Is there a useful indicator for thresholds in the AMOC?

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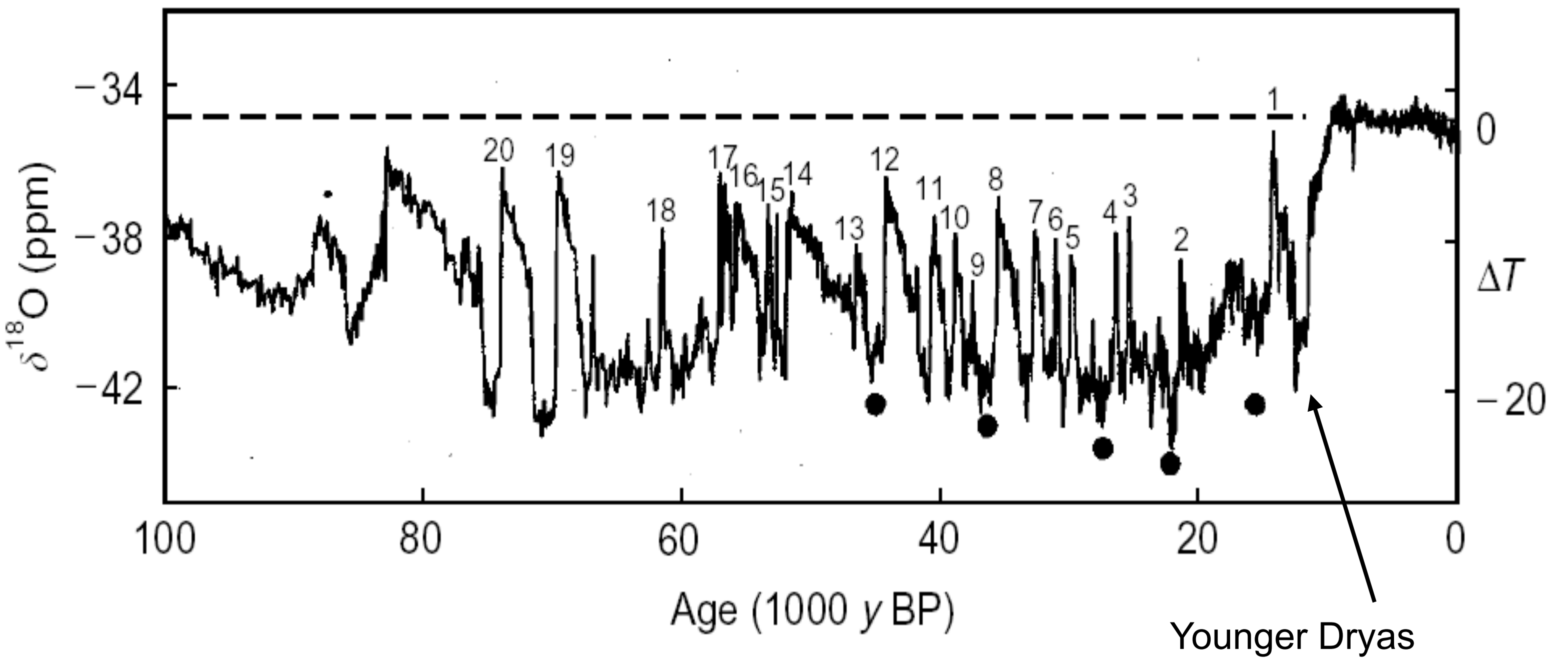
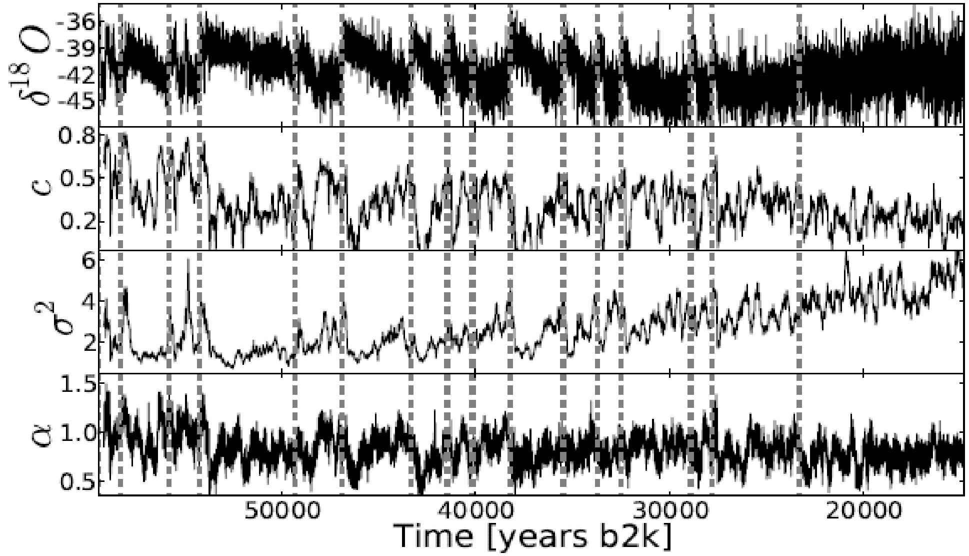
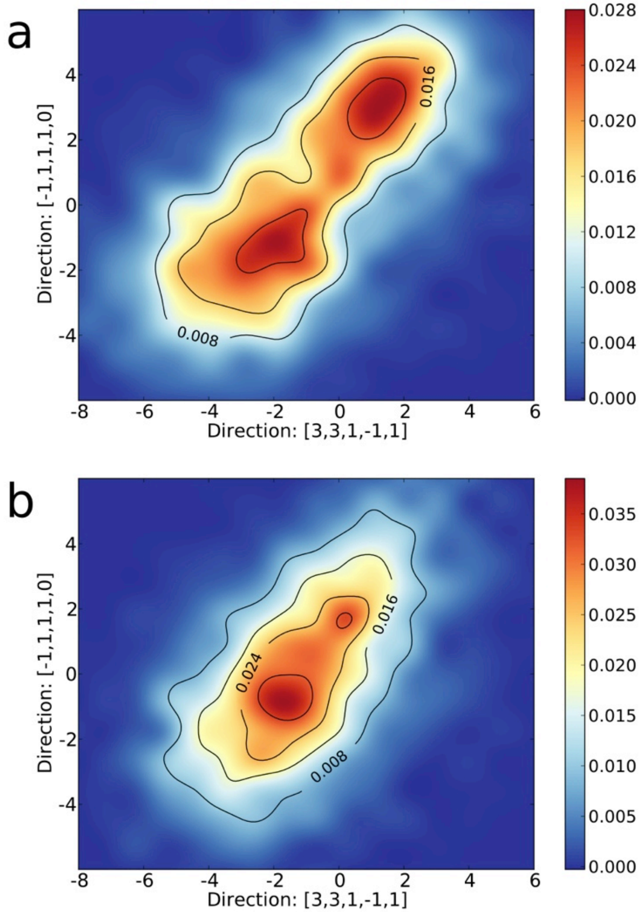


Record δ^{18}O from the GRIP ice core. The glacial climate characterized by so called Dansgaard-Oeschger events (numbered) and Heinrich events (dotted).

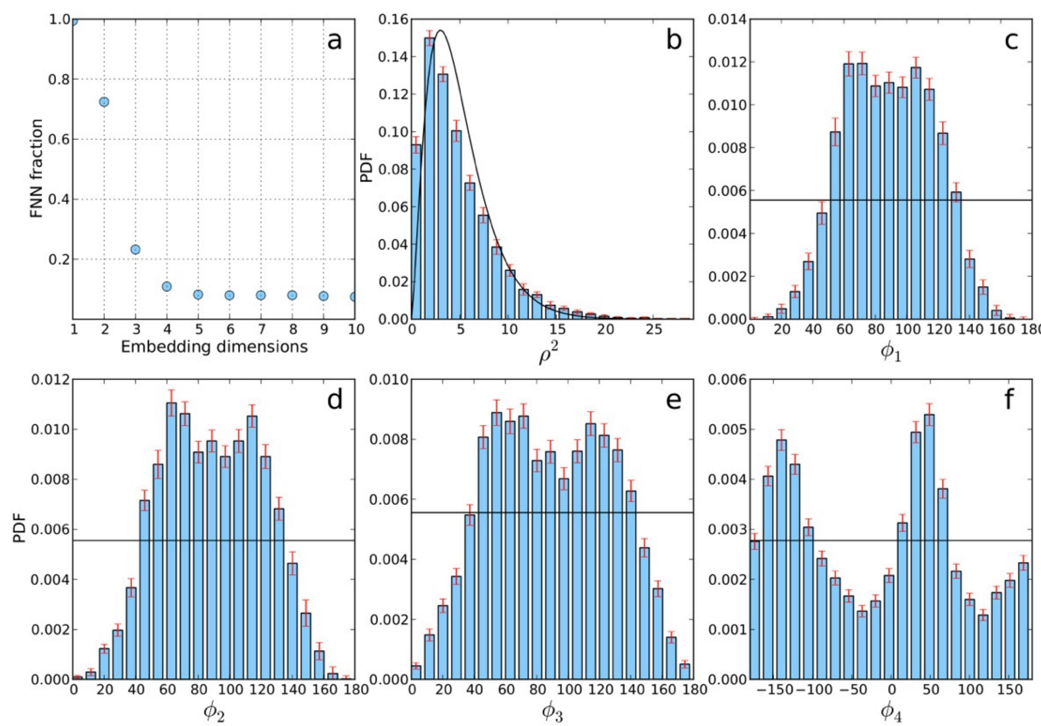
Higher resolution ice-core data

Cimatoribus et al. 2012a

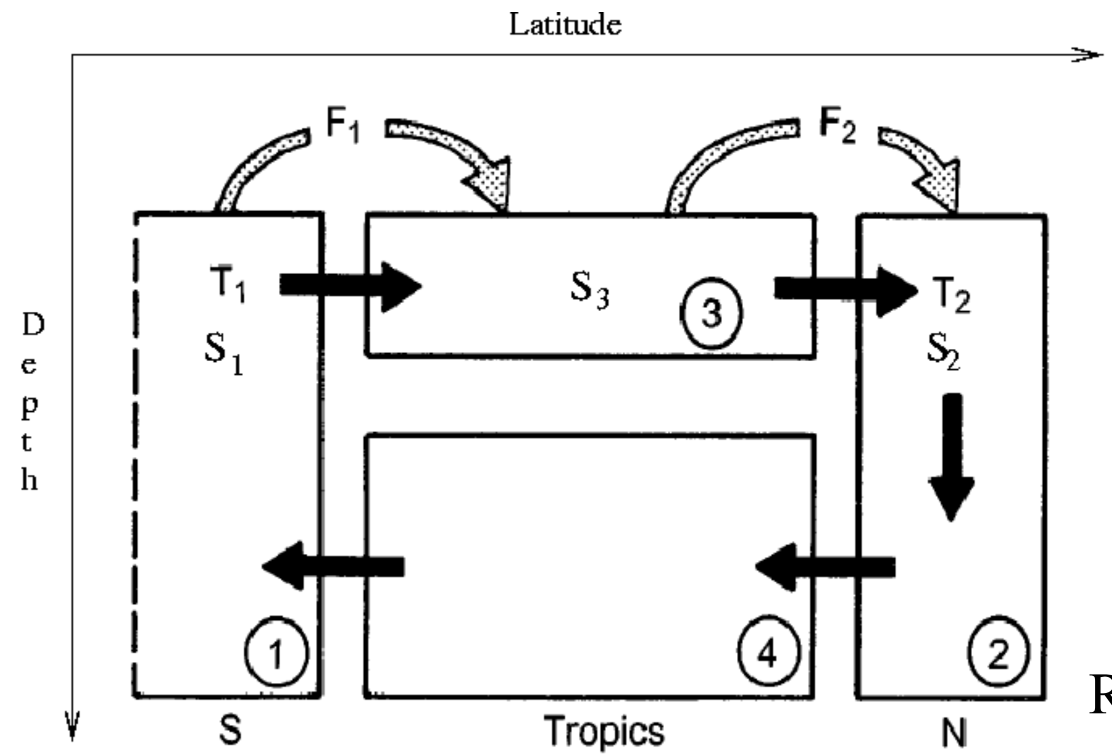




Phase space reconstruction using Takens' embedding theorem



A box model of the Atlantic MOC



Rahmstorf (1996)

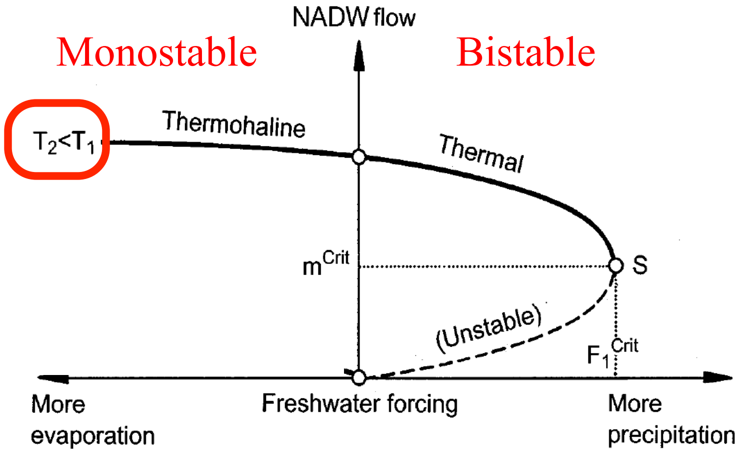
$$m = k(\rho_2 - \rho_1) = k[\beta(S_2 - S_1) - \alpha(T_2 - T_1)]$$ *

$$\dot{S}_1 = m(S_2 - S_1) + S_0 F_1$$ *

$$\dot{S}_3 = m(S_1 - S_3) - S_0 F_1 + S_0 F_2$$

$$\dot{S}_2 = m(S_3 - S_2) - S_0 F_2$$

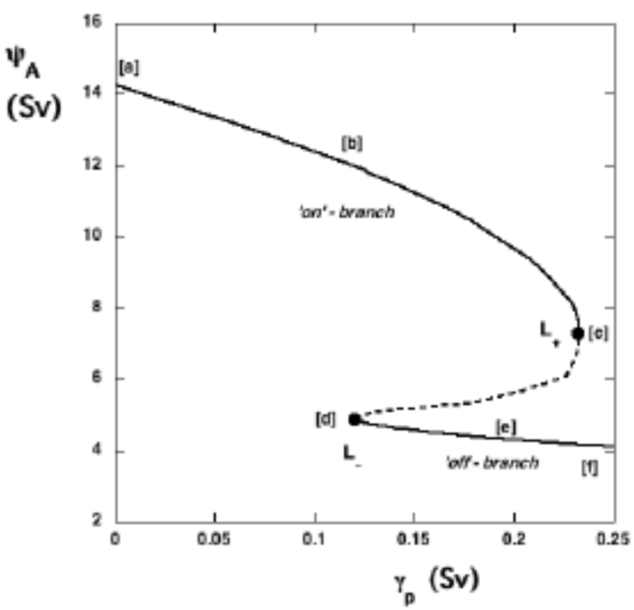
Steady state solution of equations

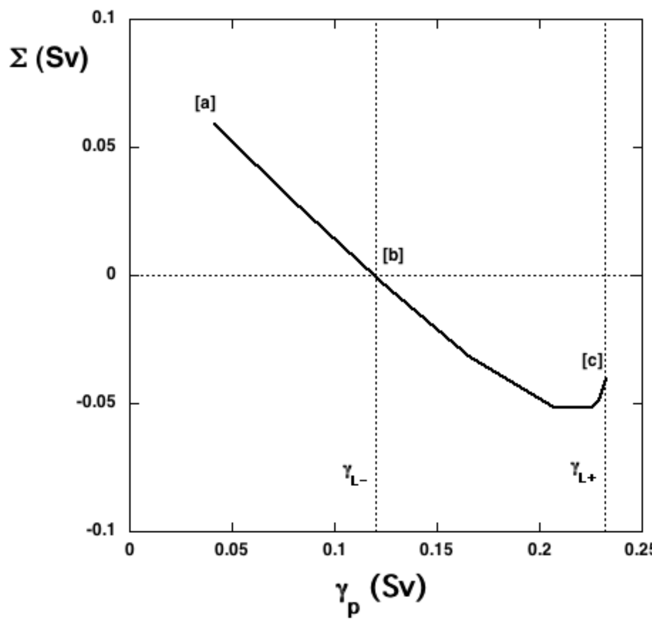


$$m = -\frac{1}{2}k\alpha(T_2 - T_1) \pm \sqrt{\frac{1}{4}(k\alpha(T_2 - T_1))^2 - k\beta S_0 F_1}$$

Rahmstorf (1996)

M_{ov} = - F_1 is: Advective Stommel feedback



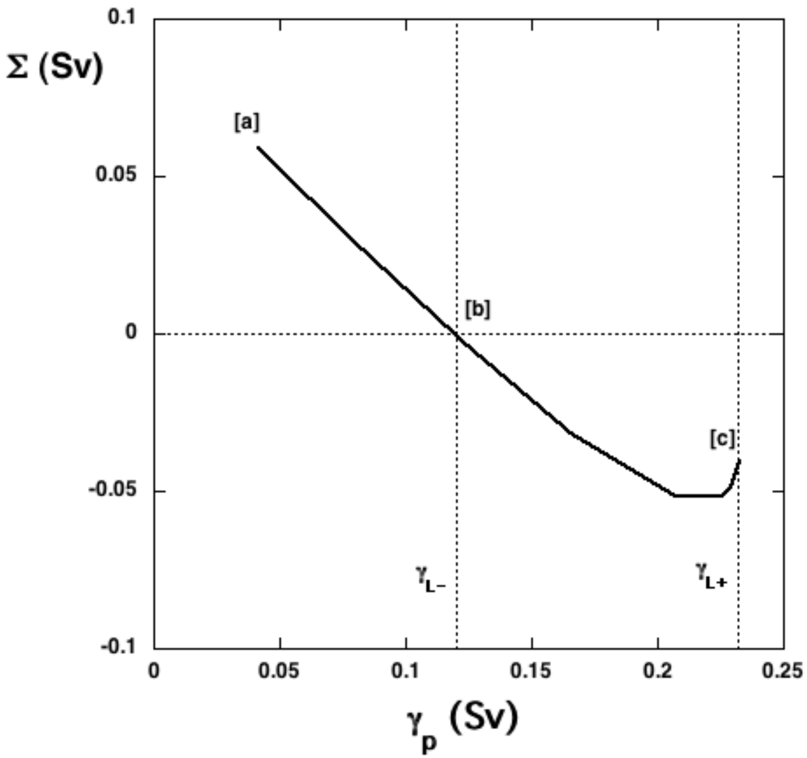


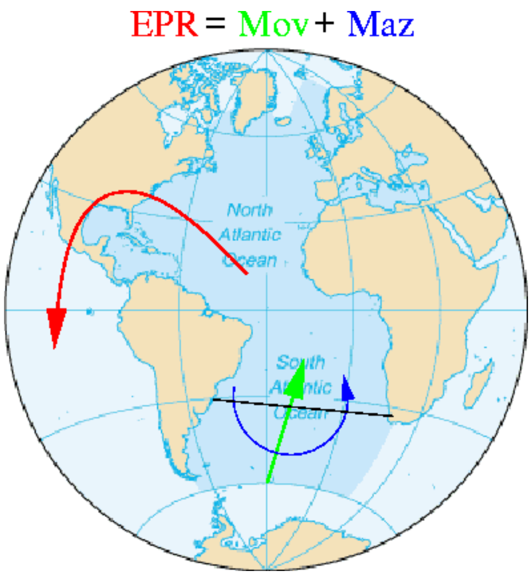
$$M_{ov} = -\frac{1}{S_0}\int_{30^\circ S} \tilde{v}(\langle S \rangle - S_0)\,\mathrm{d}x\mathrm{d}z,$$

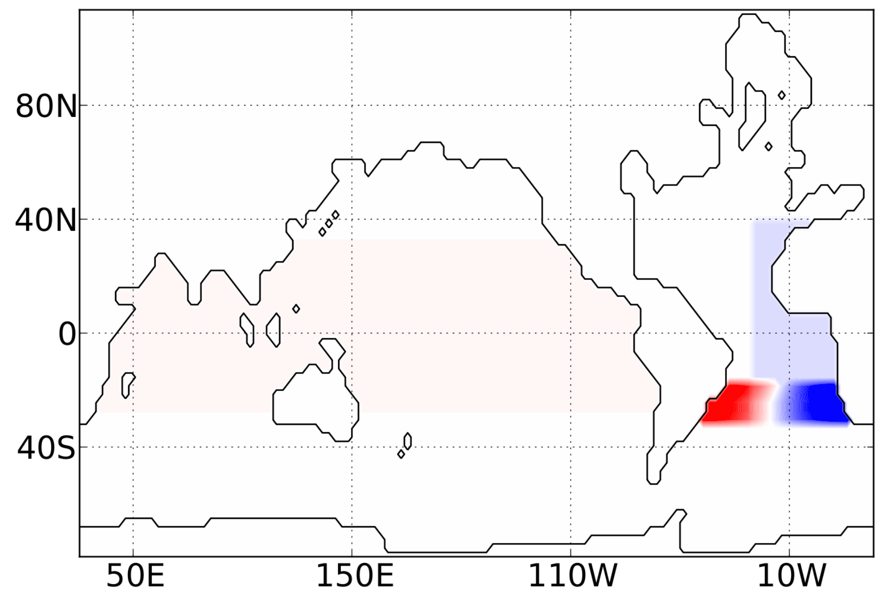
$$M_{az} = -\frac{1}{S_0}\int_{30^\circ S} v' S'\,\mathrm{d}x\mathrm{d}z.$$

Huisman et al 2009

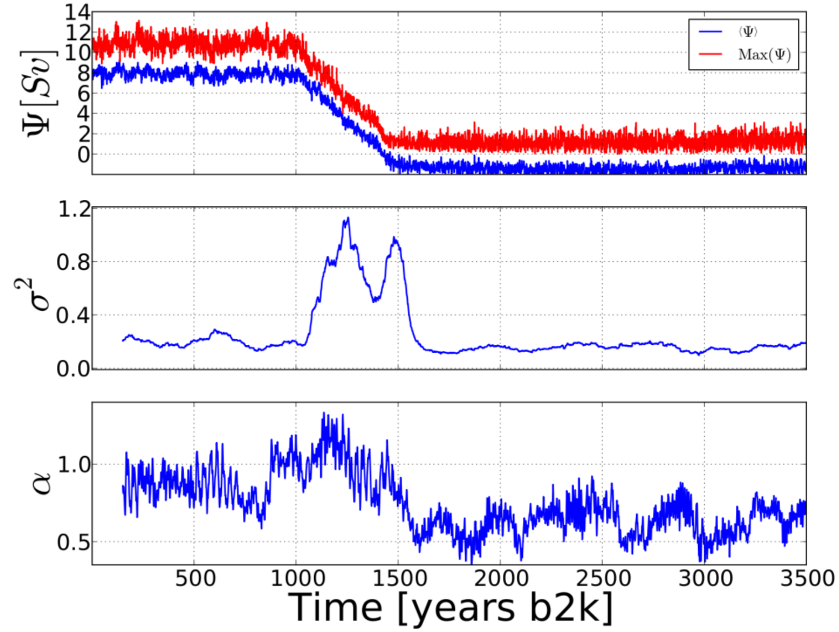
Slowly changing M_{ov} by changing M_{az}



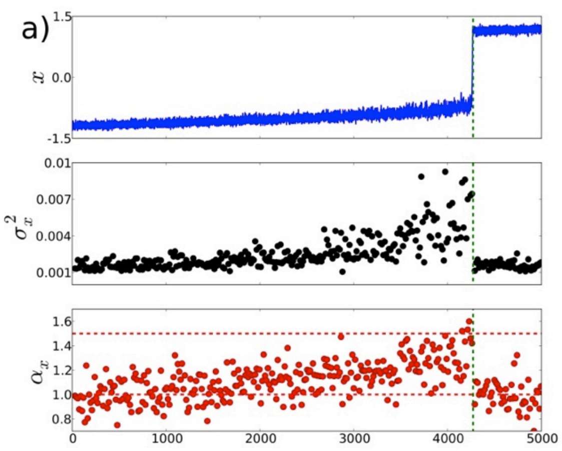




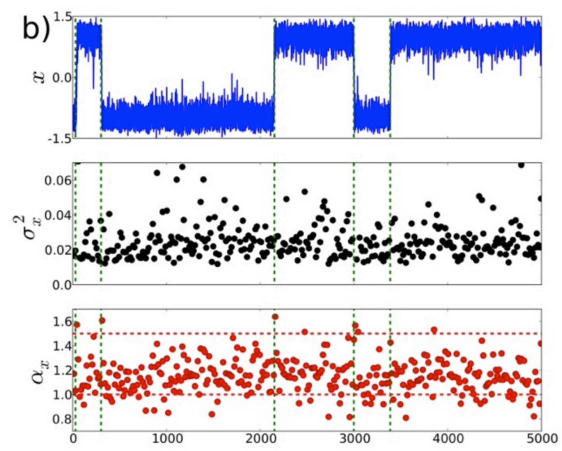
Cimatoribus et al. 2012b



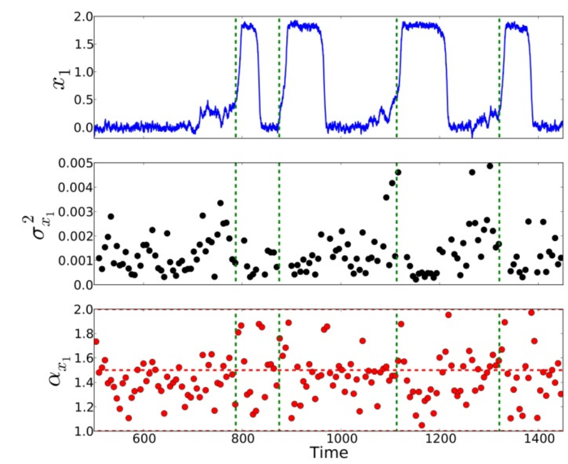
(Saddle node) bifurcation

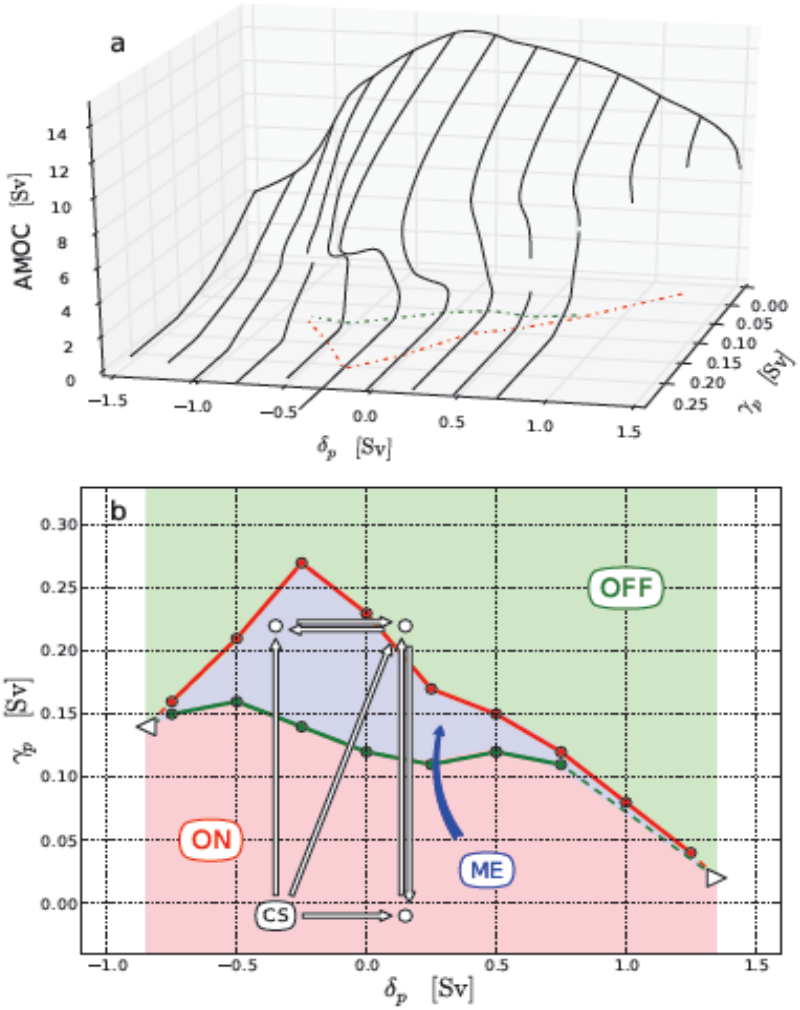


Noise induced regime shift



Heteroclinic orbit





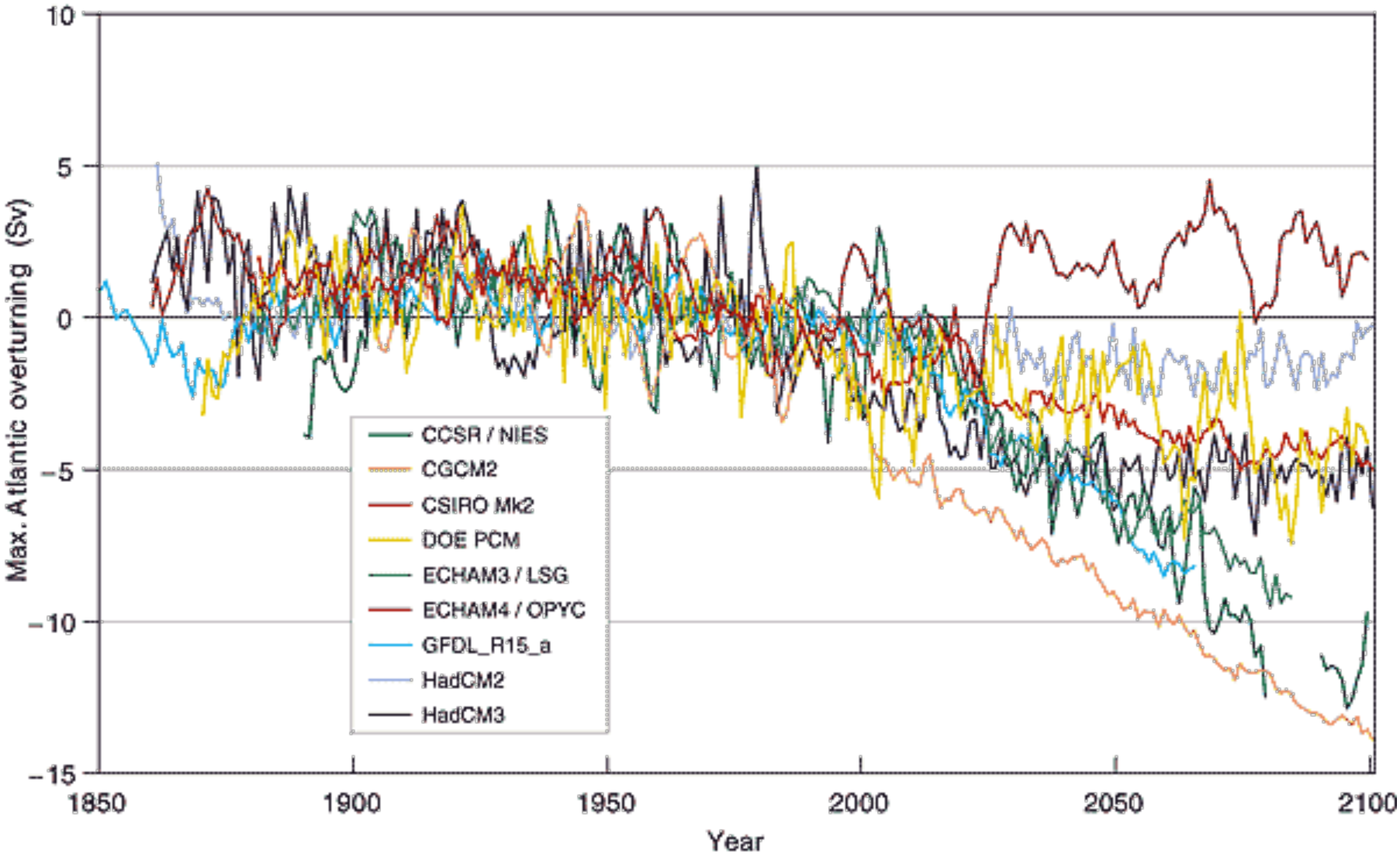
- F_{ov} is often a good but not a perfect indicator
- A sufficiently negative F_{ov} indicates the ME regime, only if E-P is not too large
- Decreasing F_{ov}, or increasing F_{az} may lead to a collapse if E-P is not too large
- The response to hosing depends on F_{ov}, but the advective salt feedback by the overturning circulation is not the only feedback.

$$L = \frac{\partial F_{ov}}{-\partial \Psi} > 0 \quad \text{if} \quad F_{ov} < 0$$

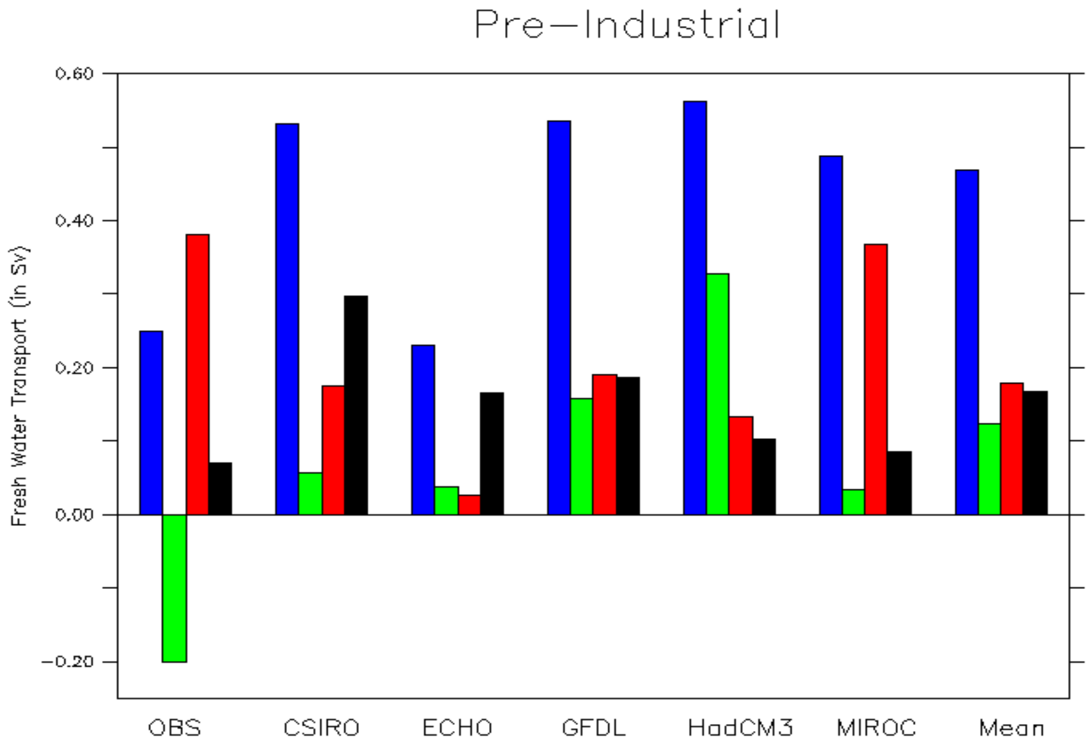
$$\frac{d(A_{FW})}{dt} = F_{sf} + F_{ov} + F_{az} + F_{mix} - F_N$$

Figure 5: a. Collective plot of bifurcation diagrams where the maximum AMOC streamfunction is shown as a function of the two control parameters δ_p (strength of the DIPO anomaly) and γ_p (strength of EVAP anomaly). Some solution branches are incomplete due to computational problems. The projection of the position of the saddle–node bifurcations on the (δ_p, γ_p) plane is also shown.

IPCC (2007): It is very unlikely that the AMOC will undergo a large abrupt transition during the course of the 21st century.



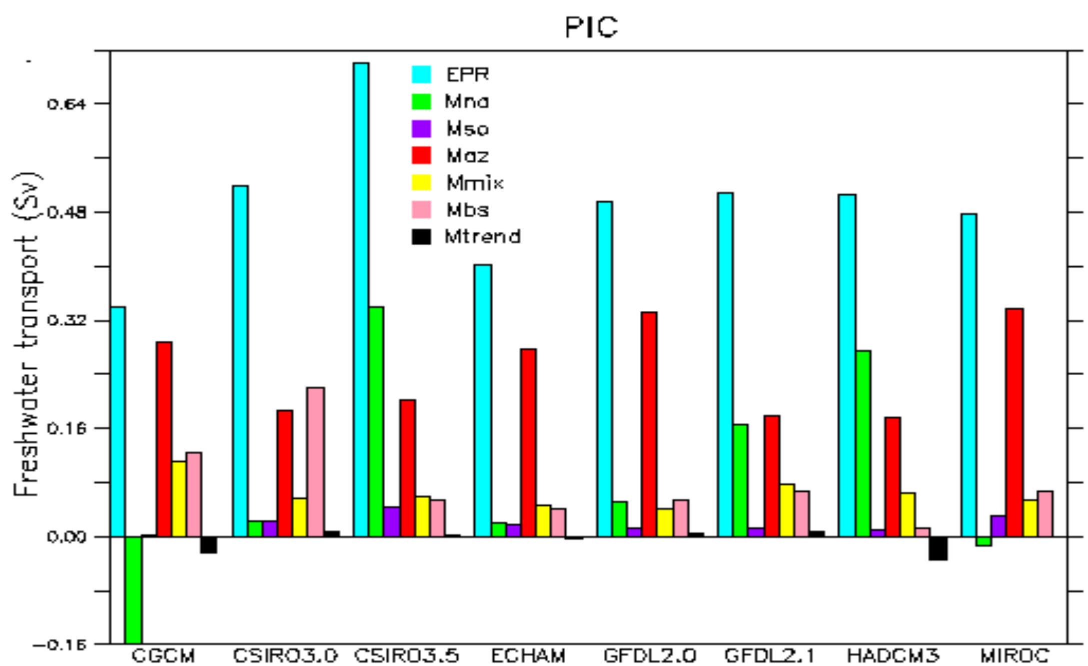
Obs: Weijer et al. (1999)



Weber et al. (2007)

New Obs: Bryden et al. 2011:
Fov= -.13;
Faz=0.12;
EPR=0.05

Diff_EPR between 24s and 34S
< 0.10



Drijfhout et al. (2011)

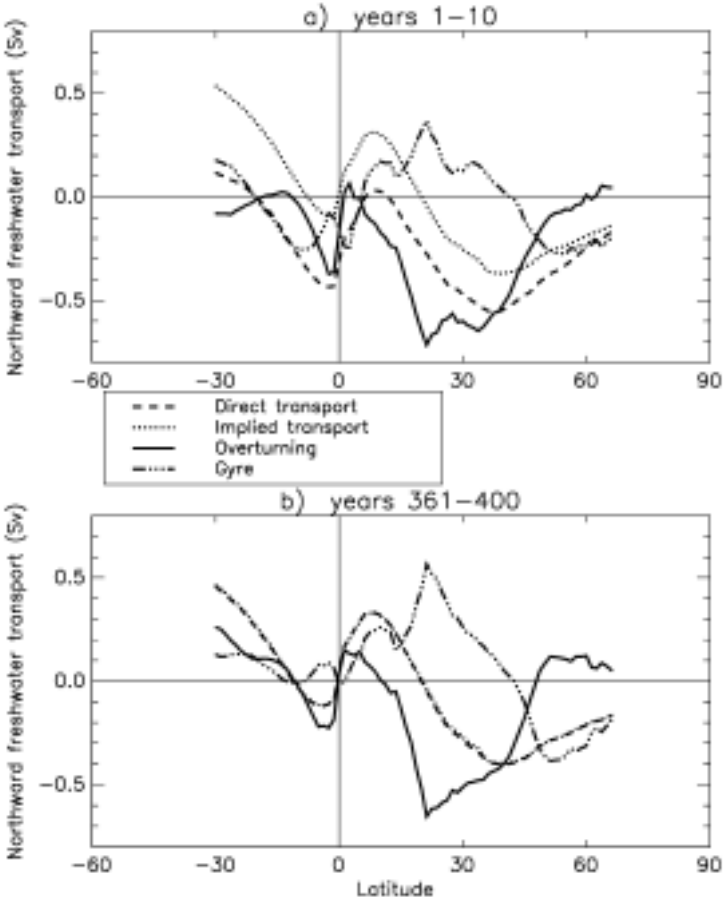
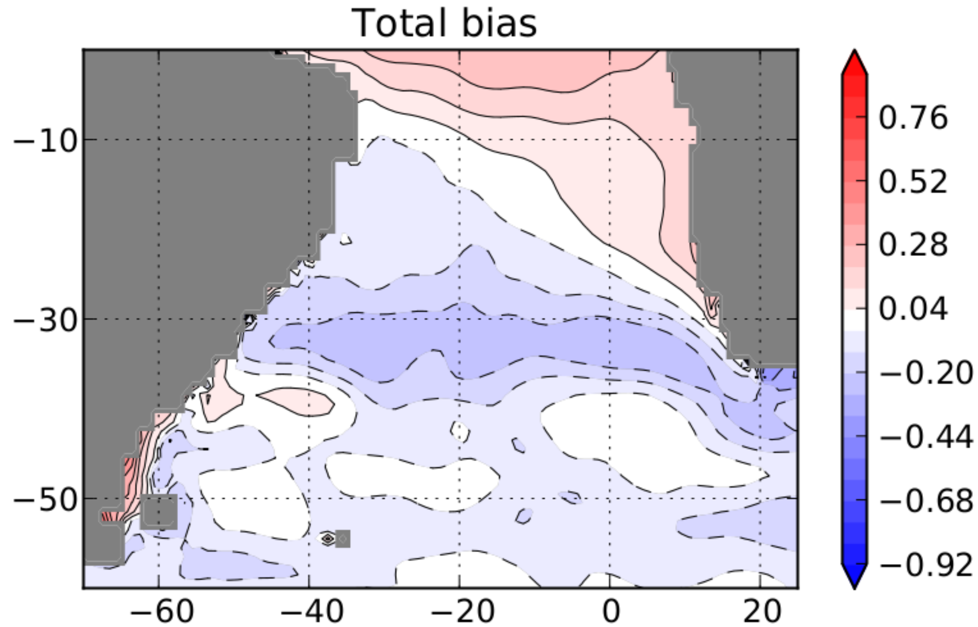
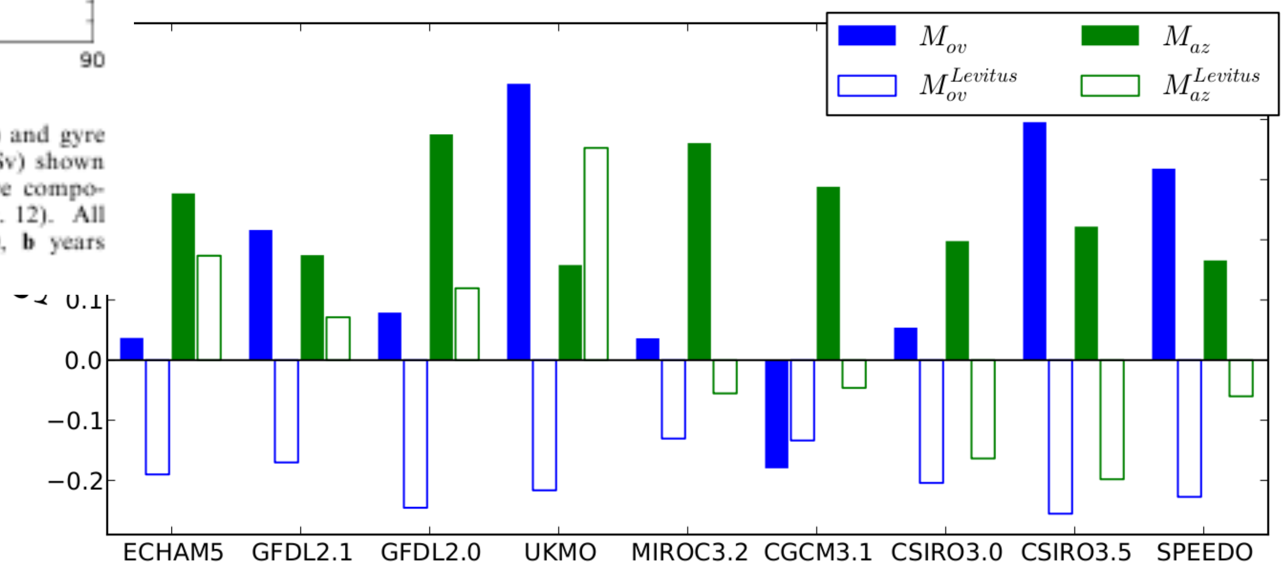
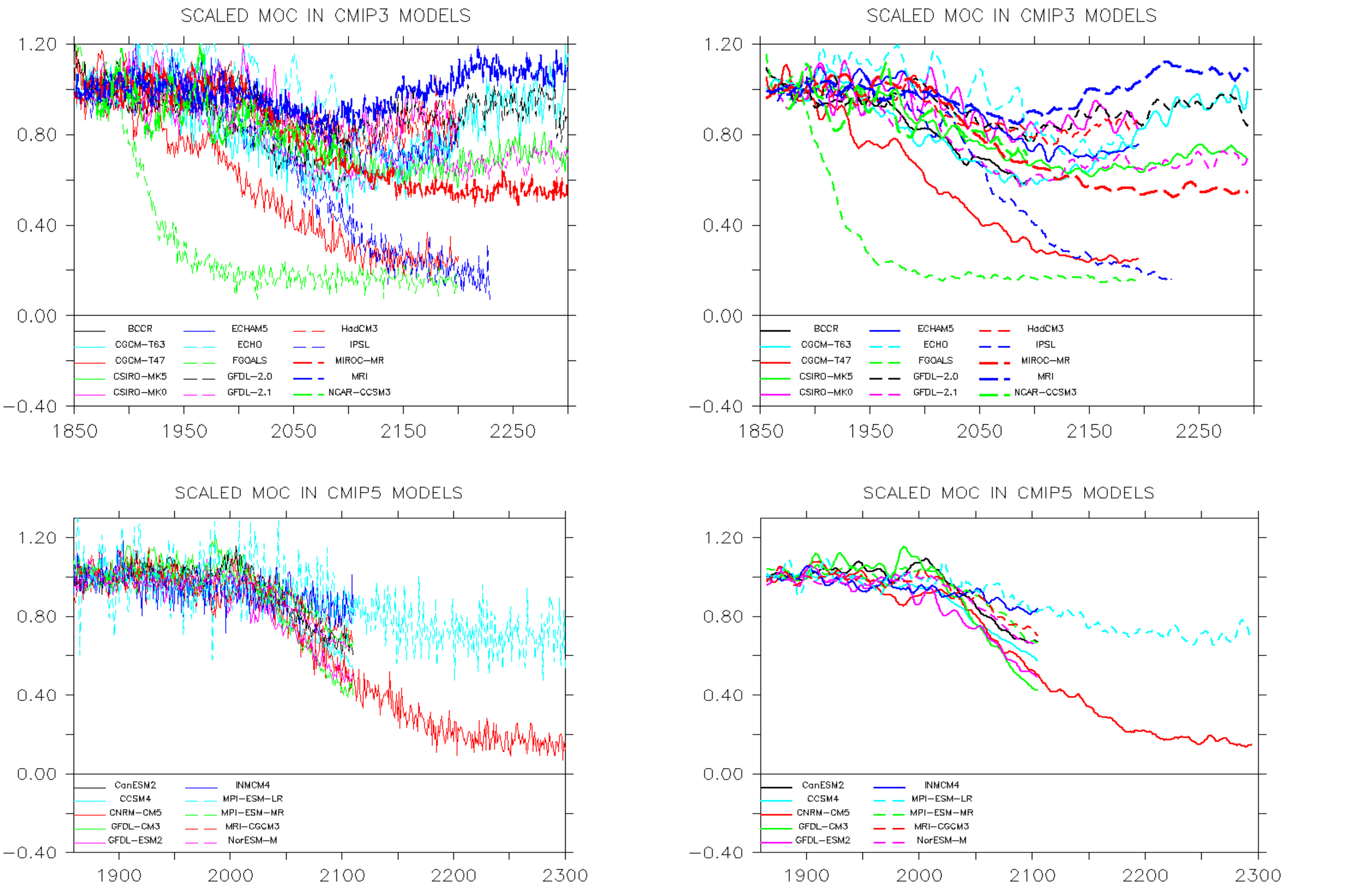


Fig. 13a, b HadCM3 Atlantic overturning (zonal-mean) and gyre components of northward freshwater transport (units Sv) shown with the model Atlantic total ocean (including diffusive component) and implied freshwater transports (as in Fig. 12). All transports are relative to Bering Strait a years 1–10, b years 361–400

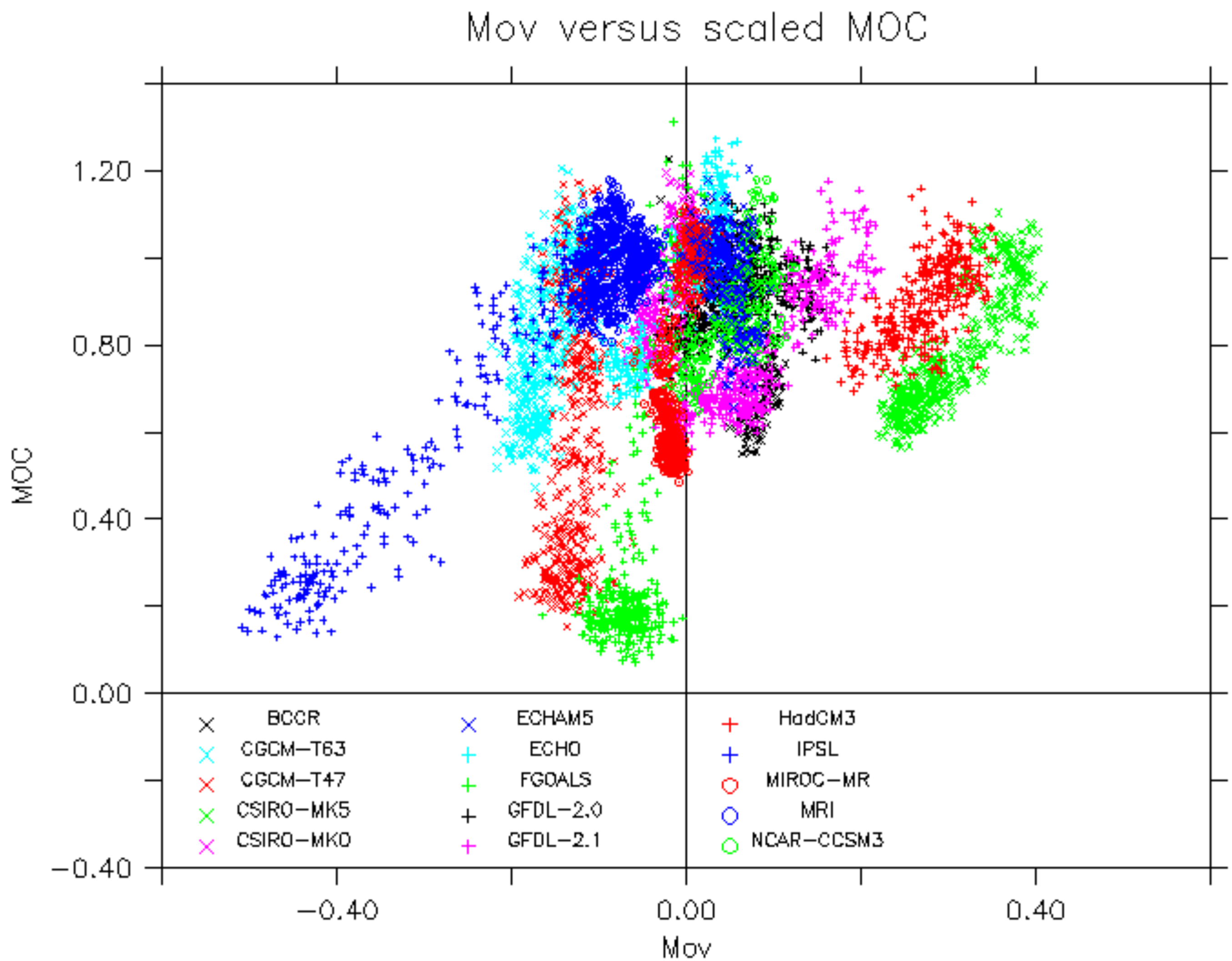




Scenarios for the next century

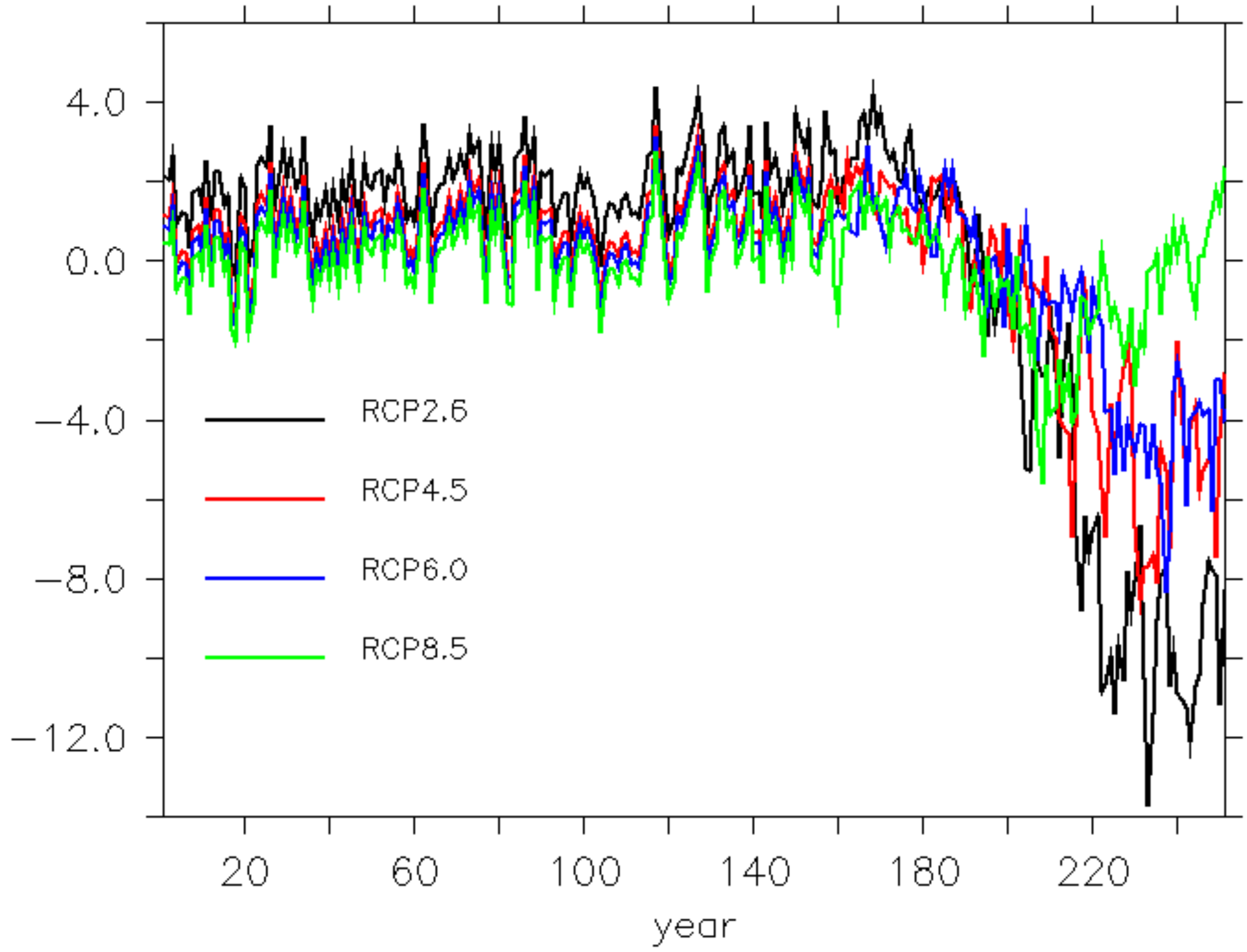


MOC in CCMs too stable because of wrong sign of salt advection feedback



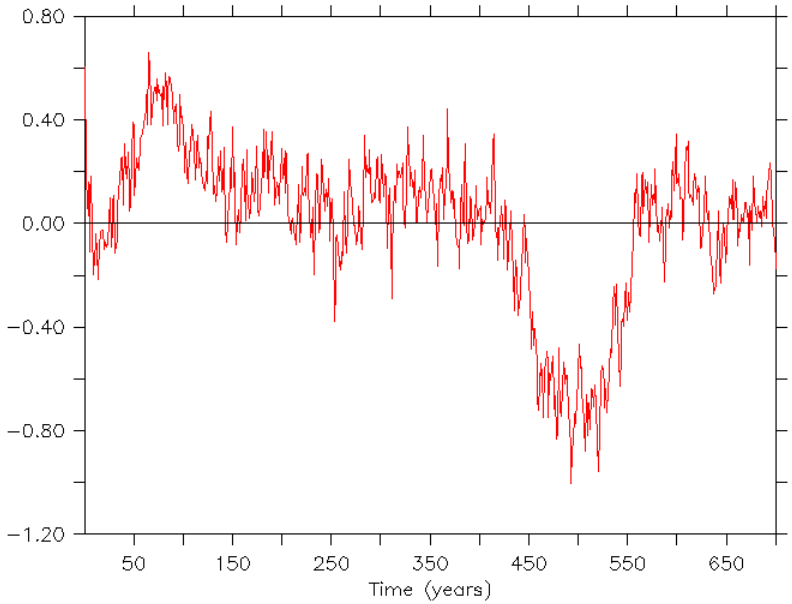
Sign of F_{ov} (salt advection feedback) determines whether large changes may occur

Temperature anomaly in GIN-sea in FIO in CMIP5 scenario runs

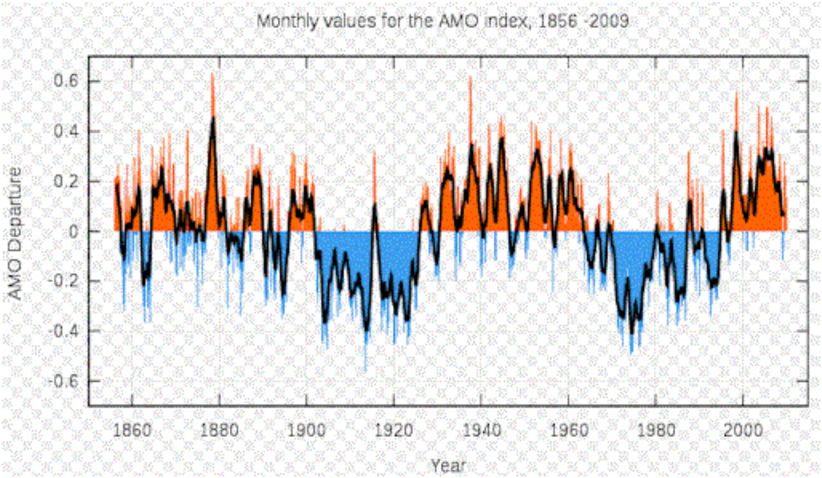


Coupled models and AMOC collapse

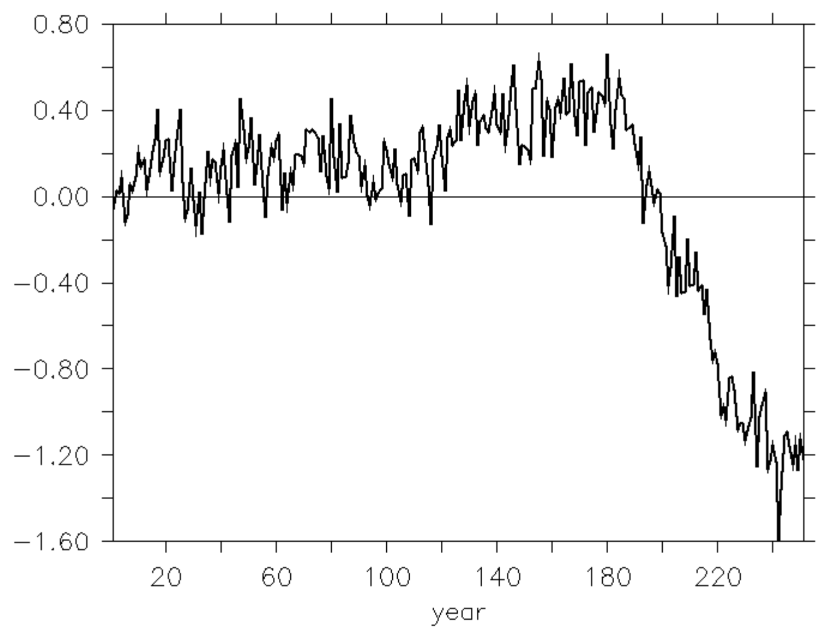
THE AMO



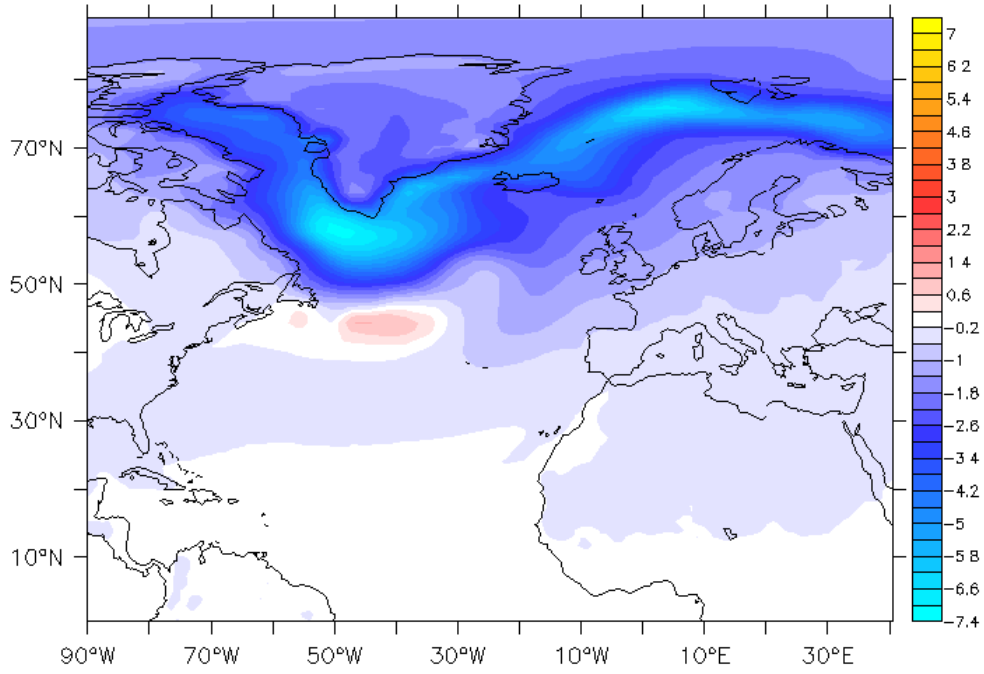
EC-EARTH Pre-industrial control



FIO-RCP2.6

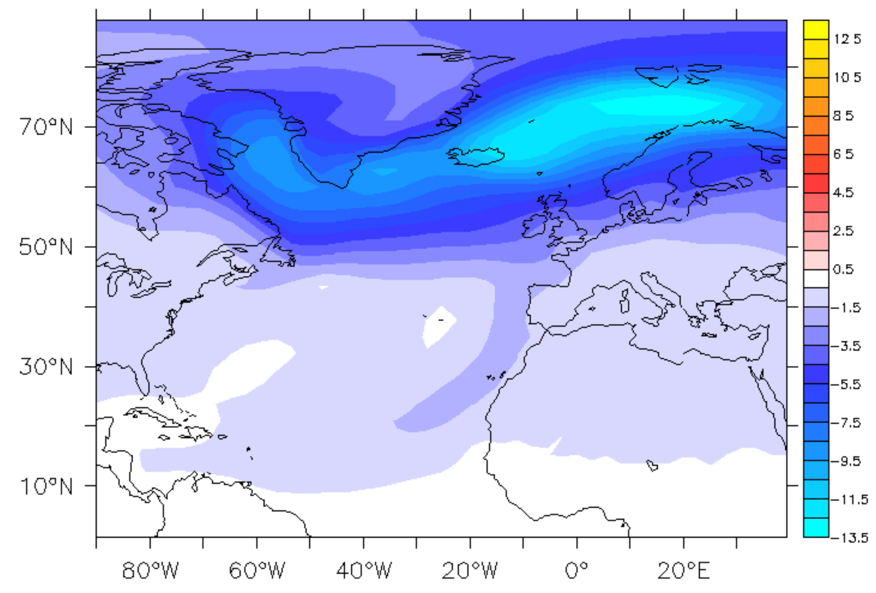


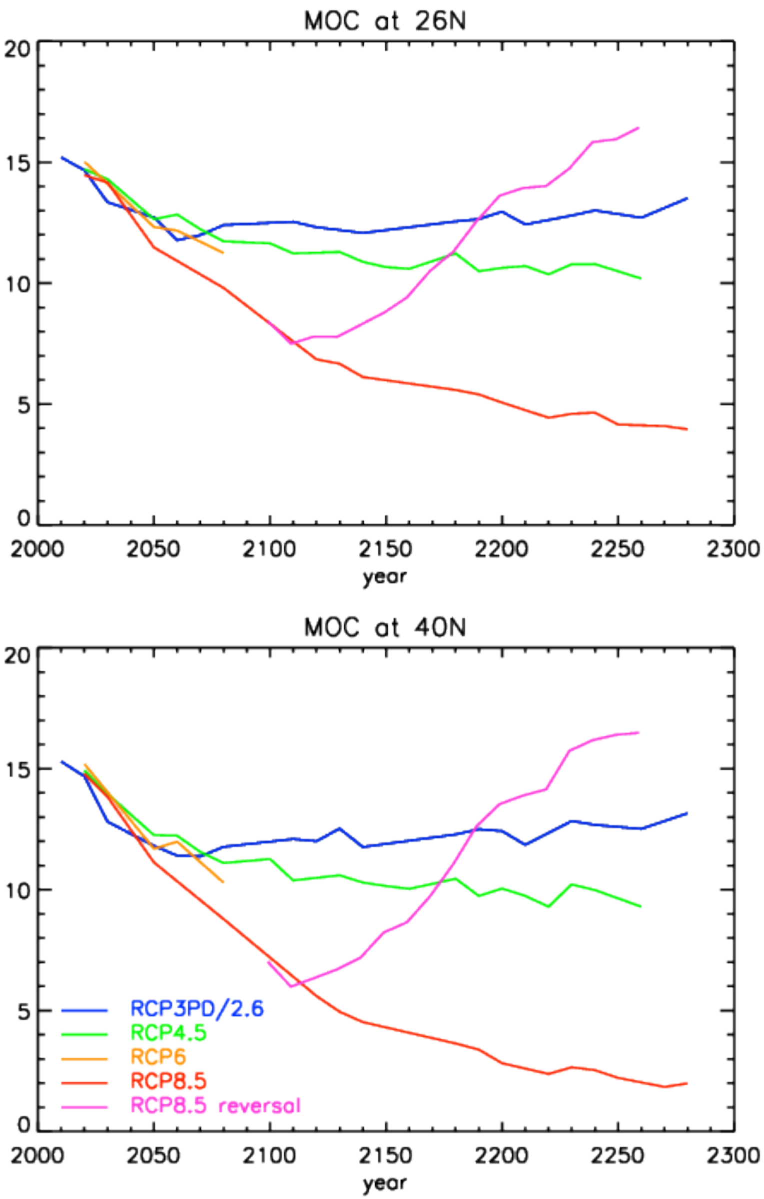
Impact: Surface air temperature



EC-EARTH

FIO

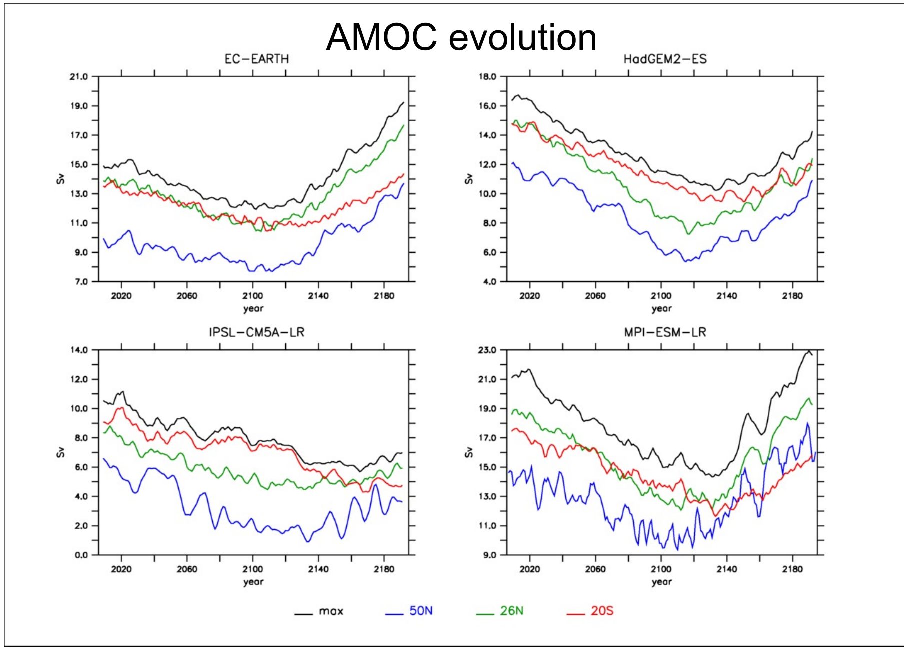


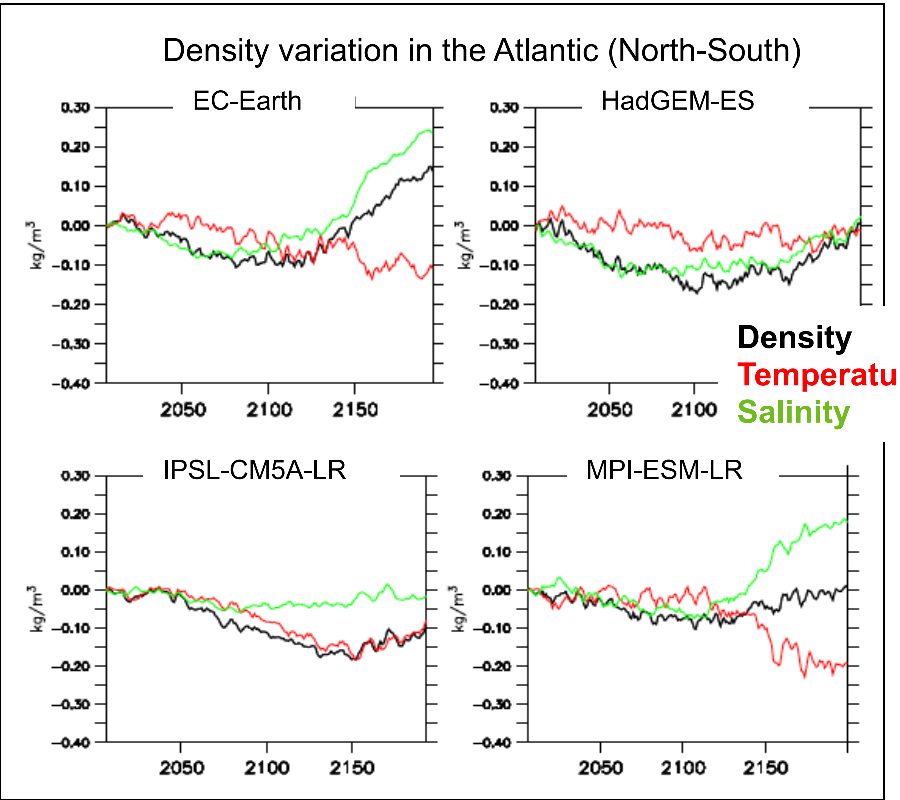

MOC at 26N
20
15
10
5
0
2000
2050
2100
2150
2200
2250
2300
year
MOC at 40N
RCP3PD/2.6
RCP4.5
RCP6
RCP8.5
RCP8.5 reversal

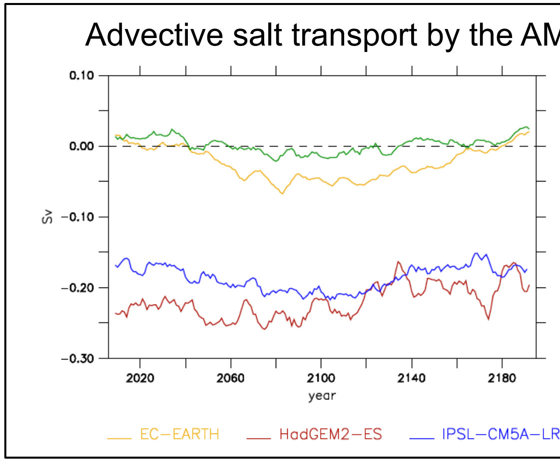
HadGEM2

Atlantic overturning response

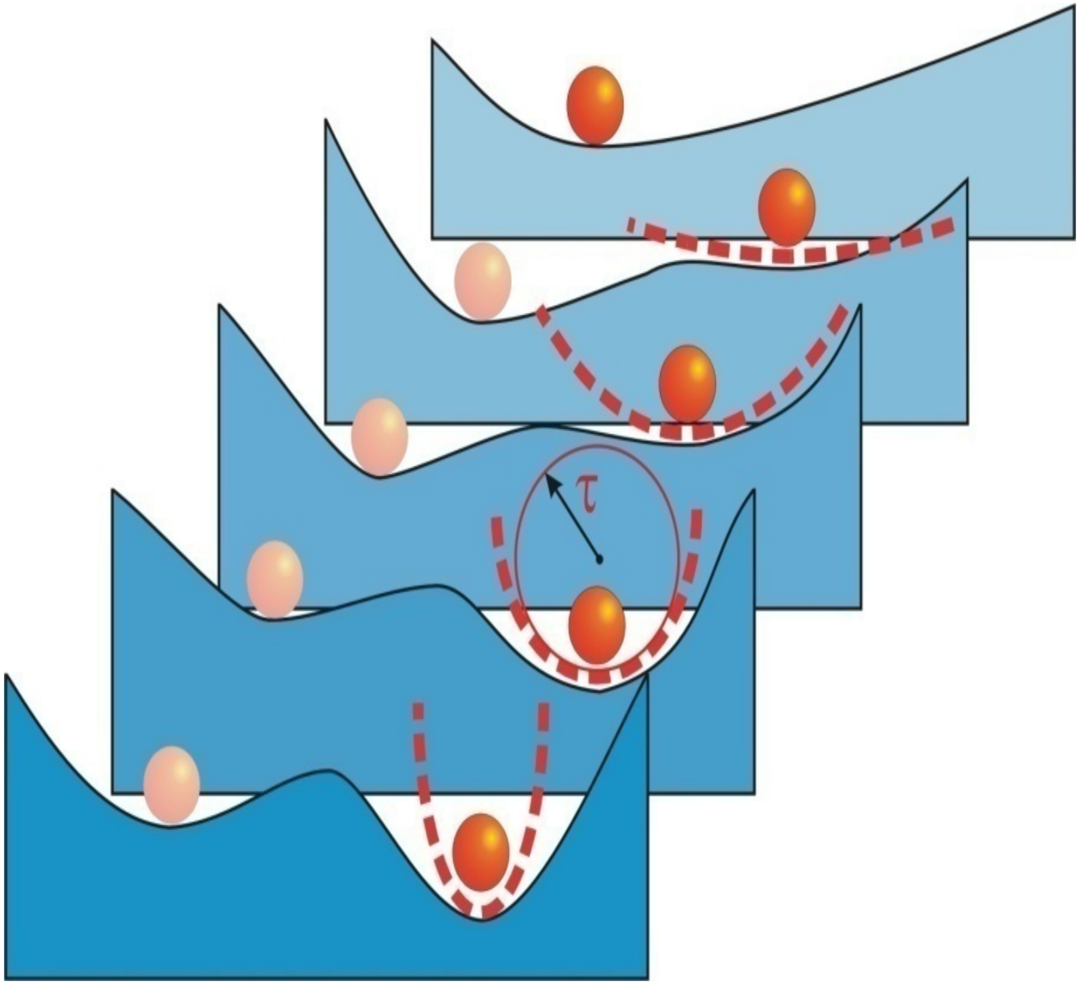
- All models show a starting of recovery
- But very large differences in term of inertia of the AMOC
- Potentially related to the sign of the classical AMOC advective salt feedback
- As confirmed by the density budget analysis of the Atlantic







If negative
=> AMOC is in a bistable mode in box models



M_{ov} determines shape of double well
Coupled feedbacks temporarily alter the height of the ridge and the size of the noise

Ditlevsen and Johnsen, 2010

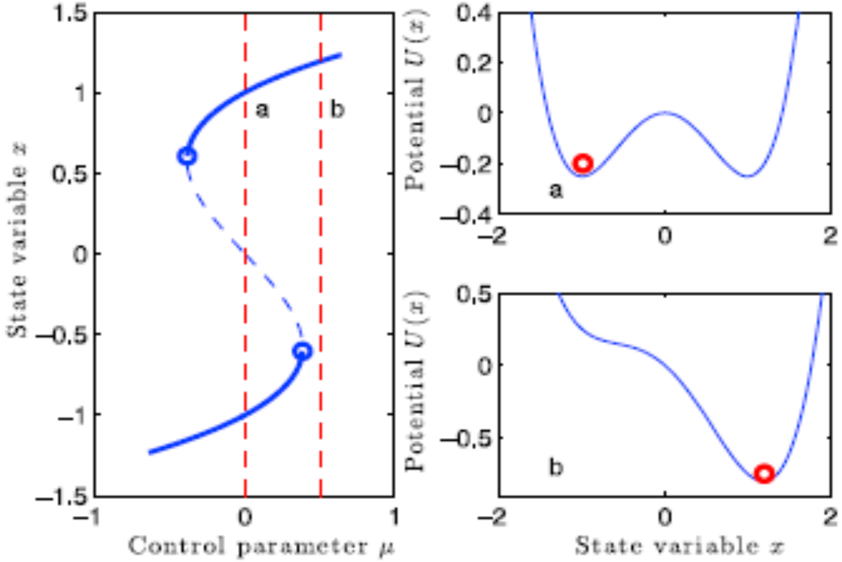


Figure 1. (left) A typical bifurcation diagram with two bifurcation points, marked with blue circles. The two fat branches of the curve are the stable states as a function of a control parameter. The dashed branch in between is the separating unstable fixed point. The vertical red lines indicate where the potentials plotted on the right are taken. (Imagine these as plots in and out of the paper along the red lines a and b). The red dots indicate the state of the system (top right) before and (bottom right) after the jump by a bifurcation.

$$\dot{x} = -\partial_x U_\mu(x) + \sigma\eta, \qquad (1)$$

[10] In order to investigate the significance in detection of a tipping point from a data series, two simulations of the Langevin equation (1) with a double well potential $U_\mu(x) = x^4/4 - x^2/2 - \mu x$ are performed. In the first the control parameter $\mu(t)$ is changing linearly with time, such that the bifurcation point μ_0 ($= -2\sqrt{3}/9$) is reached at time $t = 900$

$$M_{ov} = 0 \Leftrightarrow \mu_0 = -2\sqrt{3}/9$$

Conclusions

- Uncertainty in AMOC projections is associated with multiple equilibria that can be modelled by a double well potential (Langevin Eq.)
- M_{ov} determines the shape of the double well. When M_{ov} decreases the off-state-well deepens and the on-state-well shallows, until it disappears; when M_{ov} increases the opposite occurs.
- Net E-P over the Atlantic plays a similar role. When M_{ov} and E-P show opposing trends, strong nonlinear behaviour is to be expected.
- The amplitude of M_{ov} and of net E-P (double well structure) and the strength of the noise determine the likelihood of abrupt change
- A collapse is associated with a strong, correlated decrease in M_{ov} and overturning strength
- The factors that determine the shape of the double-well are strongly biased in coupled models