Potential for abrupt changes in the Atlantic Ocean Circulation: insights from climate models, space and *in situ* observations

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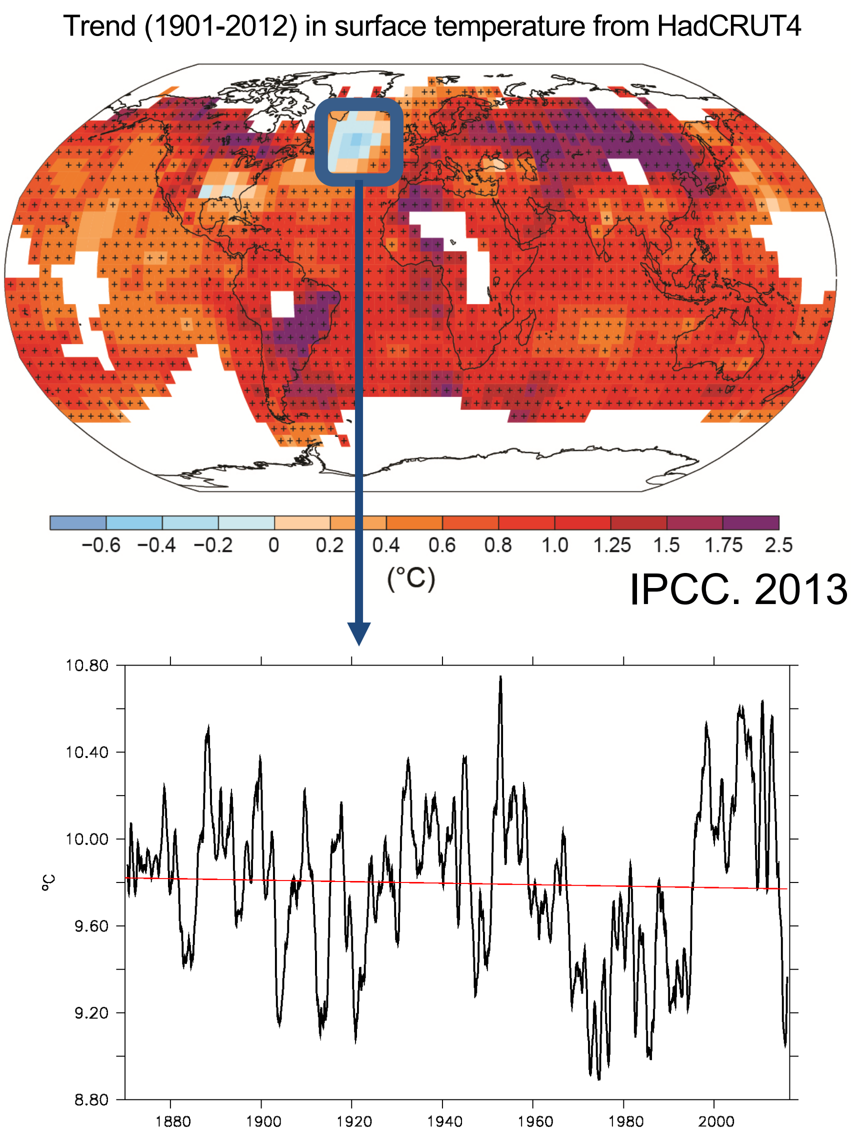
A warming climate

- At the centennial time scale, the global warming is clear almost everywhere on the Earth
- The North Atlantic is the only region that did not experience any warming over the last century in HadCRUT4
- A negative trend that masks a very large decadal variability
- A fingerprint of a weakening of the Atlantic Meridional Overturning Circulation (AMOC) (e.g. Caesar et al. 2018)?



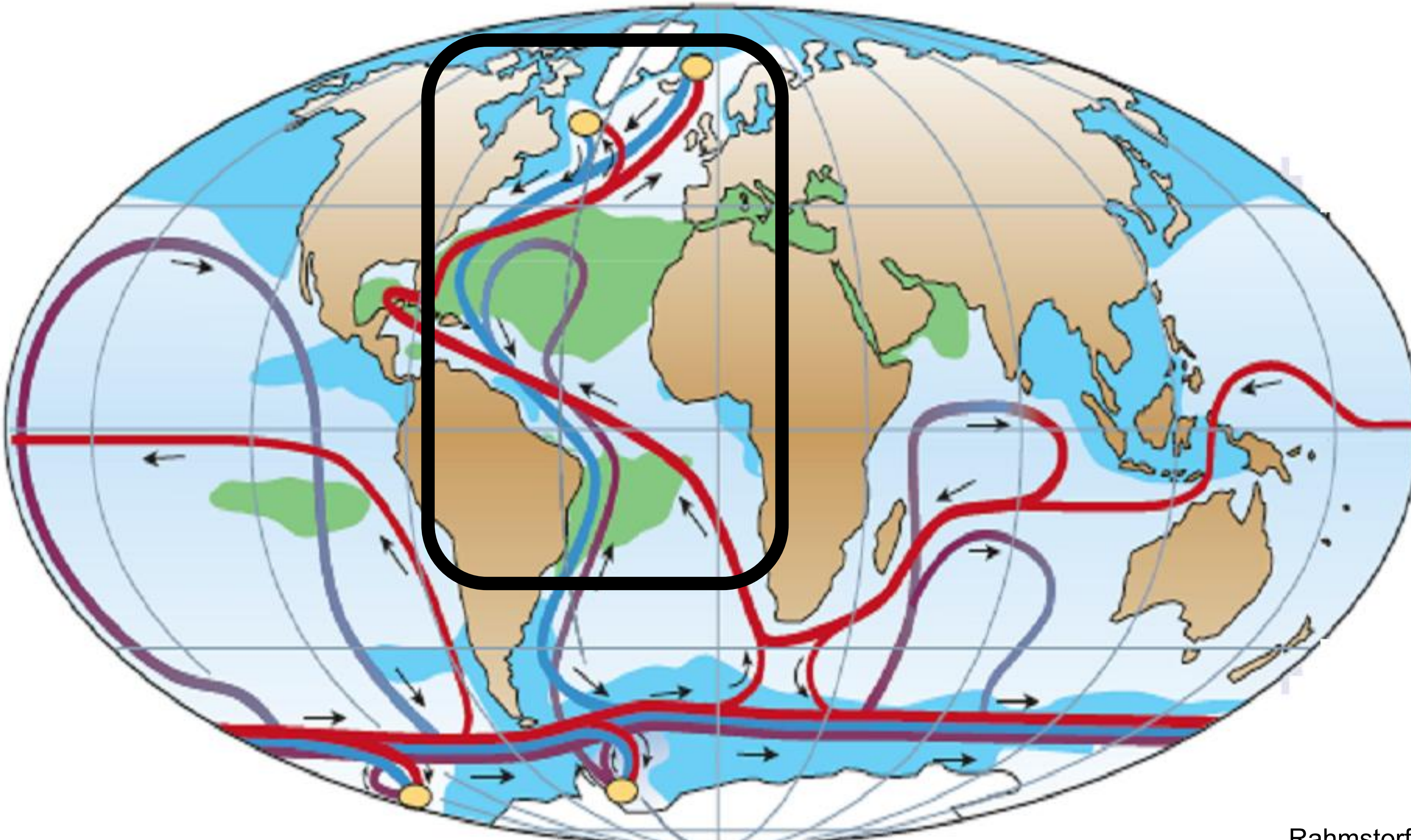
Is winter coming?

Outlines

1. The AMOC and its climatic impact
2. The AMOC: a tipping point of the climate system
3. Projections of the Atlantic circulation
4. Early warning system of Atlantic circulation potential changes

The thermohaline circulation

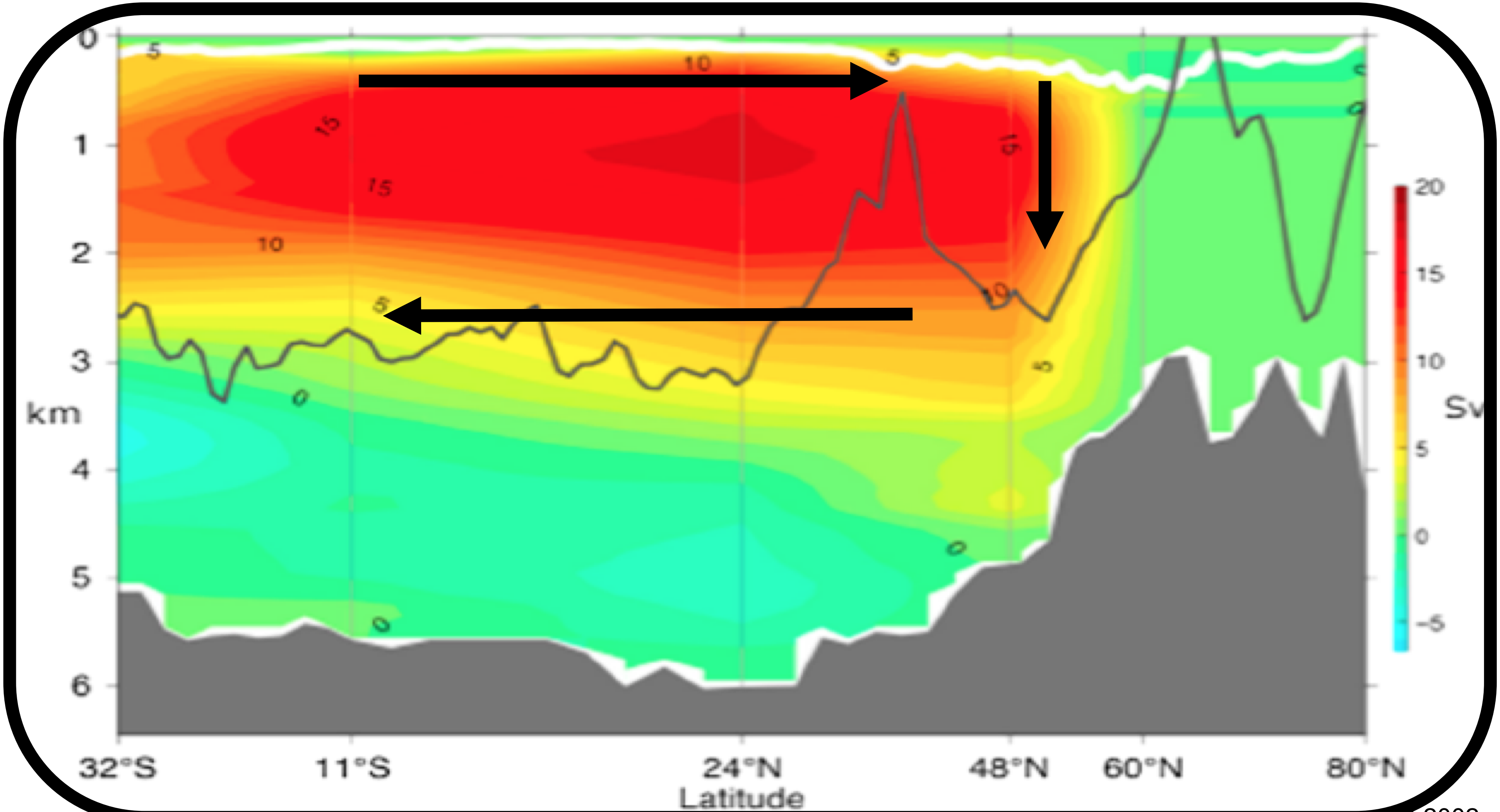
AMOC : Atlantic Meridional Overturning Circulation



Rahmstorf 2002

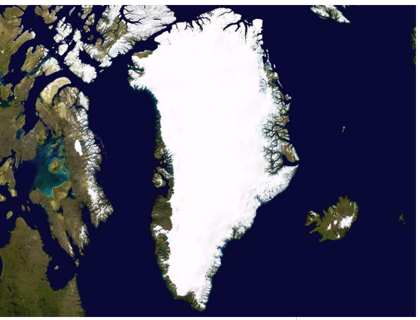
The thermohaline circulation

AMOC : Atlantic Meridional Overturning Circulation



Rahmstorf 2002

Paleo-insights



Rapid Reductions in North Atlantic Deep Water During the Peak of the Last Interglacial Period

Eirik Vinje Galaasen,[1*] Ulysses S. Ninnemann,[1,2] Nil Irvalı,[2] Helga (Kikki) F. Kleiven,[1,2] Yair Rosenthal,[3] Catherine Kissel,[4] David A. Hodell[5]

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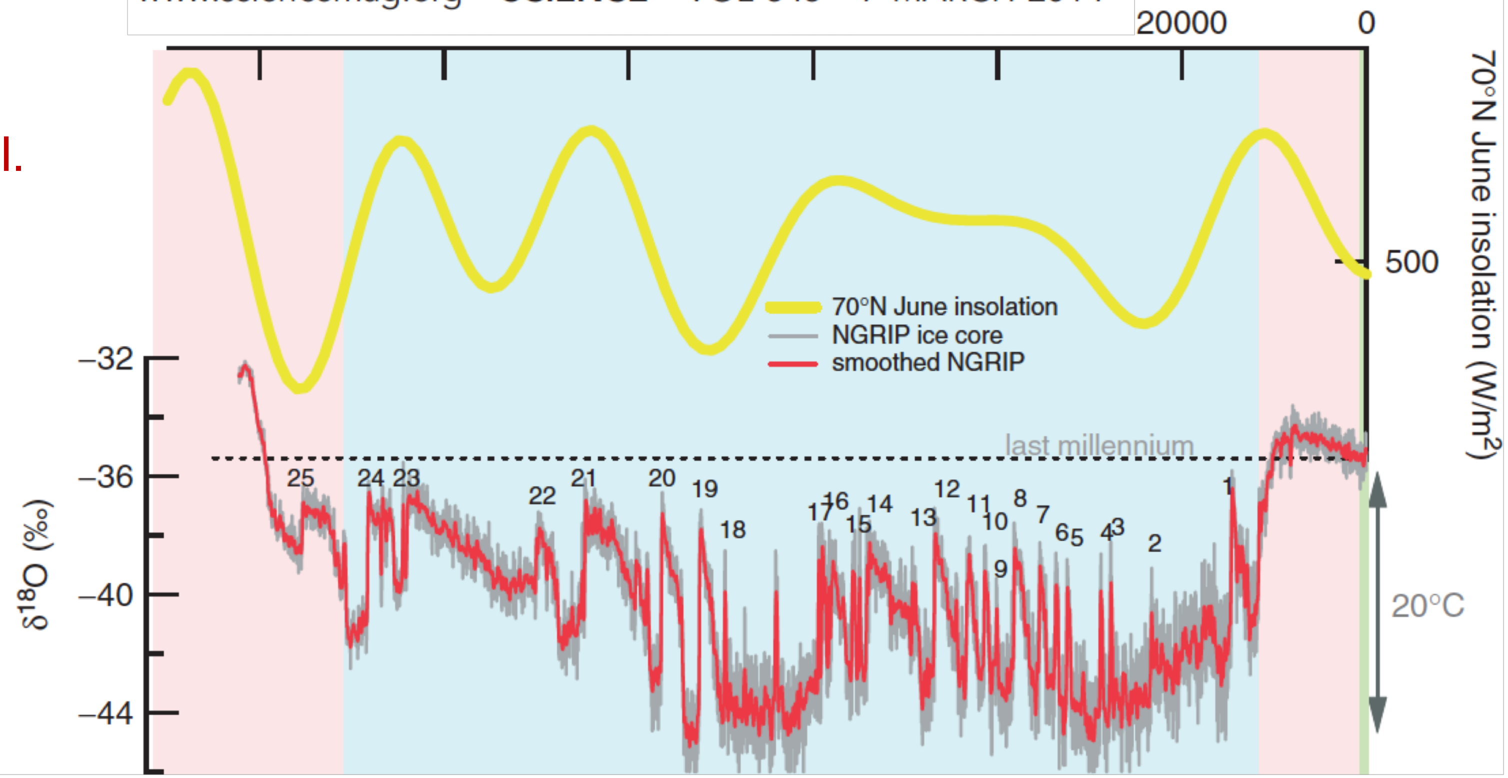
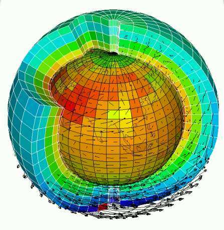
Masson-Delmotte et al. 2012

(a)

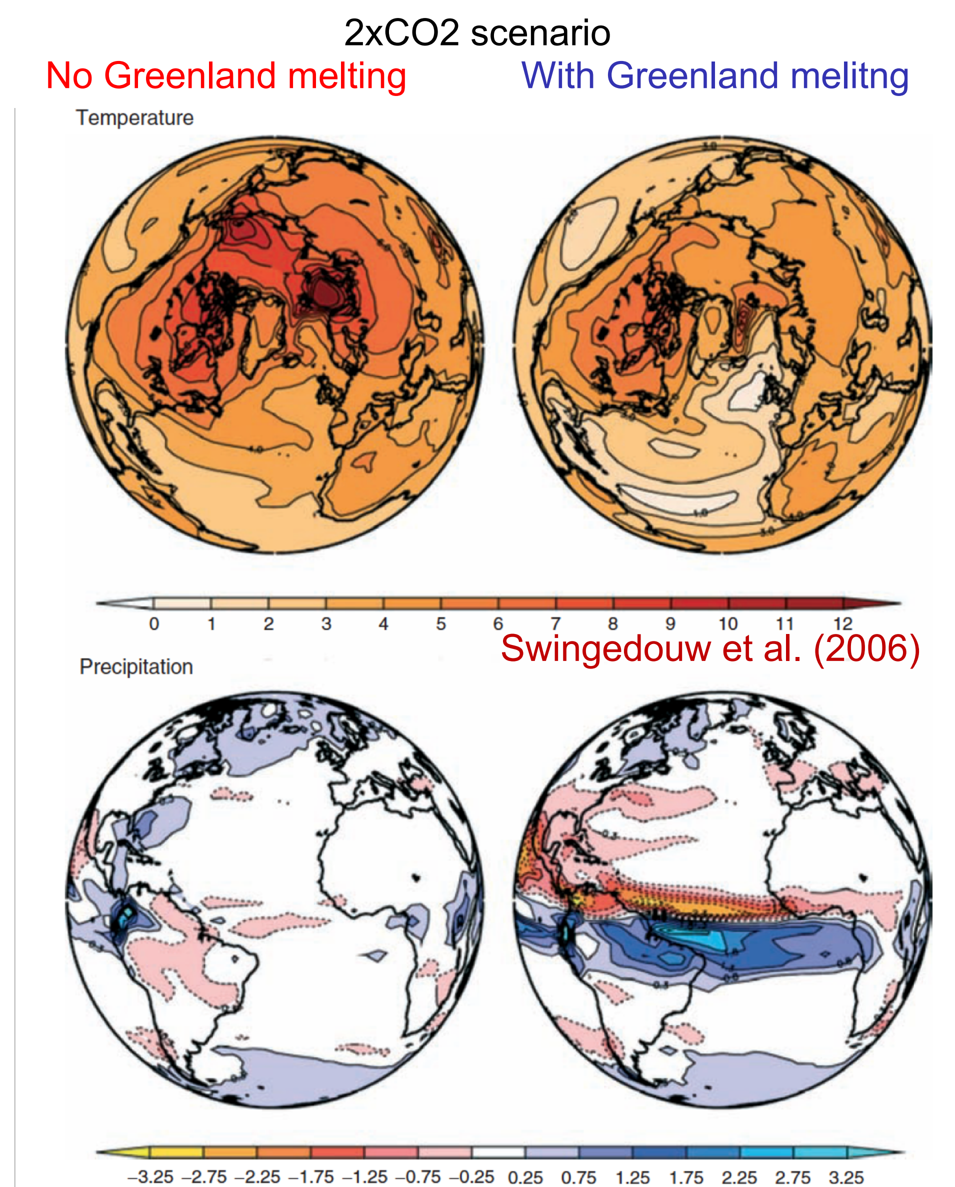


Climatic impact of an AMOC collapse

According to climate models:

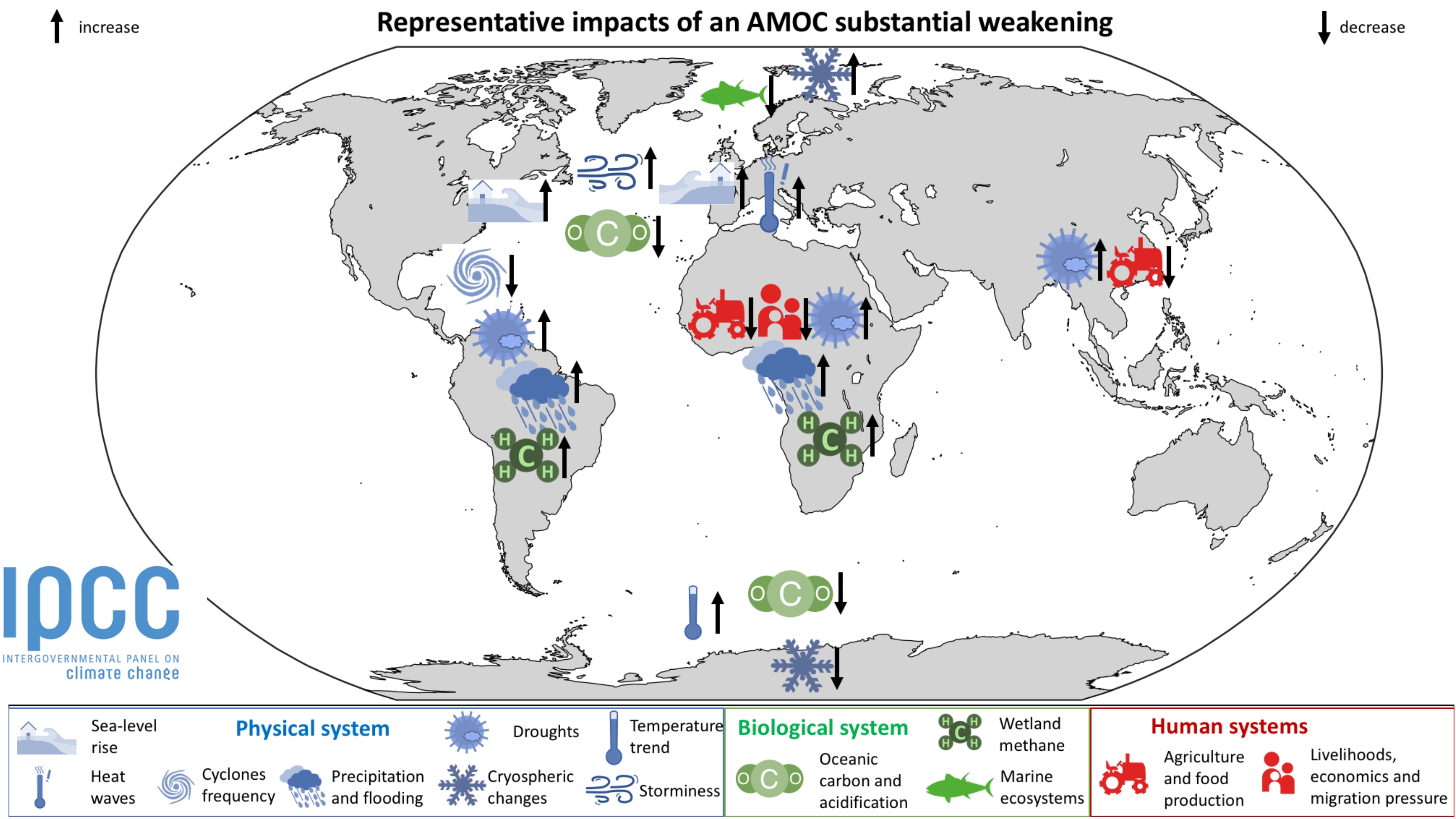


- A collapse of the AMOC cools the Northern Hemisphere and warms the Southern Hemipshere (e.g. Stouffer et al. 2006)
- It is also shifting the ITCZ southward (e.g. Swingedouw et al. 2009)
- Still very clear in latest high resolution climate model (Jackson et al. 2015)
- Impacts in projections superimposed on the global warming signal



Swingedouw et al. (2006)

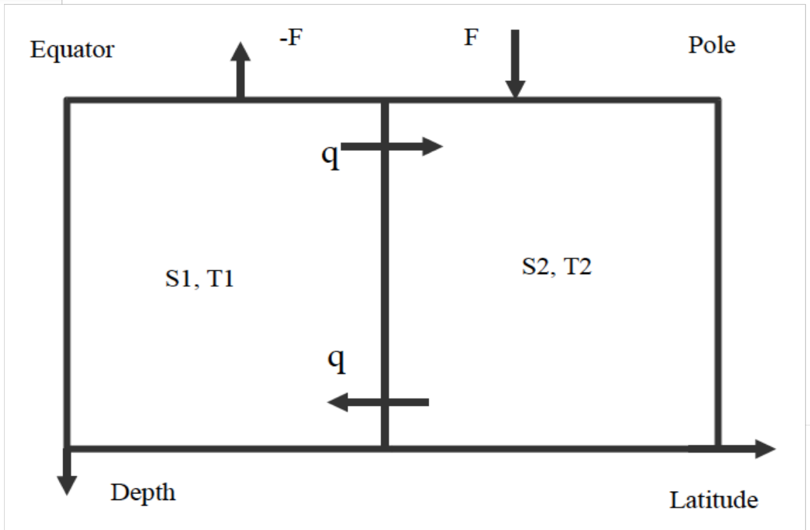
A large range of impacts

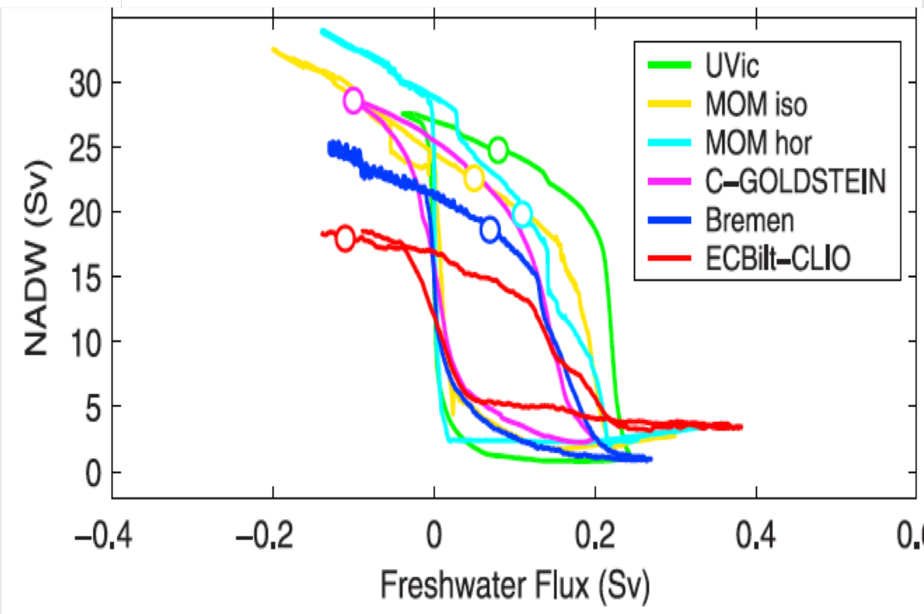


Source: Swingedouw et al. for the IPCC special report on the Ocean and the Cryopshere (SROCC)

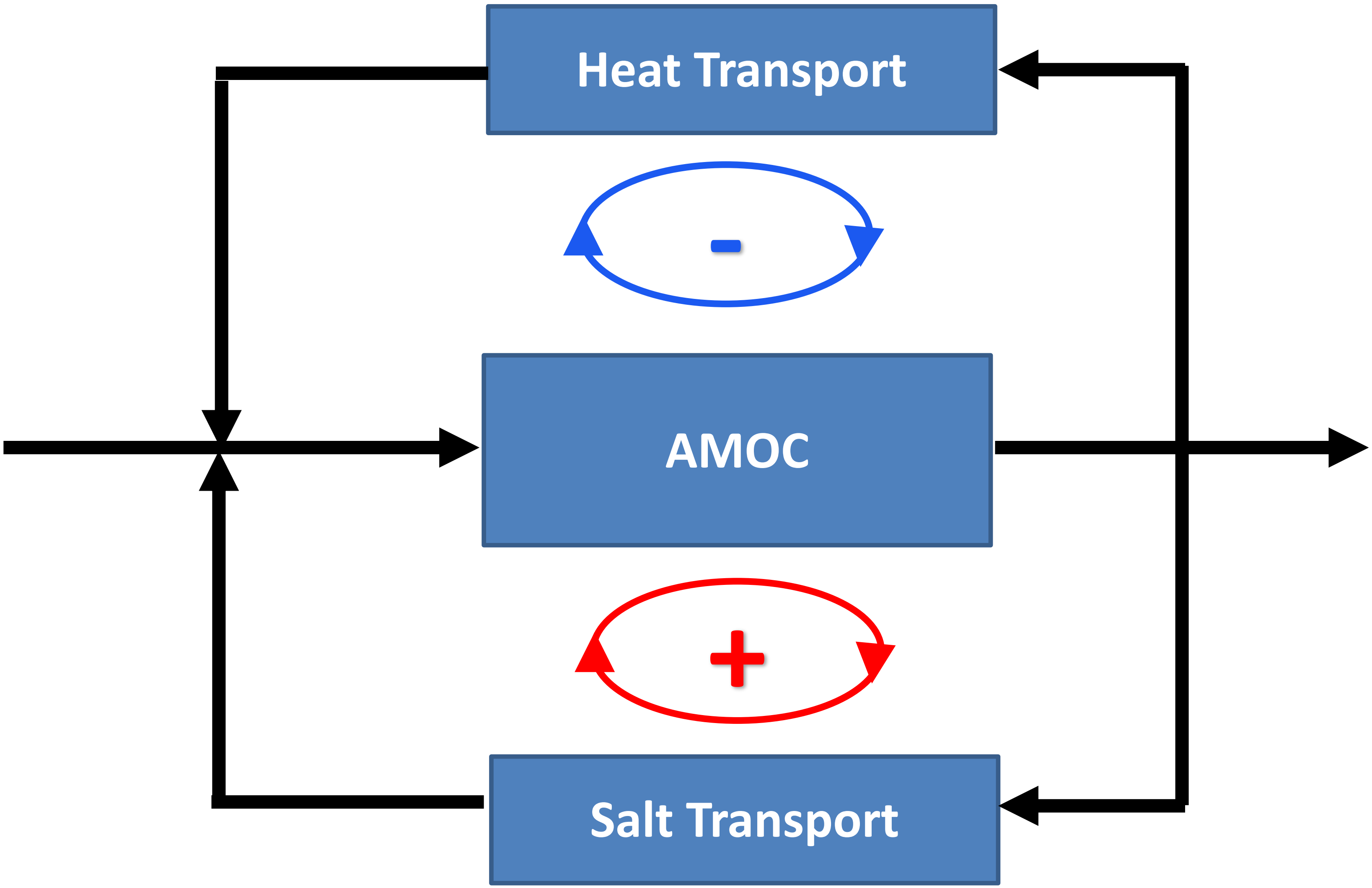
Non linearity of the AMOC

- Stommel (1961) early showed that the AMOC may exhibit strongly non-linear response to surface freshwater forcing
- His simple analytical model showed that the AMOC may have multiple solutions for a given freshwater forcing and hysteresis behavior in response to this forcing
- Still true in higher resolution models (cf. Rahmstorf et al. 2005, Hawkins 2011, …)
- **This is a steady state response (potentially millennial scale…)**

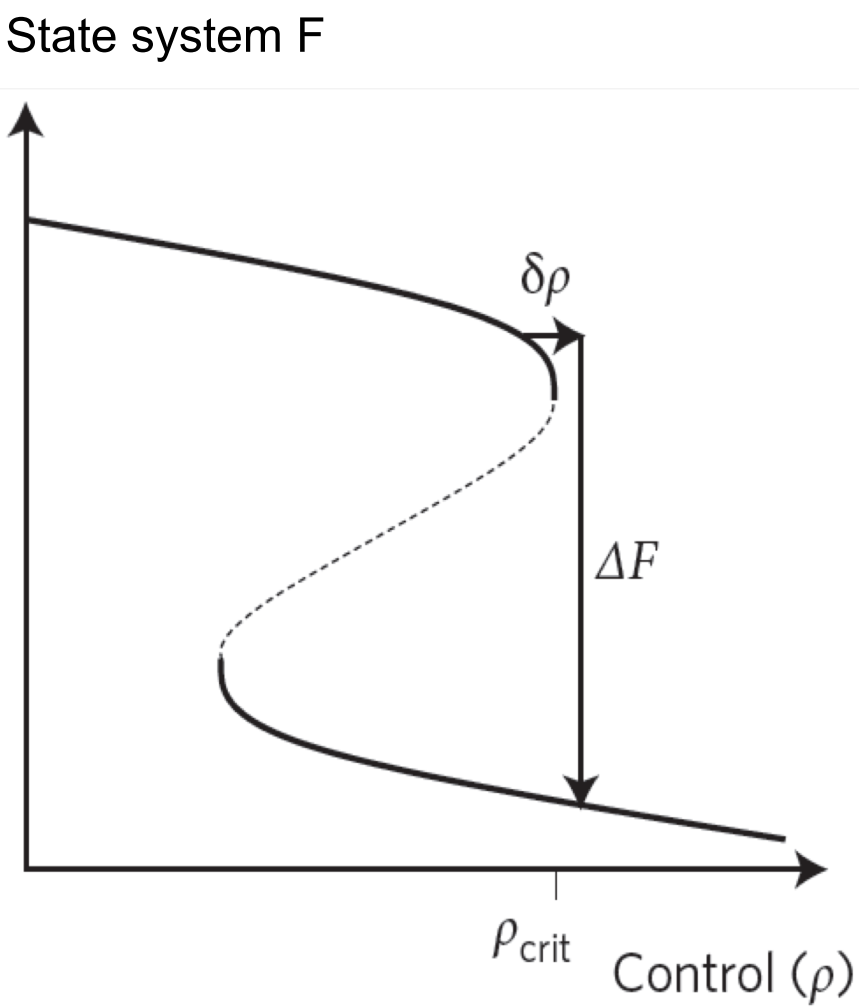


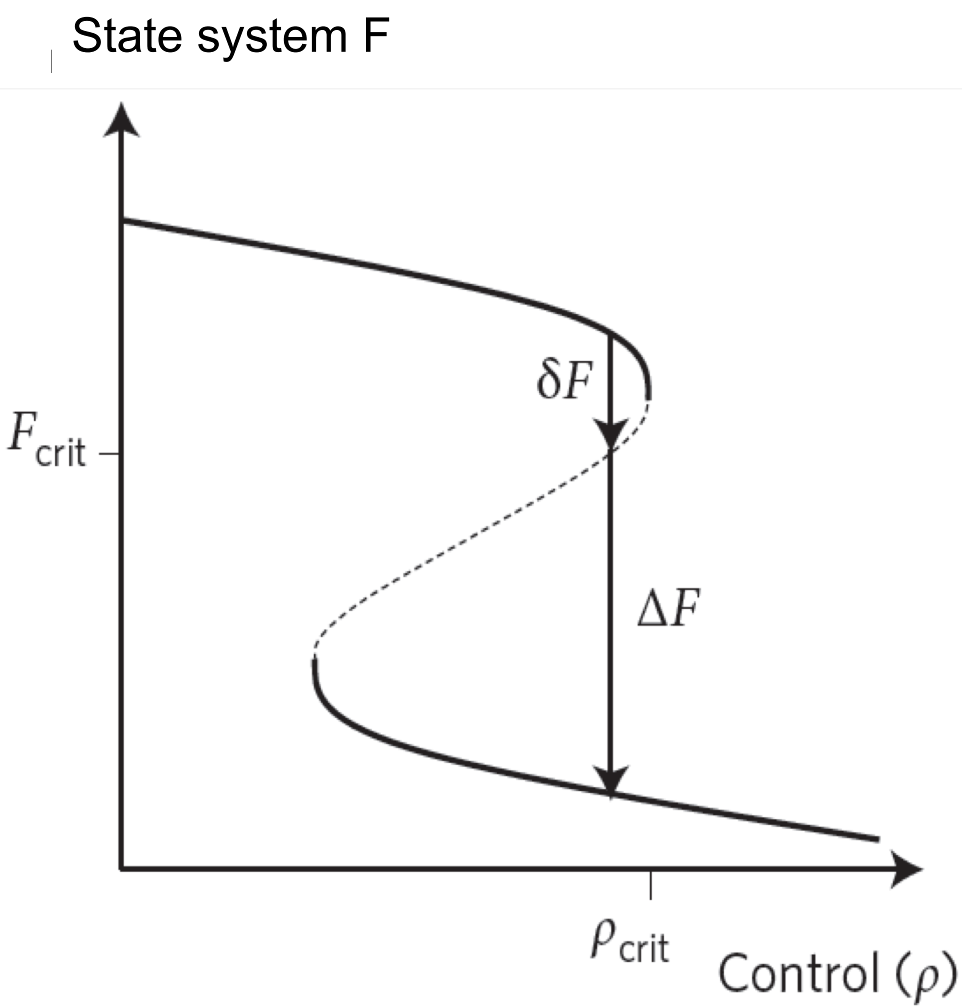


A positive feedback: salinity advection



A shift without any forcing



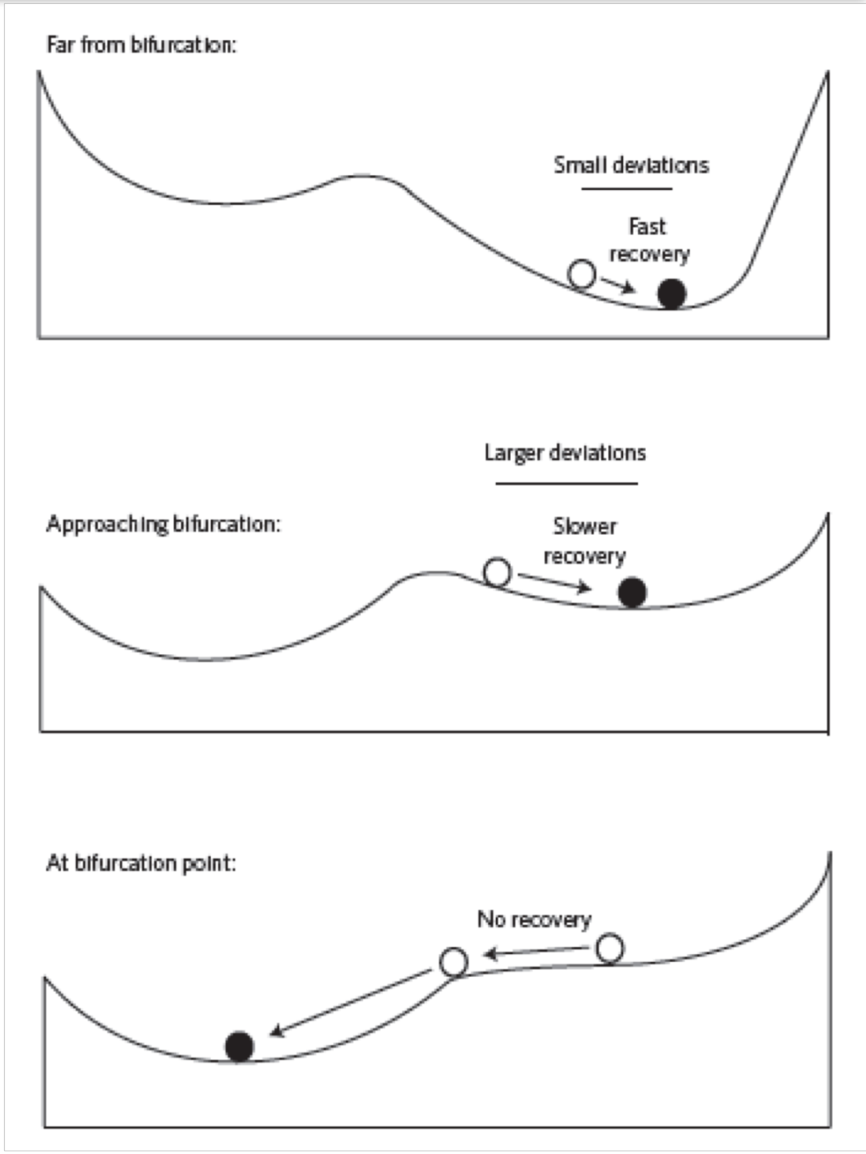


Lenton 2011

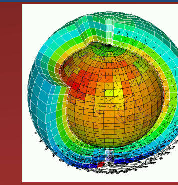
Tipping points

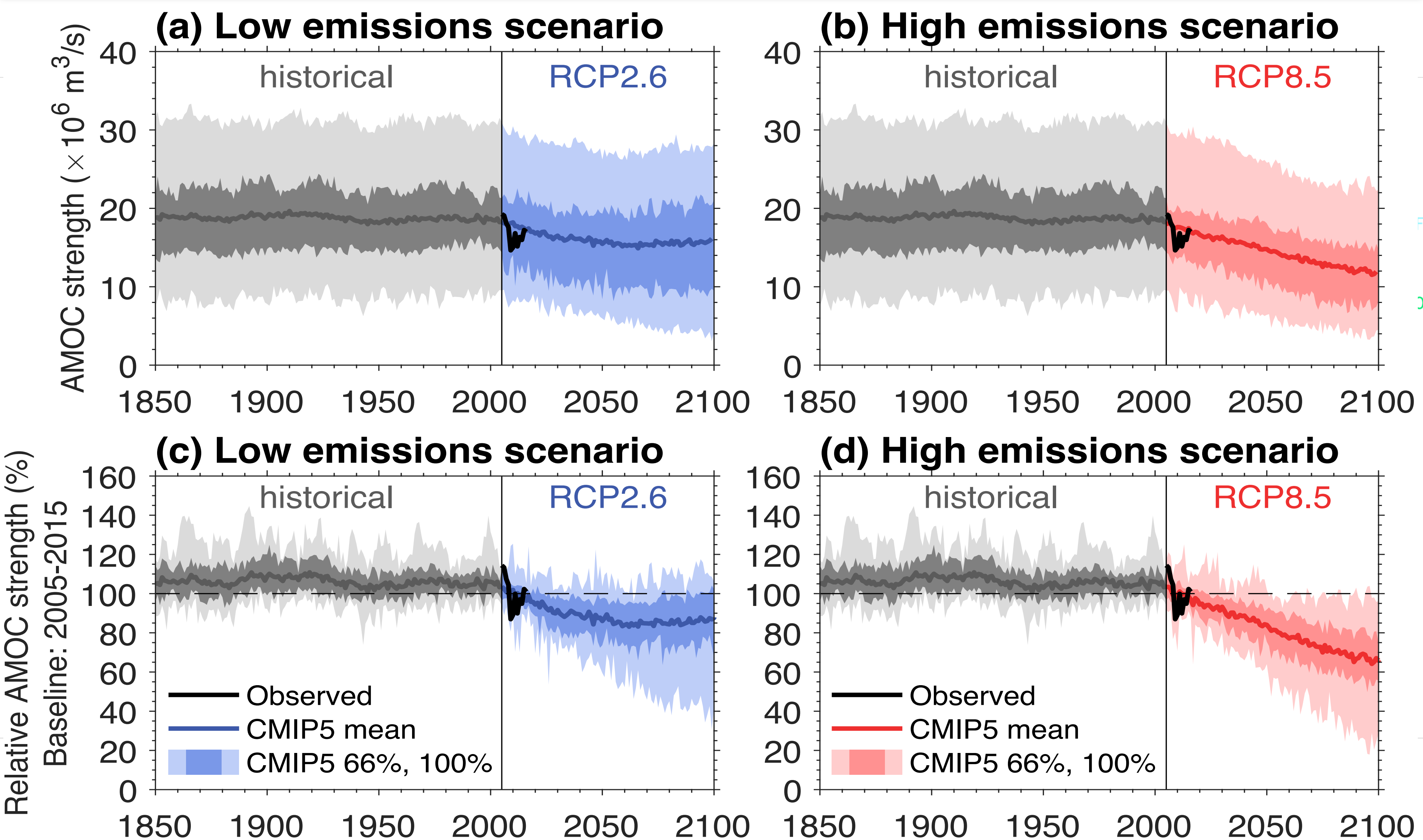
- Tipping points exhibit bifurcation behavior
- Approaching bifurcation a given system shows larger variability
- This phenomenon can be used to anticipate rapid changes : early warning system
- Boulton et al. (2014): this may require at least 500 years of AMOC measurements…

Lenton 2011



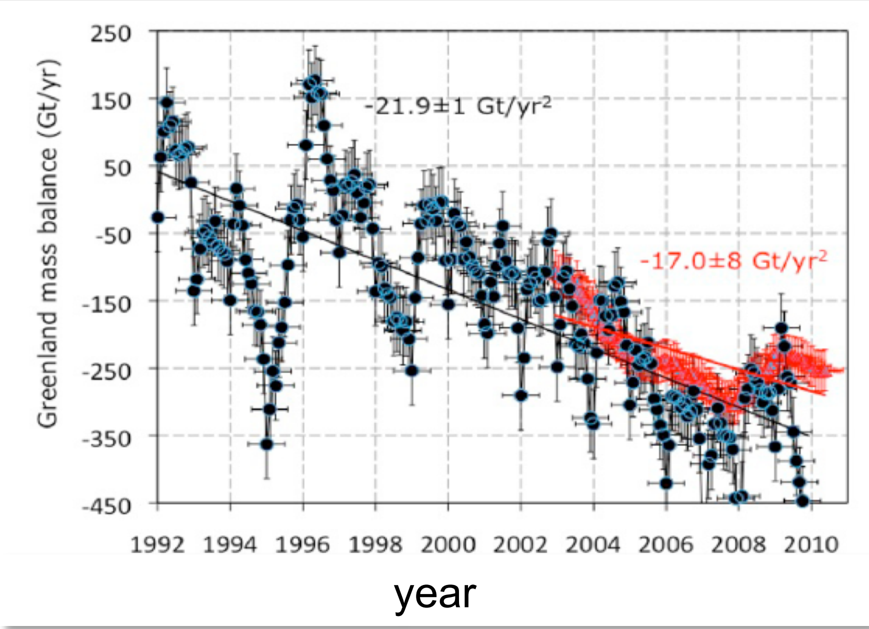
Projections of the AMOC

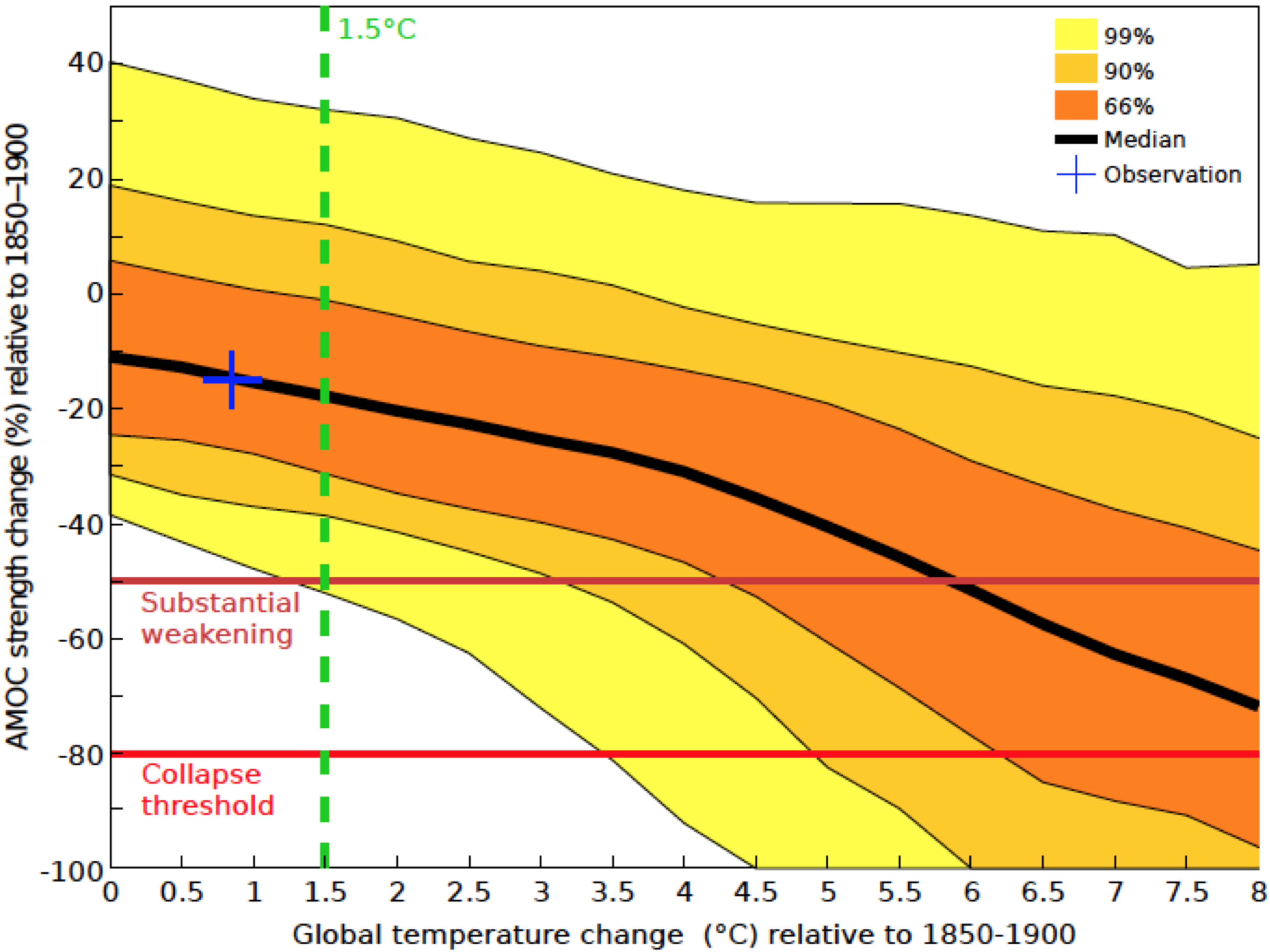




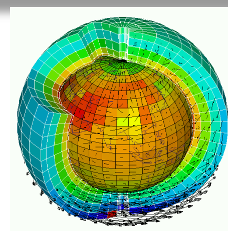
Greenland ice sheet melting is not included…

- Greenland is melting at an increasing rate (Rignot et al. 2011)
- It is very poorly included in CMIP5 models!



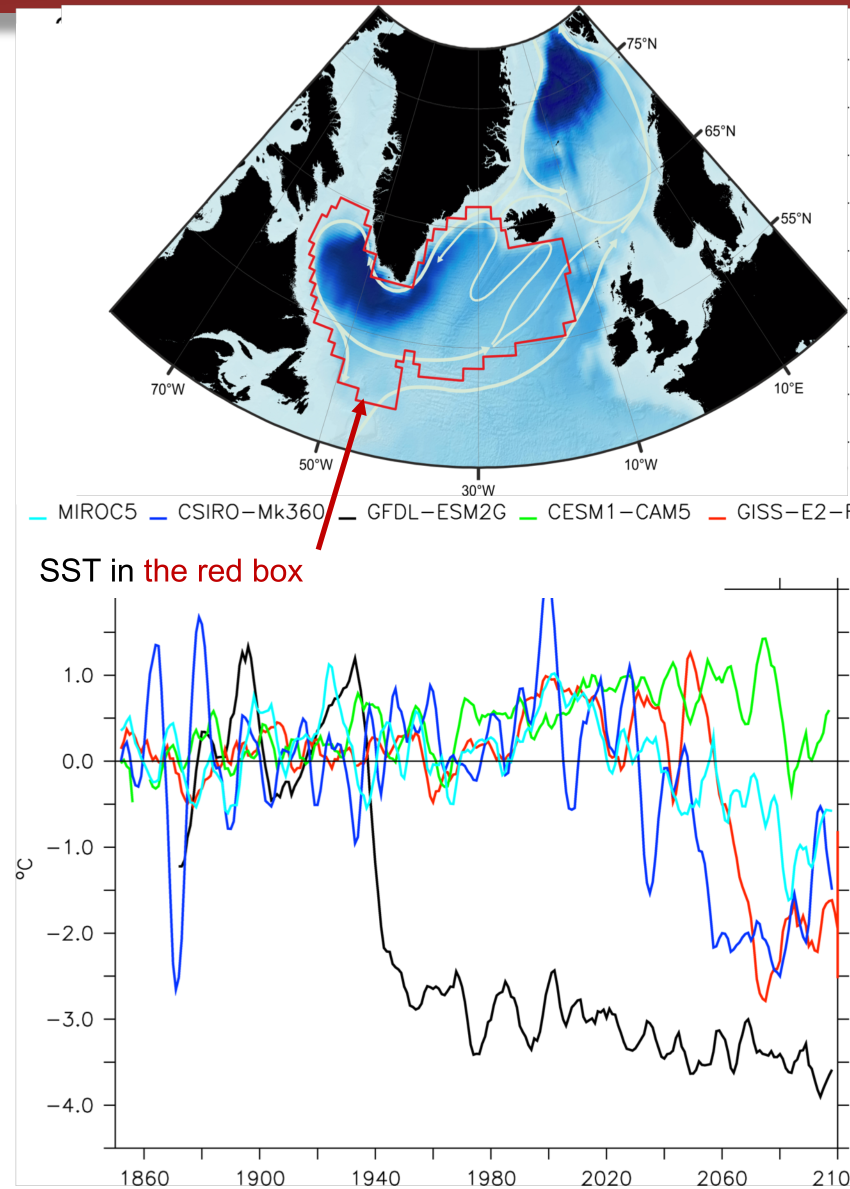

1.5°C
99%
90%
66%
Median
Observation
Substantial
weakening
Collapse
threshold
AMOC strength change (%) relative to 1850–1900
Global temperature change (°C) relative to 1850-1900
40
20
0
-20
-40
-60
-80
-100
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
5.5
6
6.5
7
7.5
8

On the possibility of abrupt changes



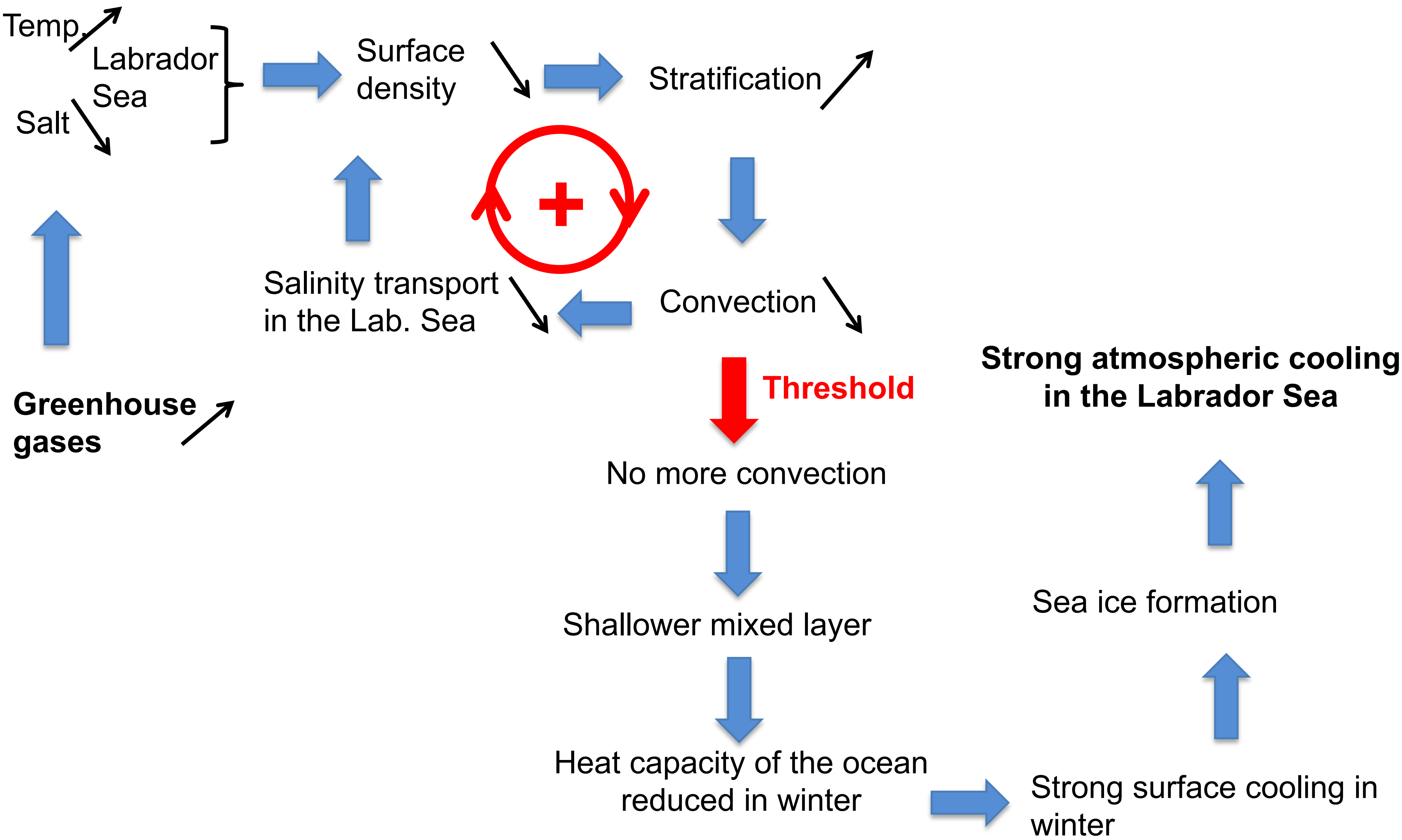
- We scanned the CMIP5 database and found abrupt variations for the near future (Drijfhout et al., *PNAS,* 2015) notably in the North Atlantic (Sgubin et al., *Nat. Com.*, 2017)

- Dynamics of this change is mainly related with **collapse of oceanic convection in the subpolar gyr**e and not only the AMOC



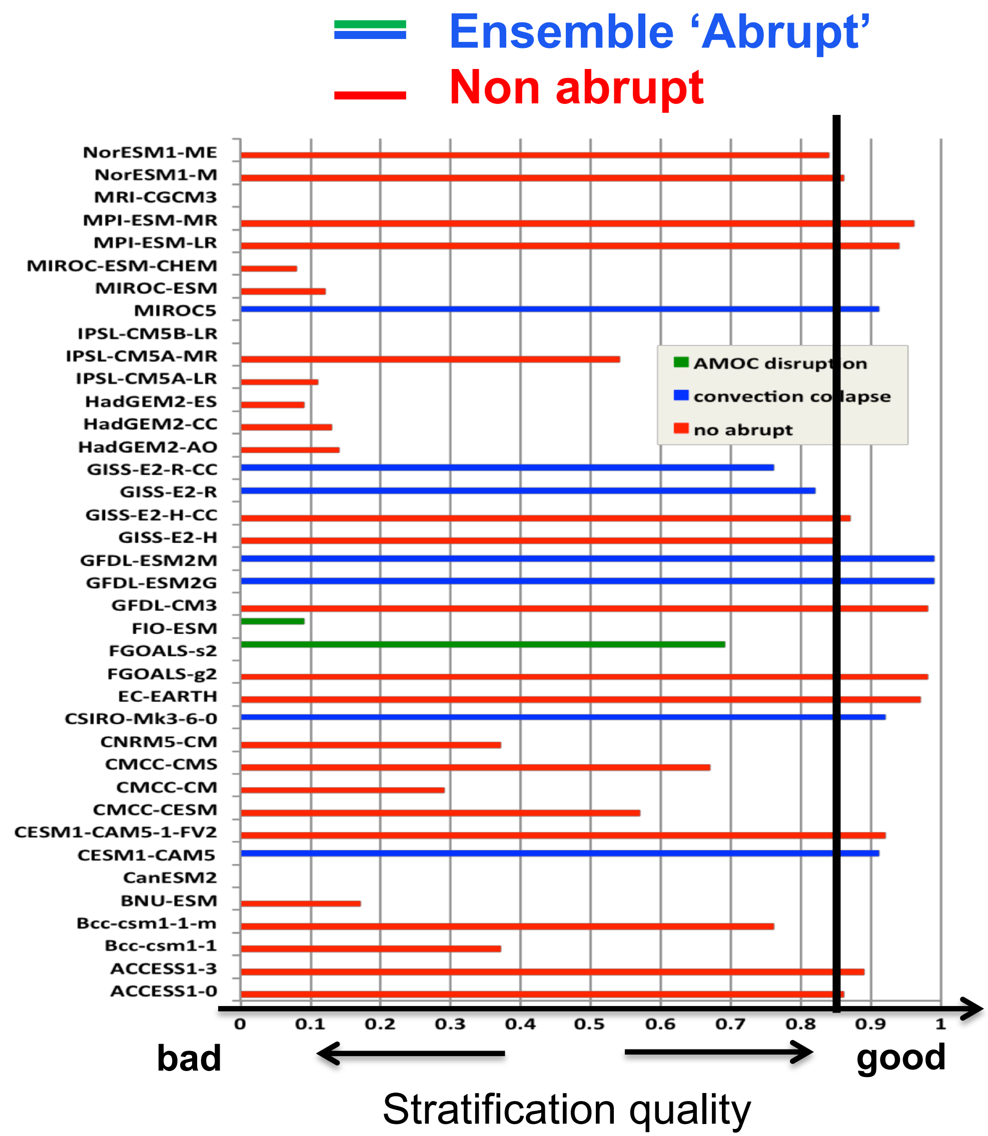
EMBRACE

Mechanism for subpolar gyre collapse



Abrupt cooling in the North Atlantic subpolar

- 9/40 (**~25%**) of all models do show a stong cooling in the near future
- Present-day ocean stratification in the subpolar gyre as an **observational emergent constraint**
- With this metric 5 from 11 best models do sho such an abrupt cooling (**~50%**)

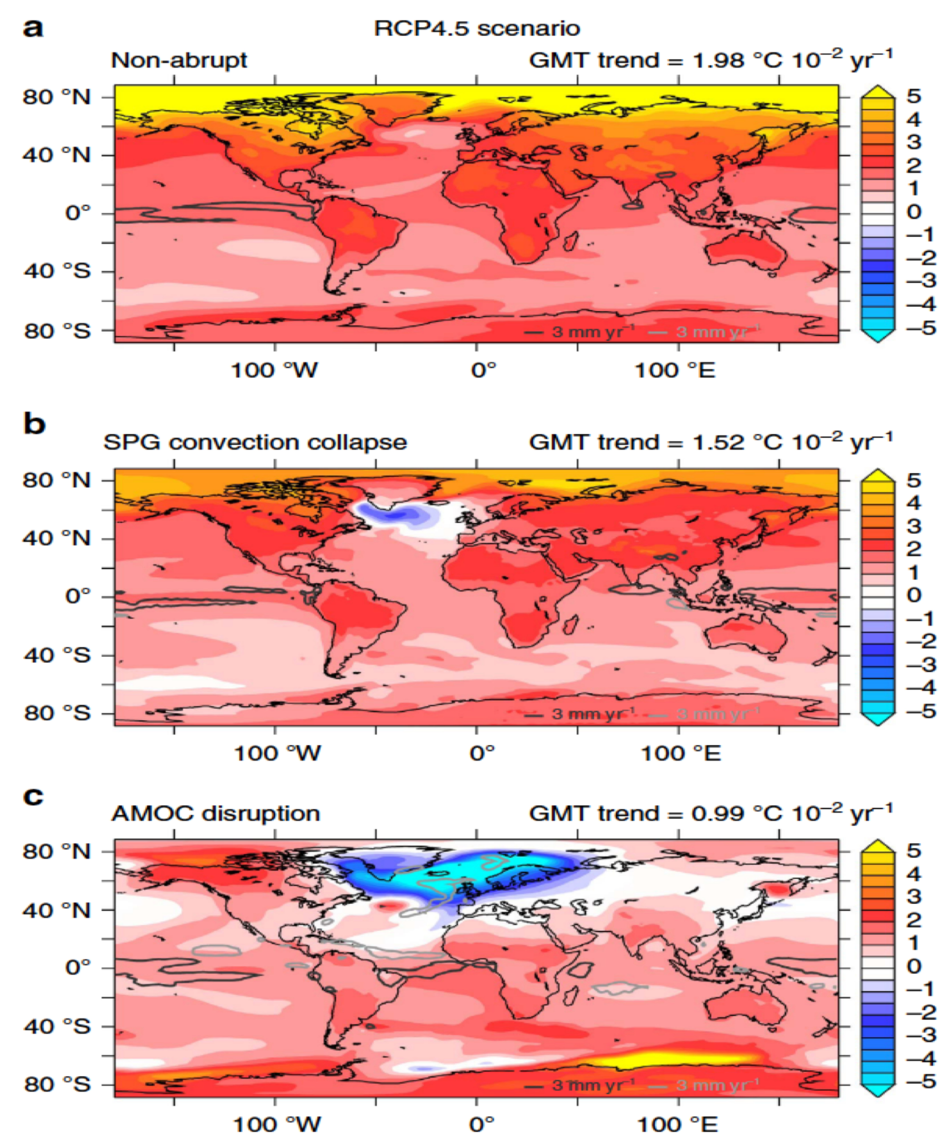


Sgubin et al., *Nat. Com.* 2017

Climatic impact

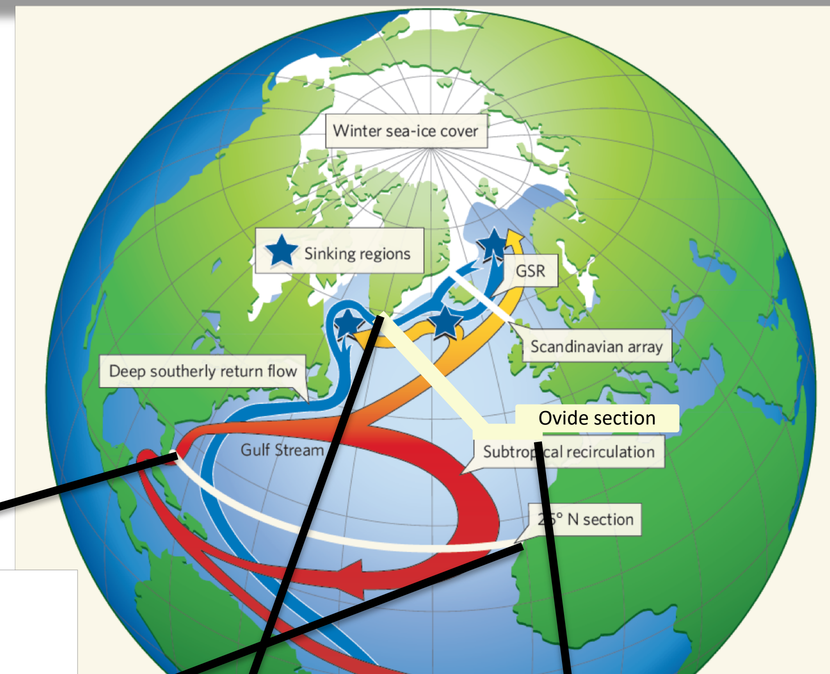
- Three different clusters of models highlighting very different warming response

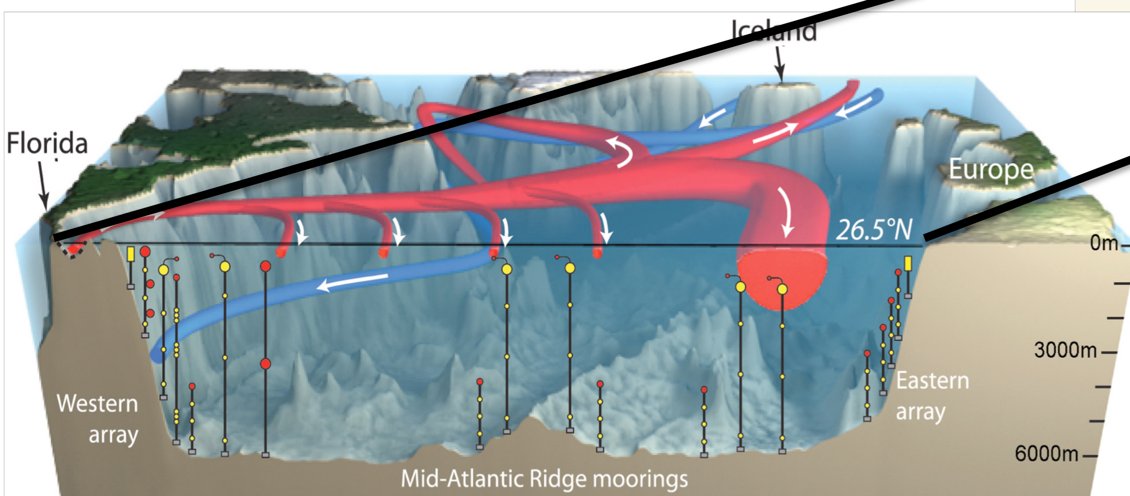
1. Warming everywhere (31 models)
2. Cooling in the subpolar gyre (7 models)
3. Cooling in large part of the North Atlantic (2 models)

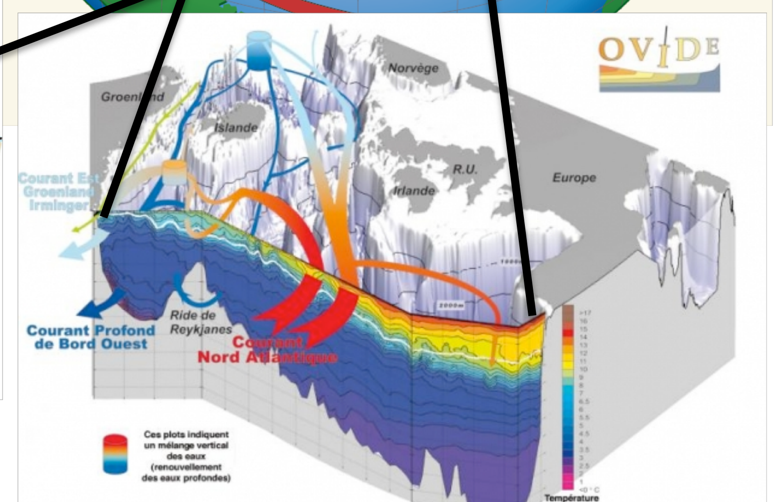


Measuring the AMOC

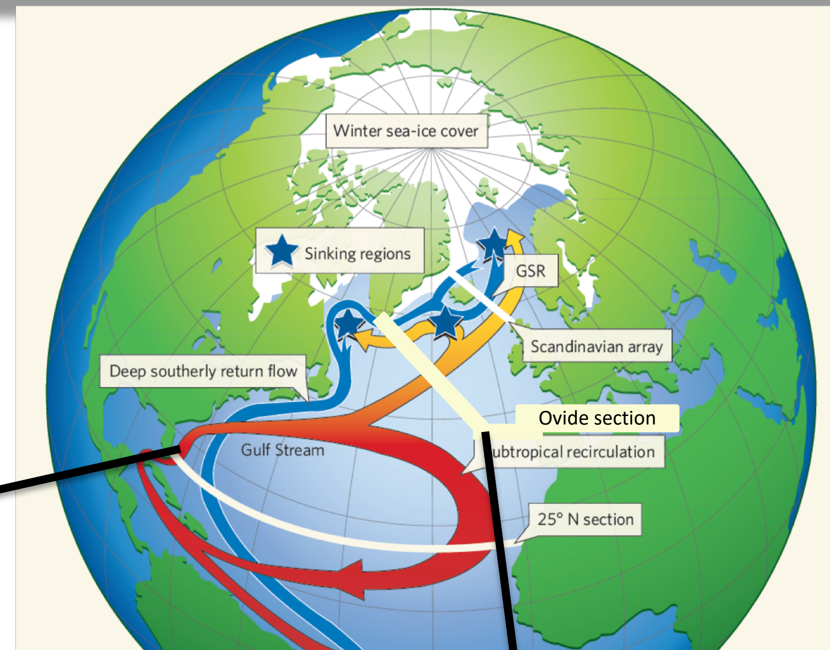
- AMOC change precedes its main impacts by 5-10 years = early warning
- OVIDE section between Portugal and Greenland tip
- RAPID section at 26°N



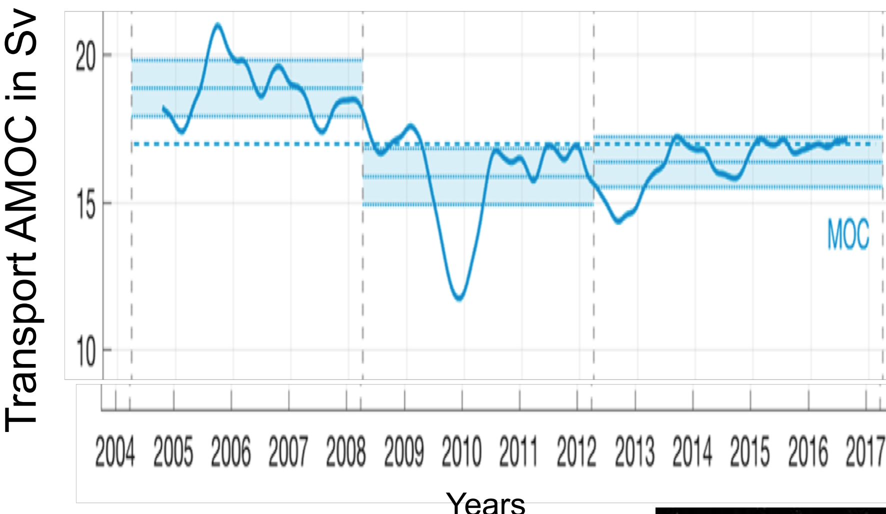




Recent evolution of the AMOC

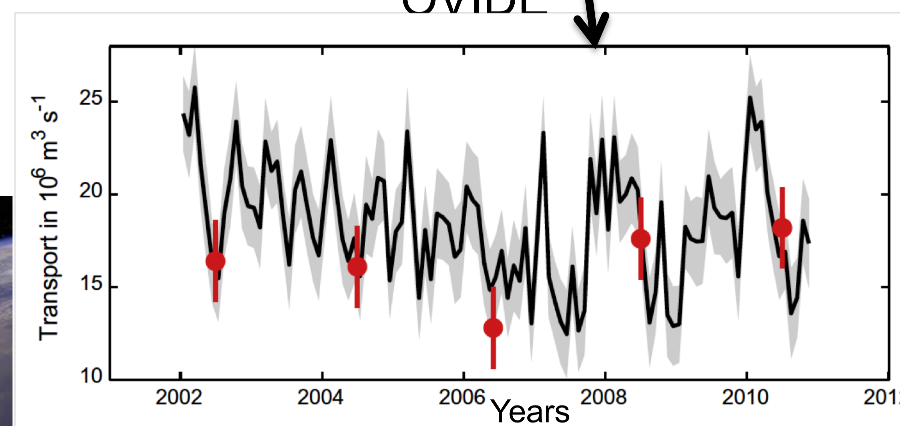


RAPID array



Smeed et al. (2018)

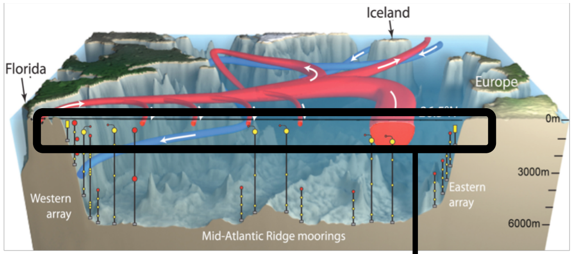
OVIDE



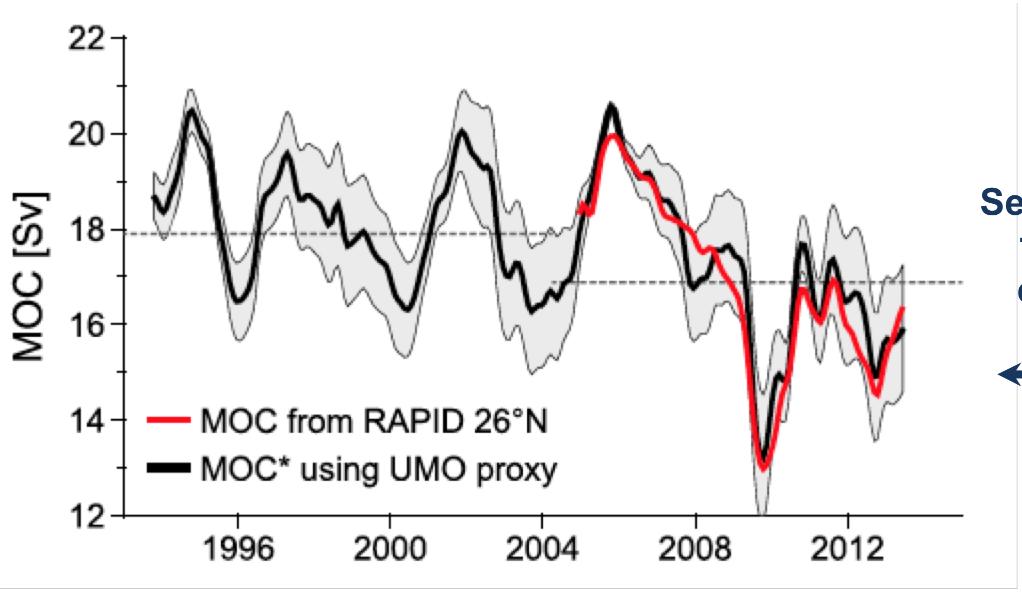
Mercier et al. (2015)

Reconstruction of the AMOC based on altimetry

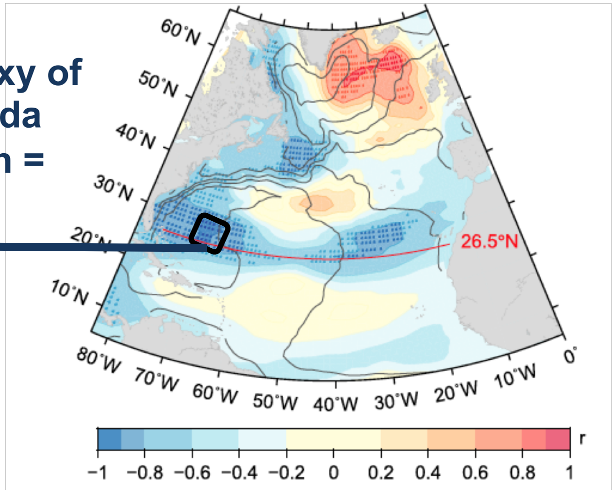
- Use of sea level as a fingerprint of AMOC variations (Frakja-Williams et al. 2015)
- Construction of a regression model based on sea level variations at 30°N, 70°W



Correlation of upper ocean transport (UMO) at 26.5N from and sea level data

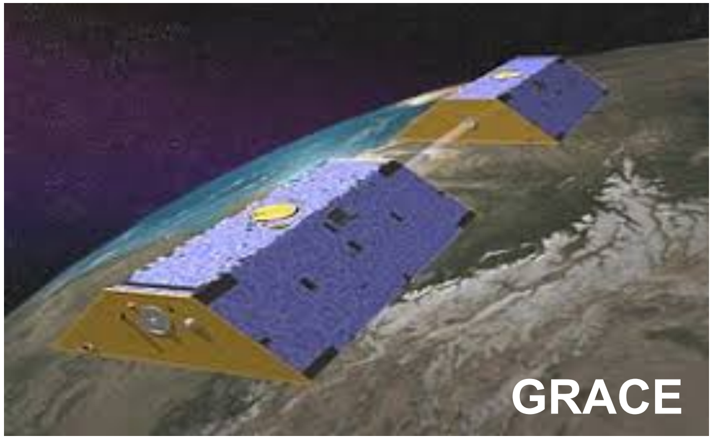


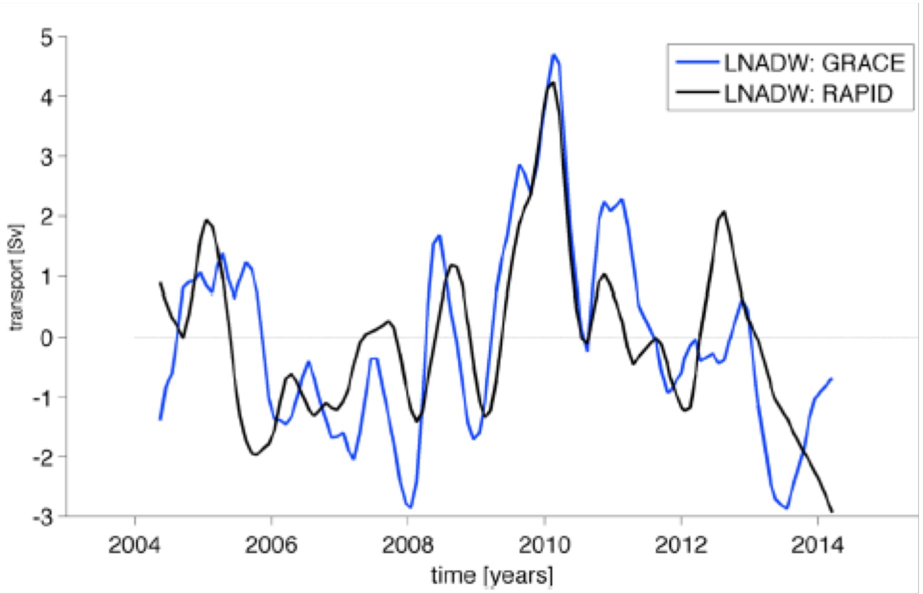
Sea level as a proxy of the UMO + Florida current + Ekman = AMOC



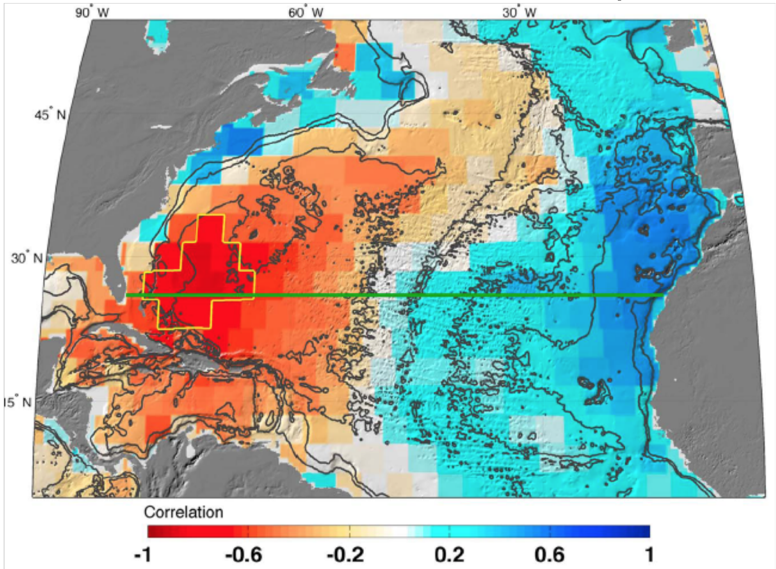
Reconstruction of the AMOC based on gravimetry

- GRACE is allowing to access ocean bottom pressure variations (Landerer et al. 2015)
- Link with transport: $$T(y) = \frac{1}{\rho_0 f} \int_{z1}^{z2} p_E(y,z) - p_W(y,z) dz.$$
- Reconstruction of Lower North Atlantic Deep Water (LNADW) between 3000 m and 5000 m depth

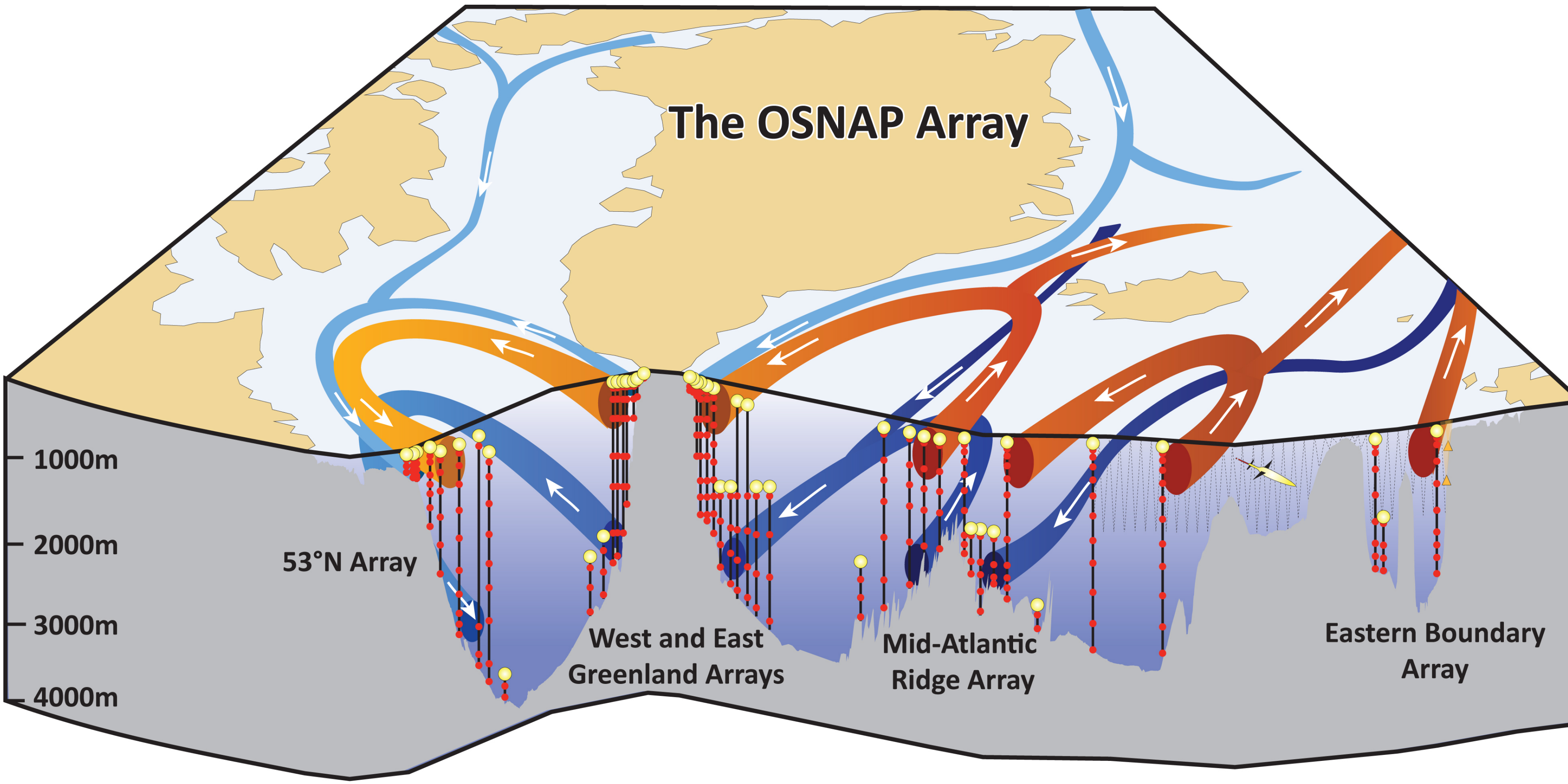




Correlation between GRACE LNADW estimate and GRACE ocean bottom pressure



The new OSNAP array



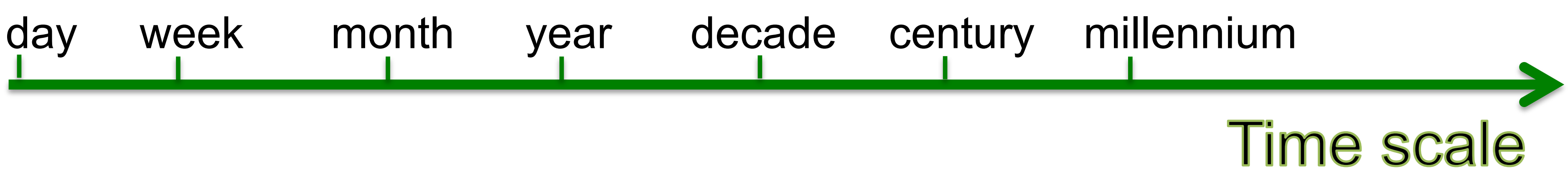
Lozier et al., Science, 2019

Decadal predictions

Initial conditions

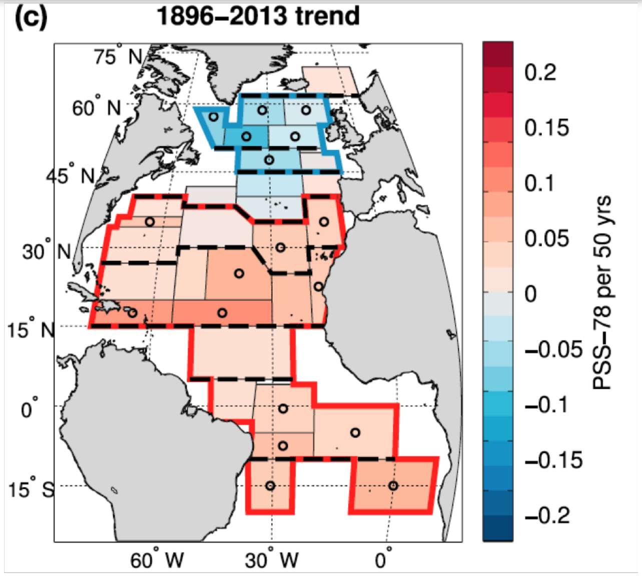
External forcing

Weather forecast | **Seasonal prediction** | **Decadal prediction** | **Centennial projections** | **Glacial cycles**



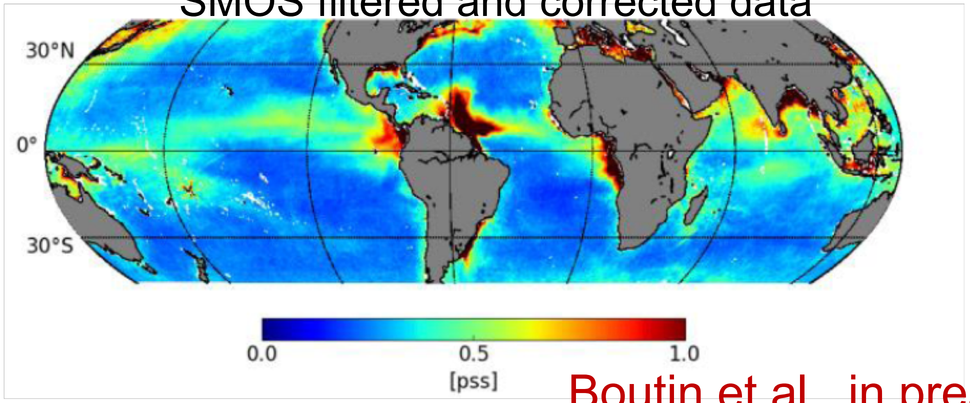
IPSL-EPOC decadal prediction system

- Use of surface nudging for SST and SSS (sea surface salinity) to initialise the hindcasts and forecasts
- CMIP6: Use of SSS reconstruction (Friedman et al. 2017)
- To come: use of new SMOS SSS
- Test the impact of uncertainty in the dataset (0.2 PSU on a 1° grid resolution)



Friedman et al., 2017

SSS variability (std) derived from 7 years of SMOS filtered and corrected data

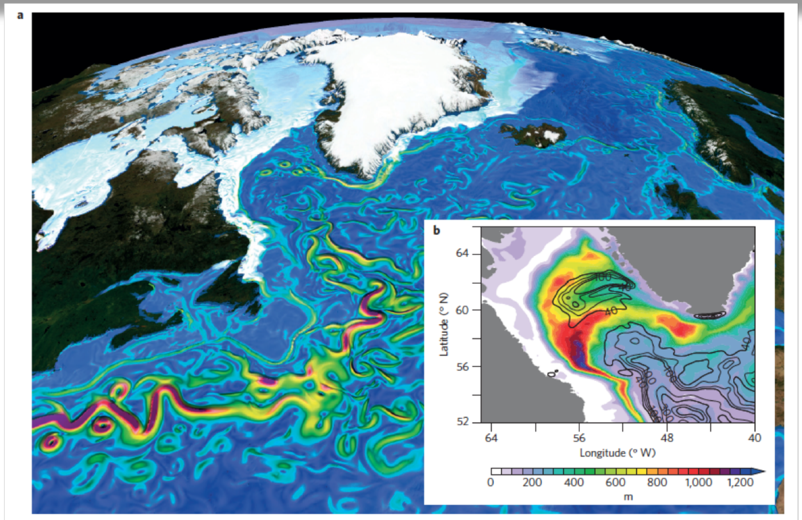


Boutin et al., in press

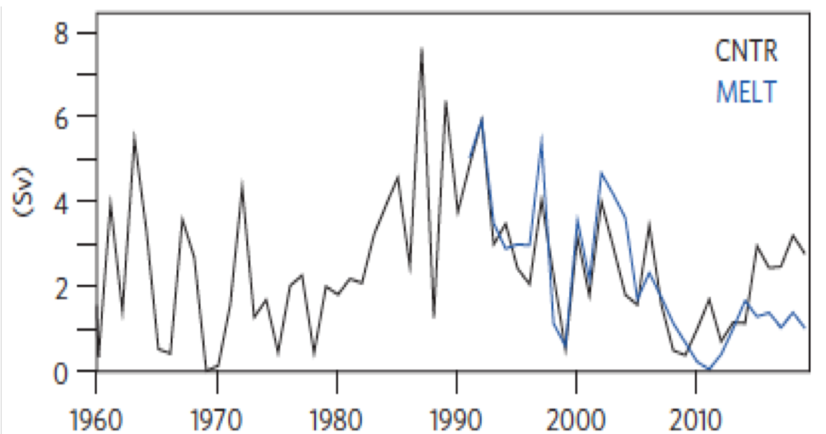
Including the Greenland melting in forecasts

- Melting of Greenland is already affecting the Labrador Sea convection (Böning et al. 2016)
- Use of an observed melting scenario based on satellite data, regional model (Bamber et al. 2018) and iceberg module (De Villiers et al. in prep.)
- Applying it to hindcasts and forecasts from the new IPSL-EPOC decadal prediction system
- Necessary for the 2015 cold blob emergence/forecast? And below?

BLUE ACTION



Deep water production in Labrador



Böning et al. 2016

Conclusions

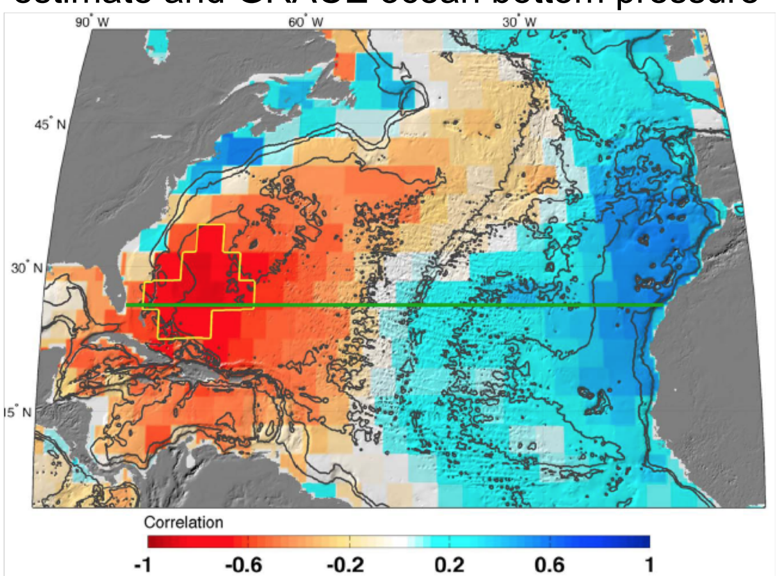
- The AMOC will *very likely* weaken over the 21^{st} century
- The AMOC will *very unlikely* collapse over the 21^{st} century
- There is a risk of 2-3°C abrupt cooling (<10 years) in the North Atlantic over the 21^{st} century due to the subpolar gyre system collapse
- Associated impacts can be large, but are not sufficiently analysed up to now
- Early warning system of changes in the 3D Atlantic circulation can clearly benefit from satellites observations
- Need for the reconstruction of the AMOC further back in time to better infer its natural variability and associated statistical early warning
- Decadal prediction systems, combining recent observations and models, are promising to better assess near-term decadal-scale hazard

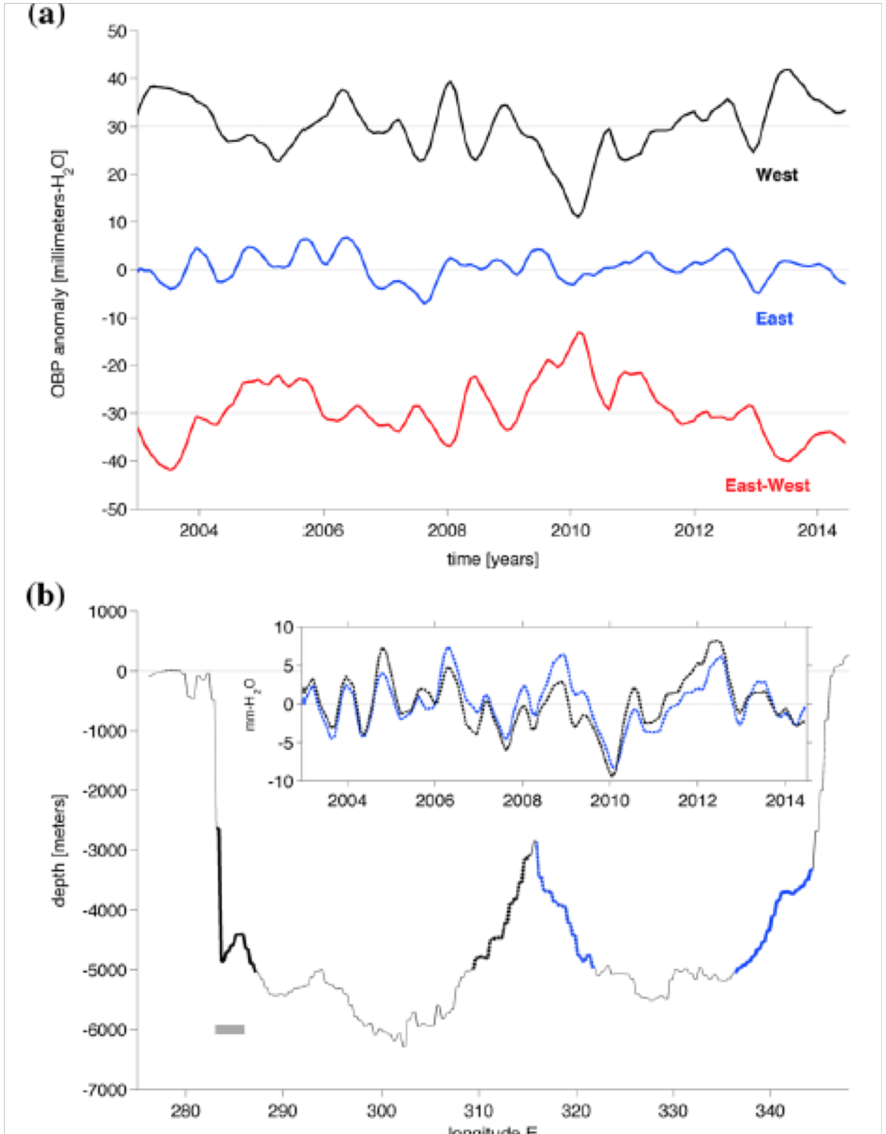

Thank you!

Reconstruction AMOC from GRACE

$$T(y) = \frac{1}{\rho_0 f} \int_{z1}^{z2} p_E(y,z) - p_W(y,z)dz.$$

Correlation between GRACE LNADW estimate and GRACE ocean bottom pressure

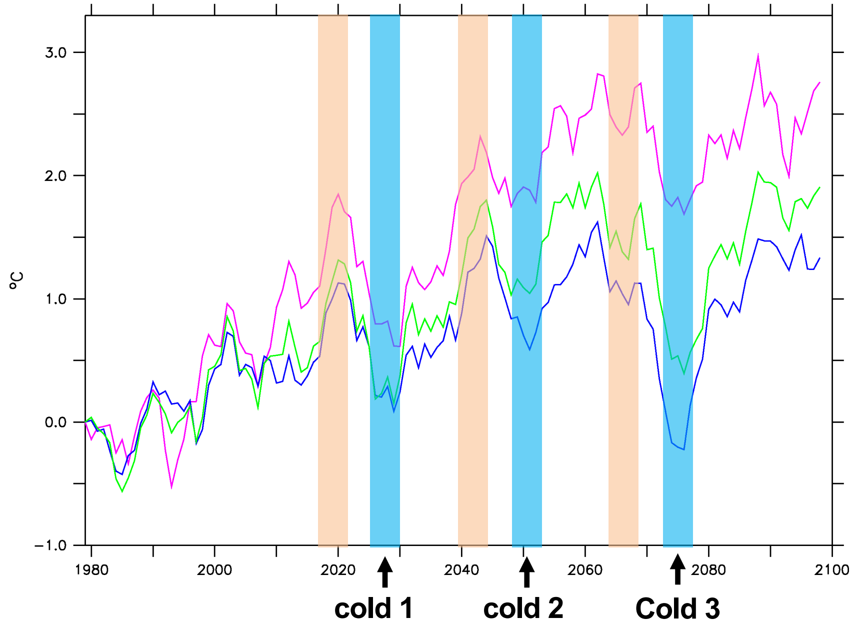


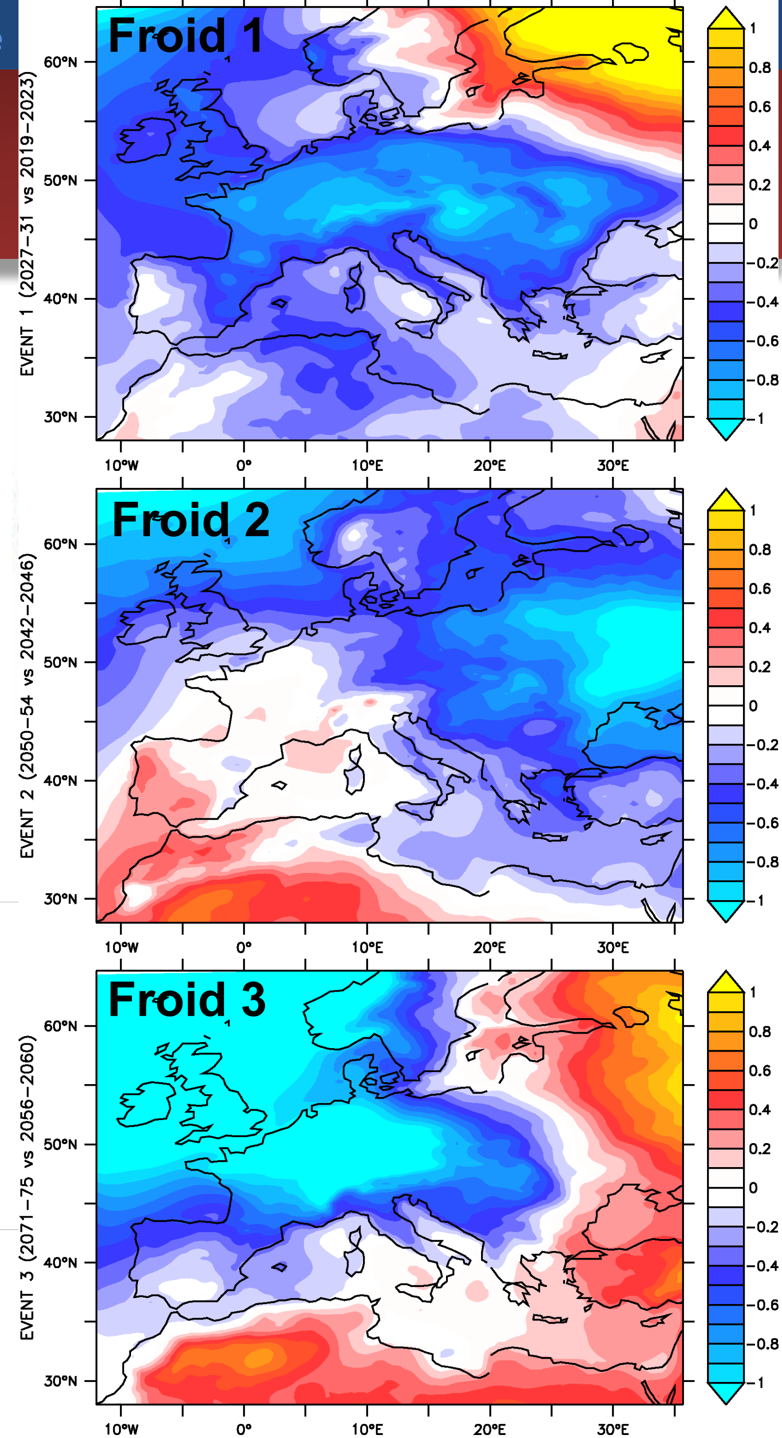


Impact of a decadal-scale cooling?

- CSIRO-Mk3-6-0 model downscaled within CORDEX using regional model SMHI-RCA4

Annual temperature

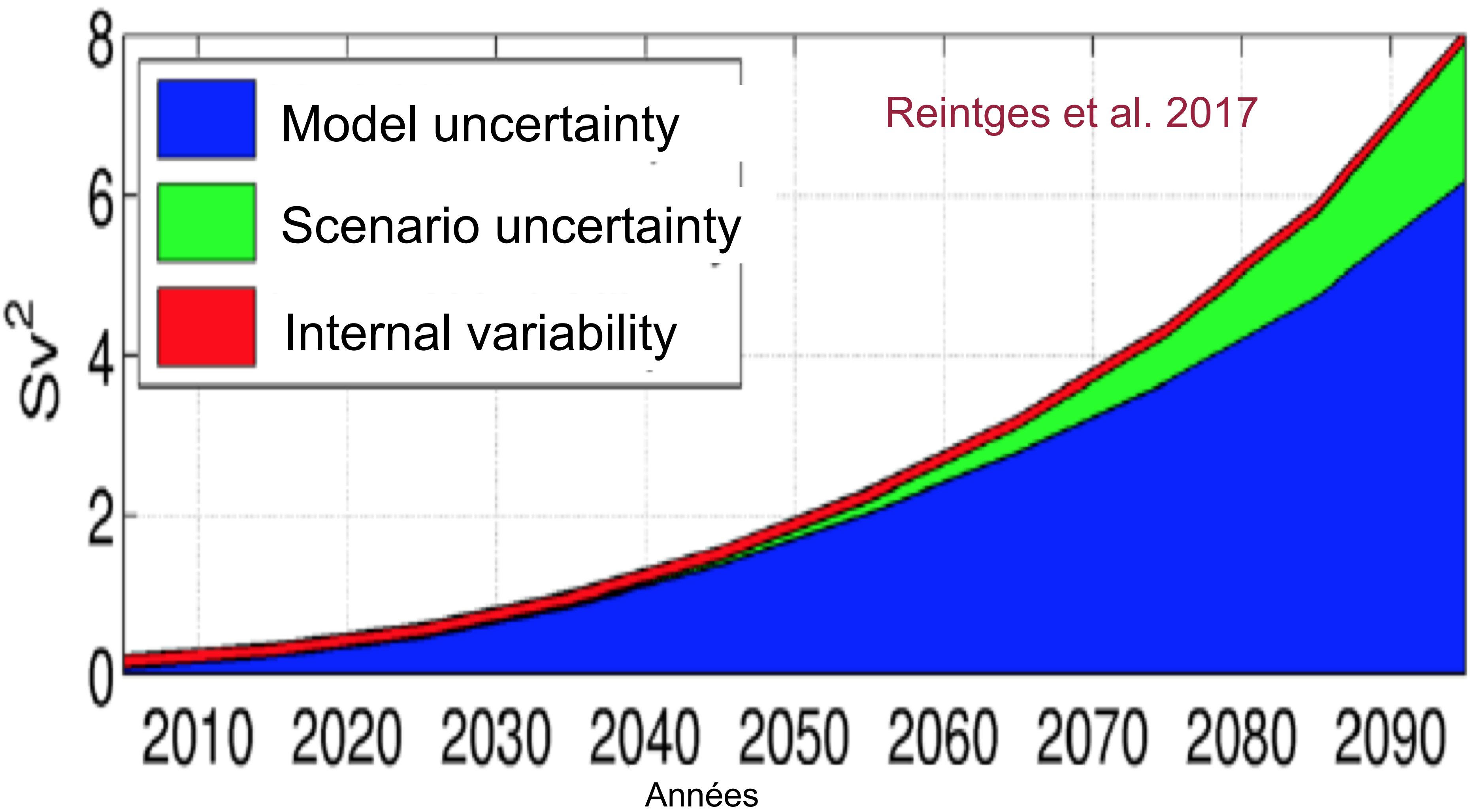




Sgubin et al. in prep.

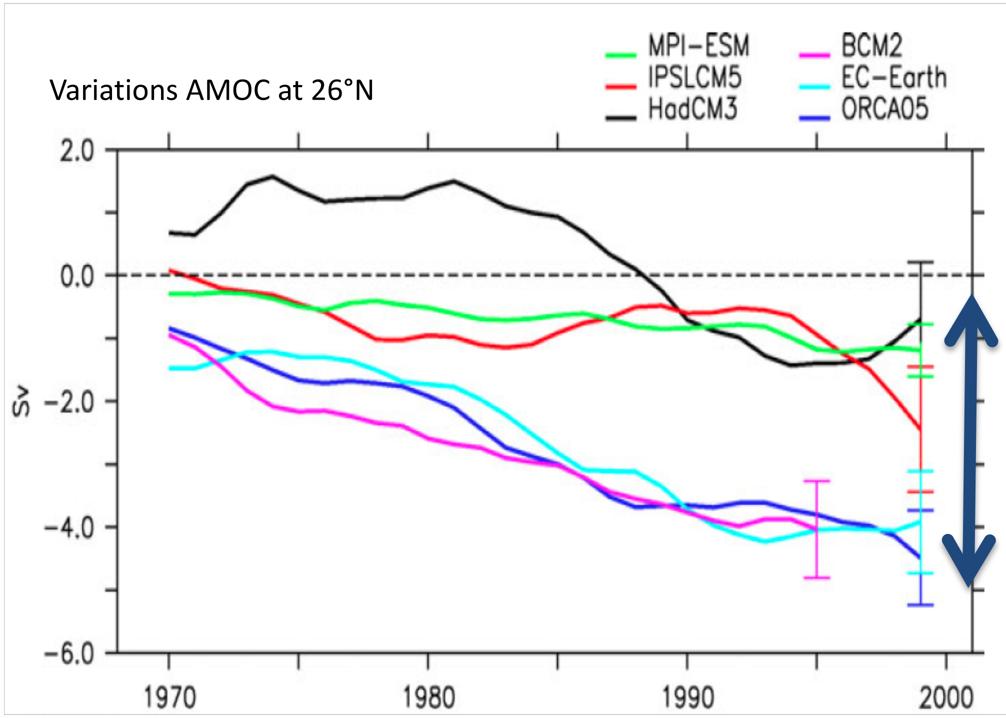
Uncertainty sources

Uncertainty sources for the AMOC at 30°N (RCP45 et RCP85)



AMOC response to Greenland melting

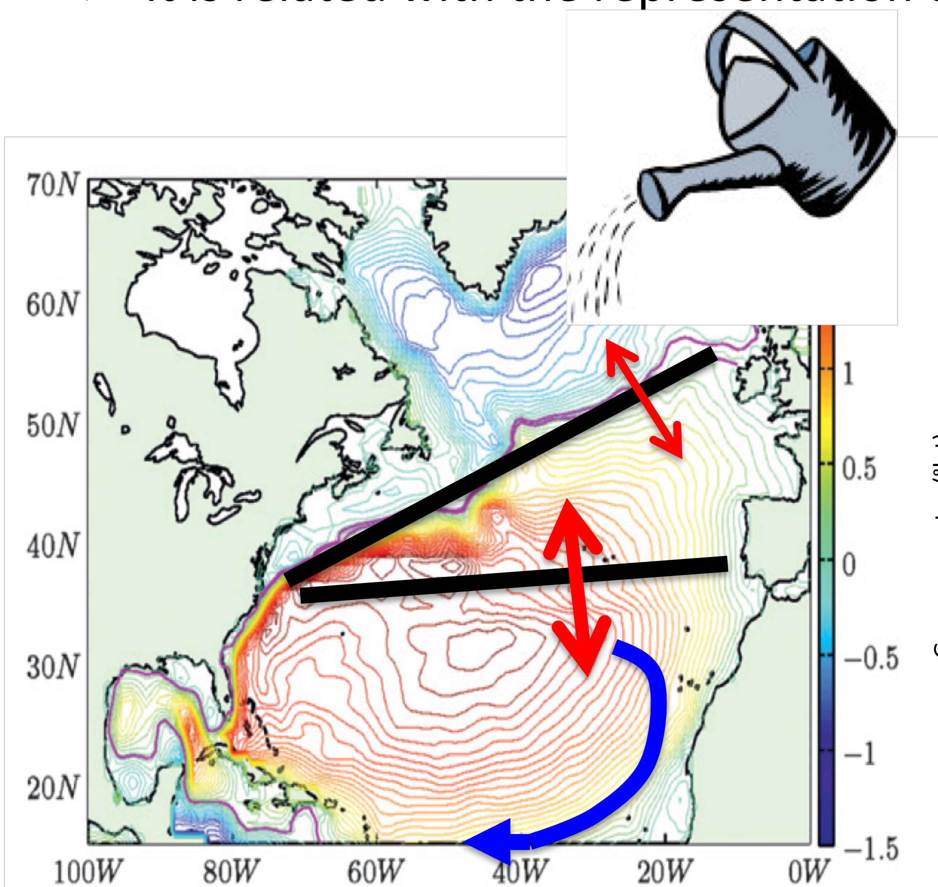
- Six models from European project THOR
- We put 0.1 Sv of melting all around the Greenland for 40 years (1965-2004)
- We find a very large spread, reminiscent of Stouffer et al. (2006) with former generation models



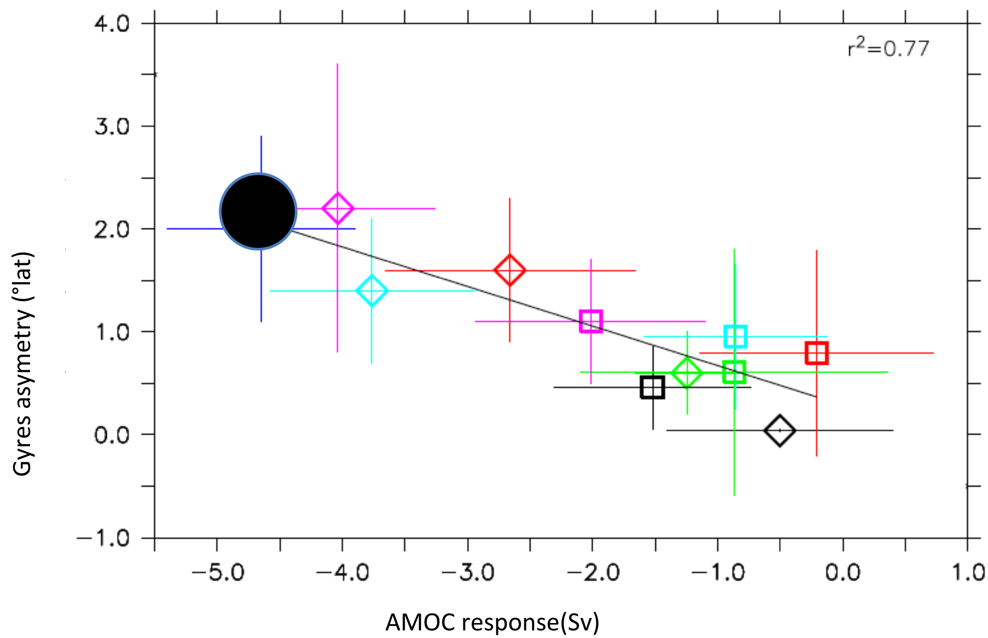
Swingedouw et al., *Clim Dyn.*, 2013b

Explaining the spread among the models

- We propose that the leakage along the Canary current is key to explain the spread
- It is related with the representation of the gyres in the models



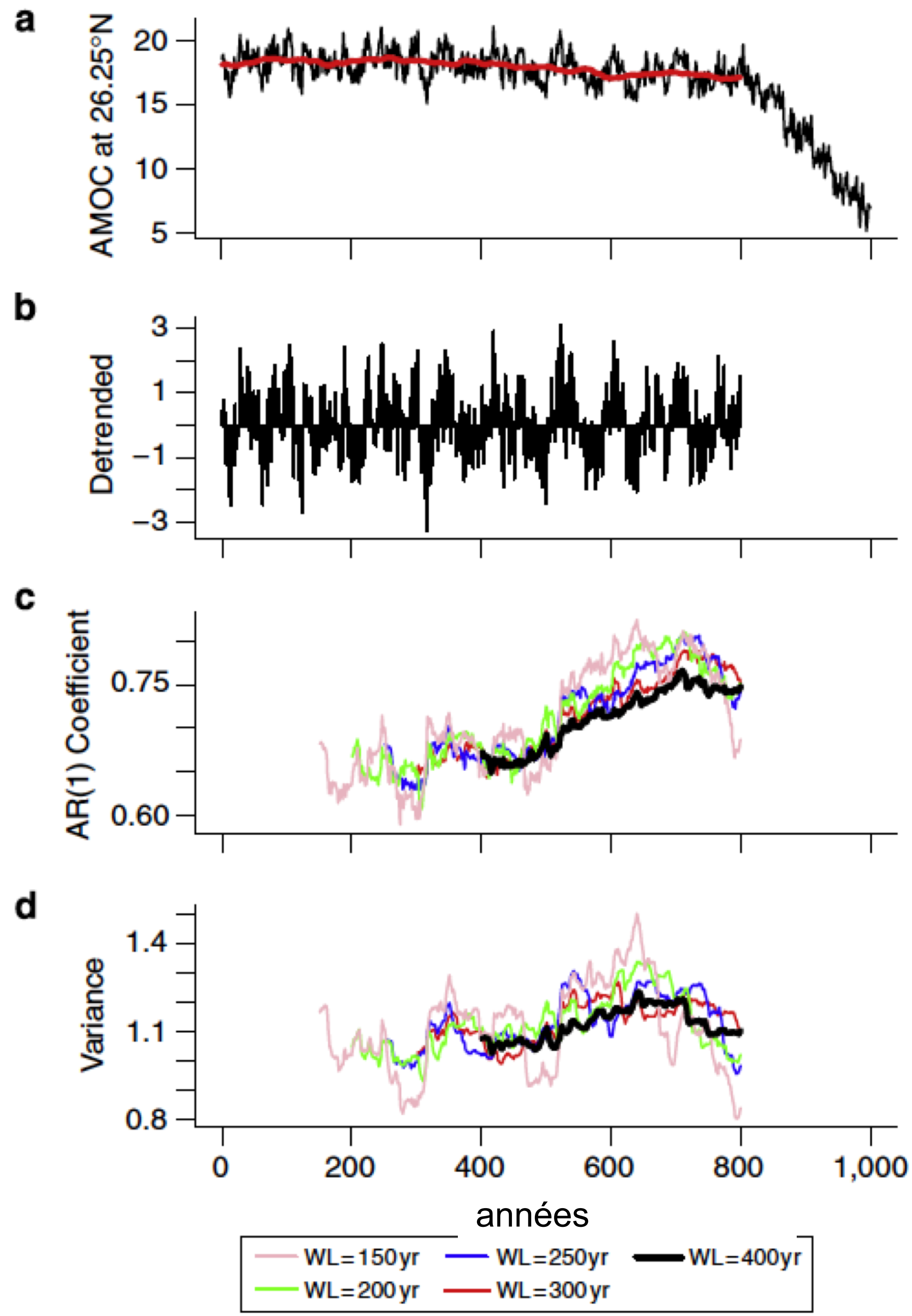
AMOC changes vs gyres asymmetry



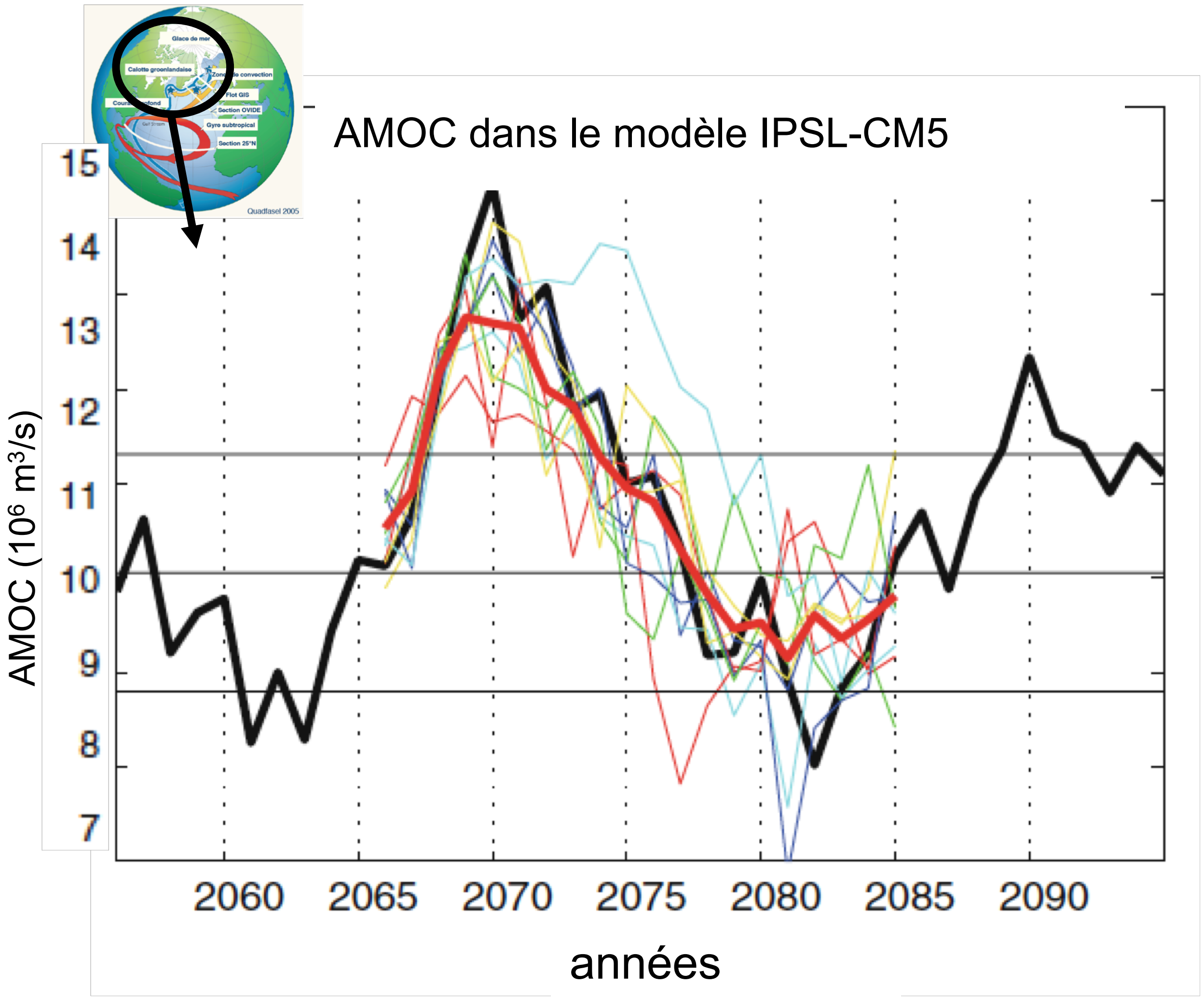
Swingedouw et al., *Clim. Dyn.*, 2013b

Early warning

- Boulton et al. (2014): We can anticipate an abrupt changes of the AMOC up to 250 years in advance!
- But for this, we need to know hundred of years of variability
- Only 15 years available, extended up to a century using SST fingerprints
- Need for longer reconstruction of the AMOC based on multiple sources of proxy records



Decadal prediction

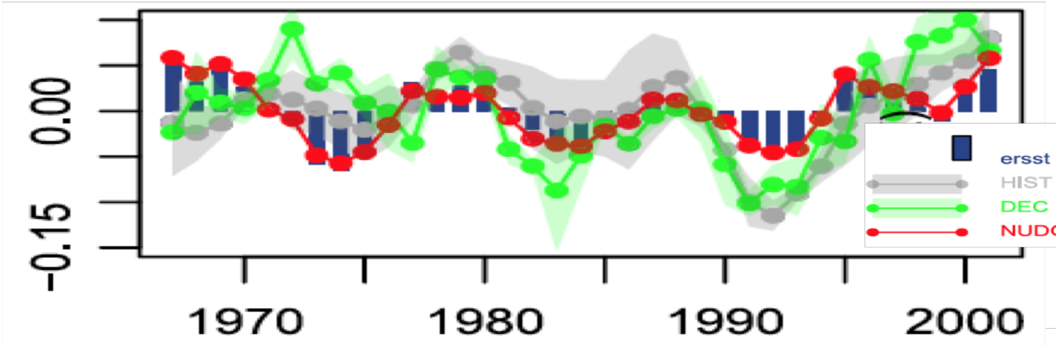


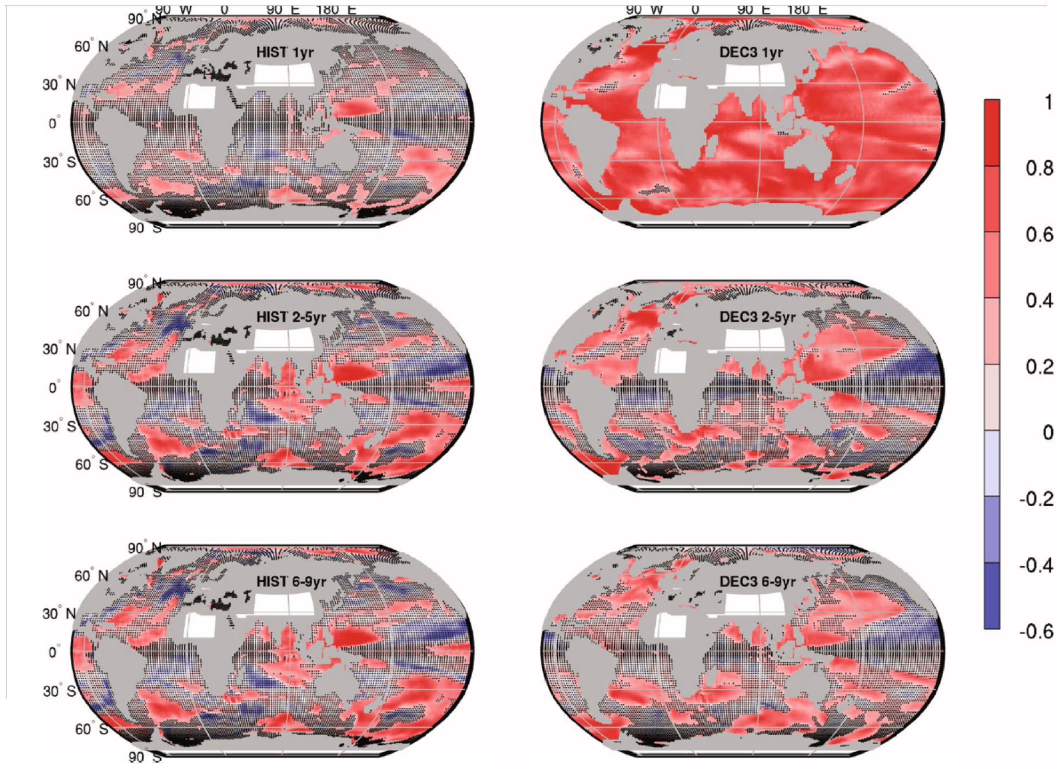
Persechino et al. (*Clim. Dyn.*, 2013)

Skill of the decadal prediction system

- We have launched a 3-member ensemble from the initialised nudged simulations every year over the period 1960-2015
- We compare the few years of hindcasted SST with observations and non-initialised forecast
- We find further skill in the North Atlantic and Pacific

Forecast skill in global SST for period 2-5 years of prediction





Mignot et al., *Clim. Dyn.*, 2015