Two stable equilibria of the Atlantic subpolar gyre

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Why subpolar gyre?

- Important role for decadal climate variability (Yeager et al., 2012; many others)

- Paleo-events:
  - Holocene climate variations (Thornalley et al., 2009)
  - 8.2 ka event
  - Transition into the last ice age (Born et al., 2010,2011; Jochum et al., 2012)
Idealized model of the western subpolar gyre

Irminger Current: 10°C, 35 psu

Icelandic Slope Water: 4°C, 34.9 psu

$T_{atm} = 2-14^\circ C$

$h = 100$ m

d = 1400 m

W = 100 km
Description of the idealized model

Temperature and salinity of the **upper** central basin:

\[
\begin{align*}
\partial_t T_1 &= c U_1 (T_2 - T_1) + \tau^{-1} \left( T_0^{atm} - T_{amp}^{atm} \cdot \cos(\omega \cdot t) - T_1 \right) \\
\partial_t S_1 &= c U_1 (S_2 - S_1) - F_S,
\end{align*}
\]

- Eddy exchange
- Constant freshwater flux
- Annual temp. cycle
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\end{align*}
\]

Eddy exchange

Temperature and salinity of the **lower** central basin:

\[
\begin{align*}
\partial_t T_3 &= cU_2(T_4 - T_3) \\
\partial_t S_3 &= cU_2(S_4 - S_3)
\end{align*}
\]

Annual temp. cycle

Constant freshwater flux

+ convection!
Description of the idealized model

Temperature and salinity of the **upper** central basin:

\[
\begin{align*}
\frac{\partial}{\partial t} T_1 &= cU_1 (T_2 - T_1) + \tau^{-1} \left( T_0^{atm} - T_{amp}^{atm} \cdot \cos(\omega \cdot t) - T_1 \right) \\
\frac{\partial}{\partial t} S_1 &= cU_1 (S_2 - S_1) - F_S,
\end{align*}
\]

**Eddy exchange**

Temperature and salinity of the **lower** central basin:

\[
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\frac{\partial}{\partial t} T_3 &= cU_2 (T_4 - T_3) \\
\frac{\partial}{\partial t} S_3 &= cU_2 (S_4 - S_3)
\end{align*}
\]

**Annual temp. cycle**

**Constant freshwater flux**

\( + \text{ convection!} \)

Velocities of upper and lower boundary current:

\[
\begin{align*}
U_2 &= U_{btp} - \frac{gd}{f\rho_0 w} \cdot (\sigma_4 - \sigma_3) \\
U_1 &= U_2 - \frac{gh}{f\rho_0 w} \cdot (\sigma_2 - \sigma_1) \\
M &= U_1 w h + U_2 w d,
\end{align*}
\]

**Thermal wind**
Constant seasonal forcing

- Three years to equilibrium
- Increase of 10 Sv (1/3) over barotropic (wind) transport
- 9.2 Sv increase in lower boundary current, 0.8 Sv in upper
- Increase in lower level density due to cooling, not salinification
- Compares well with the formation of Labrador Sea water
Mutual strengthening of circulation and (eddy) salt transport

1) Stronger circulation
2) Stronger eddy salt flux
3) Stronger cooling

\[ \partial_t S_1 = cU_1(S_2 - S_1) - F_S \]
Hysteresis with salinity of upper boundary current

Slowly vary salinity of the upper boundary current from 36 psu to 31 psu and up again.

Strong SPG circulation sustains itself.

\[
\frac{\partial}{\partial t} S_1 = c U_1 (S_2 - S_1) - F_S
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\[ \partial_t S_1 = cU_1(S_2 - S_1) - F_S \]
Analytical solution

Eddy salt flux balanced by surface freshwater flux, Baroclinic flow scales with radial density gradient:

\[
A \cdot c^* \cdot U_{bcl} (S_1 - S_2) = -S_0 \cdot A' \cdot F
\]

\[
U_{bcl} = k \cdot \Delta \rho = k \{ \beta(S_1 - S_2) - \alpha(T_1 - T_2) \}
\]

One stable, one unstable solution:

\[
U_{bcl, \pm} = -\frac{1}{2} k \alpha(T_1 - T_2) \pm \sqrt{\frac{1}{4} k^2 \alpha^2 (T_1 - T_2)^2 - \frac{k \beta A'}{c^* A} S_0 F}
\]

Mathematically identical to Stommel's model
Flow regimes

- **Thermohaline** for $T_2 < T_1$
- **Haline** for $T_2 > T_1$

- **SPG flow**

- **Thermal**

- **More evaporation**
- **Freshwater forcing**
- **More precipitation**

- $m^{\text{Crit}}$
- $F_1^{\text{Crit}}$

Marotzke (1990); Rahmstorf (Clim. Dyn., 1996)
Similar dynamics in the comprehensive GCMs

CCSM4 1000 year control experiment, second half.

Spontaneous transition to stronger SPG, stable, then spontaneous transition back to weak SPG.

Similar dynamics found in several CMIP3/5 GCMs (Born et al., Clim. Dyn., 2012)
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Summary

• First step to a mechanistic understanding of SPG dynamics

• The subpolar gyre has two stable modes of circulation, consequence of mutual intensification of flow and salt transport (Stommel's salt advection feedback)

• Bistability also found in comprehensive, last-generation climate models.
Summary

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- Bistability also found in comprehensive, last-generation climate models.

copies of papers on: www.climate.unibe.ch/~born


A. Born, T.F. Stocker, C.C. Raible and A. Levermann (2012): Is the Atlantic subpolar gyre bistable in comprehensive coupled climate models?, Climate Dynamics 40, 2993-3007