Response of the AMOC to changes in buoyancy forcing under global warming in the IPSL-CM4

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Background

- IPCC 2001 : None of the GCM models includes melting of land-ice (Greenland, Antarctic and mountain glaciers)
- Large uncertainty on the speed of the Greenland melting (Gregory et al., 2004)
  - Possible amplification processes (lubrication)
  - 0.12 Sv during the Younger Dryas (Bard et al., 1996)
  - Actual observations of the melting: faster than previously thought (Rignot and Kanagaratnam, 2006)

- Fichefet et al. (2003) and Swingedouw et al. (2006): melting of Greenland could be an important term for the AMOC response to global warming on a century time scale

Aim of this work

- Estimate the impact of land ice melting in scenario on 500 years time scale
- Analyze the mechanisms of the response of the AMOC to global warming

AMOC and convection sites buoyancy

In the IPSL-CM4, the AMOC is qualitatively correct, with two cells (NADW and AABW) but a bit weaker than observation-based estimates

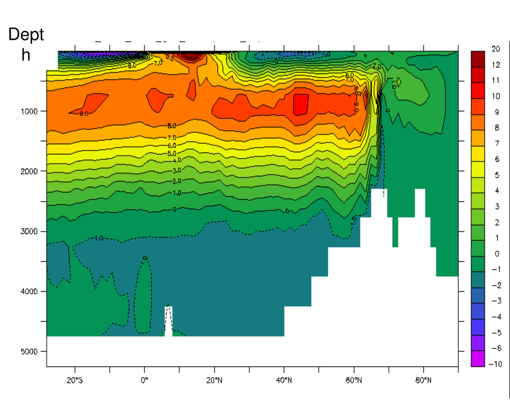

Fig. 3: Zonal mean of the Atlantic overturning stream function

We define a large convection sites region in the model:

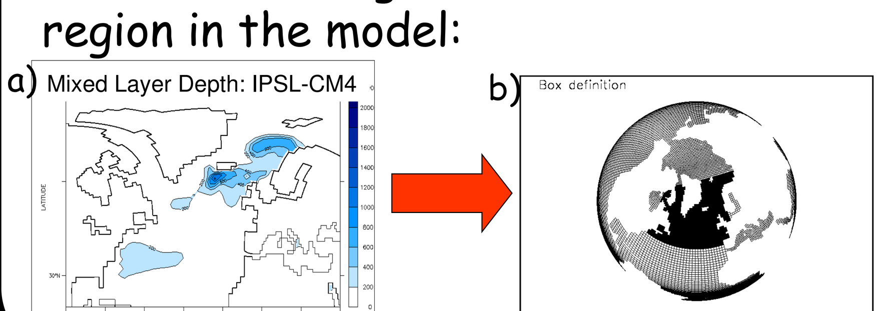

Fig. 4: a) Mixed layer depth maximum in CTRL and b) convection sites region definition (in black)

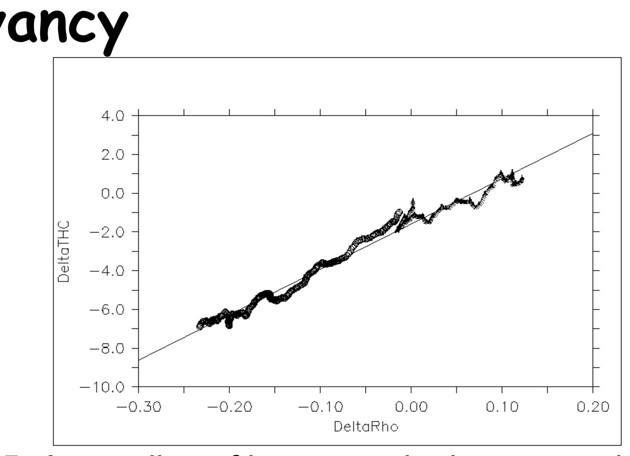

Fig. 5: Anomalies of buoyancy in the convection sites in the scenarios compared to CTRL against anomalies of AMOC index; Each point correspond to a year. 20 years internal variablity has been filtered

There is a correlation of 0.98 between density anomaly in the convection sites and AMOC anomaly:

$$\Delta\, AMOC = \gamma \Delta\rho$$

where $\gamma = 23\ Sv/kg/m^3$

AMOC internal feedbacks quantification

Following an analogy with electronic (Hansen et al. 1984), we define linear feedbacks by:

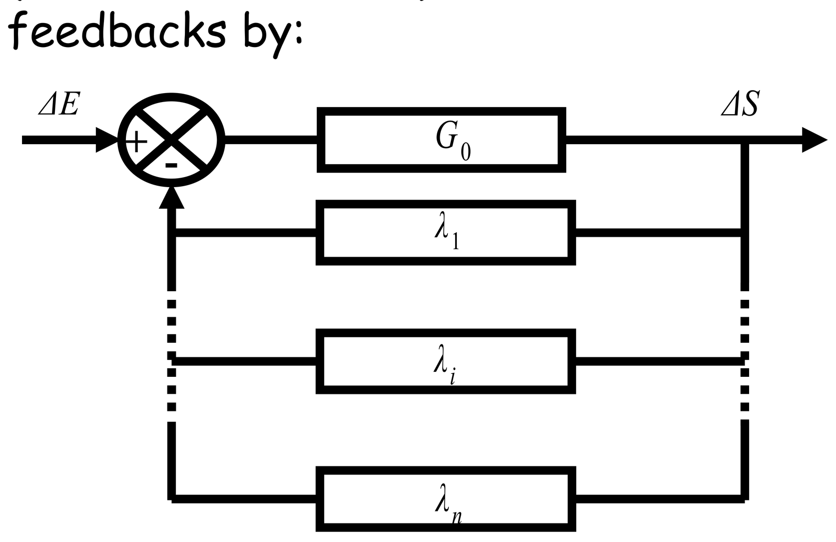

Fig.9 : Scheme of system with linear feedback loop

The equation that governs such a system is:

$$\Delta S = \frac{G_0}{1 - G_0 \sum_i \lambda_i} \Delta E$$

To apply this model to AMOC, we consider the difference between the scenarios and we rewrite the equation for buoyancy as:

$$\Delta\rho \approx \Delta\rho_0 + \sum_i \Delta\rho_i$$

where $\Delta\rho_0$ is the buoyancy anomaly due to land-ice melting

$$\Rightarrow \Delta\rho = \frac{1}{1 - \sum_i \lambda_i} \Delta\rho_0$$

where $\forall i \quad \lambda_i = \frac{\Delta\rho_i}{\Delta\rho}$ is the feedback factor

We can define a dynamical gain for the system corresponding to the amplification of an initial anomaly as an input:

$$G = \frac{\Delta\rho}{\Delta\rho_0} = \left(\frac{1}{1 - (\lambda_S + \lambda_T)} \right) = 3.0$$

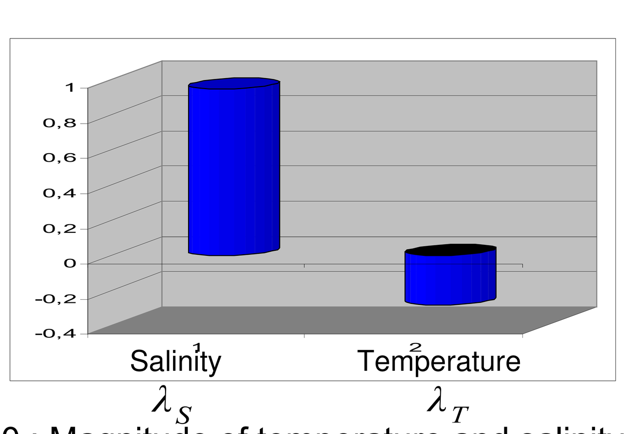

Fig.10 : Magnitude of temperature and salinity related feedback factors

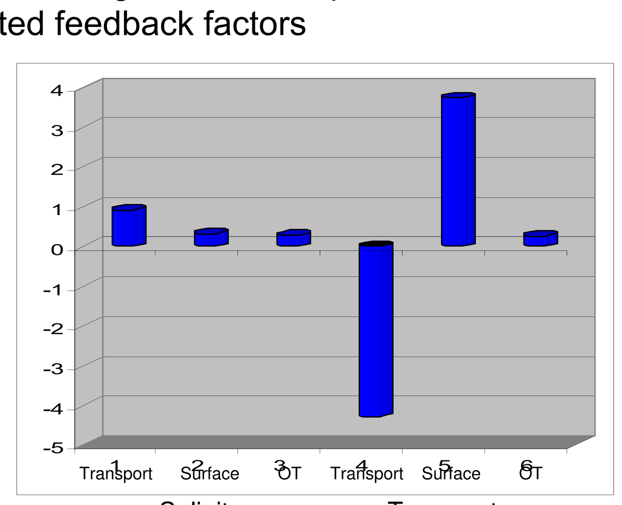

Fig.11 : Further decomposition of the magnitude of feedback factors

Heat flux damping is a strong positive feedback that limits heat transport negative feedback

Land-ice melting impact

We use the IPSL-CM4 coupled model (Ocean ORCA2: 2°x(0.5-2°) resolution, Sea-ice LIM: dynamic-thermodynamic, Atmosphere LMDz: 3.75° resolution,Land model ORCHIDEE)

We integrate the IPSL-CM4 with scenarios of 500 years with a doubling of CO2 after 70 years, which is kept constant for the rest of the study. We consider two scenarios, one with land-ice melting (WIS2), the other without (NIS2).

The parameterization of land-ice melting only considers thermodynamics processes for the melting, no dynamics processes for the ice-sheet are included.

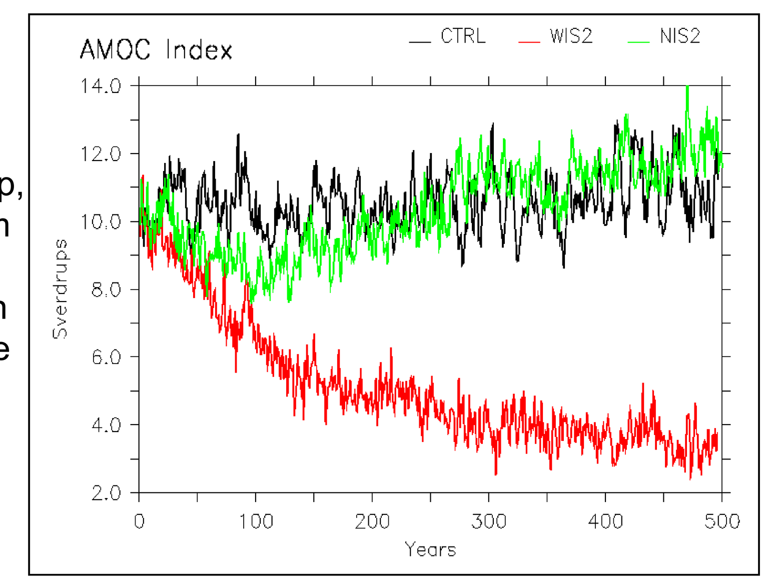

Fig. 1: Time series of AMOC index in Sverdrup, defined as the maximum of the meridional overturning circulation in the Atlantic, for the three experiments. In black is CTRL, in red WIS2, and in green NIS2.

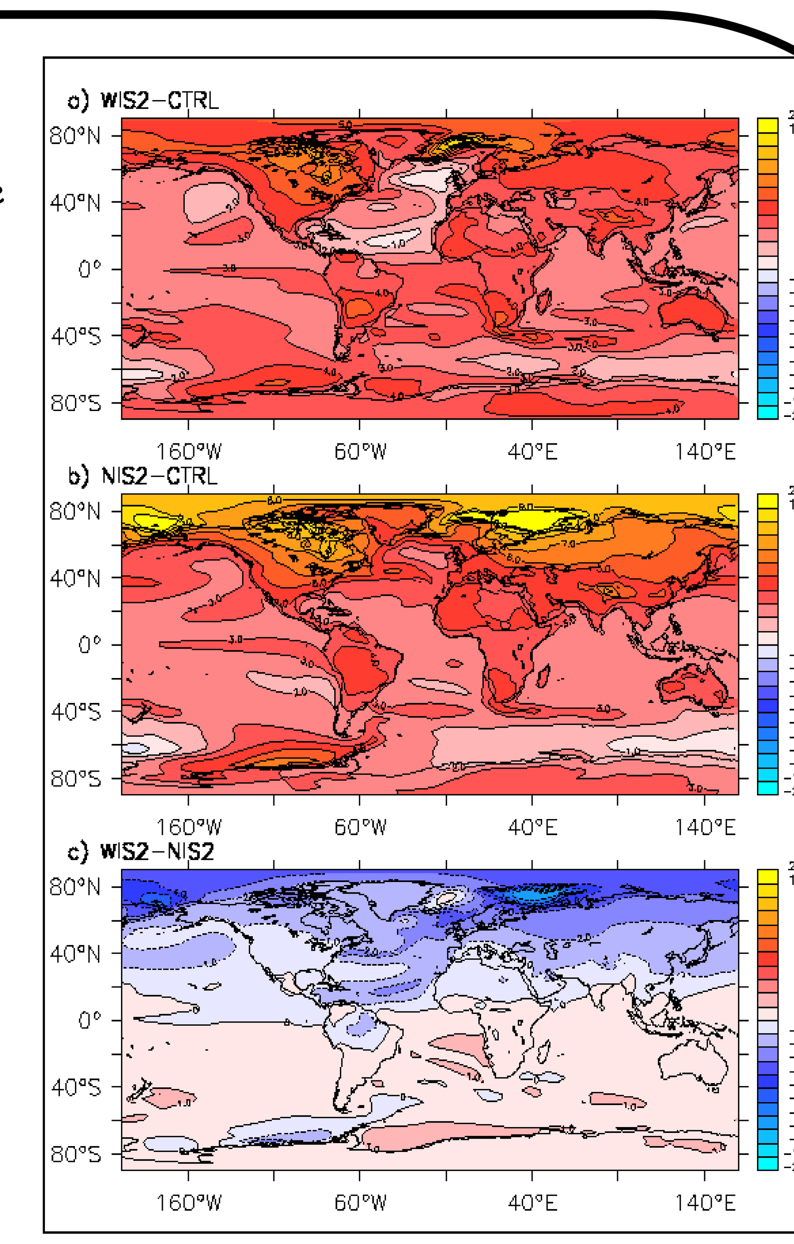

Fig.2: Difference in surface atmospheric temperatures in K for the last 30 years of simulation between a) WIS2-CTRL, b) NIS2-CTRL, c) WIS2-NIS2

Surface buoyancy forcing

We linearize the buoyancy anomalies in order to decompose it into a salinity and a temperature related components: $\Delta\rho \approx \beta\Delta S - \alpha\Delta T$

Main results

- NIS2: temperature (T) diminishes the AMOC, salinity (S) increases it
- WIS2: T et S decrease the AMOC

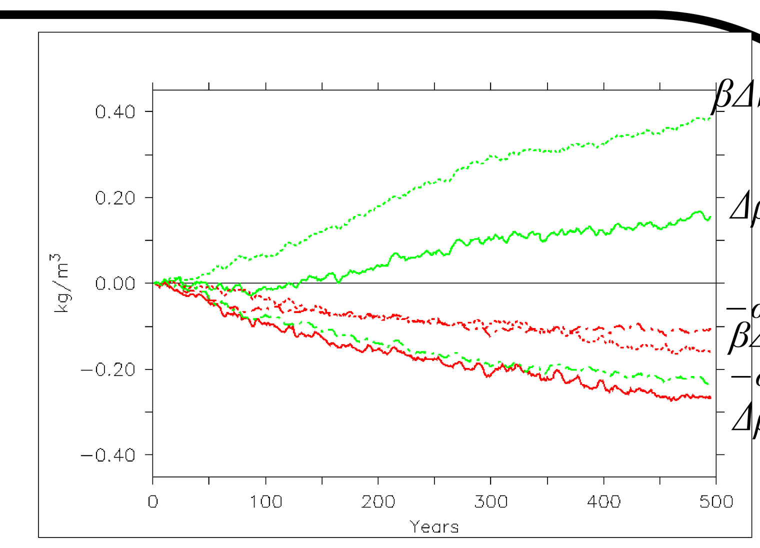

Fig. 6 Time series of buoyancy differences with CTRL (solid lines) averaged over the convection sites, defined in the North Atlantic between

We further decompose the buoyancy anomalies:

$$\Delta\rho \approx \Delta\rho^S_{Transport} + \Delta\rho^S_{surface} + \Delta\rho^S_{OT} + \Delta\rho^T_{Transport} + \Delta\rho^T_{surface} + \Delta\rho^T_{OT}$$

Main contributor to AMOC recovery in NIS2:

2. Salinity anomaly in the tropics transported by gyre t (40% of the recovery mechanisms)
3. Decrease of sea-ice transport through Fram Strait (35% of the recovery mechanisms)

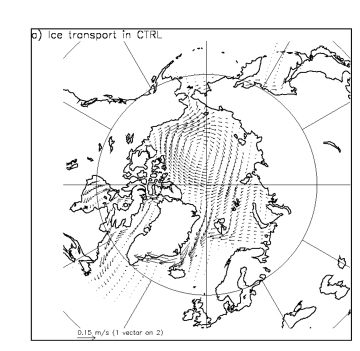

Fig. 7: Sea-ice transport in CTRL. 0.15 Sv crosses the Fram Strait each year in agreement with observations based estimates (Kwok et al., 2004)

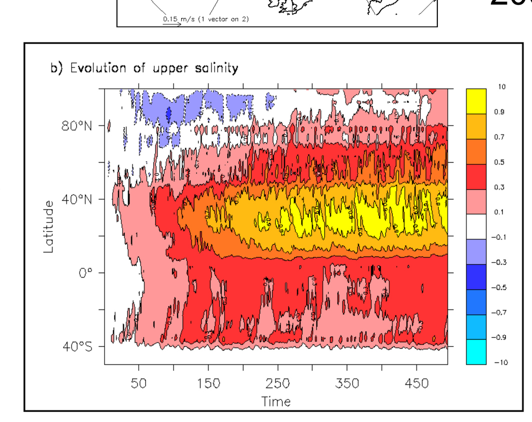

Fig. 8: Time-lattiude of salinity anomalies in surface Atlantic between NIS2 and WI2. It takes about 100 years for the tropical slainity anomaly to reach the convection sites latitude

Global Atlantic freshwater balance is of 0.26Sv in WIS2 and CTRL, and 0.39 Sv in NIS2: two states of AMOC with the same Atlantic freshwater forcing (Gregory et al., 2003)

Discussion and conclusion

- Land ice melting influences the long term future of the AMOC in the IPSL-CM4
- Our melting is and extreme melting scenario but not impossible due to the huge uncertainties concerning the Greenland discharge in the future
- Weak AMOC in IPSL-CM4 can lead to an important sensitivity of the model
- In global warming condition, the main decreasing term for the AMOC is the change in heat flux in the convection sites
- Main processes that help the AMOC to recover:
  - Transport of salinity anomalies from the tropics
  - Decrease of sea-ice melting in the convection site

- Main positive feedback for the AMOC is the heat flux
- Main negative feedback is the heat transport
- Salinity positive feedback dominates negative temperature feedback which gives a dynamical gain of 3

Outlooks

- Include an ice-sheet model to refine land-ice melting
- Apply feedbacks quantification methodology to Hosing experiments (Stouffer et al., 2006) in order to identify the origin of uncertainty among GCMs
- Compare land-ice melting effect in different GCMs: intercomparison of scenarios with artificial additional 0.1Sv