Diagnosing Changes of Winter NAO in Response to Different Climate Forcings in a Set of Atmosphere-Only Timeslice Experiments

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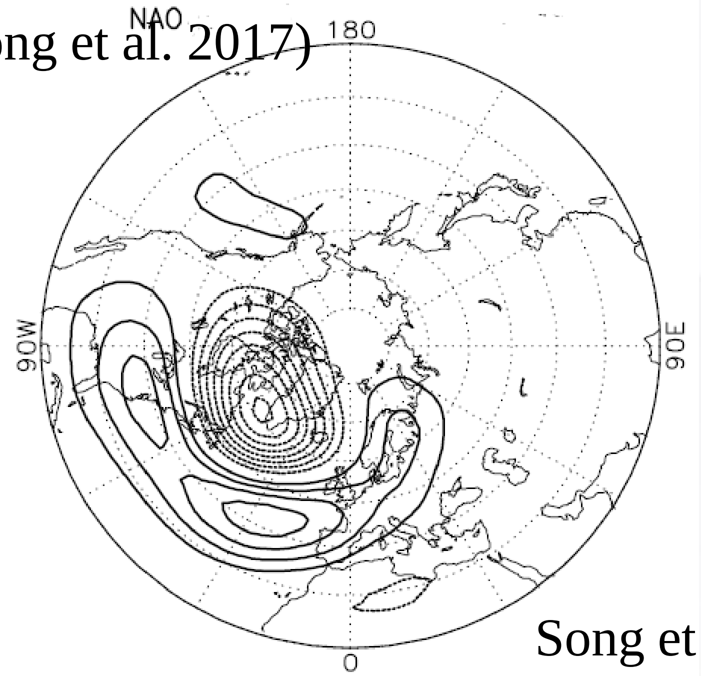
North Atlantic Oscillation (NAO)

The NAO is a major mode of interannual variability, and manifests as a seesaw in atmospheric mass between the subtropical **Azores high** and the polar **Icelandic low**, which is most pronounced during boreal winter. (Walker et al. 1932)

The NAO has a great influence on climate change and variability in the mid-latitudes, but owning to the complex and various impact factors, the understanding of the NAO is still a frustrating issue. (Xu et al. 2016; Jeong et al. 2017)



Song et al. 2009

Outlines

- Models, Experiments, and Methods.
- Changes of Winter NAO Variability in Response to Different Forcings.
- Possible Causes of the NAO Variability Changes in Response to Different Climate Forcings.
- Summary and Discussions.

- **Models used in this study:**

  HadGEM-ES, CCSM4, CNRM-CM5

- **Experiments used in this study:**

  One of the important reason for causing climate change progress hampered is the very limited outputs for investigating cloud feedback mechanisms.
  (Andrews et al. 2012; Webb and Lock 2013)

Cloud Feedback Model Intercomparison Project (CFMIP)
The primary objective of CFMIP is to inform future assessments of cloud feedbacks through improved understanding of cloud-climate feedback mechanisms and better evaluation of cloud processes and cloud feedbacks in climate models. (Web et al. 2017)

- **Experiment design**

A set of pilot experiments from CFMIP-3

Decompose 4xCO2 forcing in coupled model into different forcings

piSST (an atmosphere-only experiment with pre-industrial control run SST forcing)

piSST4K (the same as piSST, but with SST uniformly increased by 4K)

piSSTFuture (the same as piSST, but with a patterned SST anomaly)

piSST4xCO2 (the same as piSST, but the concentration of CO_2 is quadrupled (only by the radiation scheme))

piSSTCO2Veg (the same as piSST4xCO2 but this increase is seen by both the radiation scheme and the plant physiological effect)

(Not used in this study)

Methods

NAO index (NAOI): the difference between 35^{o}N and 65^{o}N in the normalized monthly SLP zonal-averaged over the North Atlantic region from 80^{o}W to 30^{o}E. (Li and Wang 2003)

The responses in distinct experiments:

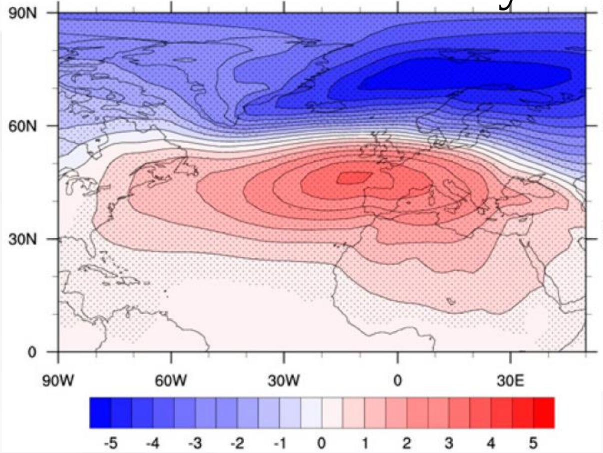
a) Uniform SST warming: piSST4K-piSST

b) SST pattern change: piSSTFuture-piSST4K

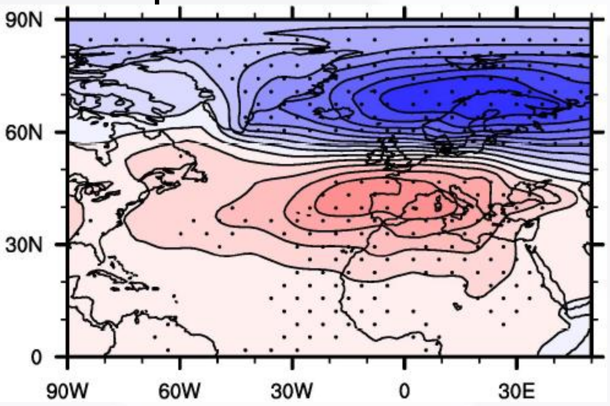
c) 4xCO2 radiation effect: piSST4xCO2-piSST

The comparison of **regression patterns of winter sea level pressure** (SLP, hPa) onto the standardized NAOI between model simulations and observation

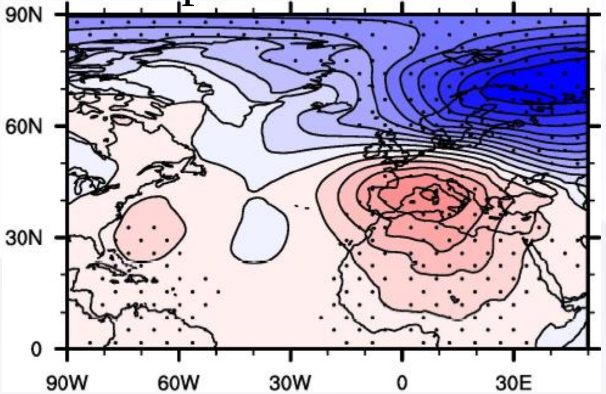
In 1948–2016 for NCEP/NCAR reanalysis



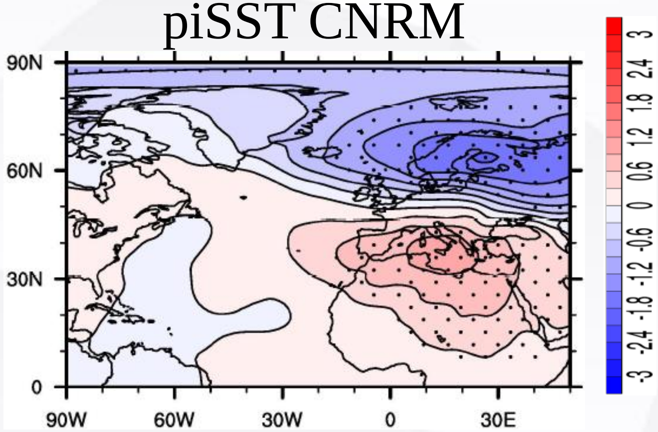
piSST HadGEM2



piSST CCSM4

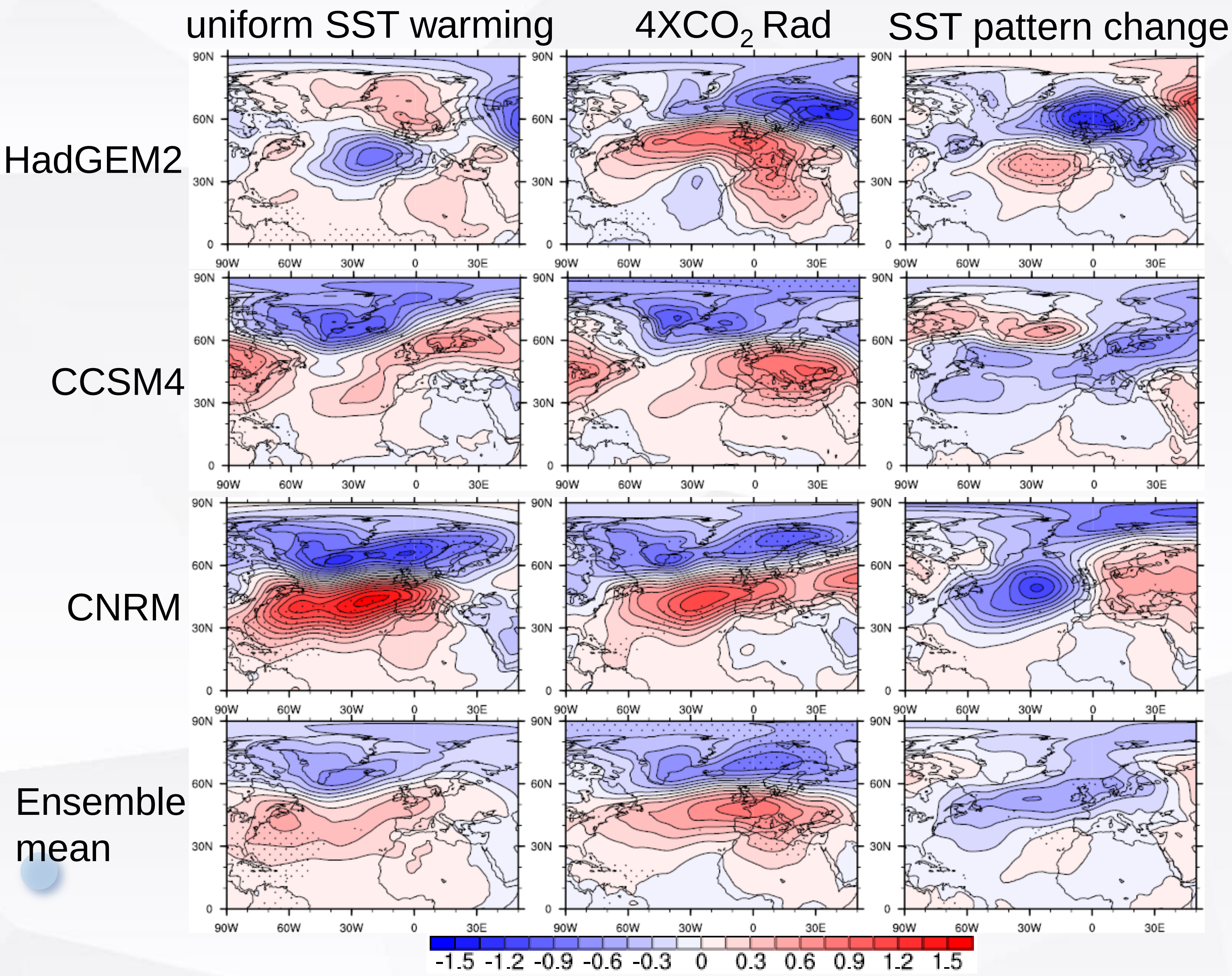


piSST CNRM



The three models generally capture the features of winter NAO pattern well in the piSST simulations.

Changes of **winter SLP patterns** (hPa) regressed onto the standardized NAOI for different forcings



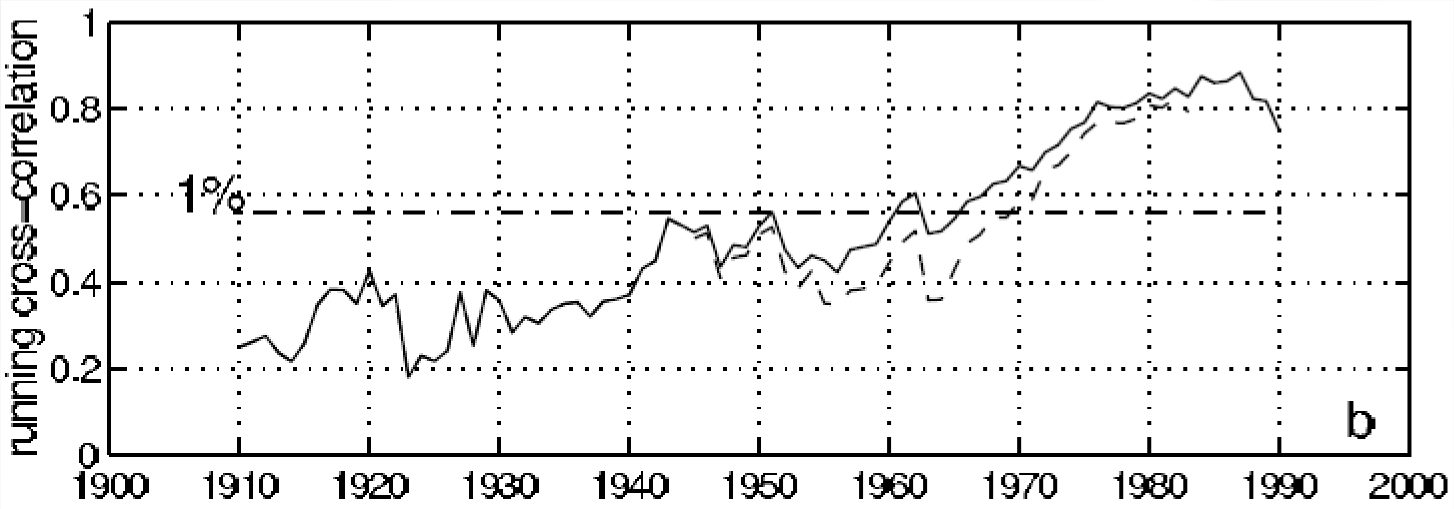
The influences of uniform SST warming and the direct CO2 radiative effect could enhance winter NAO variability.

The projected future SST pattern change in each model drive different responses in the regression pattern of SLP.

The comprehensive understanding of the **mechanisms** of NAO change, particularly under future scenarios, is essential for producing more accurate climate model simulations.
(*Jeong, et al. 2017*)

Question: what are the main reasons responsible for the NAO variability changes？

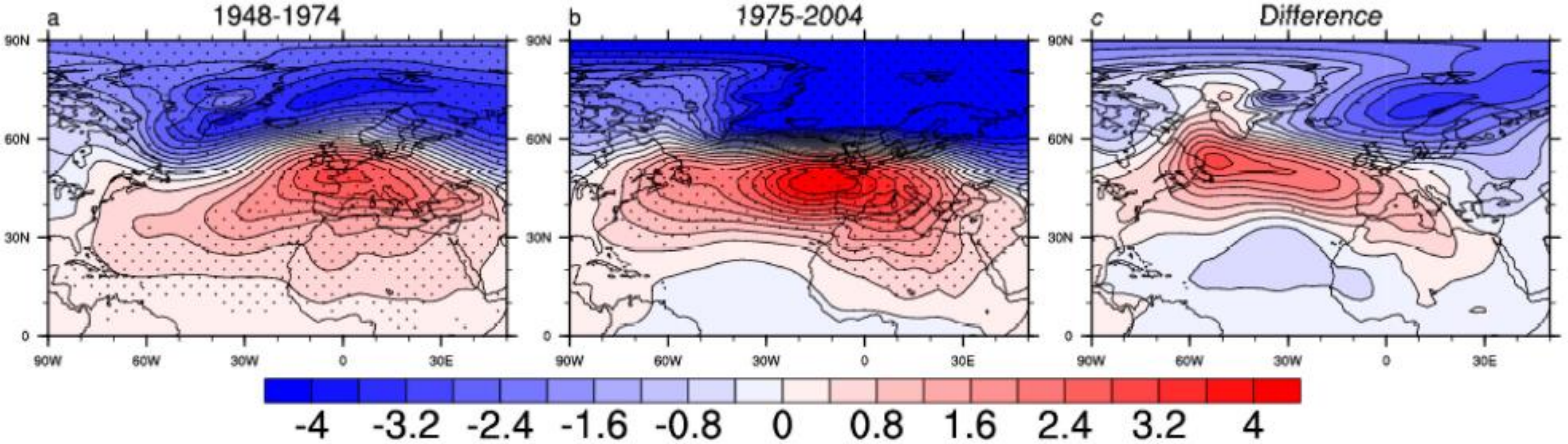
Dong et al. (2011) and Lu and Greatbatch (2002) pointed out that the **mean zonal wind** changes could have an influence on the NAO variability change by shifting the axis of the North Atlantic storm track, which are probably associated with eddy feedback change.



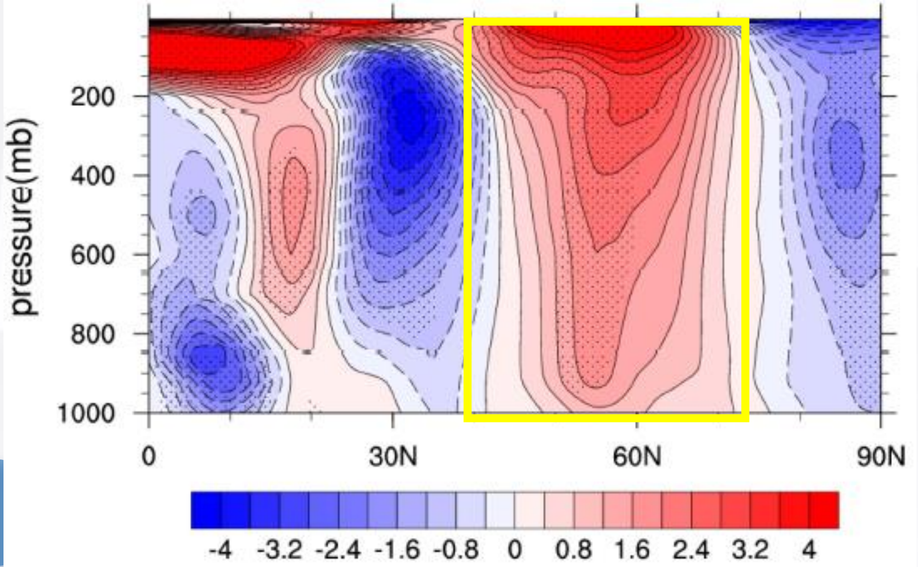
The NAOI is highly correlated with the storm index (Lu and Greatbatch. 2002; Rogers. 1997).

The positive NAO phase is associated with the enhanced zonal wind at mid-high latitudes (Woollings et al. 2015; Li et al. 2012).

Regression patterns of winter SLP (hPa) onto the standardized NAOI for distinct periods



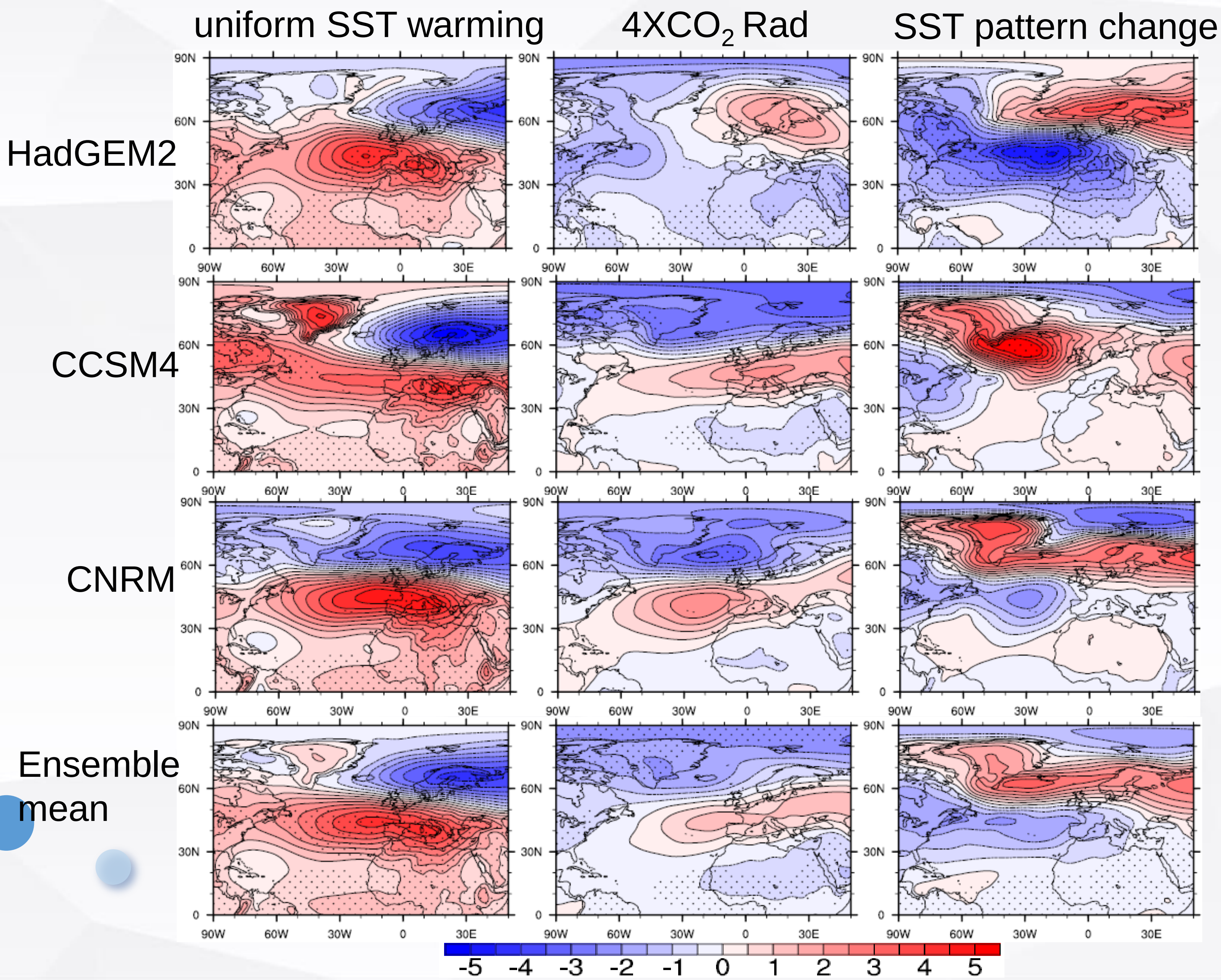
The intensified NAO variability can be seen in the latter period



The mean state change of zonal wind between the two periods is also intensified around 60^{o}N

The intensified NAO variability is probably connected with the enhanced mean state westerly wind at mid-high latitudes.

The **winter SLP changes** (hPa) in response to different forcings



The intensified Azores high and Icelandic low can be seen in both the uniform SST warming and $4XCO_2$ direct radiative effect experiments.

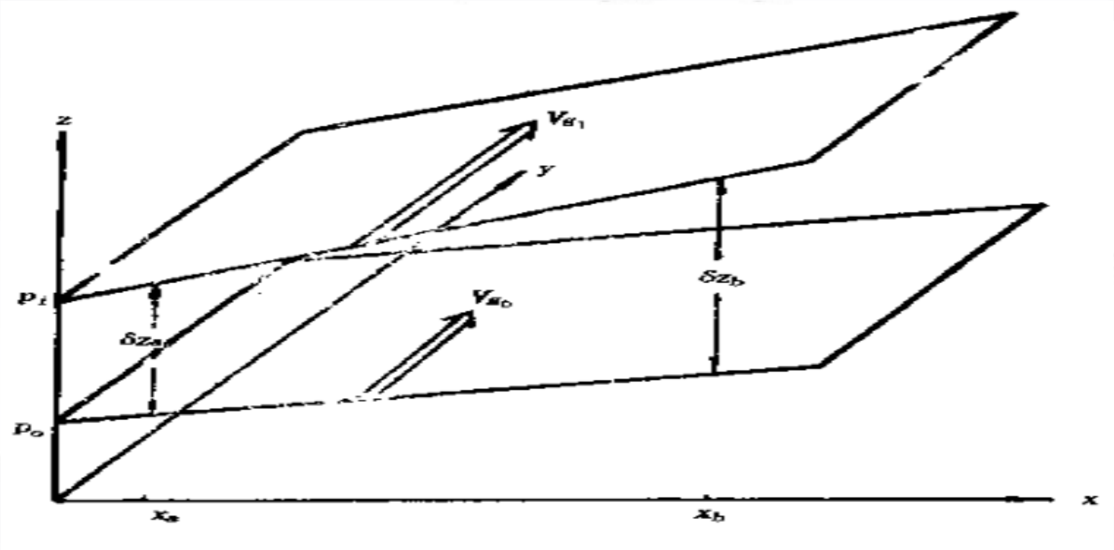
Reflecting the enhanced westerly wind at mid-high latitudes

What could be the possible reason which induces the intensified zonal wind appear around mid-high latitudes？

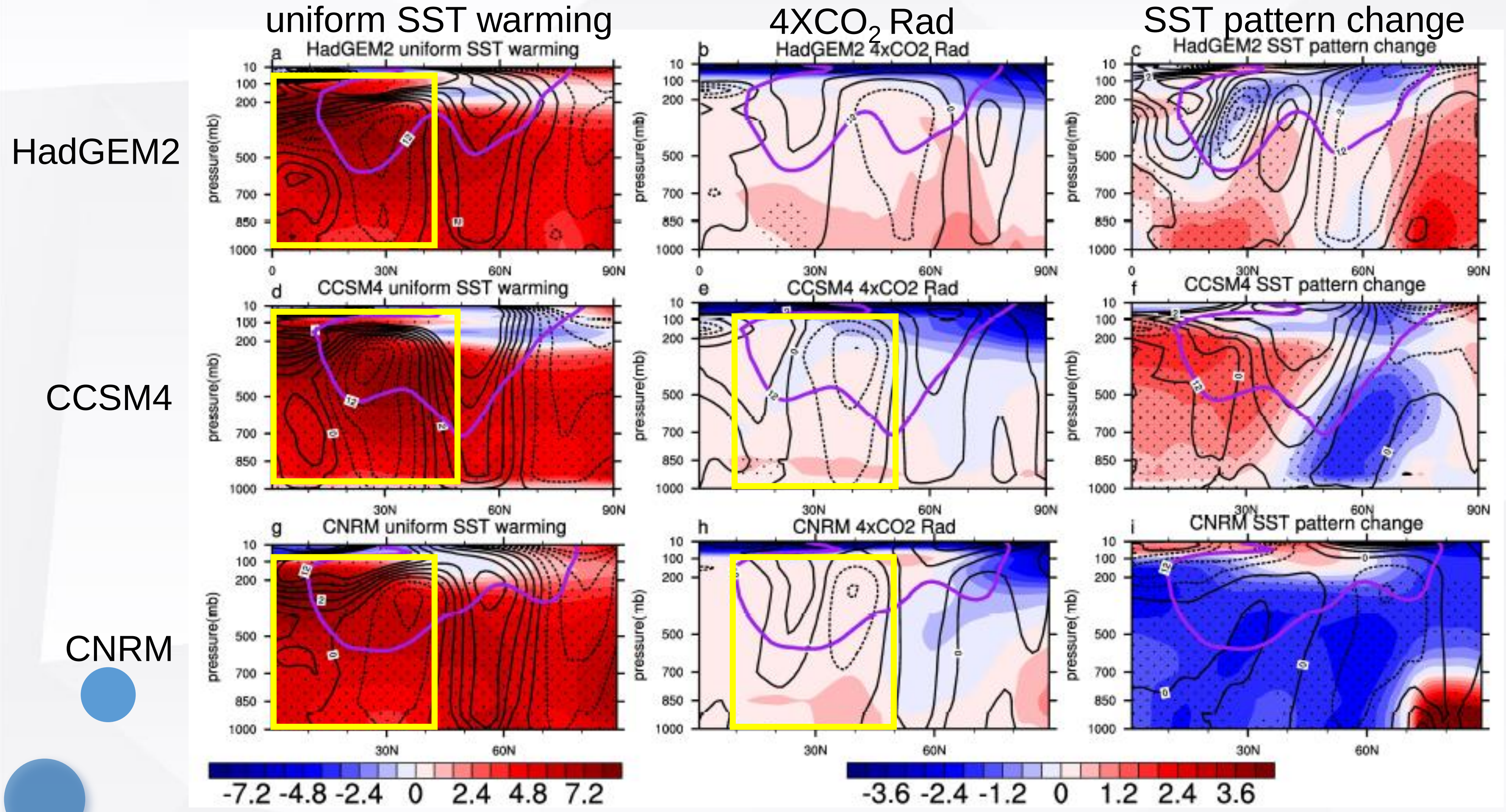
The intensified **meridional temperature gradient** would enhance the **mid-latitude zonal wind**, and the circulation change could be connected with the increased meridional temperature gradient according to the thermal wind theory. (Dong et al. 2011; Caian et al. 2017; Harvey et al. 2014)

$$\vec{V}_T = \vec{V}_{g2} - \vec{V}_{g1}$$

$$\begin{cases} u_T = -\dfrac{R}{f}\ln\dfrac{p_1}{p_2}\dfrac{\partial T_m}{\partial y} \\ v_T = \dfrac{R}{f}\ln\dfrac{p_1}{p_2}\dfrac{\partial T_m}{\partial x} \end{cases}$$

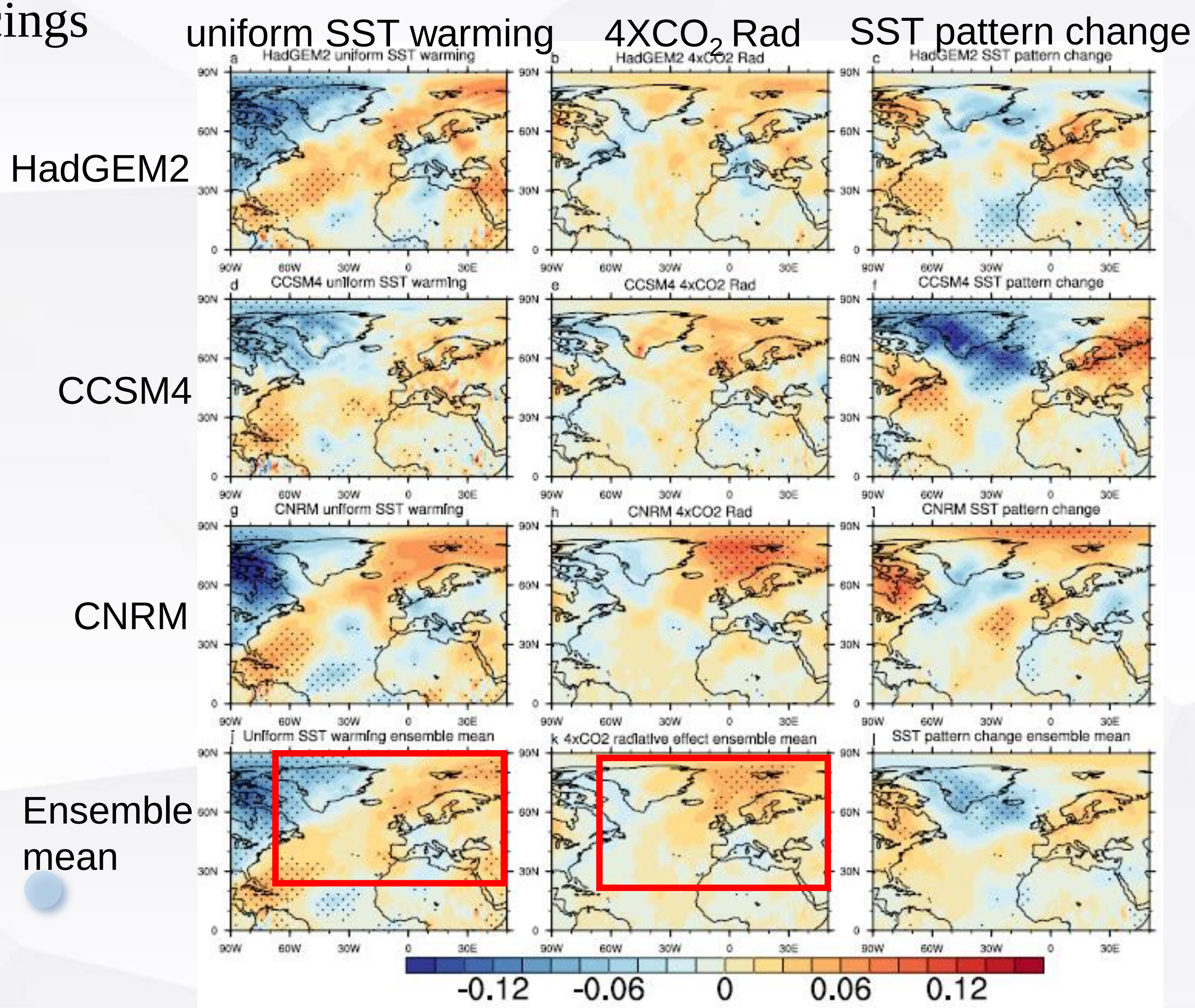


Vertical structure of **air temperature** changes (ºC, shading) and **westerly jet** changes (m/s, contours, the purple solid lines are wind profiles for 12 m/s in the piSST experiment.)



The air temperature increases at mid-low latitudes in the upper atmosphere, and the zonal wind intensifies at mid-high latitudes in uniform SST warming and $4XCO_2$ experiments.

The 500 hPa **meridional temperature gradient** changes (°C/m, shading) for different forcings



The meridional temperature gradient increases at mid-high latitudes in uniform SST warming and 4XCO_2 direct radiative effect experiments

The 300 hPa **zonal wind** changes (m/s, shading), where the purple solid lines are westerly wind for 20 m/s in the piSST experiment for different experiments

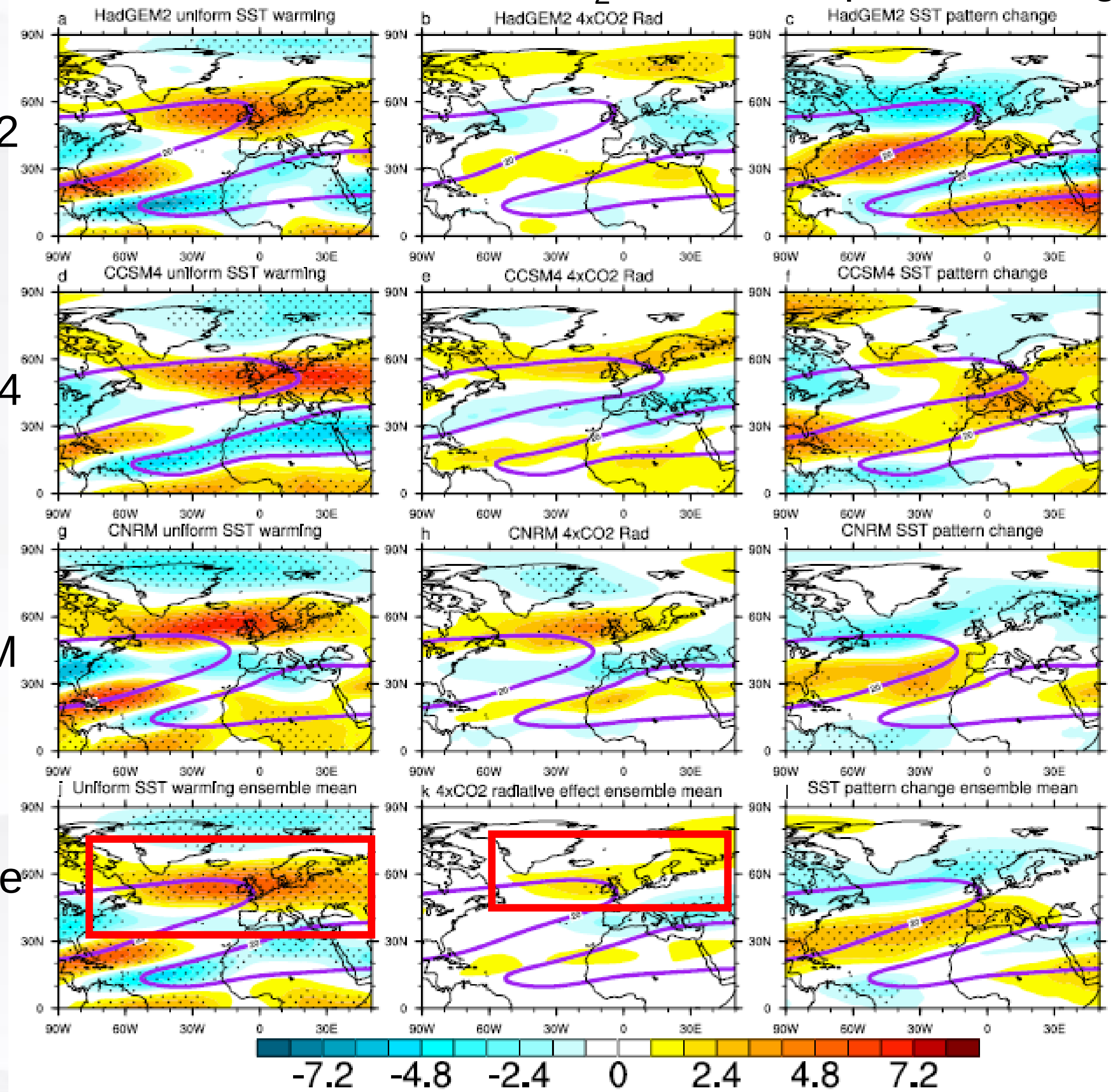
uniform SST warming | $4XCO_2$ Rad | SST pattern change

HadGEM2

CCSM4

CNRM

Ensemble mean



For **uniform SST warming**:
The 300 hPa zonal wind at mid and high latitudes intensifies with a poleward and eastward shift compared to the piSST experiment

For **$4XCO_2$ direct radiative effect**:
The westerly wind enhances with the poleward and eastward shift around 60^oN in CCSM4 and CNRM, and at higher latitudes for HadGEM2

Summary

	Uniform SST warming	$4xCO_2$	SST pattern change
NAO variability changes	Intensified (except for HagGEM2)	Intensified	Not so consistent among models
Meridional temperature gradient changes at mid-high latitudes	Intensified	Intensified	Not so consistent among models
zonal wind changes at mid-high latitudes	Intensified	Intensified	Not so consistent among models

Discussions

- What could be the possible reasons leading to the relatively large inter-model difference in HadGEM2?
  - It is also possible that the NAO variability could be influenced by not only the external forcings, but also by the internal forcing. (Ren et al. 2009)
  - This inconsistency is probably related to the distinct model representation of NAO variability change in HadGEM2.
- We can see that the projected changes in SST patterns for each model drive very different responses in this study, so how to explain this phenomenon?
  - The slightly different experimental design in CNRM: the sea ice.
  - SST pattern change could also be the main source of inter-model uncertainty for NAO variability change.

The understanding of the NAO variability change in response to SST pattern change is still an open issue!

Thank you for your attention！