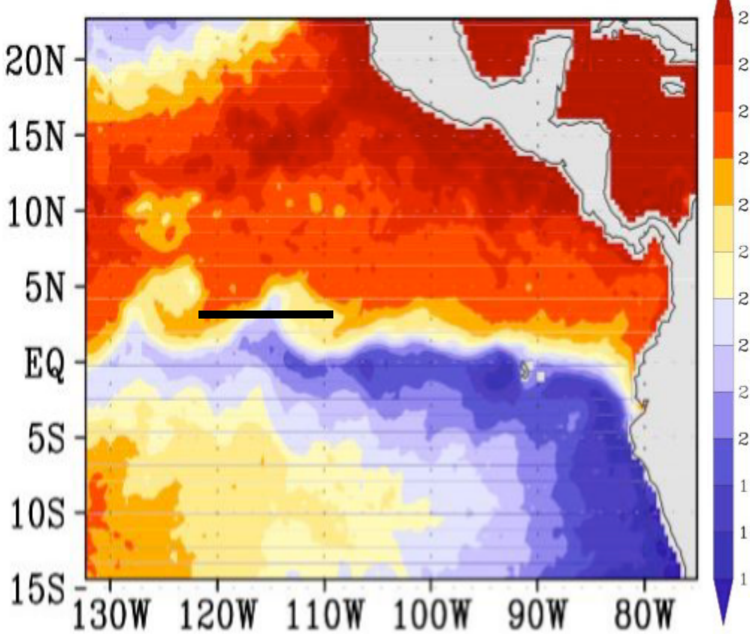
- 1D turbulent boundary layer process
- A shallow (<PBL) and rapid (hrs to days)
- Valid only at mesoscale

T′ ➔ABL Stability ➔ WS & τ

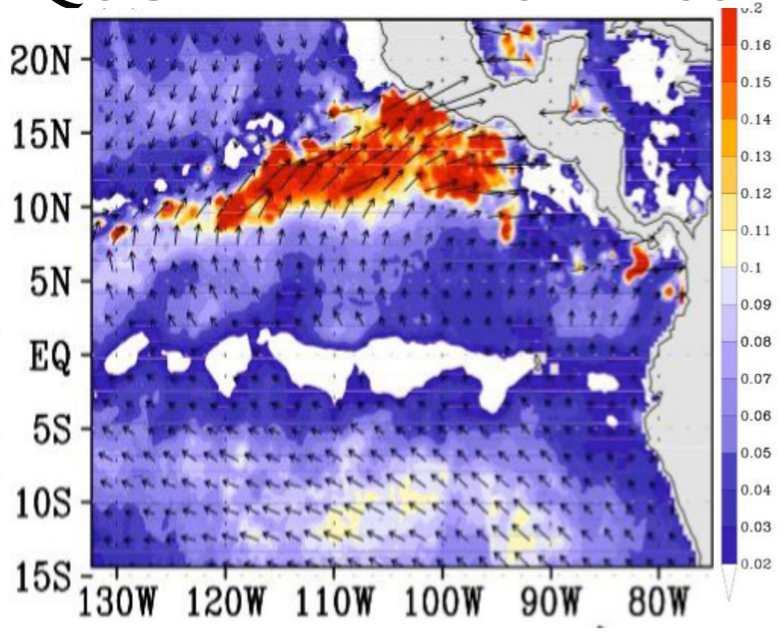
Wind speed and SST are in phase.

Vertical mixing mechanism

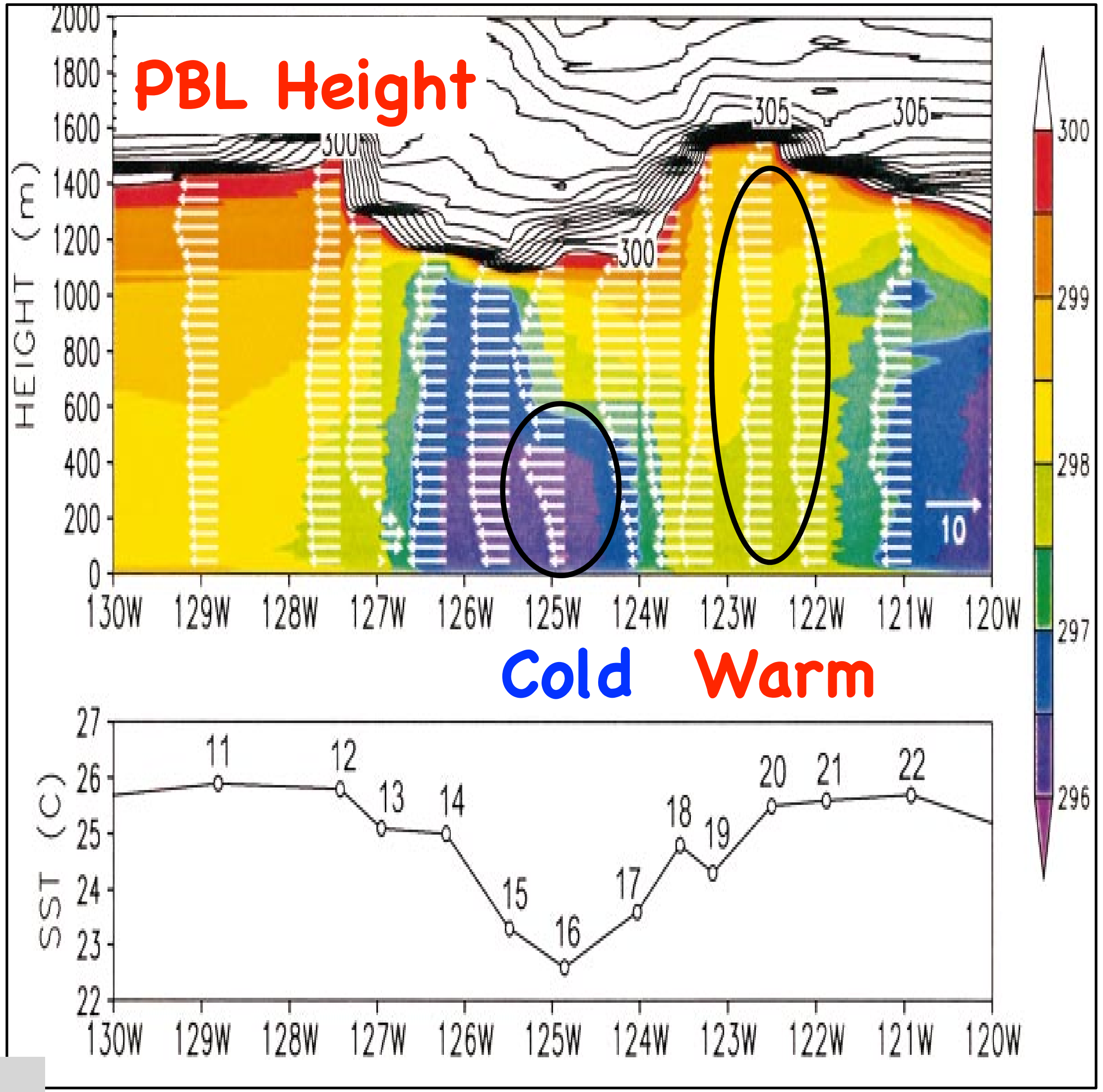
TRMM SST



QSCAT WIND STRESS

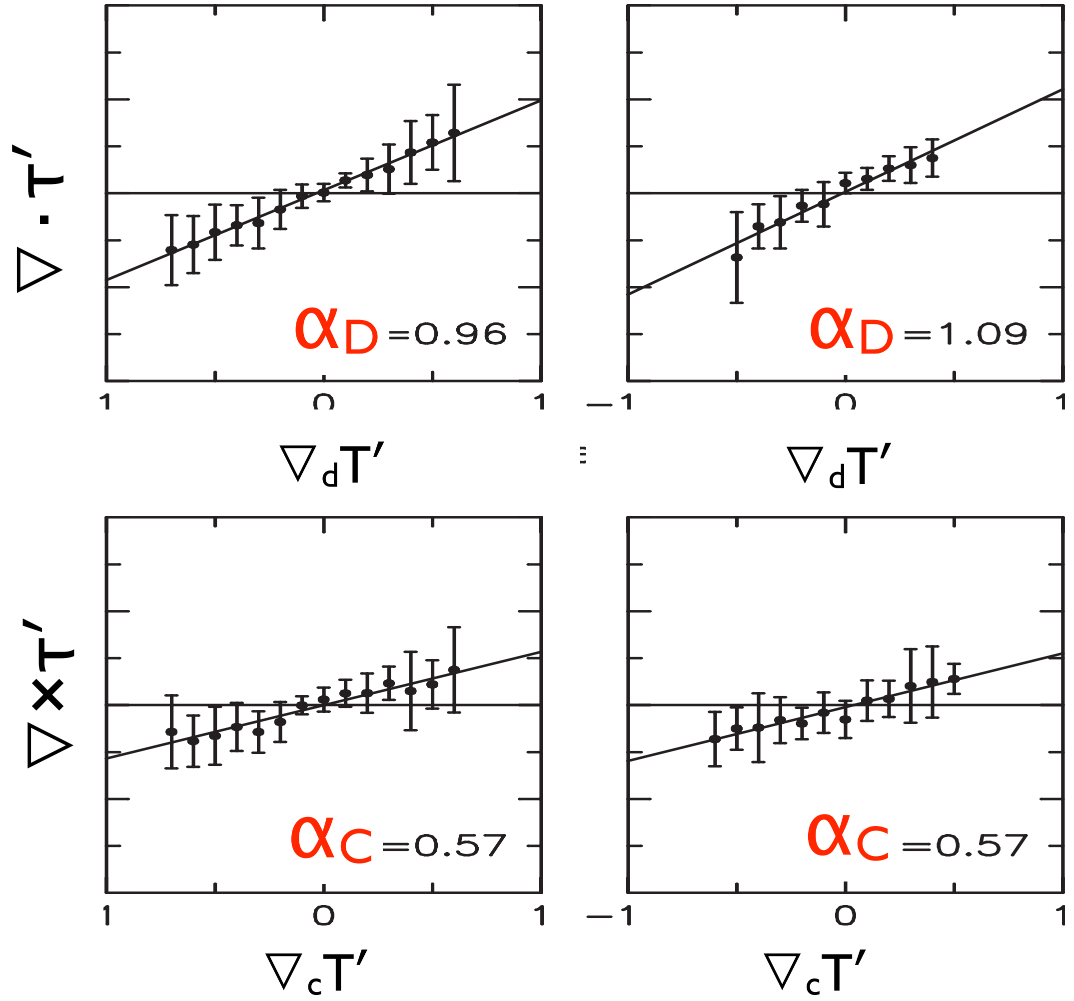


Hashizume et al. 2002



Kuroshio

Gulf Stream

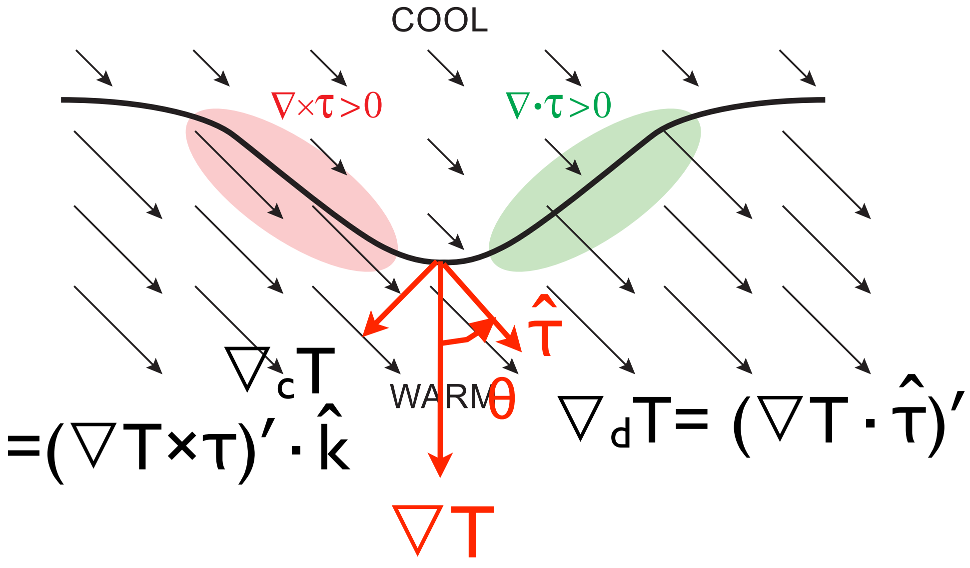


Chelton et al.
2004

$$\nabla\cdot\tau' = \alpha_D \nabla_d T'$$

Coupling coefficient

$$\nabla\times\tau' = \alpha_C \nabla_c T'$$



Vertical mixing mechanism in the Arctic

Overland (1985):

ABL stability is the dominant factor in the variability of geostrophic drag coefficient ($C_g = u_*/W_g$)

climatological value: $C_g = 0.03$

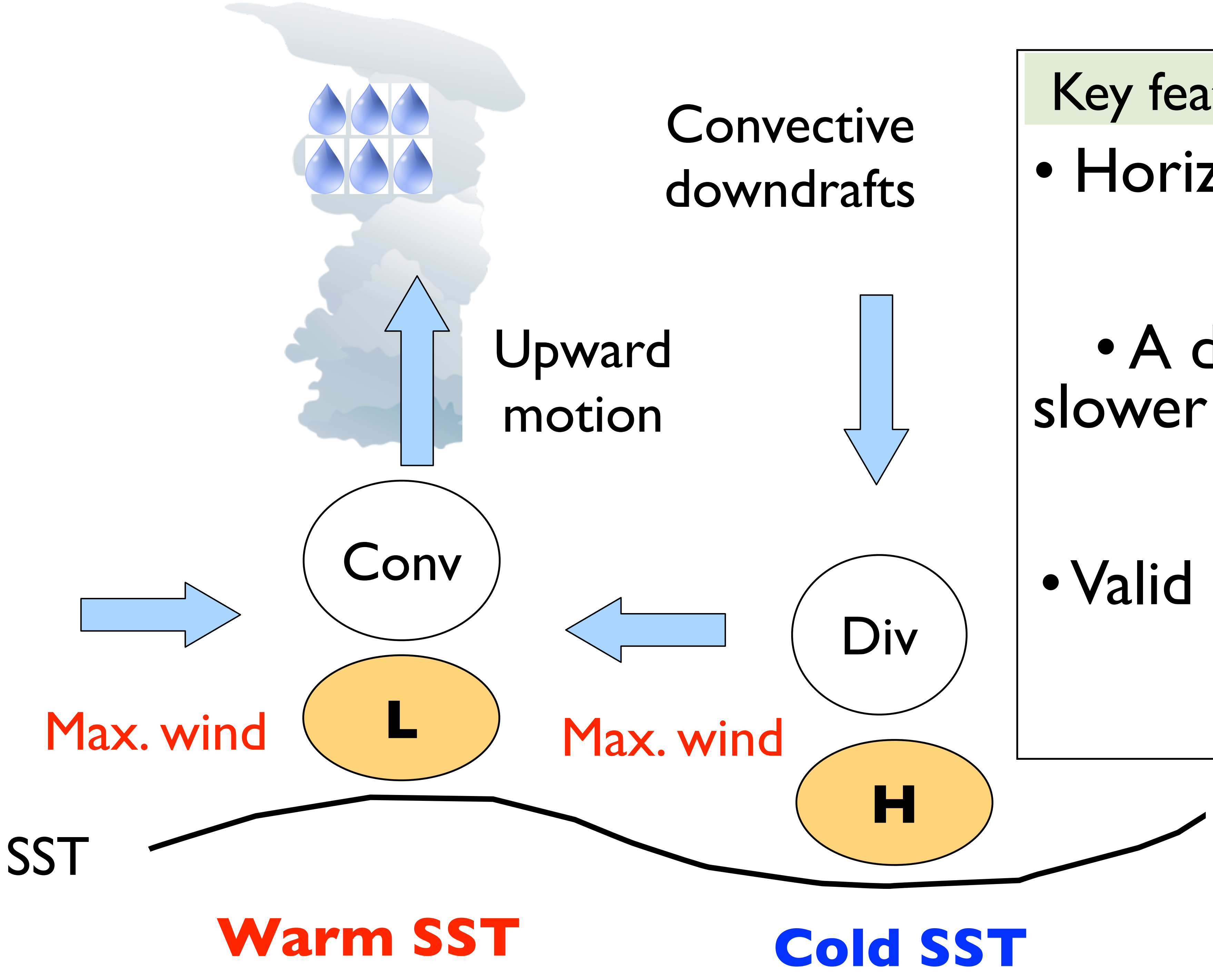
Walter and Overland (1991):

Cold/Stable Central Arctic: $C_g = 0.015$

$\rightarrow \tau = \rho_o u_*^2$

Even with the same Wg, a factor of 4 difference in surface stress.

#2. Pressure adjustment: Lindzen and Nigam (1987)



Key features

- Horizontal variations in SST
- A deep (>PBL) and slower (days to a month) process
- Valid on large-scale and mesoscale

$SST' \rightarrow \nabla P' \rightarrow \tau'$

Wind speed and SST have a 90° out of phase relationship.

Pressure adjustment mechanism

- Minobe et al. (2008): a three-way Ekman momentum balance assuming a steady flow, no advection and a linear friction.

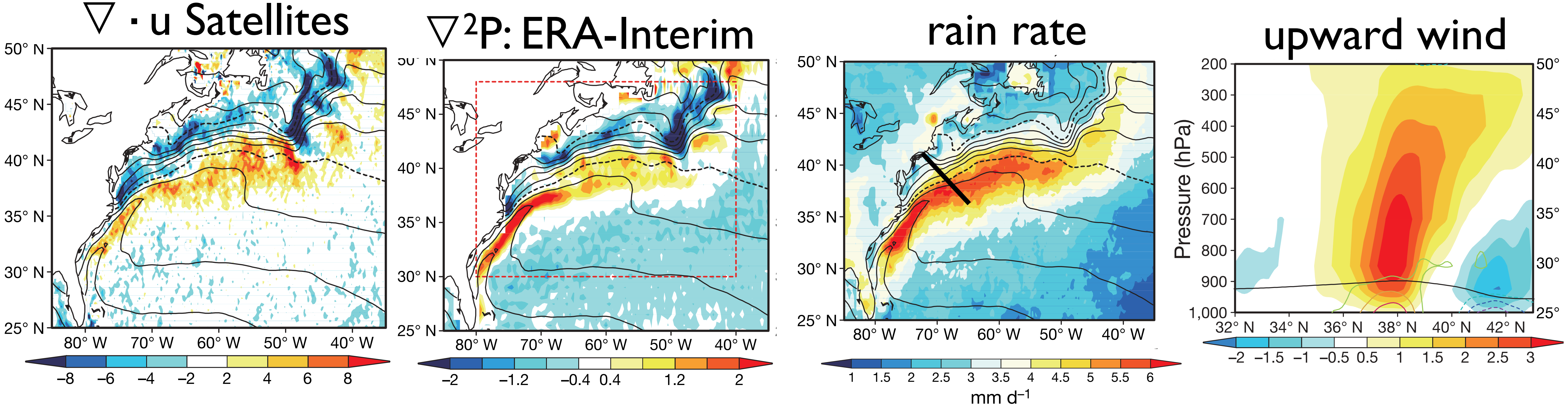
$$f\hat{k}\times u = -\frac{1}{\rho_0}\nabla p - \varepsilon u$$

where $\varepsilon p + H(u_x + v_y) = -\gamma T$

$$\rho_o(\nabla\cdot\vec{u}) = -(\nabla^2 P)\varepsilon/(\varepsilon^2 + f^2)$$

$$w(z) = \frac{1}{\rho_o}\left(\frac{\varepsilon z}{\varepsilon^2 + f^2}\right)\nabla^2 P$$

Over the Gulf Stream



$\nabla\cdot$u Satellites

∇^2P: ERA-Interim

rain rate

upward wind

Pressure adjustment mechanism in the Arctic

Large thermal contrasts exist in ice margins, ponds, polynyas, and leads.

Mesoscale SLP variation is a primary factor the wind stress (Guest et al. 1995).

The temperature (SLP) front moves with the ice edges
➔ ice-edge intensified divergence and curl

The enhanced baroclinicity promotes the cyclogenesis.

Affects the up(down)-welling, ice drift, and ecosystem dynamics.

Side-by-side comparison of the two mechanisms

SST-wind mechanisms	vertical mixing	pressure adjustment
key process	1D turbulent momentum transport	Pressure gradient and ageostrophic flows
phase relationship	in-phase $\nabla \cdot u \propto \nabla_d T$	90° out-of-phase $\nabla \cdot u \propto \nabla^2 P \propto \nabla^2 T$
time-scale	faster (<synoptic)	slower (>synoptic)
height-scale	shallower (below PBL)	deeper (beyond PBL)
horizontal-scale (Arctic)	broader (the whole Arctic basin)	narrower (the ice margins)

Why study surface wind over sea ice?

- Sparse observations of wind and stress over sea ice
  - Limited understanding of dynamics of surface wind
  - Rich small-scale features not captured in climate models
- Ocean-ice modelers often use SLP-based Wg as surface forcing

$u_{10}=0.8(u_g\cos30° - v_g\sin30°)$
$v_{10}=0.8(u_g\cos30° + v_g\sin30°)$

$\leftarrow u_g, v_g$ from buoy-measured SLP

  - An approach assuming a steady relationship, which is sensitive to ABL stability and ice condition
  - How do W10 and Wg respond to sea ice condition?

Polar WRF simulation

- *Polar WRF*: Hines and Bromwich (2008)
  - A community weather model optimized for polar regions
  - Modified land and surface-layer model to improve surface energy balance over sea ice

- Dynamically downscale with various sea ice conditions
  - to study the dynamics of surface winds
  - to provide the long-term high-quality surface wind fields

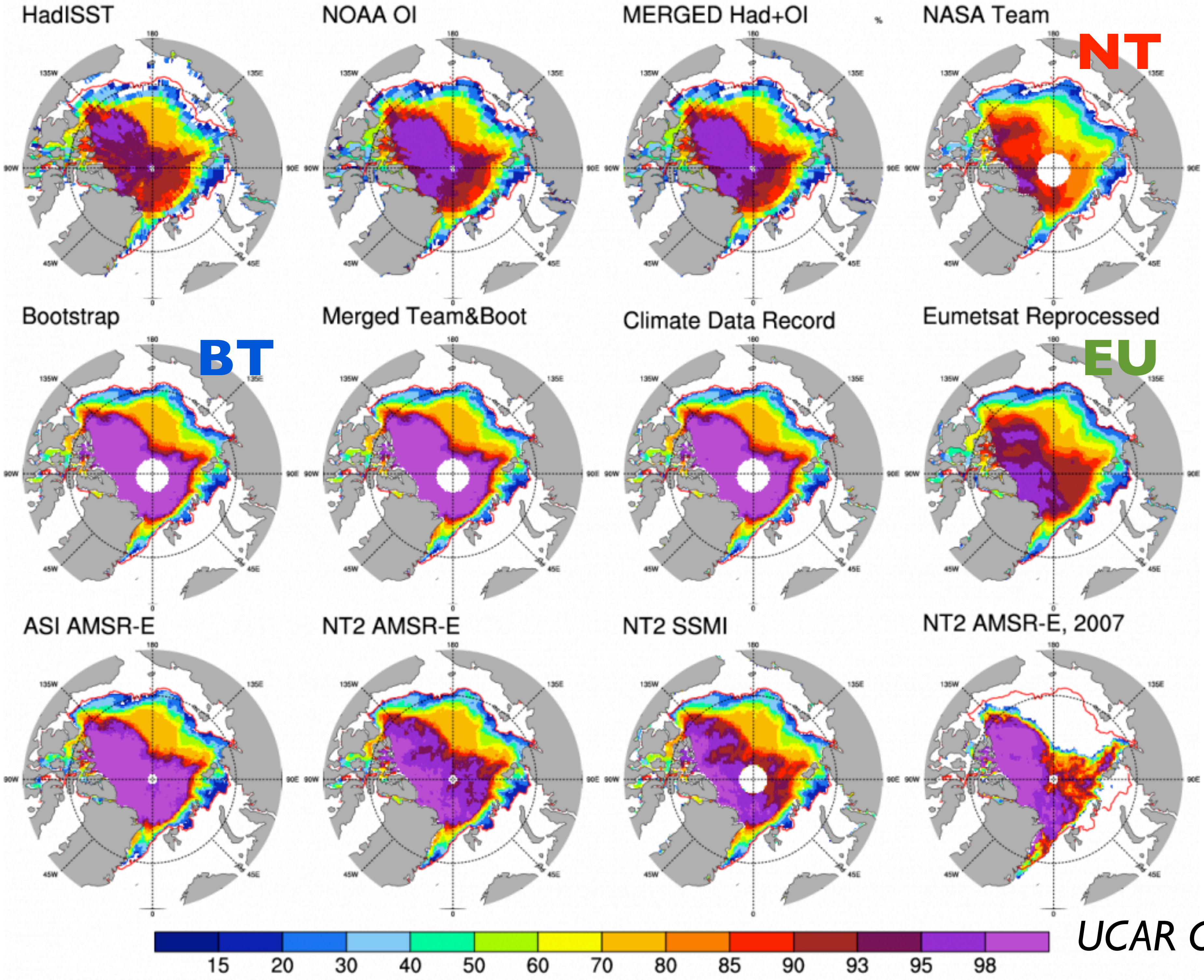
- Arctic surface conditions as input to the model:

  Ice <u>concentration</u>, thickness, roughness, drift, snow depth

Satellite SIC estimates

The most extensively and continuously observed climate variable.

Derived from the passive microwave radiometers with various retrieval algorithms



Sept. 2003:2007 climatology of Arctic Sea Ice Concentration

credit: National Center for Atmospheric Research, Climate Data Guide, climatedataguide.ucar.edu

UCAR Climate Data Guide

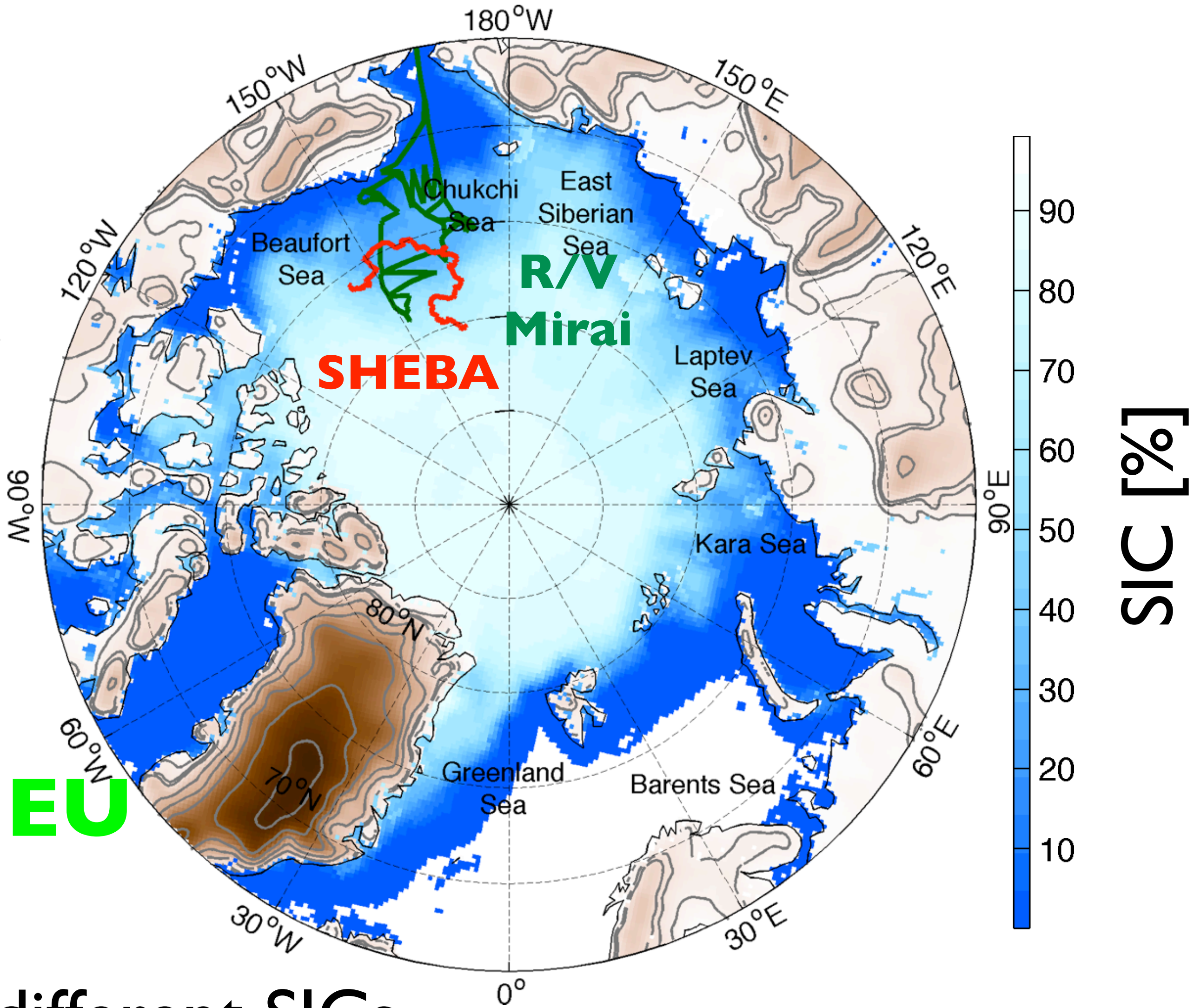
- Estimates affected by atmospheric and surface properties (e.g., absorption, emission, and wind roughness)

1) **NT**: NASA-TEAM
2) **BT**: NASA Bootstrap
3) **EU**: Eumetsat hybrid

The greatest difference is bet’n NT and BT.

Polar WRF simulation

- Experiments: 25 km, 48-hr forecasts
- Two 1-yr (Nov-Oct) runs
  - 1997-1998 : SHEBA
  - 2008-2009 : R/V Mirai
  - Each period forced with **NT**, **BT**, **EU**



Look for local atmospheric response to different SICs

Other surface conditions

Thickness: Uniform 3m: *an invalid* assumption in the MIZ

Roughness: Uniform 10^{-3}: O(1) larger than the observed from SHEBA

Drift: Not considered, but can influence the air-ice stress

Snow: Uniform 20 cm, but can be up to 1m from SHEBA

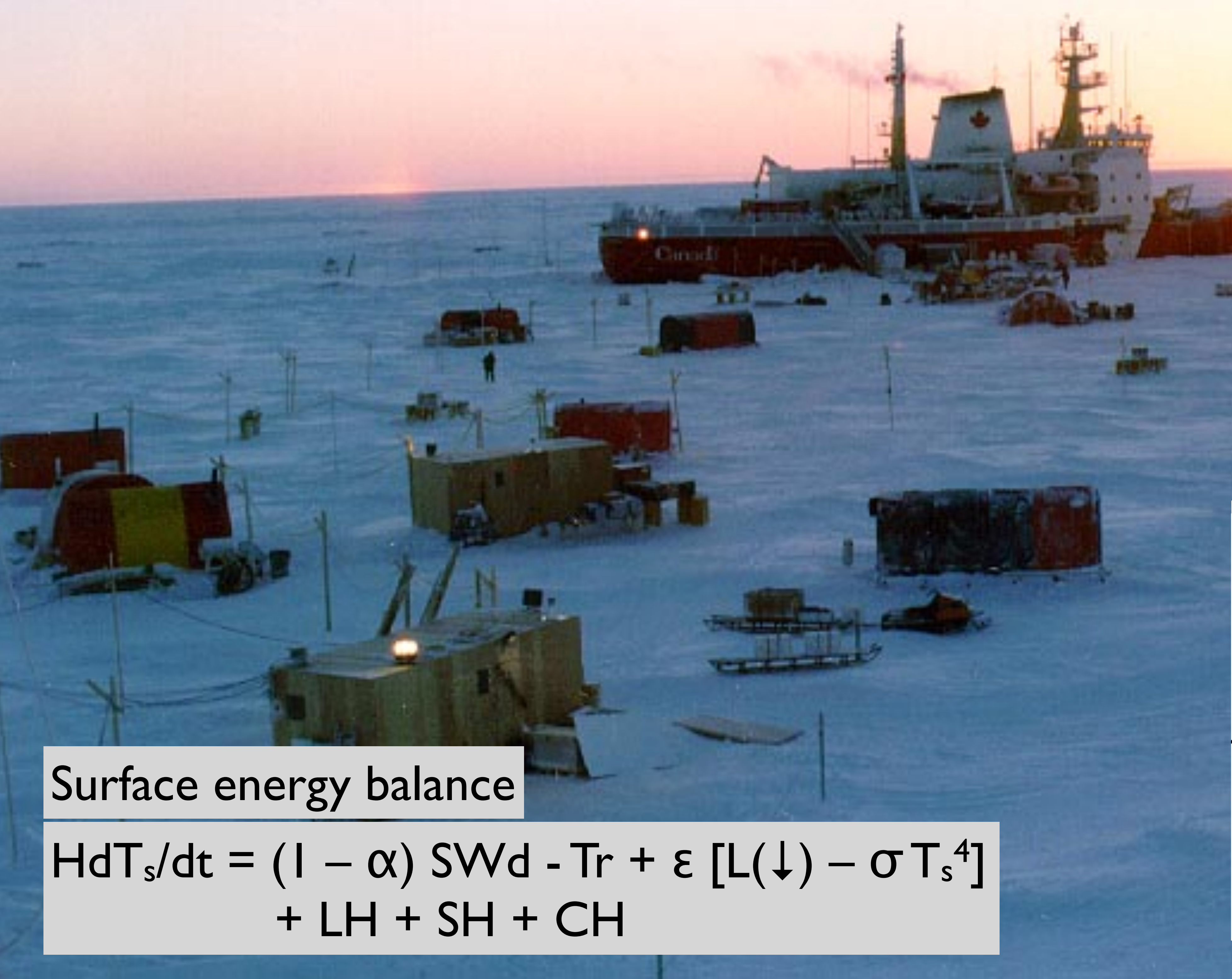
Goal of this study

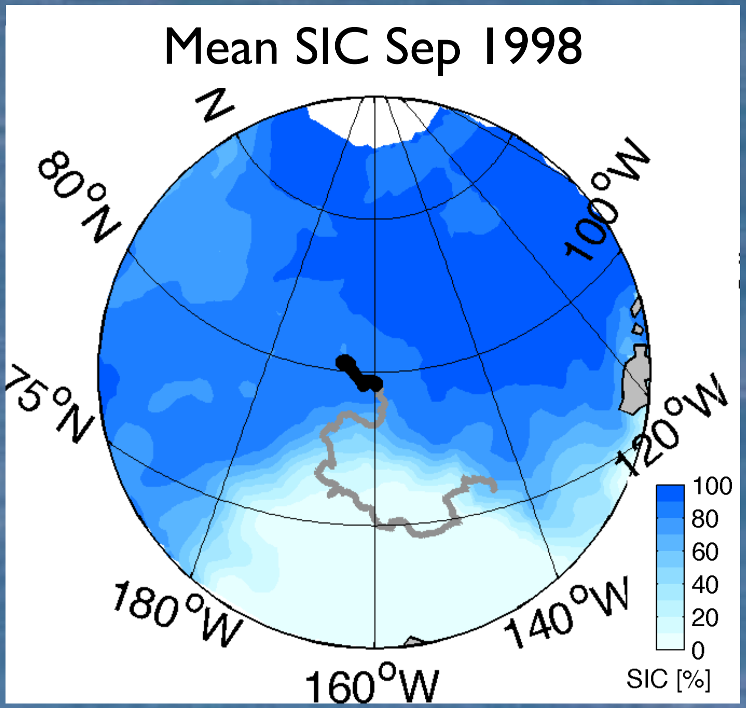
1. Skill and sensitivity of the model
2. Thermodynamic response of the ABL stability **NT-BT**
3. Responses in W10 and SLP-based Wg **NT-BT**

1. Skill and sensitivity of the model

Surface Heat Budget of the Arctic Ocean (SHEBA): Surface energy budget experiment over the Beaufort Gyre multi-year thick ice

Oct 1997- Oct 1998




Mean SIC Sep 1998

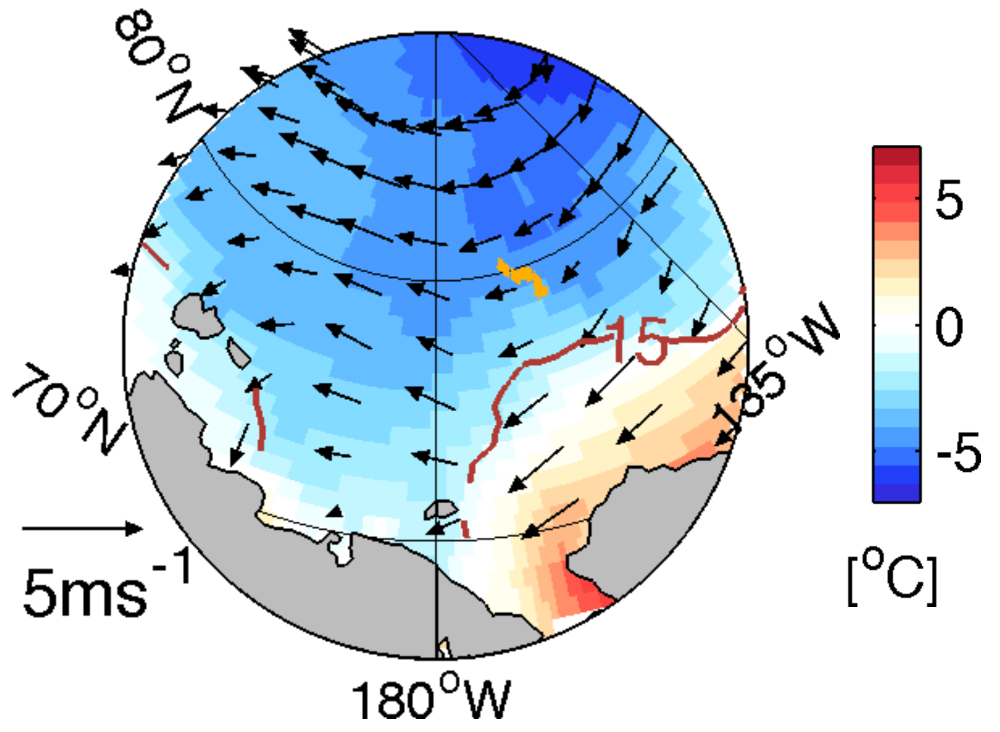
Surface energy balance

$$H dT_s/dt = (1 - \alpha)\, SWd - Tr + \varepsilon\, [L(\downarrow) - \sigma T_s^4] + LH + SH + CH$$

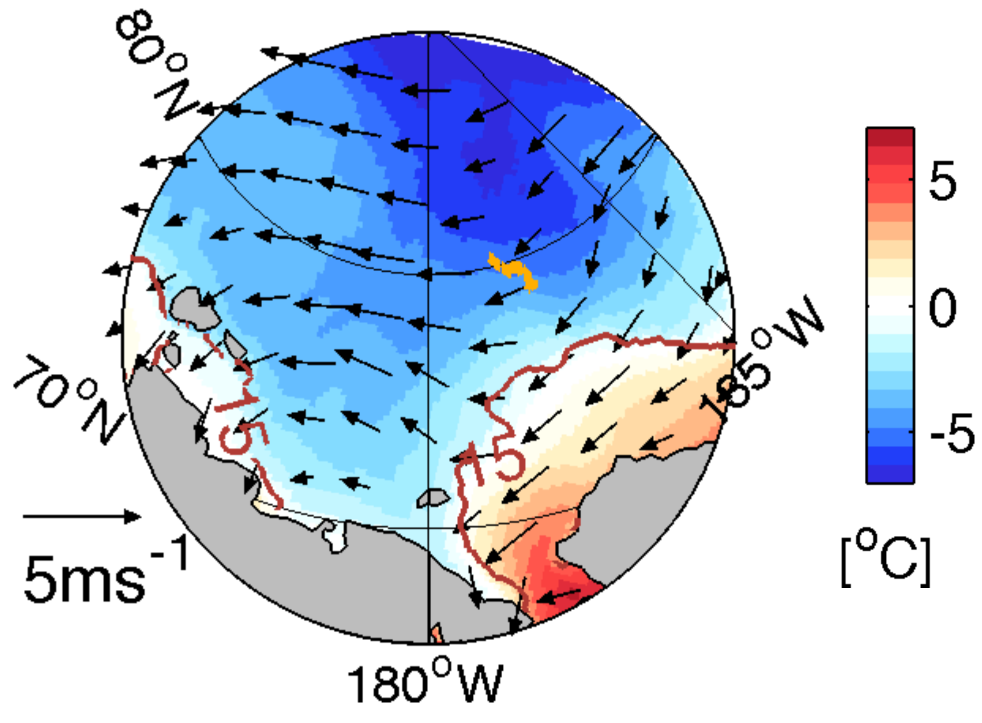
Skill of the Polar WRF

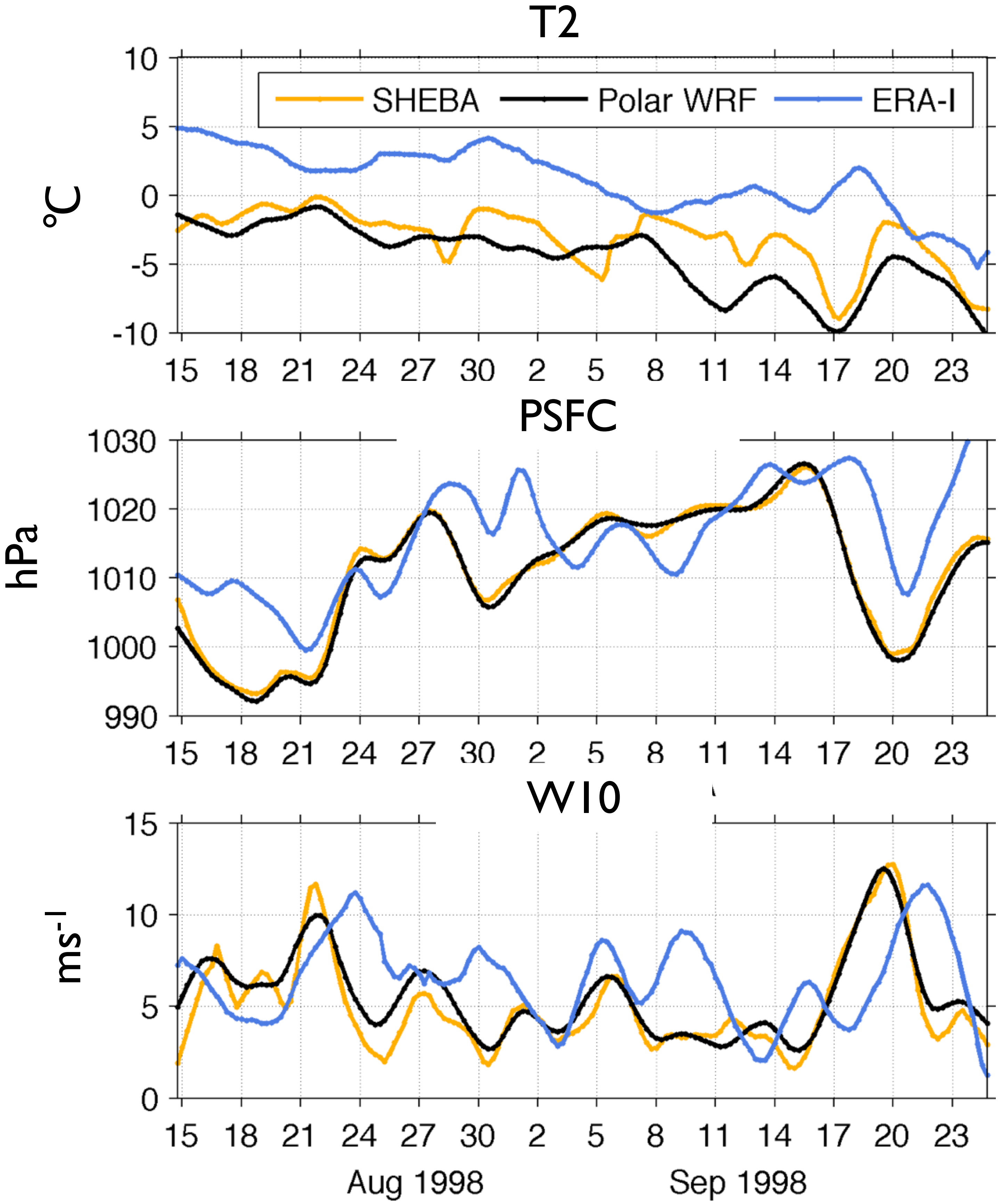
Ensemble mean compared to the ERA-Interim (lateral boundary condition)

(a) ERA-I T2 and W10

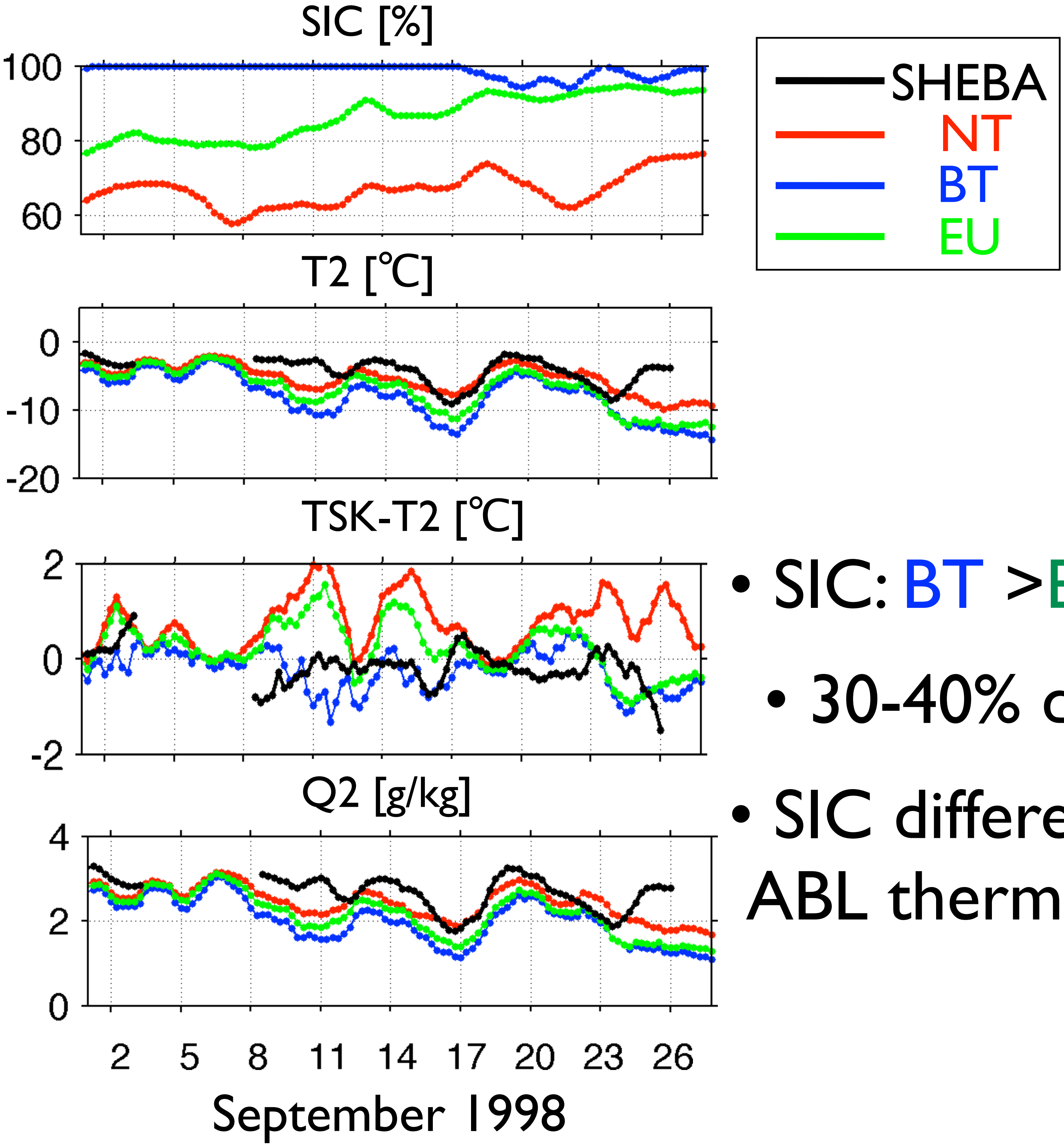


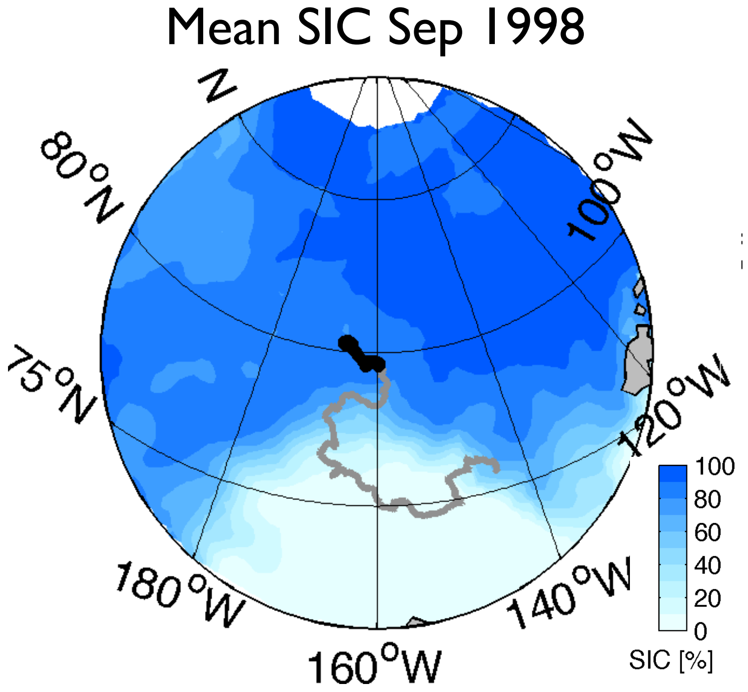
(b) Polar WRF T2 and W10





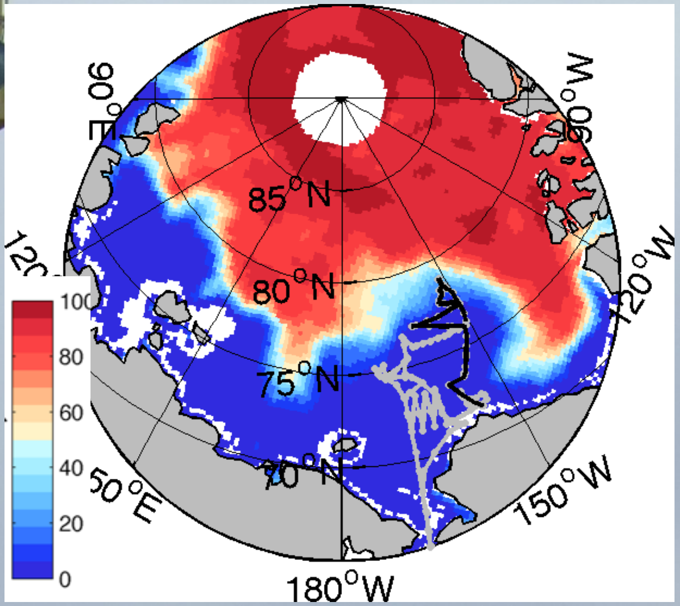
Large sensitivity of ABL and surface heat balance to the choice of SIC datasets





- SIC: BT >EU >NT
  - 30-40% difference
- SIC difference reflected in the ABL thermodynamic fields

R/V Mirai meteorological observations in the MIZ (September 19-27, 2009)

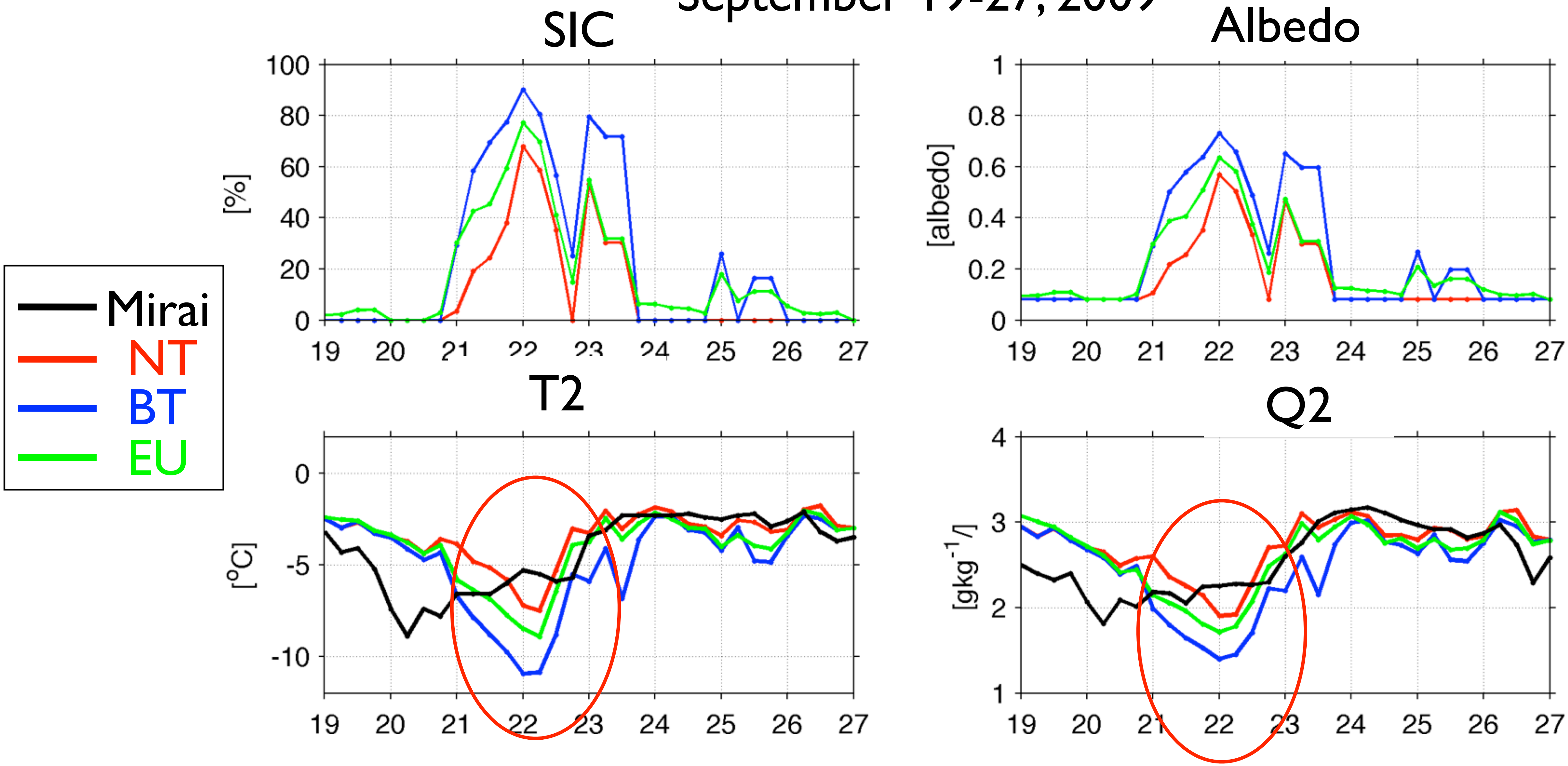



September 22, 2009

Covered 100% with thin ice
(Dr. Jun Inoue, JAMSTEC, Per. comm.)

Low skill in the MIZ
due to an inaccurate specification of ice thickness

September 19-27, 2009



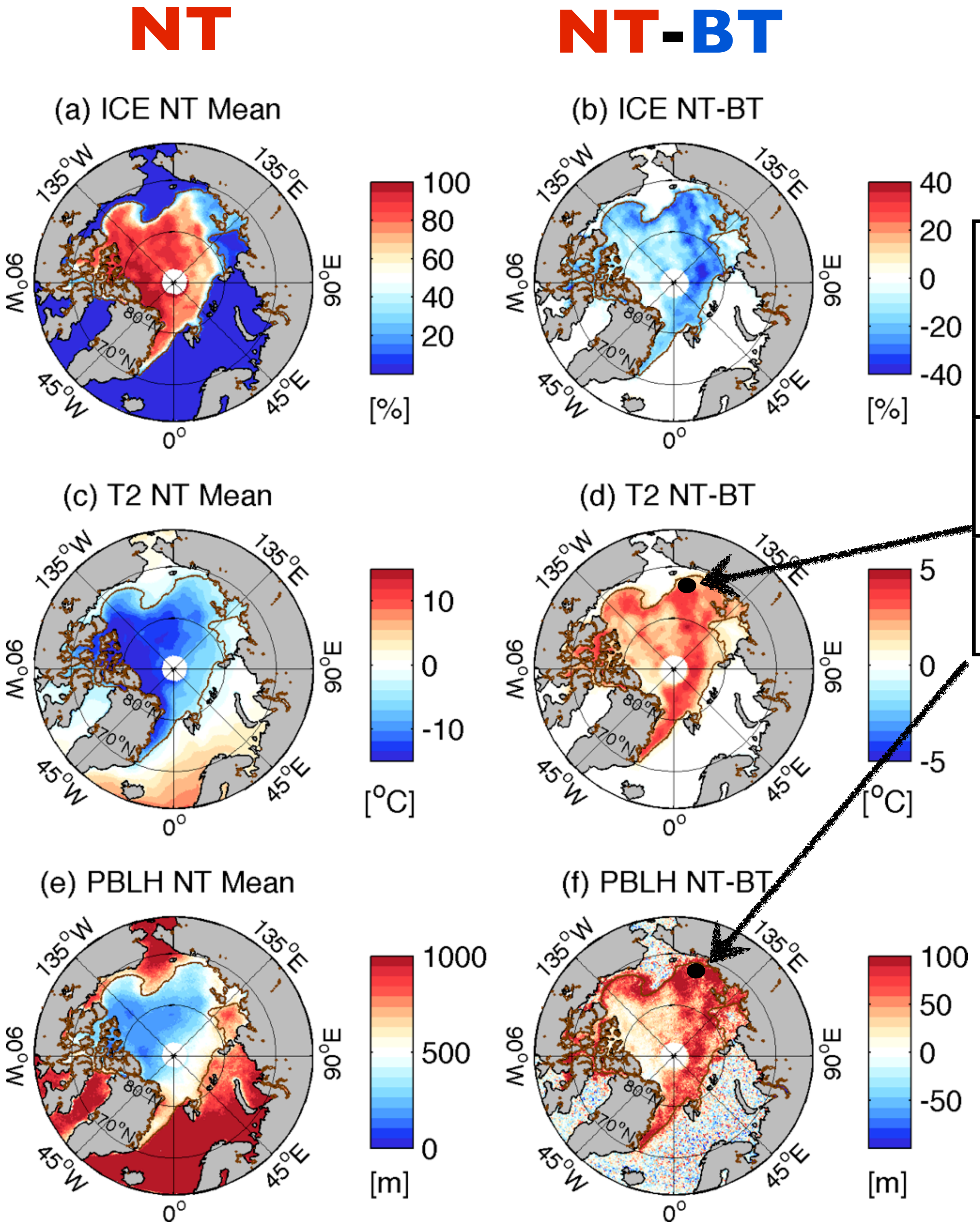
- Low bias in T2 and Q2 due to thick (3m) ice.

bias on 9/22	NT	BT	EU	model-mean
T2	-0.2	-3.4	-1.3	-1.6

2. Thermodynamic response of the ABL stability

NT-BT

ABL response to SIC September 2009



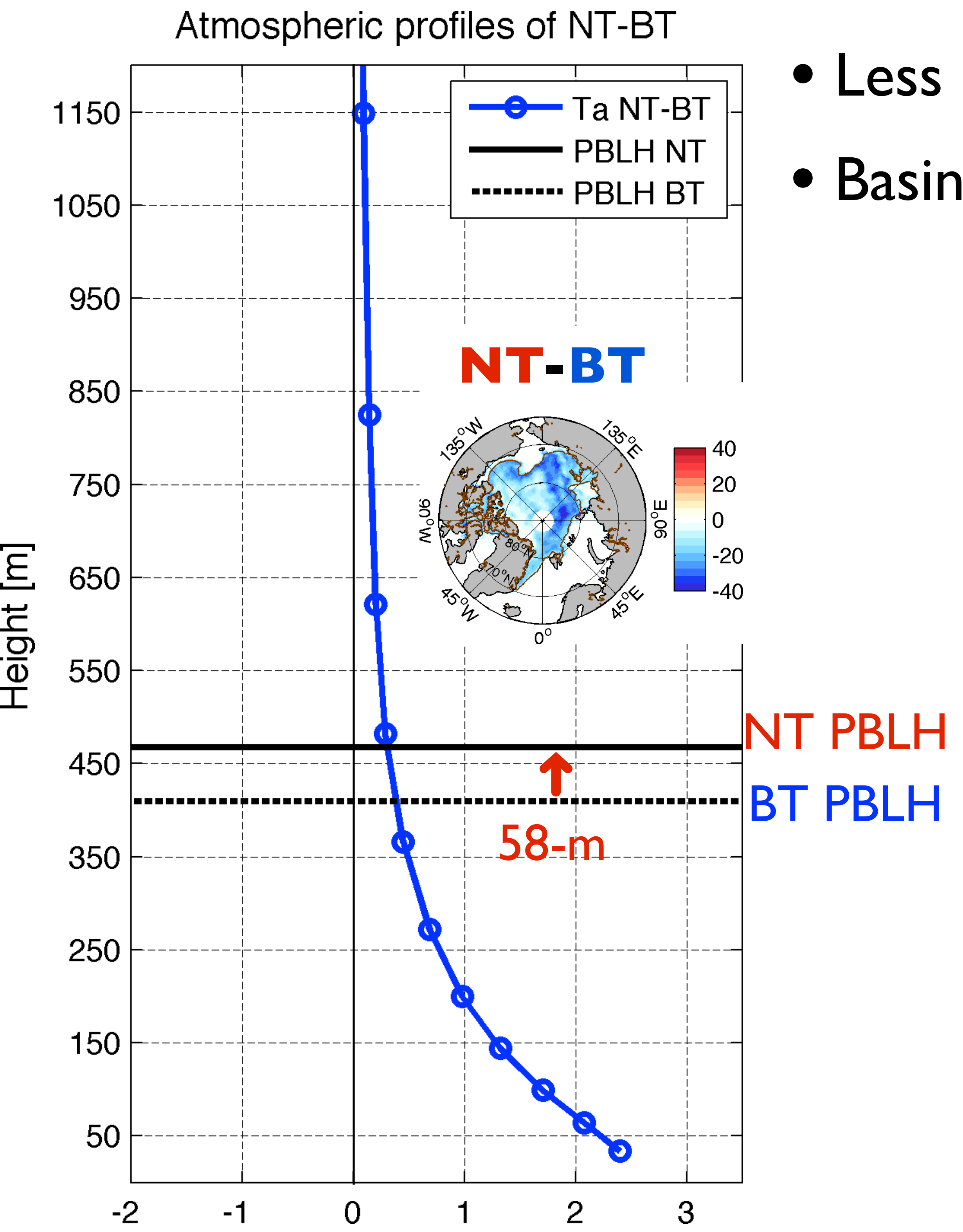
East Siberian Sea	Mean	Difference
T2	-5°C	+5°C
PBLH	450 m	100 m

SIC is a decisive factor for hindcast skill.

SIC difference and ABL sensitivity on a comparable spatial-scale

SST′ ➜ ABL stability

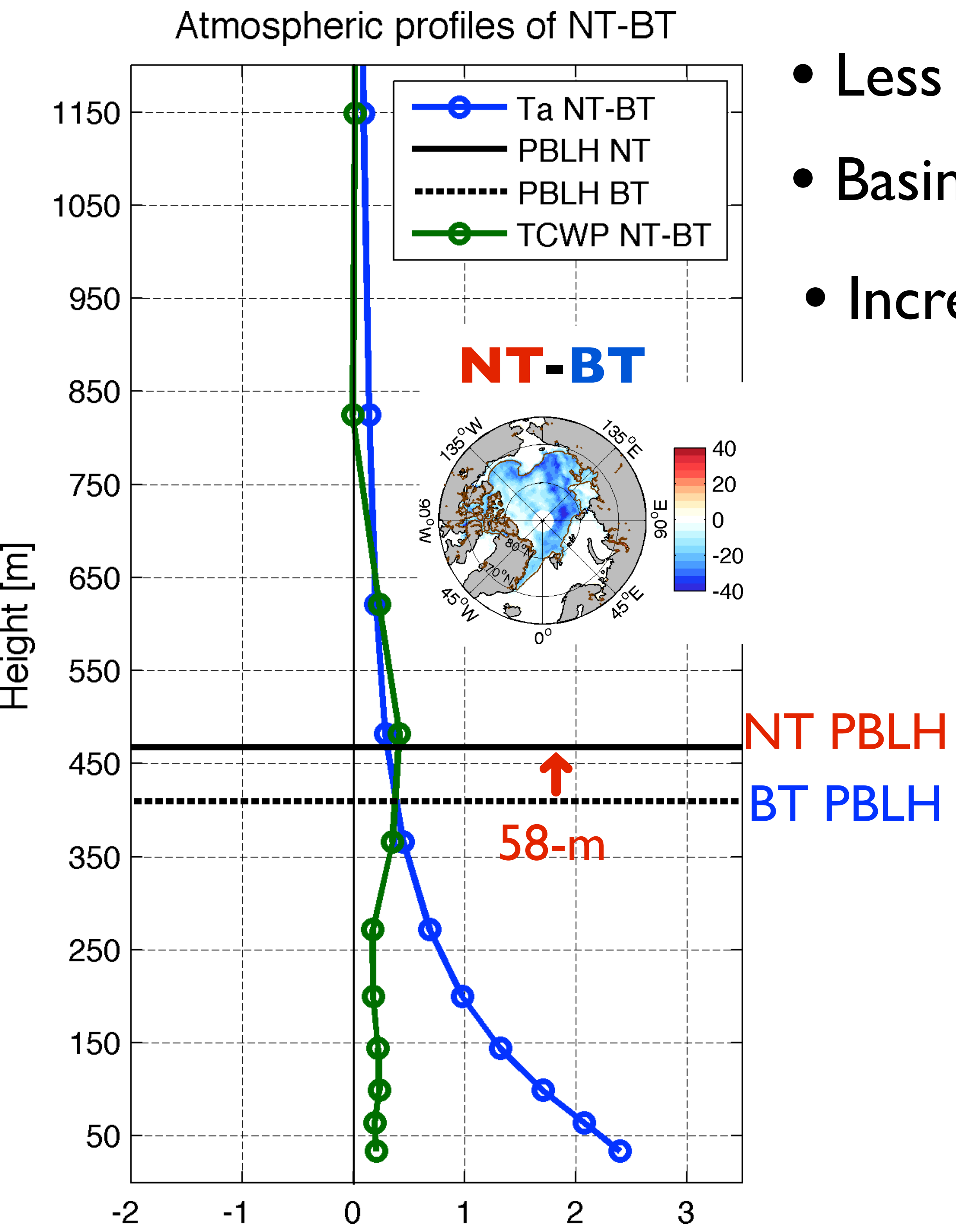
Arctic-basin averaged vertical profiles difference (NT-BT)



Atmospheric profiles of NT-BT

- Less SIC ➔ Higher PBL
- Basin-wide increase in air temperature below PBL.

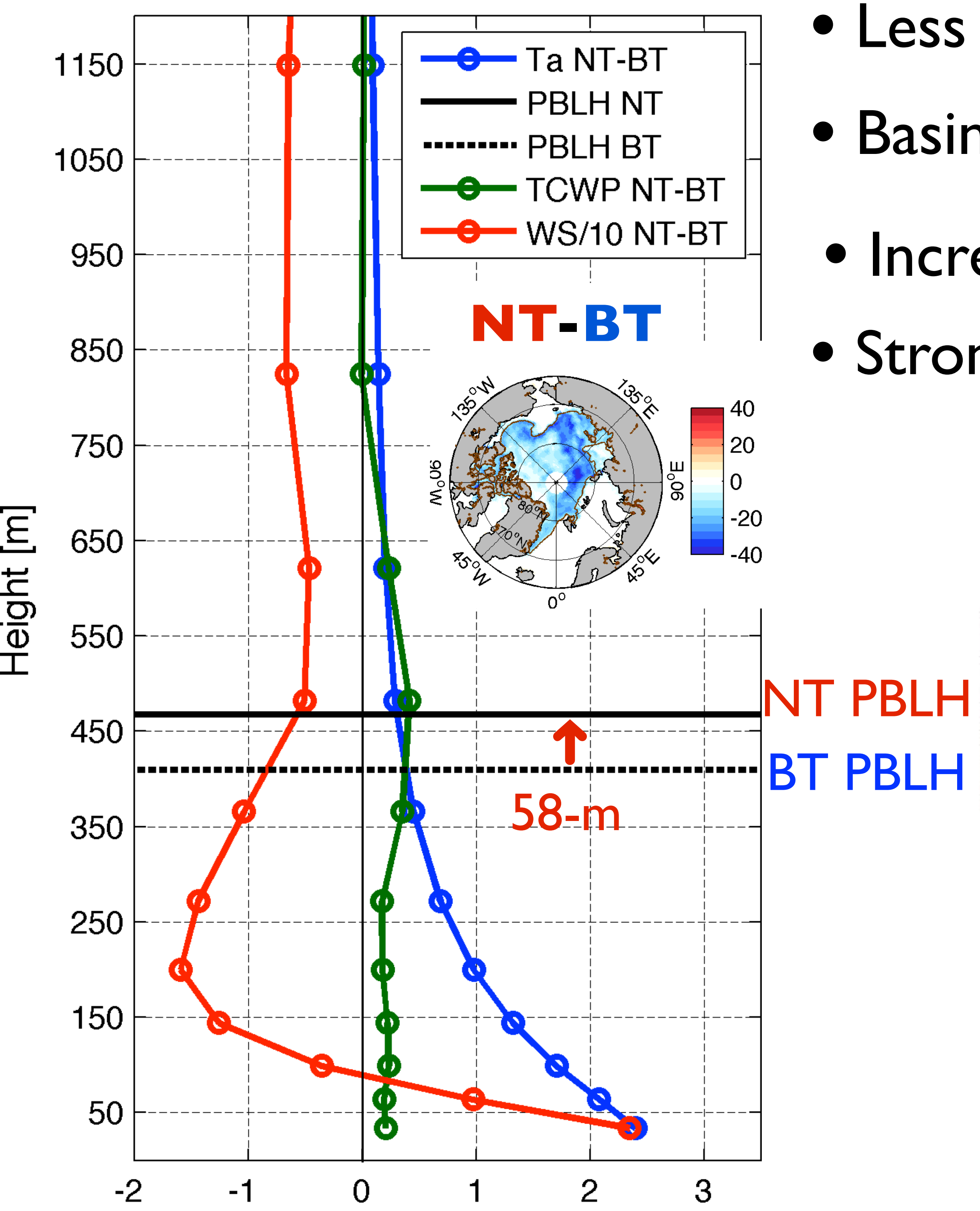
Arctic-basin averaged vertical profiles difference (NT-BT)



- Less SIC ➔ Higher PBL
- Basin-wide increase in air temperature below PBL.
- Increased cloud water path near the top of PBL.

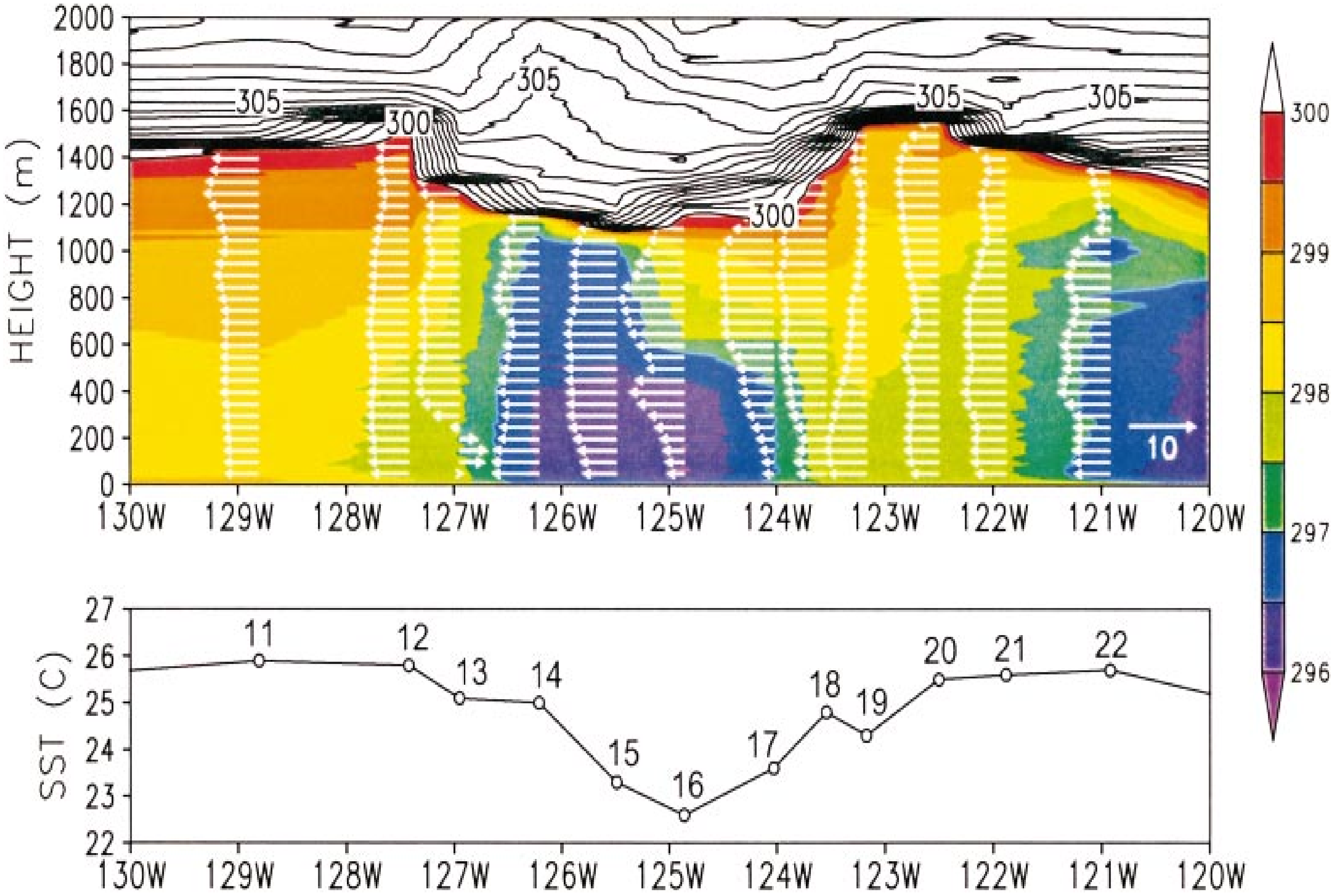
Arctic-basin averaged vertical profiles difference (NT-BT)

Profiles **NT**-**BT**



- Less SIC ➔ Higher PBL
- Basin-wide increase in air temperature below PBL.
- Increased cloud water path near the top of PBL.
- Stronger wind in the surface layer

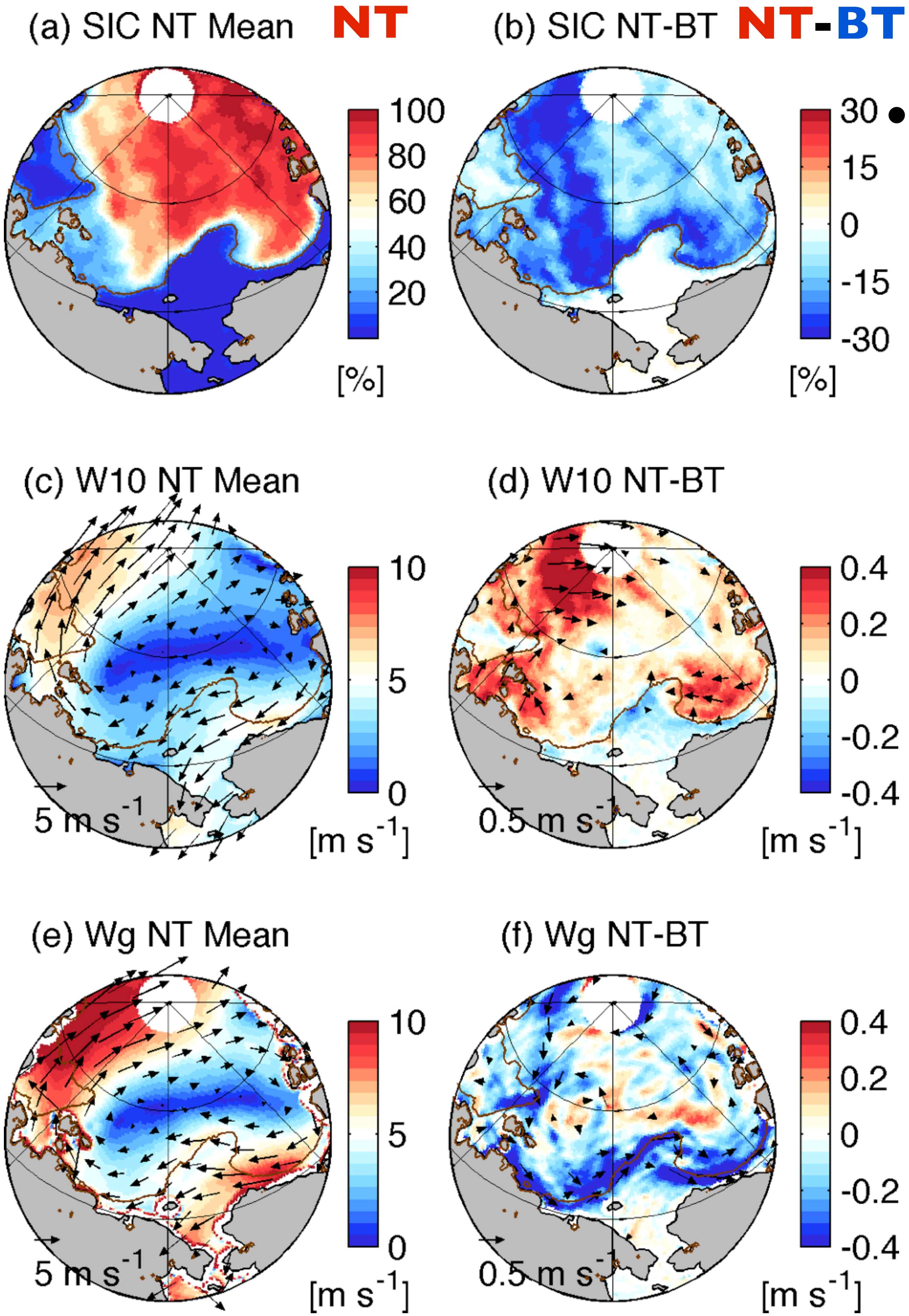
Hashizume et al. 2002



3. Responses in W10 and SLP-based Wg

NT-BT

Different response between W10 and Wg



- Increased W10 over reduced SIC
  - Poleward of the ice margins.

➜ Reflect the broad scale of SIC difference

$T' \rightarrow u'$ or

$\nabla \cdot u' = \alpha_D \nabla_d T'$ $\nabla \times u' = \alpha_C \nabla_c T'$

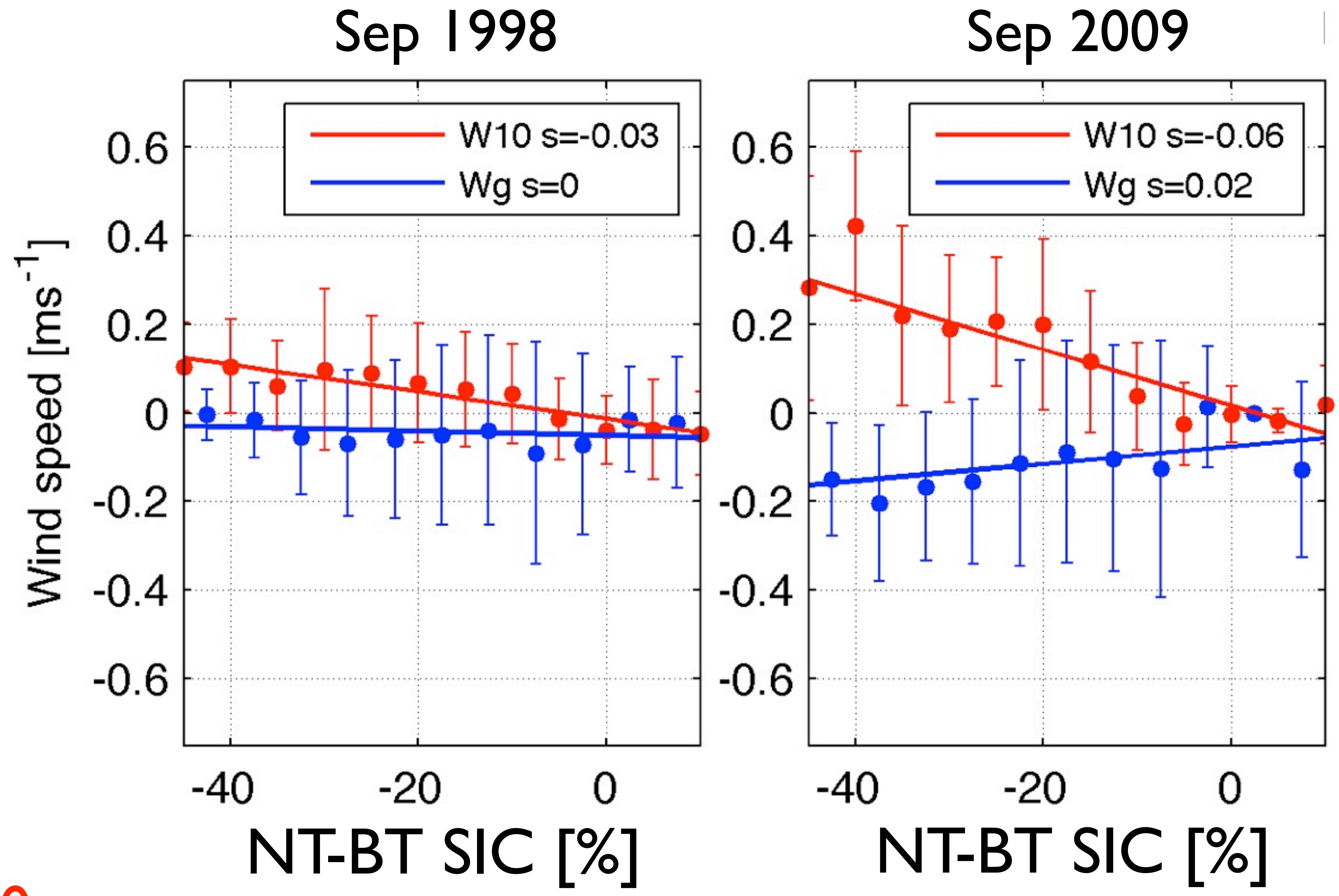
- Reduced Wg
  - Along the ice margins

➜ Length-scale of Wg response shorter than that of W10.

$\nabla^2 T \rightarrow \nabla^2 P \rightarrow \nabla \cdot u'$

Coupling coefficients (Chelton et al., 2004)

to quantify the effect of vertical mixing on W10 and Wg



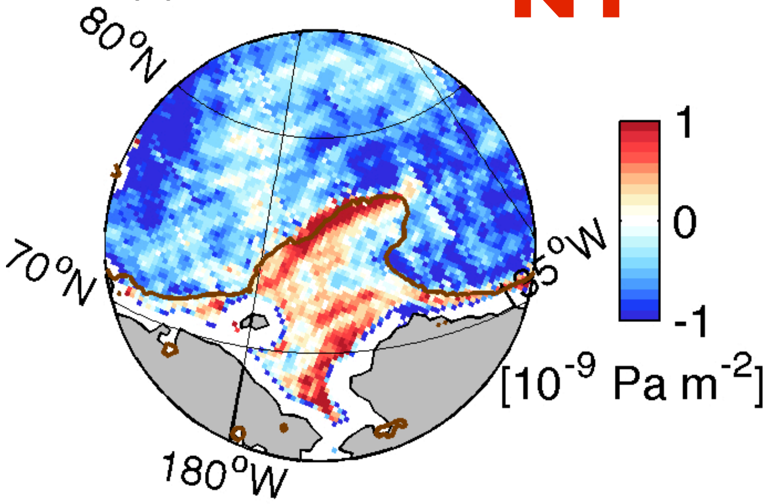
W10

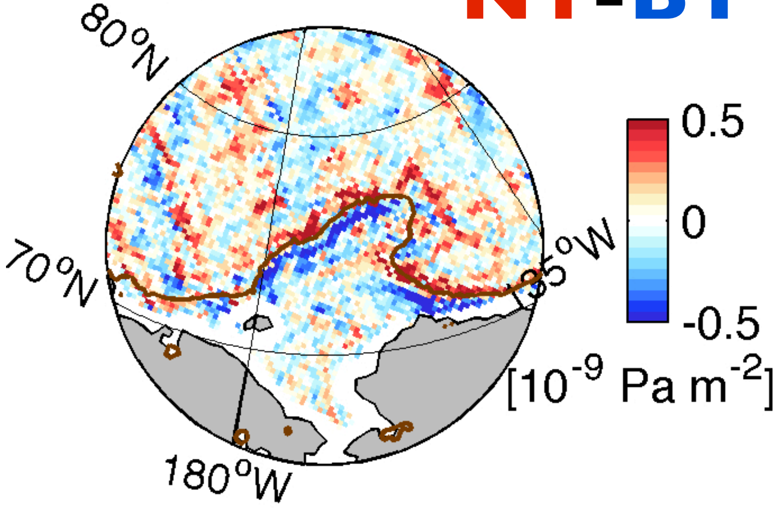
- A Significant negative relationship
- Vertical mixing mechanism works

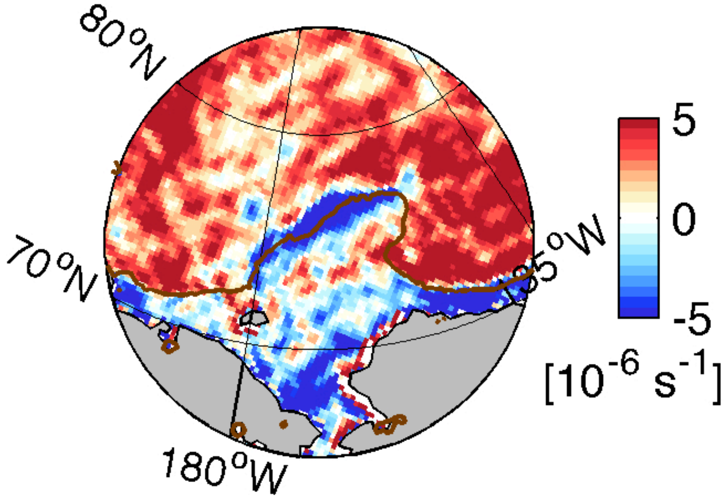
Wg

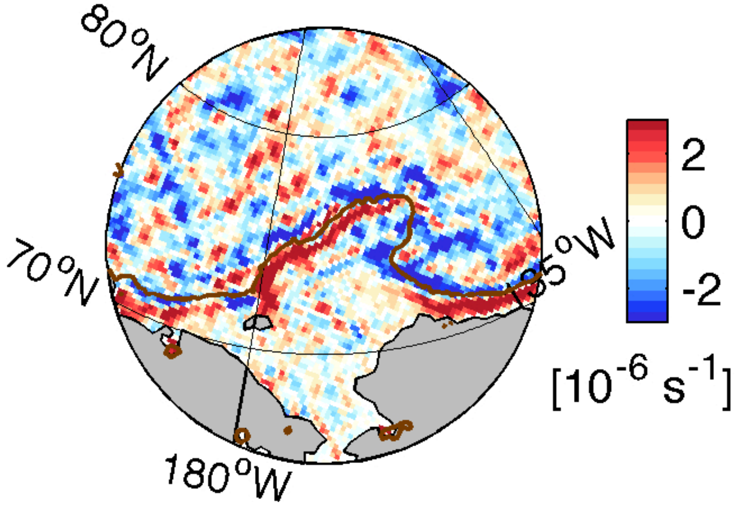
- No significant relationship
- Need a different mechanism

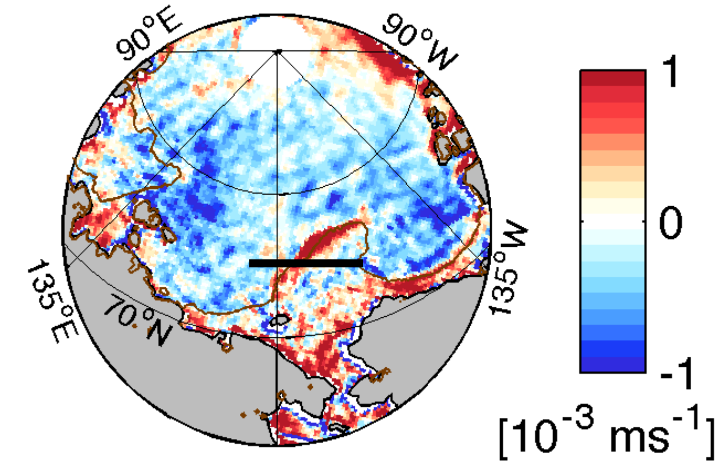
Wg response ← Pressure adjustment mechanism

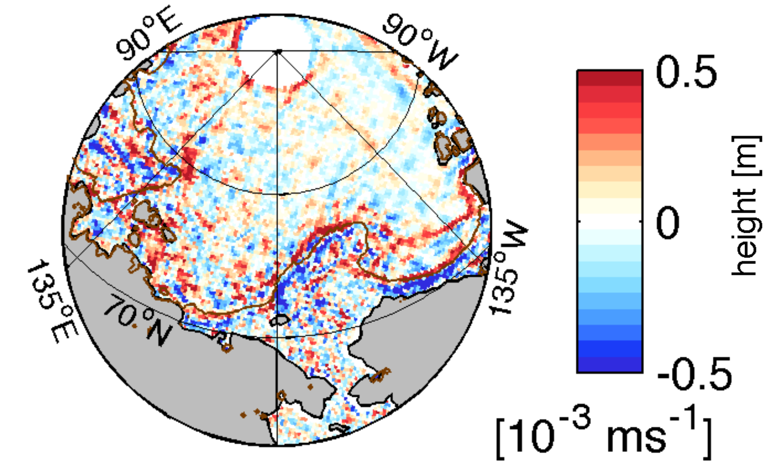

(c) ∇^2P NT Mean **NT**


(d) ∇^2P NT-BT **NT-BT**


(e) Wind div/conv NT Mean


(f) Wind div/conv NT-BT


(a) Vertical velocity NT Mean

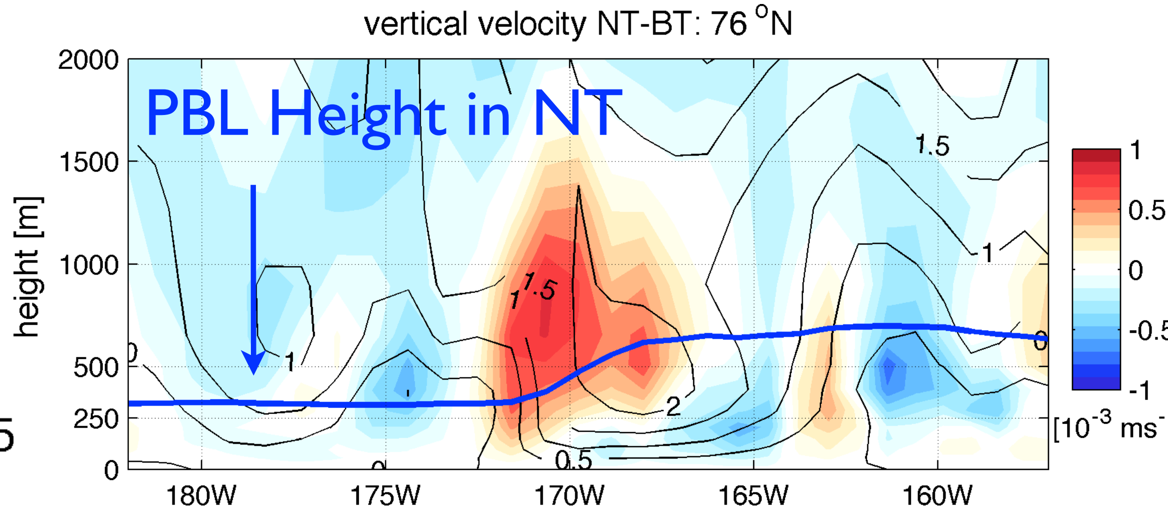

(b) Vertical velocity NT-BT

$$\rho_o\left(\nabla\cdot\vec{u}\right) = -\left(\nabla^2 P\right)\varepsilon\Big/\left(\varepsilon^2 + f^2\right)$$

$\nabla\cdot$u is proportional to $\nabla^2 P$ (*via* $\nabla^2 T$).

$$w(z) = \frac{1}{\rho_o}\left(\frac{\varepsilon z}{\varepsilon^2 + f^2}\right)\nabla^2 P$$

A "deep" atmospheric response as seen from the Gulf Stream


vertical velocity NT-BT: 76 °N

Summary

- Mesoscale surface temperature variations cause coherent perturbations in the atmosphere
  - A ubiquitous feature observed throughout the World Oceans
  - Valid in the Arctic Ocean: sea ice acting like an SST front

- *Vertical mixing*
  - 1-D turbulent momentum transport: high wind over warm SST
  - Comparable spatial scale of between wind and SST (SIC)

$SST' \rightarrow u'$ → $\nabla \cdot \tau' = \alpha_D \nabla_d T'$ $\nabla \times \tau' = \alpha_C \nabla_c T'$

- *Pressure adjustment*
  - Perturbation SLP gradient: the conv/div ageostrophic flows
  - Relates to the vertical motion in the atmosphere
  - ∇^2 highlighting small-scale change in surface temperature

$$\rho_o\left(\nabla \cdot \vec{u}\right) = -\left(\nabla^2 P\right)\varepsilon \Big/ \left(\varepsilon^2 + f^2\right)$$

Implications and future direction

W10 and Wg reflect different spatial information of ice condition

(1) In situ SLP-based Wg:

- underestimates the effect of basin-scale SIC changes (VM)

(2) W10 from coarse resolution reanalyses:

- underestimates wind variations across the ice margins (PA)

Both effects should be taken into account in the wind forcing

Ongoing and future work

- Consider thickness, roughness and drift in the energy budget
- Construct a regional arctic modeling system

→ coupling MITgcm to Polar WRF (in a pending proposal)

→ study air-ice-ocean coupling, local and large-scale climate

Thanks!

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