Unresolved processes in climate models: lessons from the laboratory

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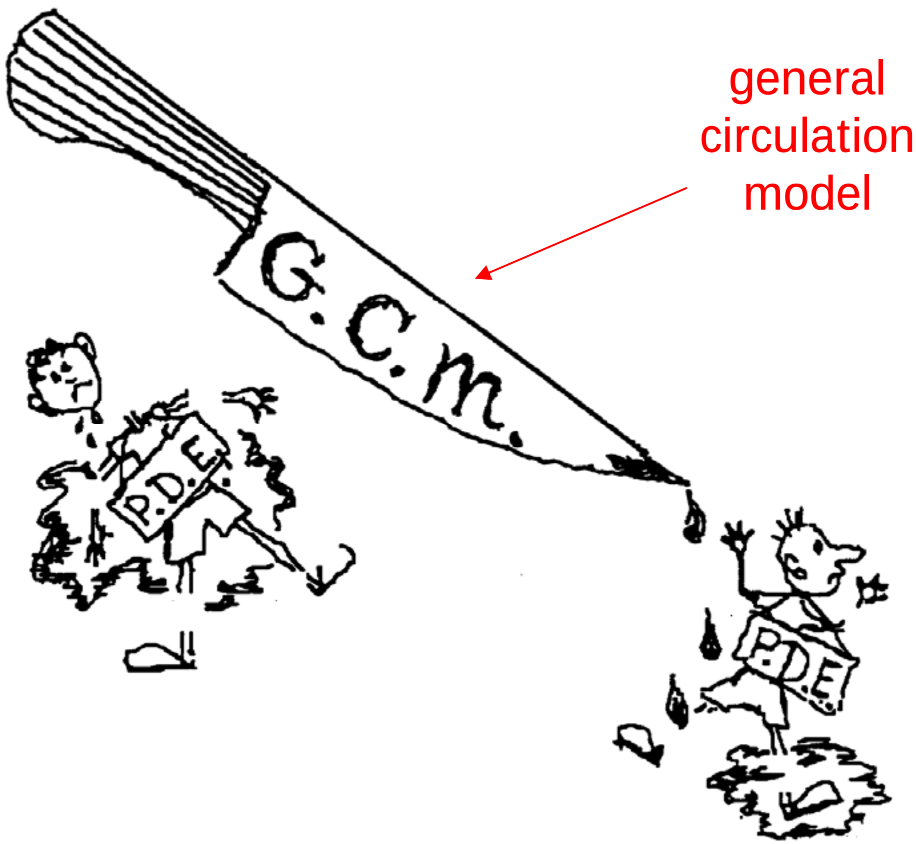
Outline

- Introduction
- Oceanic case study:
  the thermohaline circulation
- Atmospheric case study:
  sudden stratospheric warmings
- Conclusions

Why climate simulation is hard:

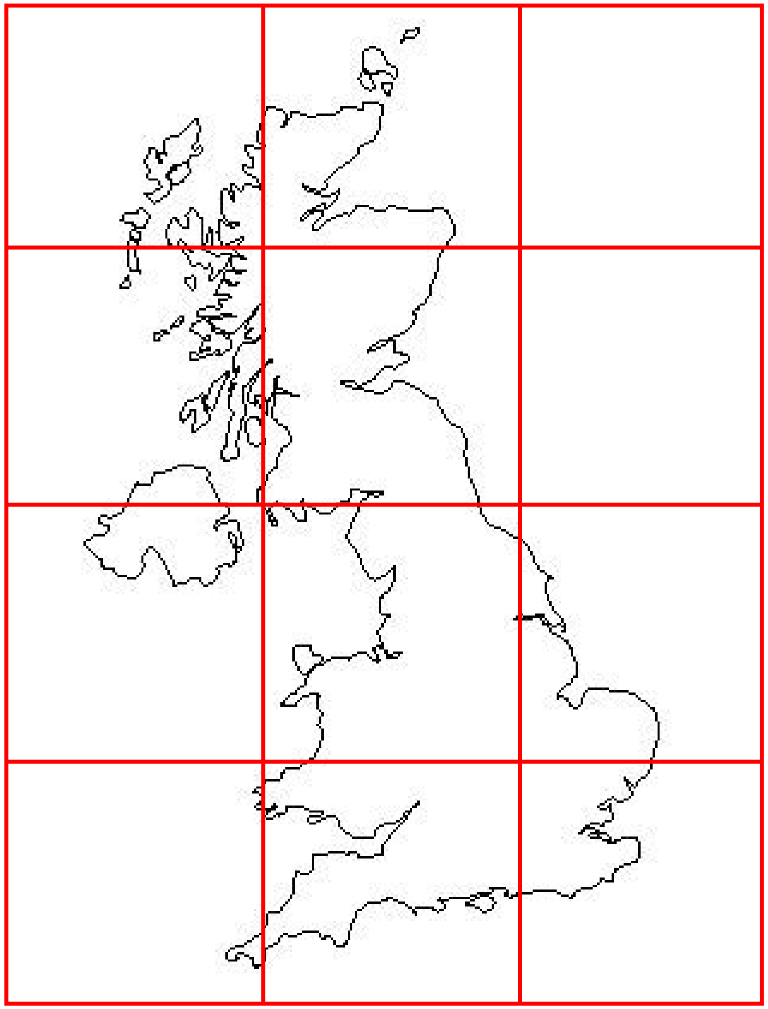
general
circulation
model



partial
differential
equations

(Schertzer & Lovejoy 1993)

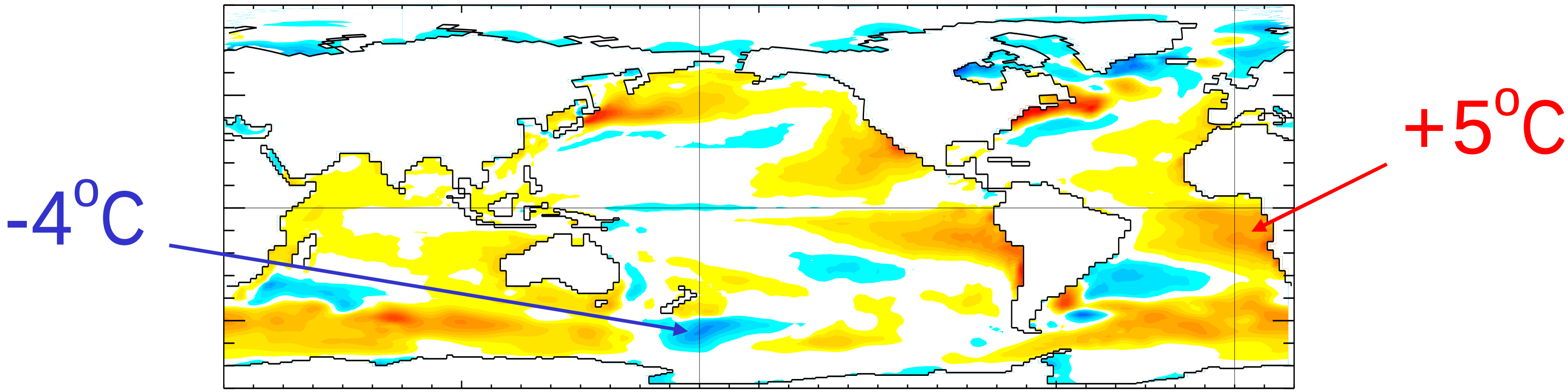
Typical grid for climate simulation:



grid boxes

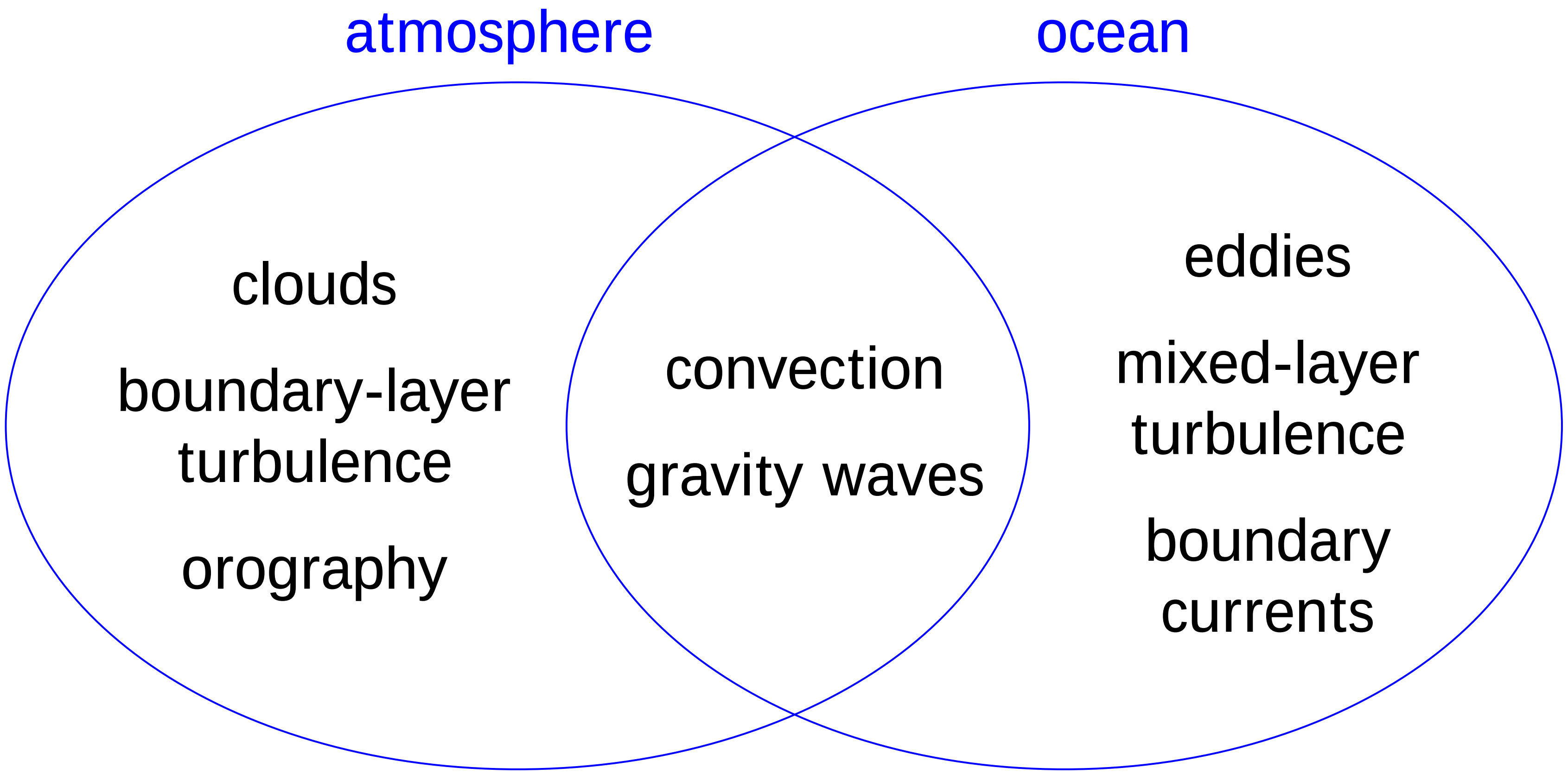
- GCMs cannot resolve many of the most important processes in the climate system

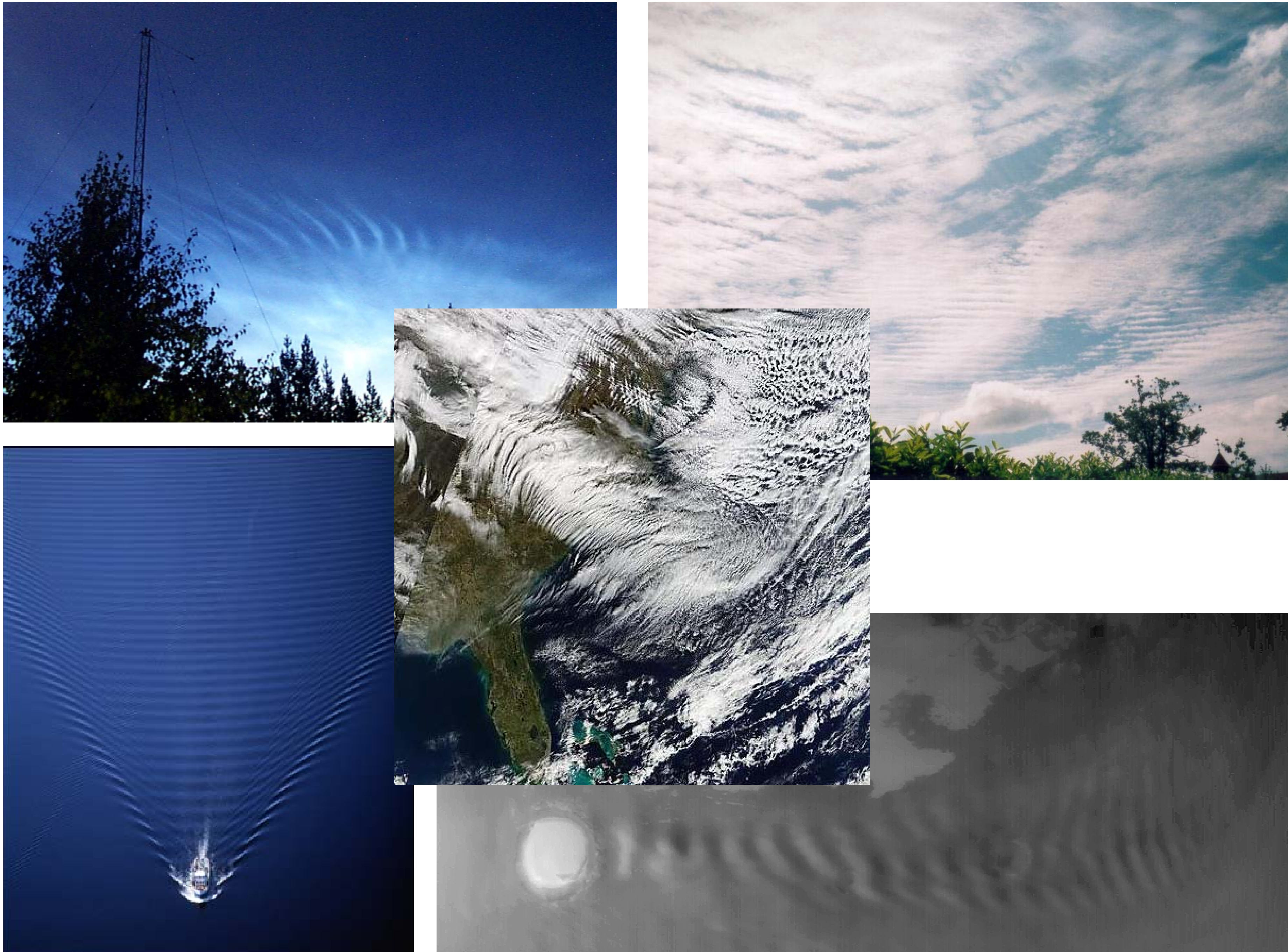
Systematic climate biases result:



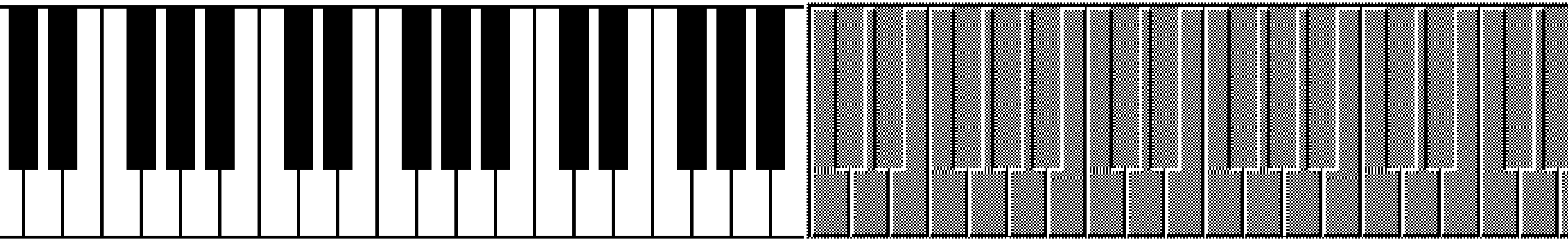
"to understand and characterise the important unresolved processes... in the climate system" is a *"high priority area for action"* (IPCC, 2001)

Unresolved processes in GCMs





GCMs = broken pianos!



Rossby waves gravity waves

"We might say that the atmosphere is a musical instrument on which one can play many tunes… and nature is a musician more of the Beethoven than of the Chopin type."

Letter from Jule Charney to Phillip Thompson, 12 February 1947

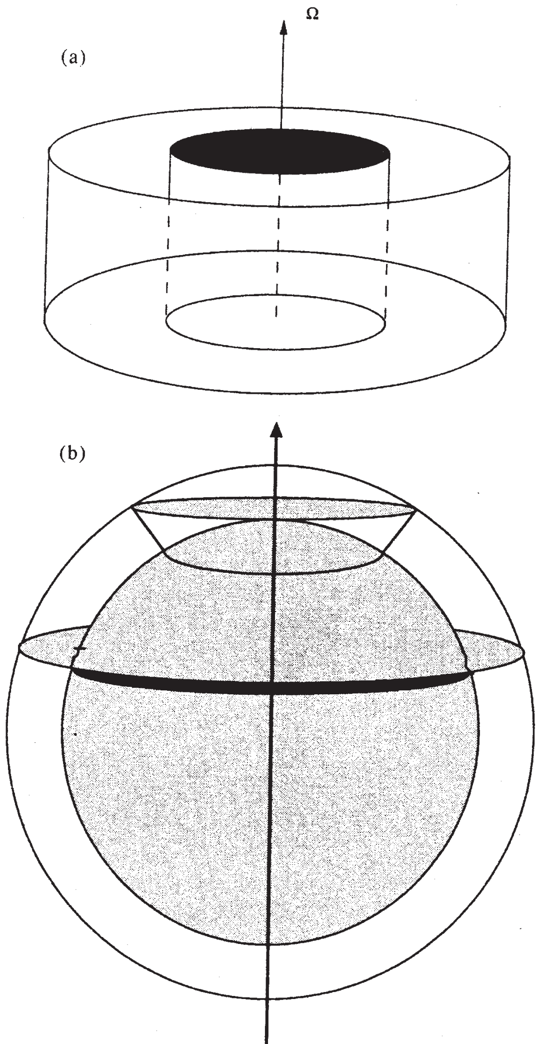
Pertinent questions:

- Does it matter than gravity waves are not resolved in weather/climate models?
- Phrased differently, do gravity waves interact with the resolved flow?
- If so, can the interaction be parameterized?
- How do we even try to find answers to these questions?!

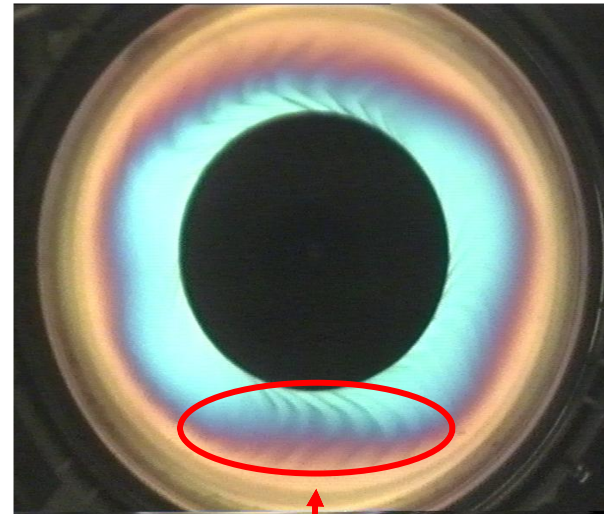
Dynamical similarity

rotating annulus:

rotating planet:



(Read et al., 1998)



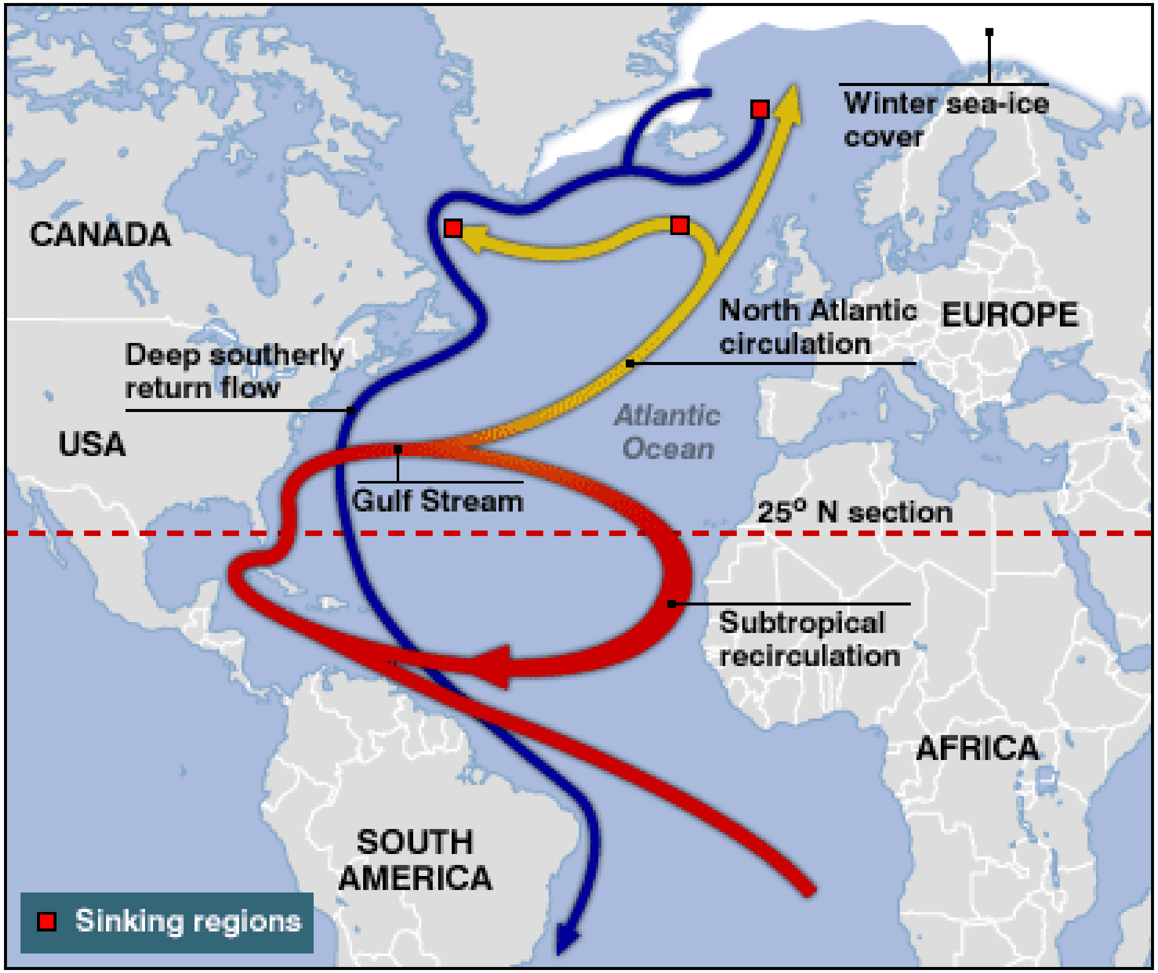
(Williams et al. 2003)

(Dalin et al. 2004)

Oceanic case study: the thermohaline circulation

Acknowledgements: Tom Haine & Peter Read

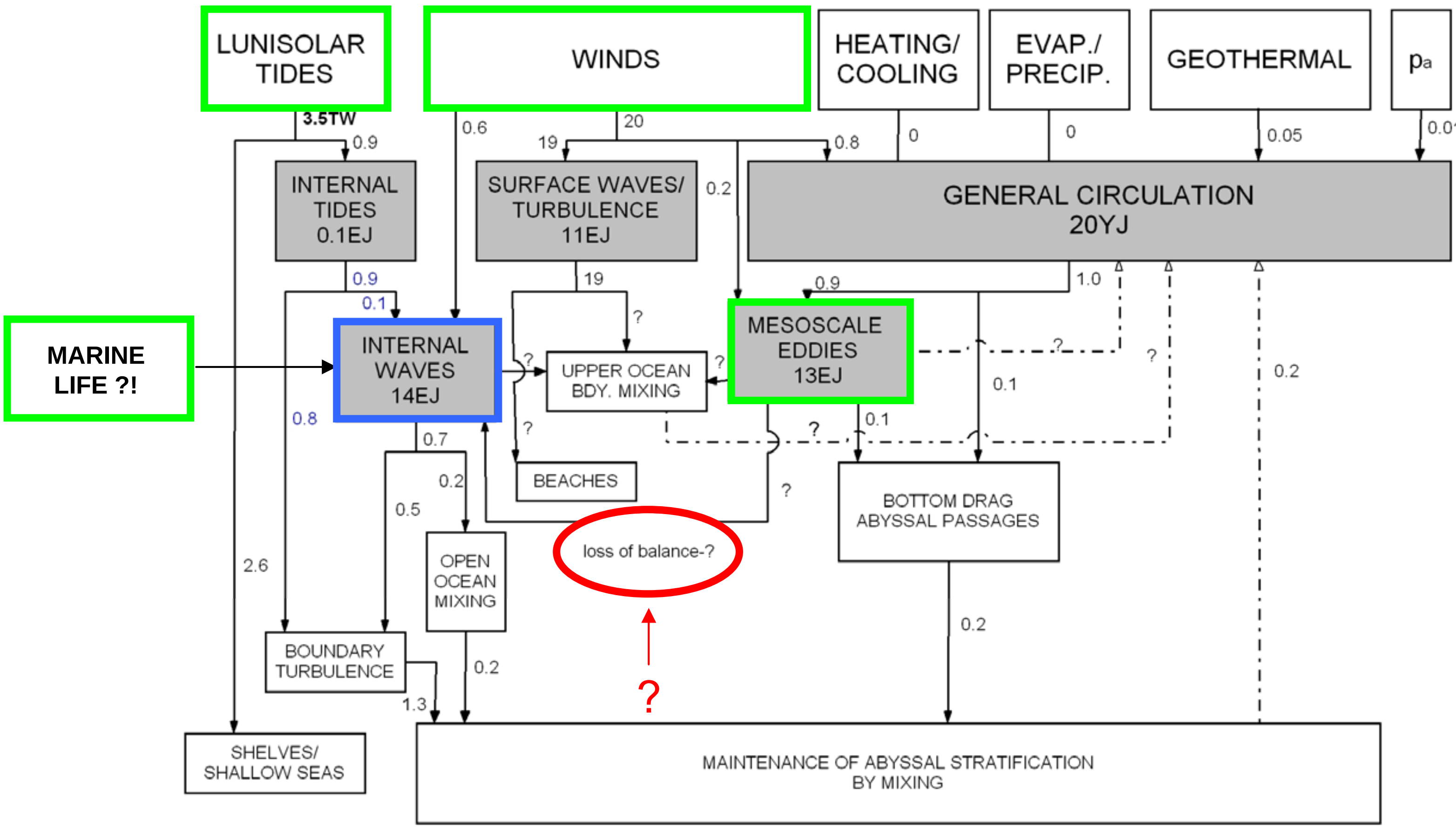
The thermohaline circulation



Ocean energetics

- deep-water formation acts to reduce the ocean's potential energy
- so does the baroclinic generation of eddies
- but the ocean is in a steady state ⇨ need to re-supply this lost potential energy
- this is achieved via vertical mixing due to internal gravity waves (without which the deep ocean fills with uniformly cold, motionless water; Sandström, 1908)
- how are internal waves (and hence deep ocean mixing) powered?

Energy budget for global ocean circulation

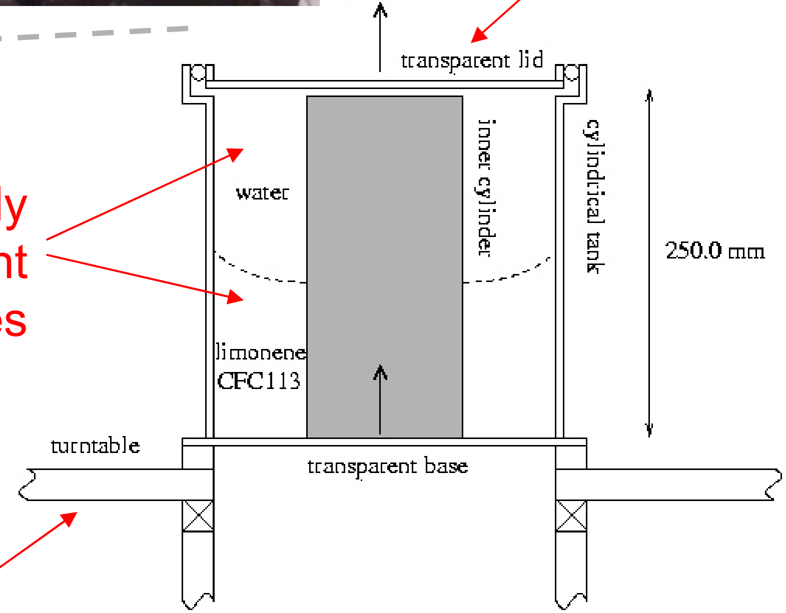


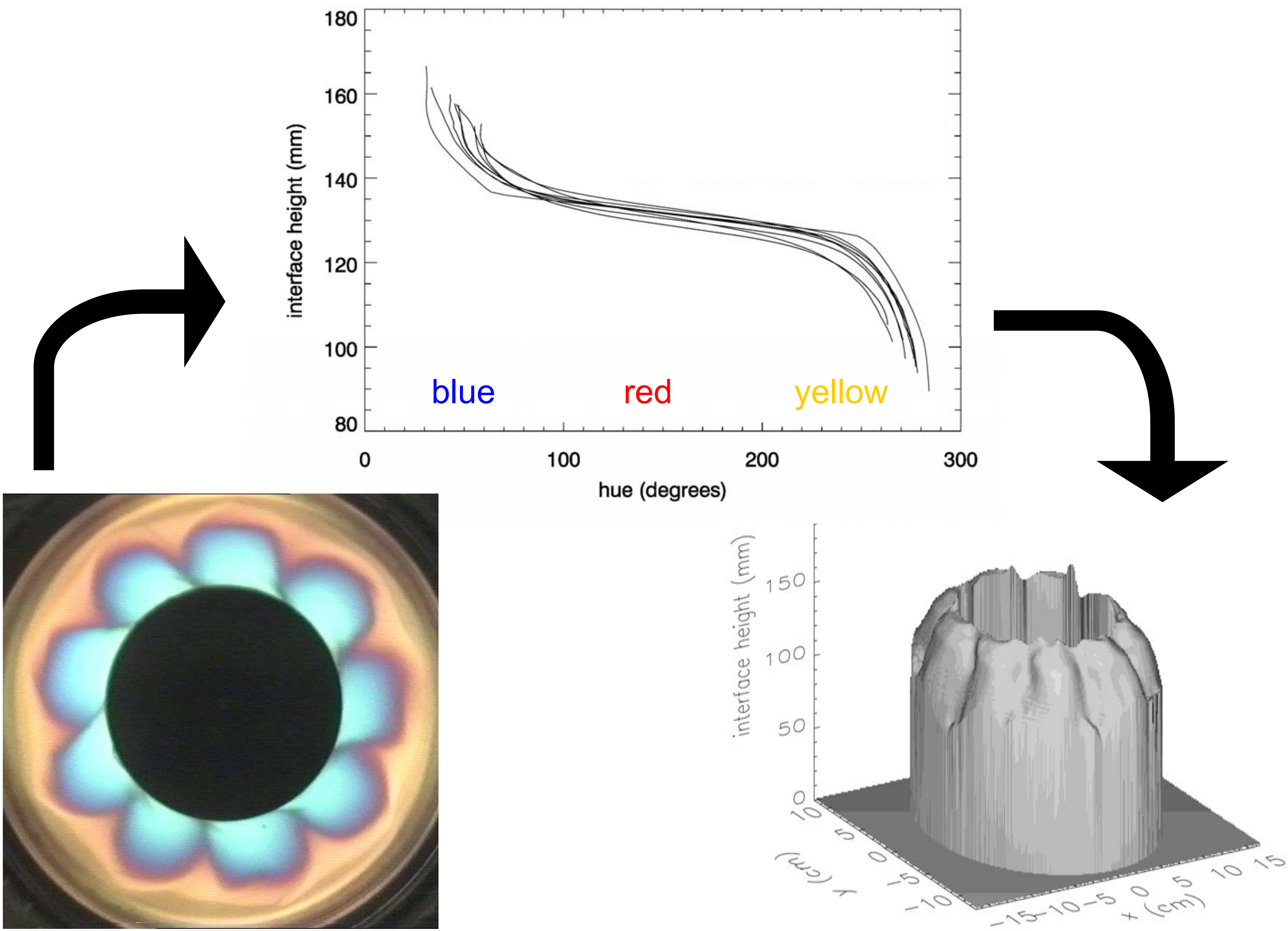
(Wunsch & Ferrari, 2004)

How can we quantify the “loss of balance” energy pathway?

- slow manifold theories? But they contain many *ad hoc* approximations in order to make them analytically tractable
- numerical models? But global General Circulation Model grids are usually to coarse to resolve eddies and internal waves
- laboratory experiments? Let’s see!

Rotating two-layer annulus experiment

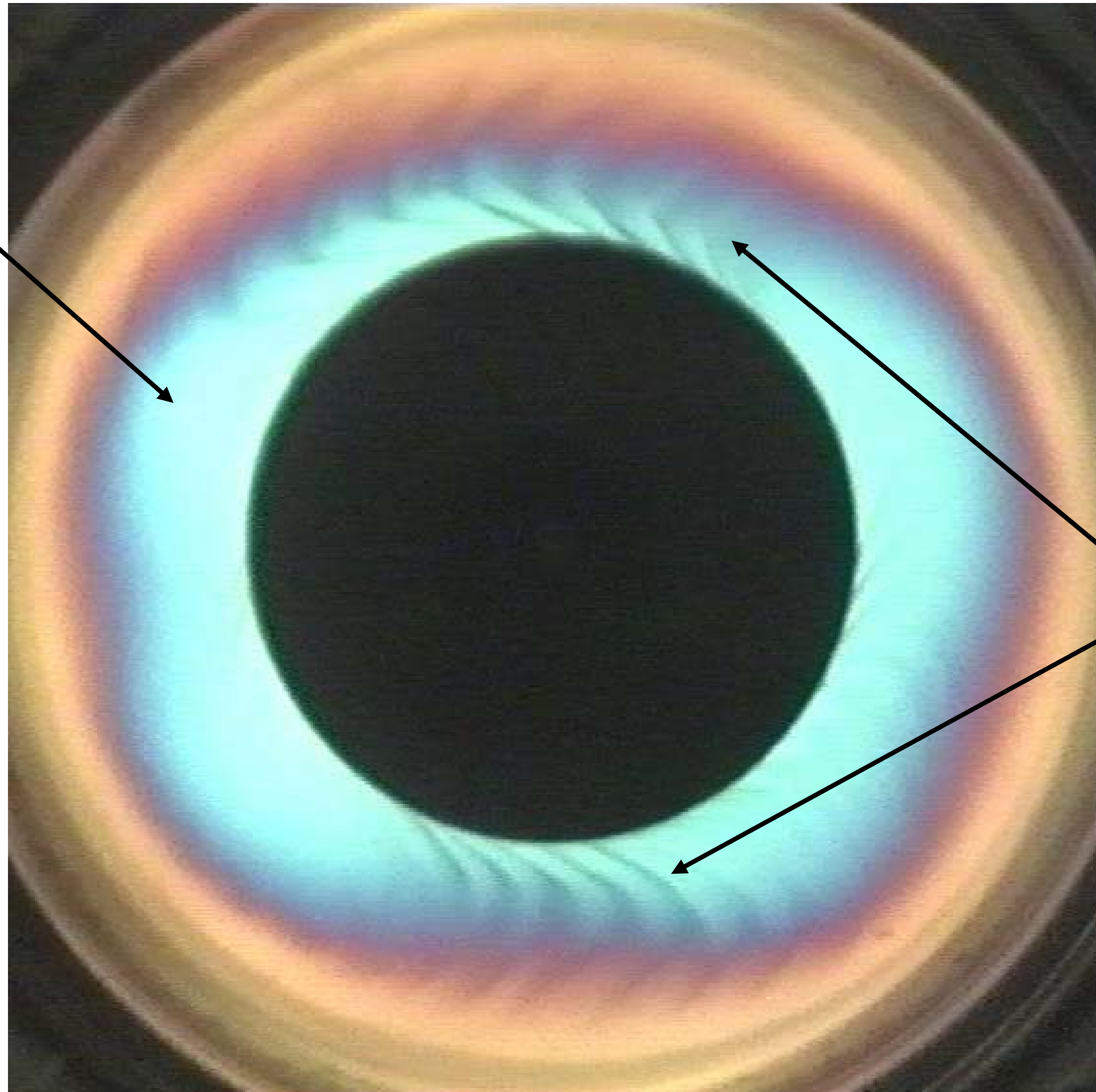




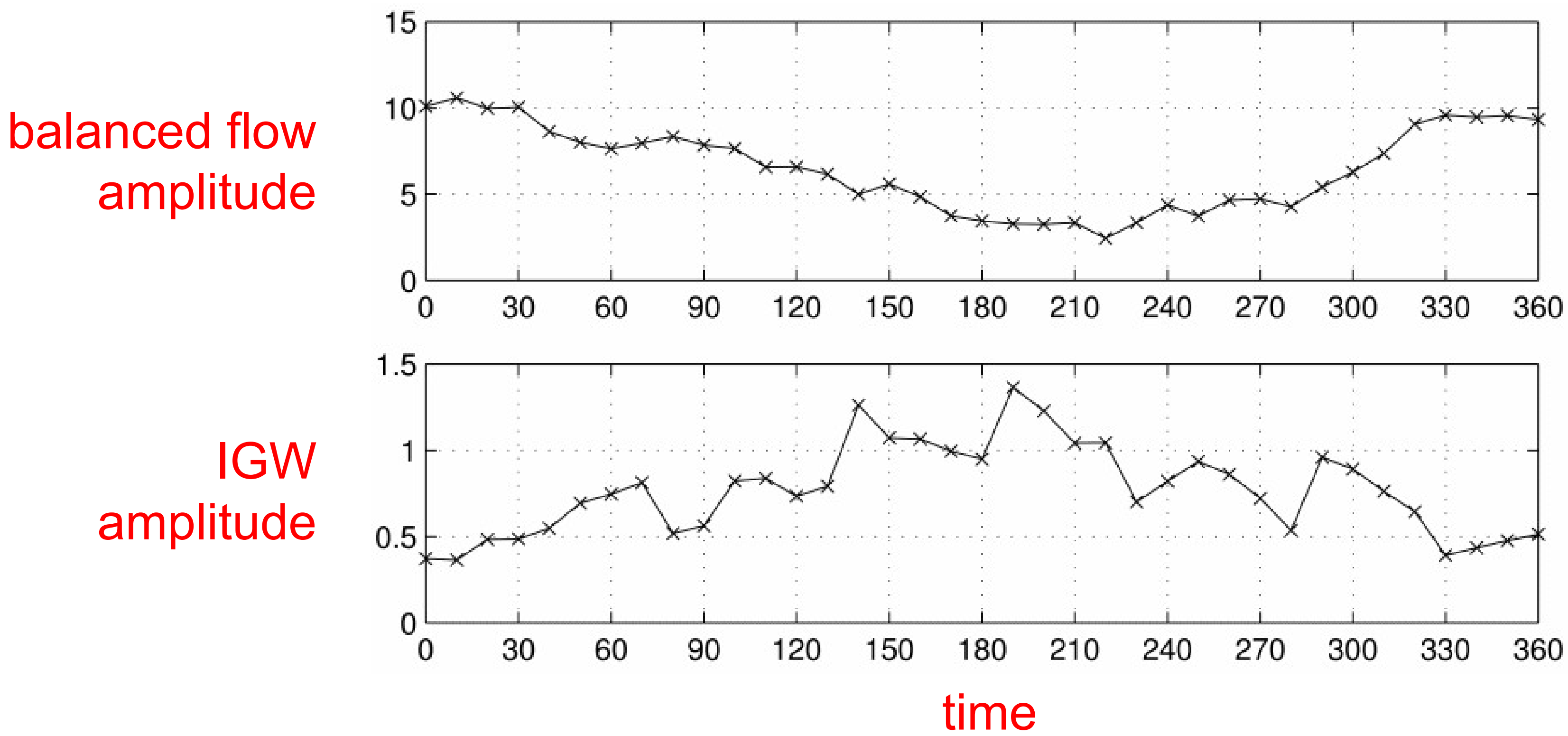
interface height (mm)
180
160
140
120
100
80
0
100
200
300
hue (degrees)
blue
red
yellow
interface height (mm)
150
100
50
0
10
5
0
−5
−10
y (cm)
−15
−10
−5
0
5
10
15
x (cm)

Typical interface height field seen by camera

balanced flow

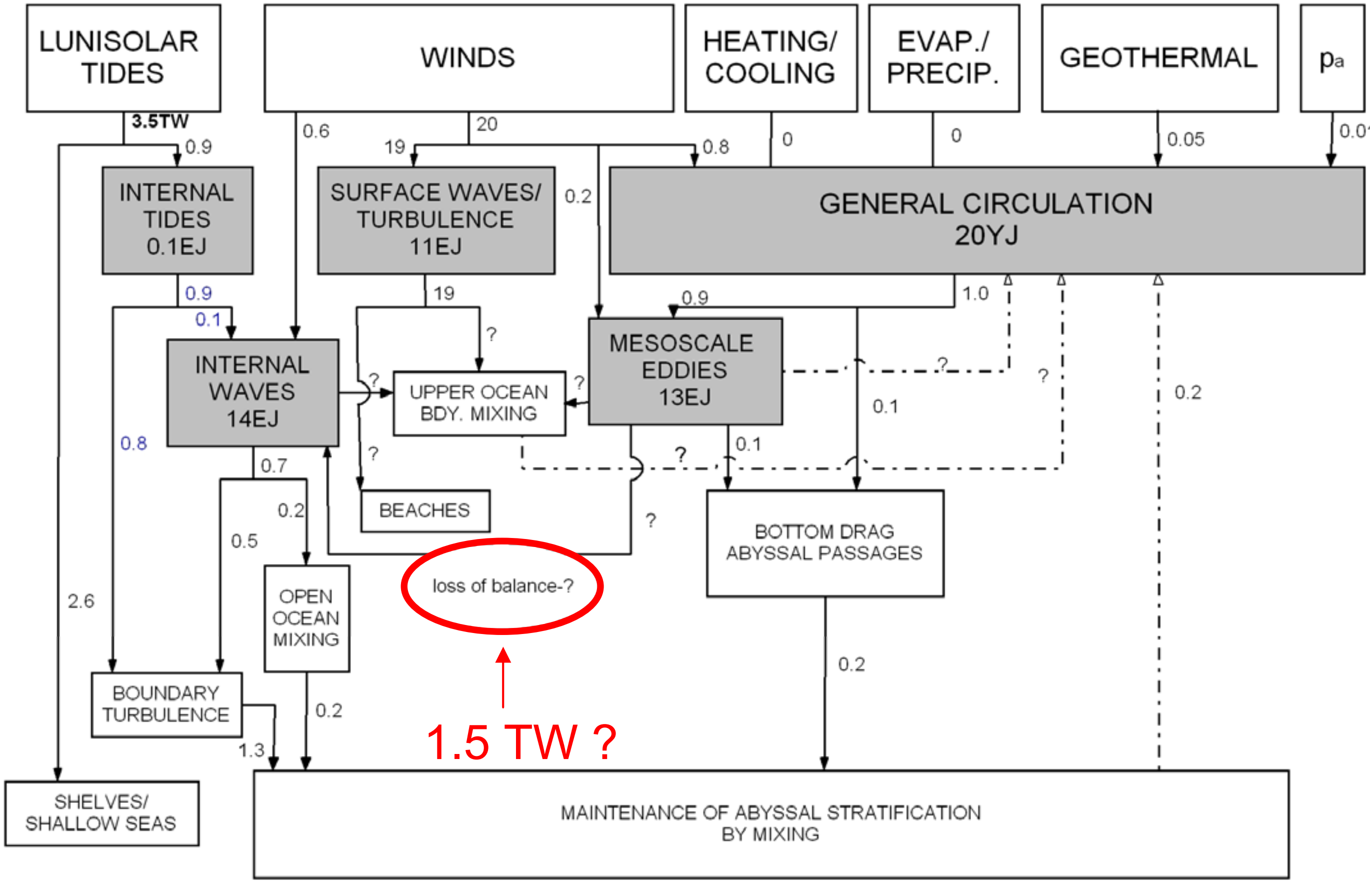


internal inertia-gravity waves (IGWs) generated by loss of balance



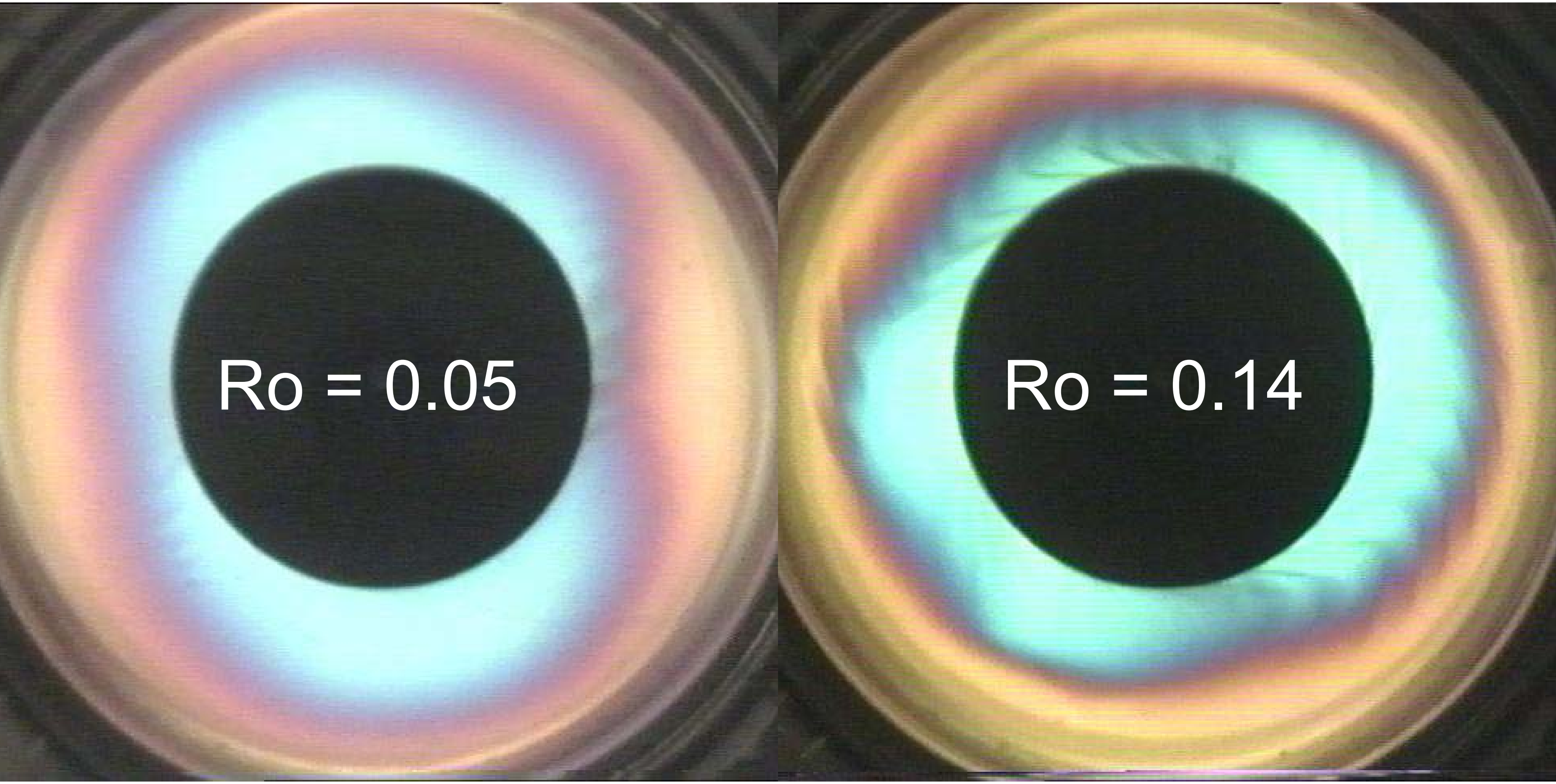
→ rate of energy growth in IGWs, as a fraction of the balanced flow energy, is ~1% per rotation period

Energy budget for global ocean circulation:

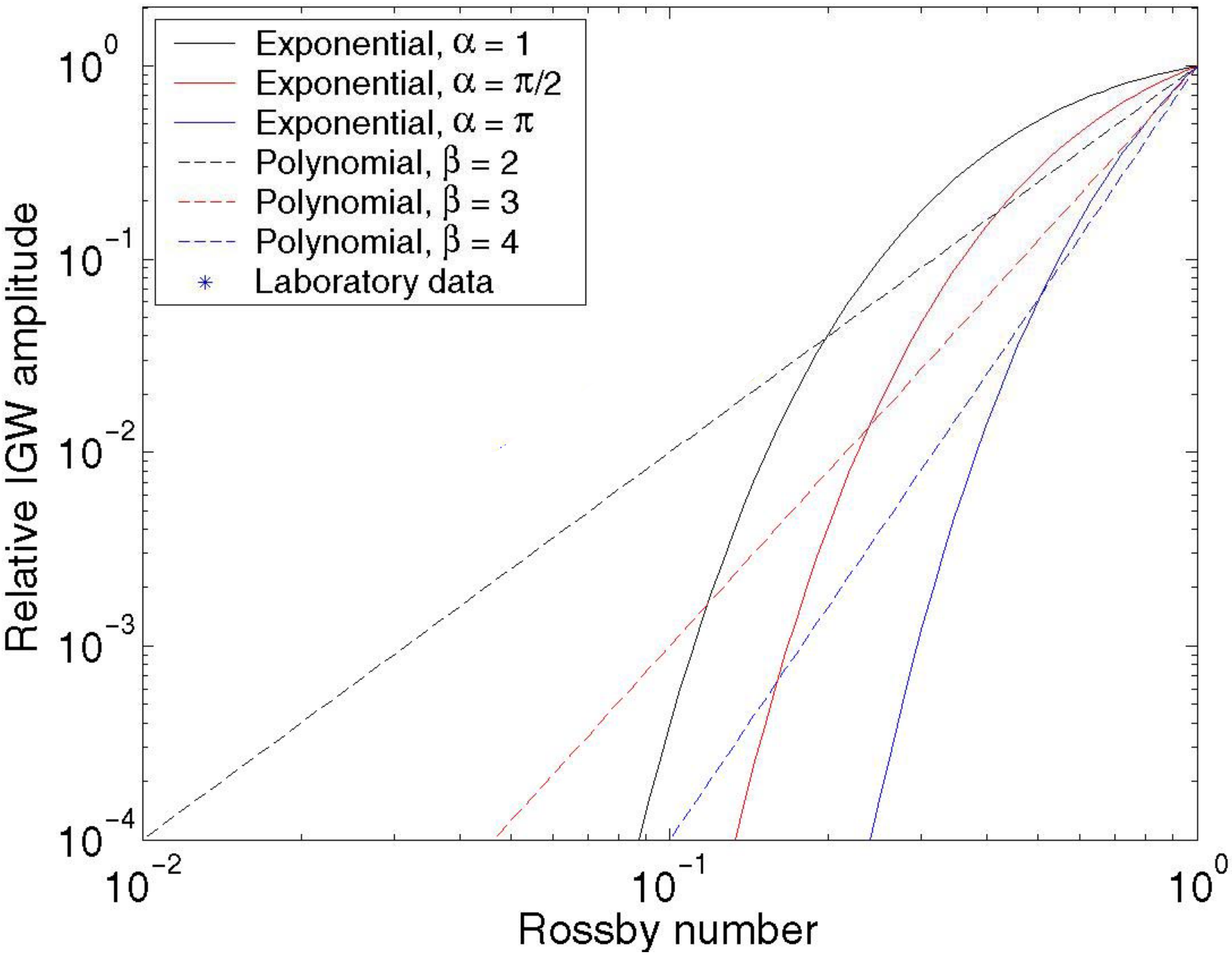


(Wunsch & Ferrari, 2004)

How do IGWs vary with Rossby number?



How do IGWs vary with Rossby number?



- non-asymptotic theories suggest $\sim Ro^{-1/2}\exp(-\alpha/Ro)$ (e.g. Vanneste & Yavneh 2004; Plougonven et al. 2005 find that $\alpha >= \pi/2$)
- standard asymptotic analysis suggests $\sim Ro^{\beta}$, $\beta >= 2$
- but the laboratory data suggest $\sim Ro^{1.2}$

THC case study: conclusions

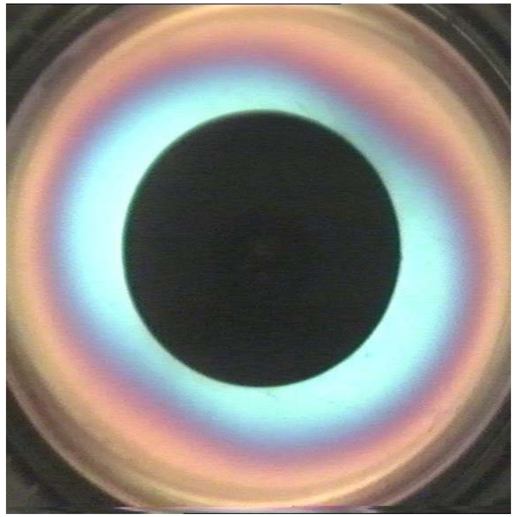
- vertical mixing due to (unresolved) breaking internal waves plays a critical role in maintaining the global ocean circulation
- about 1% of the large-scale flow energy is lost to internal waves each ‘day’ in the lab
- crude extrapolation to the ocean ⇨ 1.5 TW
- but at least the vertical mixing due to unresolved internal waves is amenable to parameterisation in GCMs…

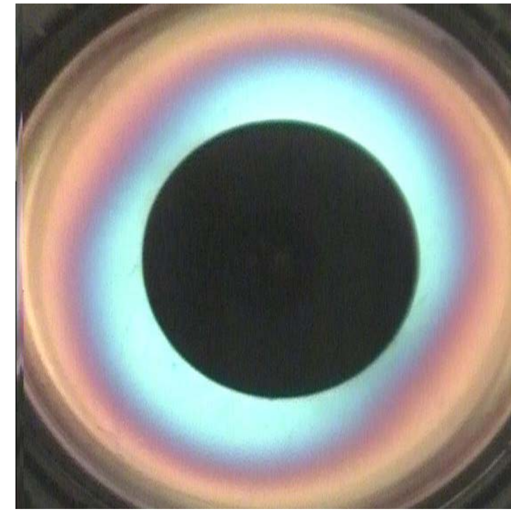
Atmospheric case study: sudden stratospheric warmings

Acknowledgements: Thomas Birner

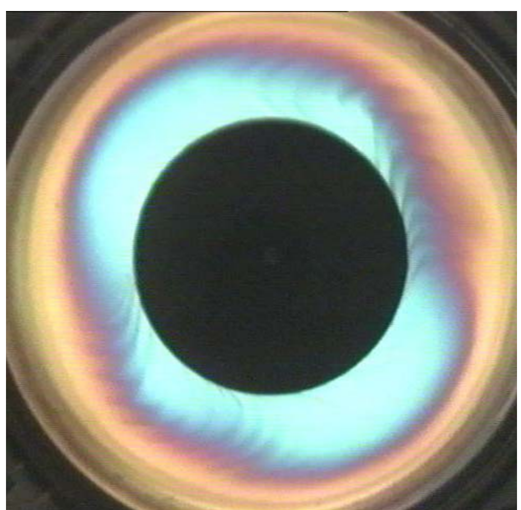
‘Noise’-induced transitions in the lab

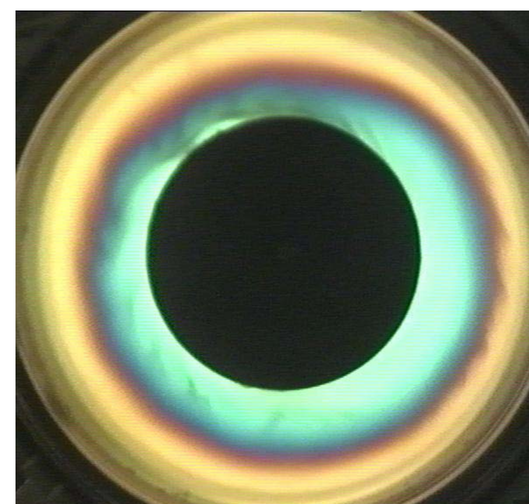
without gravity waves:



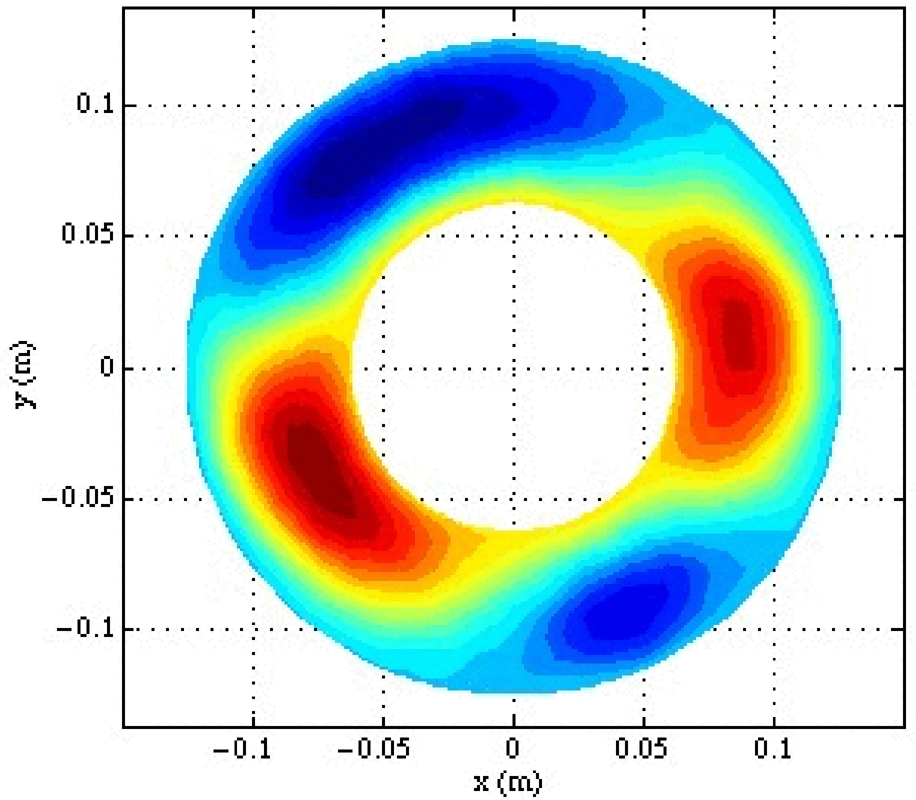


with gravity waves:



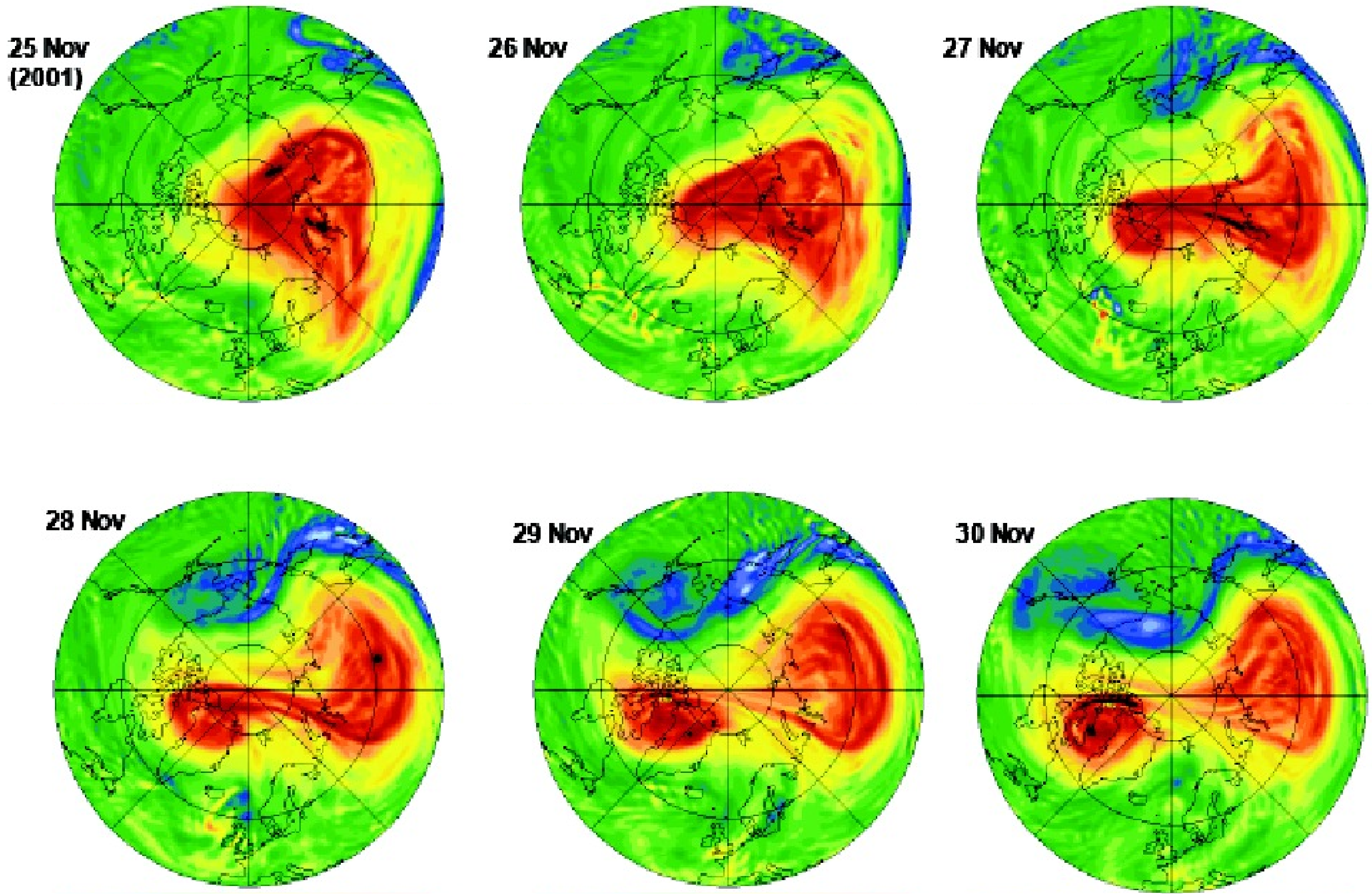


Noise-induced transition in a QG model with a stochastic GW parameterisation

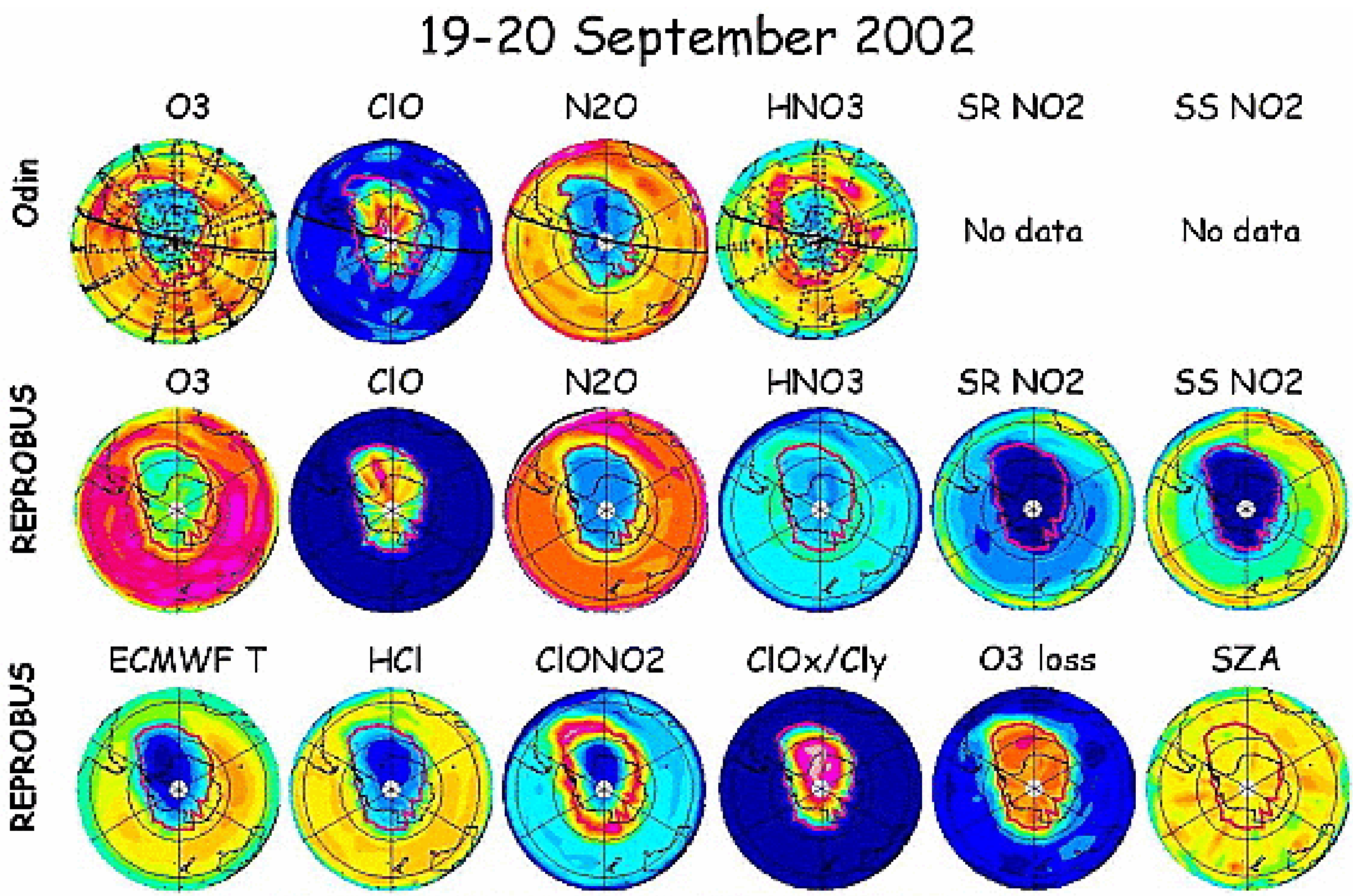


Williams et al. (2003)

Arctic polar vortex split



Antarctic polar vortex split



Ricaud et al. (2005)

Holton and Mass (1976) model

Quasi-geostrophic β-plane channel, 30-90°N, from tropopause to mesopause:

'linearised' QGPV equation: $$(\partial_t + \overline{u}\partial_x)\, q' + \beta'\partial_x\psi' \;+\; \frac{f_0^2}{\rho}\partial_z\left(\frac{\alpha\rho}{N^2}\partial_z\psi'\right) = 0$$

equation for zonal-mean flow: $$\partial_t\left[\partial_{yy}\overline{u} + \frac{f_0^2}{N^2\rho}\partial_z\left(\rho\partial_z\overline{u}\right)\right] = -\frac{f_0^2}{N^2\rho}\partial_z\left[\alpha\rho\partial_z\left(\overline{u} - U_R\right)\right] + \frac{f_0^2}{N^2}\partial_{yy}\left[\rho^{-1}\partial_z\left(\rho\overline{\partial_x\psi'\partial_z\psi'}\right)\right]$$

where $q' = \nabla^2\psi' + \frac{f_0^2}{\rho}\partial_z\left(\frac{\rho}{N^2}\partial_z\psi'\right)$ and $\beta' = \beta - \partial_{yy}\overline{u} - \frac{f_0^2}{\rho}\partial_z\left(\frac{\rho}{N^2}\partial_z\overline{u}\right)$

$$\begin{aligned}\overline{u}(y,z,t) &= U(z,t)\sin ly \\ \psi'(x,y,z,t) &= \mathrm{Re}\{\Psi(z,t)e^{ikx}\}e^{z/2H}\sin ly\end{aligned}$$

$l = 1$

$k = 2$

⇨ coupled equations for $U(z,t)$ and $\Psi(z,t)$

Ruzmaikin et al. (2003) model

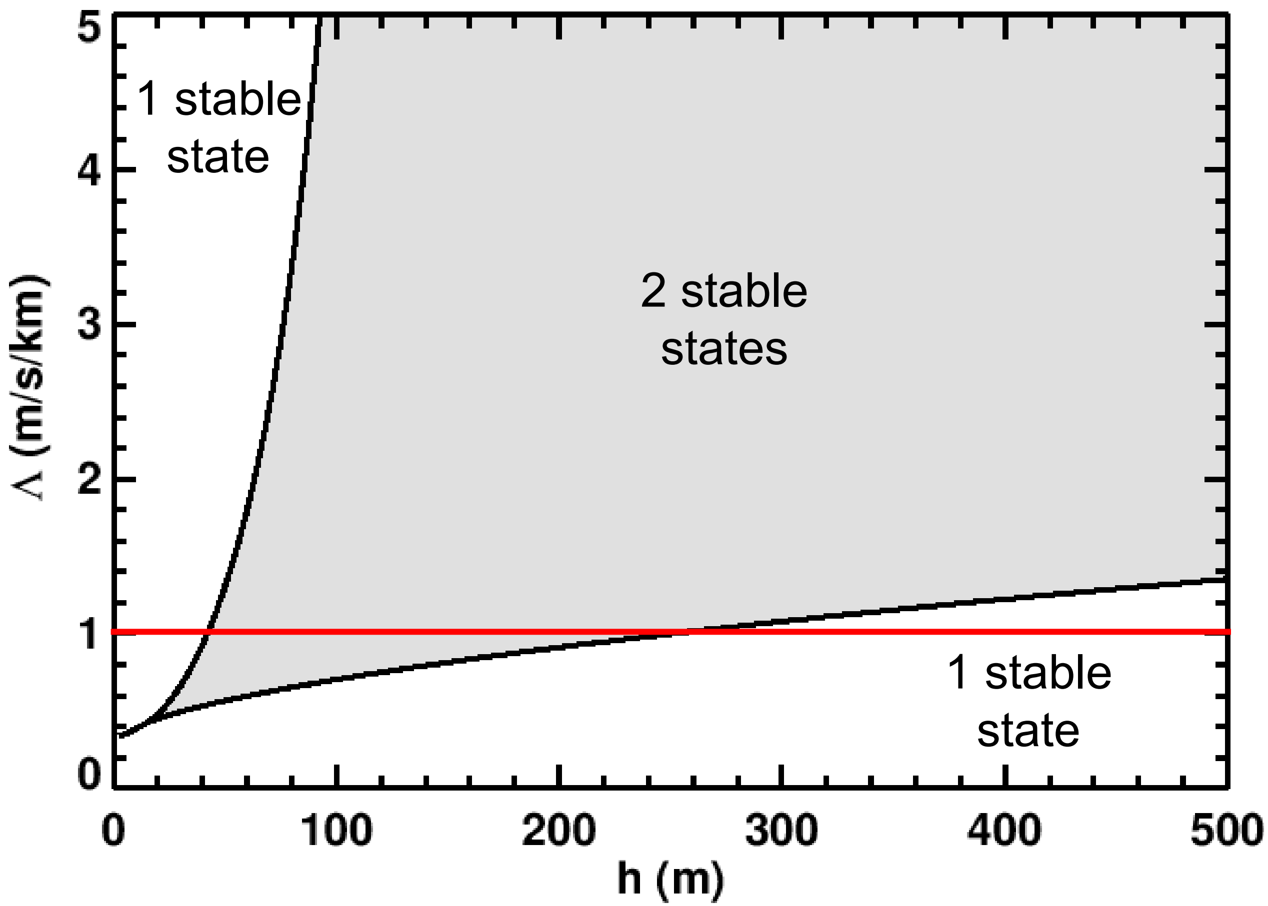
⇨ coarsely discretize HM76 in *z* (using 3 levels) and substitute $\Psi = X + iY$ to obtain 3 coupled equations for *X(t), Y(t), U(t)* at mid-height:

$$\begin{aligned} \dot{X} &= -\alpha_1 X - rY + sUY - \xi h \\ \dot{Y} &= -\alpha_1 Y + rX - sUX + \zeta hU \\ \dot{U} &= -\alpha_2(U - U_R) - \eta hY \end{aligned}$$

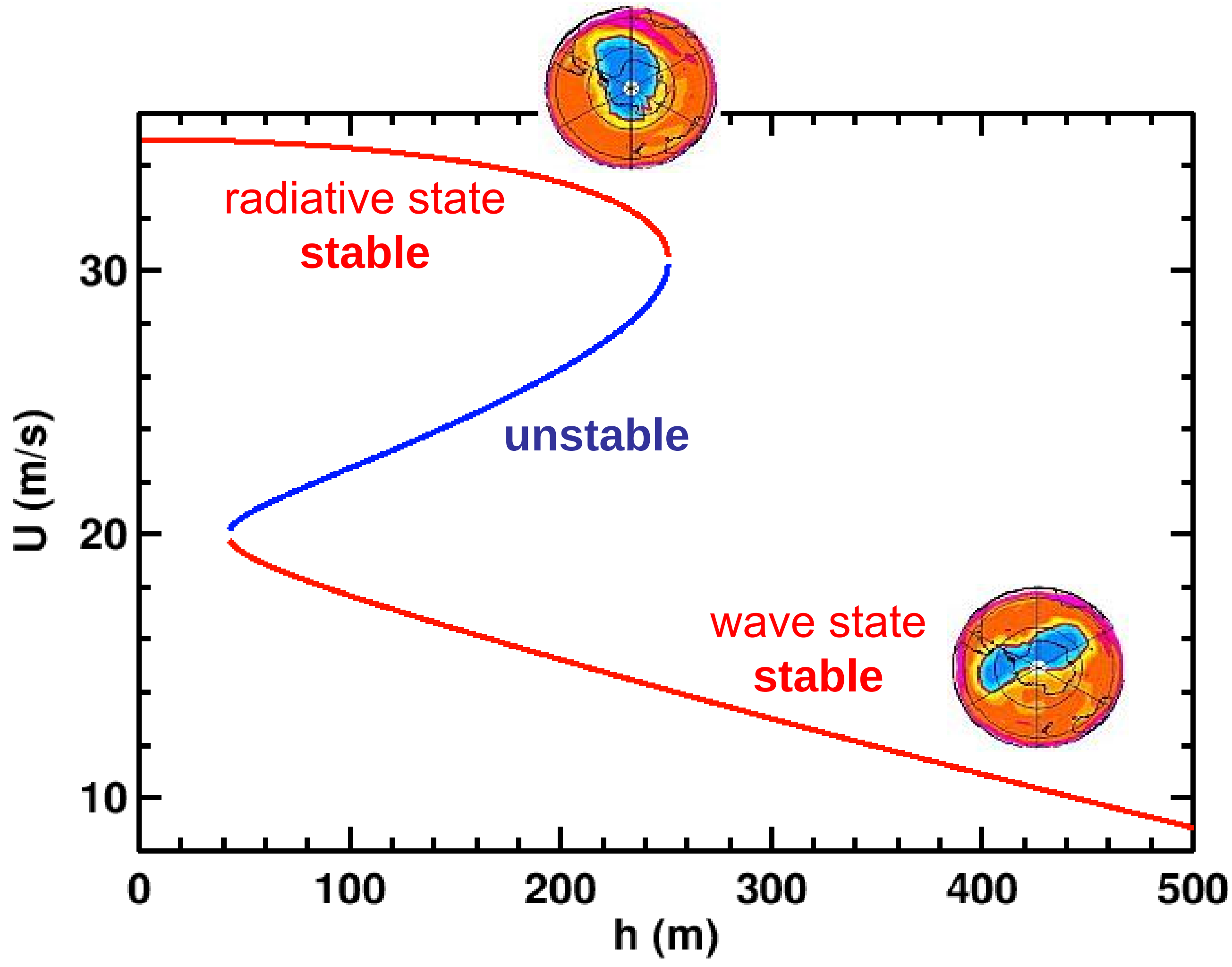
where *h* = planetary wave forcing (geopotential height perturbation at tropopause)

Λ = vertical shear of radiative equilibrium flow = $U_R / \Delta z$

Regime diagram



Equilibrium solutions for Λ = 1 m/s/km



Unresolved processes

- The atmosphere exhibits small-scale variability, e.g. induced by gravity wave momentum fluxes that are neither captured in our simple model nor in GCMs (in the latter they are of course parameterized to some extent).

- Since the gravity wave field is highly variable, conventional deterministic parameterizations are likely to be inadequate, suggesting the need for a stochastic approach.

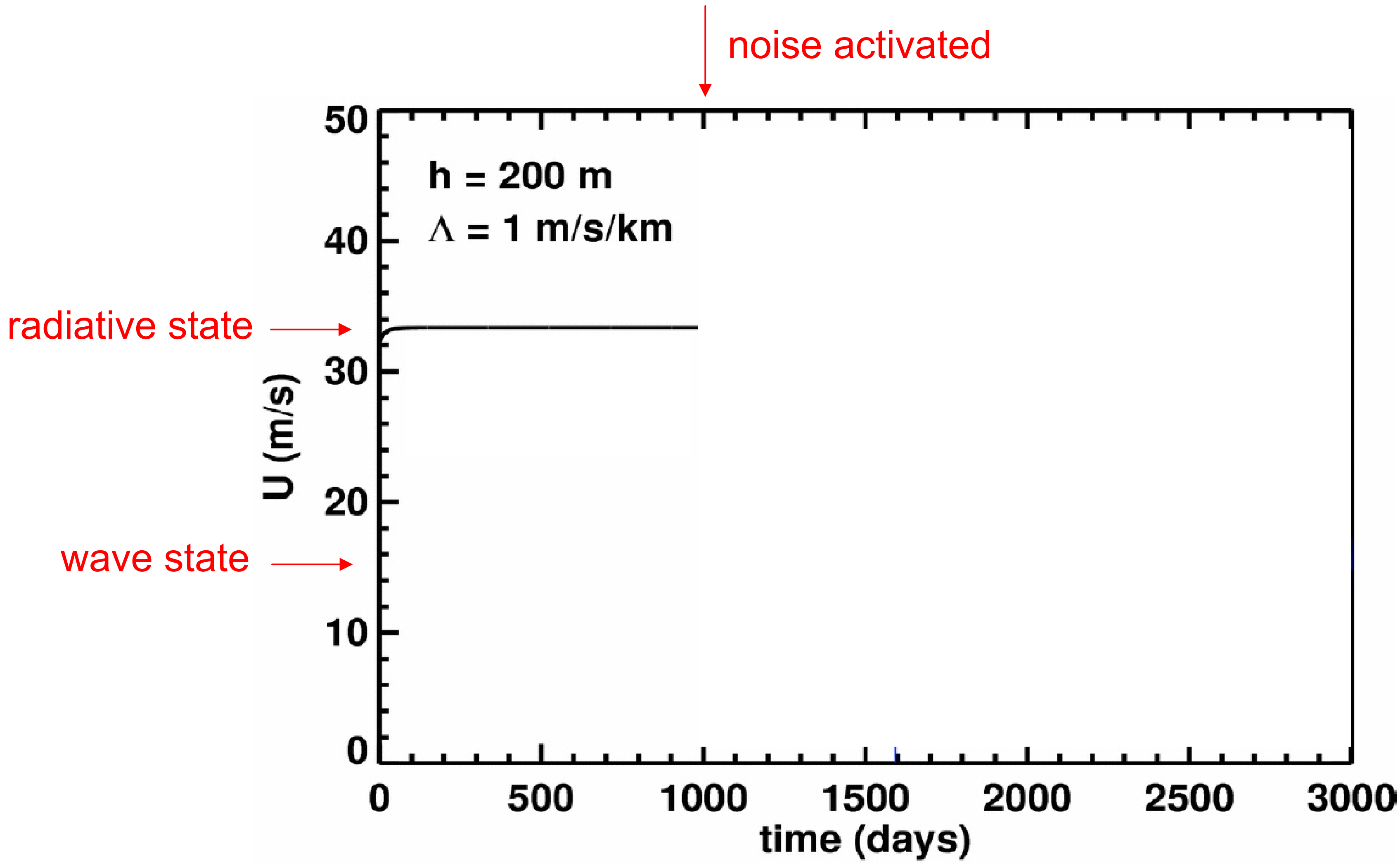
- A natural way to represent gravity wave drag is to introduce an additive noise term to the right-hand side of the evolution equation for U…

Ruzmaikin et al. (2003) + noise

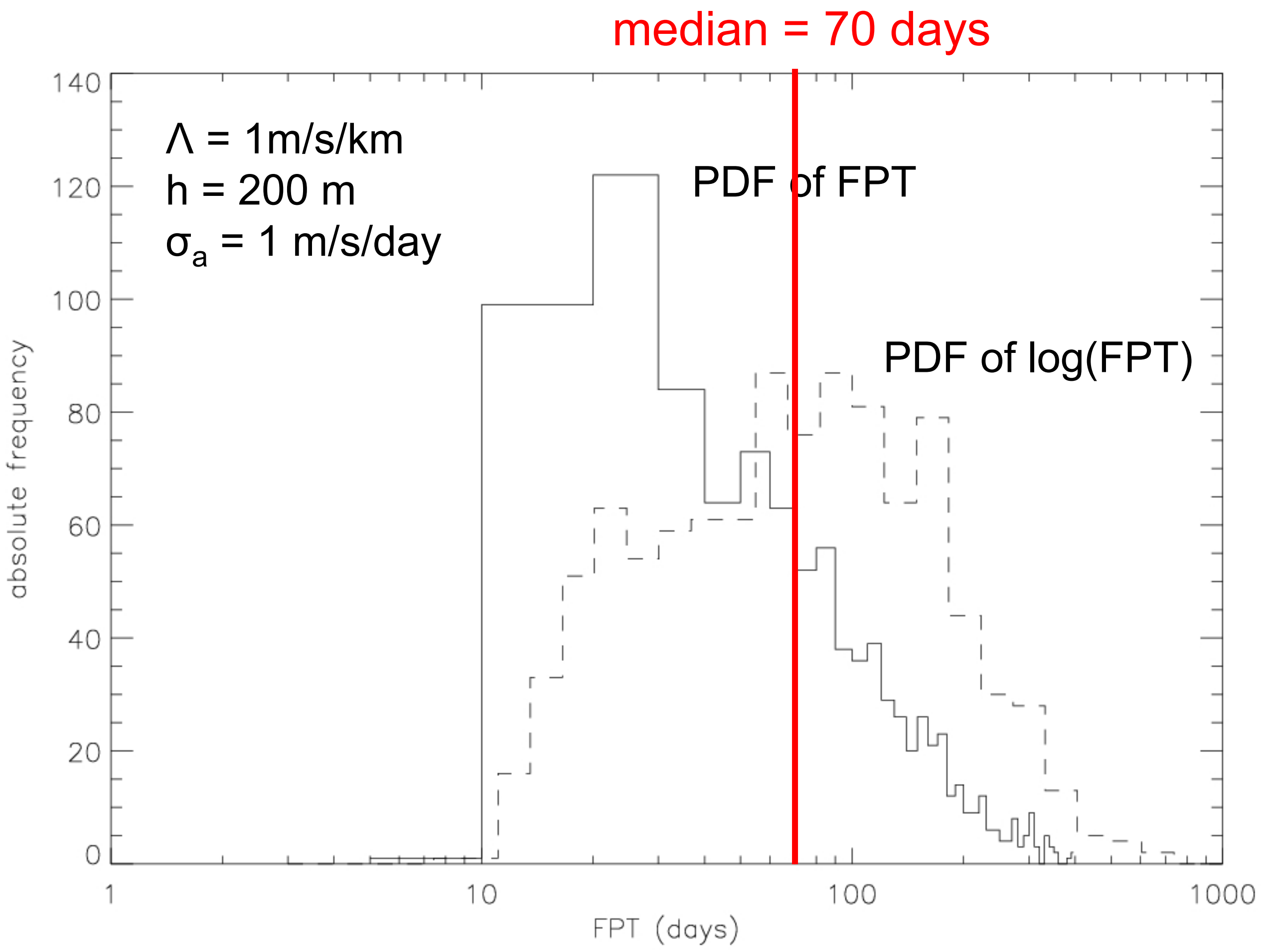
$$
\begin{aligned}
\dot{X} &= -\alpha_1 X - rY + sUY - \xi h \\
\dot{Y} &= -\alpha_1 Y + rX - sUX + \zeta hU \\
\dot{U} &= -\alpha_2 (U - U_R) - \eta hY + \chi_a
\end{aligned}
$$

Gaussian white noise: $\overline{\chi_a(t)\chi_a(t')} = \sigma_a^2 \delta(t - t')$

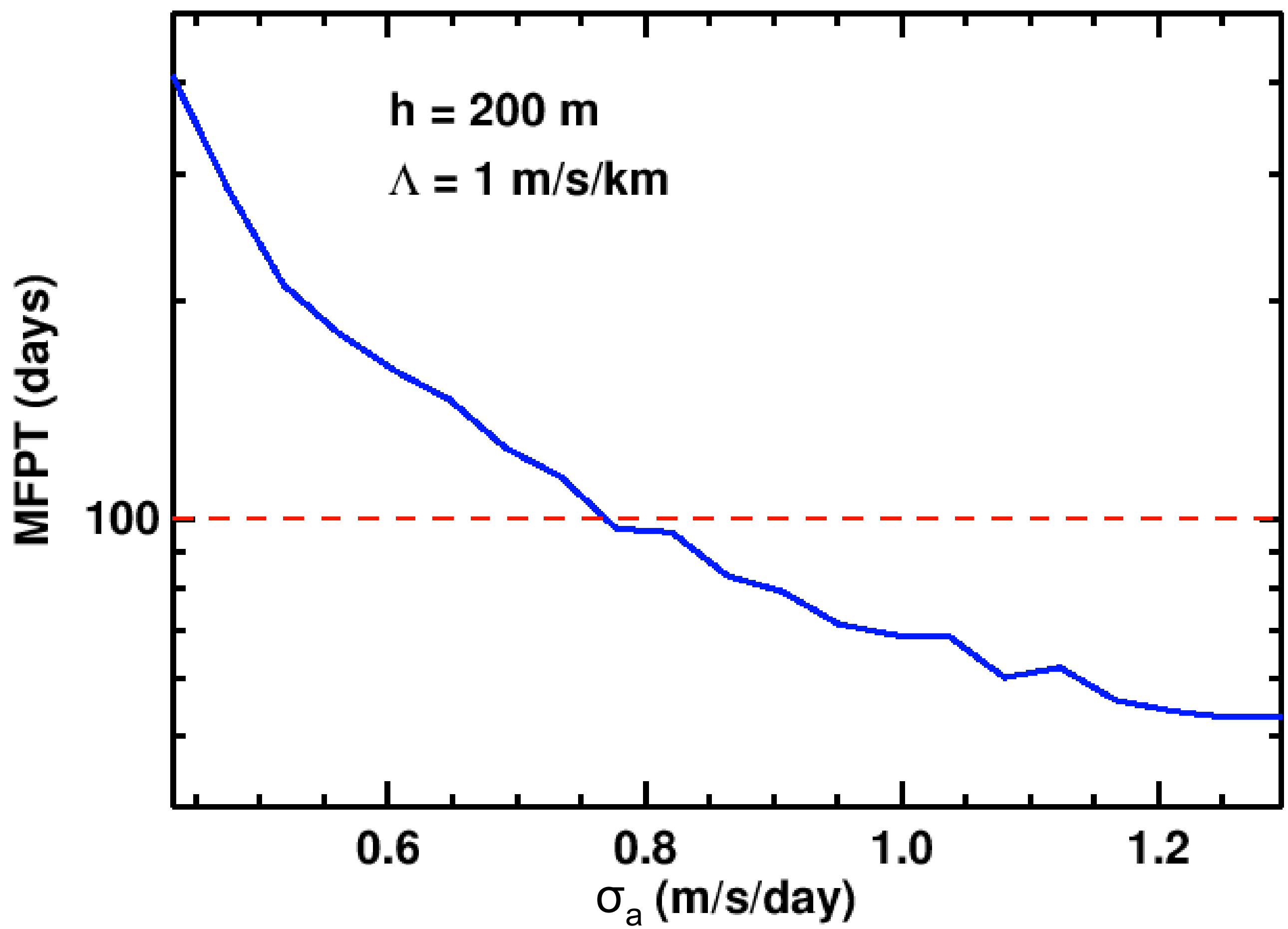
Typical solution for *U*(*t*)



Distribution of First Passage Times



Median First Passage Time (MFPT)



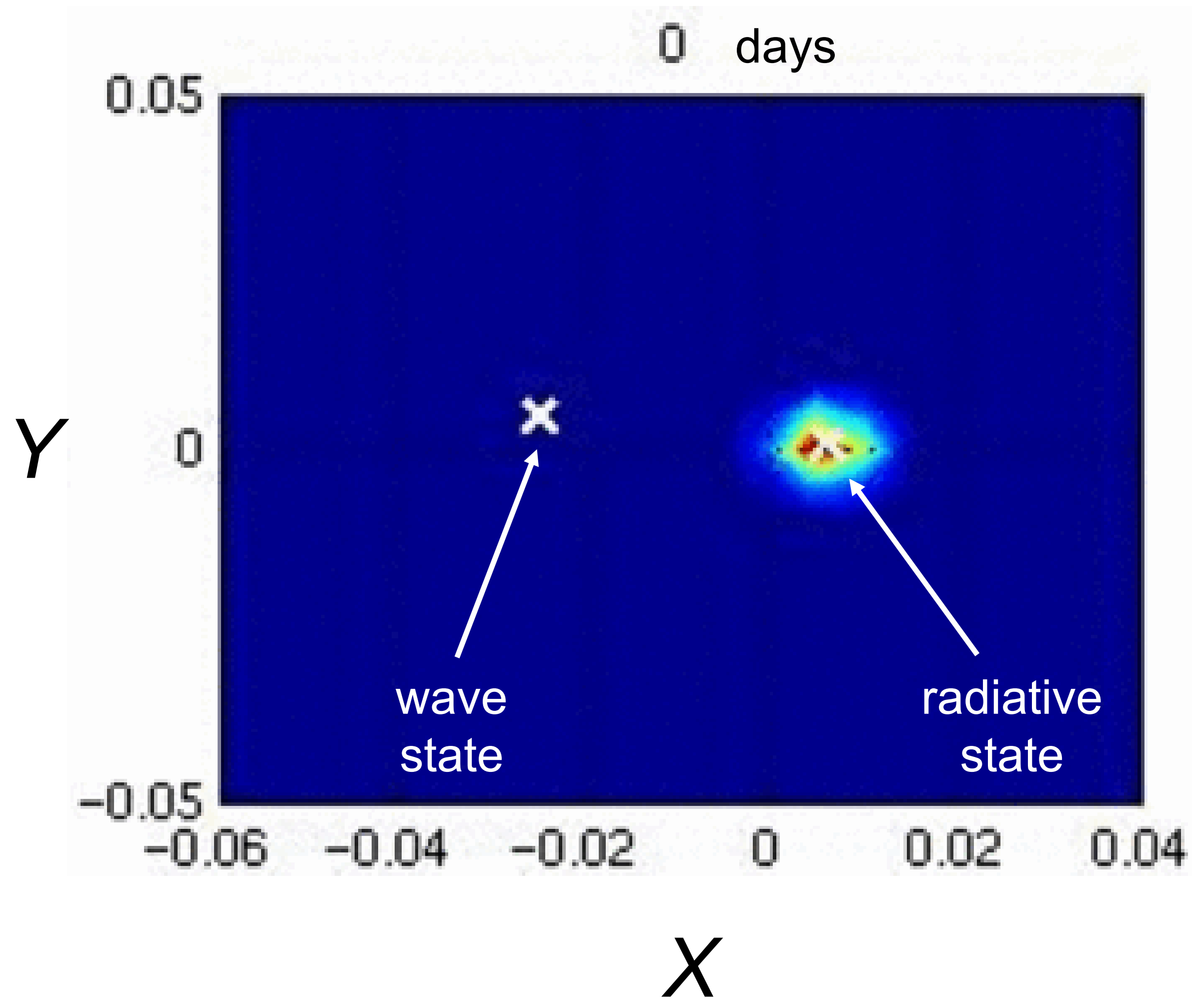
Fokker-Planck equation

For a system governed by $$\frac{d\mathbf{x}}{dt} = \mathbf{A}(\mathbf{x}) + \mathbf{B}(\mathbf{x})\boldsymbol{\eta}^M + \boldsymbol{\eta}^A$$

the F-P equation is $$\frac{\partial p(\mathbf{x},t)}{\partial t}$$
$$= -\sum_i \frac{\partial}{\partial x_i}\left[A_i + \alpha \sum_{j,k} (\sigma^M)^2 \left(\frac{\partial}{\partial x_j} B_{ik}\right) B_{jk}\right] p(\mathbf{x},t)$$
$$+ \frac{1}{2}\sum_{i,j} (\sigma^M)^2 \frac{\partial^2}{\partial x_i \partial x_j} (\mathbf{B}\mathbf{B}^{\mathrm{T}})_{ij} p(\mathbf{x},t)$$
$$+ \frac{1}{2}\sum_i (\sigma_i^A)^2 \frac{\partial^2}{\partial x_i^2} p(\mathbf{x},t),$$

(e.g. Sura, 2002; Sura et al., 2005)

Evolution of $\overline{p(\mathbf{x},t)}^{U}$ when σ_a = 3 m/s/day



SSW case study: conclusions

- gravity wave ‘noise’-induced regime transitions occur in laboratory fluid flows
- polar vortex splits may also have a possible interpretation as gravity wave ‘noise’-induced transitions
- such transitions are unlikely to be captured by deterministic gravity wave drag parameterisations in GCMs
- motivates stochastic parameterisation

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