Climate response to projected Arctic sea ice decline

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Thanks to Svenya Chripko

AOS department seminars, McGill University, Canada

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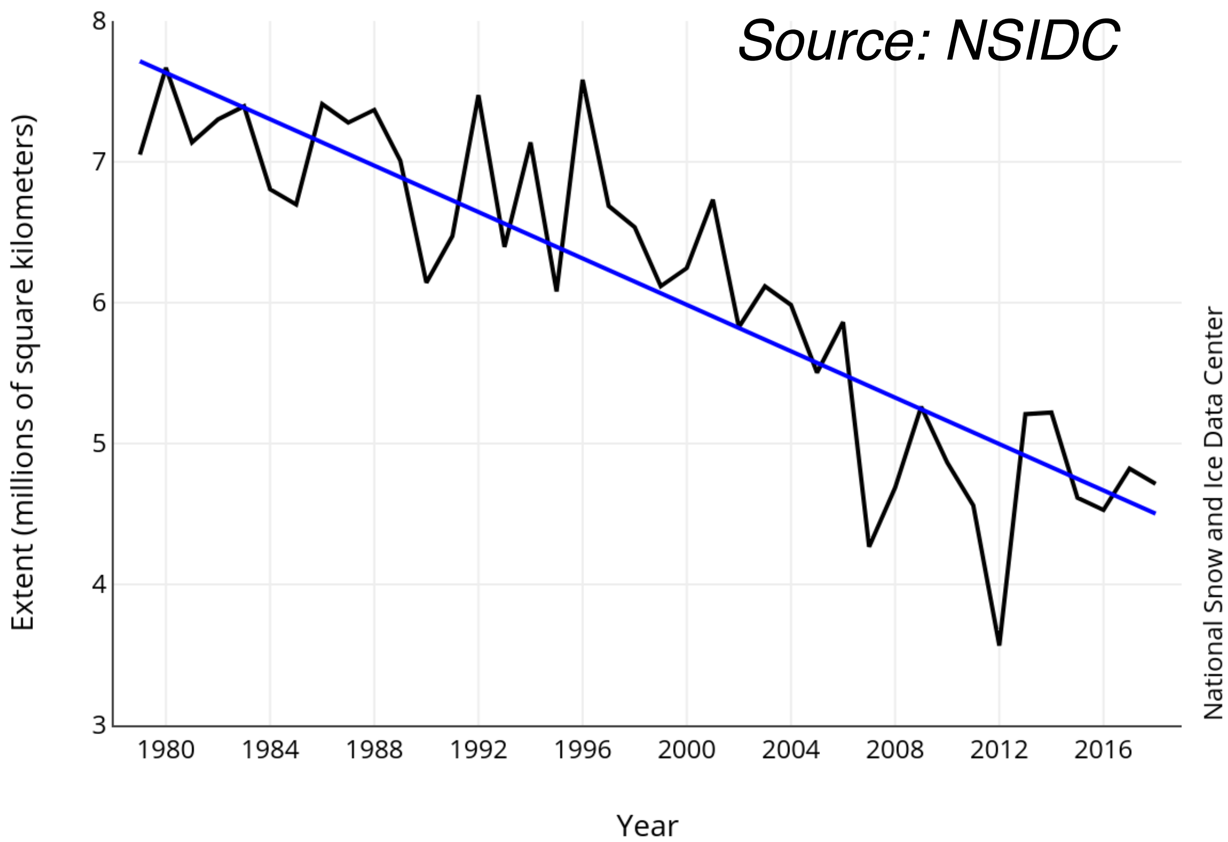
CERFACS

CNRS

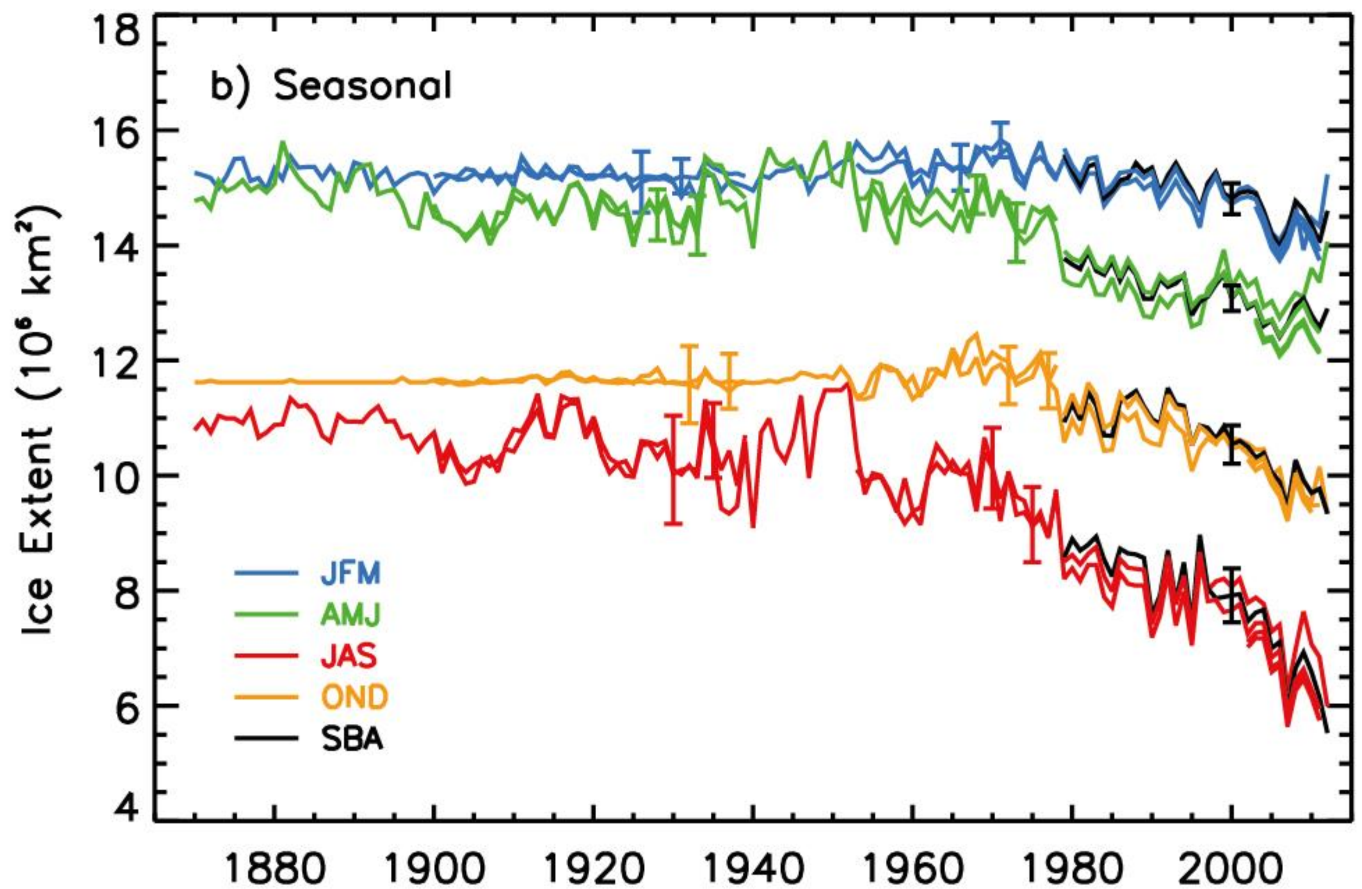
APPLICATE.eu
Advanced prediction in polar regions and beyond

Arctic sea ice in observations

September Arctic Sea Ice extent



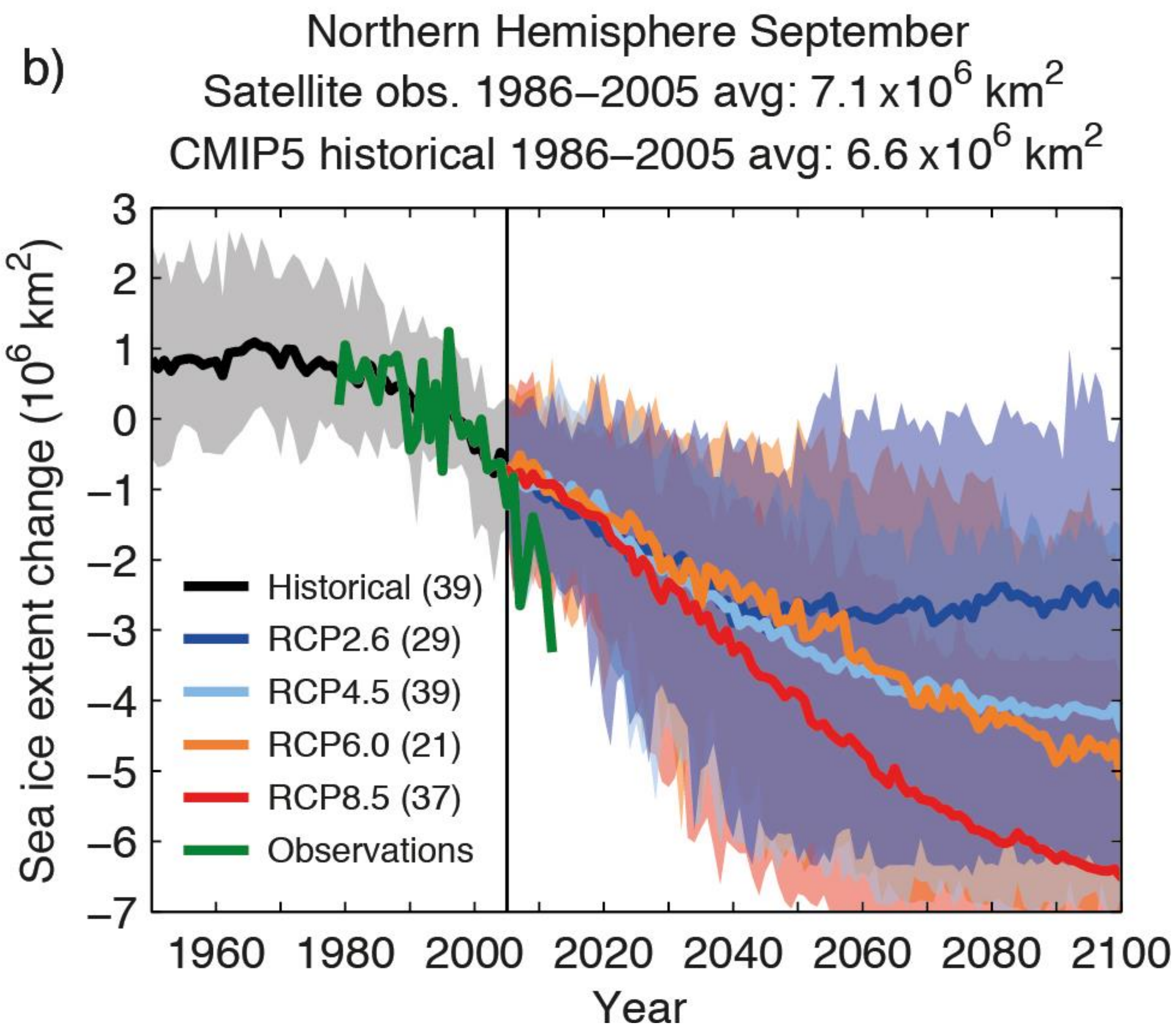
Seasonal Arctic Sea Ice extent in HadISST and Walsh and Chapman reconstruction (prior 1979) and satellite estimates (after 1979)



IPCC AR5 Working Group 1
Climate Change 2013: The Physical Basis

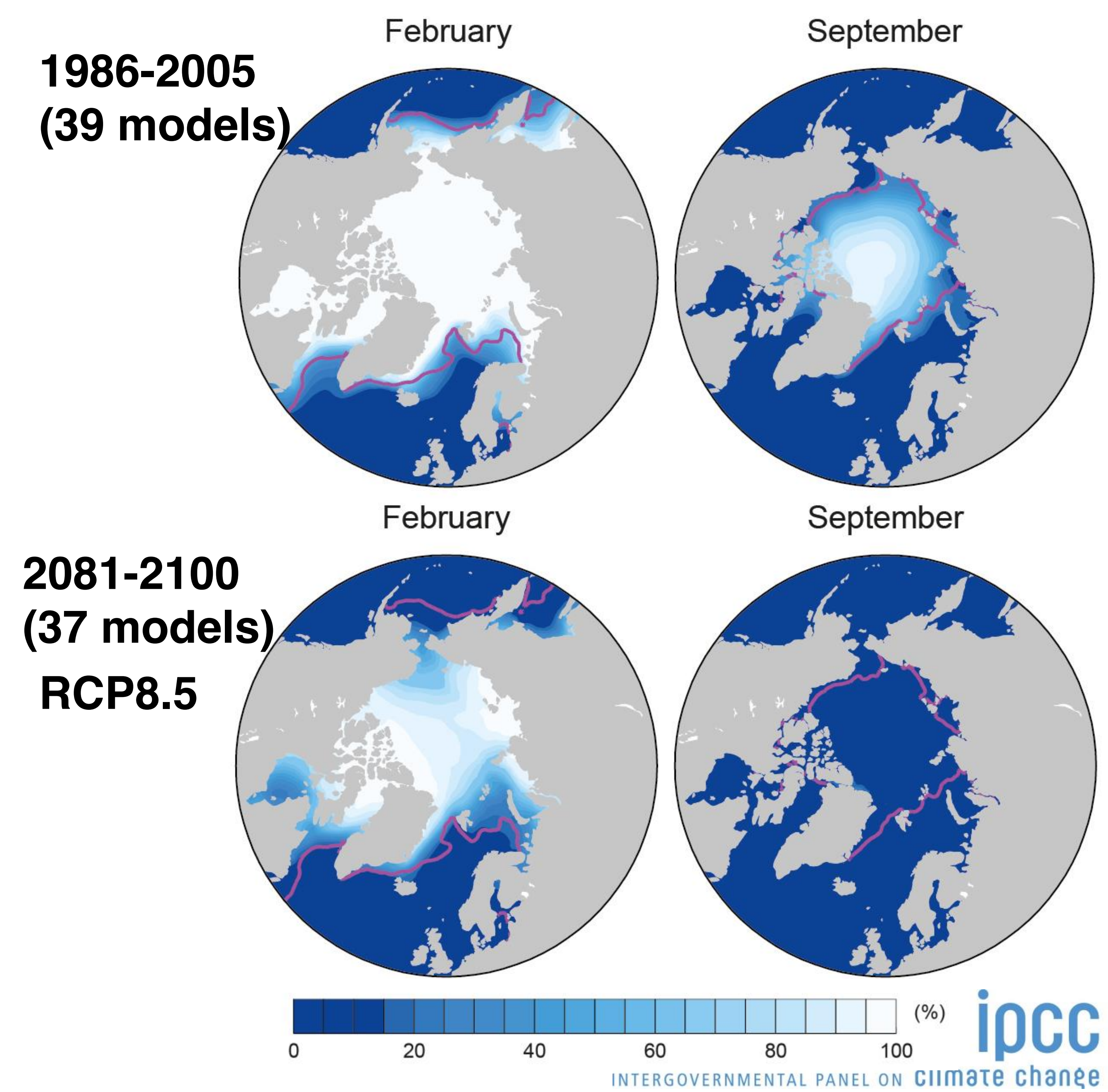
- **Summer Arctic sea ice has been declining by about 14% per decade since 1979 *(Stroeve et al. 2012)***
- **All seasons show a decline even though it is less pronounced in winter**

Arctic sea ice in climate projections



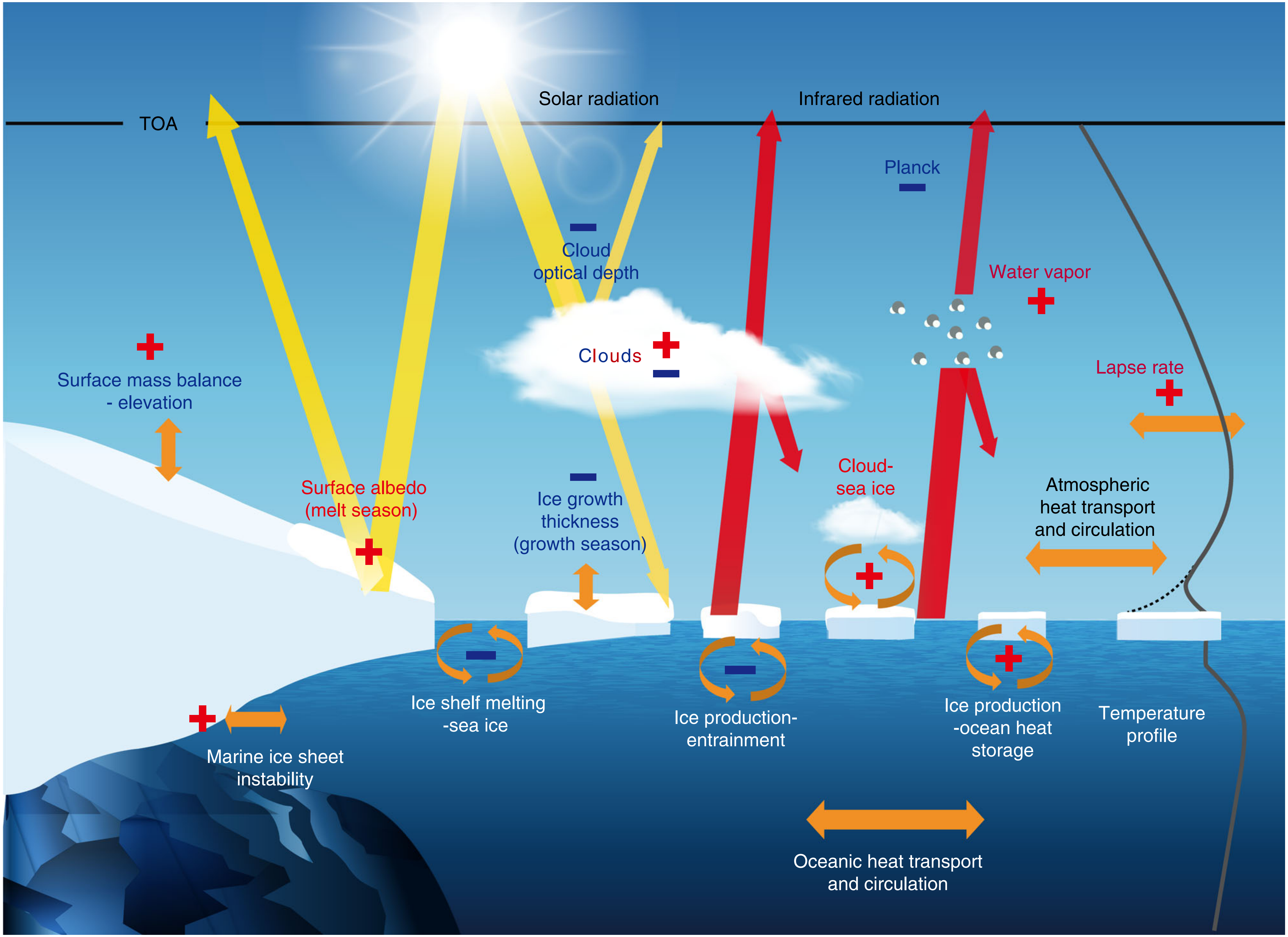
IPCC AR5 Working Group I
Climate Change 2013: The Physical Science Basis

Multi-model mean Arctic sea ice concentration



High probability of having ice-free summers by 2100

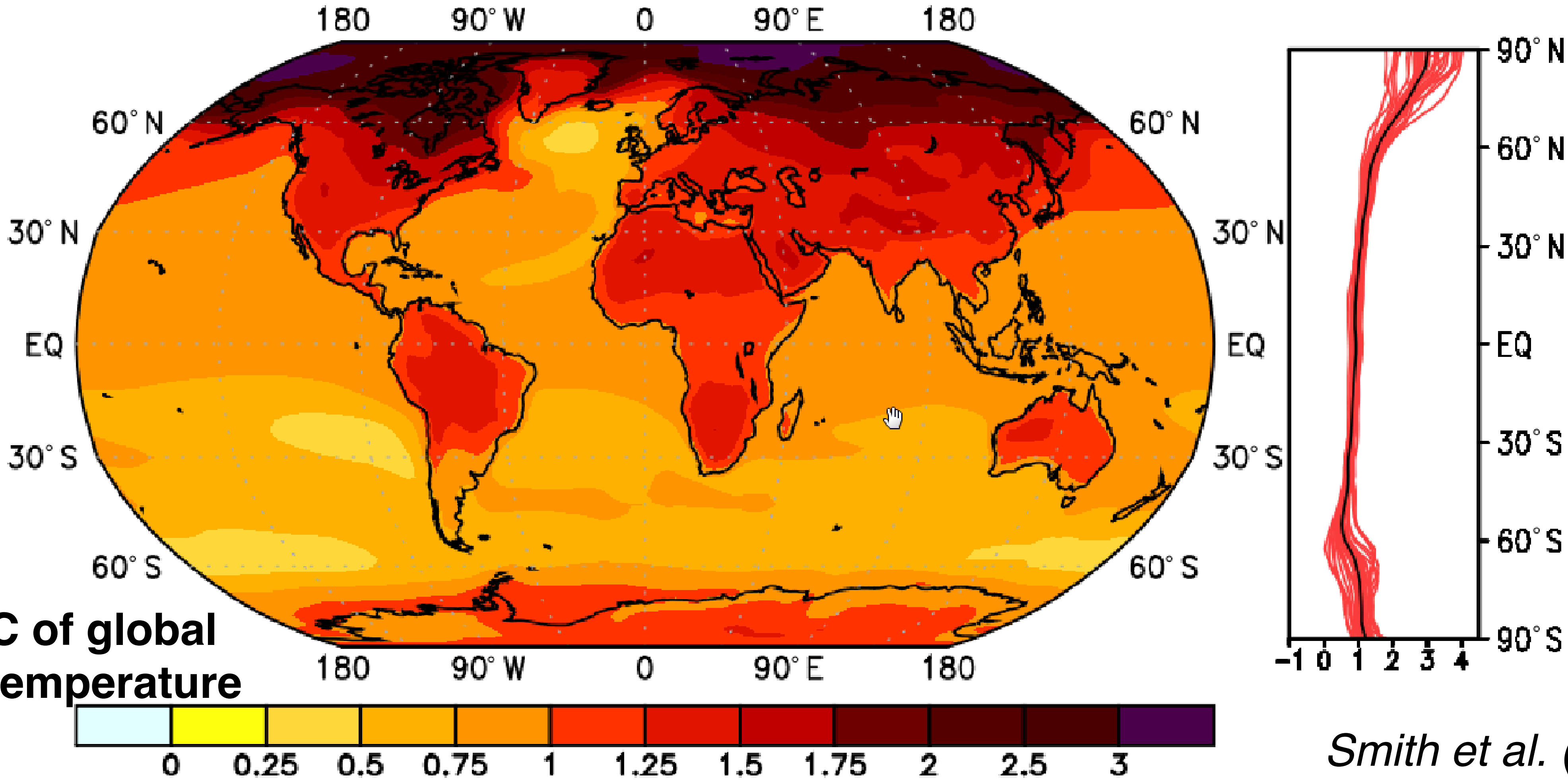
Sea ice at the heart of important local feedbacks



Goosse et al. (2018)

Polar amplification

Temperature change in CMIP5 models : difference between end of 21st and 20th century (RCP8.5) normalized by the global average temperature change



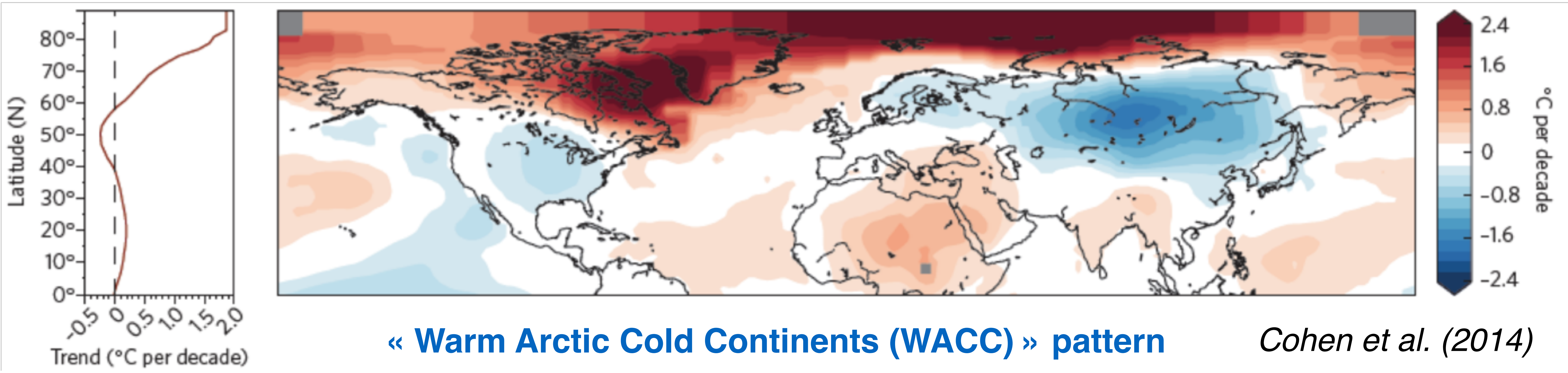
°C per 1°C of global average temperature change

Smith et al. (2019)

- **Arctic amplification is a robust feature of climate model projections.**
- **Magnitude and mechanisms remain uncertain. Role of sea ice ?**

Role of sea ice decline in observed midlatitude trends

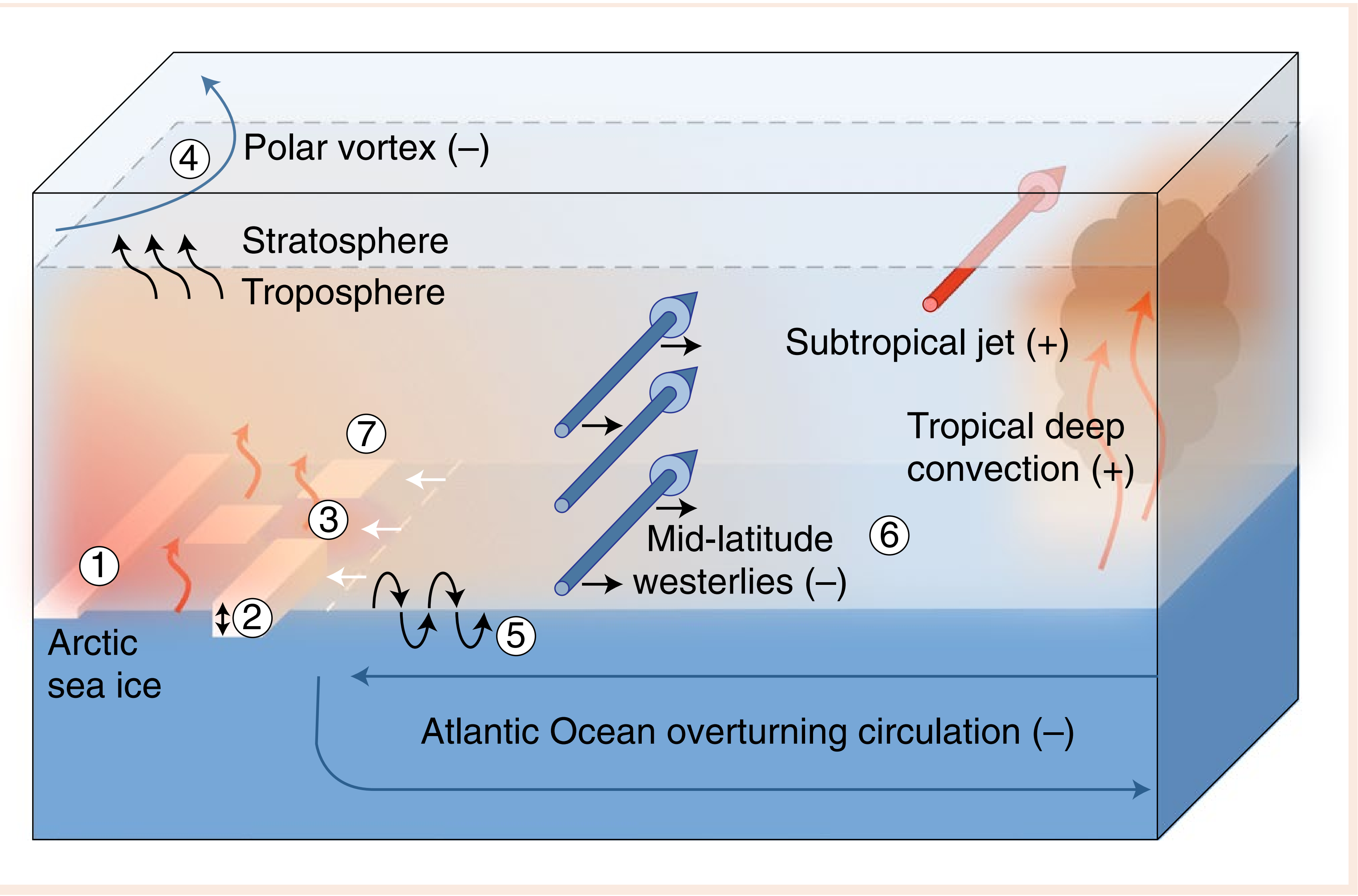
Observed trend of surface air temperature (1990-2013)



« Warm Arctic Cold Continents (WACC) » pattern *Cohen et al. (2014)*

- Role of sea ice in the observed temperature trend highly debated (e.g. *Blackport and Screen 2020, Mori et al. 2020*)
- What will be the midlatitude response in future climate ? What is the role of sea ice decline ?

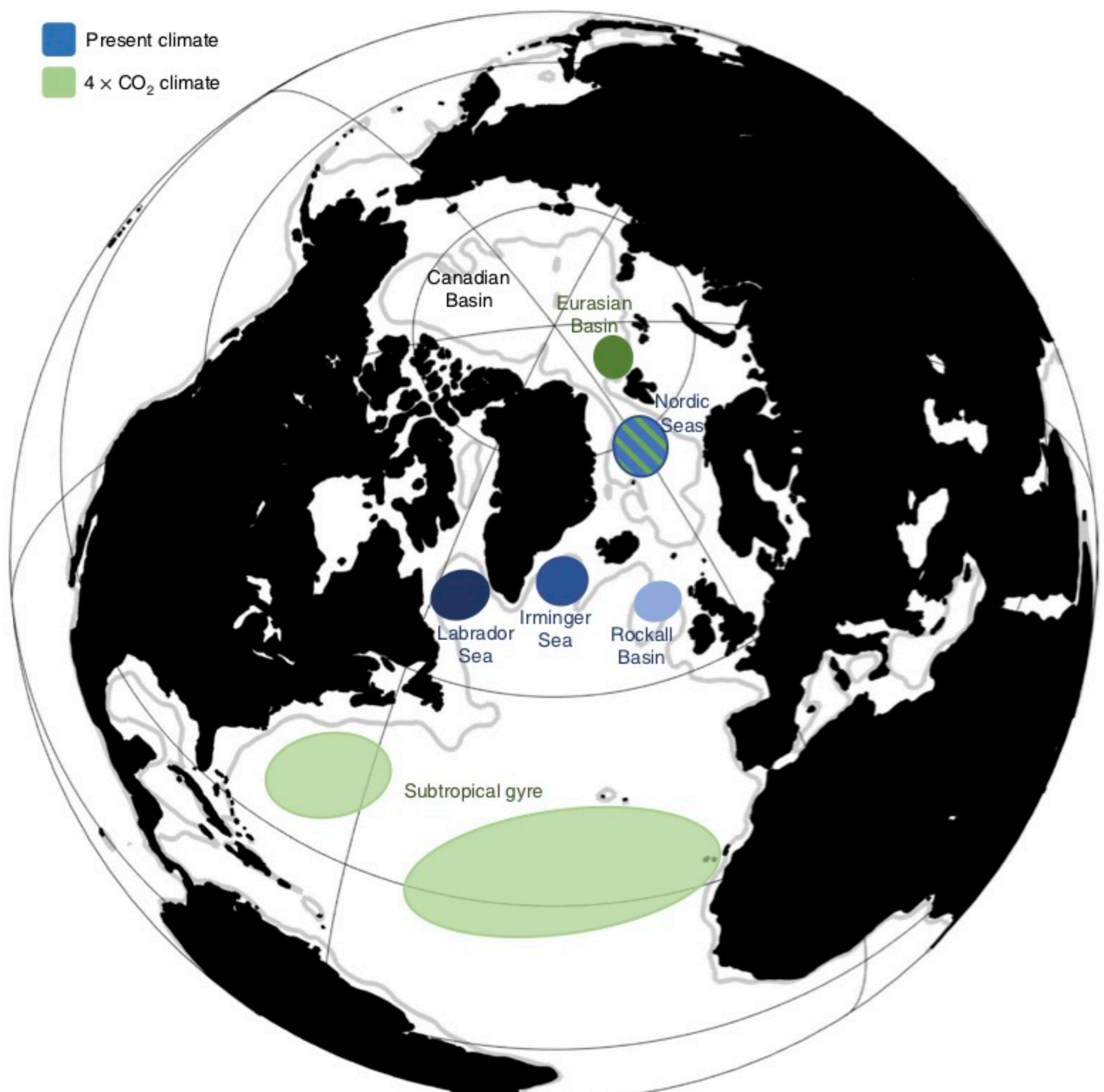
Summary of the mechanism of climate response to Arctic sea ice loss



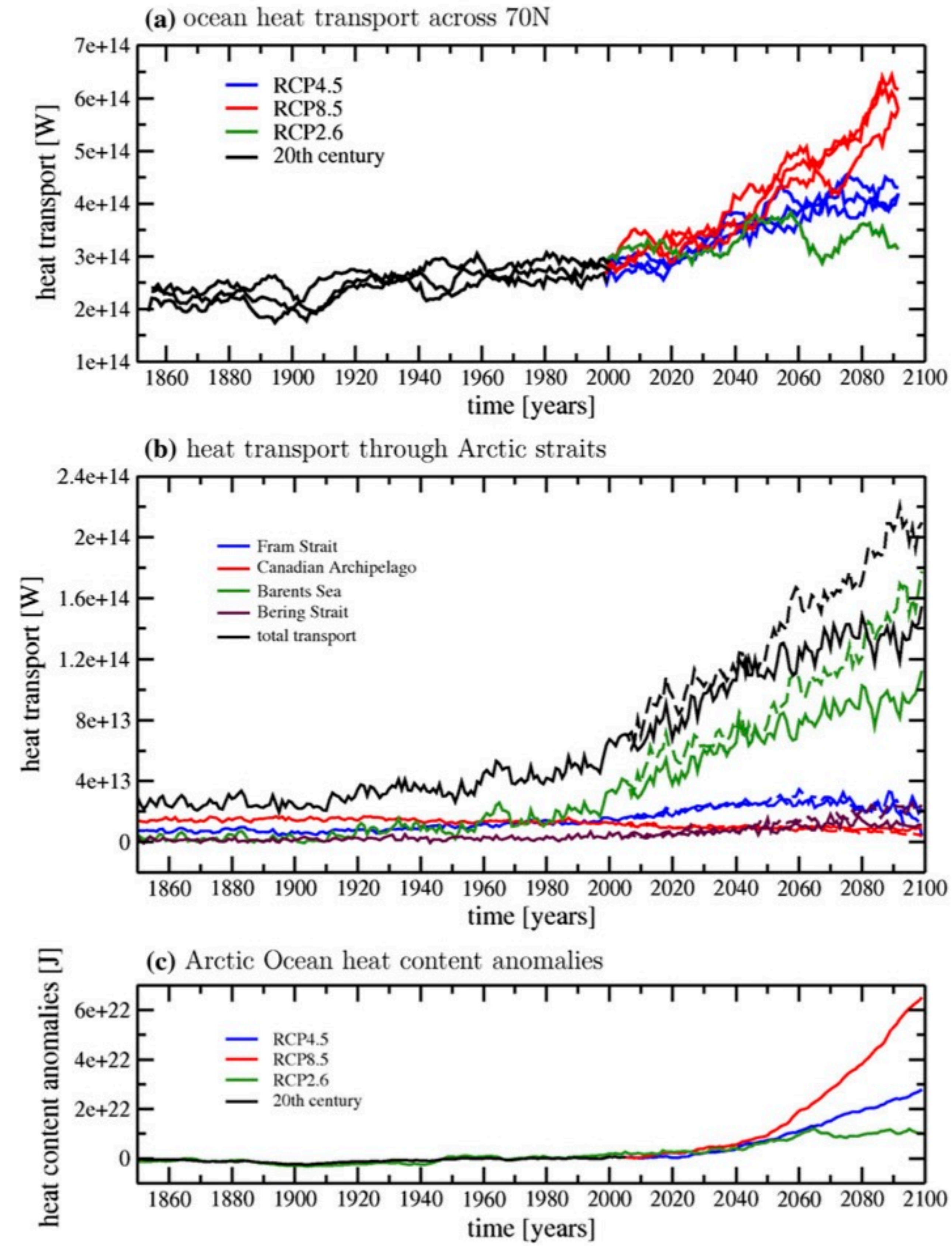
Screen et al. (2018).

See also Cohen et al. (2014, 2020), Overland et al. (2019), Vihma (2014)

Projected oceanic changes in a warmer climate



Lique et al. (2018)



- **Latitudinal shift in the deep water formation regions**
- **Increased heat transport into the Arctic**

Can sea ice reduction solely induce such changes?

Koenig et al. (2013)

Outline

Objective : Characterize the climate response to Arctic sea ice decline

1. Atmospheric response to abrupt sea ice changes

2. Comparison with a more moderate decline associated to a 2° global warming

3. Sources of uncertainty of the climate response: model uncertainty, role of resolution, coupling, regional patterns

4. Oceanic response to Arctic sea ice decline on multidecadal time scales

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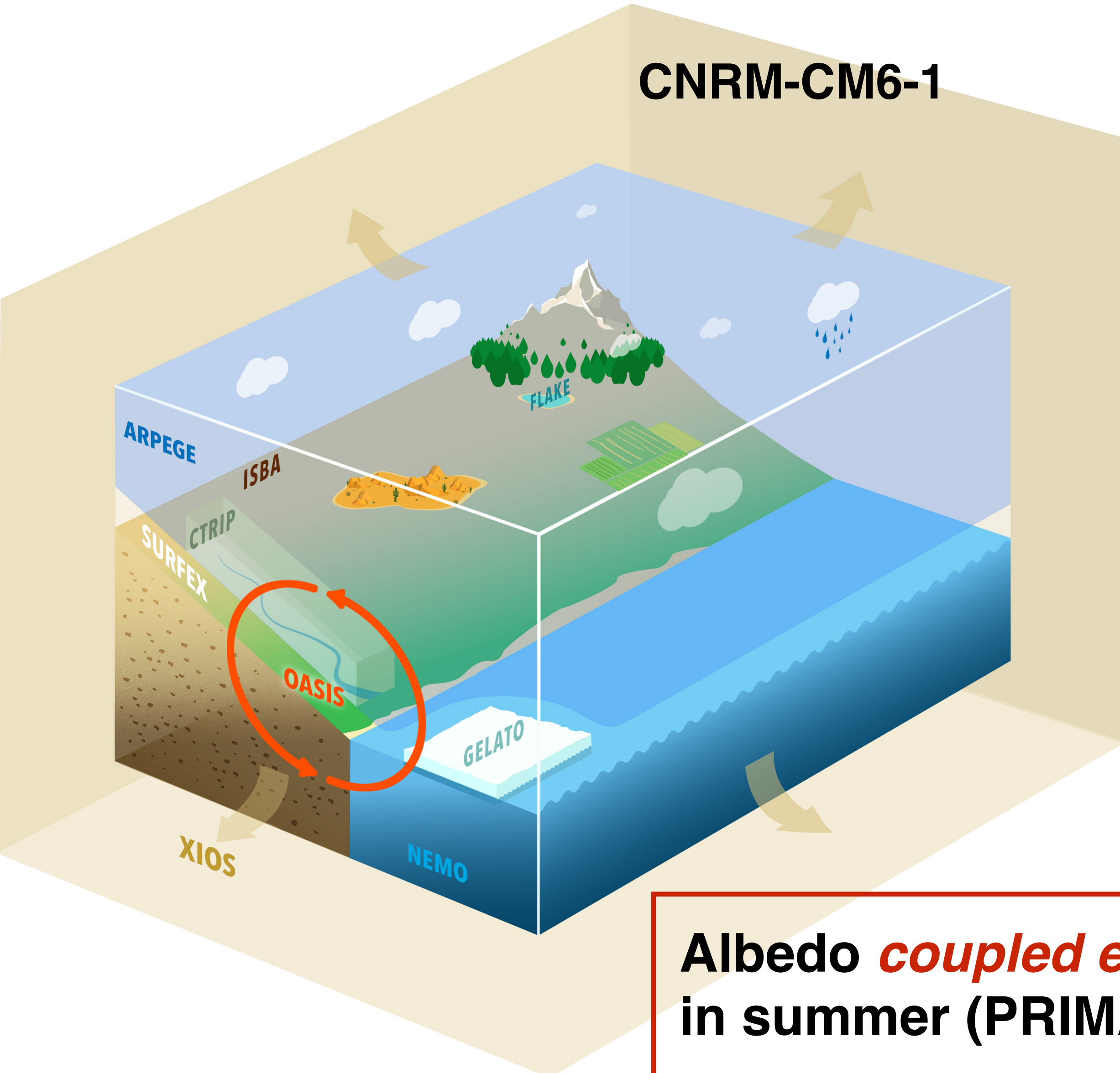
Protocole simulating a strong sea ice loss



NEMO 3.6 for ocean
GELATO v6 for sea-ice
PISCESv2-gas in the ESM version
ARPEGE-SURFEX for atm/land

LR: ORCA1 / ATM ~130km 91 levels

Voldoire et al. (2019)

Albedo *coupled experiments* simulating a complete melt in summer (PRIMAVERA project)

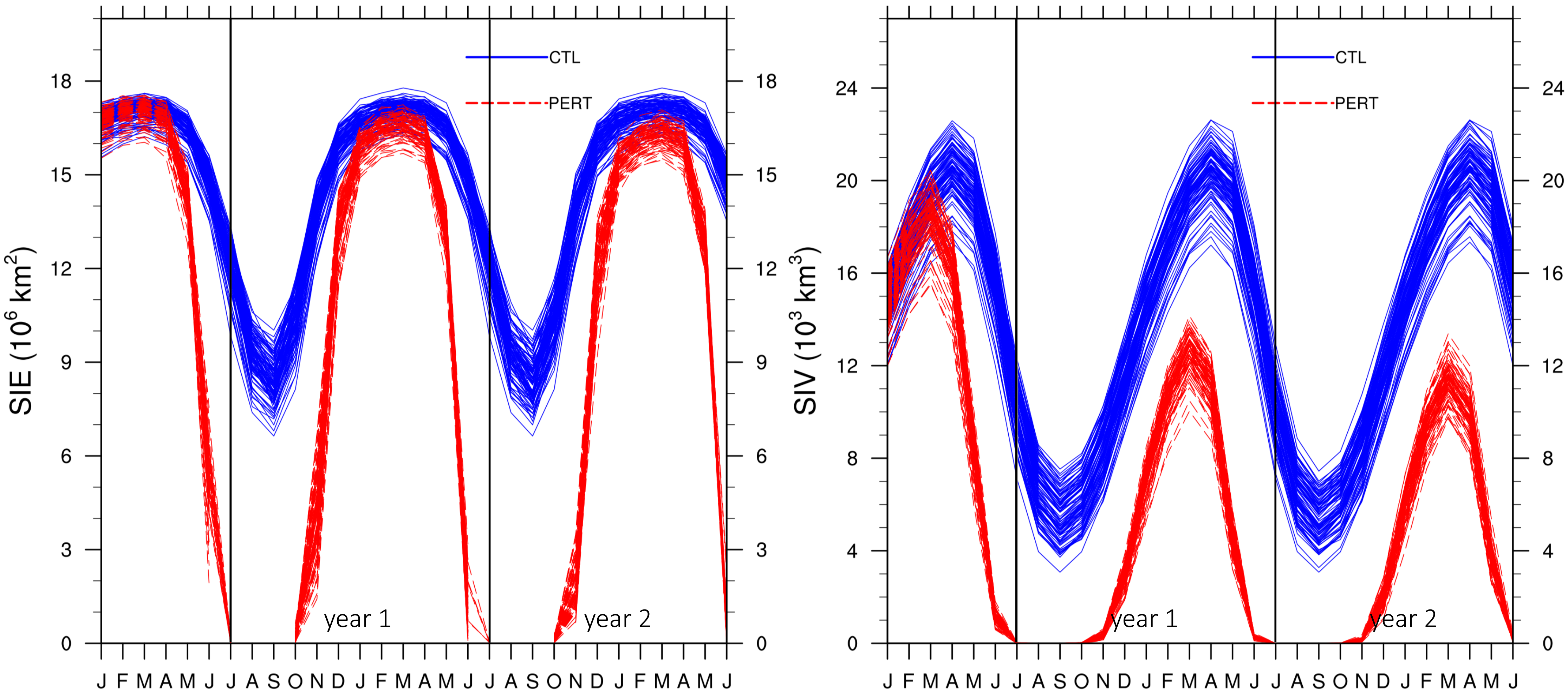
- **Sea ice albedo reduced to ocean value**
- **Initial state: 1950-control CNRM-CM6-1**
- **100 members starting January 1 and run for 3 years**

=> Sea ice perturbation reflecting sea ice loss comparable to end of century projections

Chripko et al. in rev.

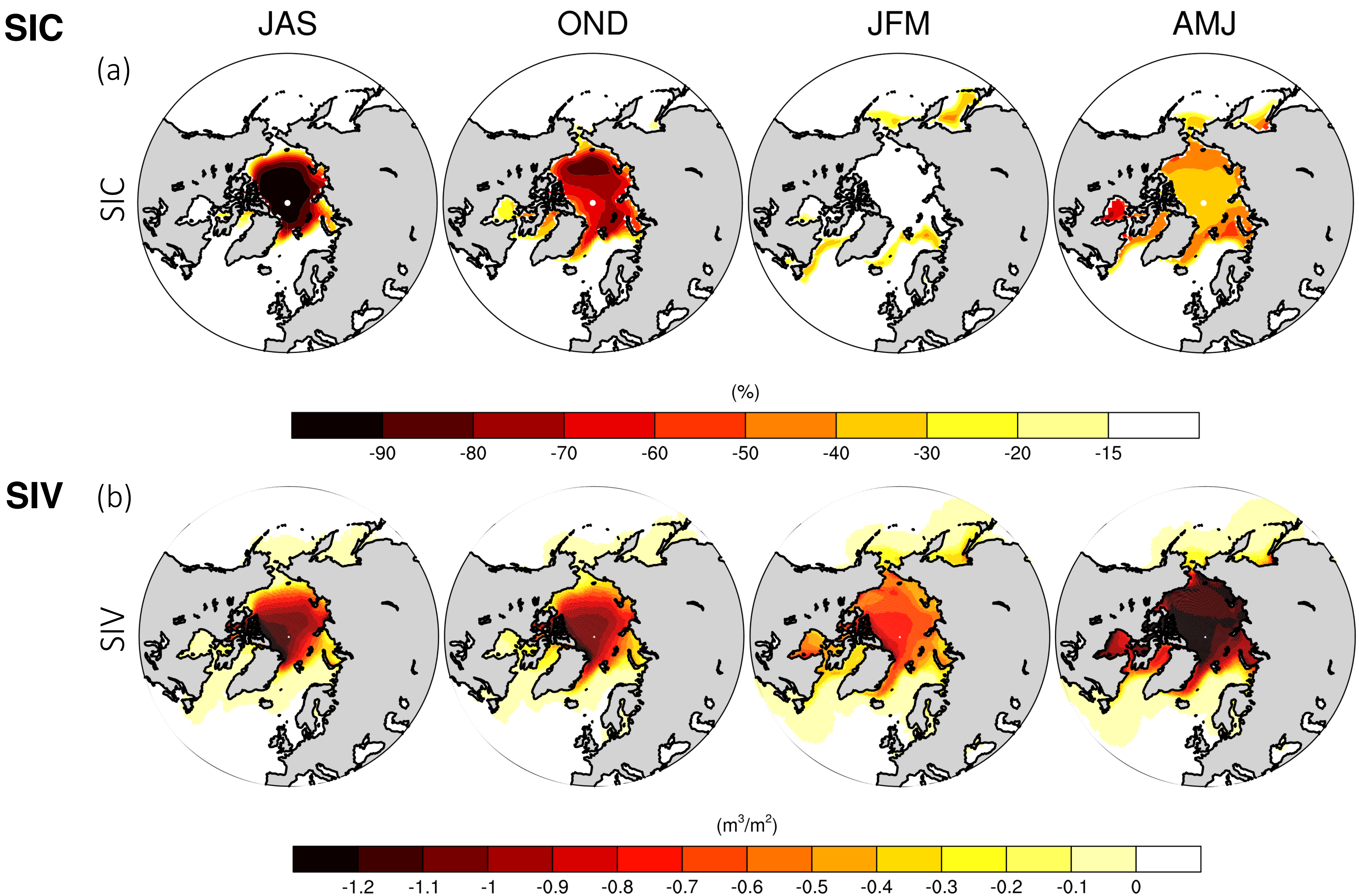
Protocole simulating a strong sea ice loss

Sea ice in the control (CTL) and perturbed (PERT) simulations



- **100 members run for 3 years : 2 years following the summer melt**
- **Statistical independence of these 2 years => 200 members in total**
- **The response = PERT - CTL**

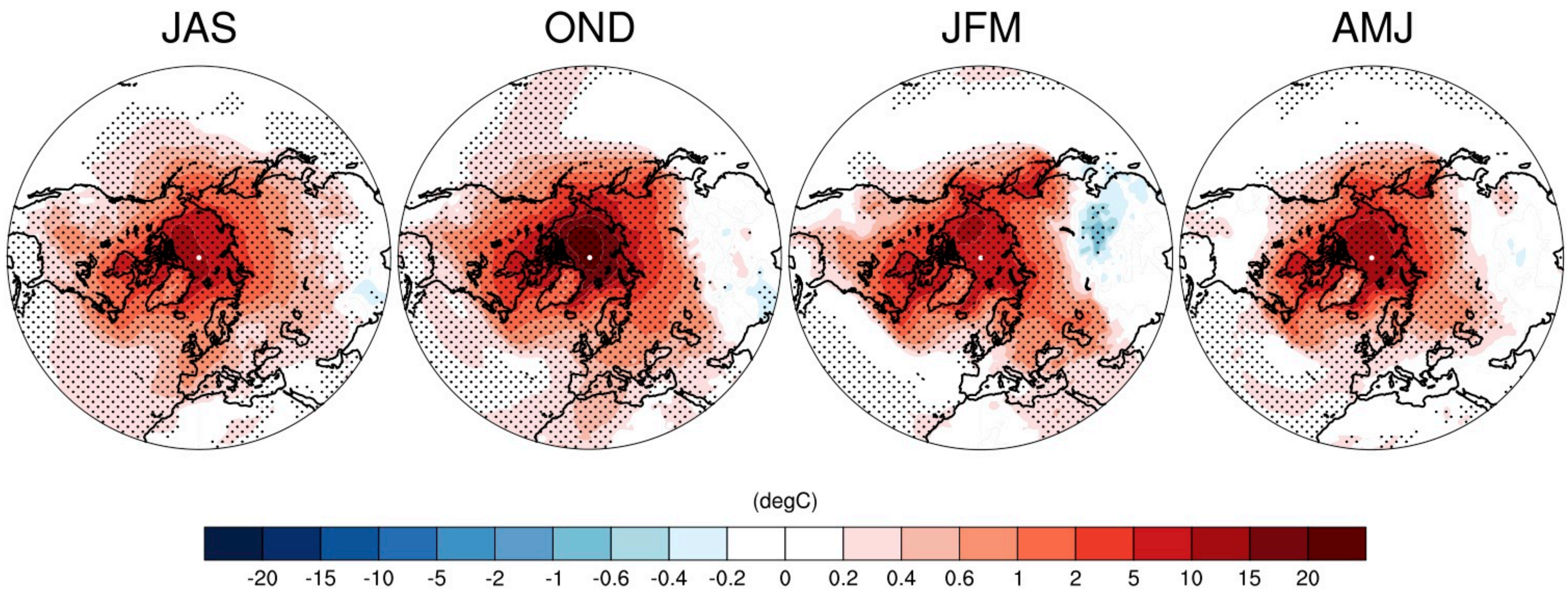
Arctic sea ice forcing



Idealised and strong sea ice forcing in summer and fall

Surface air temperature response

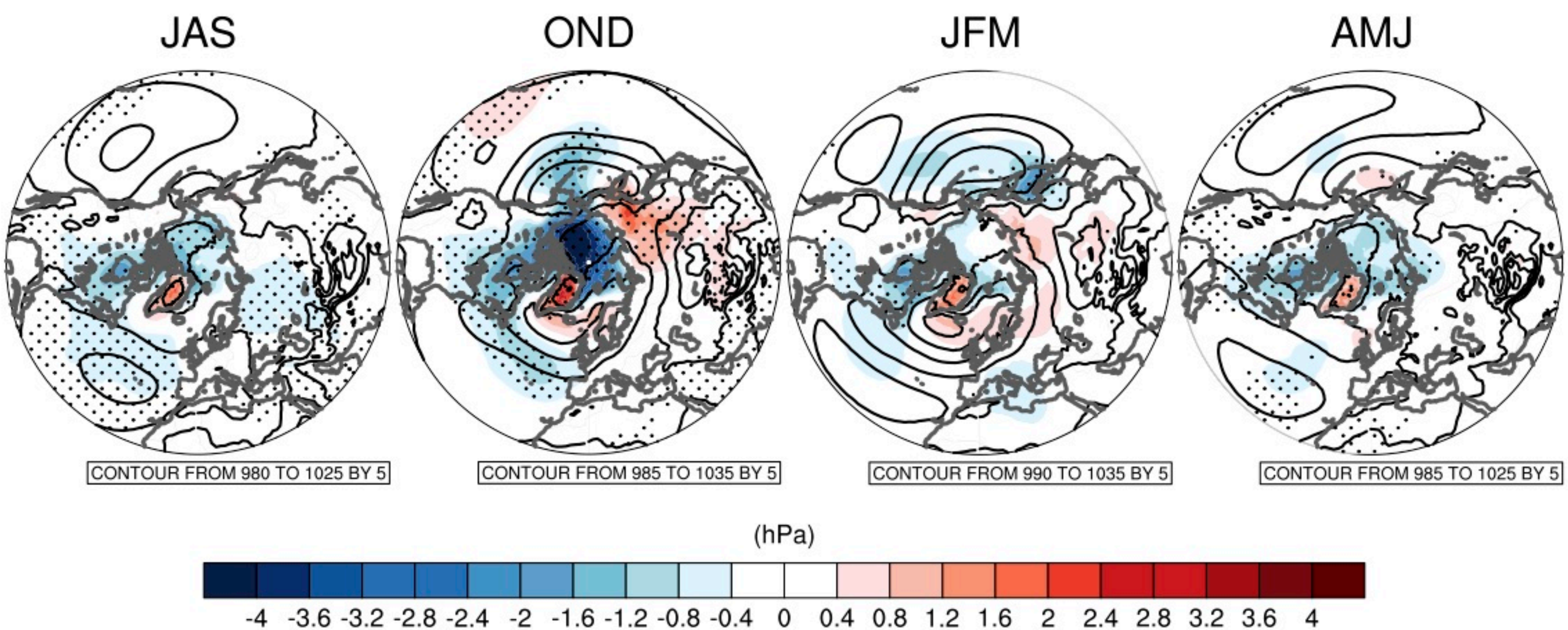
TAS



- **Large Arctic amplification**
- **Largest warming in fall**
- **Over land: Warming over Siberia and North America, consistent with Peings et al. (2014). Cooling over Eurasia like in Honda et al. (2009), Mori et al. (2014, 2019), warming over western Europe.**

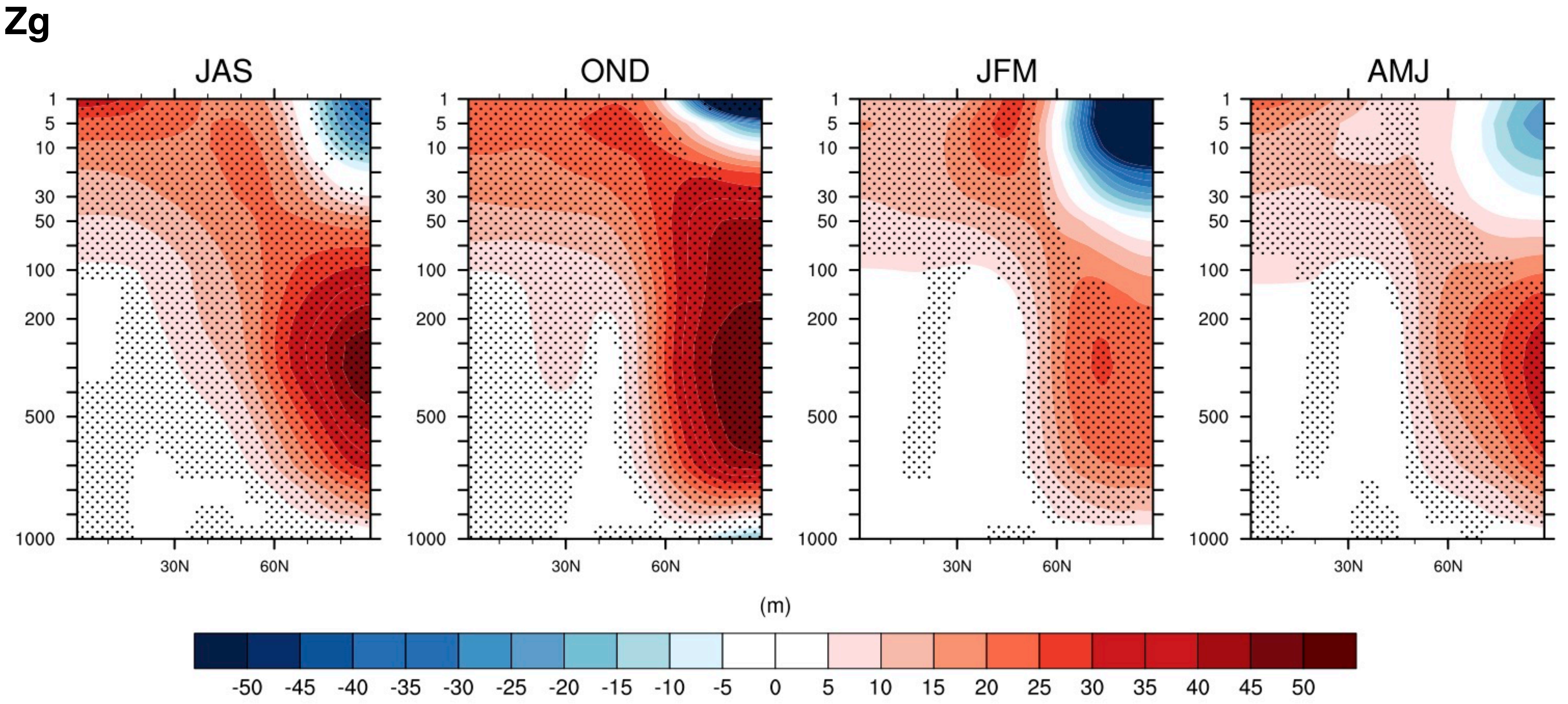
Large scale atmospheric response

SLP



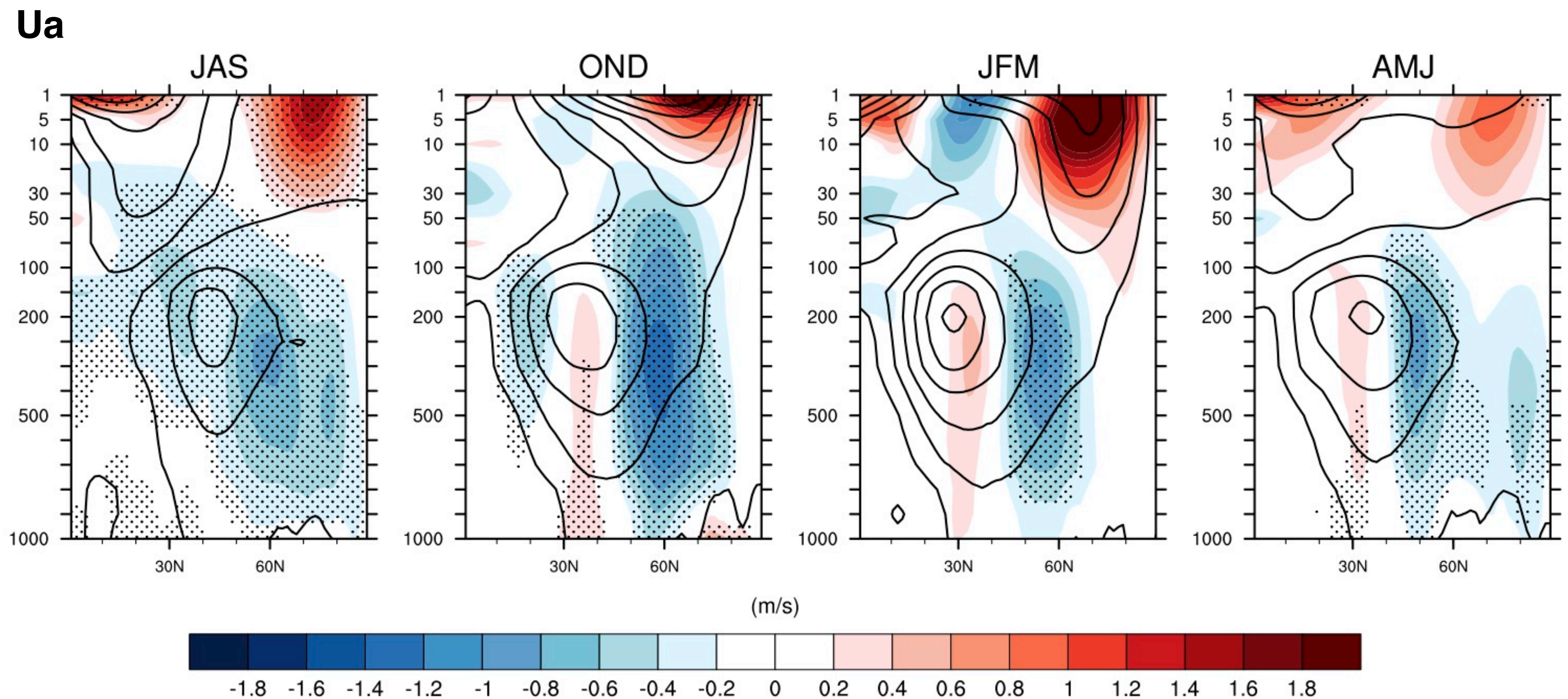
- **The response is consistent with other studies (Screen et al. 2018)**
- **It is hardly significant in winter**

Zonal mean response: geopotential height



- **Baroclinic response in fall. Reaches the stratosphere.**
- **Barotropic response in winter. Change of sign in the upper stratosphere.**

Vertical structure of the circulation response

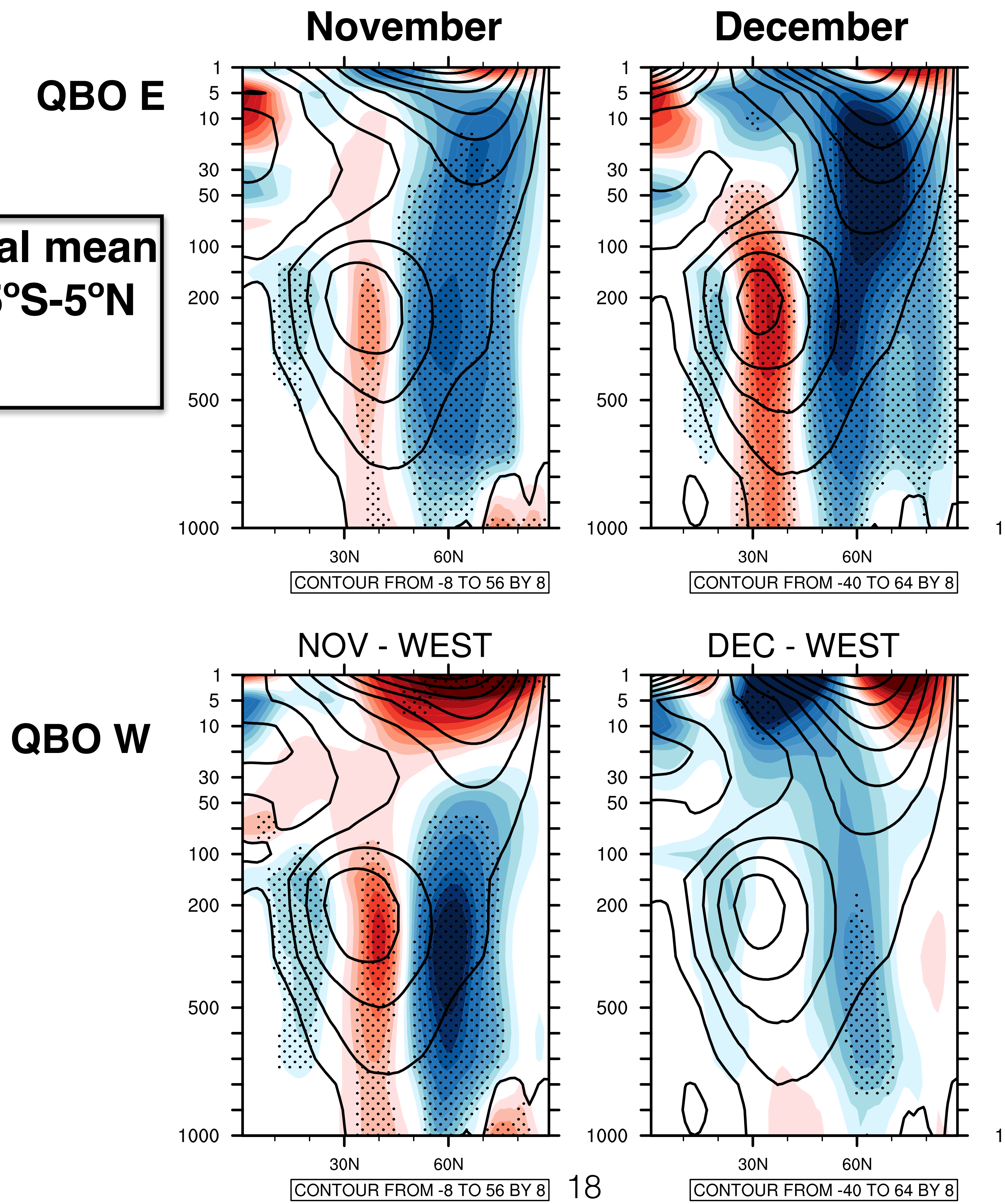


- **Narrowing of the subtropical jet stream in fall**
- **Southward shift in winter**
- **The response is hardly significant in the stratosphere**

Very similar response at higher resolution (50km atmosphere, 0.25°ocean)

Role of the QBO

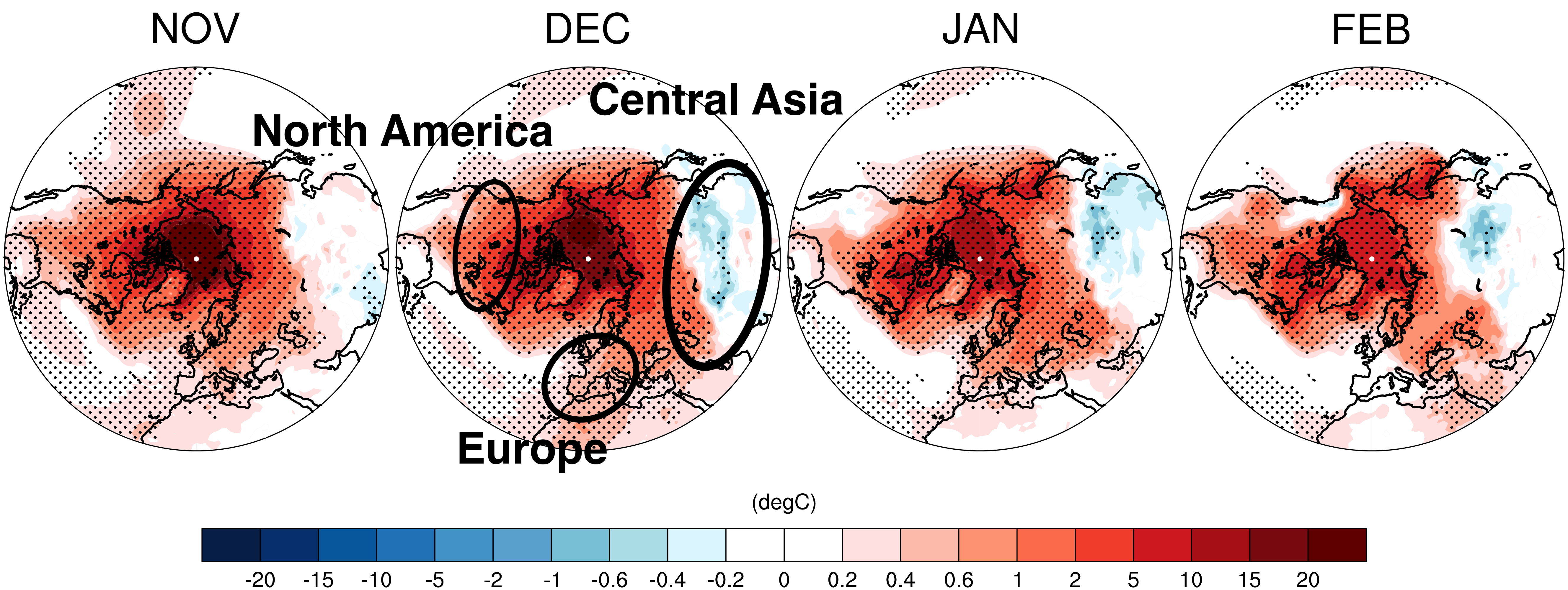
QBO index : zonal mean U@10hPa from 5ºS-5ºN in Oct-Nov



QBO-E is favoring a response of the polar vortex (Labe et al. 2019)

Understanding the winter regional response

2m air temperature



- **Can we explain the different regional responses ?**
- **What is the role of the circulation ?**

Decomposition into dynamical and thermodynamical contribution

$$\Delta T_{tot} = \boxed{\Delta T_{dynamical}} + \boxed{\Delta T_{thermodynamical}}$$

(1) Dynamical contribution :

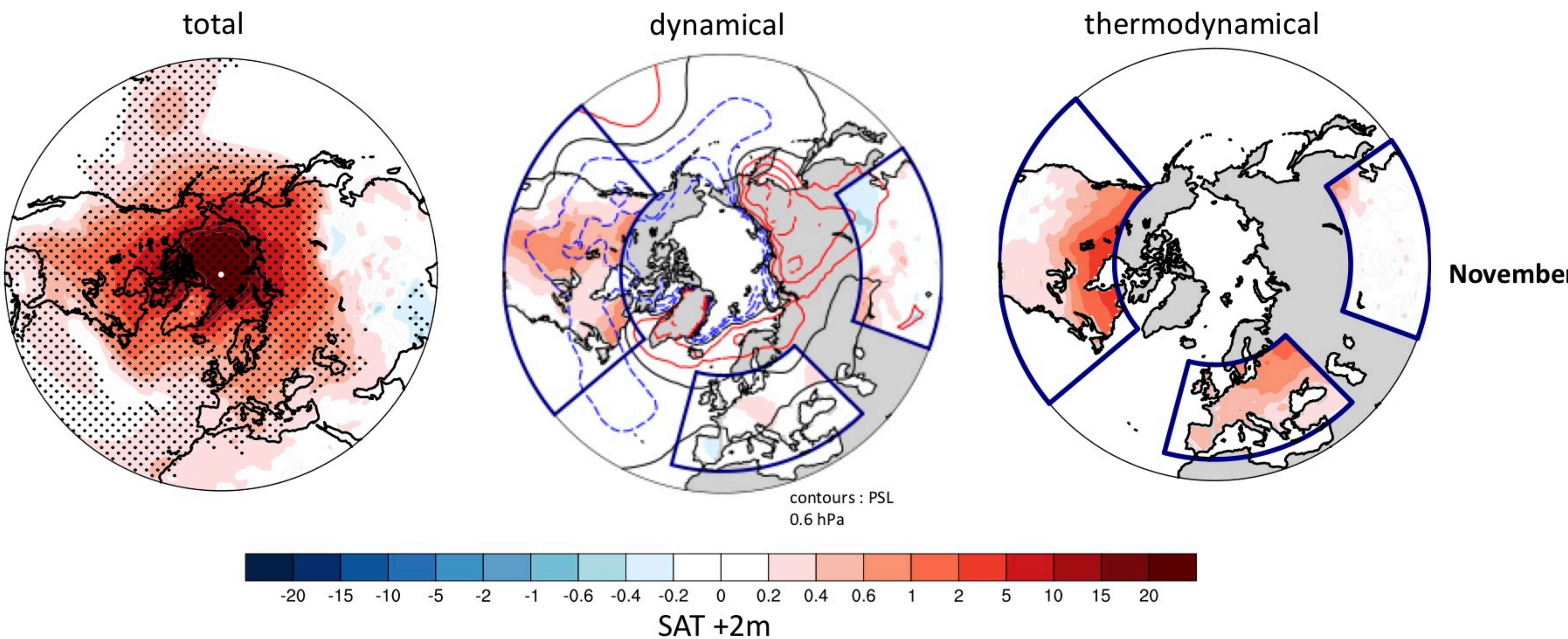
SAT changes explained by circulation (SLP) changes

→ Dynamical adjustment method,
based on a regional reconstruction of circulation analogs (Deser, Terray & Phillips 2016)

(2) Thermodynamical/Residual contribution :

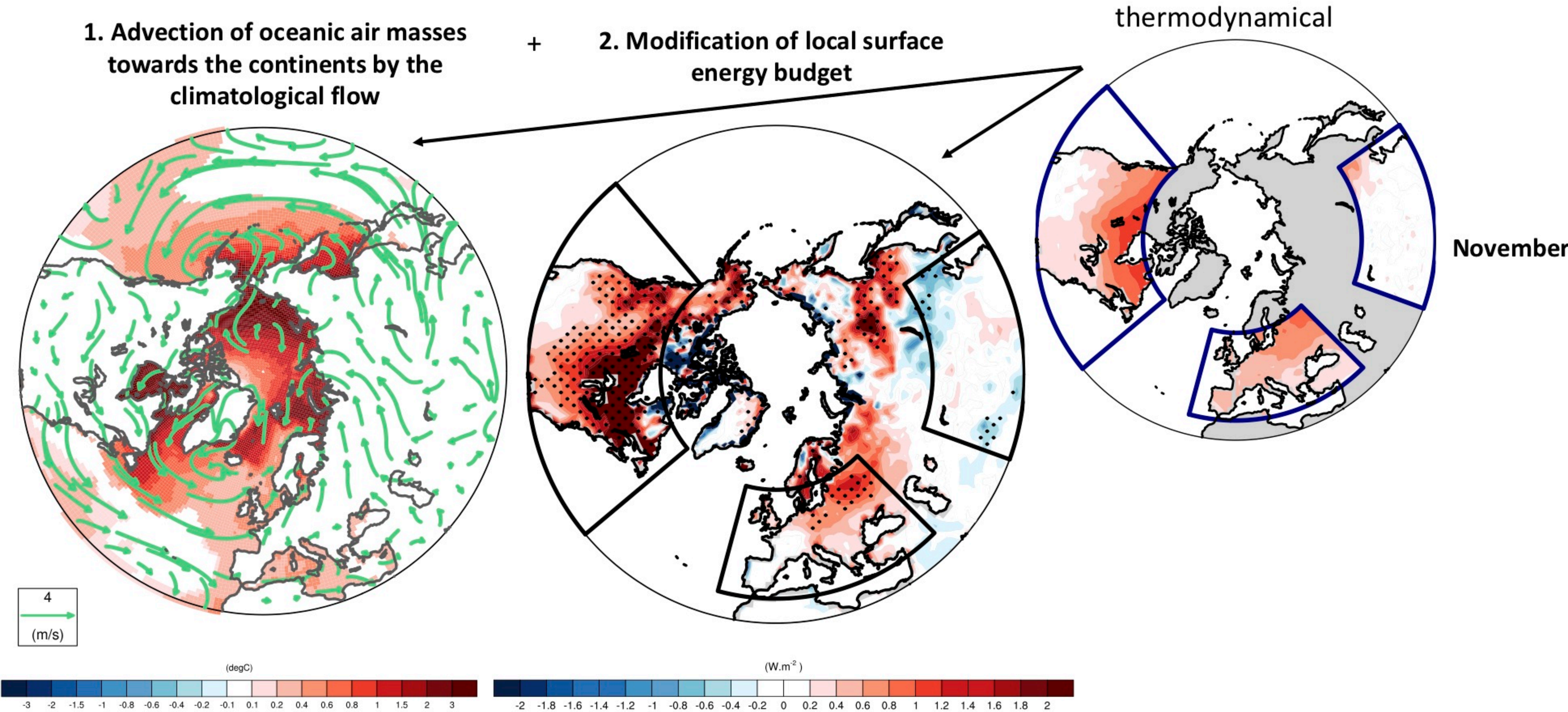
SAT changes explained by advection of warmer air masses
and local modification of surface energy budget

SAT dynamical and thermodynamical decomposition

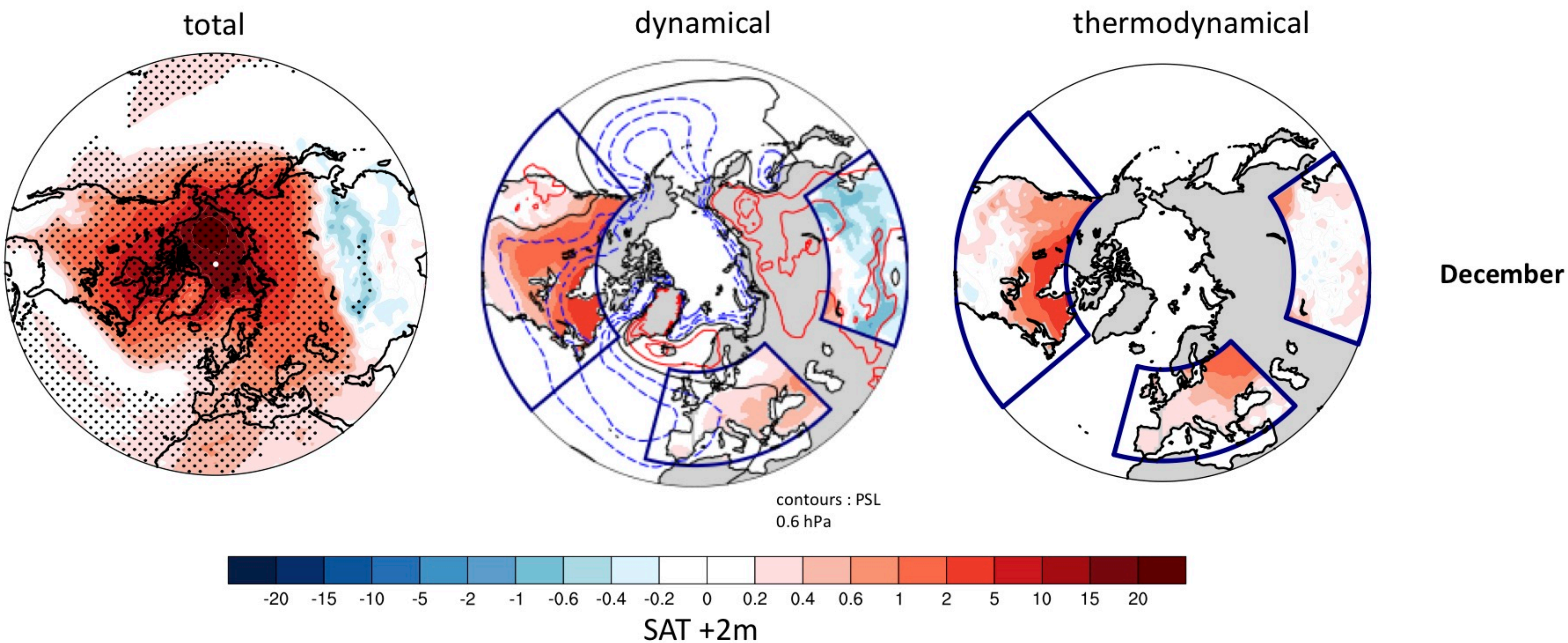


November SAT response over North America and Europe explained by thermodynamical contribution (i.e advection + local radiative effects)

SAT dynamical and thermodynamical decomposition



SAT dynamical and thermodynamical decomposition



December SAT response over Central Asia explained by dynamical contribution: the intensification of the Siberian high

Outline

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2. **Comparison with a more moderate decline associated to a 2º global warming**

3. Sources of uncertainty of the climate response: model uncertainty, role of resolution, coupling, regional patterns

4. Oceanic response to Arctic sea ice decline on multidecadal time scales

PAMIP protocol

Objective: create SST/SIC forcing fields corresponding to present-day and future warming of 2ºC

1. Define the target temperature for Present Day and Future conditions.

Present-day global mean SAT = average 1979-2008 from HadCRUT4 = 14.24ºC
Pre-industrial global mean SAT = present-day SAT - global warming (0.57ºC) = 13.67ºC
Future global mean SAT = pre-industrial SAT + 2ºC = 15.67ºC

2. We use 31 CMIP5 models, historical and RCP8.5 simulations.

- For each model find the period when the 30-yr mean GLB SAT matches the target temperature.
- Average the SIC and SST forcing fields over that 30-yr period.
- Use a quantile linear regression to get sharper ice edge and give more weight to models with less sea ice and warmer SST

Note: Future SSTs imposed in grid points where future SIC deviates by more than 10% to present day value (Screen et al. 2013)

In this presentation: 2 atmosphere only simulations pdSST-pdSIC and pdSST-futArcSIC

The difference = response to future sea ice changes

Each experiment is run for 14 months starting in April

Constant forcing yr 2000

300 members

Smith et al. (2019)

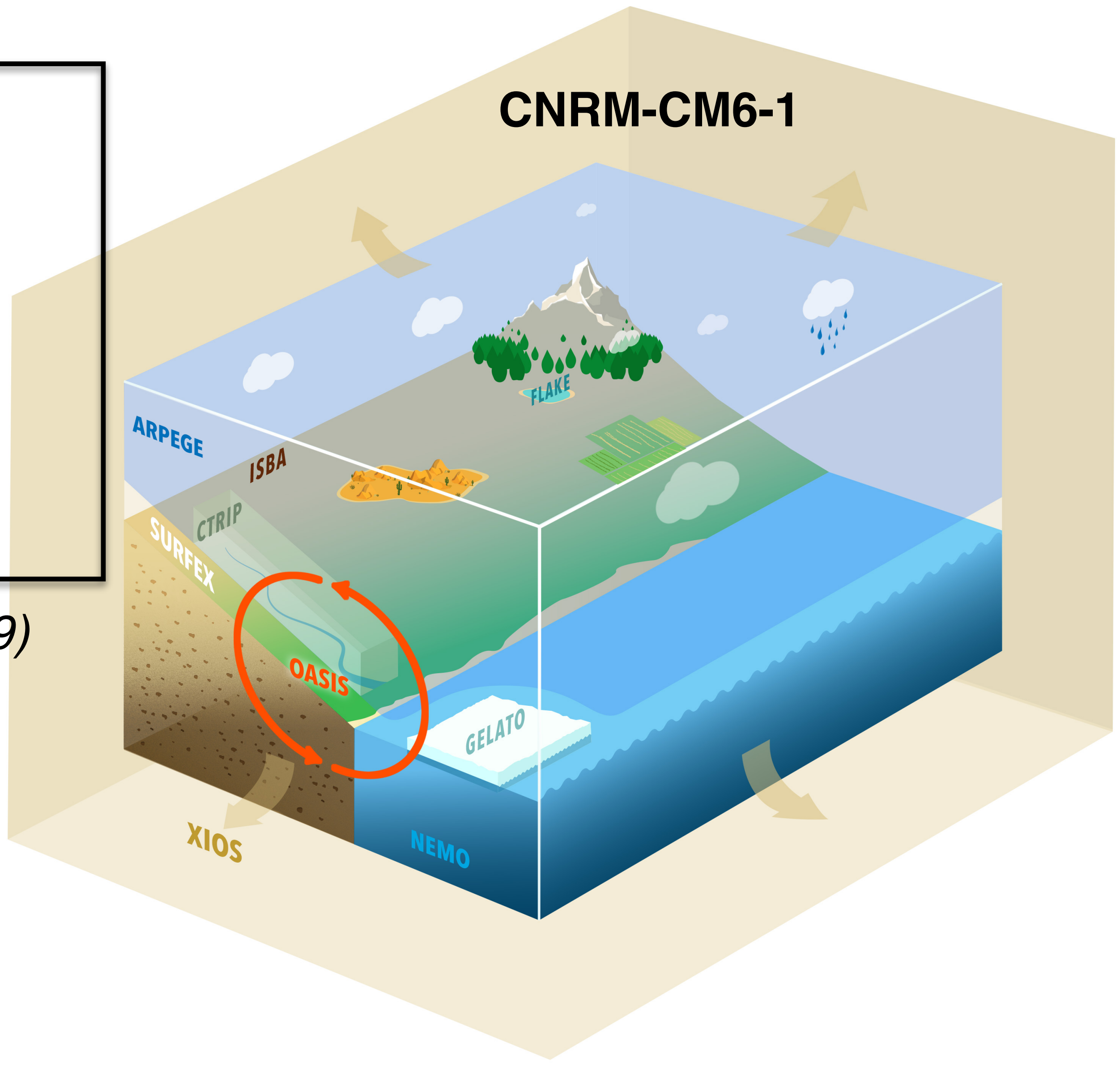
Model experiments

CNRM-CM6-1

NEMO 3.6 for ocean
GELATO v6 for sea-ice
ARPEGE-SURFEX for atm/land

ATM ~140km 91 levels

Voldoire et al. (2019)



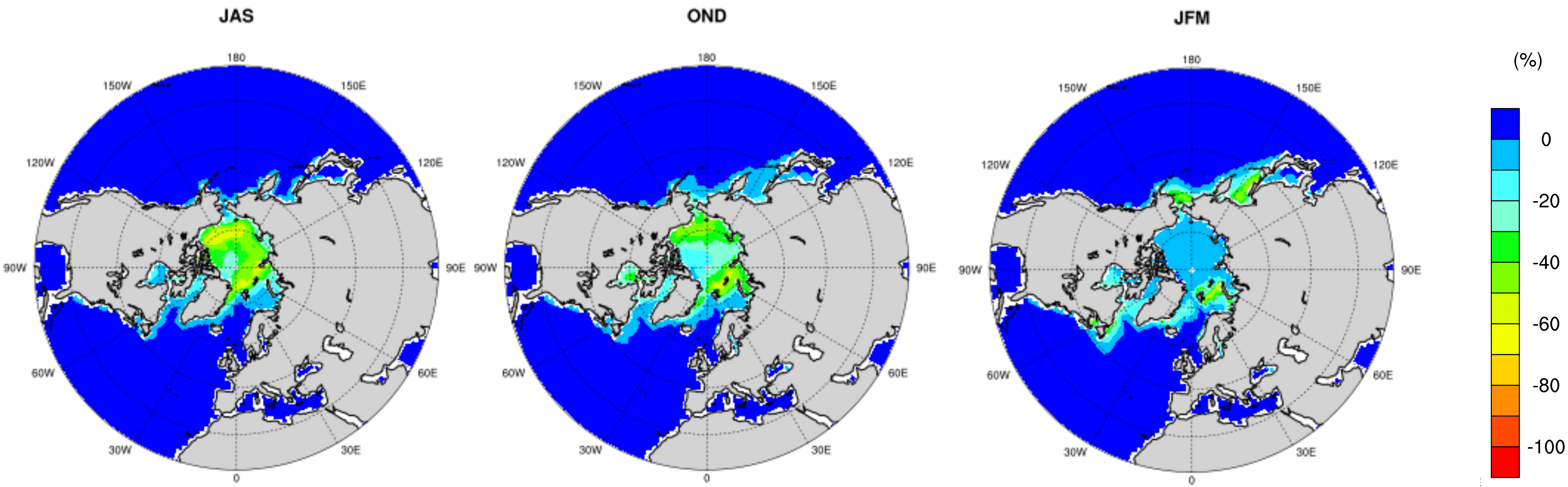
PAMIP experiments presented: *atmosphere only* simulations forced by SST and Sea ice

METEO FRANCE

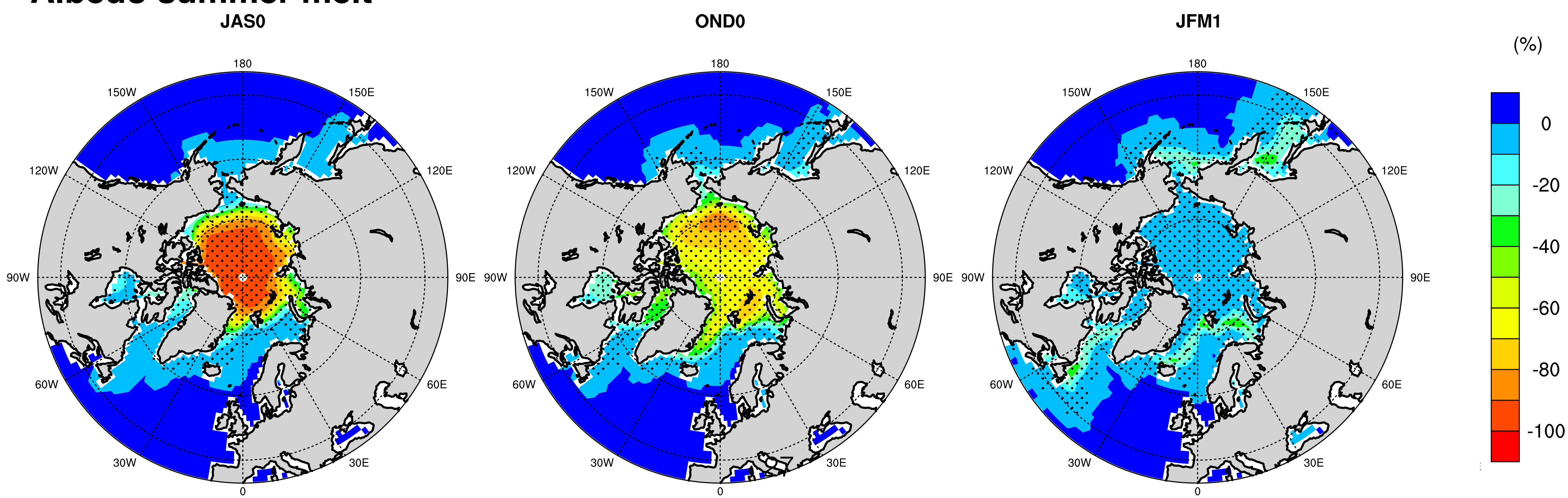
CERFACS

Arctic sea ice forcing in the two experiments

PAMIP 2C warming



Albedo summer melt



Vertical structure of the circulation response

PAMIP 2C warming

(pdSST-futArcSIC)

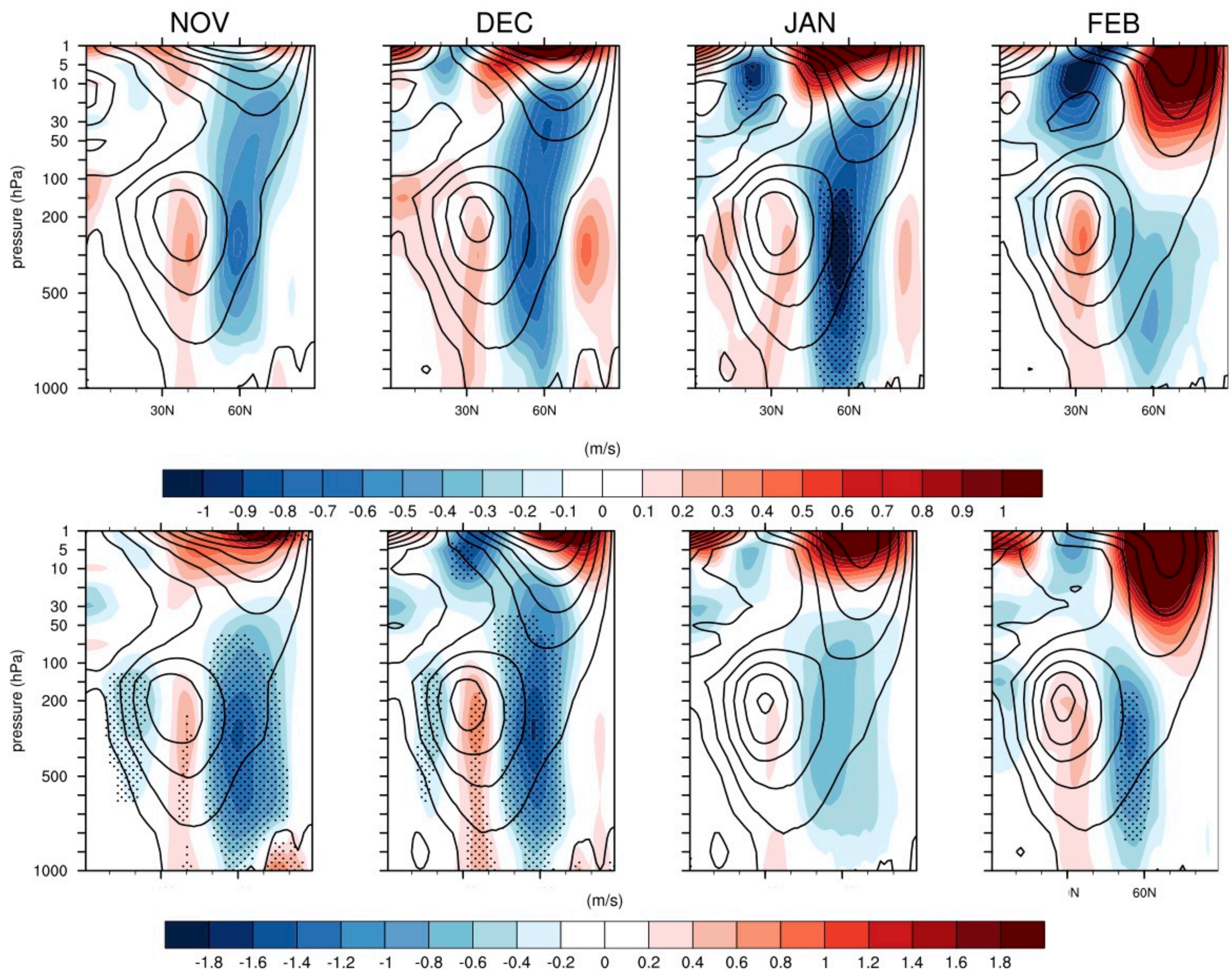
-

(pdSST-pdSIC)

300 members

Albedo experiment (strong forcing)

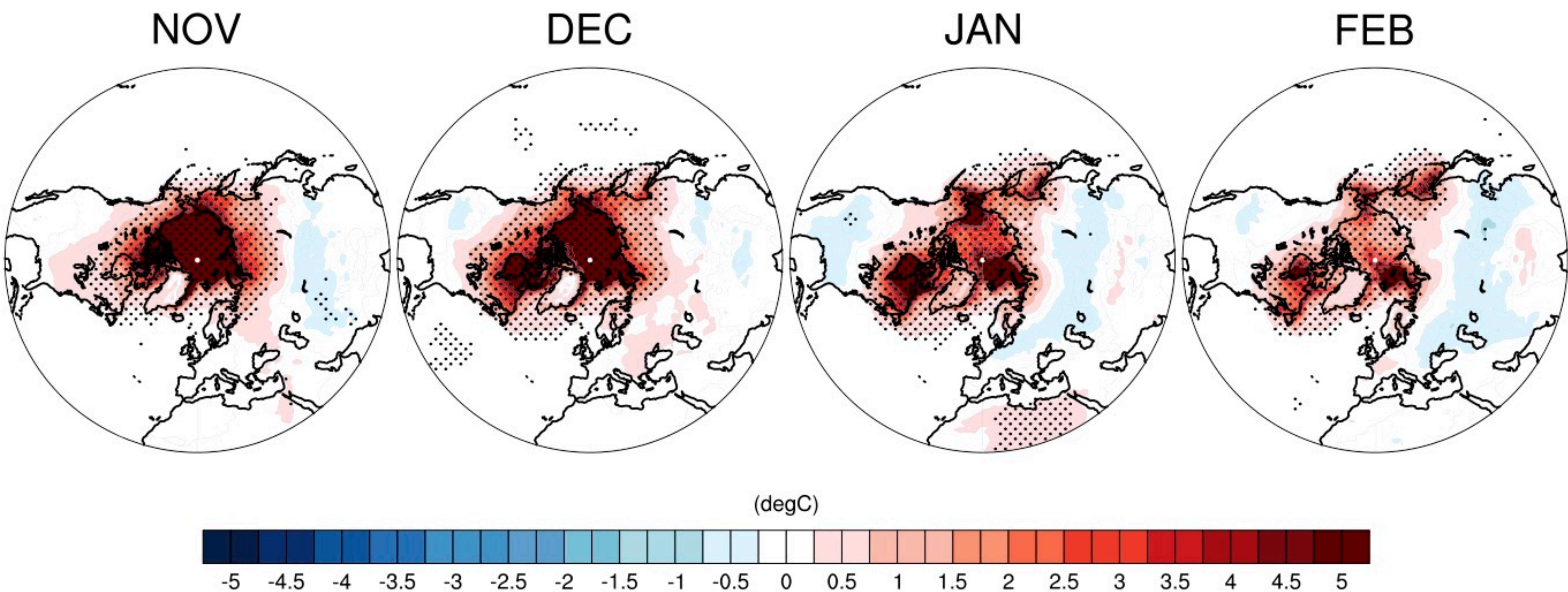
200 members



Not the same colorbar

SAT response

PAMIP 2C warming



SAT +2m

***Warm Arctic Cold Continent* pattern but much weaker midlatitude response than in the albedo experiments**

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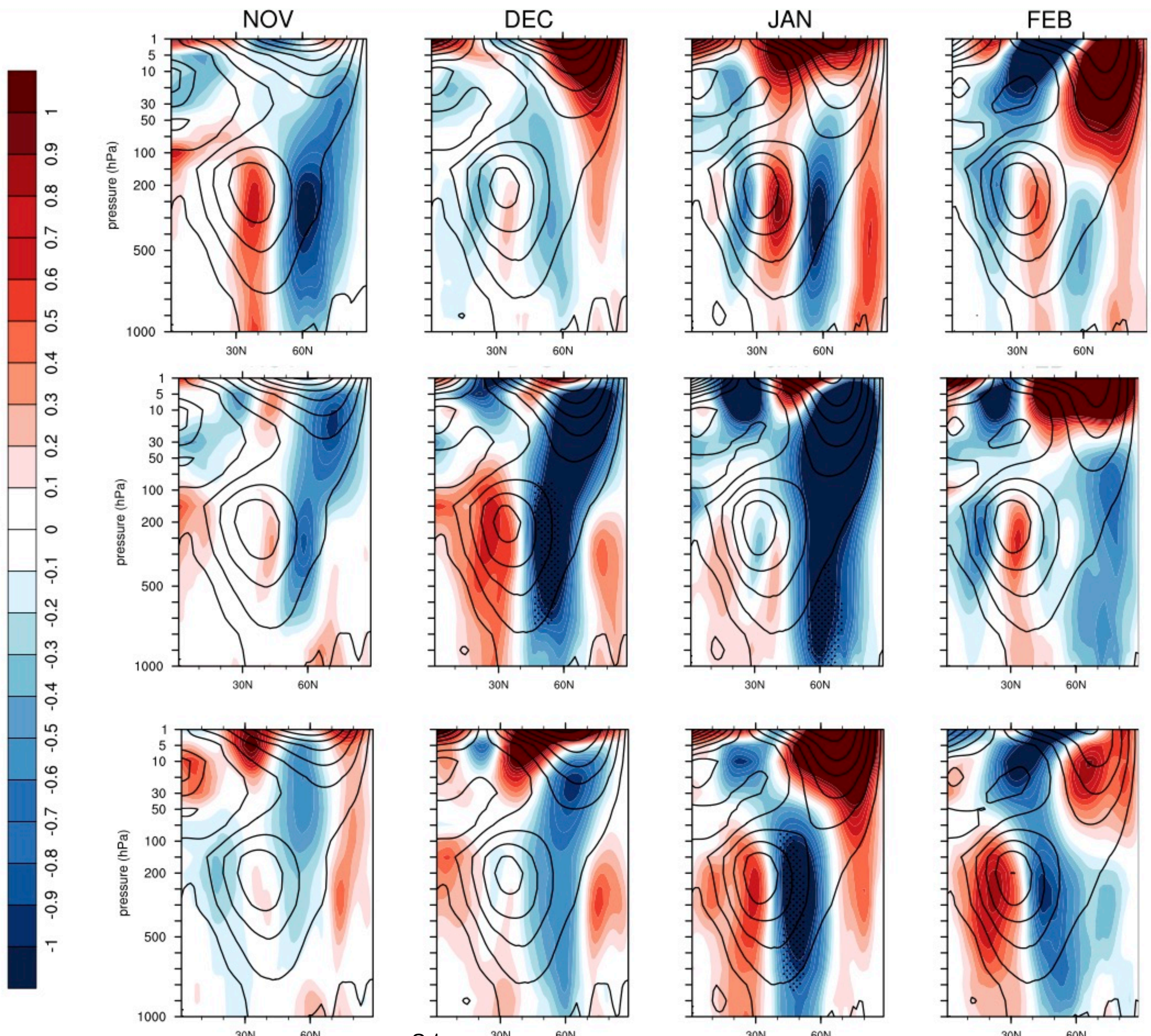
Sources of uncertainty:
#1 Atmospheric internal variability

PAMIP 2C warming

Members 1 - 100

Members 101 - 200

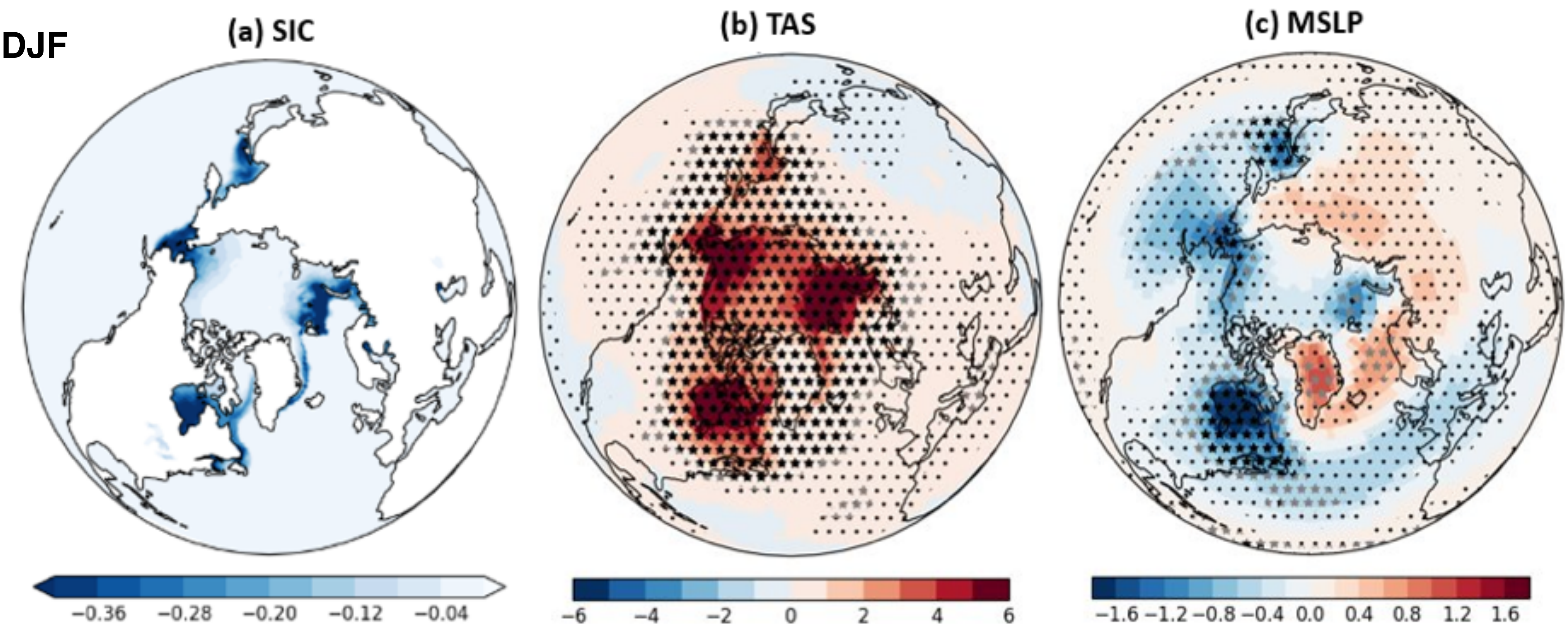
Members 201 - 300



Sources of uncertainty: #2 models uncertainty

15 models, about 2650 years

DJF

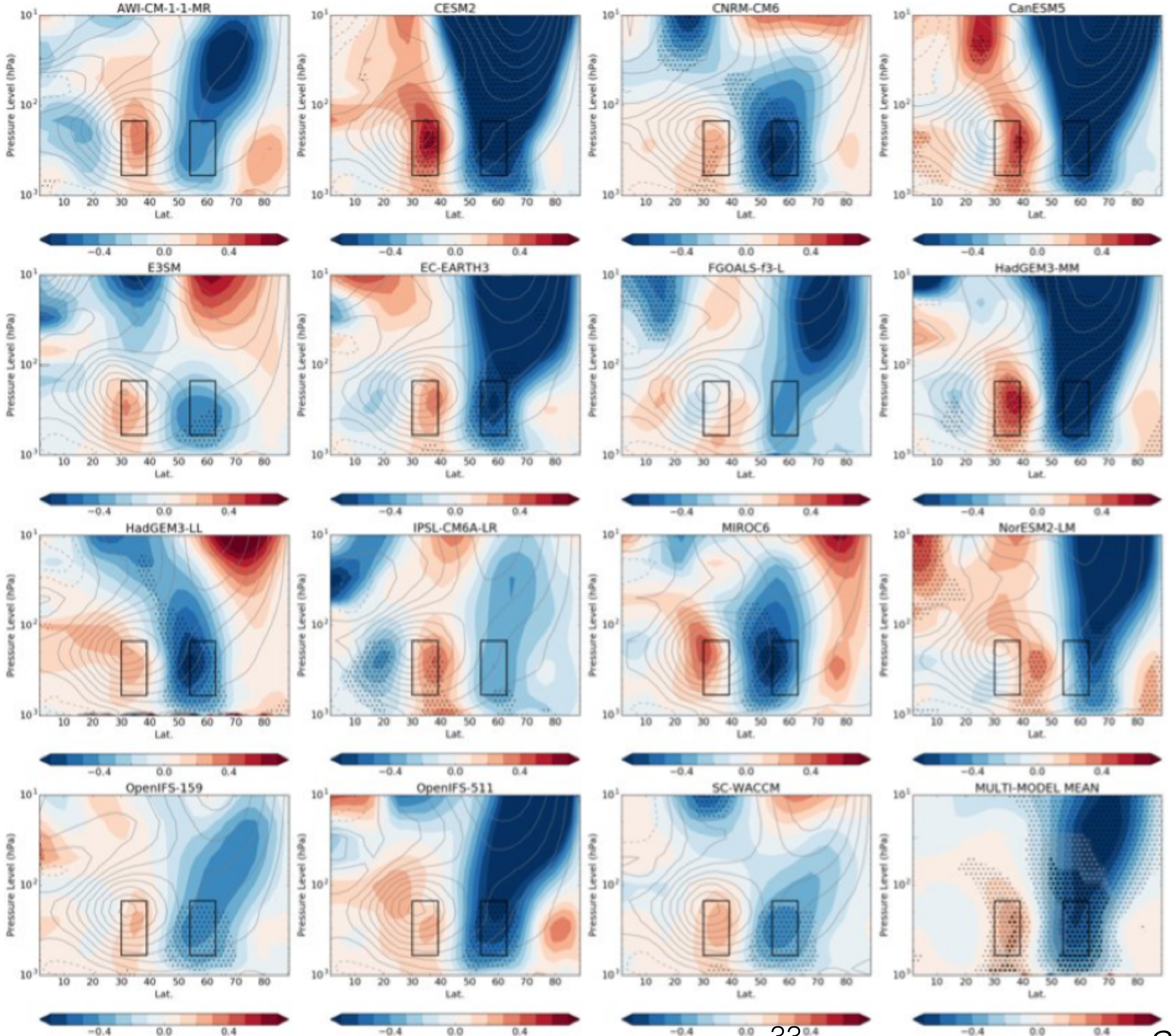


Stars indicate where models agree on the sign of the response.

Smith et al. to be submitted

Sources of uncertainty:
#2 models uncertainty

DJF zonal mean winds

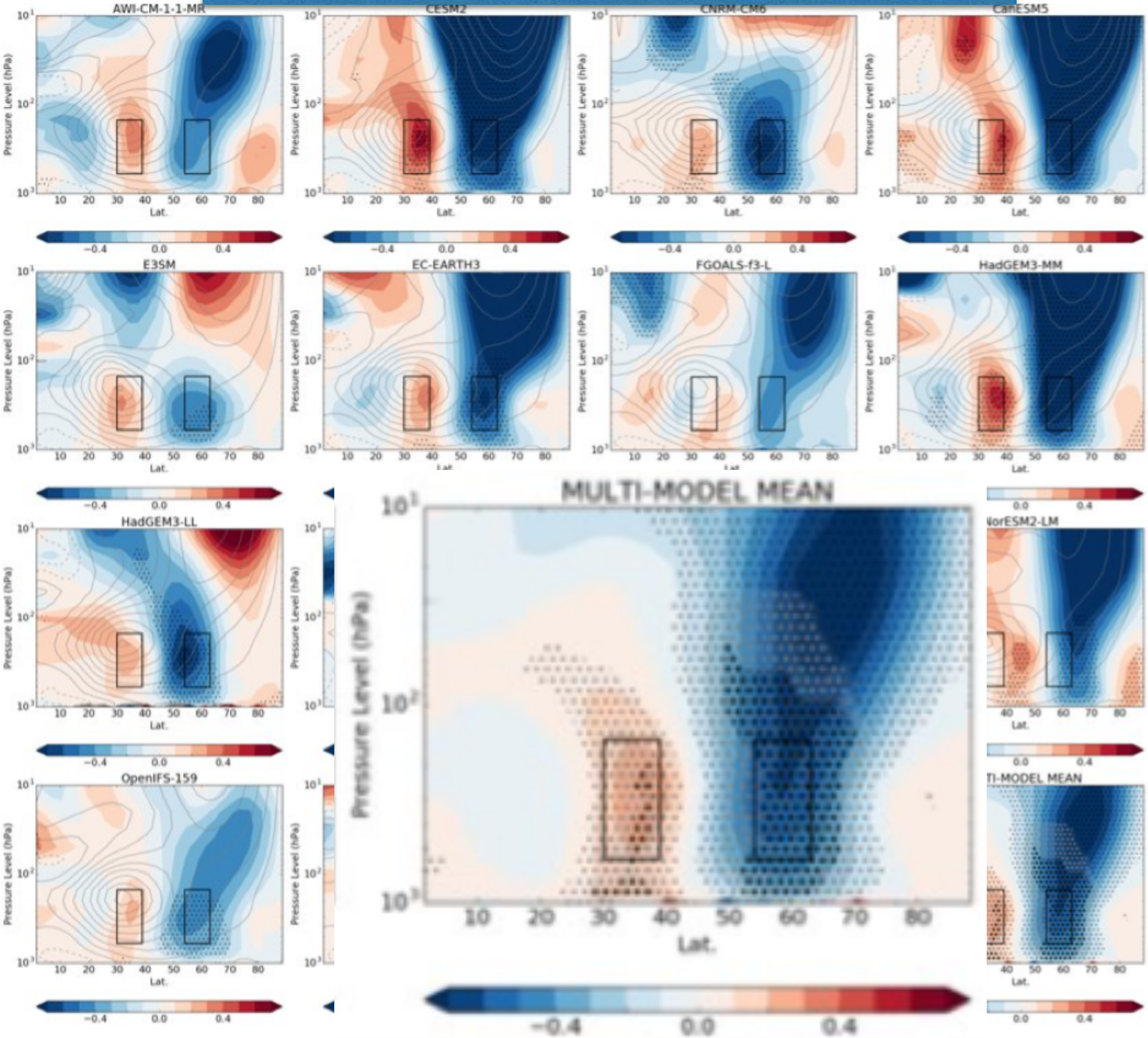


Weak response compared to inter annual variability

Smith et al. to be submitted

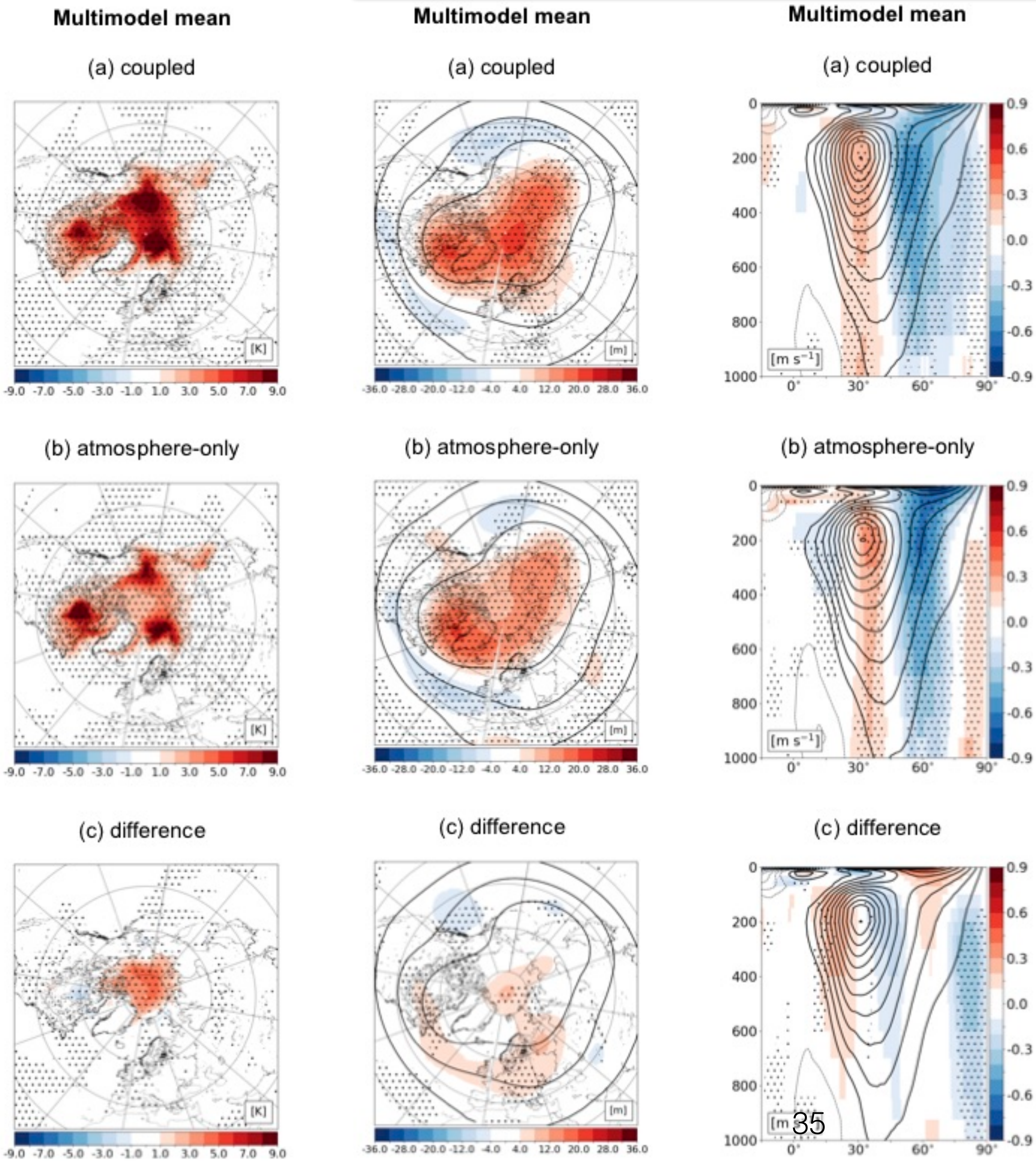
DJF zonal mean winds

Sources of uncertainty: #2 models uncertainty



Smith et al. to be submitted

Sources of uncertainty: Role of ocean coupling



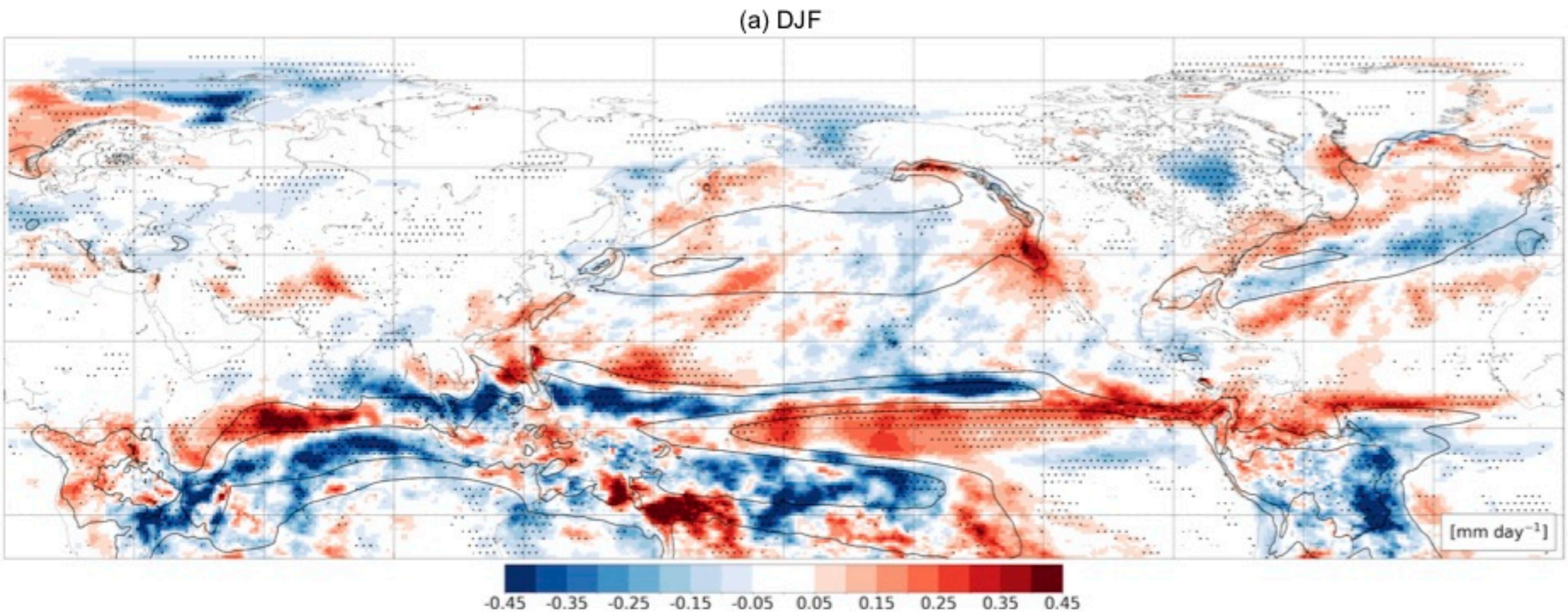
3 coupled models. Same SIC forcing than PAMIP atm only

- **Larger polar amplification**
- **Larger shift of the jet**
- **Stronger NAO-like response**

Courtesy X.Levine (BSC)

Sources of uncertainty: Role of ocean coupling

DJF Precipitation induced by sea ice decline. Multi model difference between coupled - atmosphere only experiments

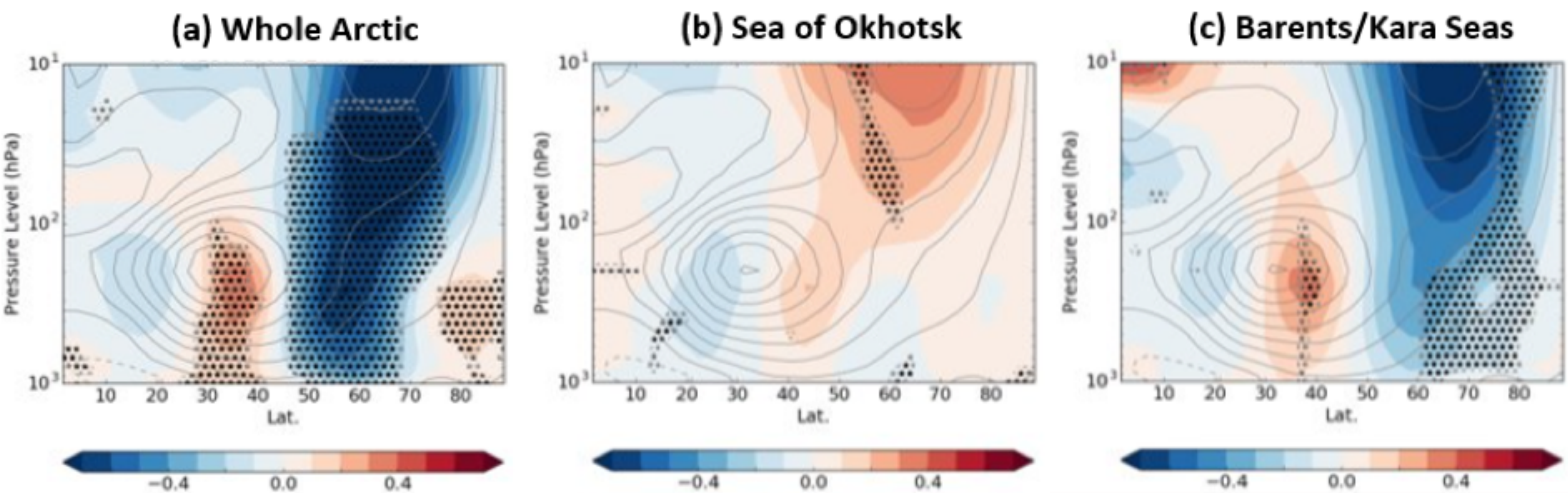


- **Southward shift of the ITCZ**
- **Increased rainfall over California**

Courtesy X.Levine (BSC)

Sources of uncertainty: Role of regional sea ice forcing

Contribution of Atlantic vs Pacific sea ice forcing
Atm only experiments



Smith et al. to be submitted

- **Same sign in the troposphere**
- **Opposite response in the stratosphere (like in Sun et al. 2015)**

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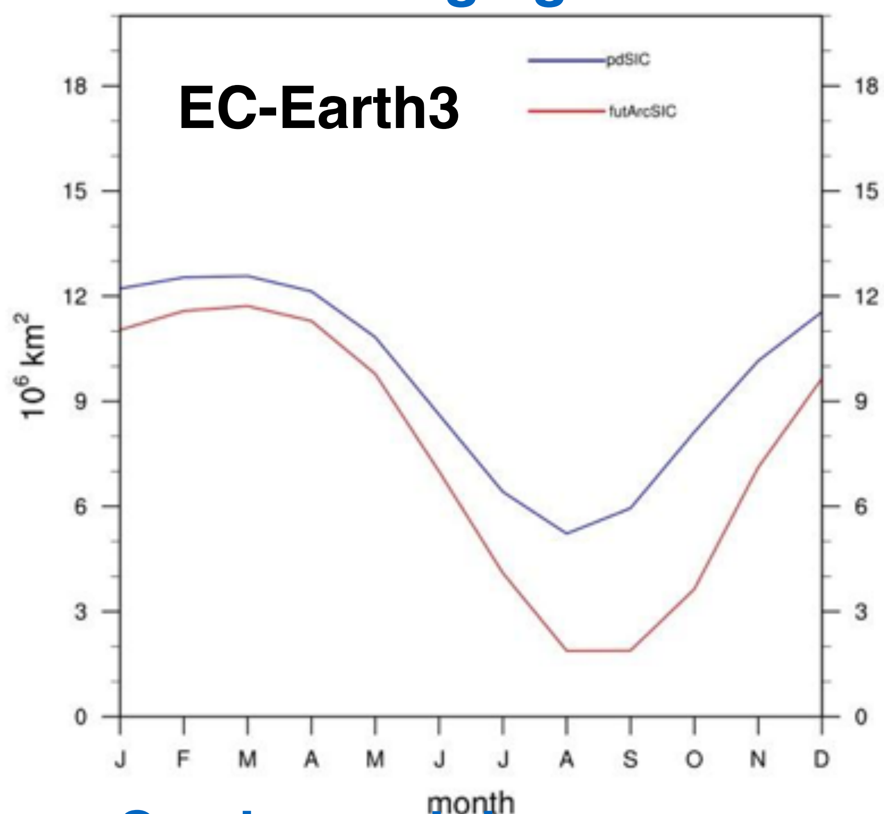
PAMIP long coupled simulations: Arctic sea ice perturbation

Arctic sea ice area
Yrs 51-100

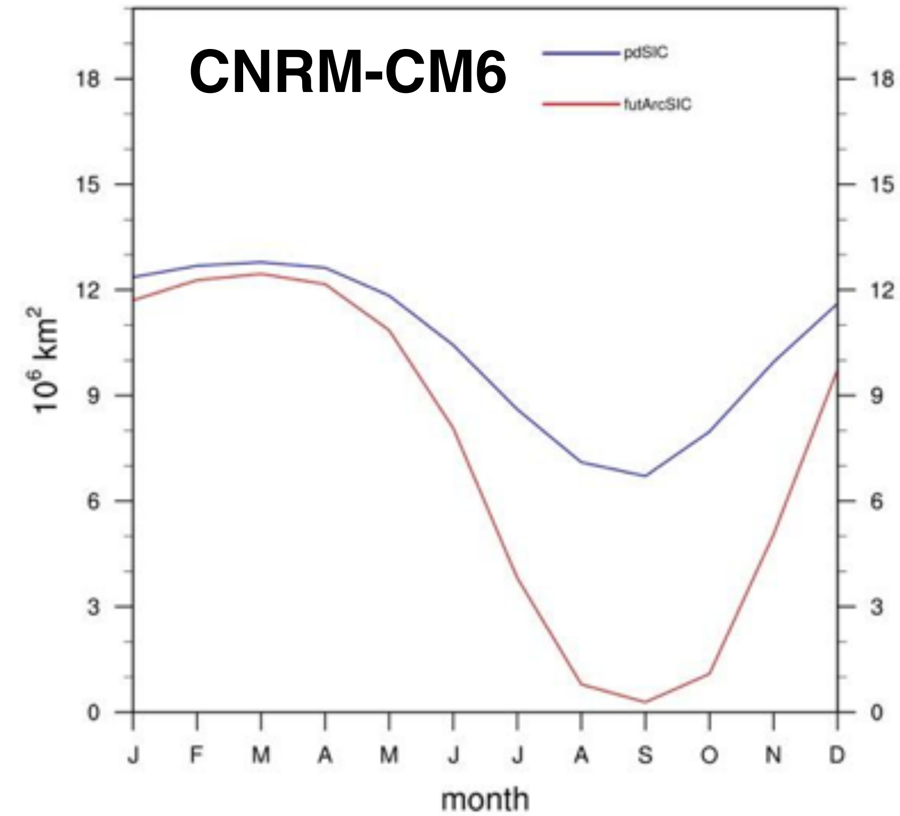
CTL: present day
PERT: 2C warming

- **4 coupled models**
- **Different protocols to melt sea ice**
- **100 yr simulations (after spin up)**

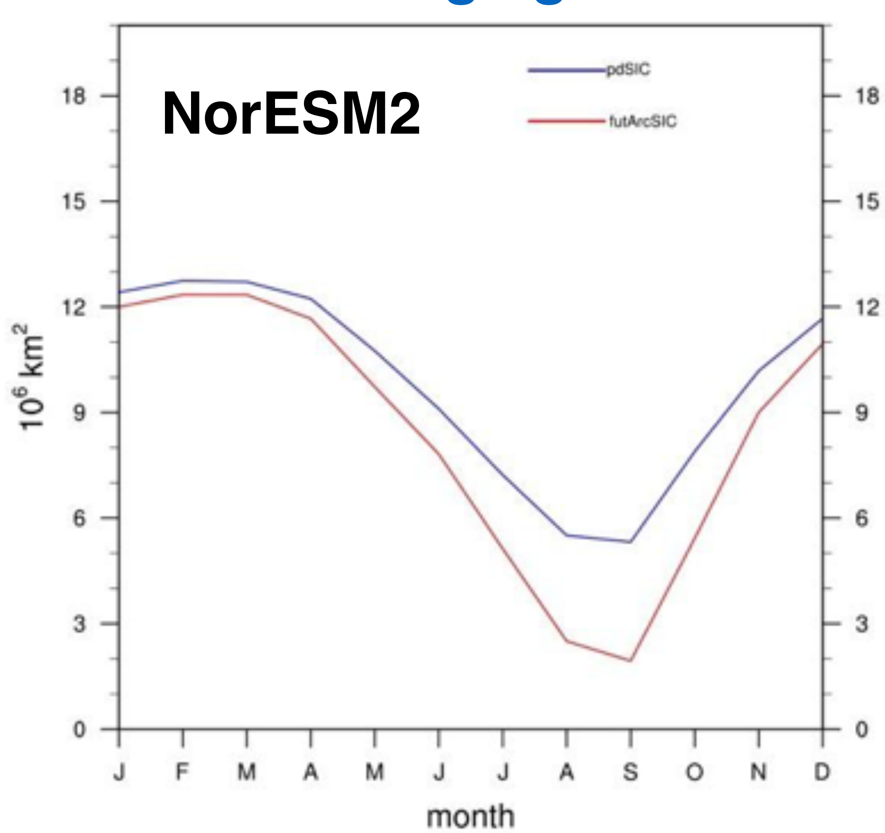
Sea ice nudging



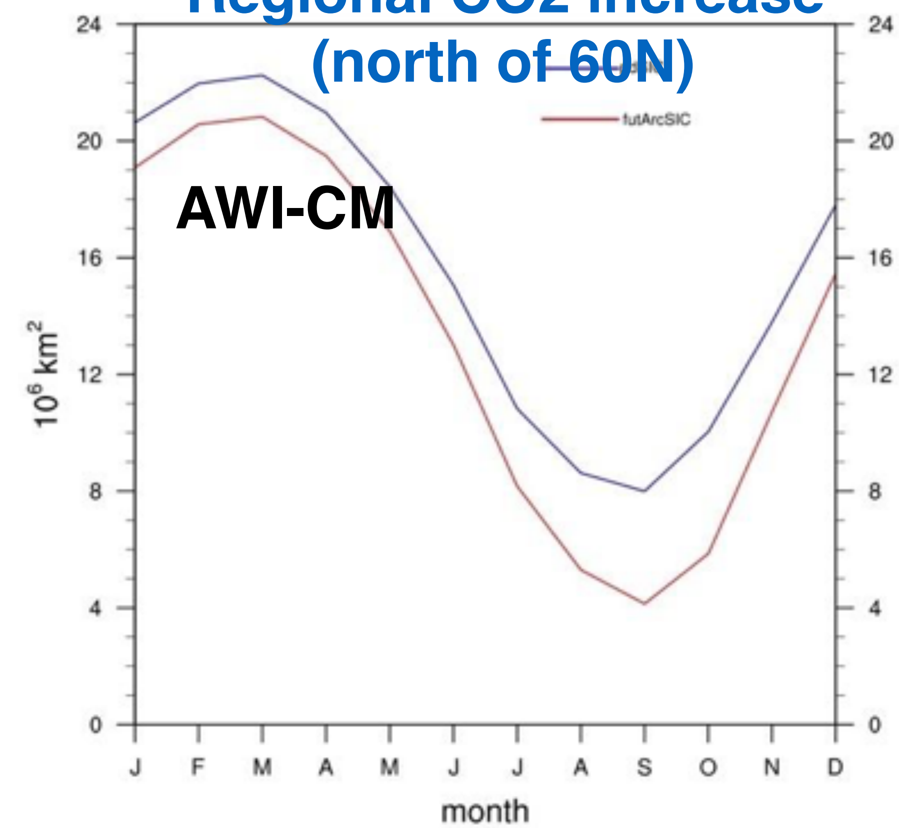
Albedo/conductivity changes



Sea ice nudging

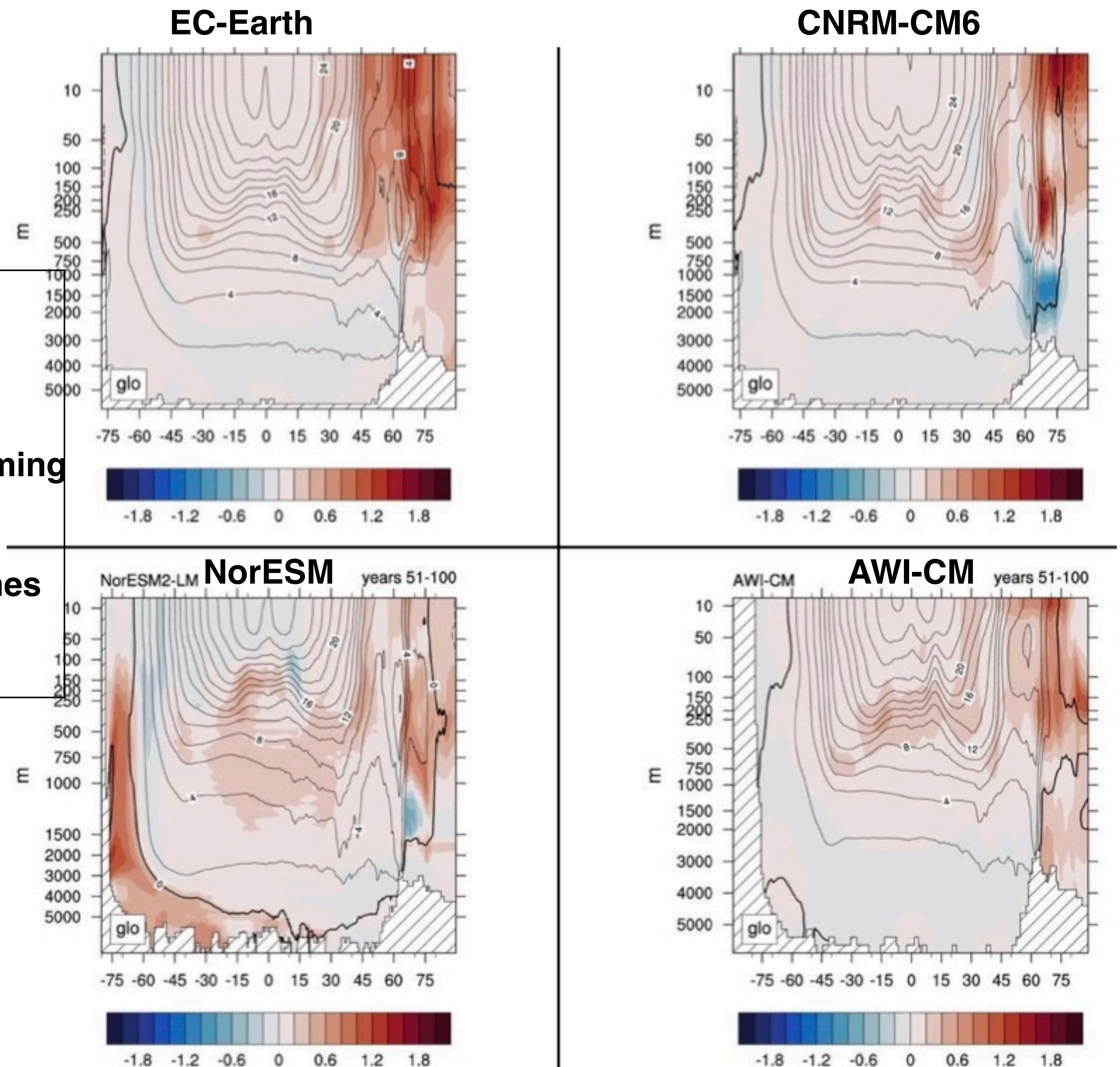


Regional CO2 increase (north of 60N)



Global potential temperature response (zonal mean)

PERT - CTL. Yrs 51-100



At high latitudes

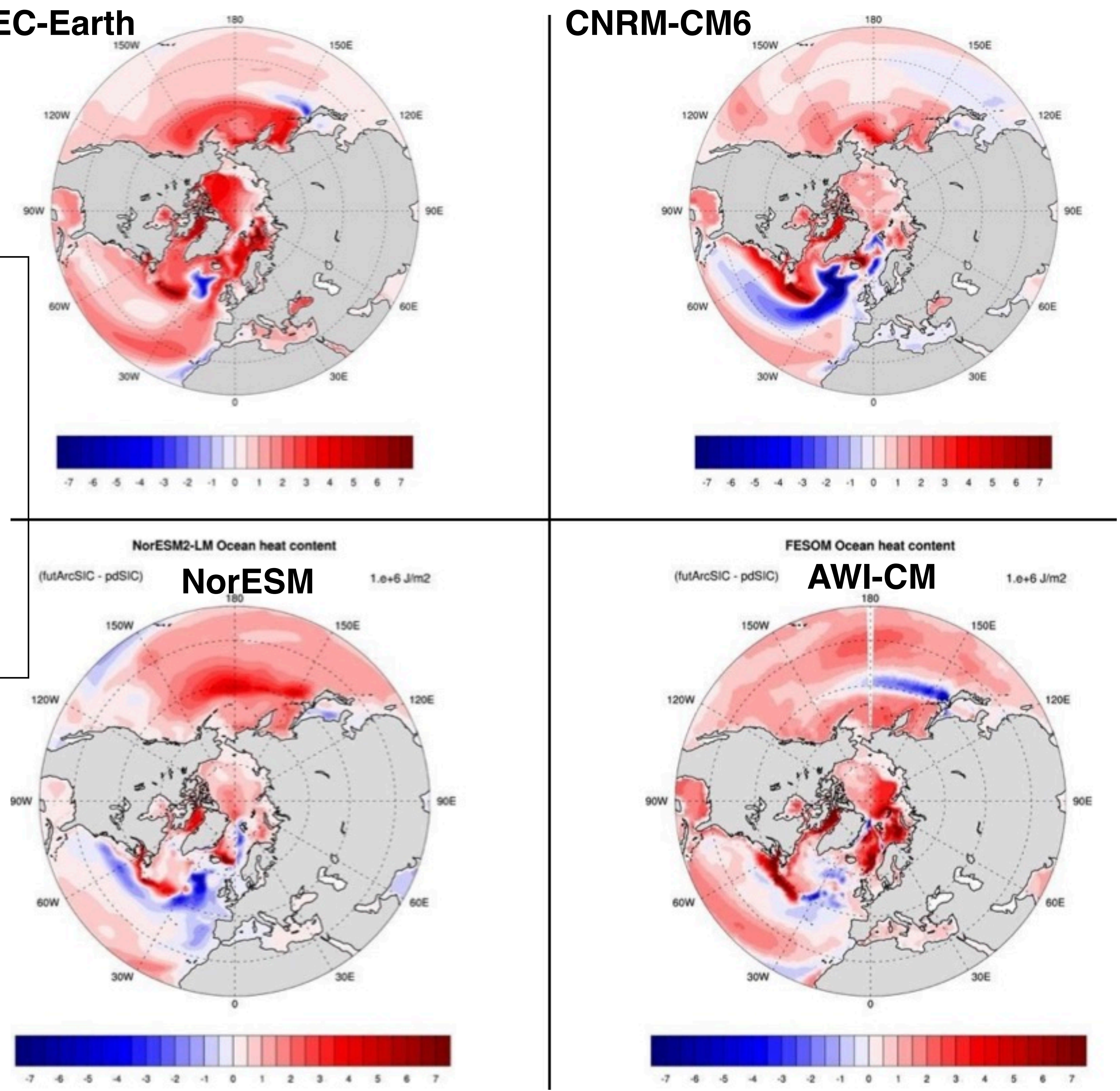
- **Warming in the upper 1000m**
- **Cooling or reduced warming below 1000m**
- **A weaker warming reaches the subtropics**

Ocean heat content response

OHC @300m

PERT - CTL. Yrs 51-100

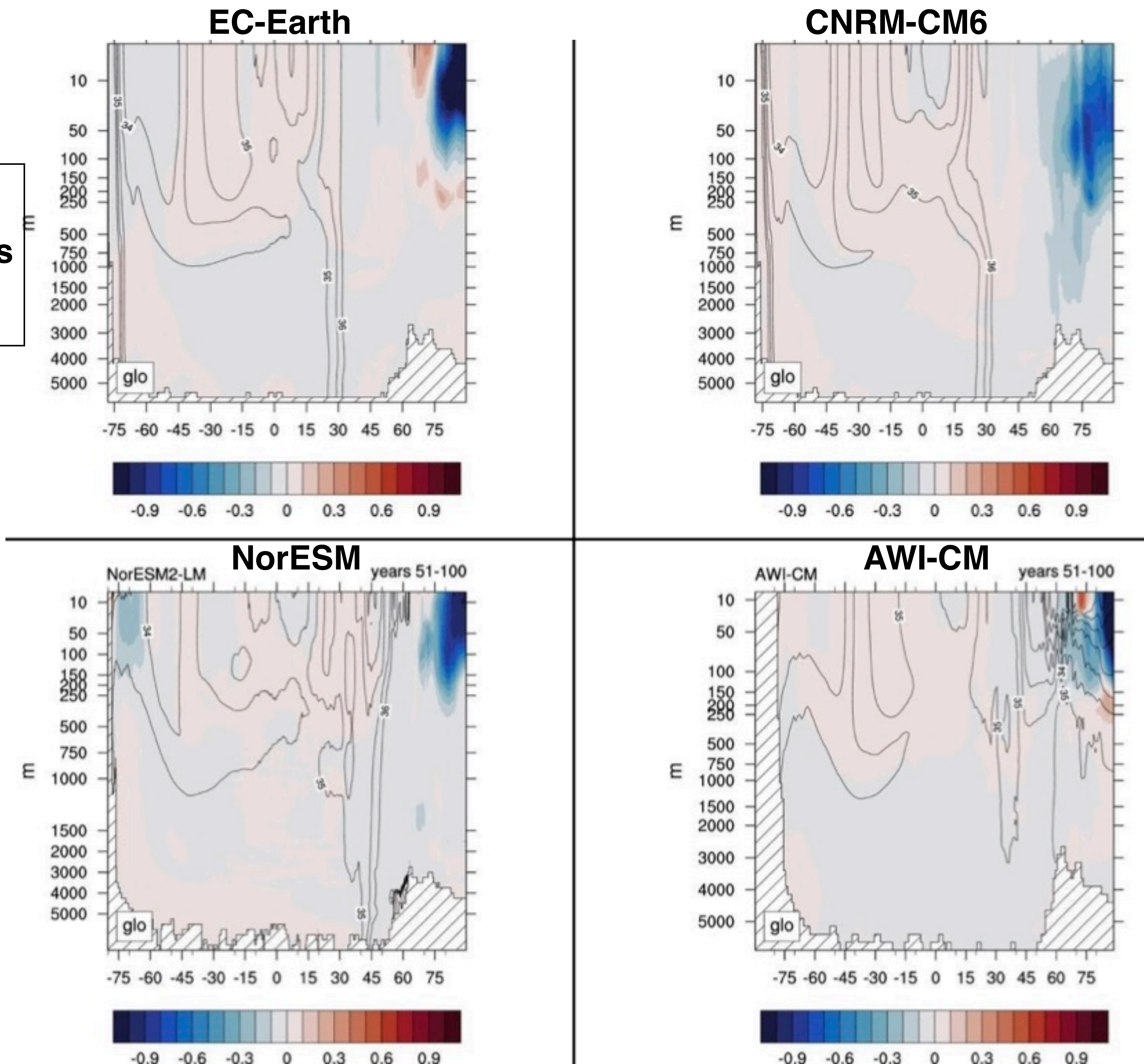
- **Warming in the Arctic**
- **Reduced warming in the North Atlantic eastern subpolar gyre, consistent with a weakening of the AMOC and North Atlantic current**



Global salinity response (zonal mean)

PERT - CTL. Yrs 51-100

Salinity changes more confined to high latitudes



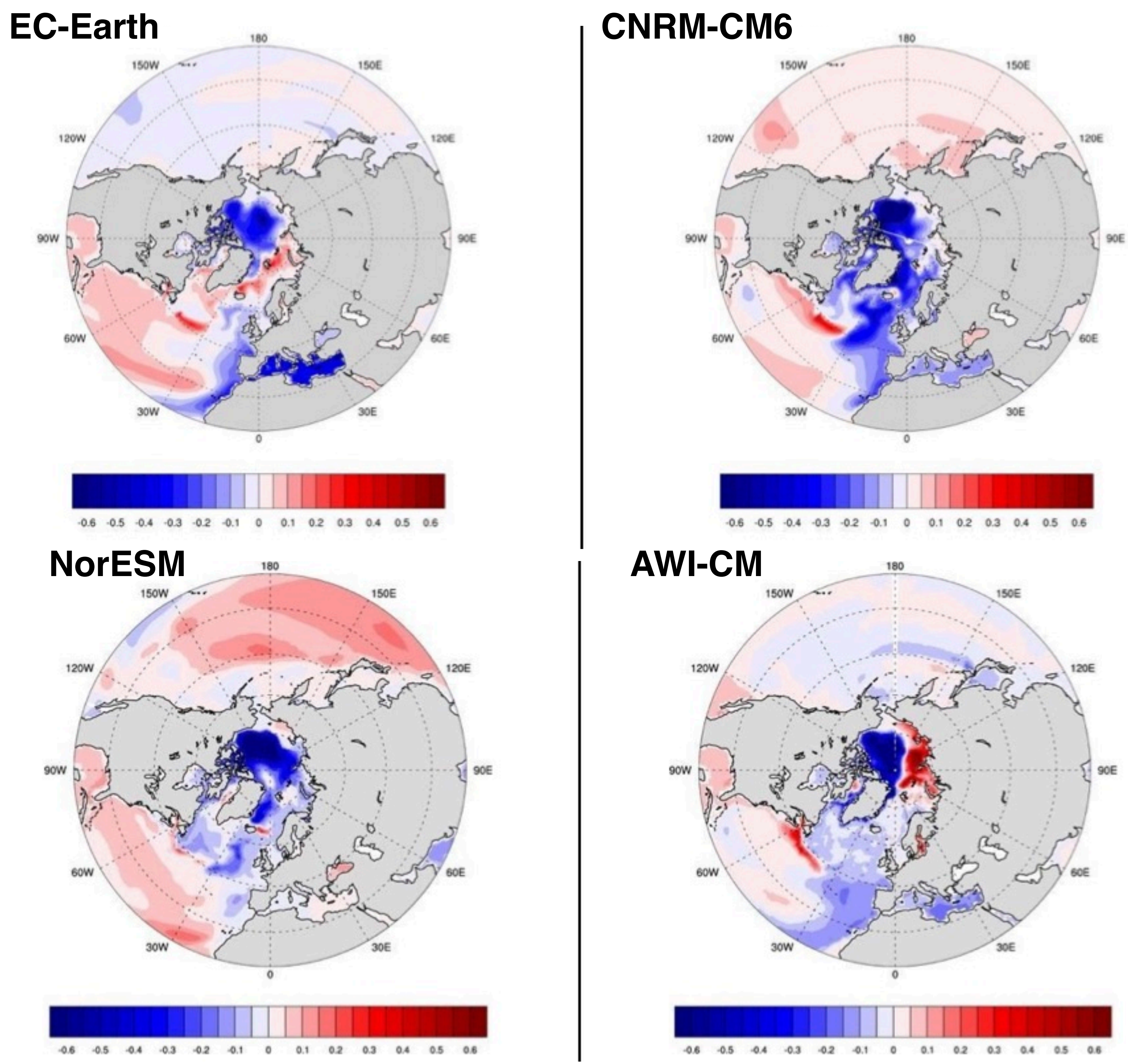
Salt content response

-FWC @300m

PERT - CTL. Yrs 51-100

- **Freshening of the Central Arctic and Beaufort gyre. Less good agreement in the eastern part of the Arctic.**

- **Dipolar pattern similar to the OHC**

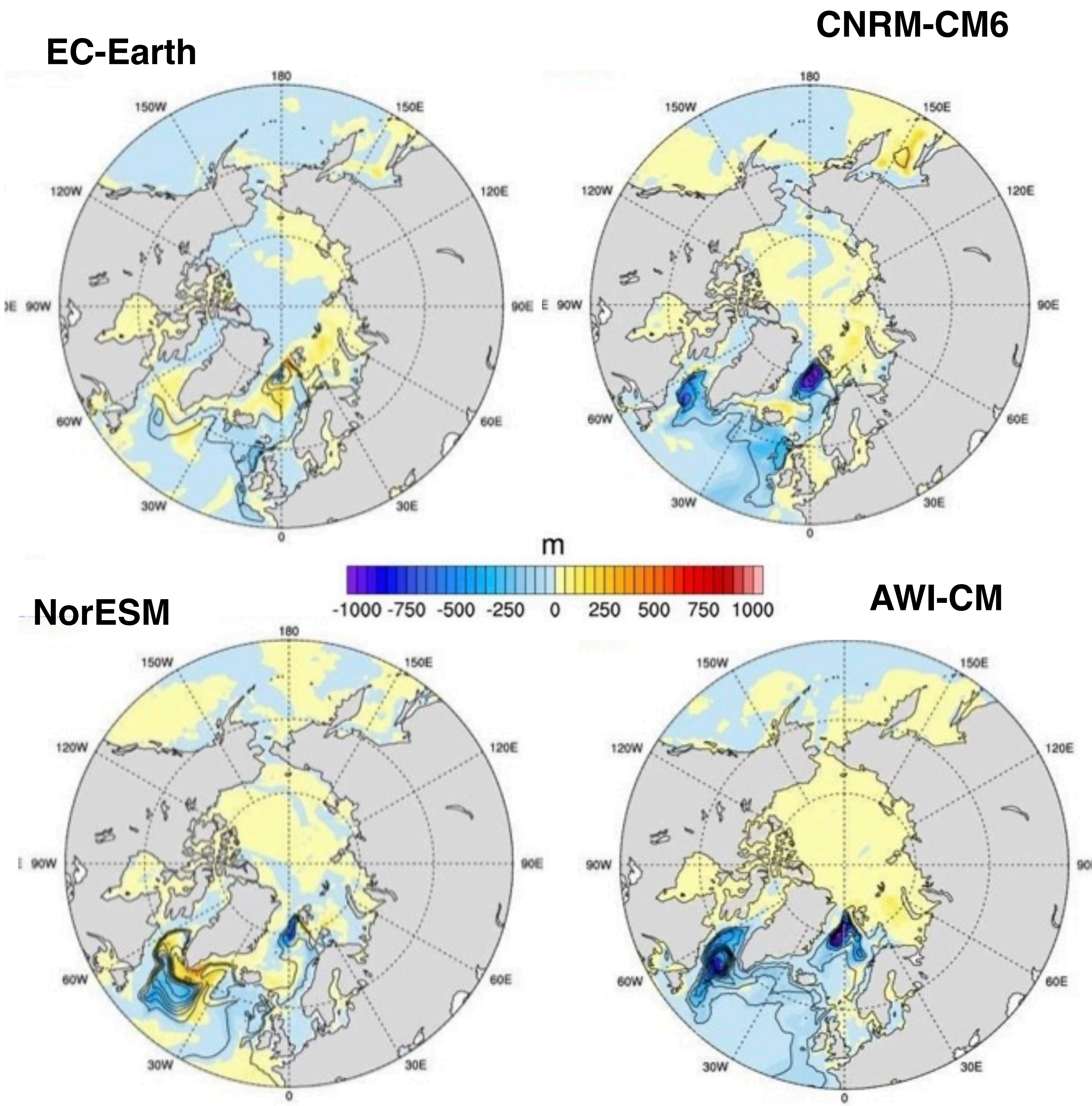


Changes in mixed layer depth

March mixed layer depth

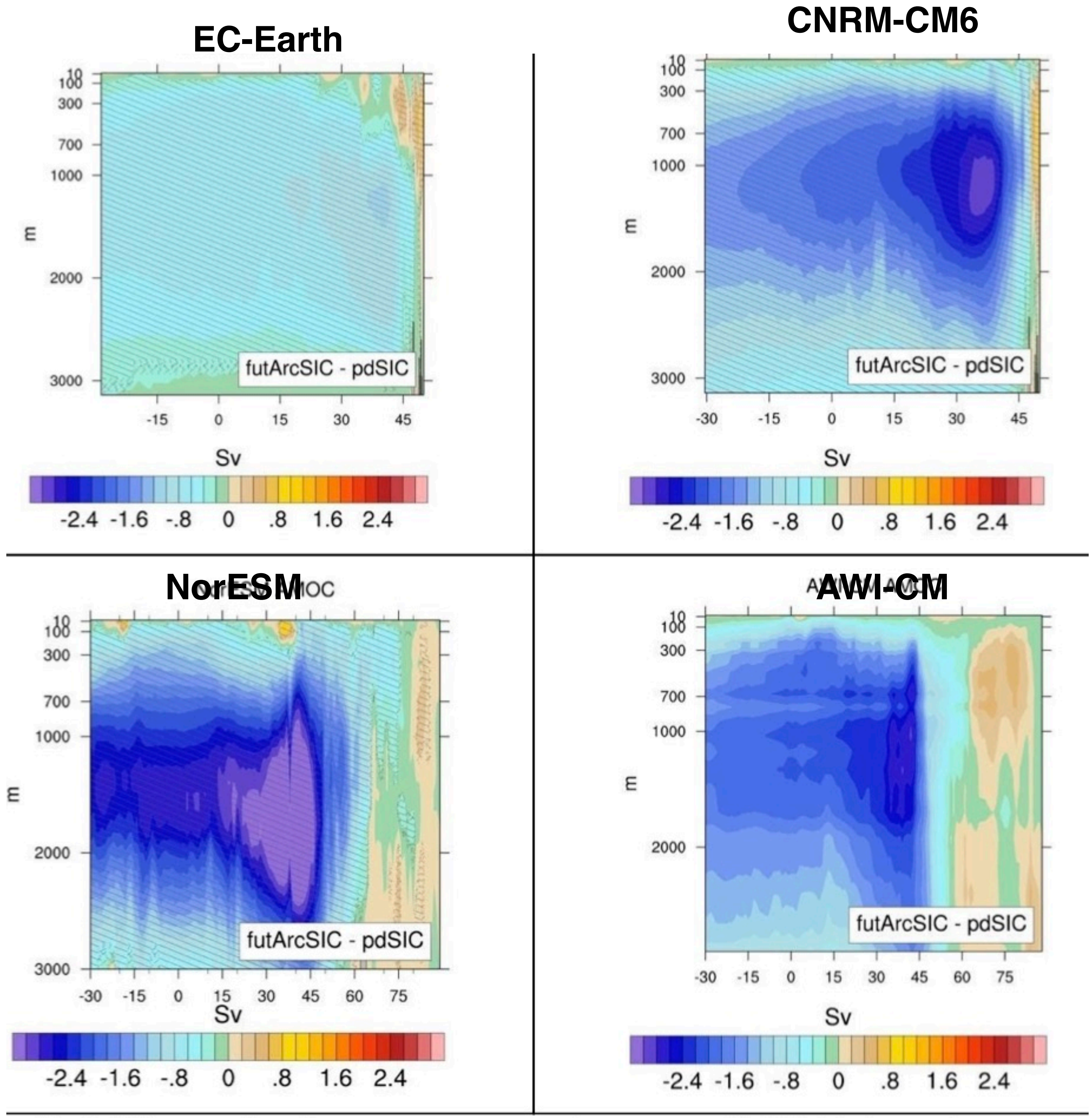
PERT - CTL. Yrs 51-100

- **Reduced deep water formation in the Labrador and GIN Seas.**
- **Density changes seem to be temperature-driven in the Labrador Sea and salinity-driven in the GIN Seas**
- **The timing of the response is model dependent**



AMOC response

- **Weakening of the AMOC in all the models**
- **Magnitude is model-dependent (1Sv to 3Sv) and not directly related to the amount of sea ice loss**

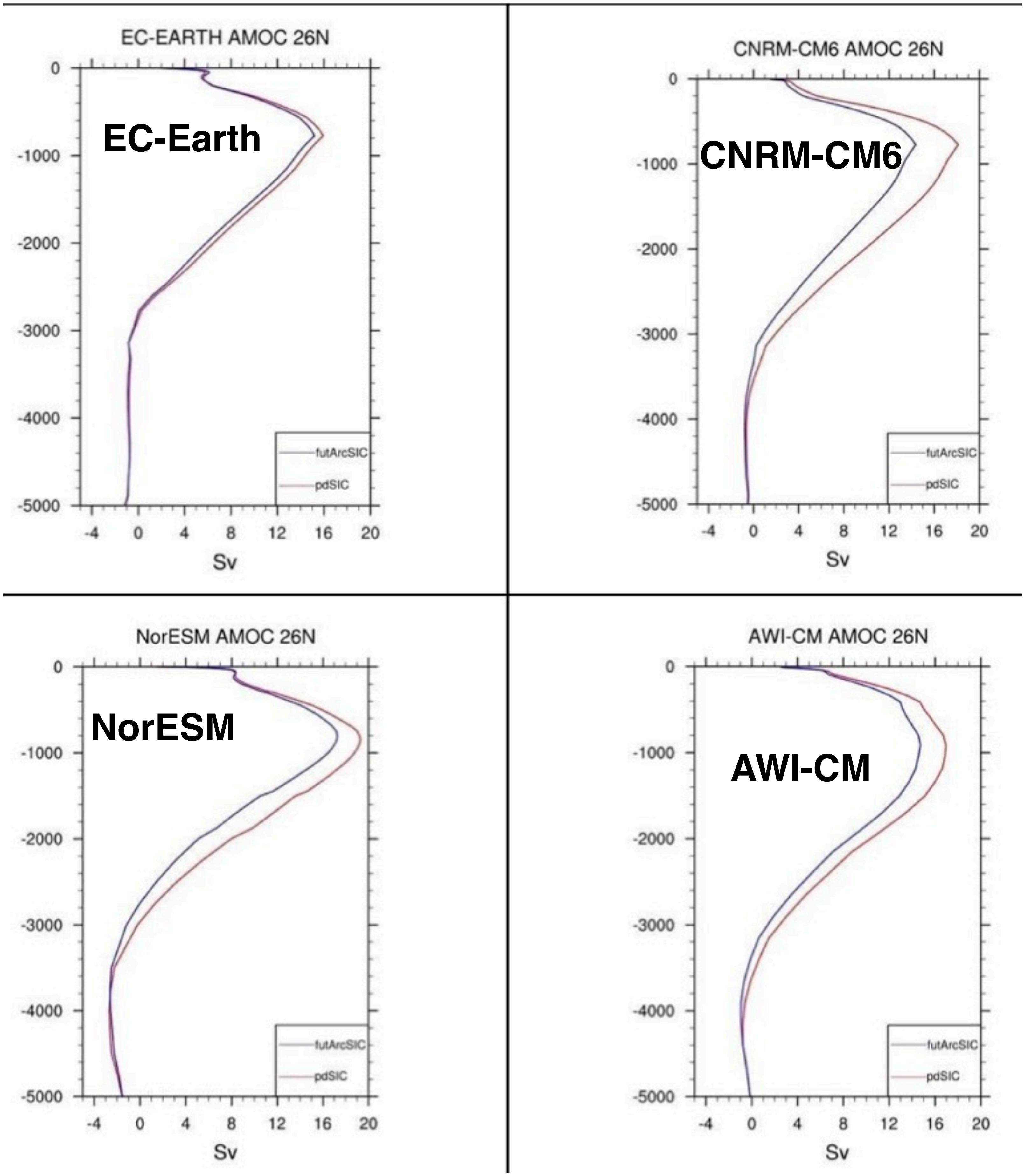


AMOC response at 26N

CTL: present day

PERT: 2C warming

- **Weakening of the NADW cell**

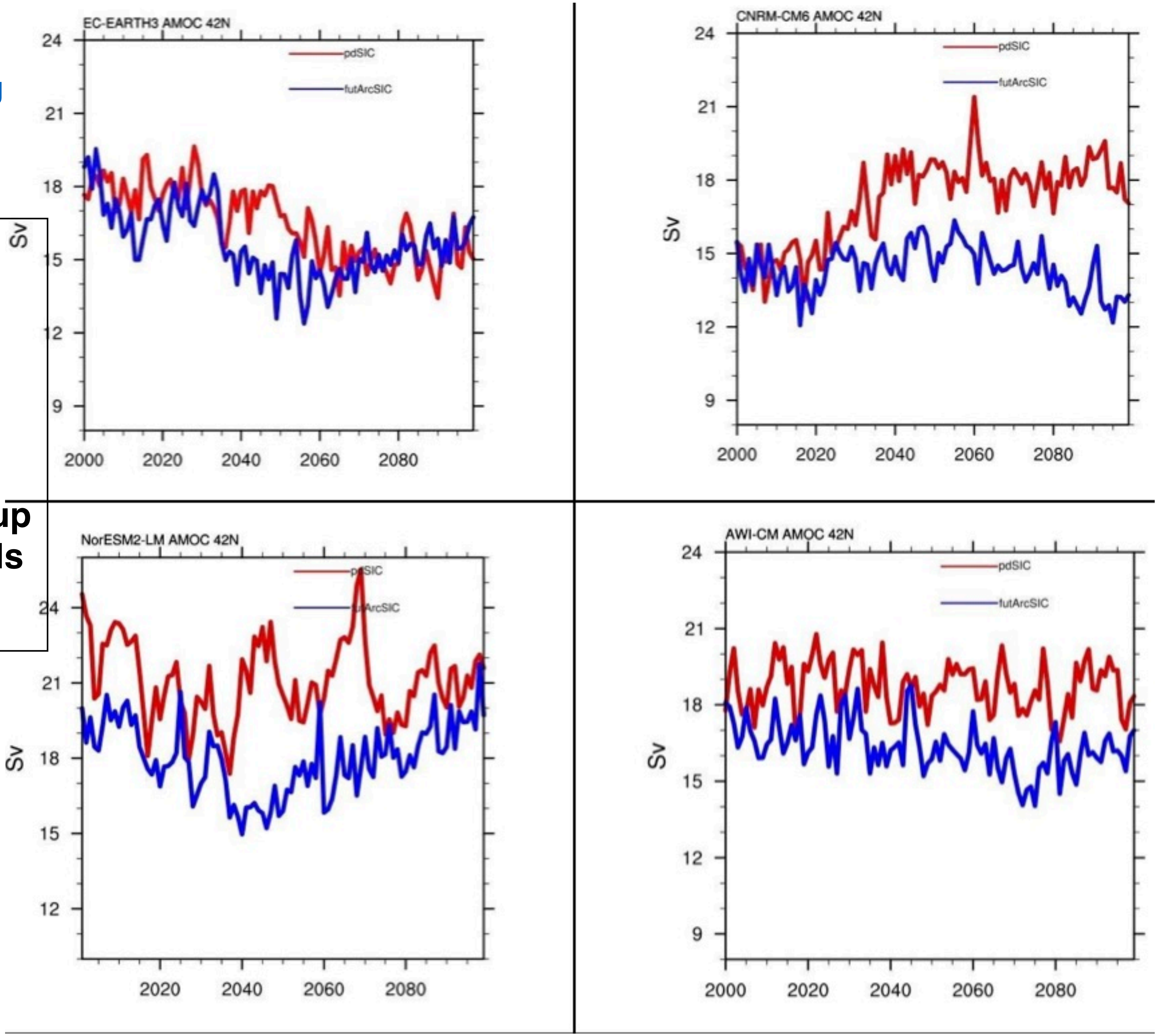


AMOC response at 42N

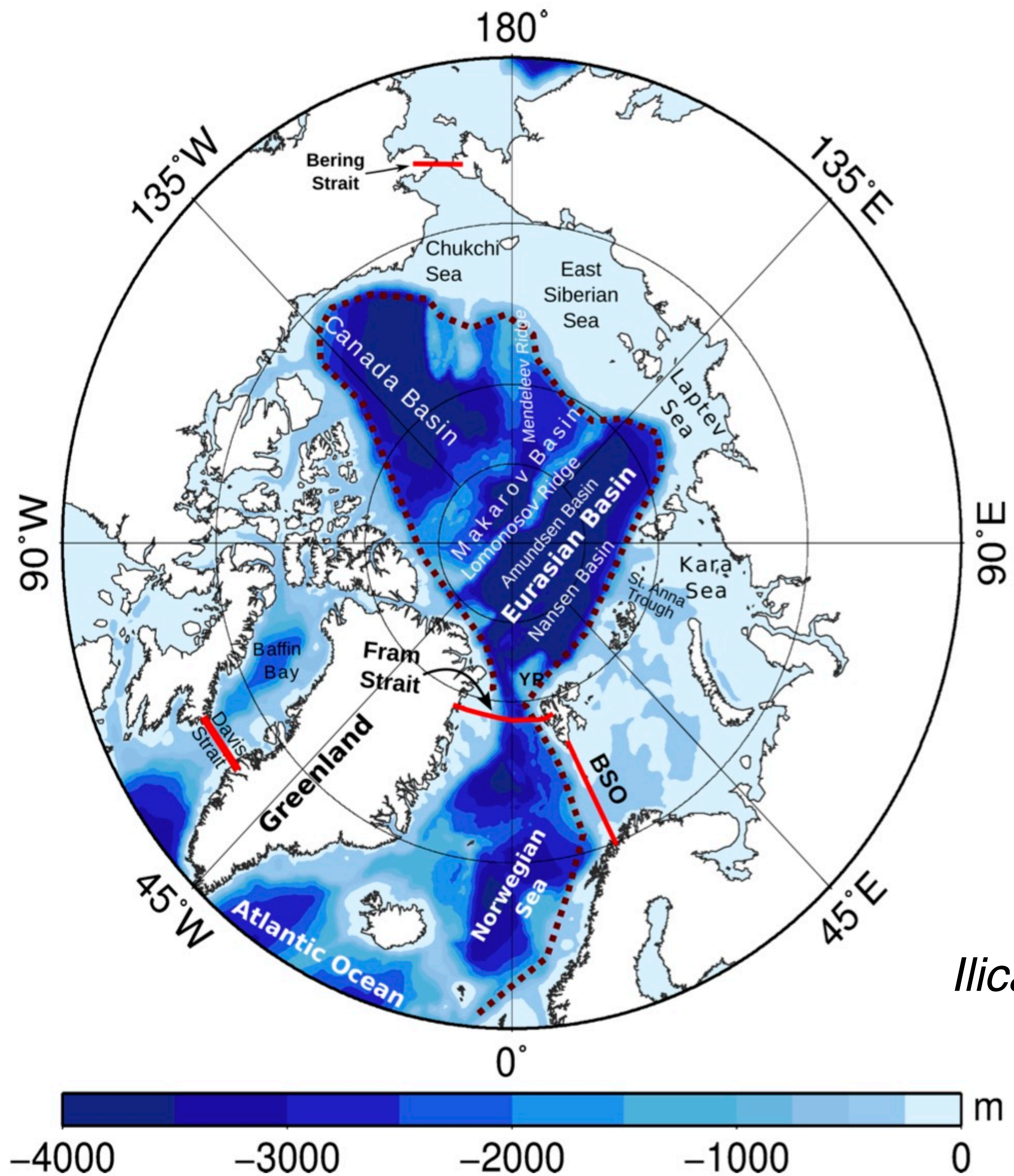
CTL: present day

PERT: 2C warming

- The recovery of the AMOC is model-dependent
- Different time adjustment probably due to different spin up and different protocols

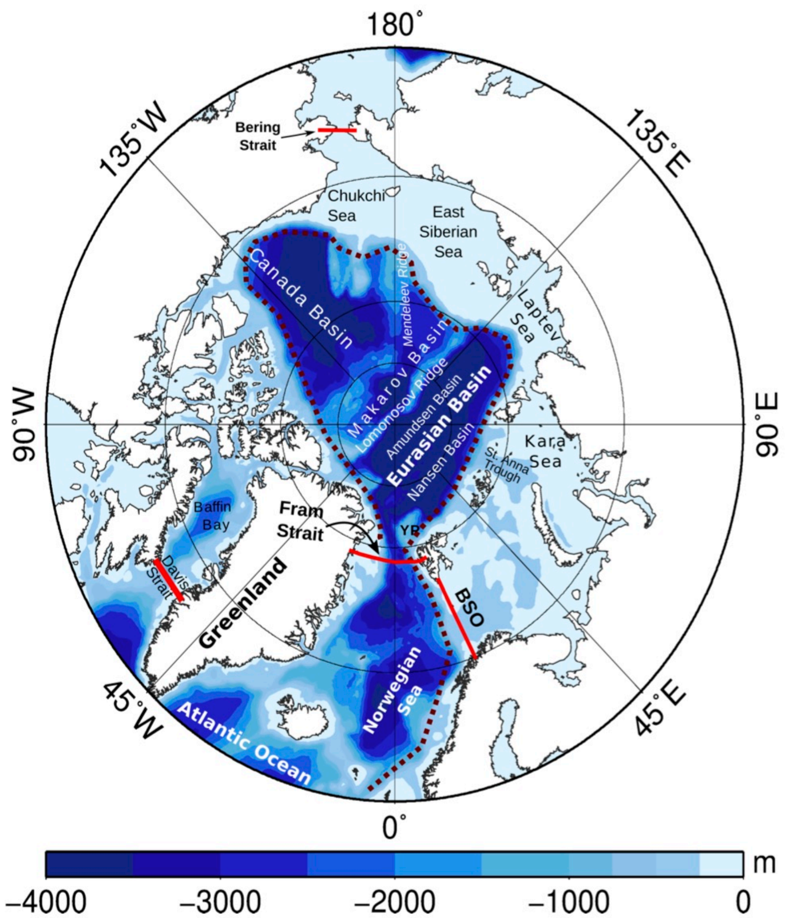


Investigating changes in volume and heat transport



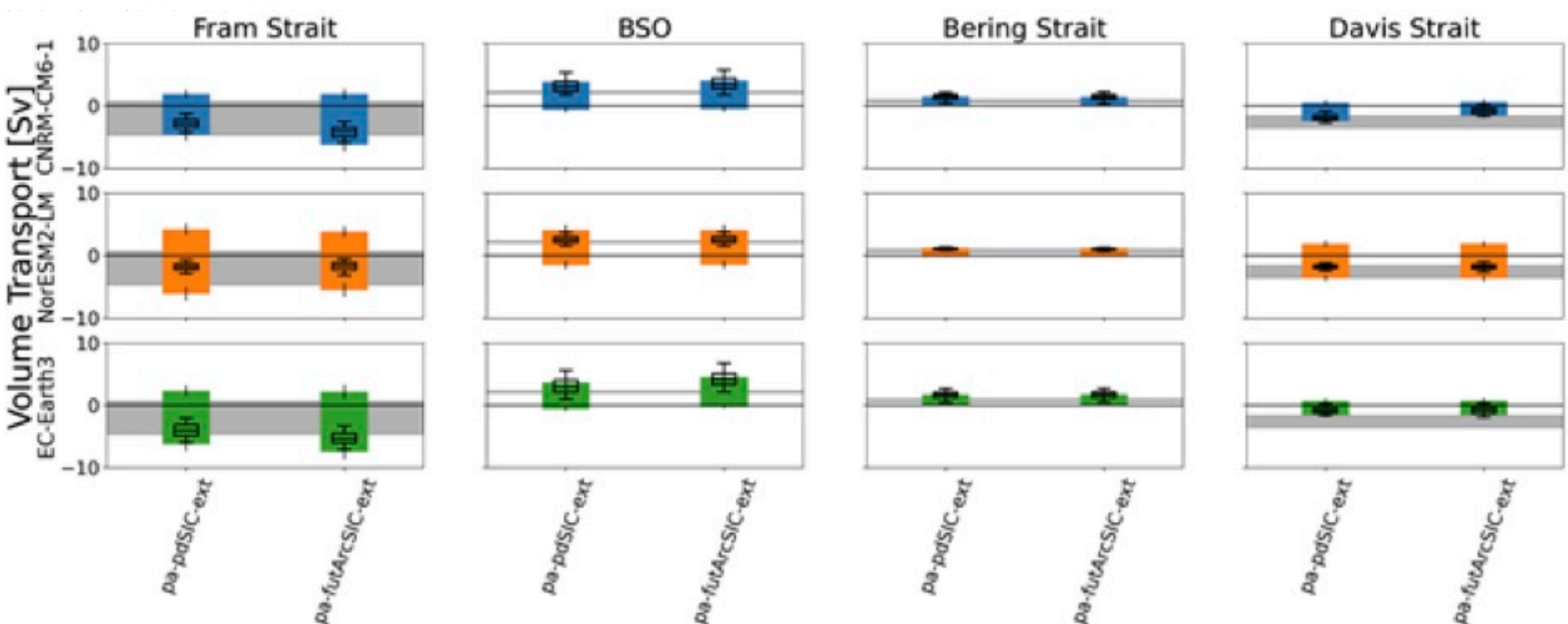
Ilicak et al. (2016)

Volume transport



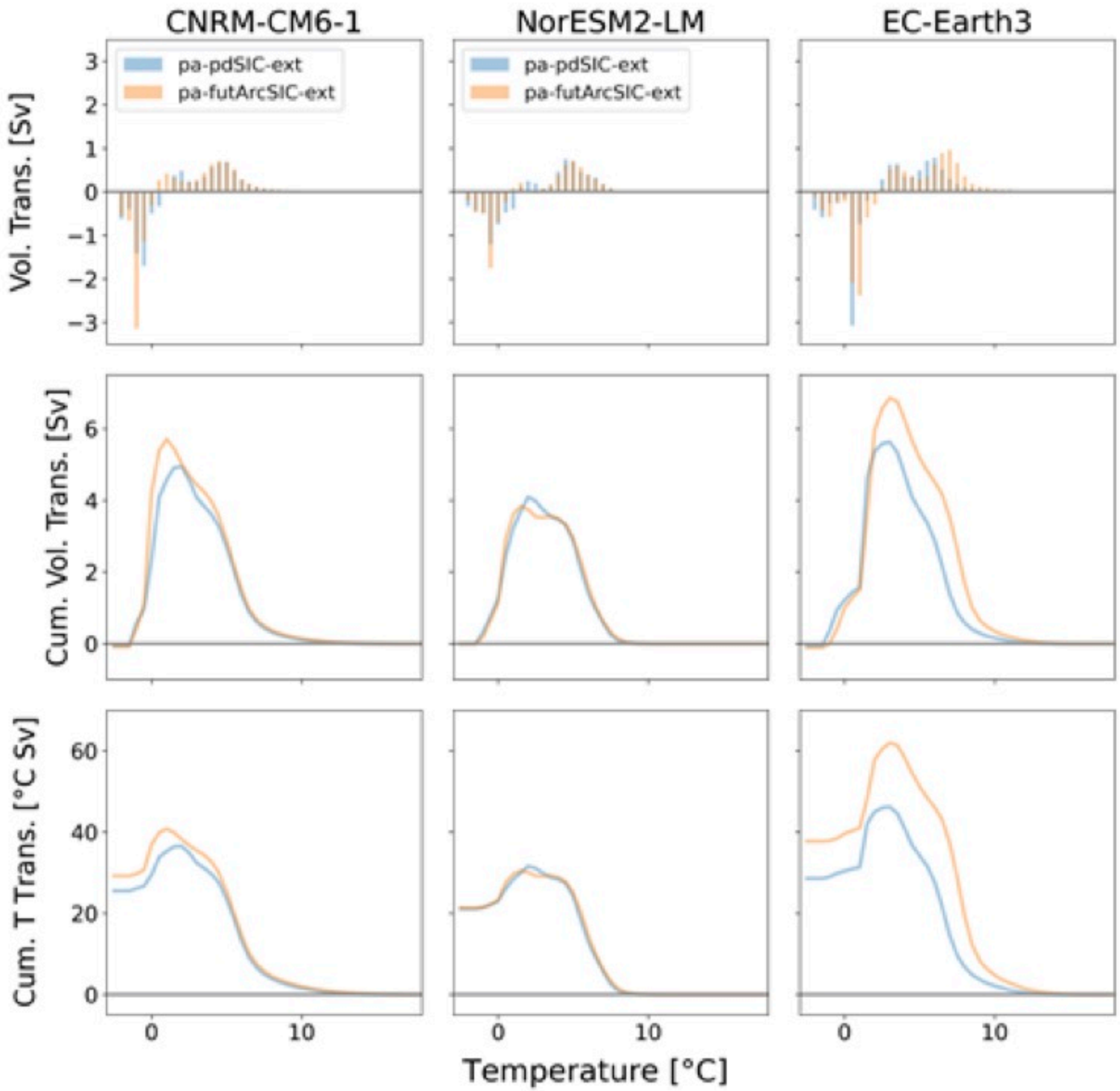
- **2 out of 3 models simulate an increase in the BSO volume transport (14% in CNRM-CM6, 40% in EC-Earth3). Compensated partly by an outflow through Fram Strait.**
- **No change in NorESM2**

Thanks to Aleksi Nummelin



Transport changes in temperature space

- The models that simulate an increased inflow of Atlantic waters through BSO show a larger heat transport into the Arctic
- Largest increase in EC-Earth3 due to a larger inflow and a shift of the inflow toward warmer classes, i.e., a stronger and warmer inflow of Atlantic waters.
- EC-Earth also has the largest mean heat transport values under present day conditions.
- Non trivial relationship between AMOC and ocean heat transport in future climate (Bitz et al. 2006, Oldenburg et al. 2018)



Thanks to Aleksi Nummelin

Conclusions

- A strong reduction of Arctic sea ice induces significant climate impacts in the atmosphere and the ocean in the Arctic and beyond, at lower latitudes
- The atmospheric response is characterized by
  - a weakening of midlatitude westerlies and a southward shift of the subtropical jet in late fall/early winter => negative NAM
  - A weakening of the polar vortex in late fall/early winter that is difficult to detect because of the large internal variability. Possible key role of the QBO.
  - Regional cooling over Central Eurasia driven by dynamical changes

- The atmospheric response to a more moderate sea ice loss (2ºC global mean warming) is comparable but much smaller in magnitude.
- A multi-model analysis allows to show the uncertainty of the atmospheric response over mid latitudes. Large internal variability in the models.
- Stronger response when coupling with the ocean is allowed
- Weak effect of the model horizontal resolution

- The oceanic response to Arctic sea ice loss includes a warming and freshening of the Arctic, a reduction of the AMOC in response to a restratification in the deep water formation regions, weak changes in the volume and heat transport into the Arctic.

Discussion

- Difficult to compare the results of the two experiments because not a clean comparison (different background states, different magnitude and geographical pattern for the forcing, different model configuration, different protocole)

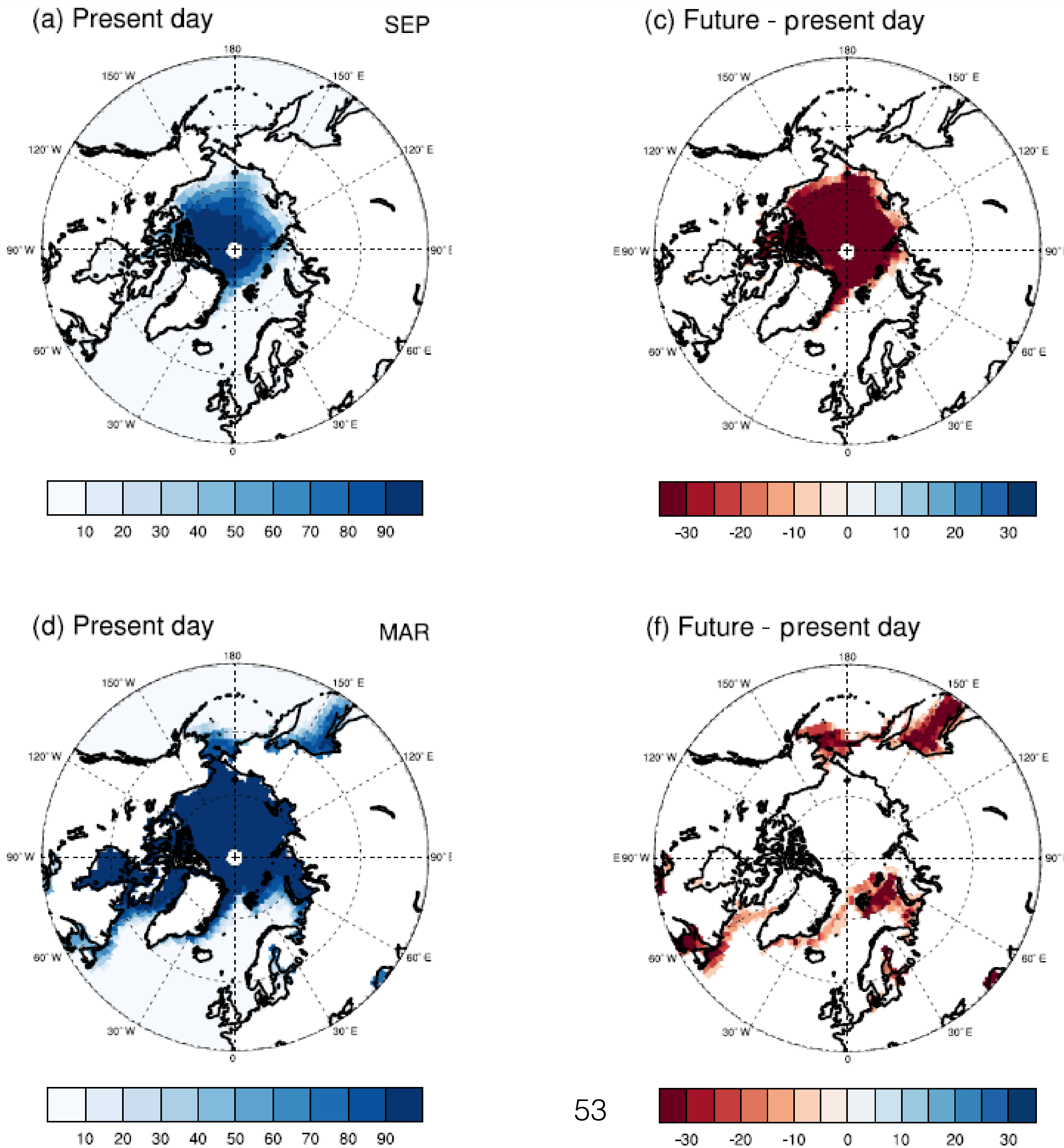
=> Good illustration of the limitations that motivated the coordinated PAMIP experiments

- Albedo: strong sea ice forcing in summer and fall but weak in winter

- A lot of members are needed to detect a significant response: very small signal, in particular compared to the strong forcing of CO_2

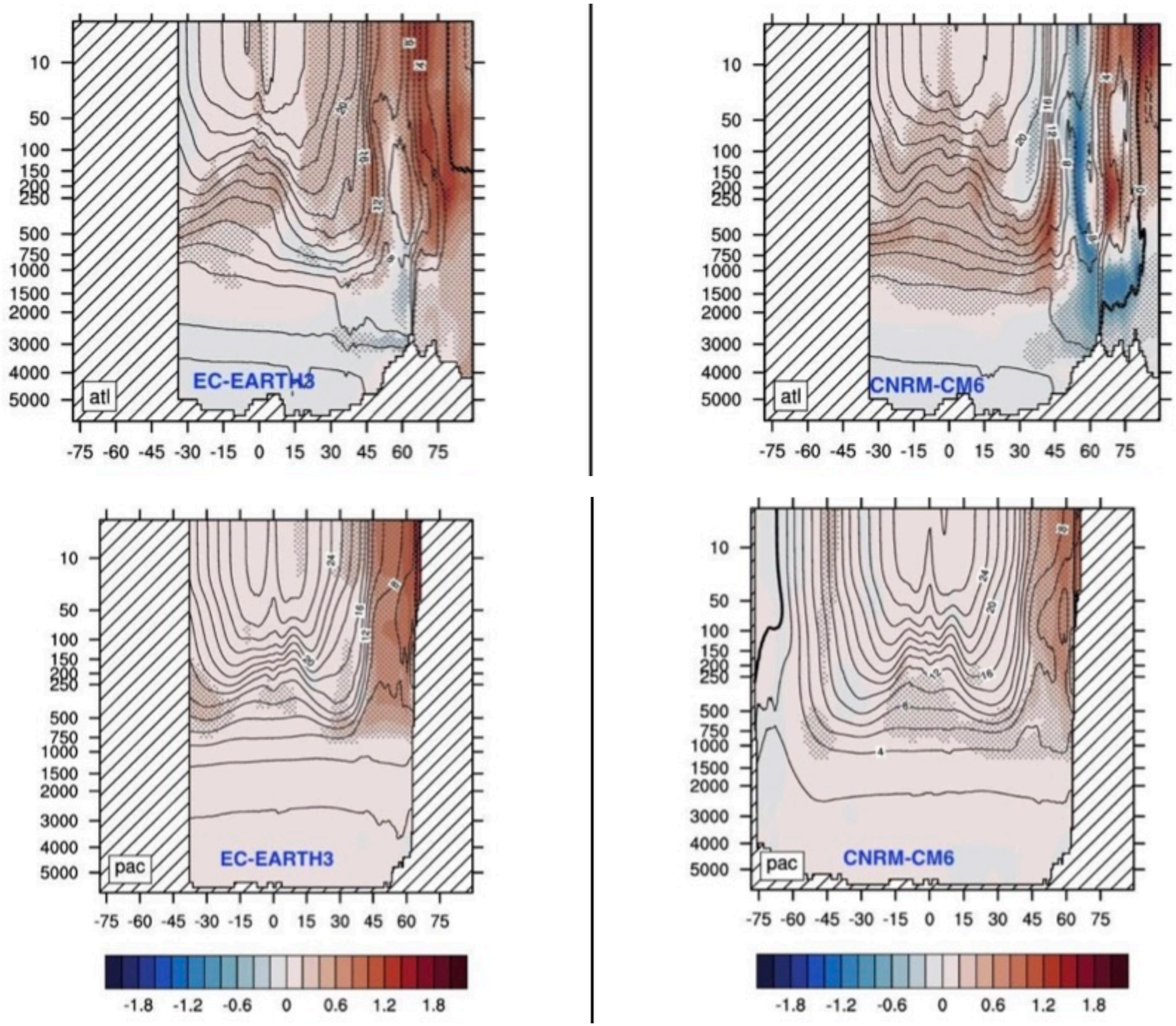
- The use of different protocol to constrain sea ice in a coupled framework is a source of uncertainty to assess the long-term multi decadal oceanic response to sea ice reduction. Further work is needed to assess how well the different protocols reproduce the true response to future sea ice melting induced by greenhouse gases.

Arctic sea ice forcing



Smith et al. (2019)

Basin temperature response



Zonal mean salinity response