Ocean circulation under climate change: Examples of qualitative changes

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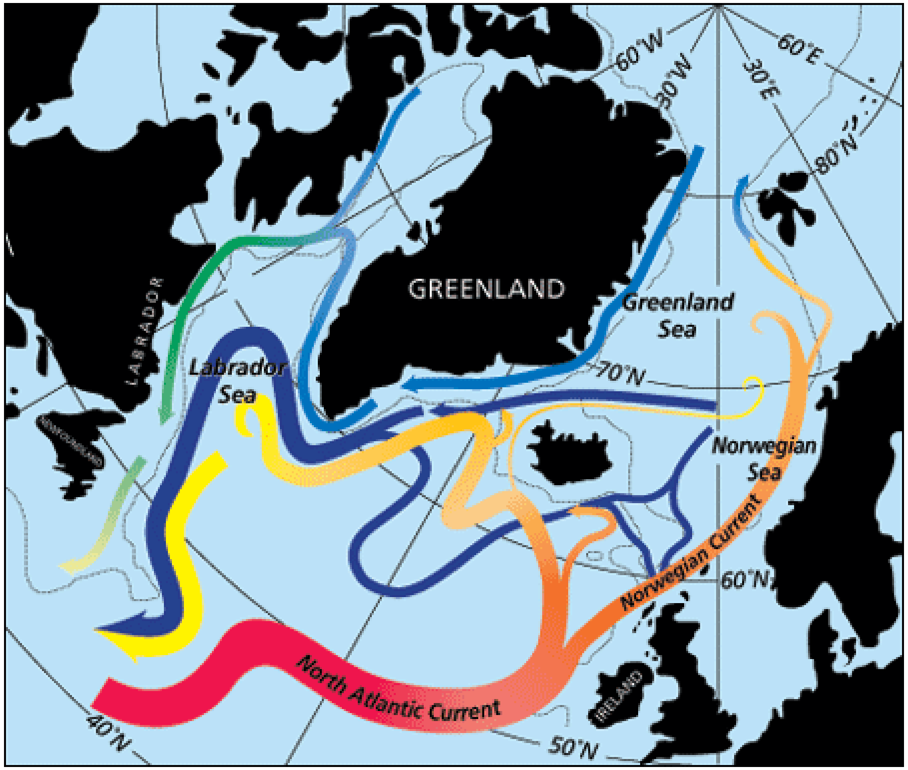

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Potsdam Institute for
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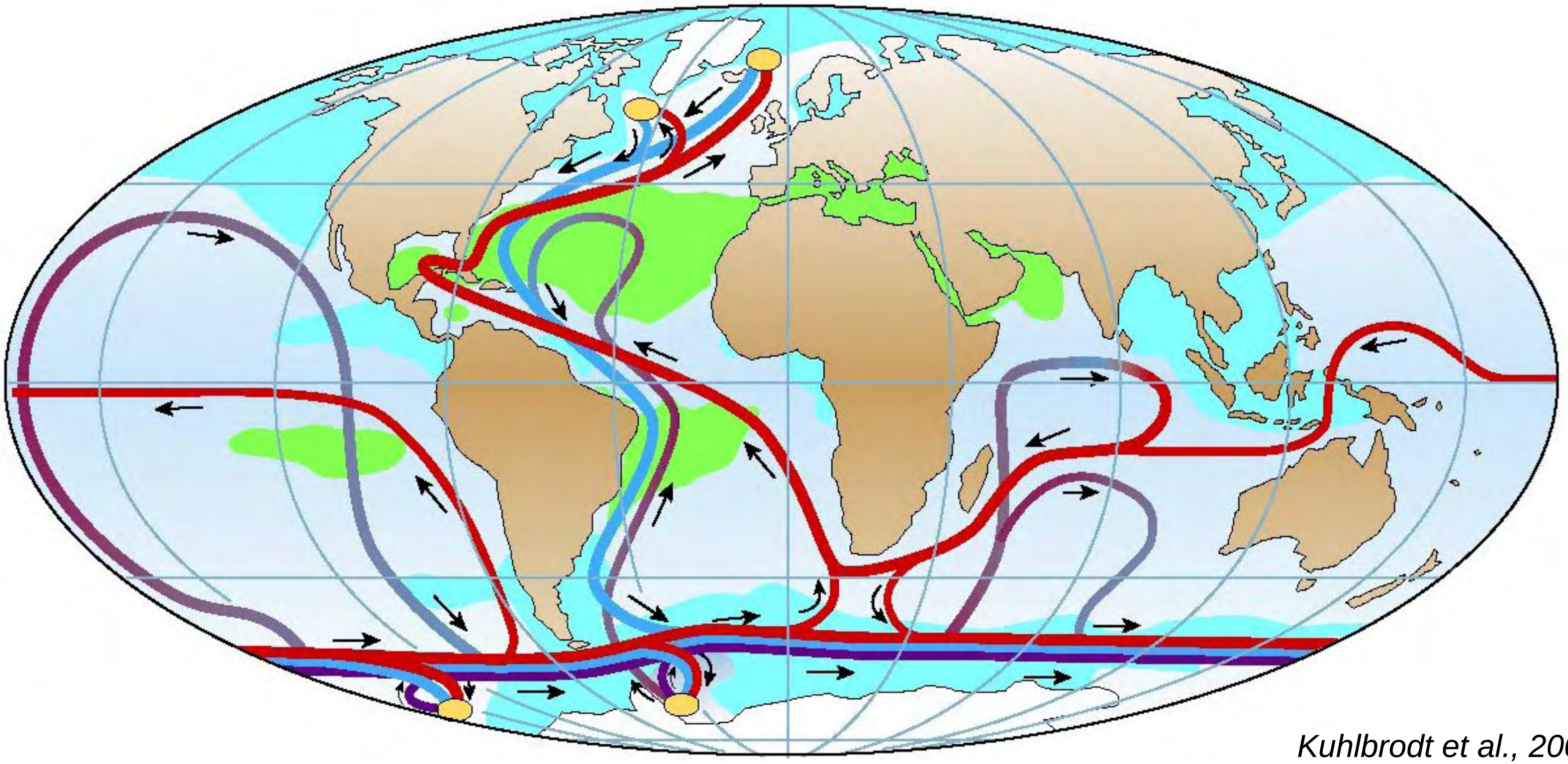
Andreas Born
University of Bern

The global ocean circulation



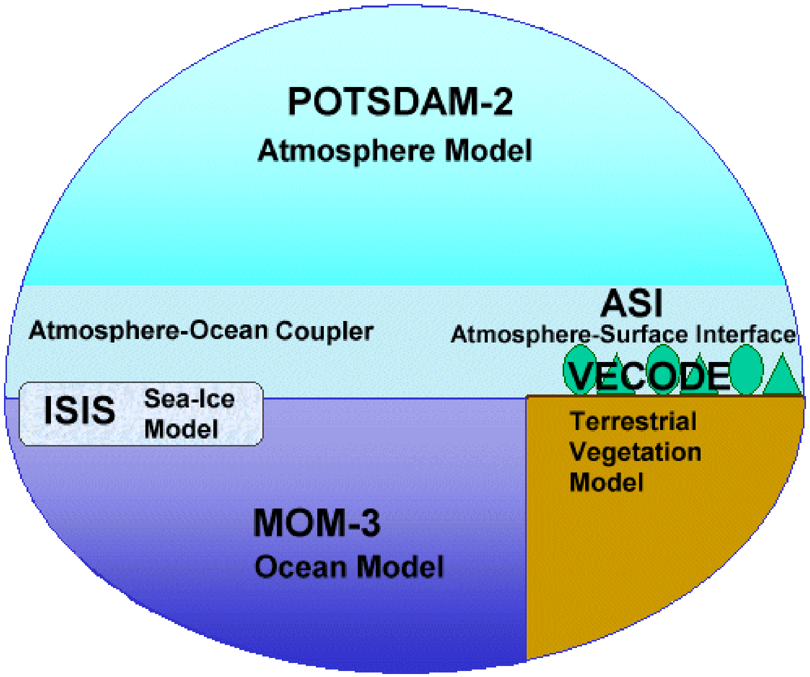
Kuhlbrodt et al., 2007.

- interconnected through basin-wide currents and the Antarctic Circumpolar Current
- regional features have their own specific dynamics

How might these circulation patterns respond to climate change?

Method

• Explore ocean dynamics with Intermediate Complexity model (CLIM*BER*-3α)
• Reconcile results with AOGCMs and observations/paleo-records

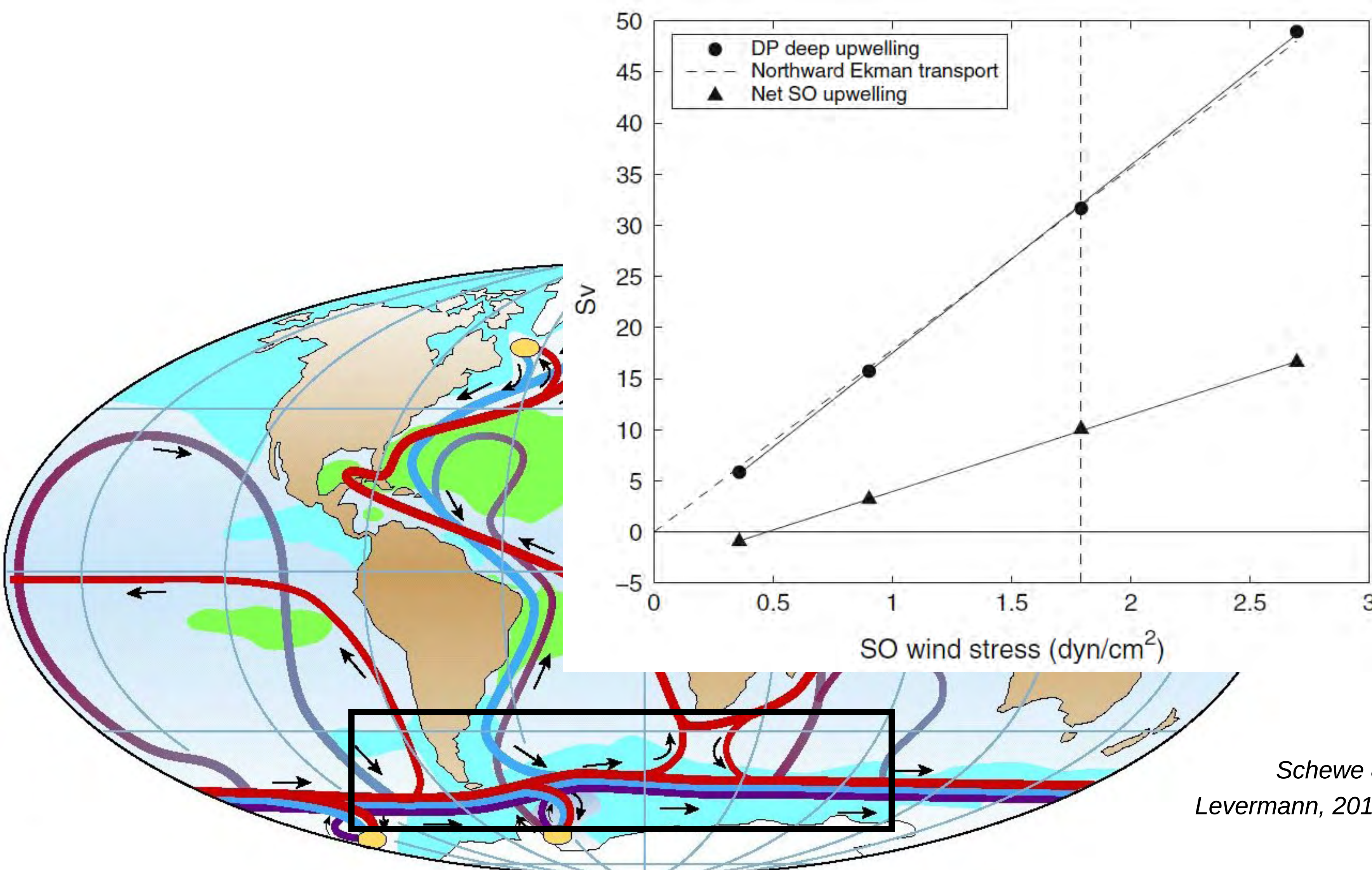


Montoya et al., 2005

MOM-3 ocean model:
3.75° x3.75° , 24 variably spaced vertical levels (25 m to 500 m)
Low background value of vertical diffusivity (0.1-0.4 cm^2/s)
Low-diffusive tracer advection scheme *(Prather, 1986; Hofmann & Maqueda, 2005)*
Explicit free surface

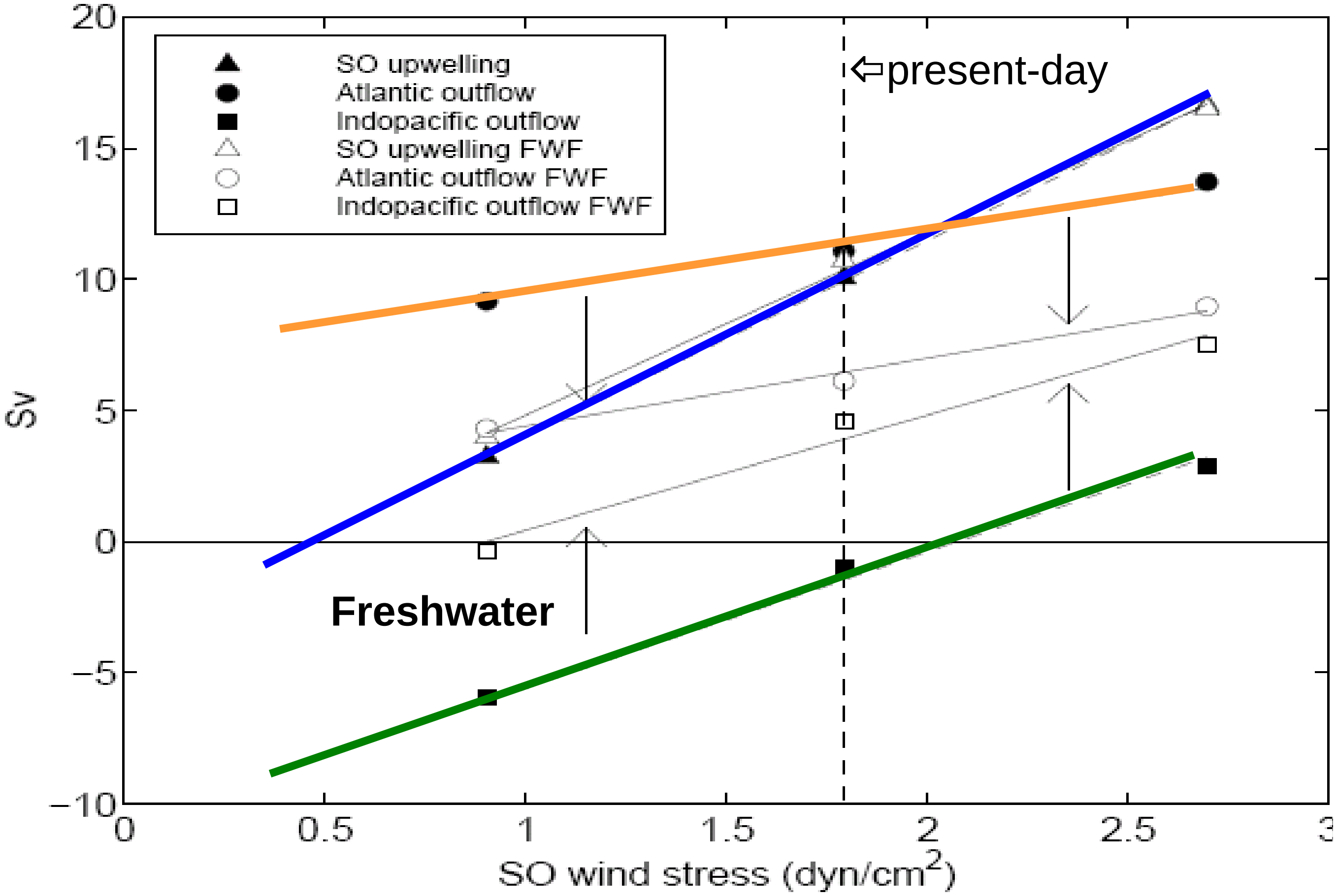
POTSDAM2 atmosphere model
(Petoukhov et al., 2000, Ganopolski et al. 2001)
2.5-dim. statistical-dynamical model
7.5° x 22.5° horizontal resolution and parameterized vertical

Driver of global overturning circulation: Wind-driven upwelling in Southern Ocean



Schewe & Levermann, 2010

Relative contributions of different basins determined by density distribution



Net SO upwelling

Atlantic outflow

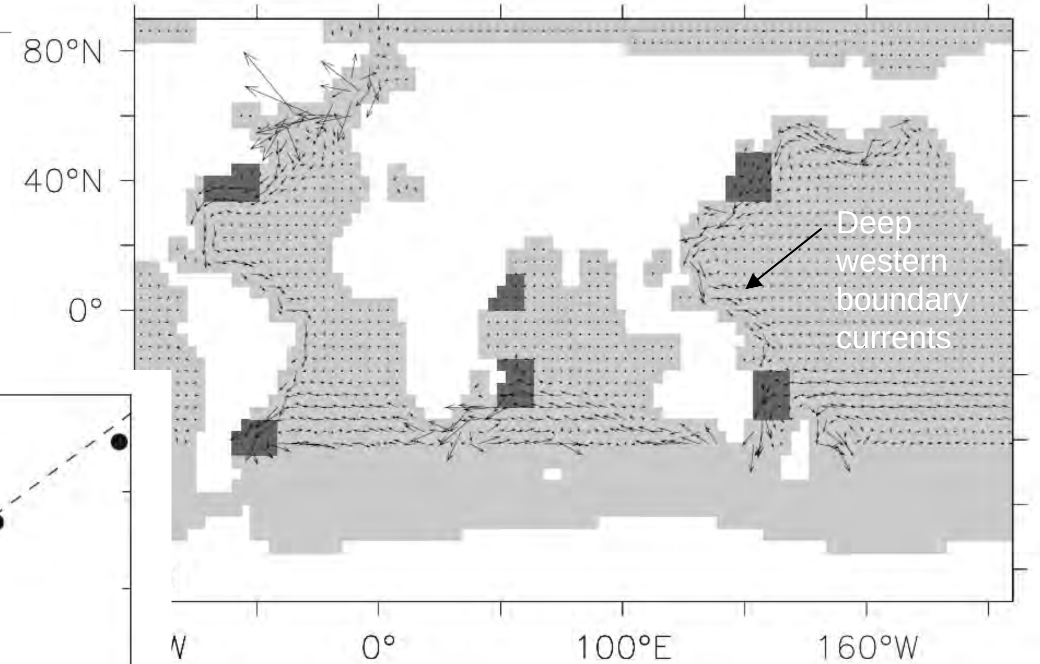
Indopacific outflow

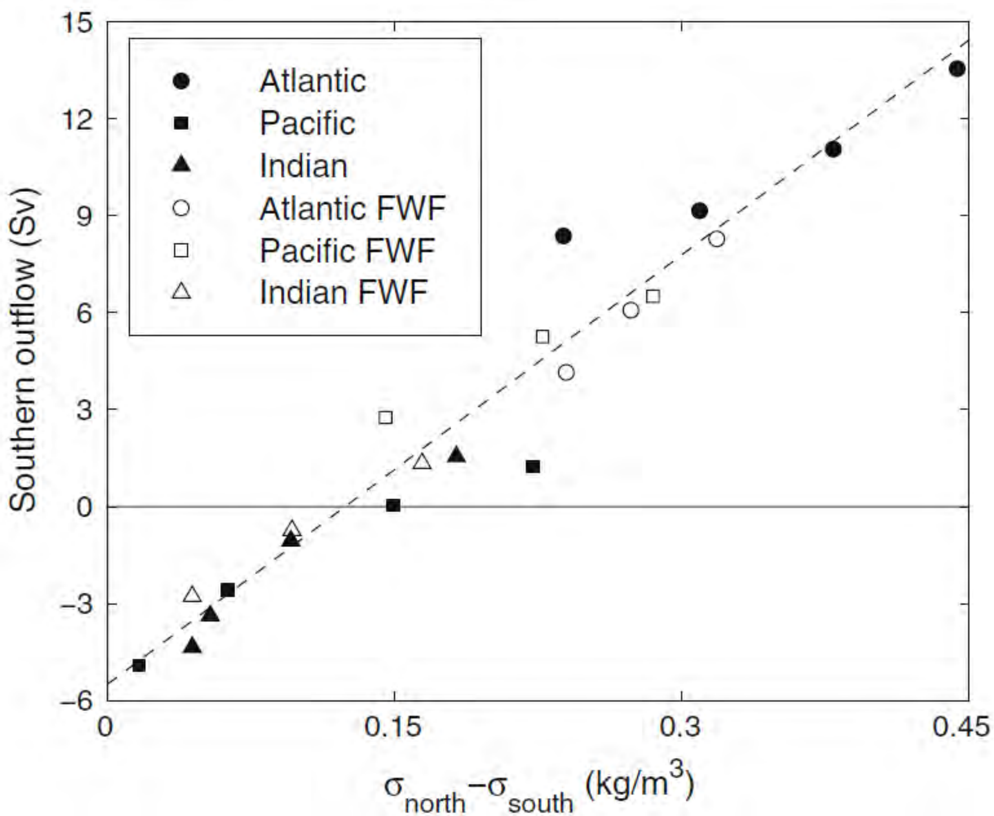
(Indian ≈ Pacific)

Schewe & Levermann, 2010

Consistent response to wind stress and freshwater forcing

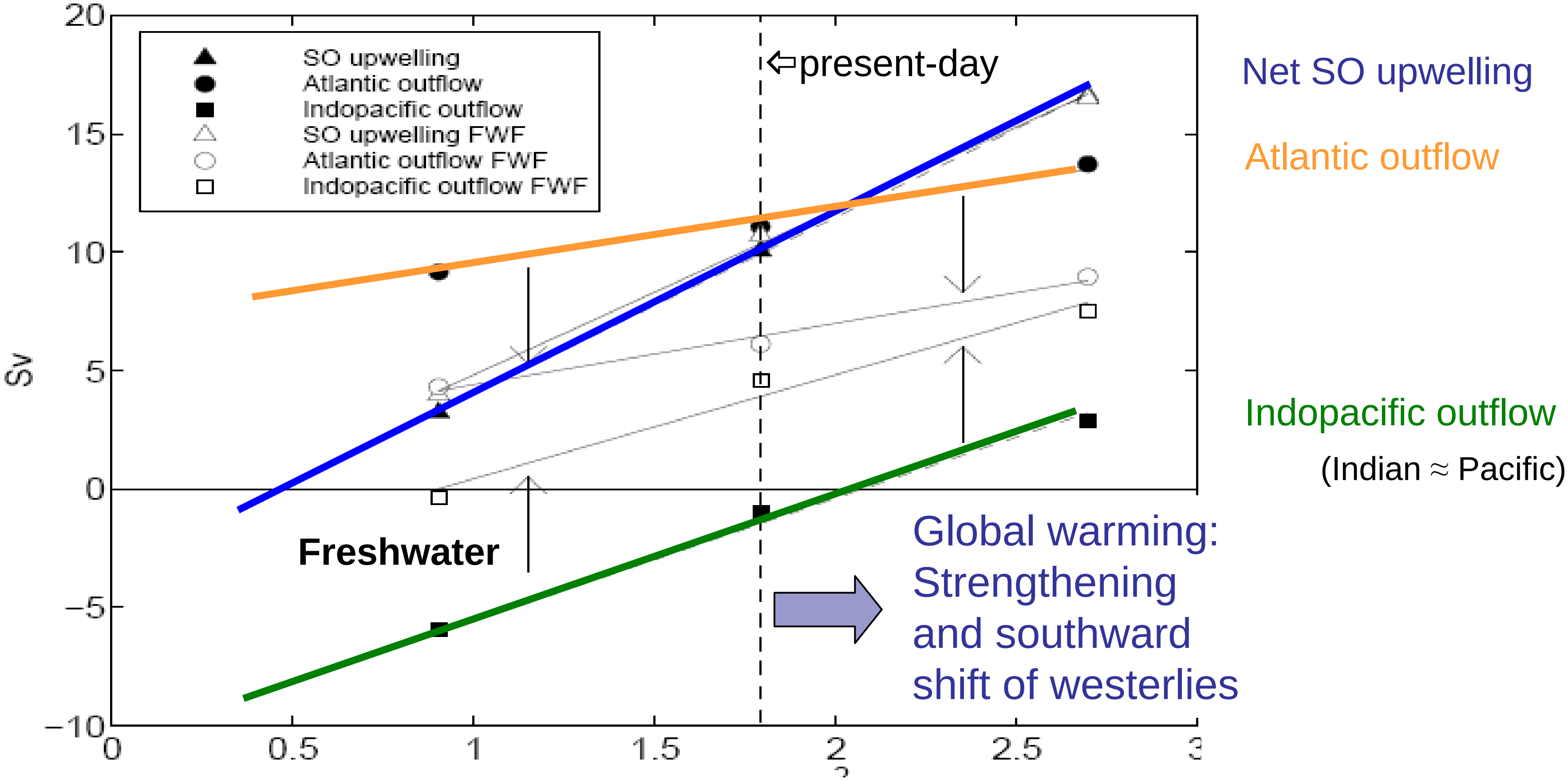
Quasi-universal, linear relationship of basin-scale transport to meridional density differences





Schewe & Levermann, 2010

Consistent response to wind stress and freshwater forcing



- Global-scale ocean circulation responds linearly to changes in wind stress and buoancy distribution
- But regional circulation patterns may have more complex dynamics, not necessarily linear

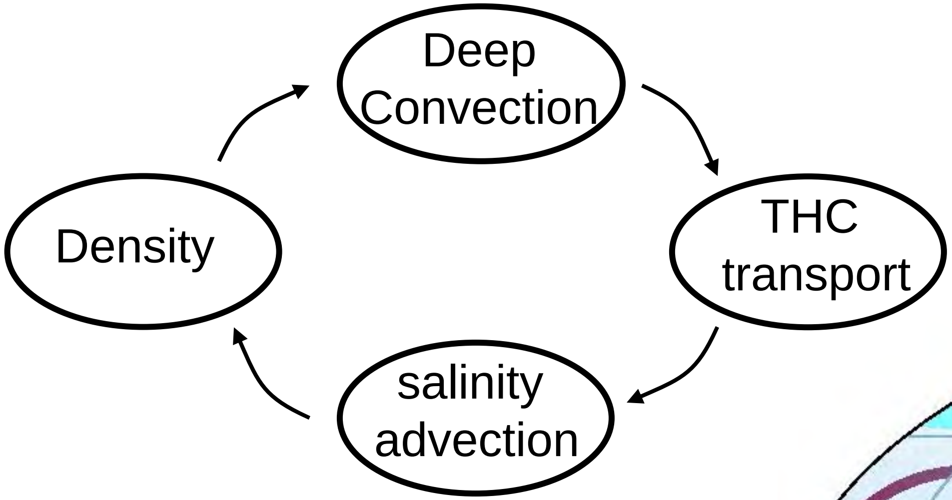
'010

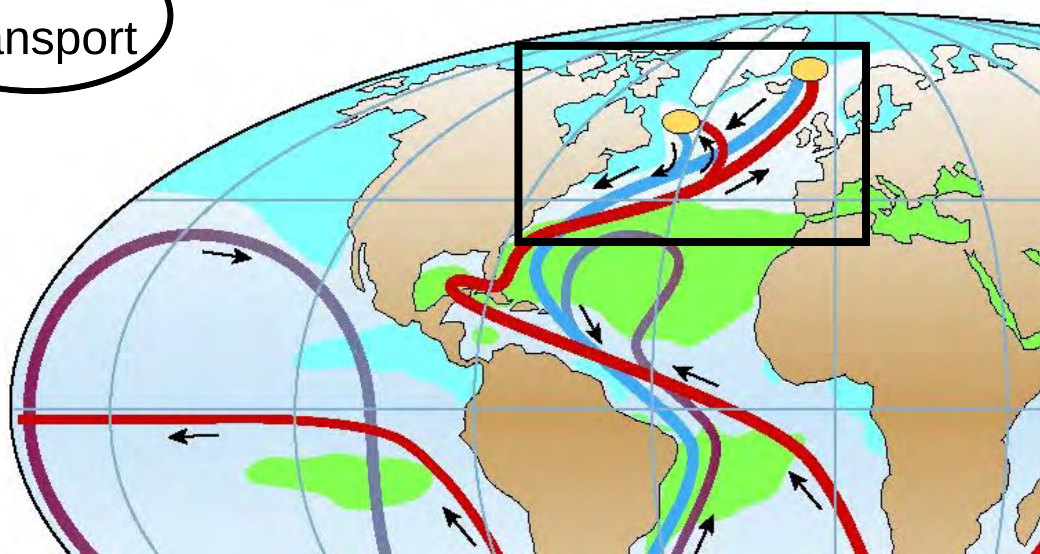
Prominent example: North Atlantic Deep Water Formation (Thermohaline circulation)

Unlike upwelling, sinking is confined to a few small regions in the North Atlantic

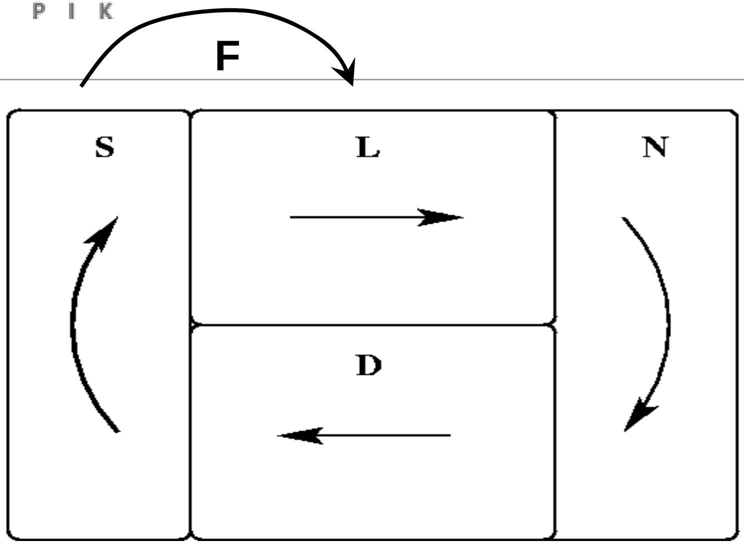
Dense surface waters are required for deep convection → Cold & salty

Circulation advects "its own" salinity → internal positive feedback…





Bistability through salt-advection feedback

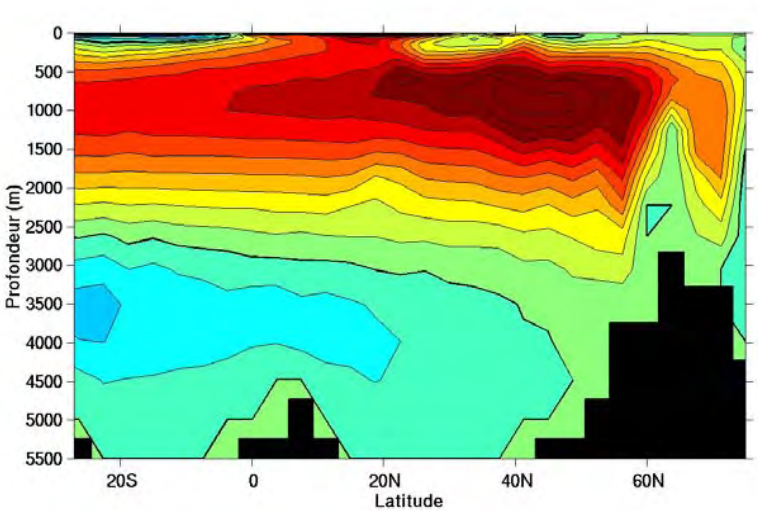


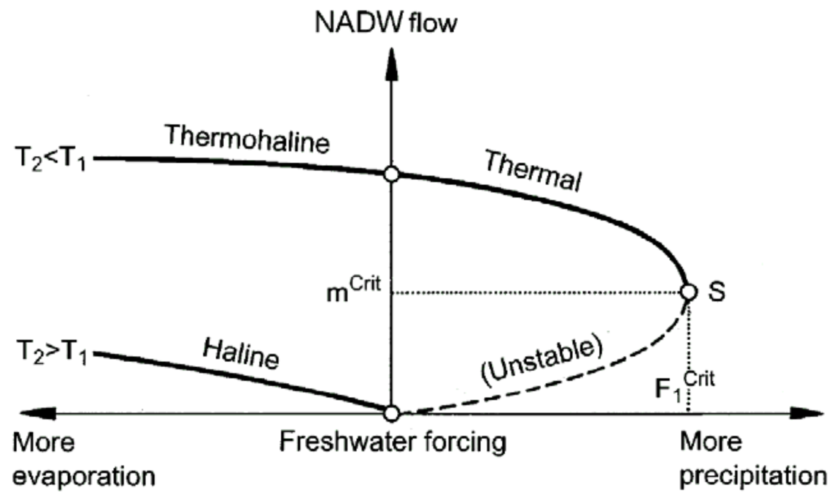
Advection of temperature and salinity
(Stommel 1961; Rahmstorf 1995)

plus assumption:

$$M = K \cdot \left(\rho_{North} - \rho_{South}\right)$$

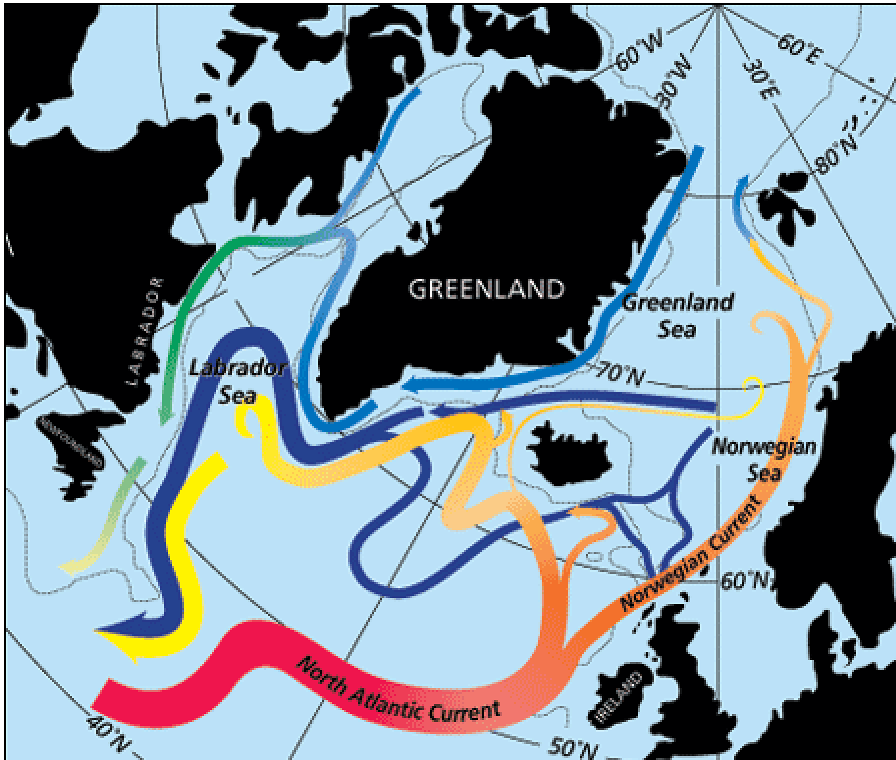
$$\rho = \rho_0 \cdot \left(1 + \beta \cdot S - \alpha \cdot T\right)$$



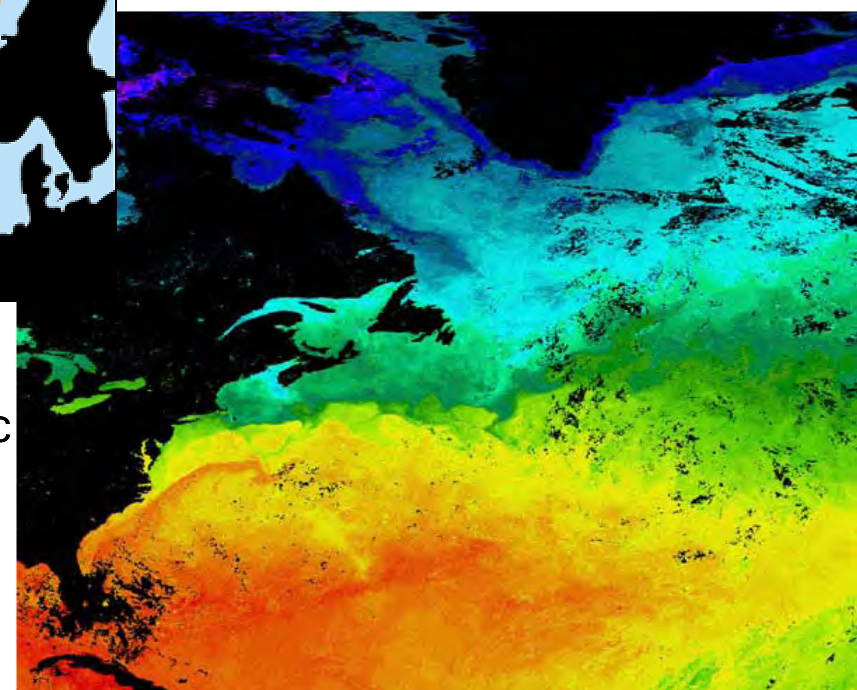


External forcing can be amplified by bistability

The subpolar gyre



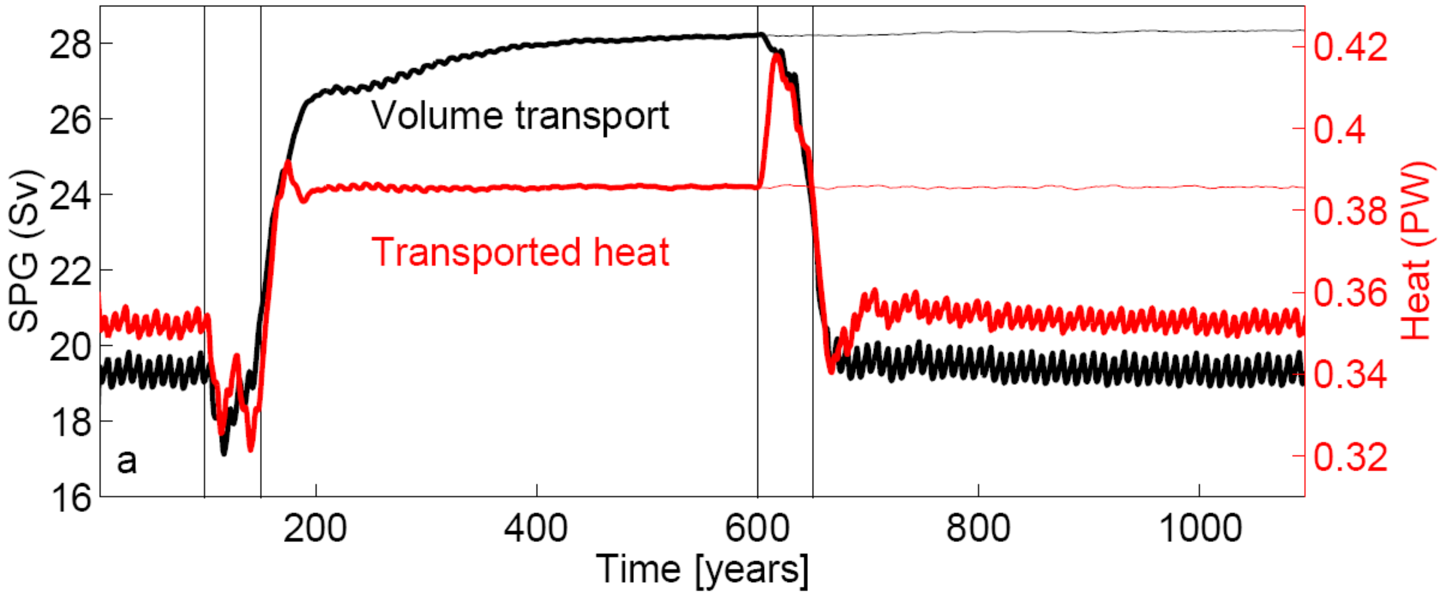
Nasa



Horizontal recirculation pattern in North Atlantic

Deep Water formation happens *inside* the gyre

Bistability of Atlantic subpolar gyre

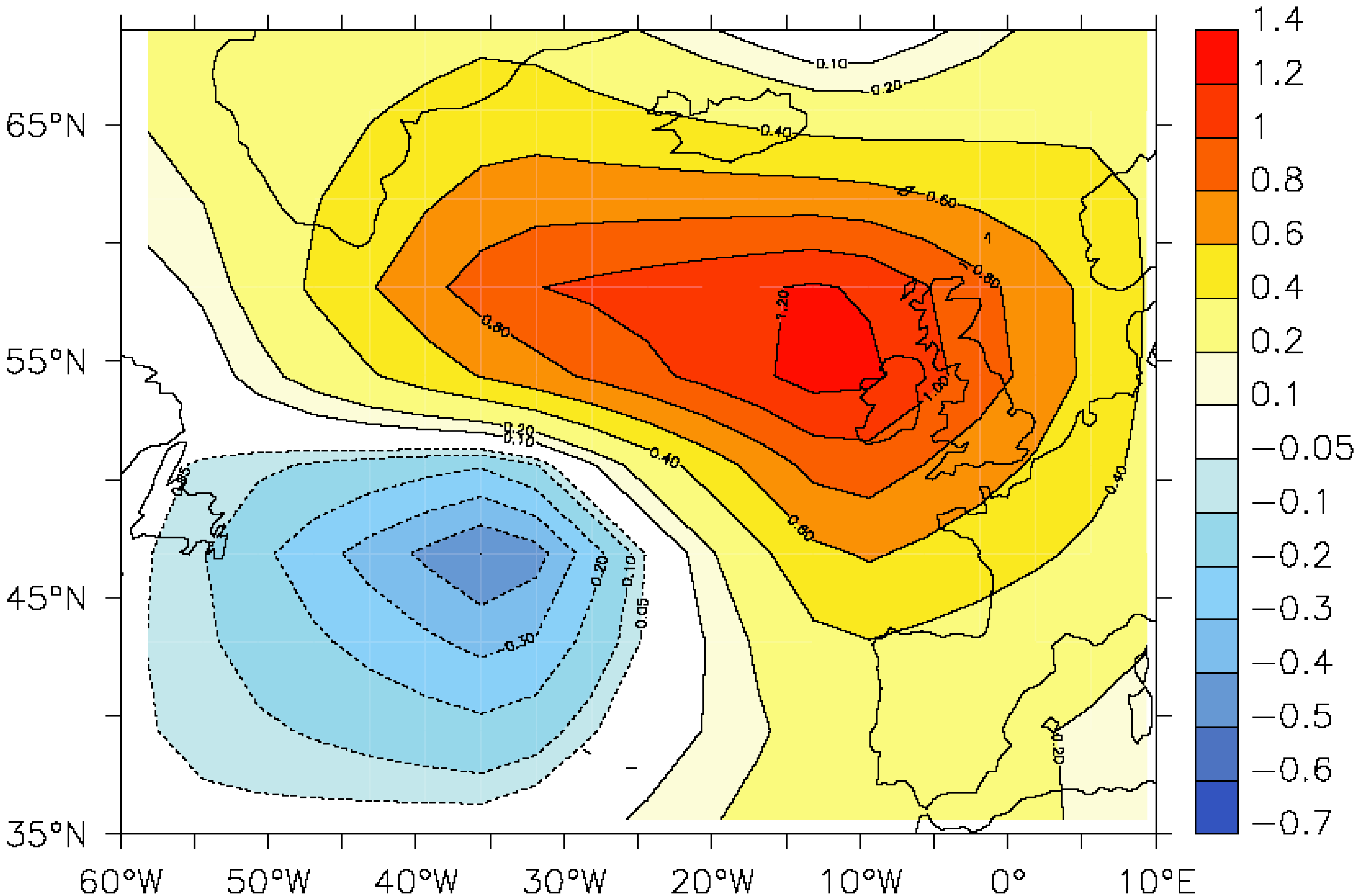


Freshwater pulse of 0.05 Sv for 25 years is sufficient for transition between two stable states of subpolar gyre circulation

Levermann & Born, GRL, 2007.

Subpolar gyre bistability

SAT difference

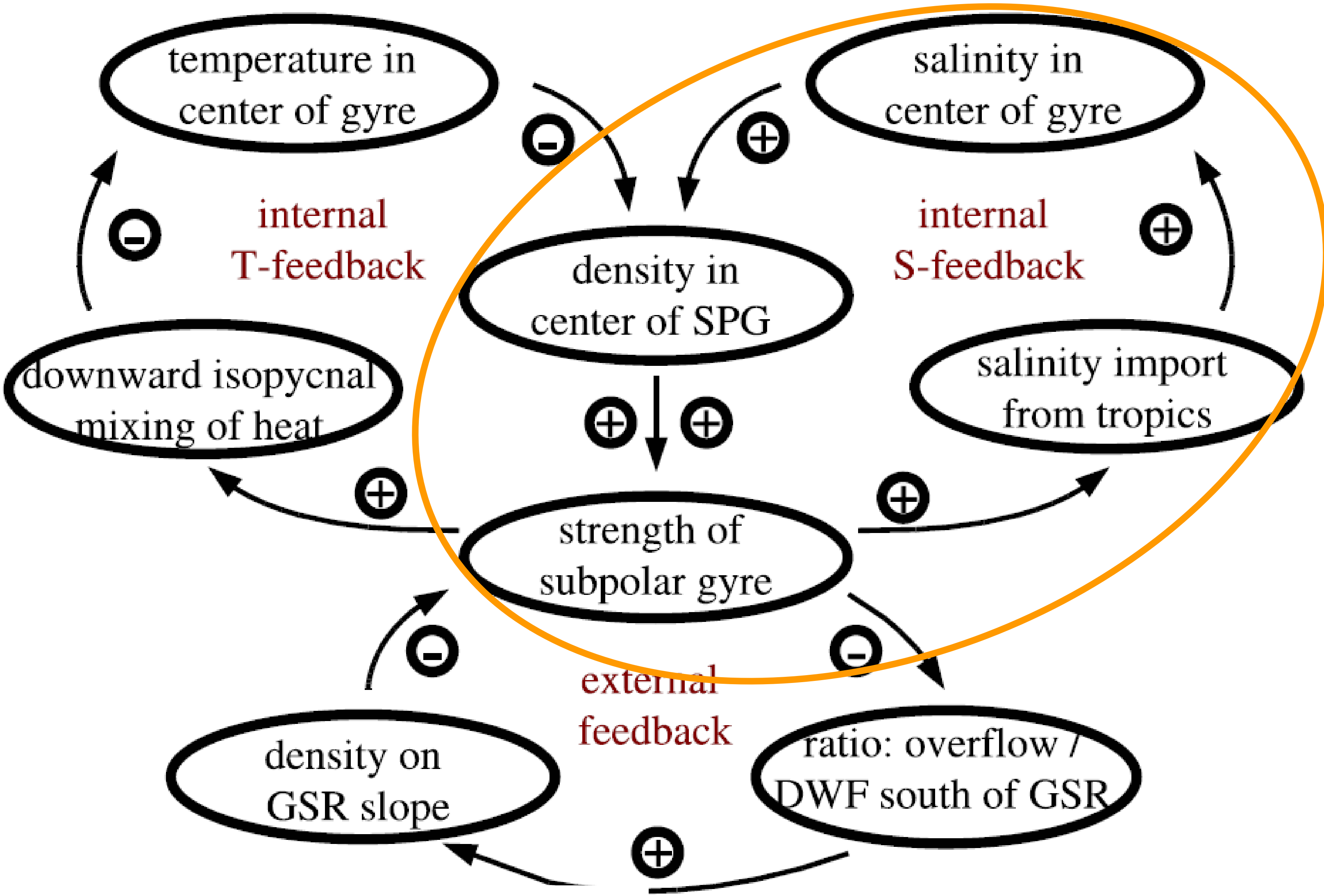


Mechanism

Baroclinic feedbacks

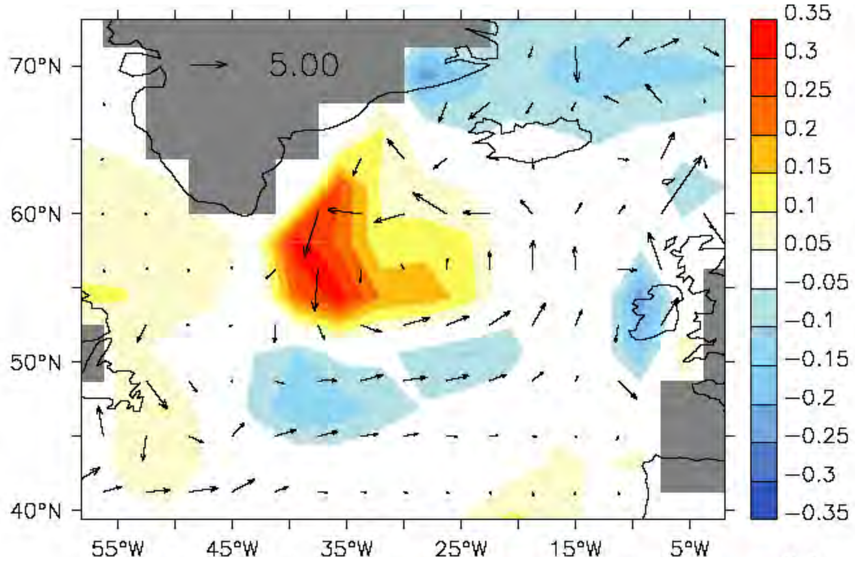
Salinity feedback

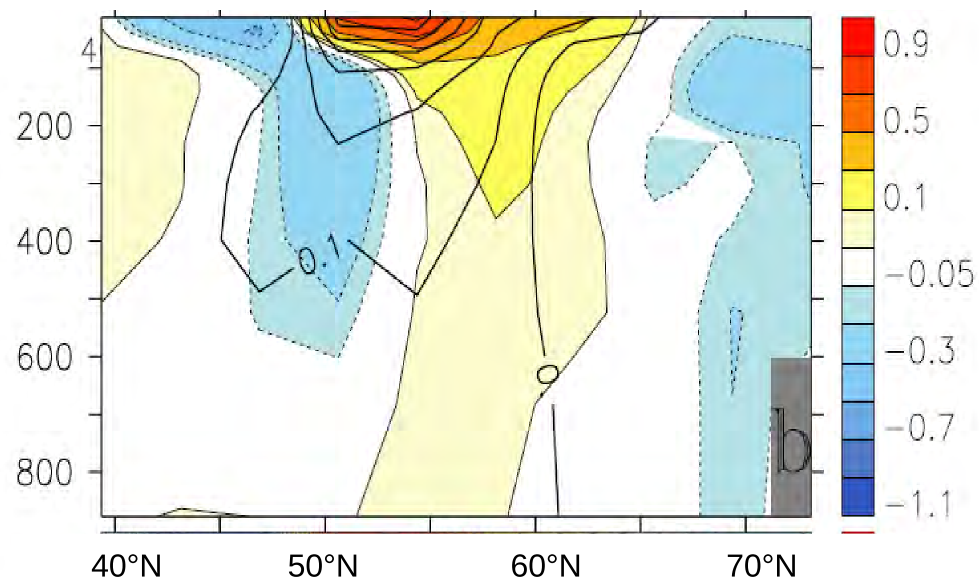
“Internal feedback”



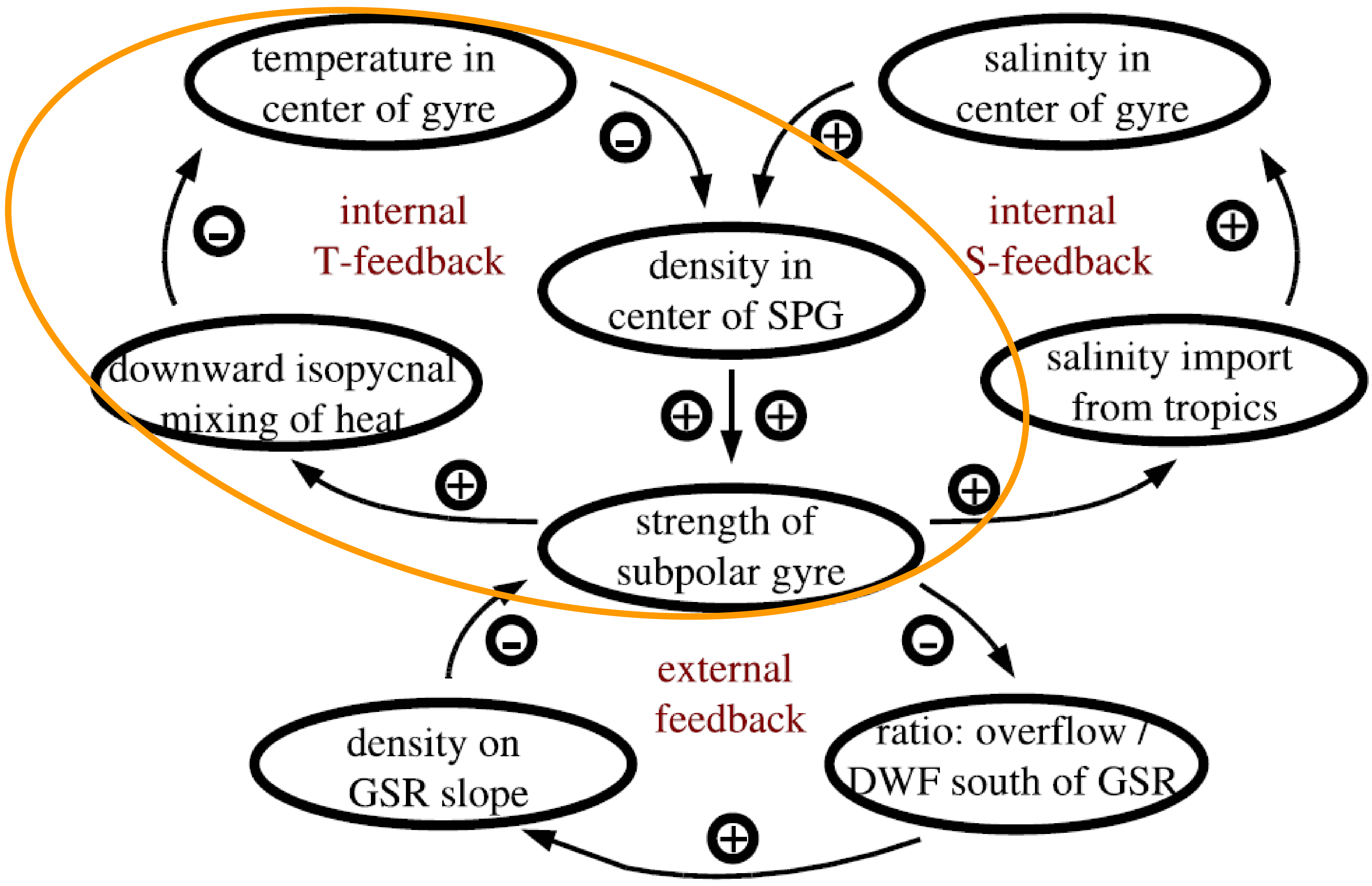
Levermann & Born, GRL, 2007.

Salinity differences

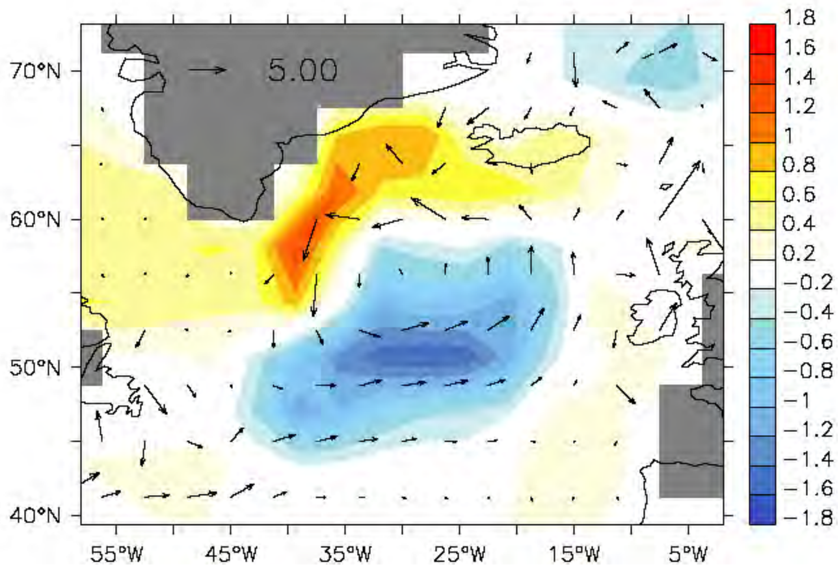


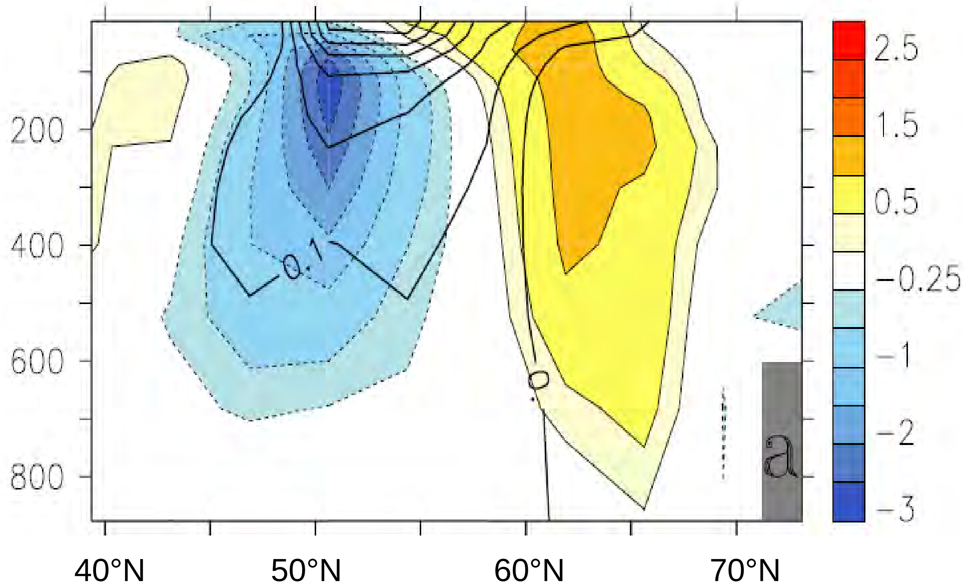


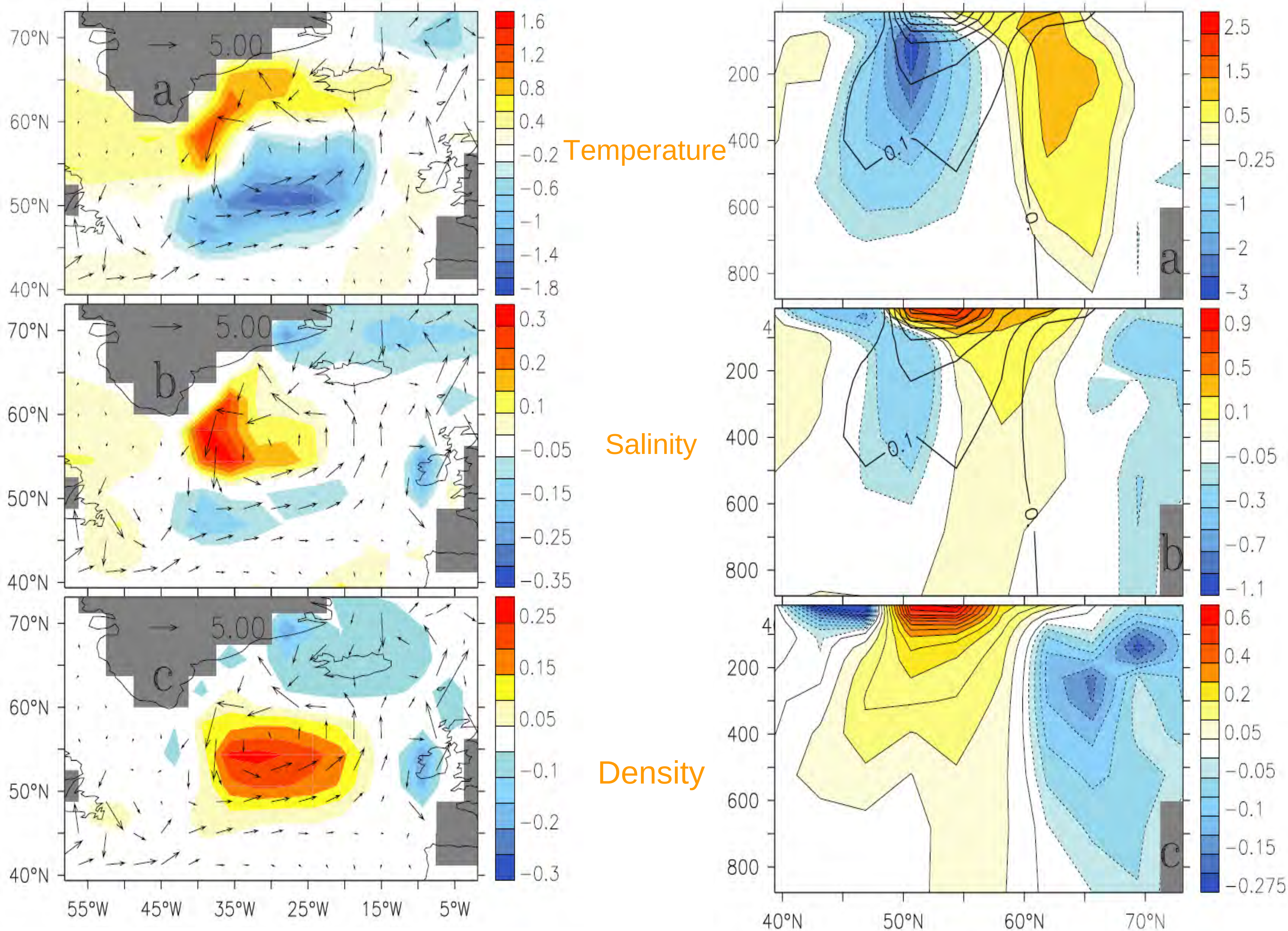
Temperature feedback
"Internal feedback"



Temperature differences



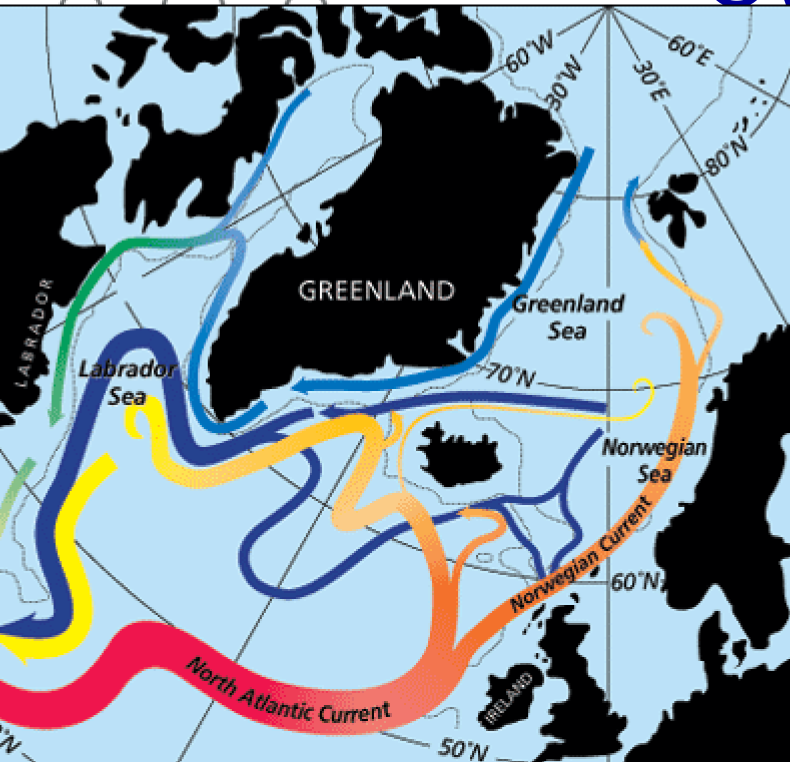


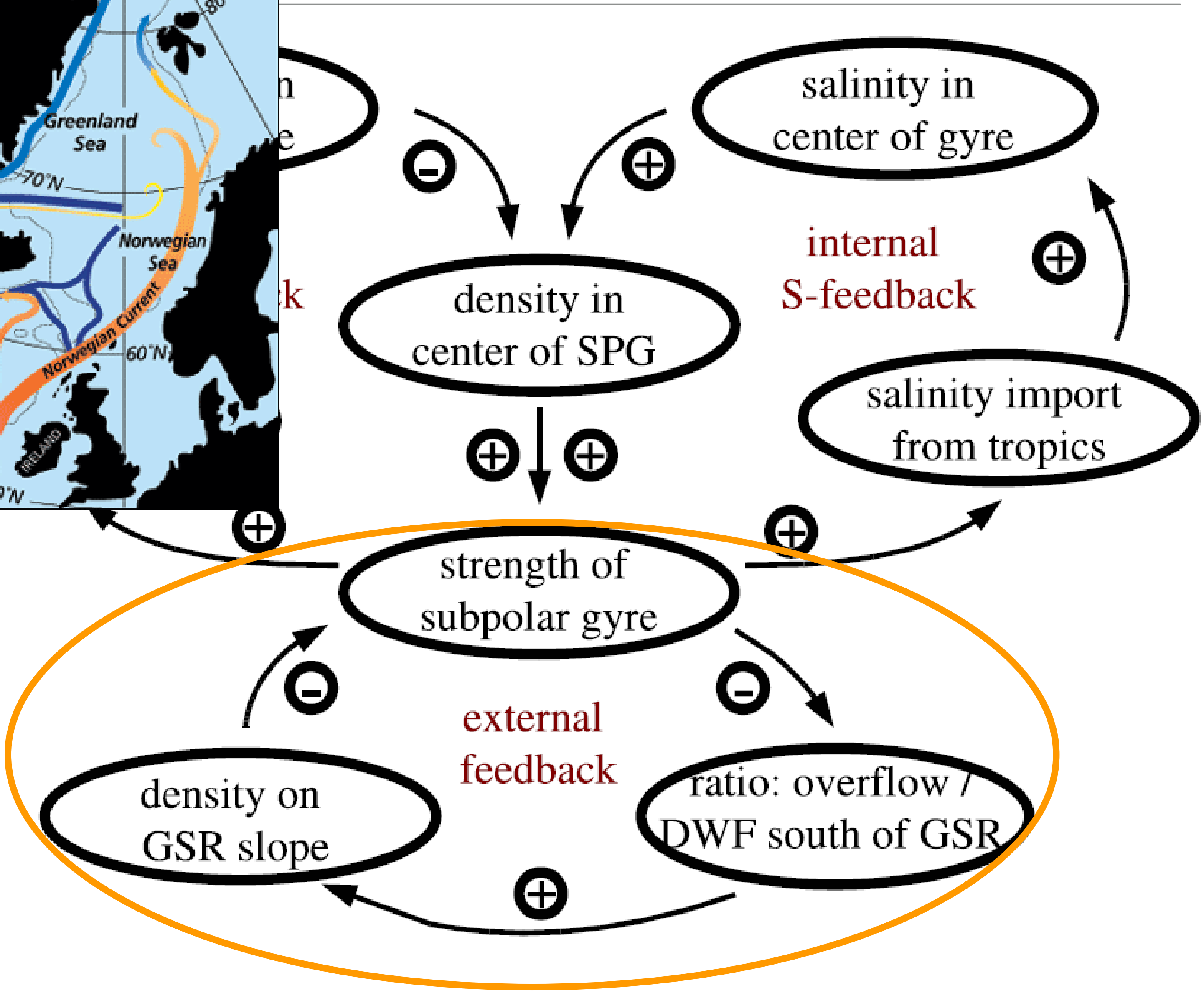


Temperature
Salinity
Density
a
b
c
5.00
70°N
60°N
50°N
40°N
55°W
45°W
35°W
25°W
15°W
5°W
1.6
1.2
0.8
0.4
−0.2
−0.6
−1
−1.4
−1.8
0.3
0.2
0.1
−0.05
−0.15
−0.25
−0.35
0.25
0.15
0.05
−0.1
−0.2
−0.3
200
400
600
800
0.1
0
40°N
50°N
60°N
70°N
2.5
1.5
0.5
−0.25
−1
−2
−3
0.9
0.5
0.1
−0.05
−0.3
−0.7
−1.1
0.6
0.4
0.2
0.05
−0.05
−0.1
−0.15
−0.275

Overflow feedback

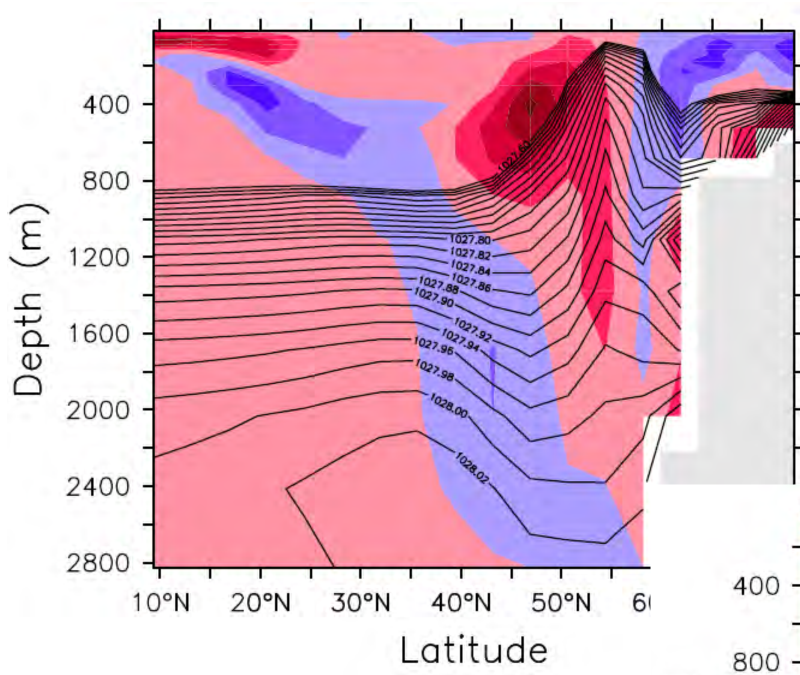
"External feedback"



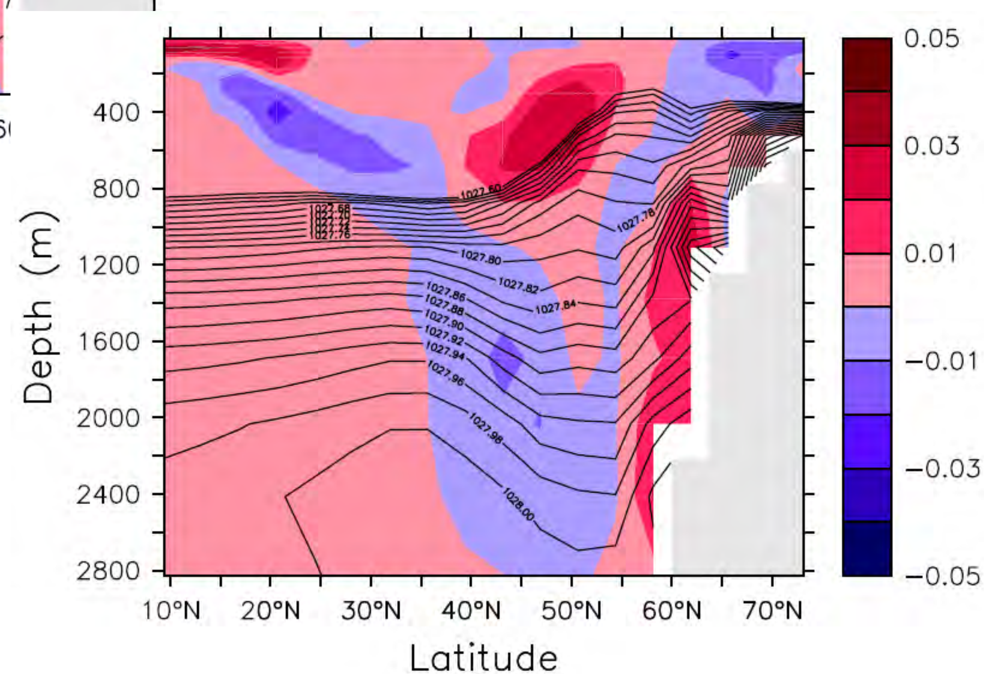


Meridional gradient of potential energy

Strong SPG



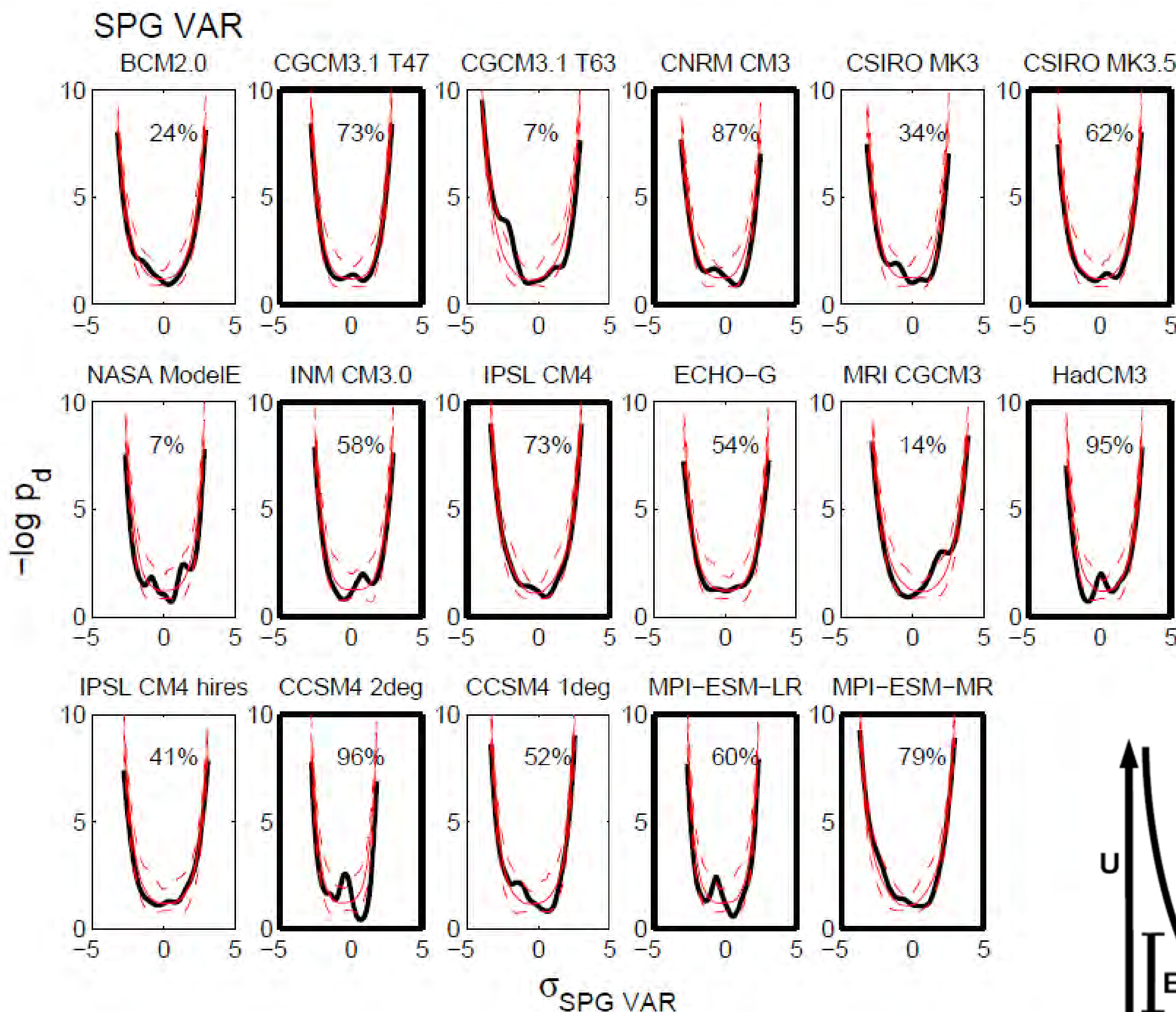
Weak SPG



$$\phi \equiv \int_{-H}^{0} dz \cdot z \cdot g \cdot \frac{\rho_0 - \rho}{\rho_0}$$

Born et al., 2009.

Bistability of Atlantic subpolar gyre

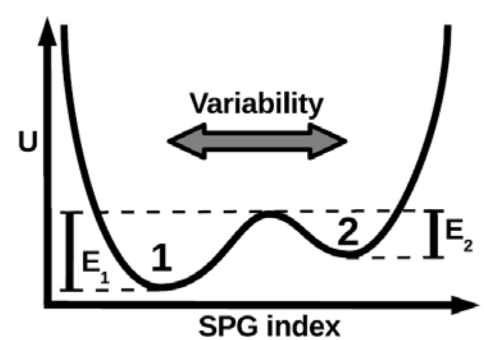


Born et al. (2012), in rev.

Can be detected in some AOGCMs as well

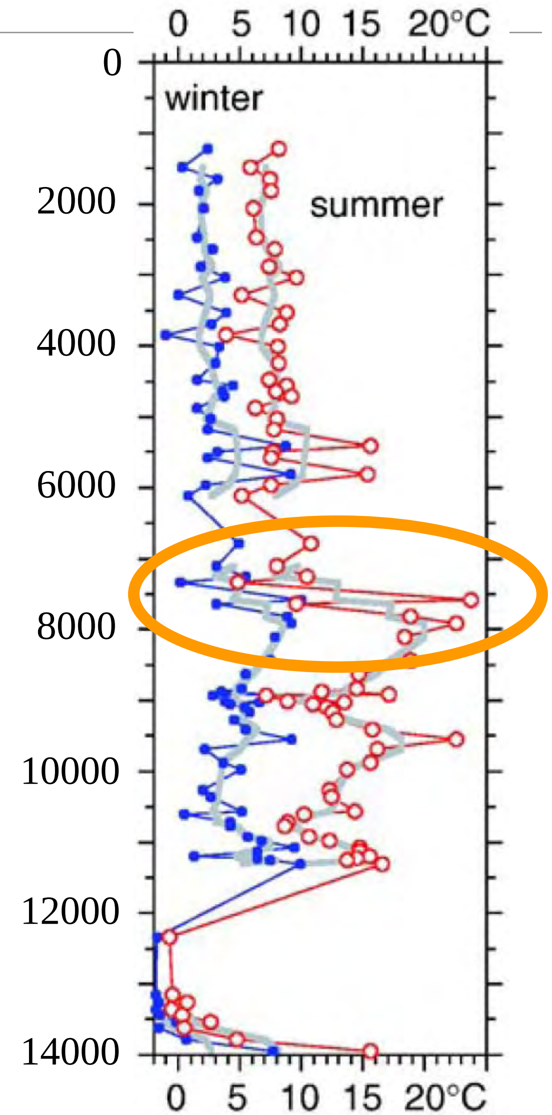
Feedback mechanisms are the same

Bistability masked by natural variability to varying degree



Evidence from the past

(Jakobsson, 2008)



8.2k event: abrupt cooling in Greenland, aprupt and persistent cooling in NW North Atlantic

Explainable by persistent transition of SPG towards a stronger state

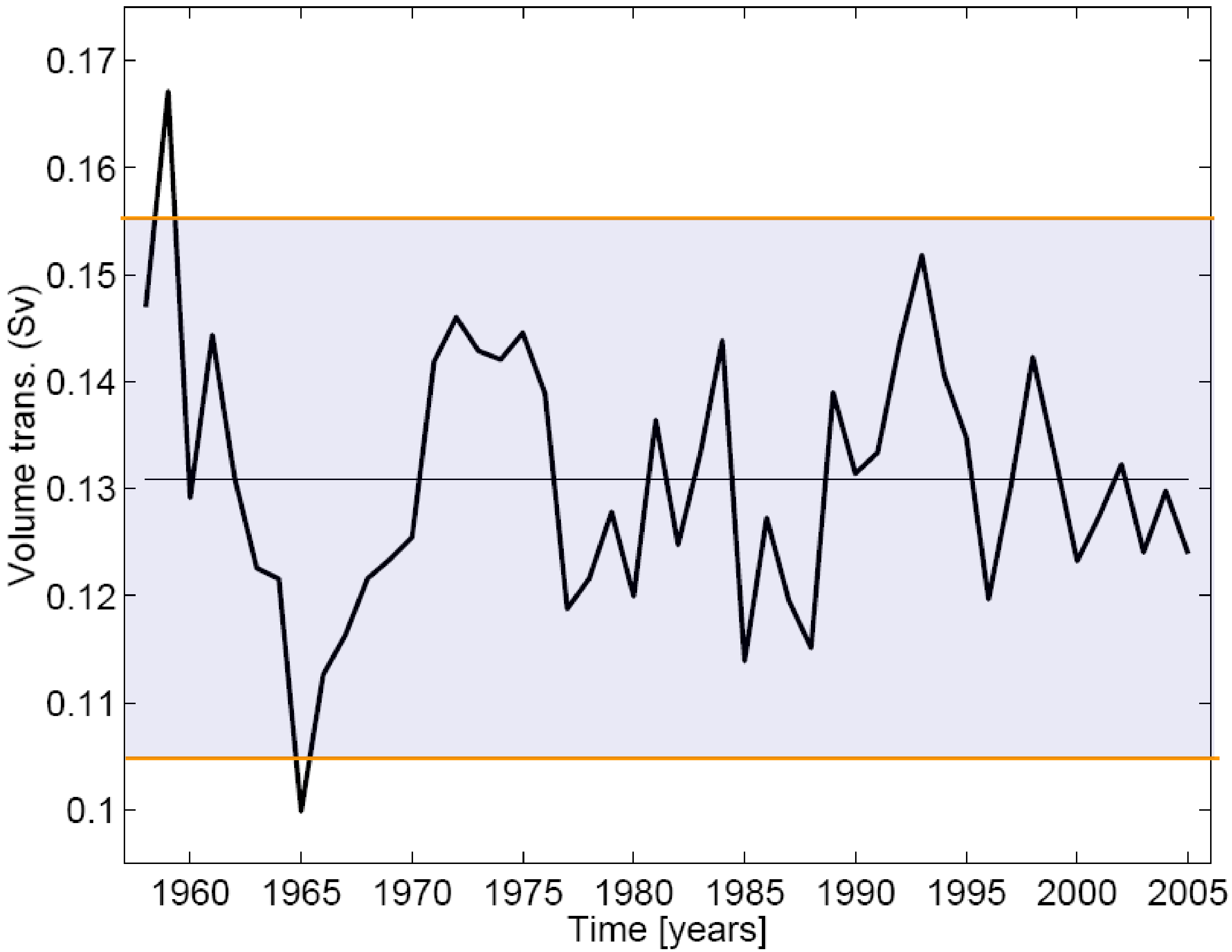
Transition is associated with reorganization of North Atlantic circulation

Dynamical reason: Bistability of subpolar gyre

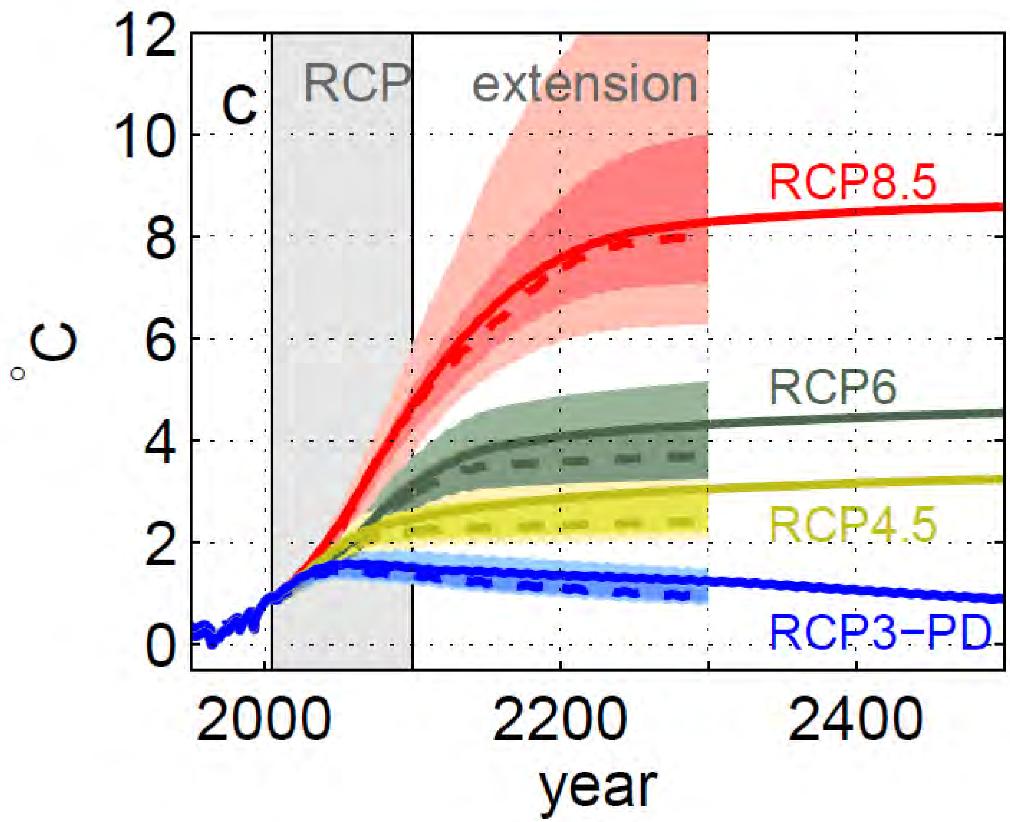
(de Vernal and Hillaire-Marcel, 2006)

Subpolar gyre bistability

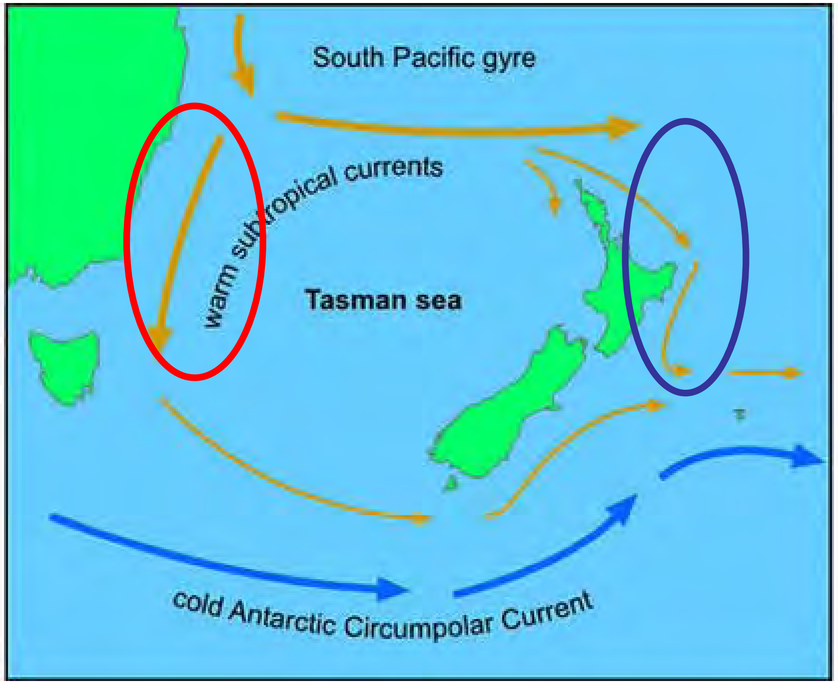
Precipitation into the Nordic Seas from NCEP-NCAR reanalysis



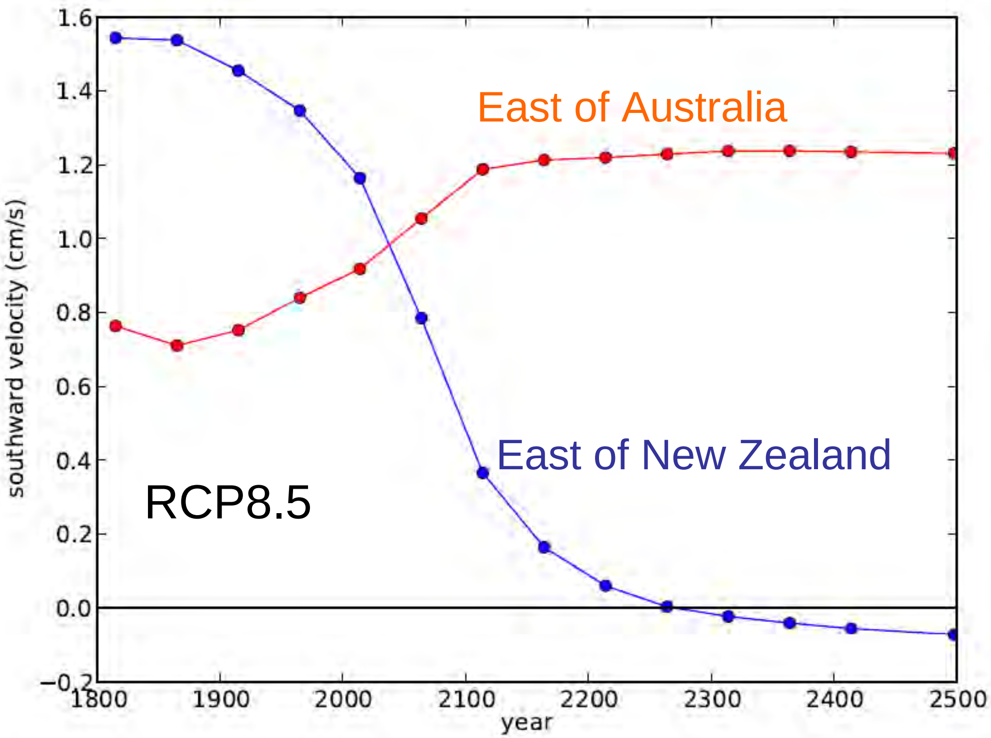
Southwest Pacific circulation under global warming



Schewe et al., 2011



The University of Waikato

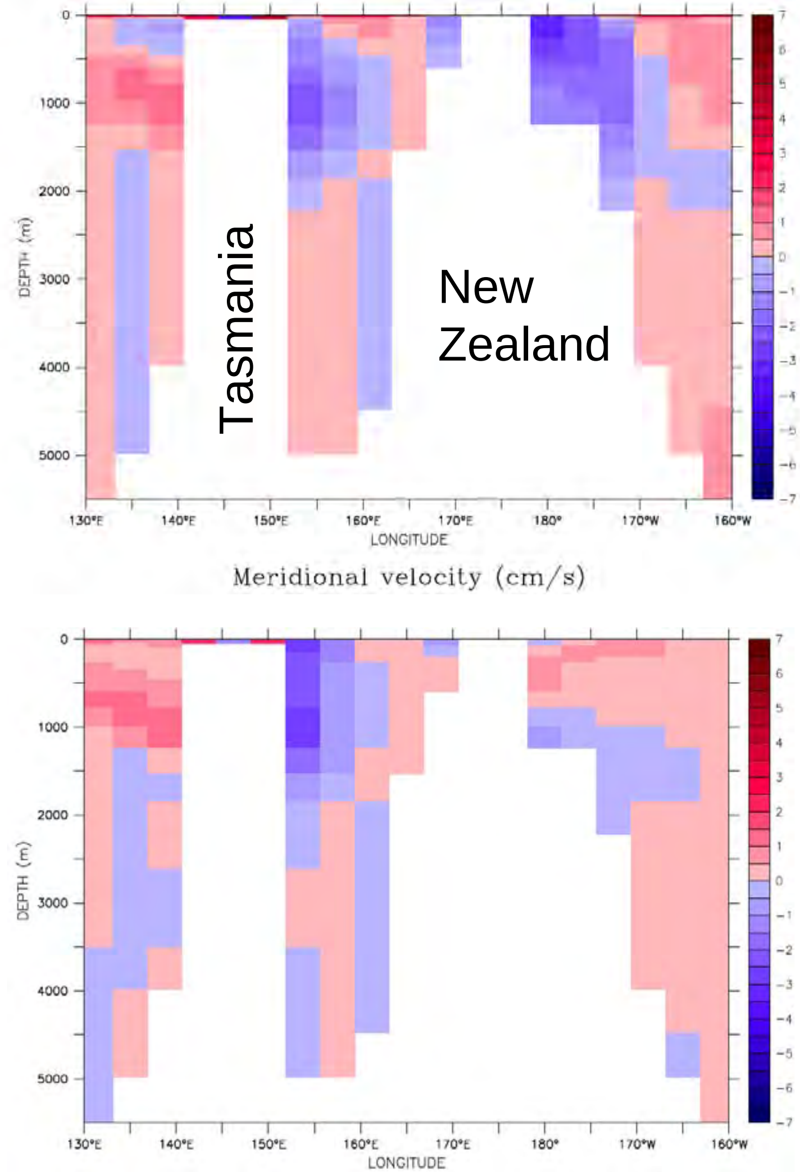


Implications for sea-level …

Self-amplification?

Or simply magnitude of forcing?

Schewe & Levermann, in prep.



Conclusions

- While some components of the global ocean circulation react quasi-linearly to climate changes, others are governed by positive feedbacks
- These feedbacks can amplify external forcing, and lead to abrupt and/or persistent changes in response to climate change.
- Because of such non-linearities, and also because of the magnitude of expected forcing, fundamental changes in large-scale circulation patterns cannot be excluded