What is driving Arctic change: local vs remote?

Sukyoung Lee
(The Pennsylvania State University)

Contributor: Frédéric Laliberté
(Environment Canada)

“local vs remote”? is a difficult question

Many different spatial and time scales are involved and they are not independent of each other. These are just a few examples of the different mechanisms that can lead to amplified warming in the Arctic:

	Local to the Arctic	Remote influence
submonthly	sea ice-cloud feedback sea ice-cloud feedback at the retreating ice edge wind forcing can remove sea-ice from the Arctic Ocean	heat influx associated with midlatitude cyclones & anticyclones; heat & moisture influx by planetary-scale wave trains forced by tropical convection; downward IR (including MJO influence)
seasonal	enhanced winter downward IR reduces following summer sea ice area; springtime atmospheric heat fluxes enhance sea-ice retreat; summer ice-albedo warming of the Arctic Ocean hinders sea ice growth in the following winter	seasonal variations in the submonthly wave train characteristics
Interannual & decadal	thinning of sea ice reduces insulation accumulation of black carbon gradually reduces the albedo of multi-year sea ice	ENSO, PDO, AMO

“local vs remote”? is a difficult question

they are not independent of each other

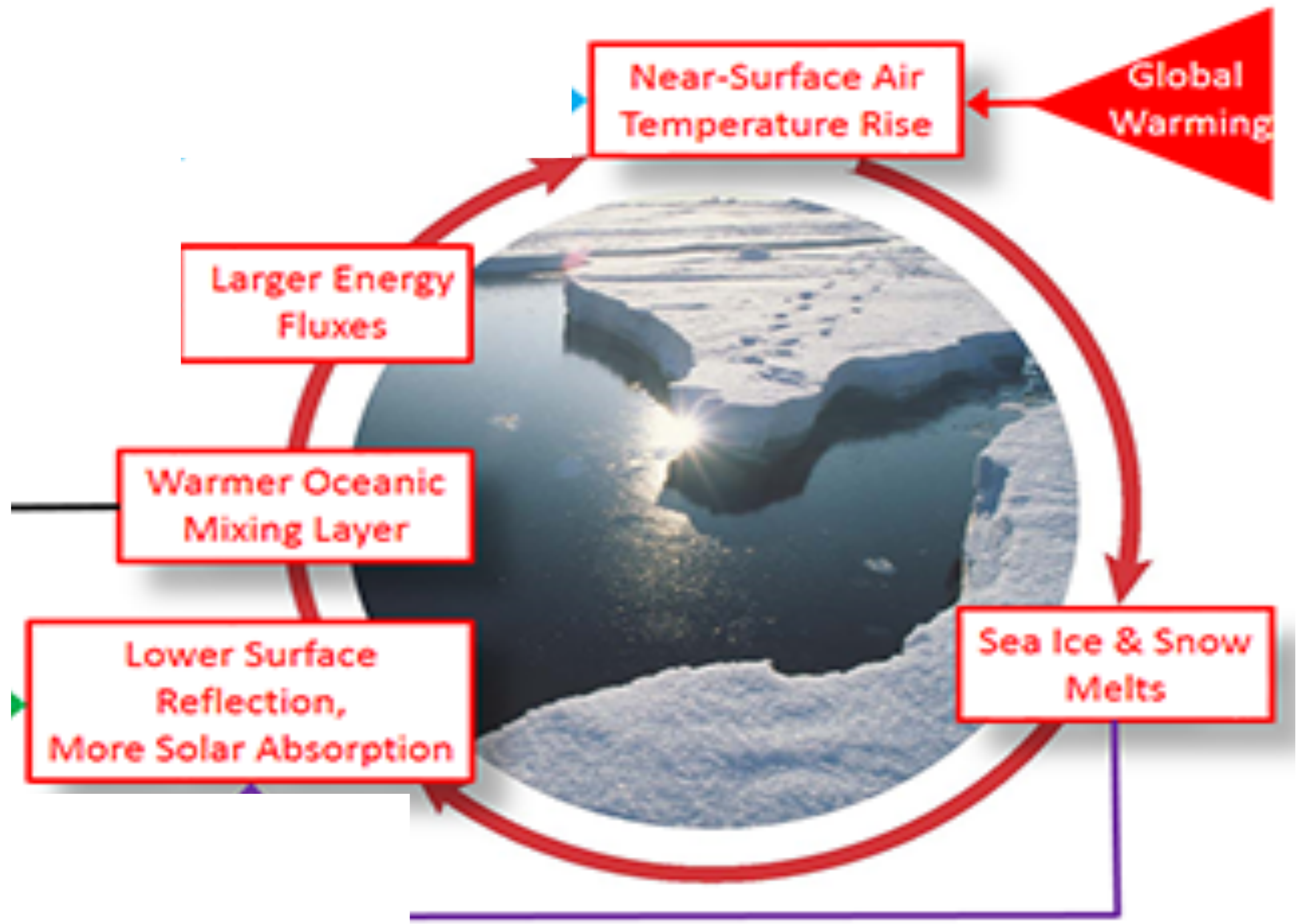


Fig. 2. Examples of feedback processes that amplify an initial near-surface air temperature rise caused by global warming. Red, surface albedo effect; blue, changes in north–south atmospheric and oceanic transport; black, effects of water vapor and clouds; green, effects of aerosol particles; purple, increased oceanic biological activity.

Source: Wendisch, M., et al. (2017), Understanding causes and effects of rapid warming in the Arctic, Eos, 98, doi:10.1029/2017EO064803. Published on 17 January 2017.

Observational evidence of a local source

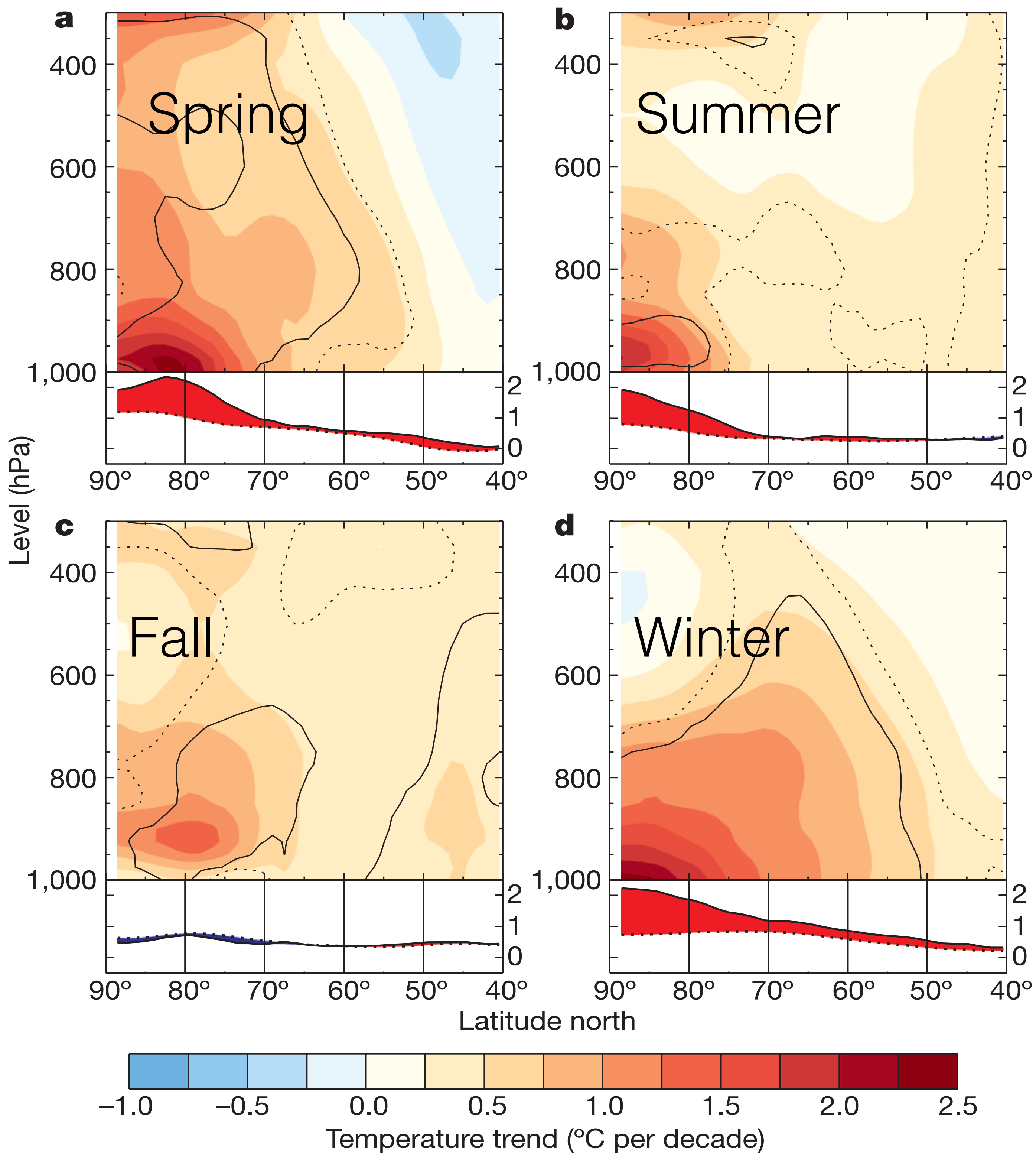


Figure 1 | Surface amplification of temperature trends, 1989–2008.

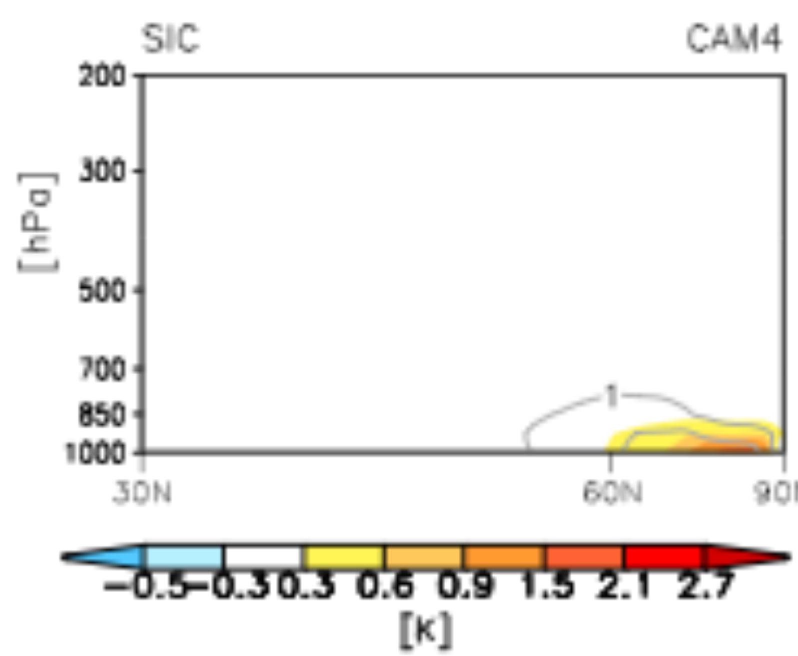
The bottom-heavy warming pattern may support the idea that the major driving force is surface turbulent heat flux caused by increasing ocean heat storage and sea ice decline

Source: Screen & Simmonds (2010, Nature)

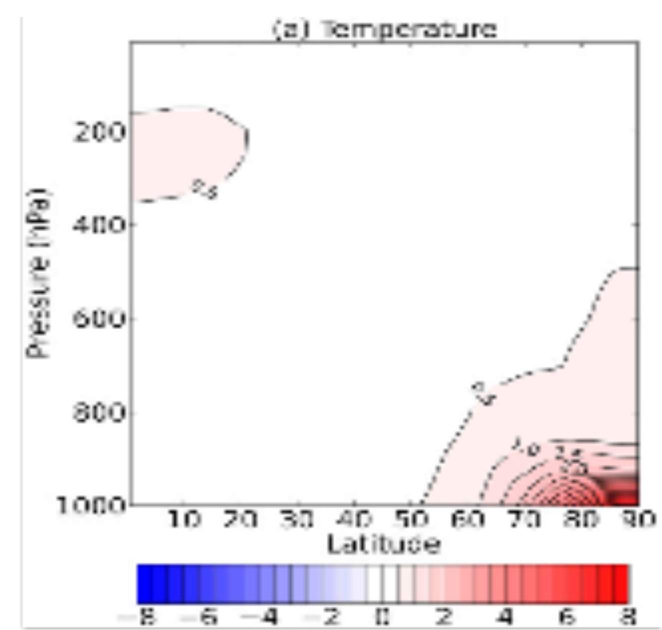
Modeling evidence of a local source

Approach: specify sea ice conditions to isolate the influence of sea ice on amplification

- Simulations with specified sea ice (Screen et al. 2012, Kumar et al. 2010, Screen et al. 2013, Perlwitz et al. 2015, Blackport & Kushner 2016…).
- They generally show a strong yet localized warming associated with sea ice removal.



Perlwitz et al. 2015

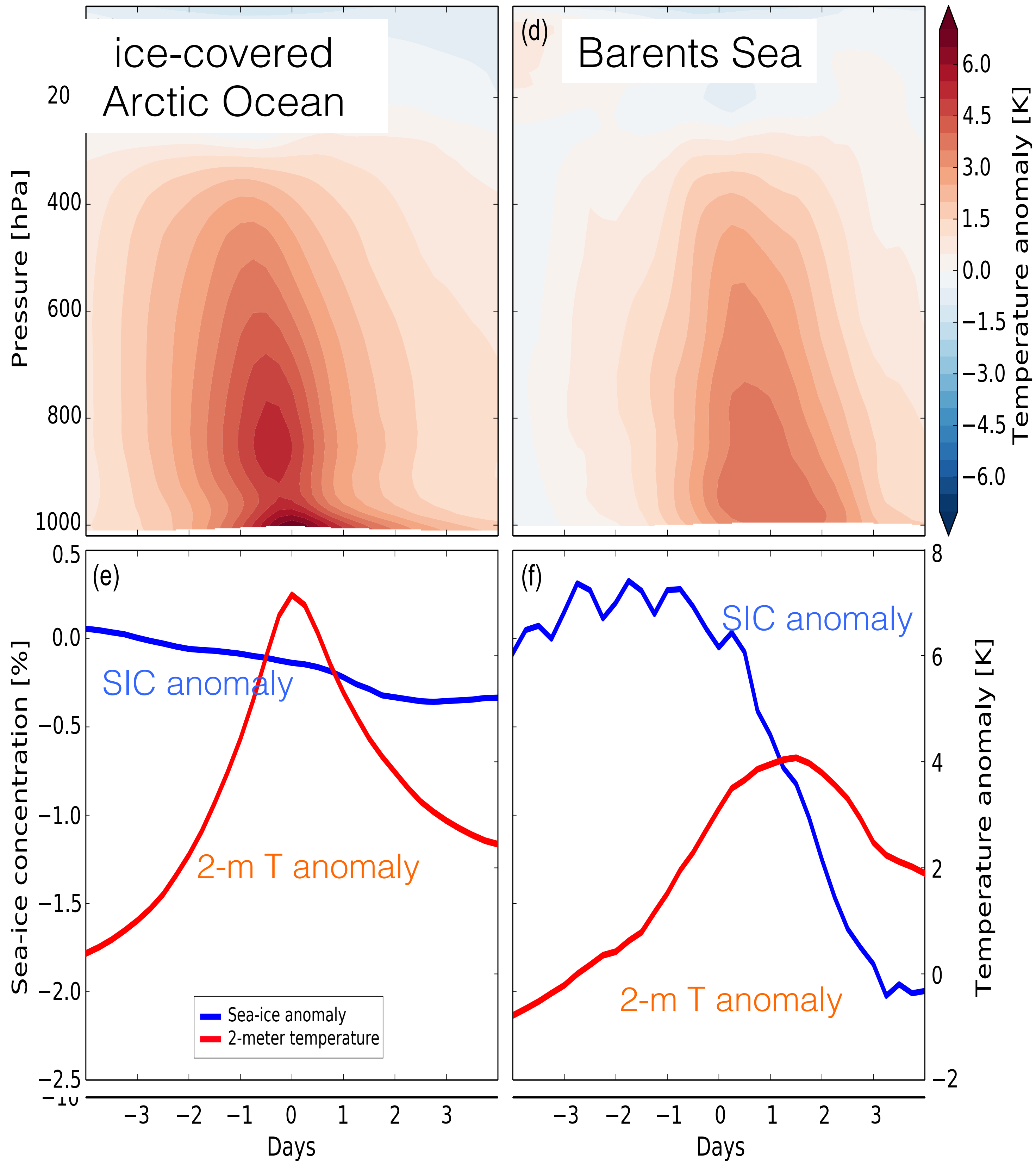


Blackport & Kushner 2016

Further question: What causes the sea ice to melt in the first place?

The bottom-heavy vertical structure is not necessarily caused by surface turbulent heat fluxes

Composites of moisture intrusion events: again, the temperature anomaly shows a bottom-heavy vertical structure.



Source: Woods & Caballero 2016
Data: 1990-2012 ERAI October-January

Similar findings by Park et al. (2015); Evaporation increases after the IR warming

The bottom-heavy vertical structure is not necessarily caused by surface turbulent heat fluxes

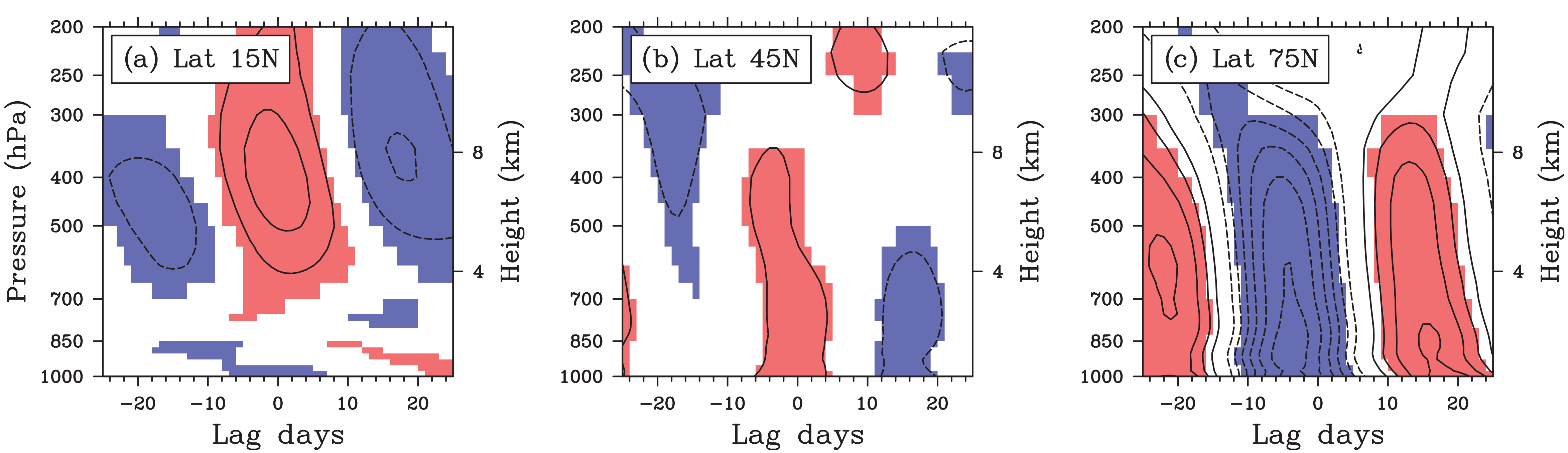


Figure 4. Lagged composites of zonal-mean temperature for MJO phase 5 events at (a) 15°N, (b) 45°N, and (c) 75°N. Solid contours are positive, dashed contours negative, and the zero contours are omitted. Contour interval is 0.1 K. Positive (negative) statistically significant ($p < 0.05$, for a two-sided Student t test) values are shaded in red (blue).

Source: Yoo et al. (2013)
Data: ERAI (1979-2011) November-March

The MJO is a remote source of Arctic variability, yet the surface temperature anomaly associated with the MJO shows a bottom-heavy vertical temperature structure.

Observational evidence of a local source: surface turbulent heat flux trend pattern matches the surface air temperature (SAT) & sea ice trend patterns

1989-2009 October-January trend of

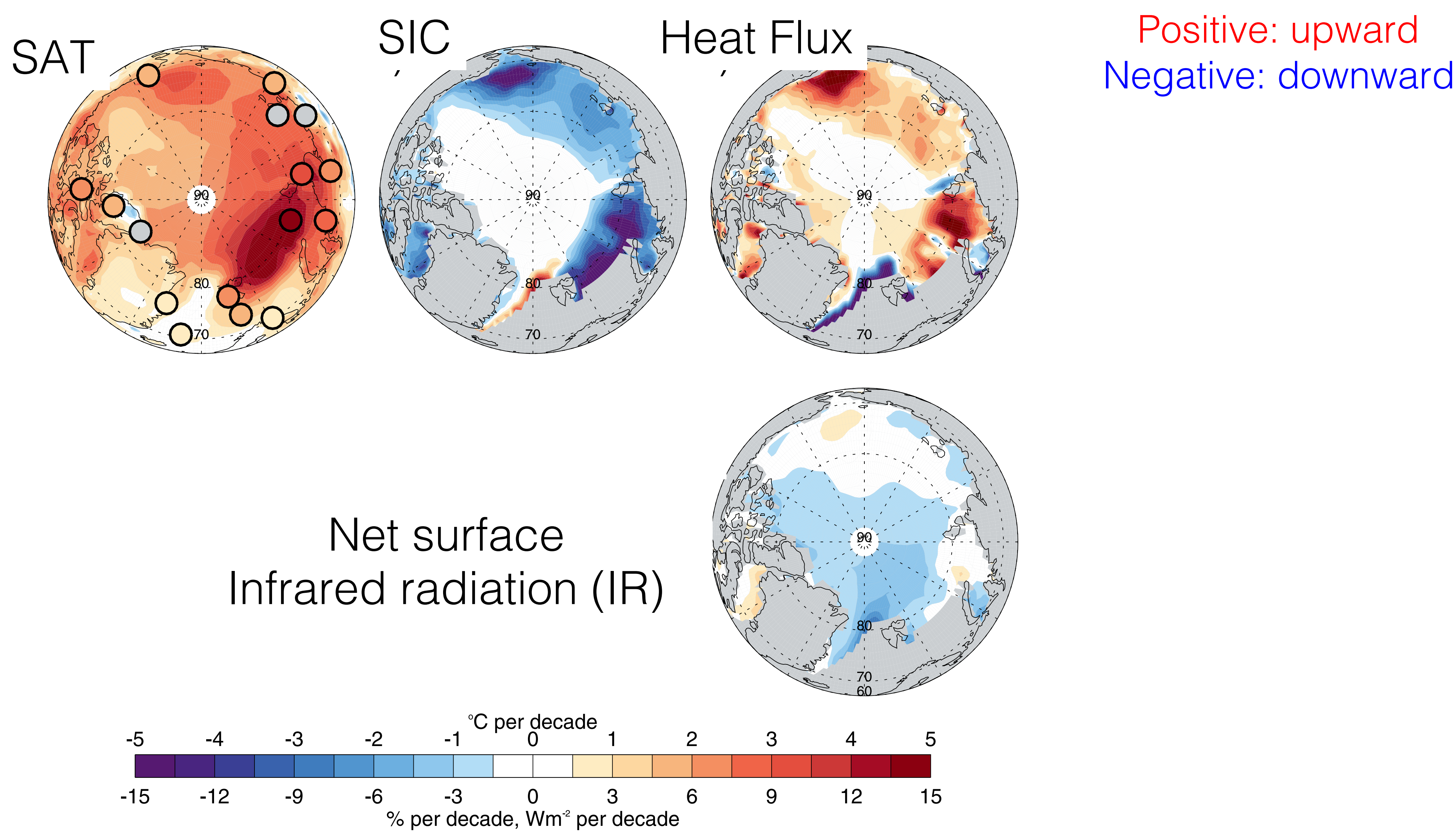


Figure 2. (a) Surface air temperature trends (°C per decade) during October–January, 1989–2009, from observations (colored dots) and from ERA-Interim (shading). Gray dots indicate insufficient data was available to calculate the trends. The corresponding trends in ERA-Interim for (b) sea ice concentration (% per decade), (c) surface turbulent heat fluxes (sensible plus latent), (d) surface sensible heat flux, (e) surface latent heat flux, and (f) net surface longwave radiation. The heat flux trends (Wm^{-2} per decade) are defined as positive in the upward direction.

Source: Screen & Simmonds (2011, GRL)

Is the net IR the best variable to look at?

Surface Energy Budget Analysis

Trend (Δ) of the Surface Energy Budget terms (Lesins et al. 2012)

$$\Delta G = \Delta I_d + \Delta I_u + \Delta F_{sh} + \Delta C$$

ΔG	ΔI_d	ΔI_u	ΔF_{sh}	ΔC
Storage (very small)	downward IR	upward IR	surface turbulence heat fluxes	conduction through ice

Expressing the upward infrared radiation (IR) as $-\varepsilon\sigma T_s^4$, the energy balance equation can be written as

$$\boxed{\Delta T_s = (\Delta I_d + \Delta F_{sh} + \Delta C - \Delta G)/(4\varepsilon\sigma T_s^3)}$$

Using the same ERAI data as Screen & Simmonds (2010), a very different conclusion can be drawn by analyzing the surface energy budget :

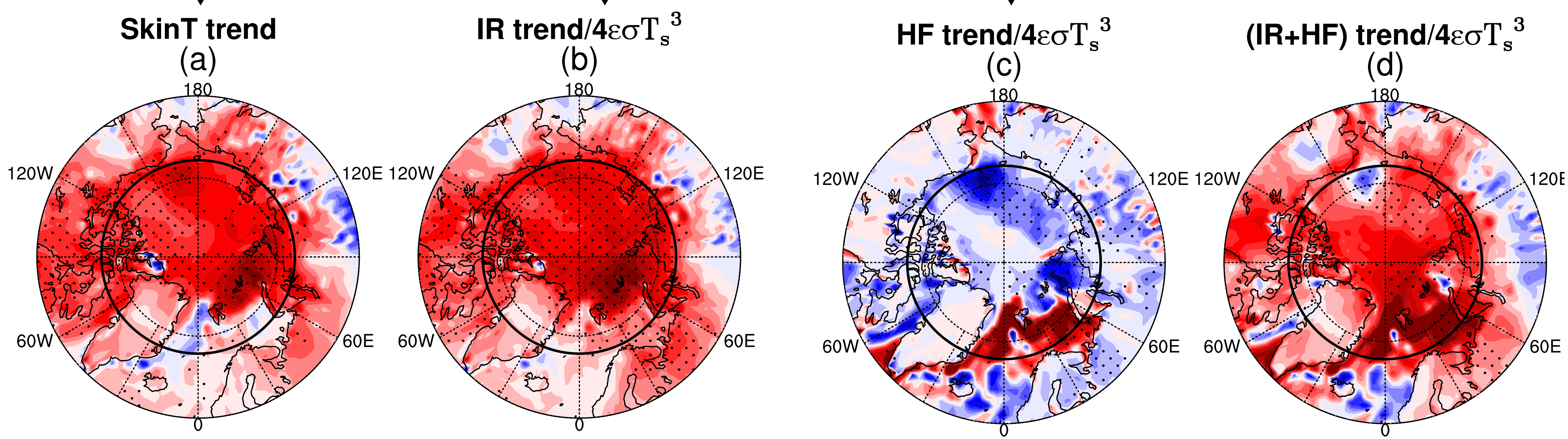
Downward IR trend is the dominant contributor

Downward IR trend pattern has an *e*-folding time scale of ~10 days (Park et al. 2015; Gong et al. 2017)

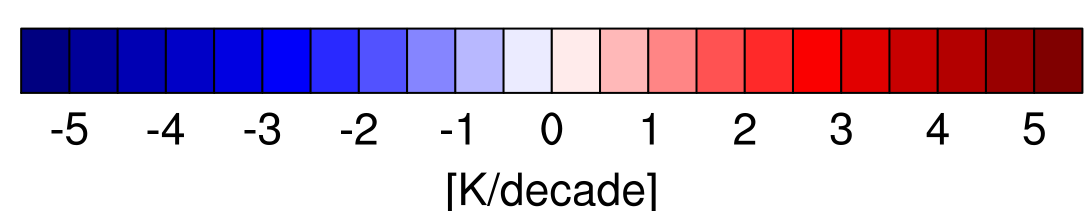
Skin temperature trend due to trend in downward IR

Skin temperature trend due to trend in surface heat flux

$$\Delta T_s \approx \Delta I_d/(4\varepsilon\sigma T_s^3) + \Delta F_{sh}/(4\varepsilon\sigma T_s^3)$$



October-December 1989-2009 trends
(ERA-Interim data)



Research on remote influence

Intra-seasonal

- Warm, moist air intrusion → downward IR (Doyle et al. 2011 & ~ 10 others)
- More intense and/or frequent intra-seasonal moisture intrusion events can contribute to long-term Arctic amplification (Doyle et al. 2011 & ~ 10 others)
- Moisture flux trend is mostly due to circulation change, and not due to moisture increase (Gong et al. 2017)
- Some papers in the above group also showed that a La-Nina-like tropical convection pattern plays a role (Lee et al. 2011 & ~8 others) through teleconnections (Rossby wave train)

Multi-decadal

- Equilibrium model run with an observed tropical SST anomaly generates warming in the Arctic (Ding et al. 2014).
- Local SST anomaly →Teleconnection is shown, but it's unclear what warms the Arctic surface

Climate change

- Theory & modeling: As climate warms, upper tropospheric equator-to-pole temperature gradient increases → enhanced poleward heat flux in the upper troposphere → increased downward IR (Cai 2005….)
- Enhanced moisture → enhanced poleward latent heat flux (Langen & Alexeev 2007)

Nonlinearity between local & remote processes

An example: remote processes during the preceding spring & winter could initiate/promote local feedback

Local process

- September Arctic sea-ice minimum predicted by spring melt-pond fraction; this is explained by a positive feedback mechanism: more ponds reduce the albedo → a lower albedo causes more melting → more melting increases pond fraction (Schröder et al. 2014)

Energy balance techniques to attribute amplification to different components

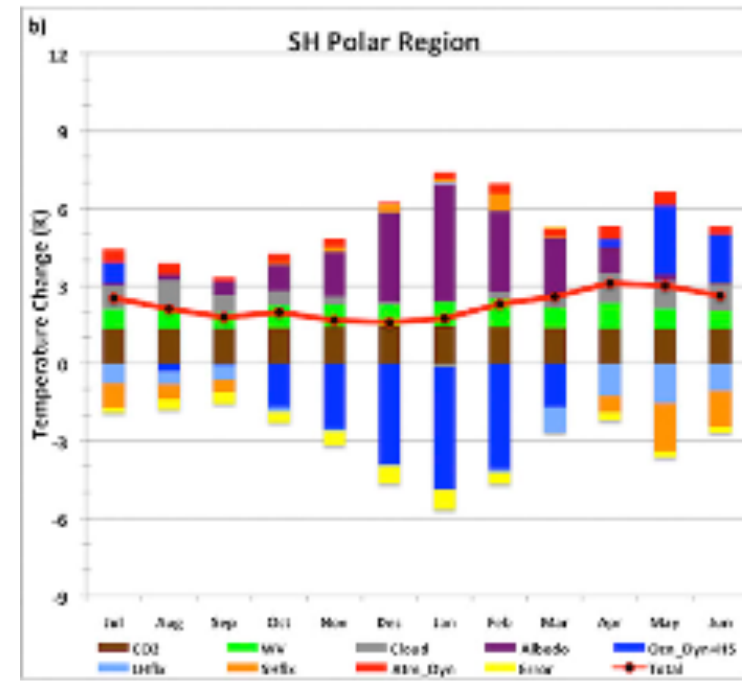
- Use energy balance arguments to determine which component dominates the Arctic energy balance. Some use simple 1-D energy balance models (Hwang et al 2013) and some use complex multidimensional techniques (Taylor et al. 2013).

- These analyses have been applied to the CMIP5 and are therefore portable methods (Hwang et al 2013, Pithan and Mauritian 2014).

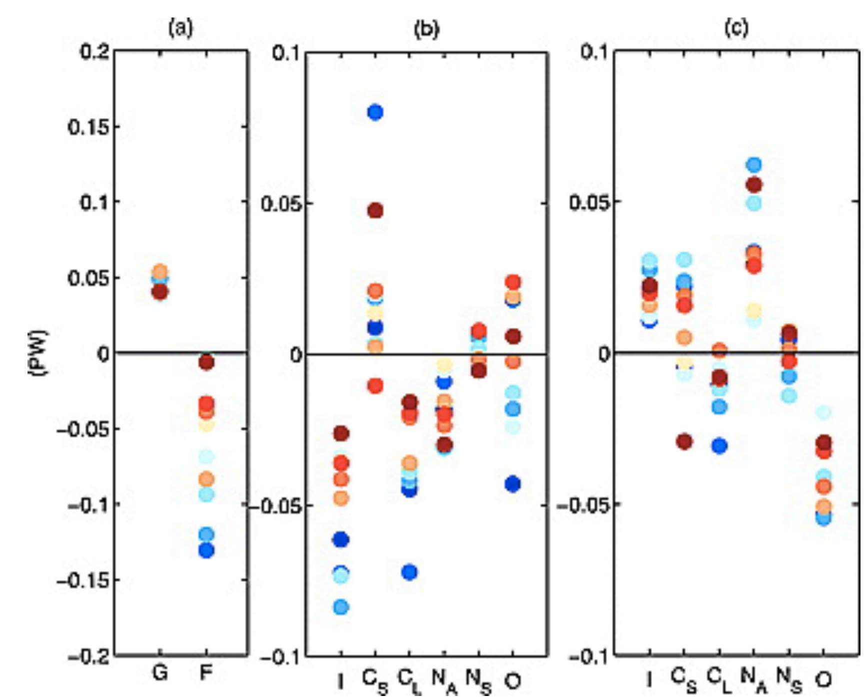
- These methods tend to emphasize the role of local mechanisms like the albedo, CO_2 and water vapor.

Advantage: quantitative analysis

Limitation: This method determins which terms in the budget have undergone the largest change in the context of a linear approximation. Therefore, the method is
1. unable to identify nonlinear interactions;
2. difficult to identify causality



Sejas et al. 2014



Hwang et al 2013

Concluding Remarks

- Arctic amplification is greatest during the winter & spring
- Surface energy budget analysis shows that the net surface IR trend is very small (1989-2009): Because the storage is very small, to balance the energy budget, the surface heat fluxes must also be small. This means that surface warming (which causes upward IR change) is mostly caused by downward IR.
- At least so far, for the cold season, remote atmospheric circulation appears to have played a major role; ocean circulation could also play a role, but direct evidence seems to be lacking (long-term average approach makes it difficult to establish cause & effect)
- As more sea ice melts, local processes (albedo, local evaporation, convection, surface heat fluxes) are expected to become increasingly important.
- Remote – local processes are intertwined nonlinearly; unlike the traditional view, at least so far, cold season processes seem to have a bigger impact on summer rather than the other way around; this may change in the future
- Interpretation: the effect of the climate change may be manifested by fast (intraseasonal) atmospheric circulation processes; do models represent relevant fast processes correctly? Deviation from multi-model mean is not necessarily due to internal variability.

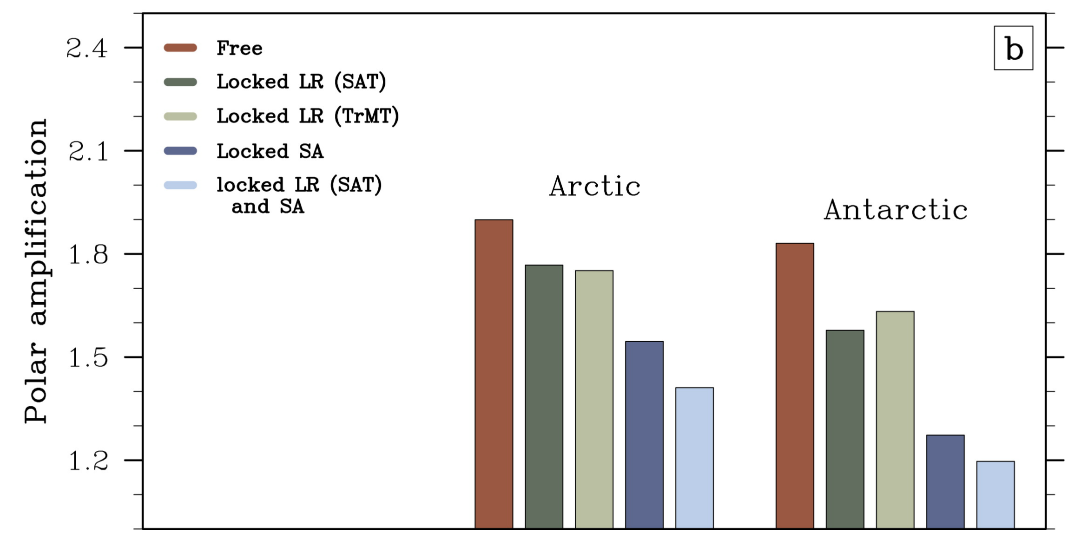
Extra slides from here

Mechanism denial methods to determine which feedbacks influences amplification

- Use either comprehensive or simplified models where some feedback mechanisms are denied.

- Examples of mechanisms are albedo feedbacks (Hall 2004, Alexeev et al. 2005, Graversen and Wang, 2009, …), radiative feedbacks (Langen et al. 2012, …), cloud feedbacks (Vavrus 2004, …), lapse rate feedback (Graversen et al. 2014).

- These approaches generally show a large local impact from these feedbacks on Arctic amplification.



Graversen et al. 2014

Observation-based evidences of remote influence 1986-2013 minus 1958-1985 (JRA-55)

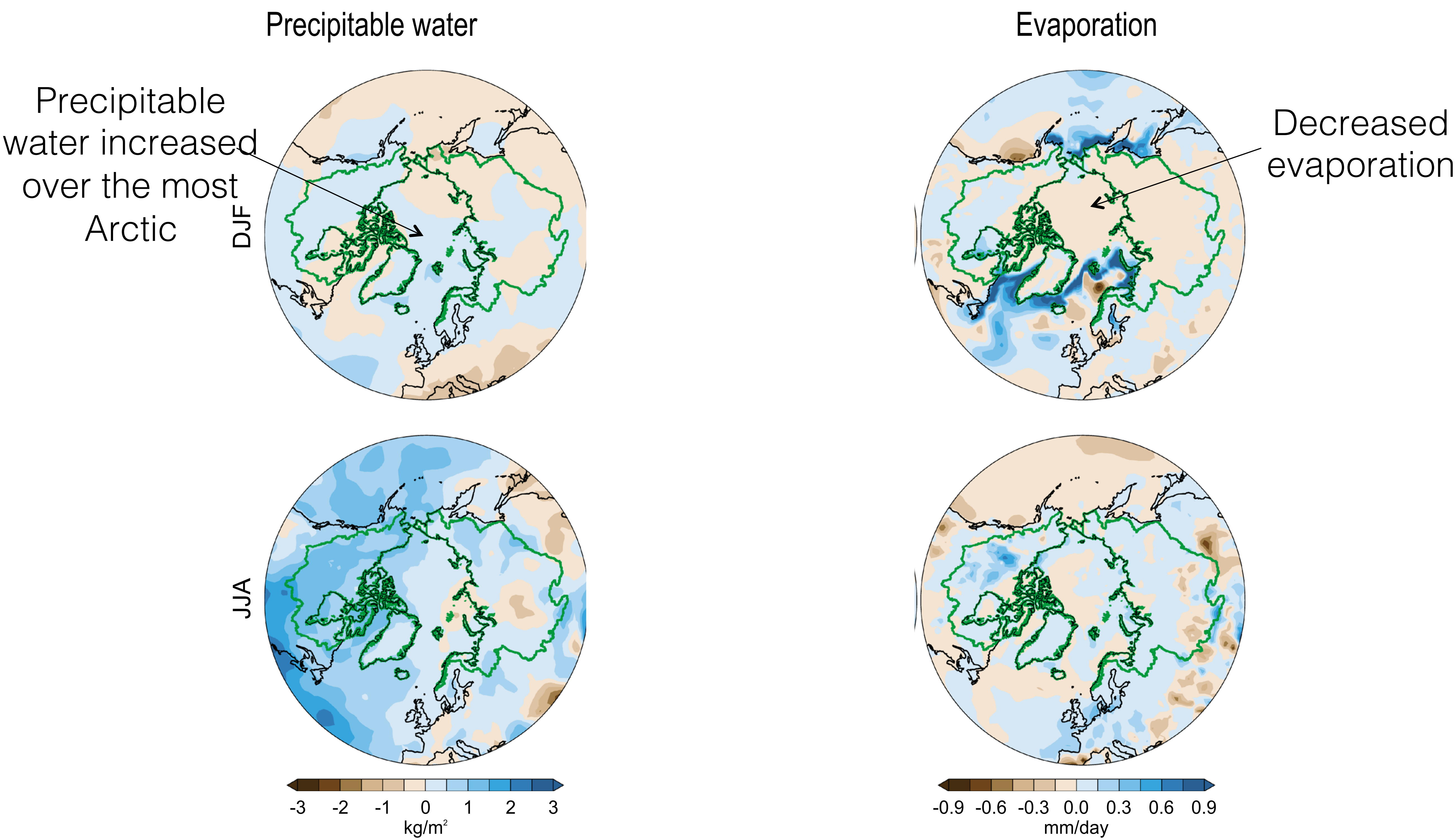
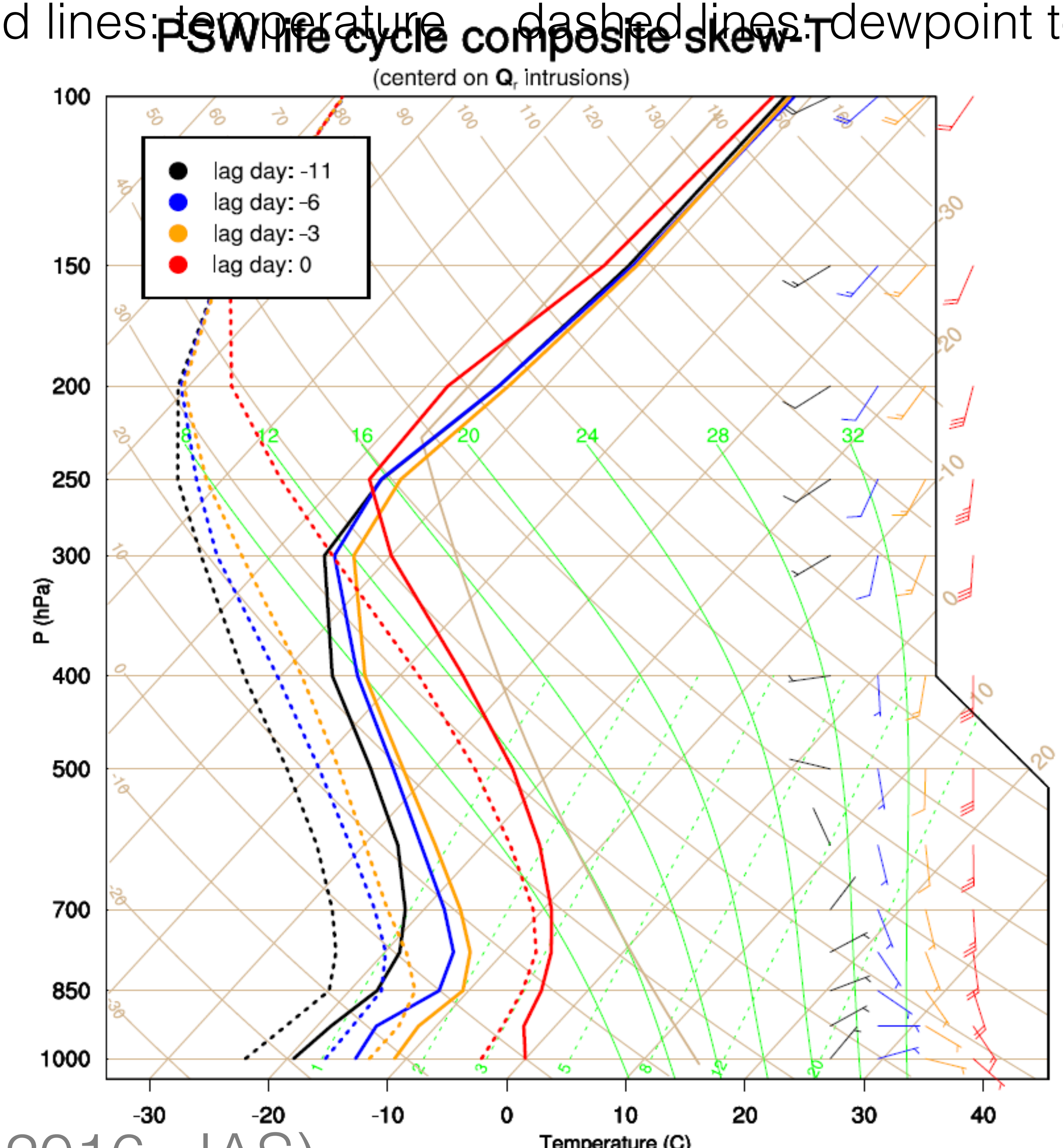


Figure 3. Epoch differences between 1986–2013 and 1958–1985 for precipitable water, precipitation, and evaporation on the basis of JRA-55 reanalysis for annual means, winter (DJF), and summer (JJA). The green lines indicate the boundaries of the Arctic river catchment.

Source: Vihma et al. (2015, JGR)

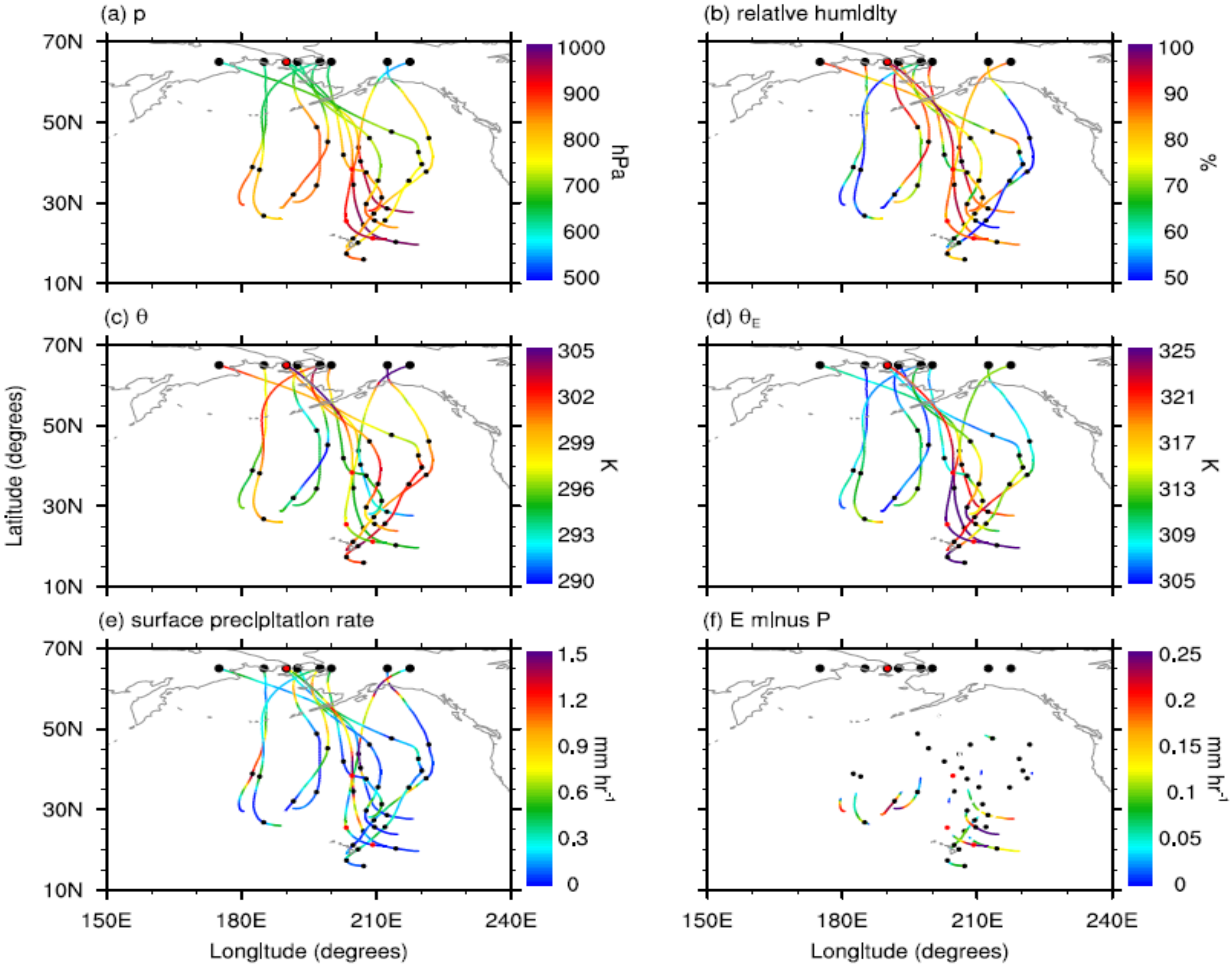
Composite skew T of moisture intrusions into the Arctic during PSW life cycle events

Solid lines: temperature   dashed lines: dewpoint temperature



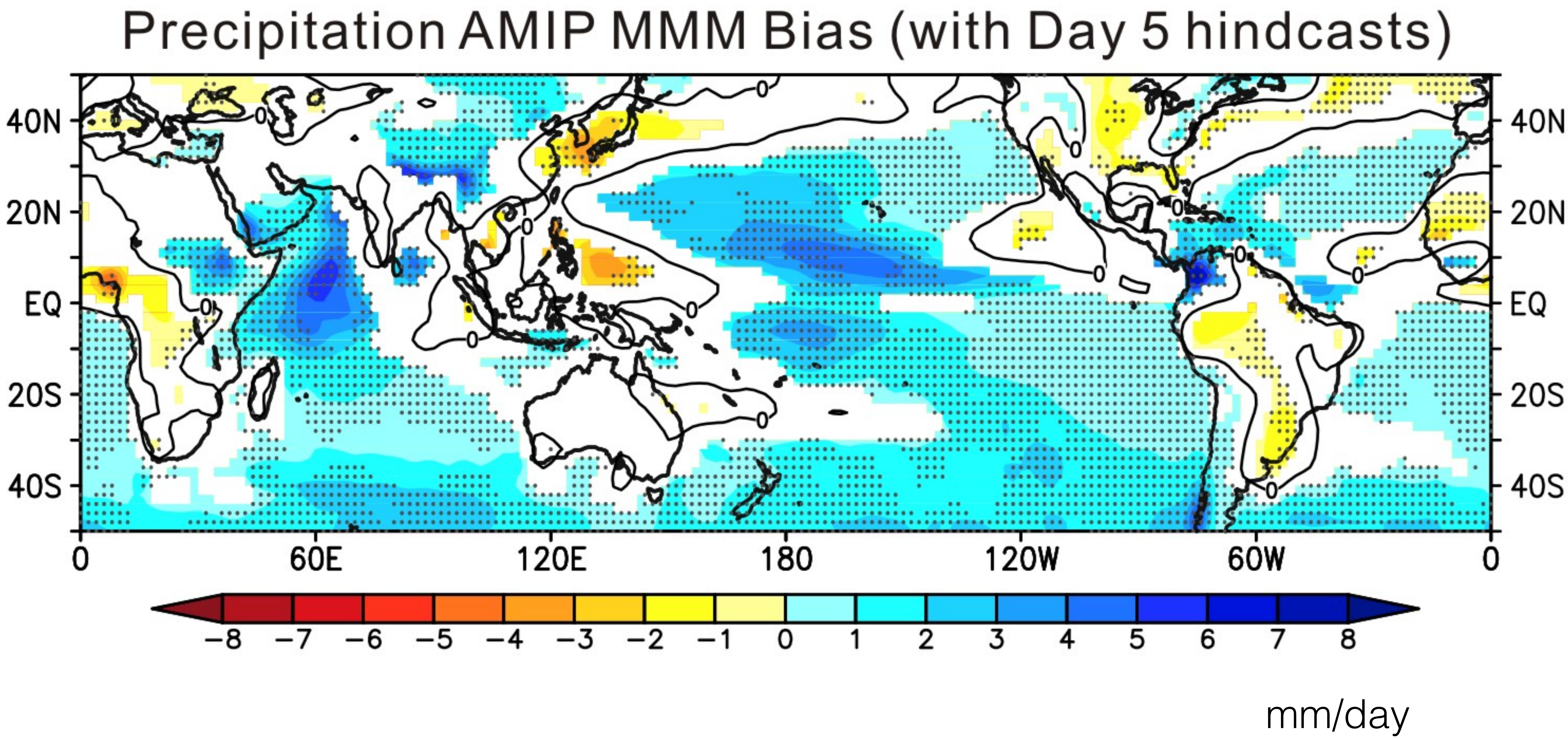
ggett et al. (2016, JAS)

Backward trajectories during PSW life cycle events



Baggett et al. (2016, JAS, in press)

CMIP5 Atmospheric models produce El-Niño-like bias

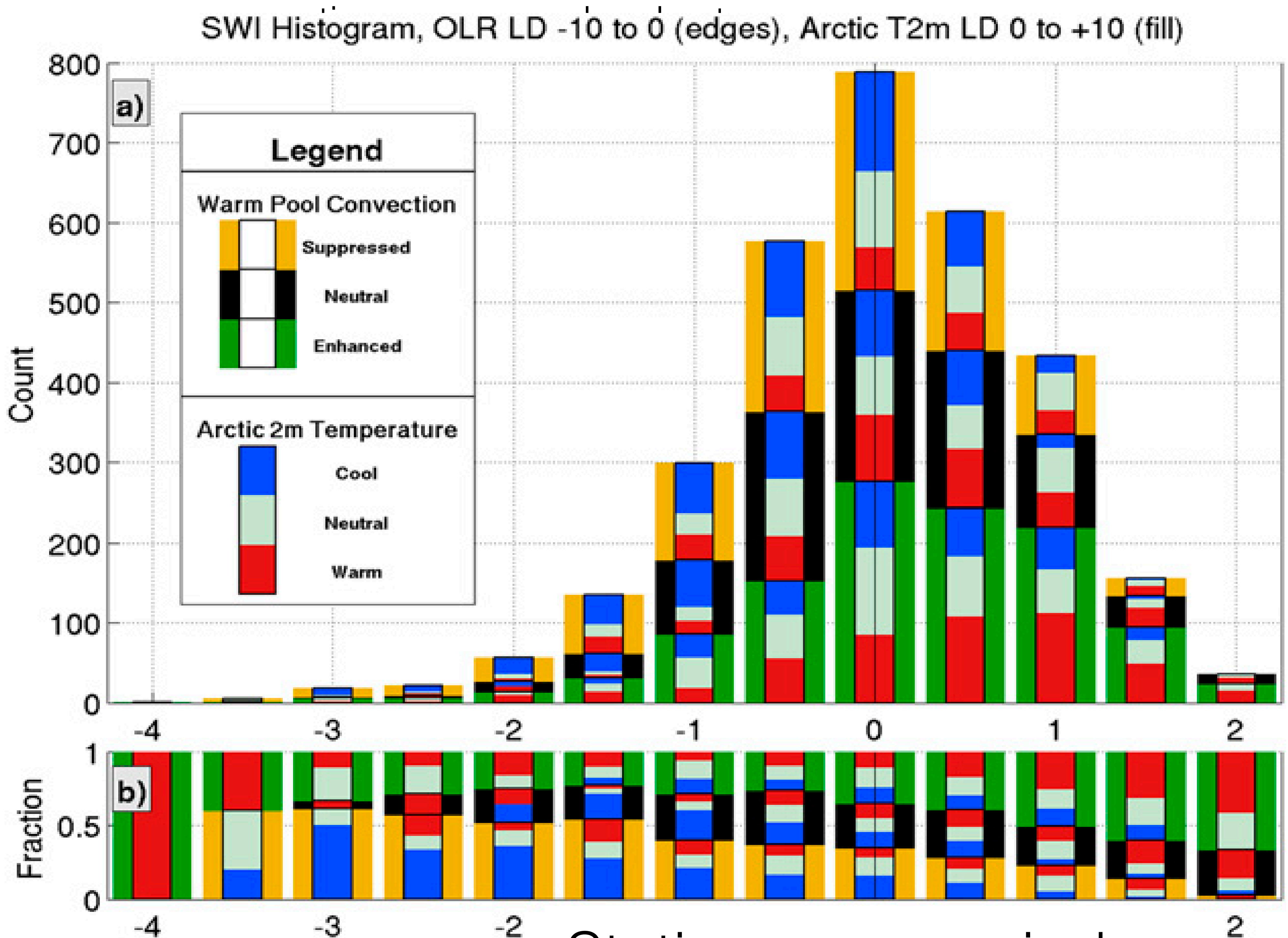


Ma et al. 2014, J. Climate

histogram of the daily stationary wave index

Stationary waves can intensify with suppressed warm pool convection;
Arctic warming can occur with suppressed warm pool convection:

But strong stationary wave events tend to occur when warm pool convection is enhanced, and Arctic warming is stronger when both stationary eddies & warm pool



Stationary wave index

oss et al. 2016)

1979-2012 winter sea-ice decline (Park et al. 2015a, J. Climate)

Method: $f \approx f(X_1, X_2, X_3, X_4) \rightarrow df/dt \approx \sum (\partial f/\partial X_n)(dX_n/dt)$

f: winter sea-ice concent-ration

$(\partial f/\partial X_n)(dX_n/dt)$	$(\partial f/\partial X_n)$	(dX_n/dt)
Contribution from X_n to the winter sea ice trend	linear regression between f and X_n	linear trend of each of the 4 variables

X_1: Autumnal Sea-ice Concentration

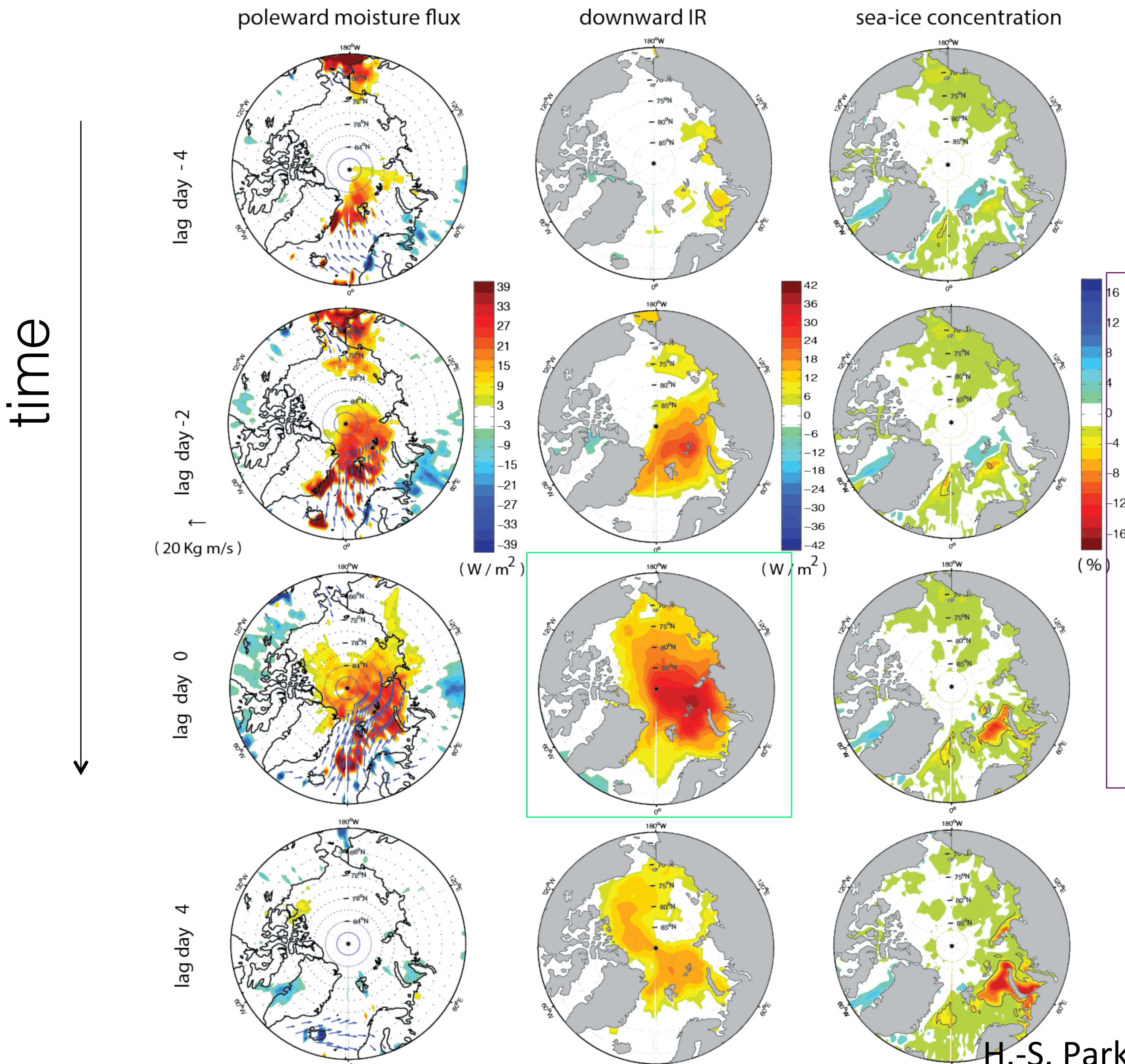
X_2: Sea surface Temperature

X_3: Sea surface Motion

X_4: Downward Infrared (IR) Radiation

Time-lagged composites based on downward IR events during DJF (1979-2012)

poleward moisture flux → downward IR → and sea-ice concentration



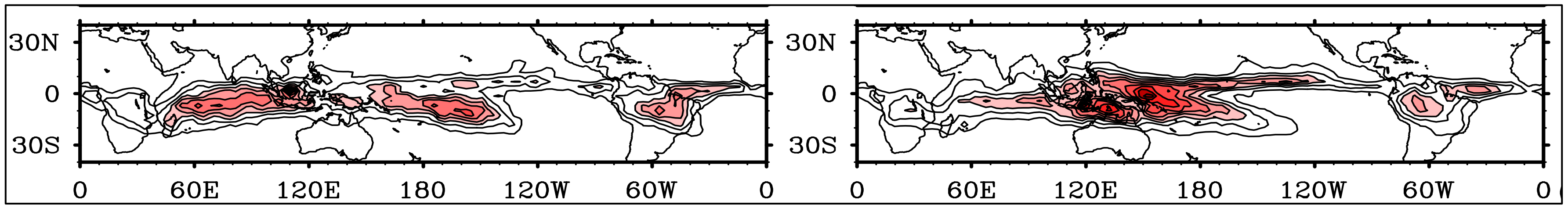
Intraseasonal Timescale Atmospheric Circulation can Melt sea ice Even during The dark winter

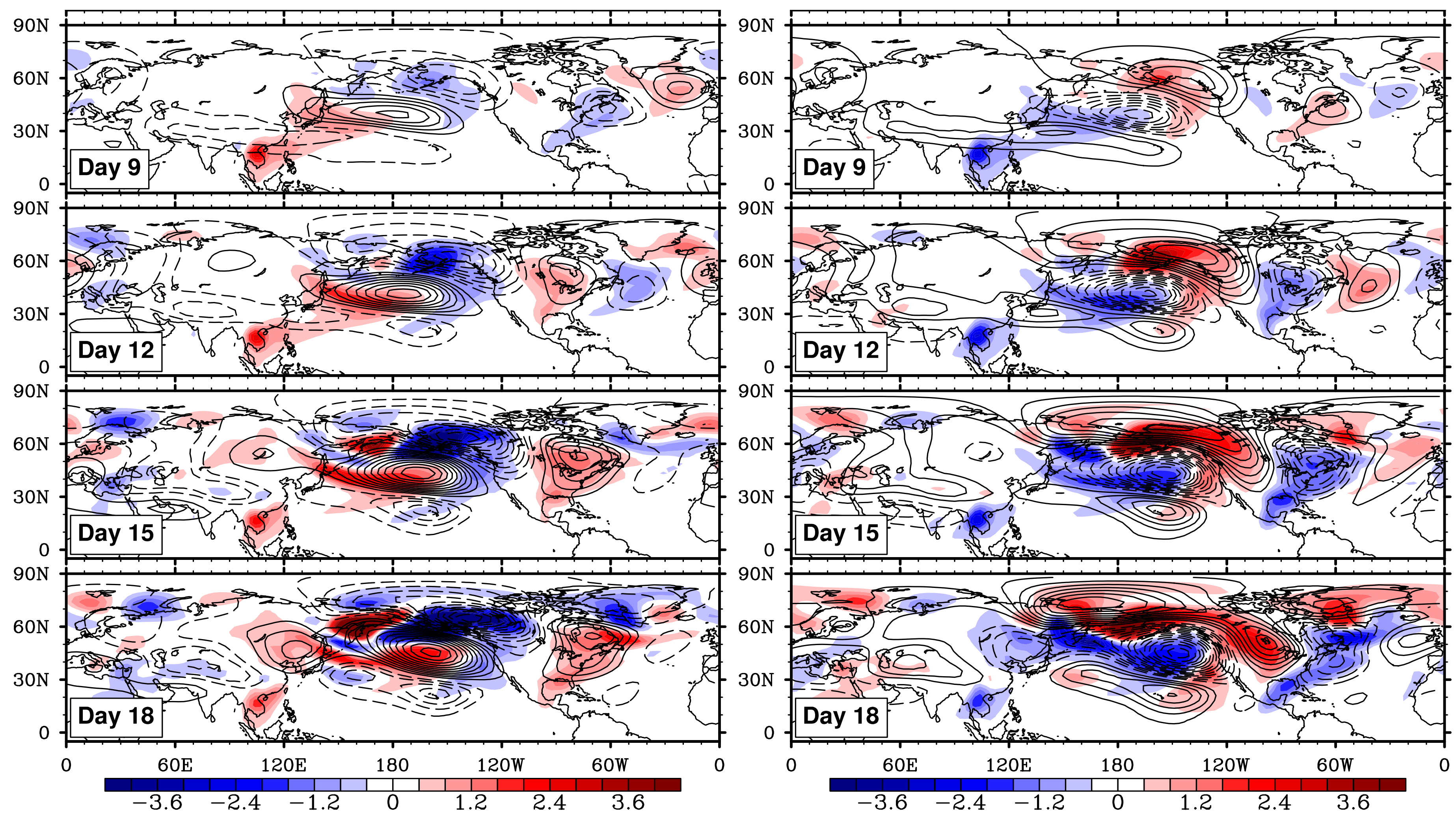
H.-S. Park et al. (2015b, J. Climate)

Testing the tropically excited Arctic warming mechanism (TEAM) using MJO
Initial-value calculations with a dynamical core: response to MJO-like heating

hPa stream function (contours) & surface air temperature (colors

MJO phase 1 MJO phase 5

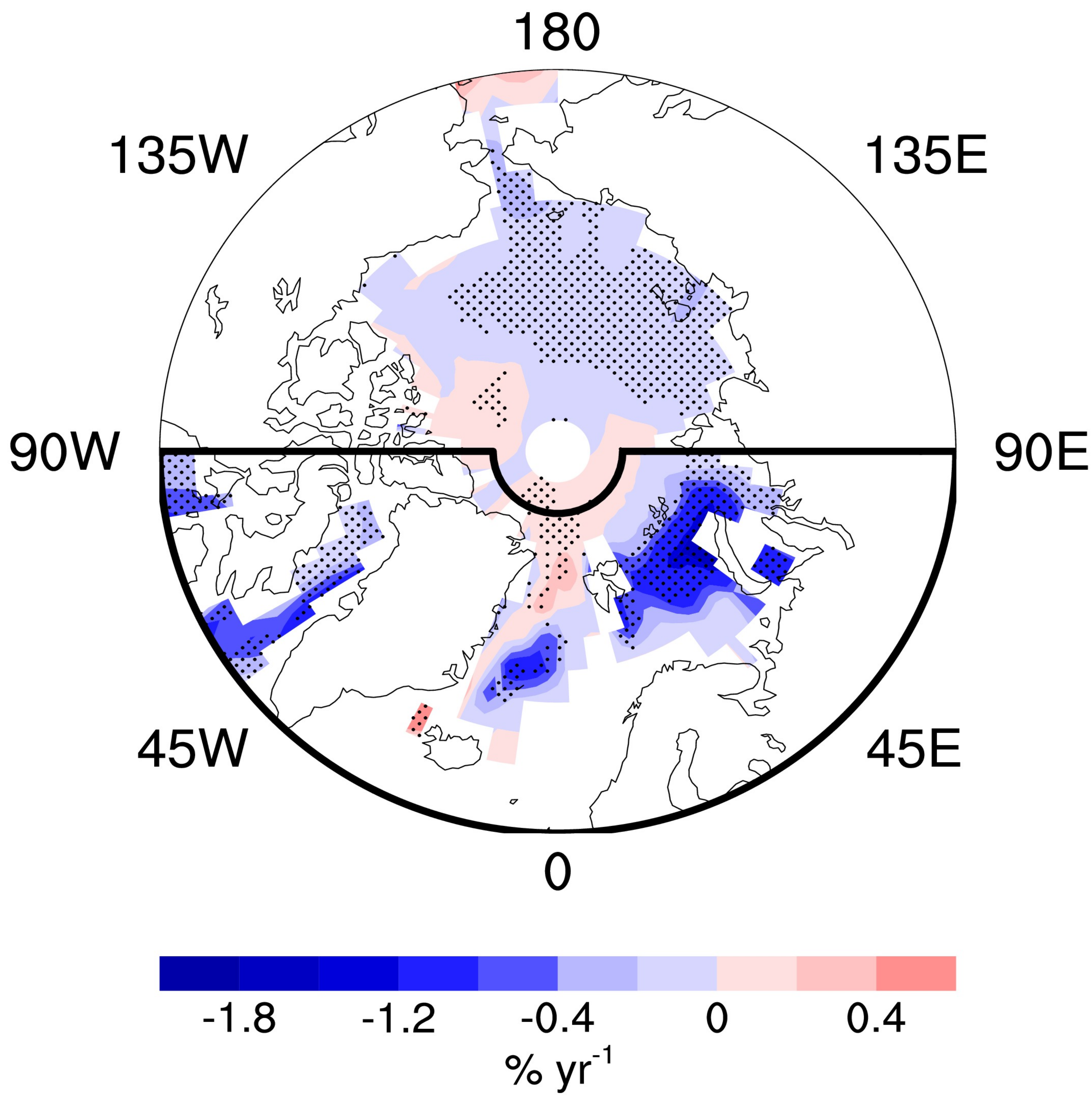




Zonally localized tropical heating produces high-latitude warming

Yoo, Lee, Feldstein (2012, JAS)

1979–2011 DJF sea-ice-concentration (SIC) trend
Data source: National Snow and Ice Data Center (NSIDC)

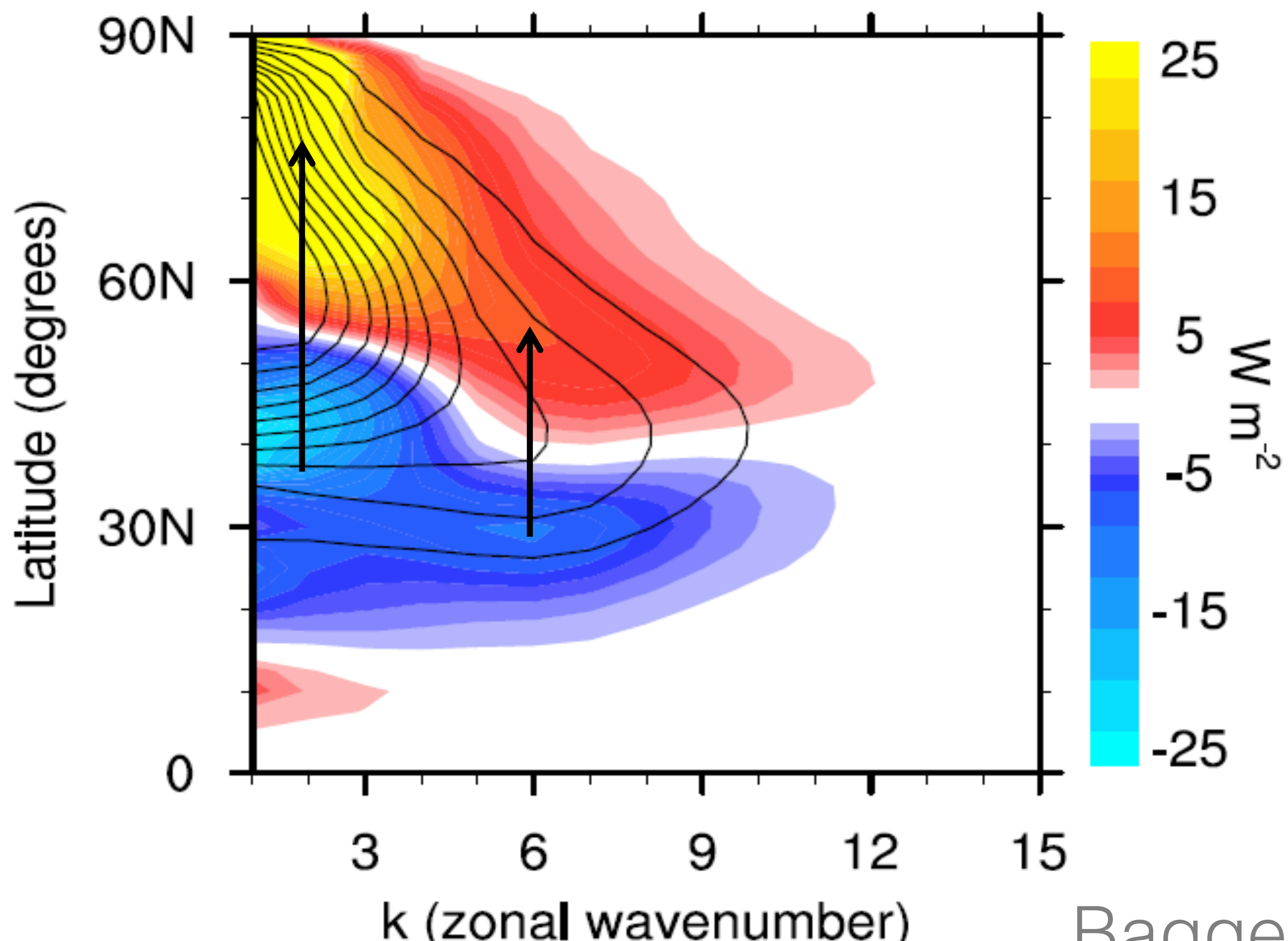


Park et al. 2015a, J. Climate

Poleward eddy heat flux & heat flux convergence

heat flux convergence into the Arctic is carried out mostly by planetary-scale (k = 1-3) waves

(ERA-Interim. 1979-2012 DJFM climatology)



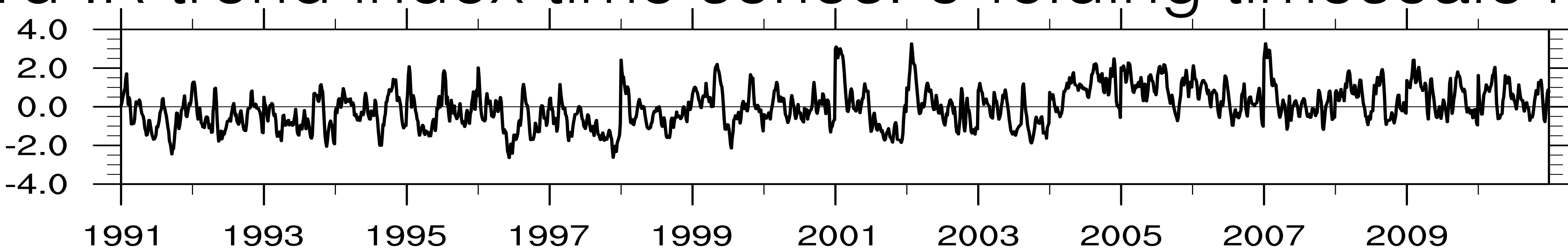
Baggett et al. (2016)

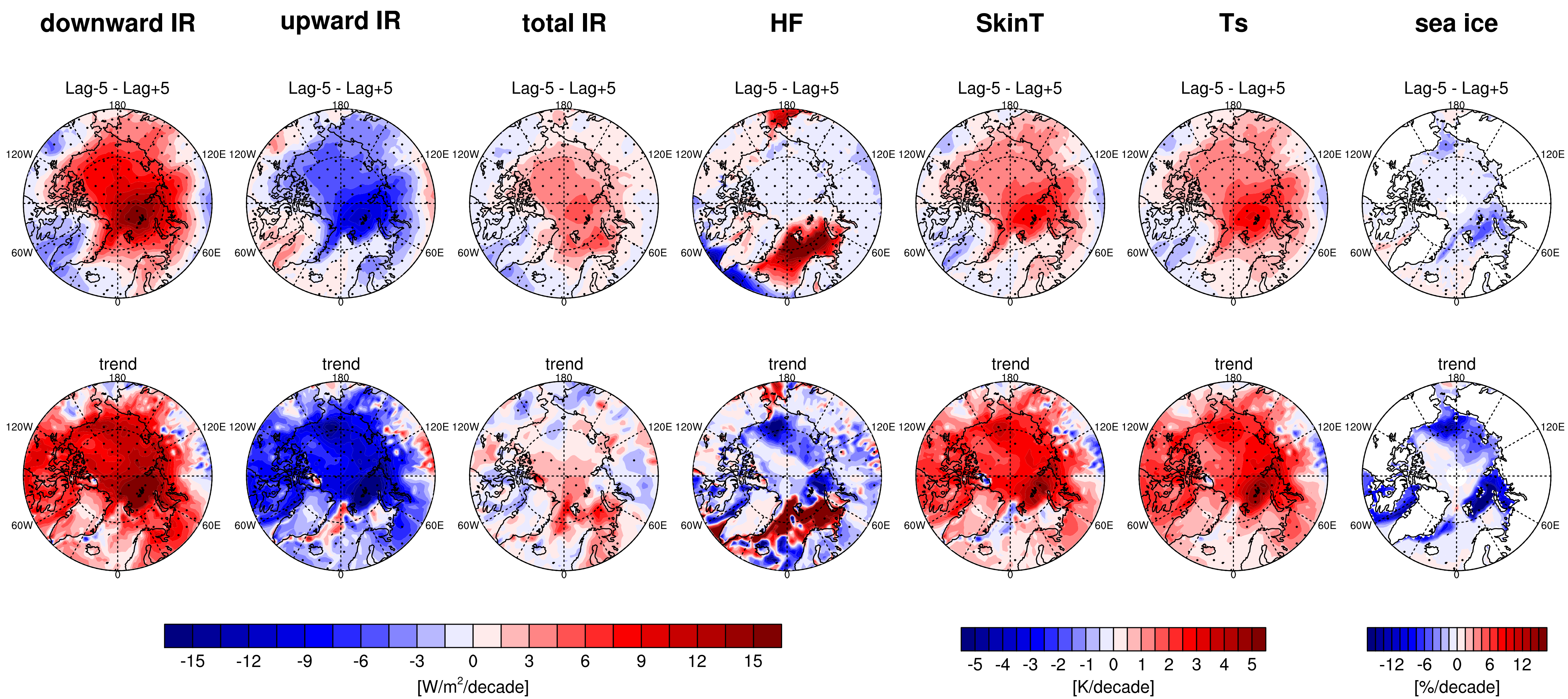
Intraseasonal time-scale moisture flux is a significant contributor to the downward IR trend

$$IR(\boldsymbol{x},t) = IR_{index}(t) IR_{trend}(\boldsymbol{x}) + \text{residual}$$ (from Feldstein 2003)

$$IR_{index}(t) = \left(\sum_{i,j} IR(\boldsymbol{x},t)\, IR_{trend}(\boldsymbol{x}) \cos\theta\right) / \left(\sum_{i,j} IR_{trend}(\boldsymbol{x})^2 \cos\theta\right)$$

ownward IR trend index time series: e-folding timescale is ~ 10 d




downward IR
upward IR
total IR
HF
SkinT
Ts
sea ice
Lag-5 - Lag+5
trend
180
120W
120E
60W
60E
0
-15 -12 -9 -6 -3 0 3 6 9 12 15
[W/m2/decade]
-5 -4 -3 -2 -1 0 1 2 3 4 5
[K/decade]
-12 -6 0 6 12
[%/decade]

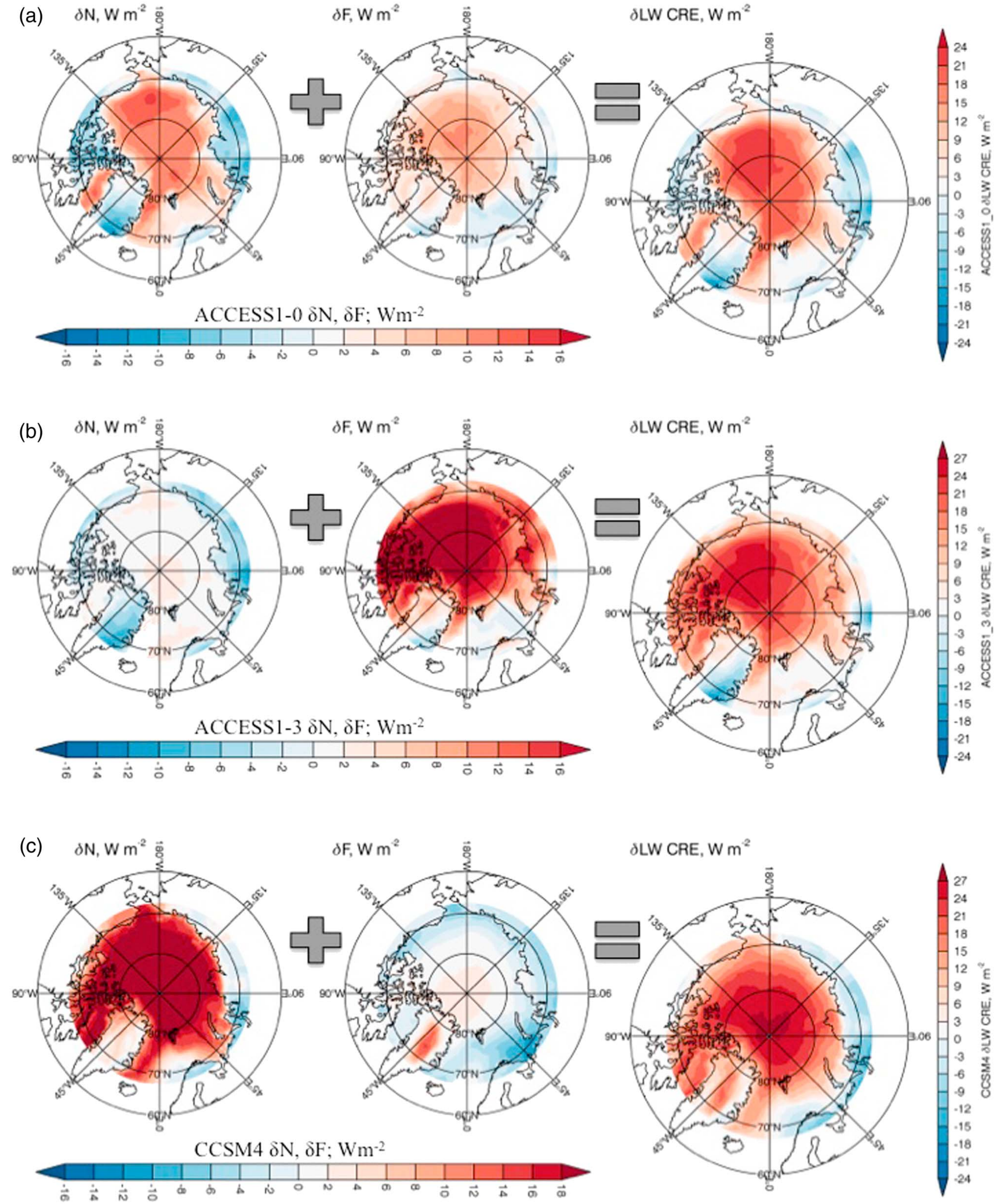


Figure 10. Spatial distributions of the LW CRE decomposition terms for (a) ACCESS1.0, (b) ACCESS1.3, and (c) CCSM4.

AGU PUBLICATIONS

JGR

Journal of Geophysical Research: Atmospheres

RESEARCH ARTICLE

10.1002/2016JD025099

Key Points:

- Significant regional variations are found in Arctic surface radiation biases
- Unrealistic compensation contributes to realistic simulation of seasonal cycle

Evaluation of the Arctic surface radiation budget in CMIP5 models

Robyn C. Boeke[1] and Patrick C. Taylor[2]

[1]Science Systems Applications Inc., Hampton, Virginia, USA, [2]Climate Science Branch, NASA Langley Research Center, Hampton, Virginia, USA

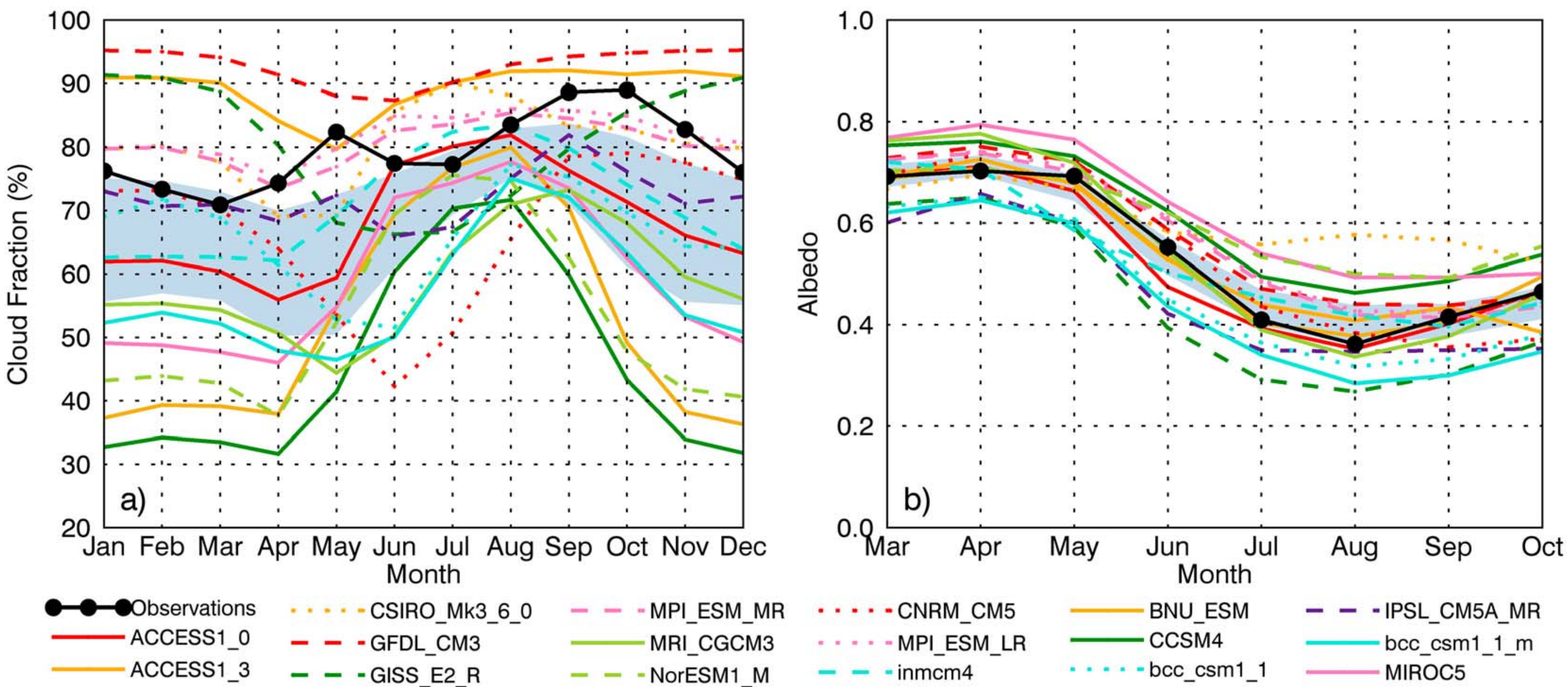


Figure 5. Arctic domain average—latitude > 66°N—seasonal cycle of (a) cloud fraction and (b) surface albedo from observations and CMIP5 models. Cloud fraction annual cycle is from the C3M data set using active remote sensing. Albedo annual cycle is from CERES SFC-EBAF. The grey shaded region is the 90% confidence interval for the difference in means between the models and CERES.