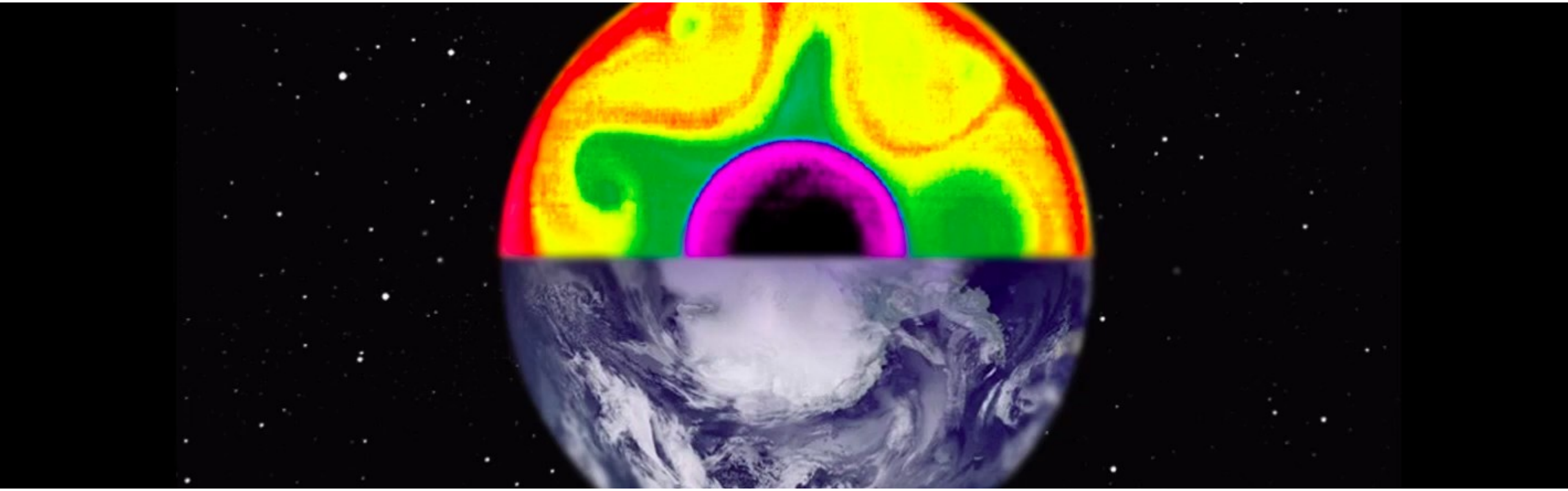
# Modeling atmospheric and ocean dynamics in the lab



**Miklós Vincze**
*(von Kármán Laboratory for Environmental Flows; ELKH-ELTE Theoretical Physics Research Group)*

Tamás Bozóki *(SZTE)*, Mátyás Herein *(ELKH-ELTE)*, Uwe Harlander *(BTU)*, Costanza Rodda *(BTU)*, Cathrine Hancock *(FSU)*, Kevin Speer *(FSU)*

Particle Physics Seminar 10/18/2022

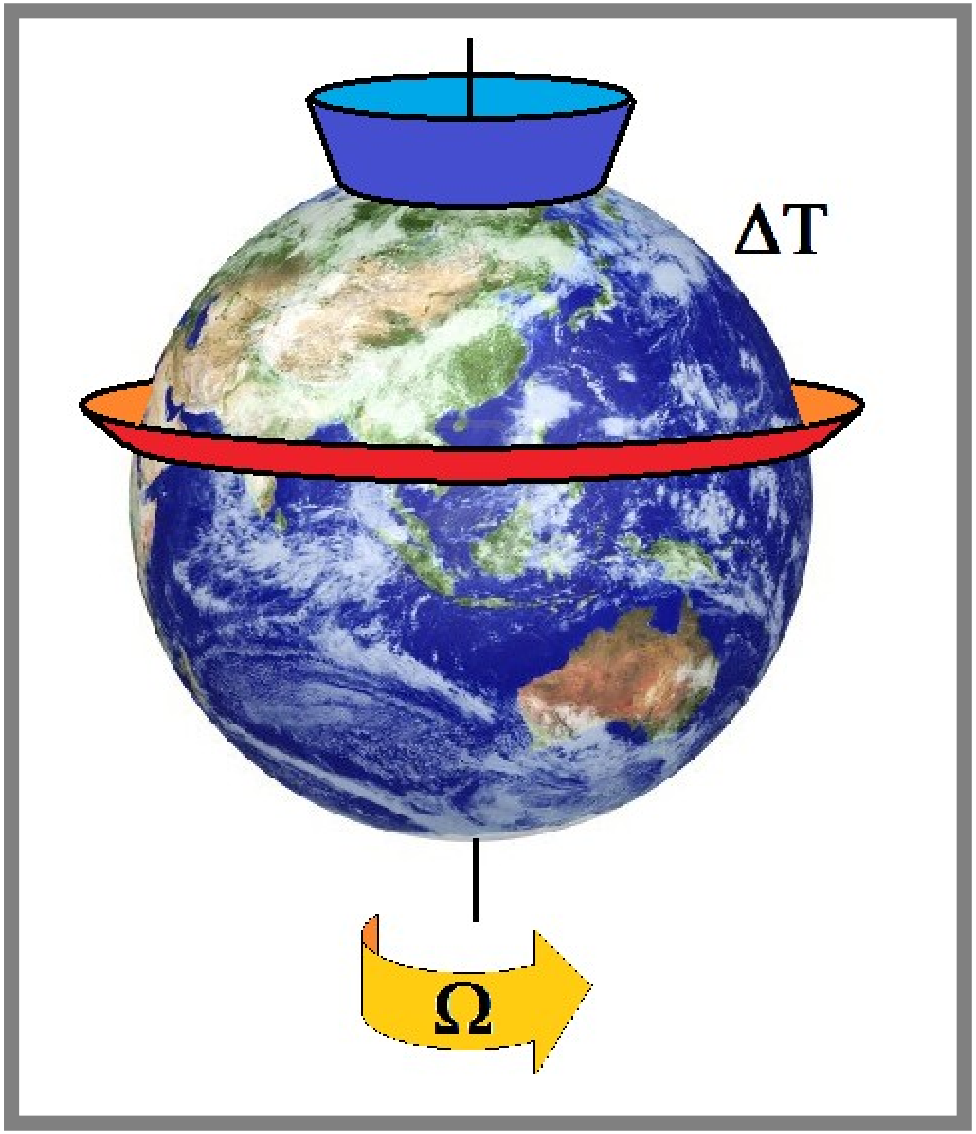
The test of all knowledge is experiment. Experiment is the sole judge of scientific truth.

— Richard P. Feynman —

# The minimal model of the weather system/ ocean circulation (mid-latitudes)

- Rotation + meridional temperature difference = weather (or ocean circulation)

- **Idea:** Let's construct minimalistic laboratory analogs to better understand the basic underlying dynamics



# A minimal model

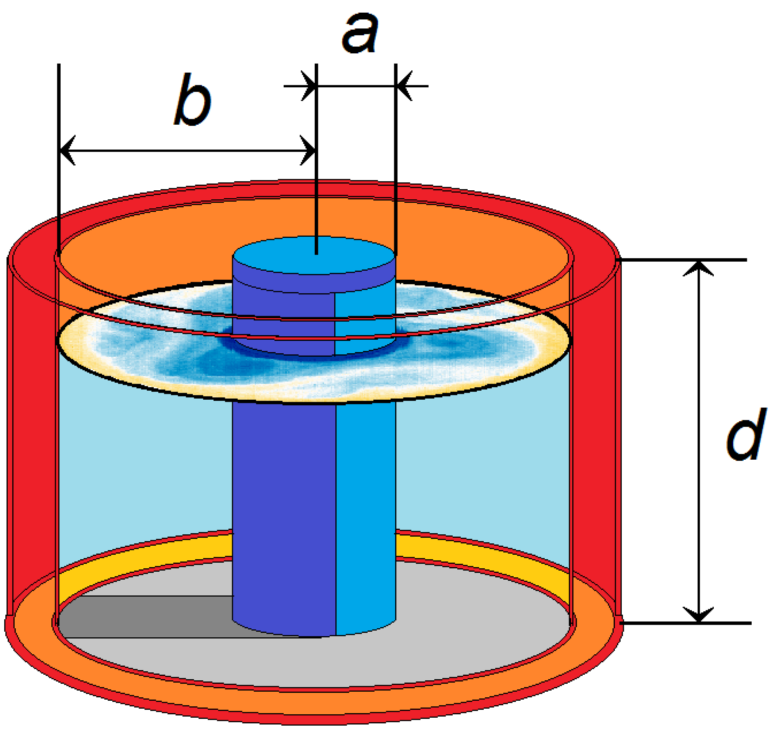
- **A differentially heated cylindrical tank, mounted on a turntable. "Rotating annulus"**

**Dimensions (Cottbus):**

*a = 45 mm*

*b = 120 mm*

*d = 135 mm*



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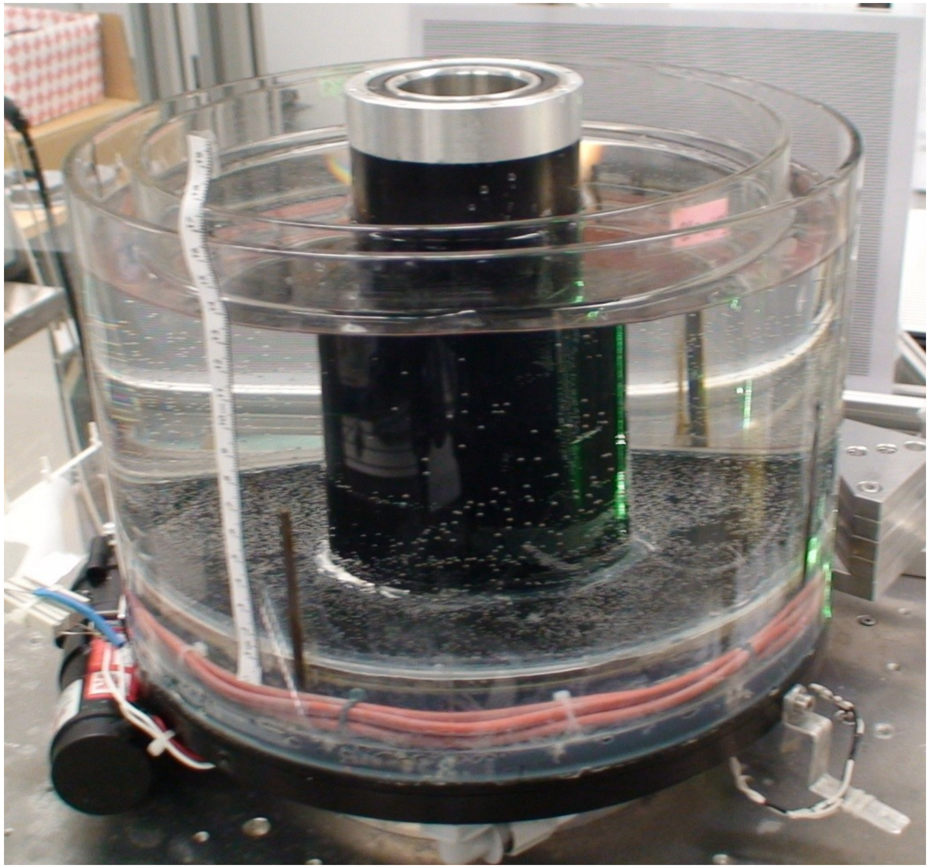

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# A minimal model

- **A differentially heated cylindrical tank, mounted on a turntable.** **"Rotating annulus"**

**Dimensions (Budapest):**

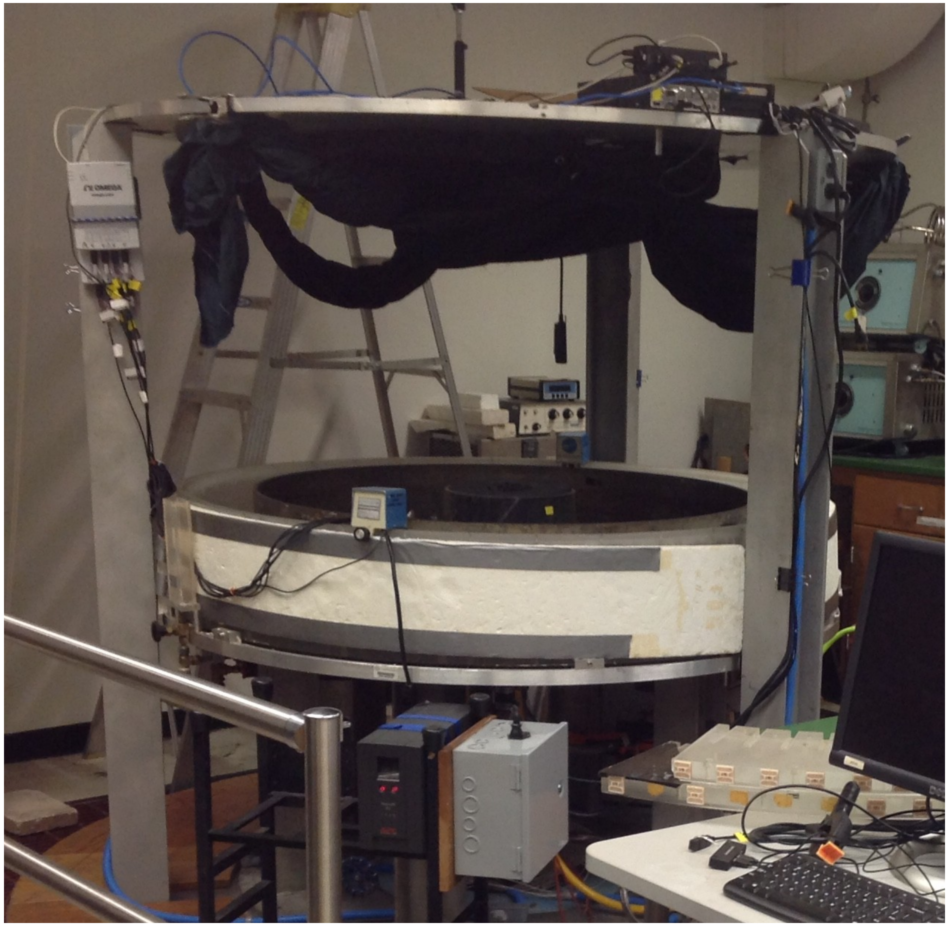
$a = 45\ mm$

$b = 150\ mm$

$d = 40\ mm$

# A minimal model

- **A differentially heated cylindrical tank, mounted on a turntable. "Rotating annulus"**



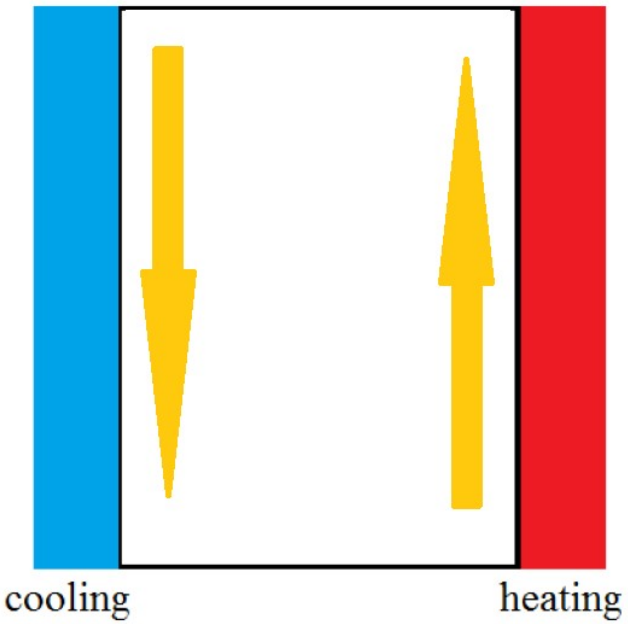
**Dimensions (Tallahassee):**

$a = 160\ mm$

$b = 610\ mm$

$d = 80\ mm$

# Basics: baroclinic instability



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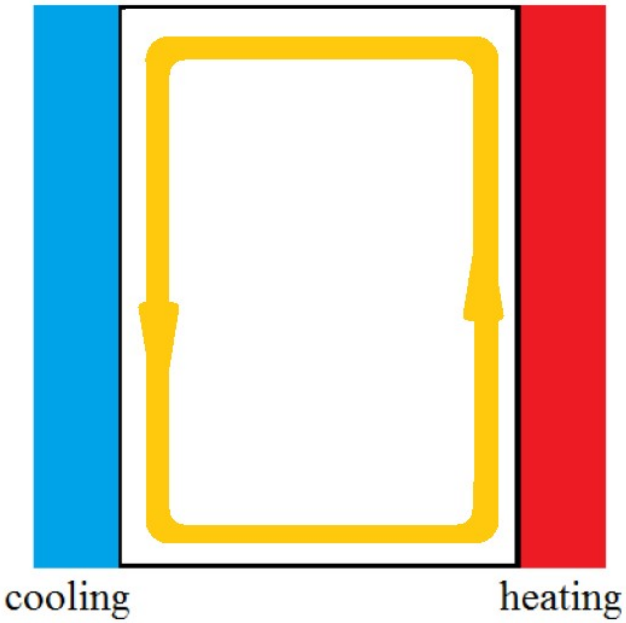


**"Sideways convection" – no threshold in ΔT**
**(i.e. No 'critical Rayleigh number')**

***Any*** **temperature difference can initiate the flow**

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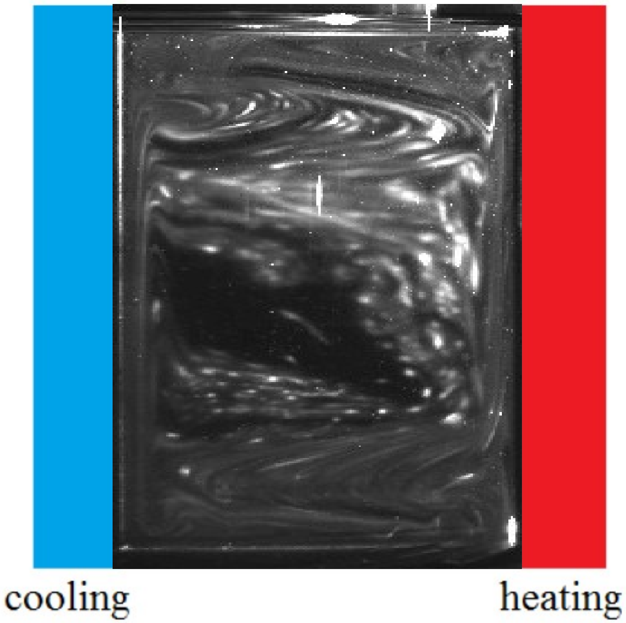


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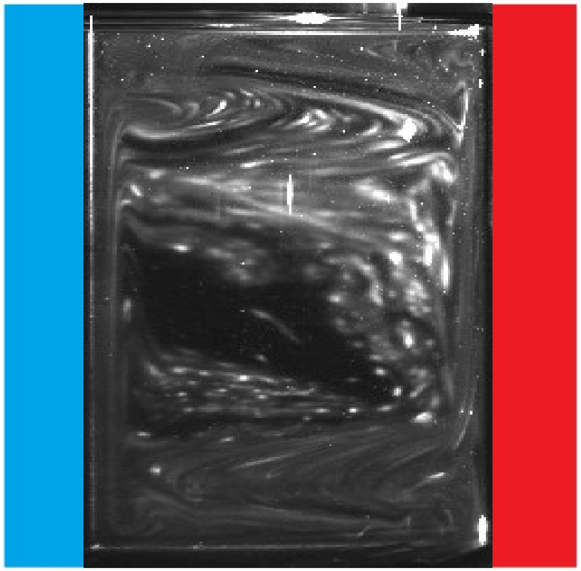
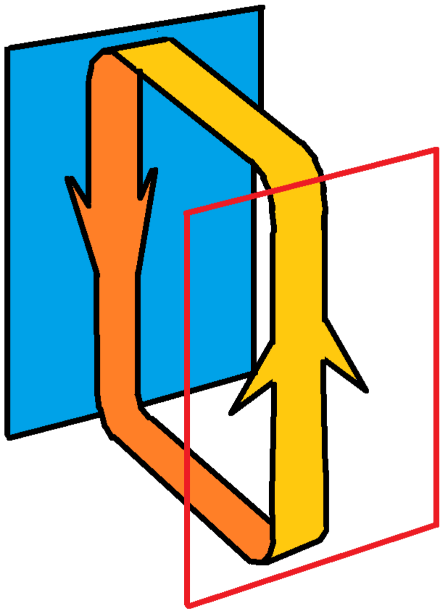


cooling heating



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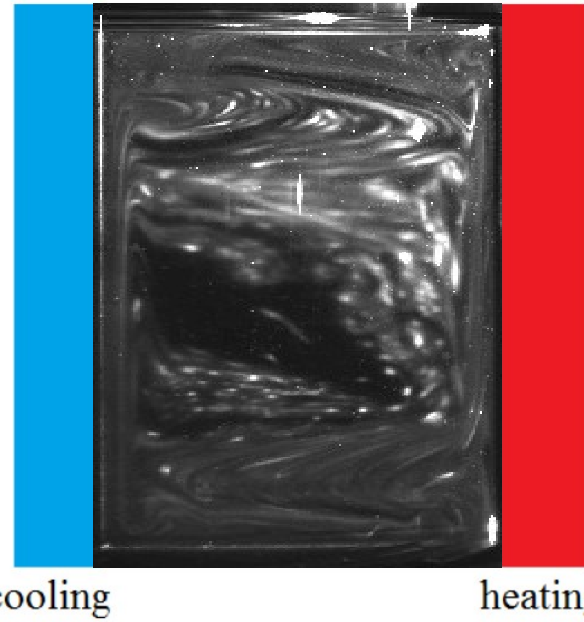
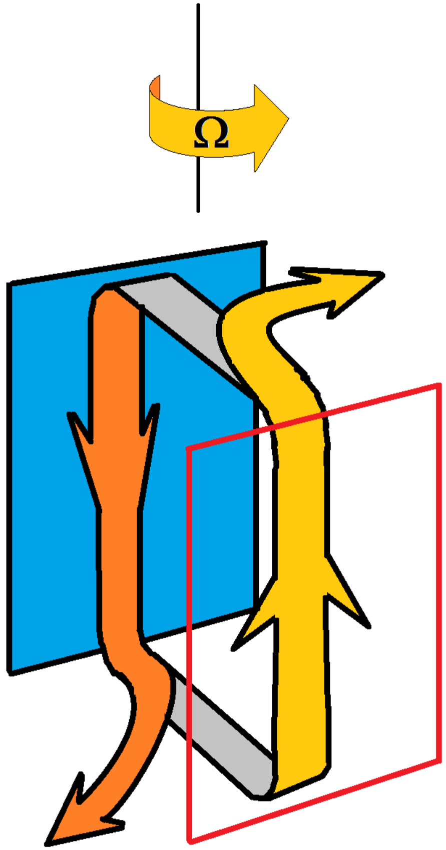
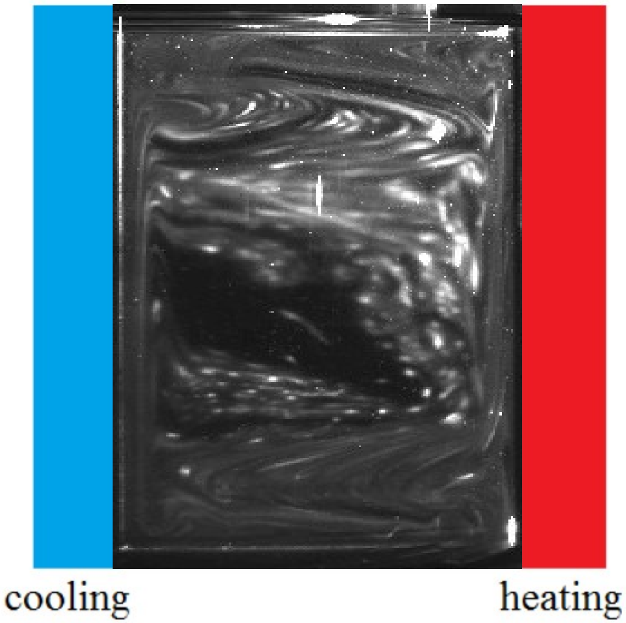



**Rotation!**




$$\boxed{-2\Omega\vec{e_z} \times \vec{u}}$$

# Baroclinic instability





**Rotation!**

**Zonal flow (thermal wind)**

**Geostrophic theory:**
**Tilted density surfaces**

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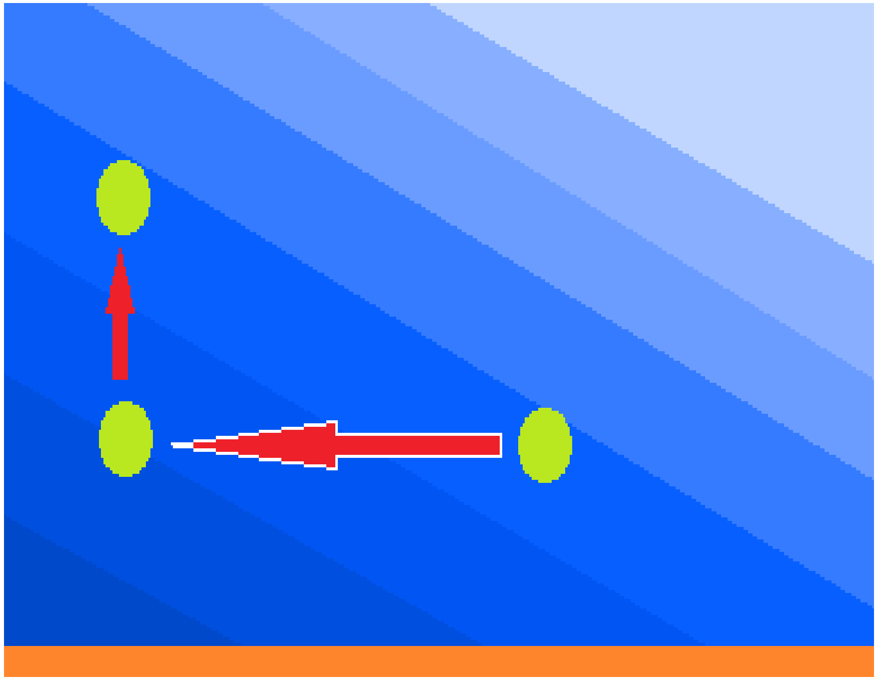

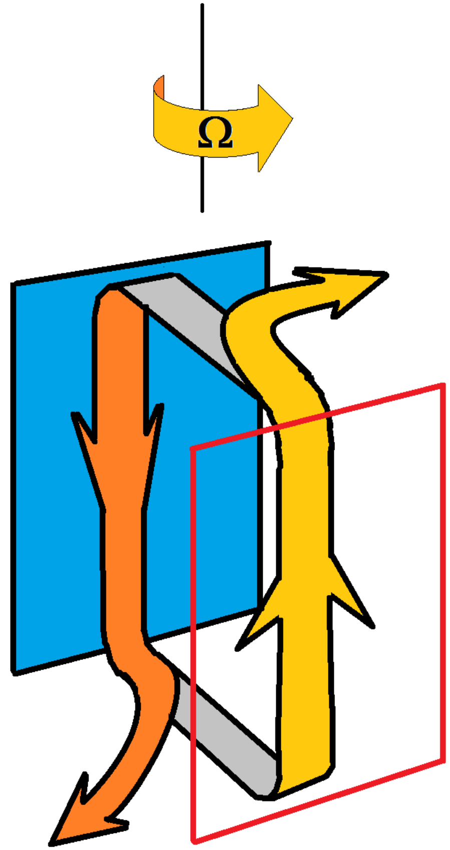


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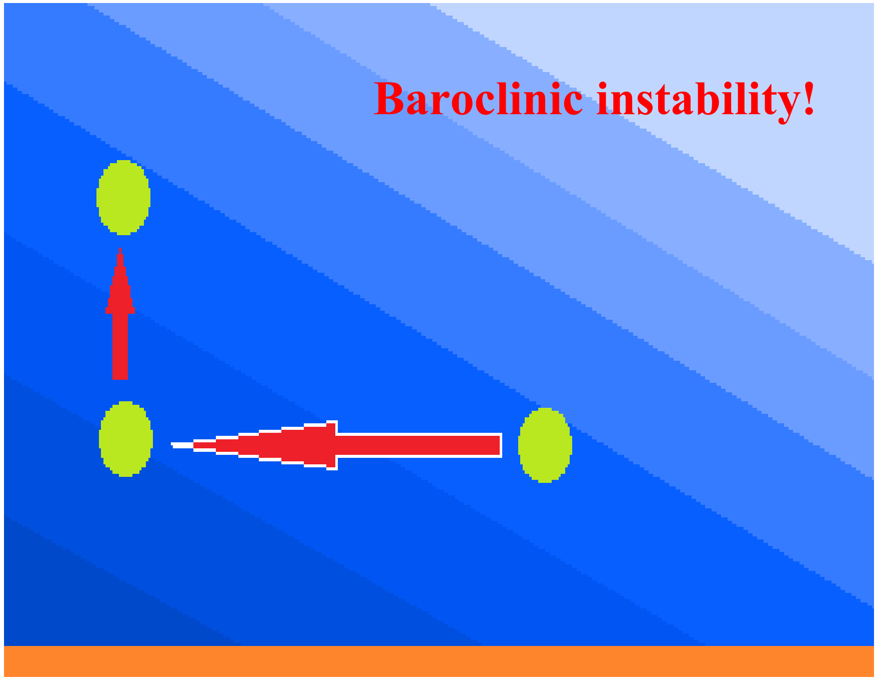
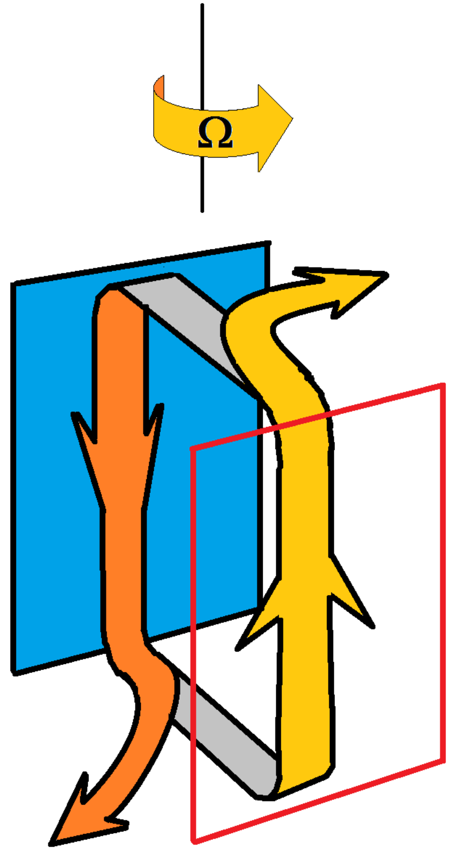
# Baroclinic instability




**Rotation!**

**Zonal flow (thermal wind)**

**Geostrophic theory:** **Tilted density surfaces**




$$\boxed{-2\Omega\vec{e_z}\times\vec{u}}$$

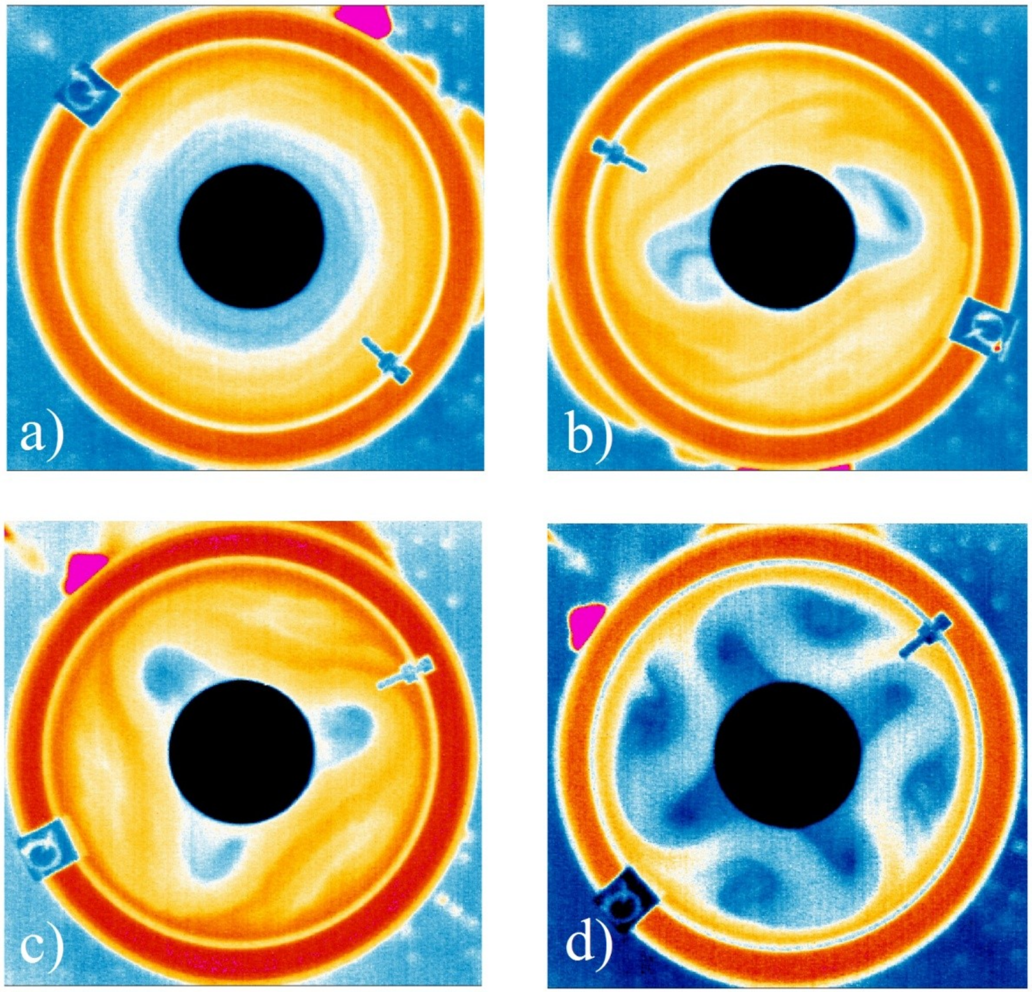
# Baroclinic waves

control parameters:

- rotation rate, radial temperature difference

*Different planetary atmospheres can be modelled*

- Venus: slow rotation, zonal flow
- Earth: fast rotation → Coriolis effect, cyclones ("weather")



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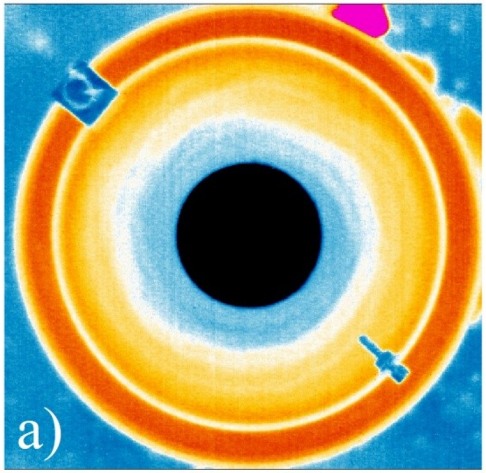
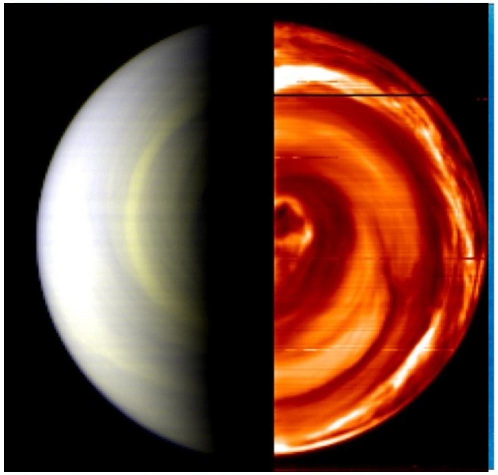
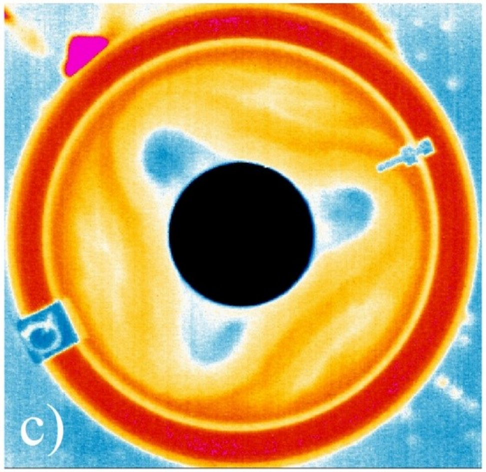
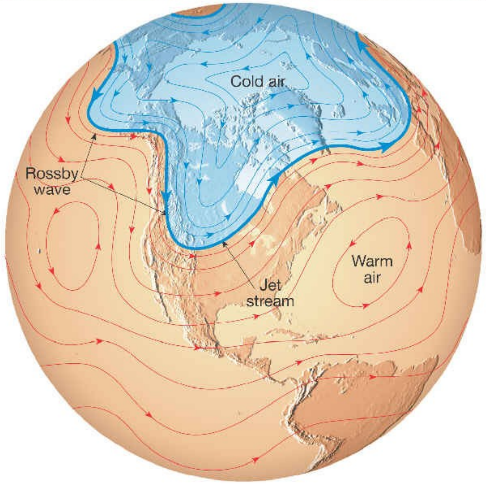
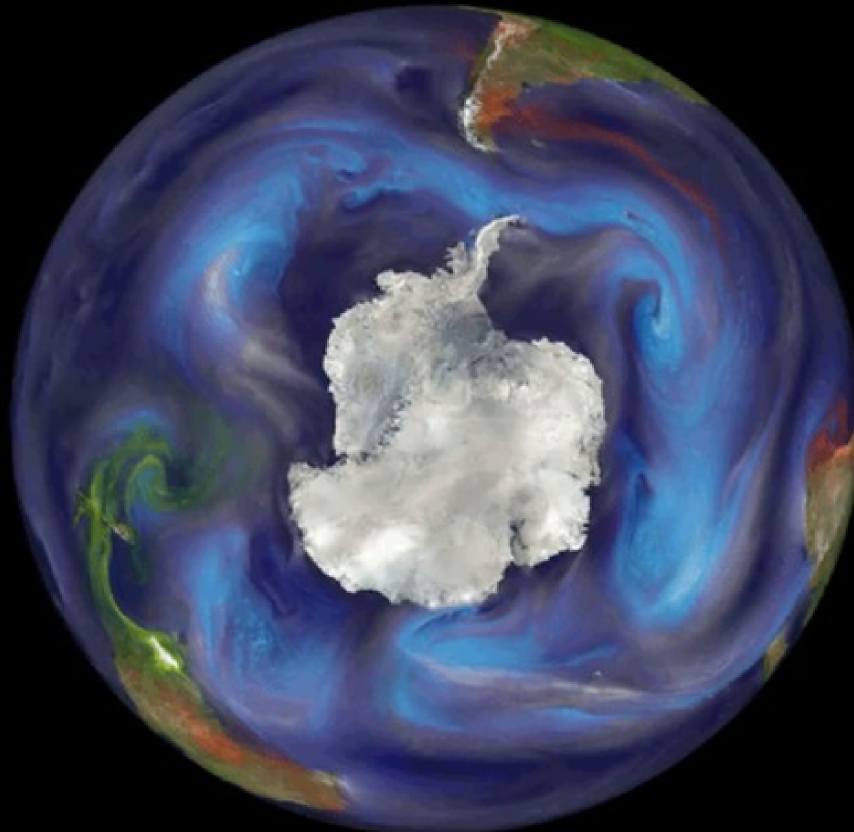
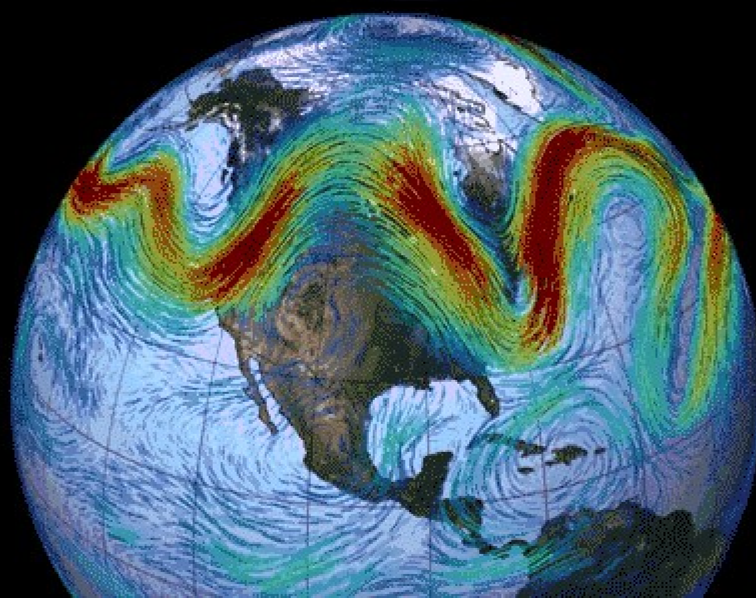


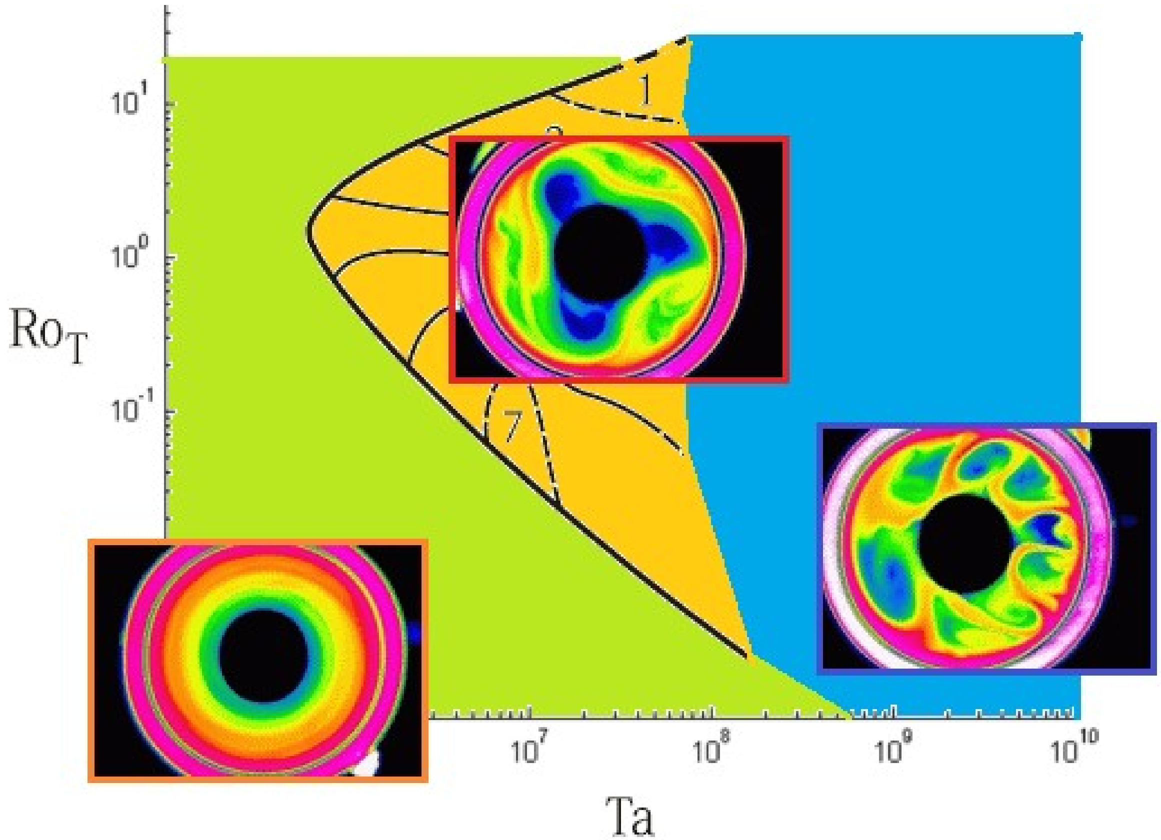






# The regime diagram (after Fultz)




$$Ta = \frac{4 \cdot \Omega^2 \cdot (b-a)^5}{\nu^2 \cdot d}$$

$$Ro = \frac{g \cdot d \cdot \alpha \Delta T}{\Omega^2 \cdot (b-a)^2}$$

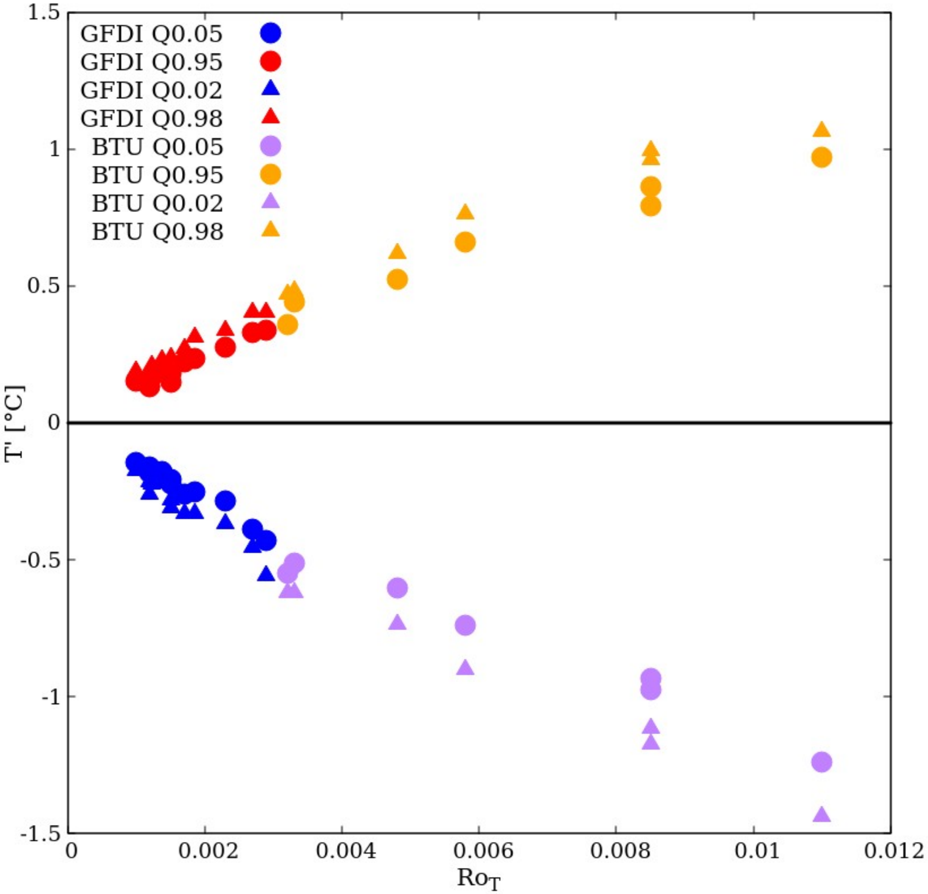
# “Meridional” temperature contrast vs. temperature fluctuations

- Large annulus → very small Rossby numbers (quasigeostrophic turbulence)
- Temperature time series from fixed locations

- **Question:** How do the statistical properties of extreme events in this model weather (and climate) depend on the meridional temperature contrast?

# "Meridional" temperature contrast vs. temperature fluctuations

- The distribution of fluctuations widens with the increasing temperature contrast → **increasing Rossby number (~ ΔT).**



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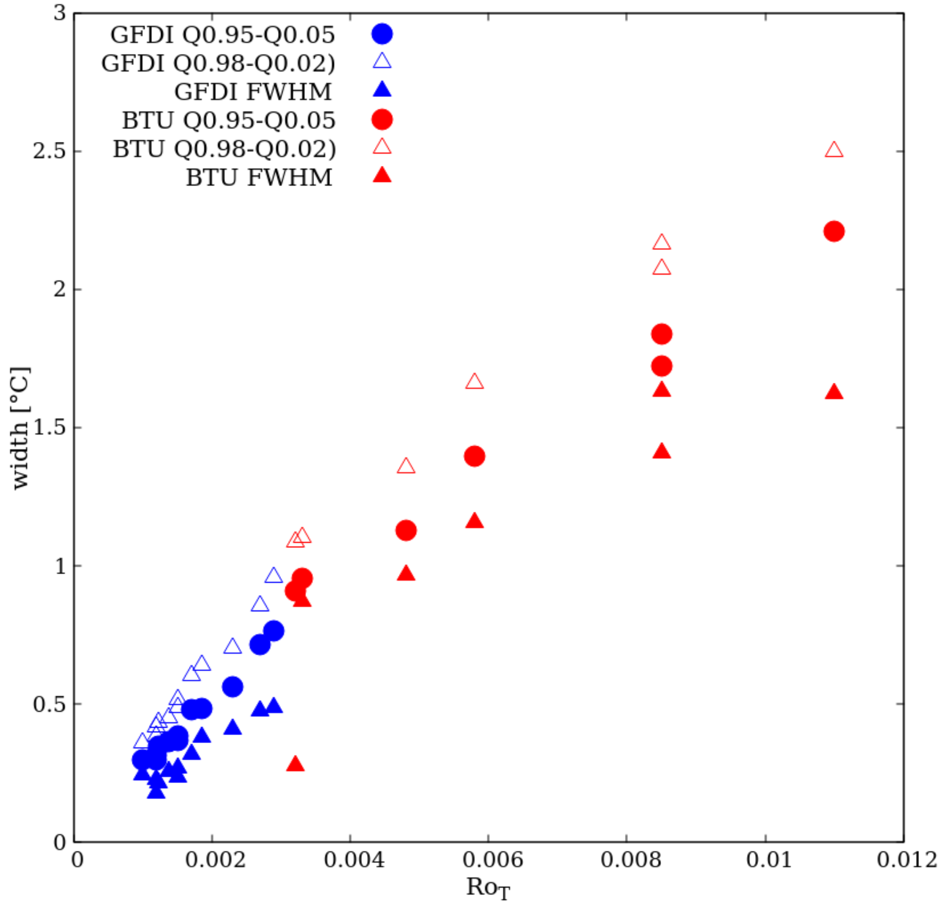


# “Meridional” temperature contrast vs. temperature fluctuations

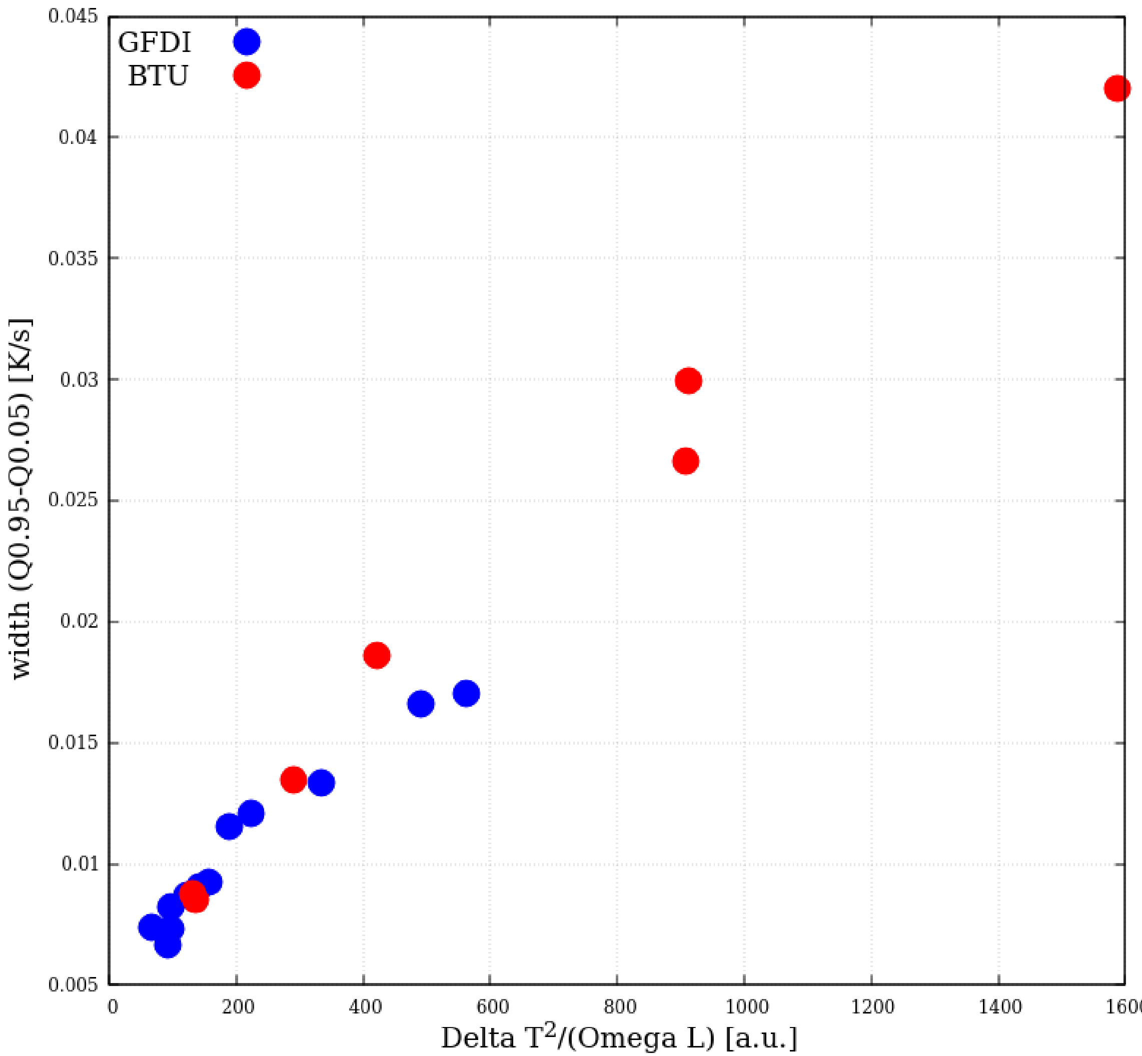
Taking the histograms of the (smoothed)

time derivatives

of the temperature fluctuation time series, and their “width” based on the Q0.05 and Q0.95 quantiles

→ **data collapse via *advective scaling***

(dT/dt ~ $U \cdot \nabla T$ ~ $\Delta T^2/(\Omega L)$)



# “Meridional” temperature contrast vs. temperature fluctuations

**Question:** How do the statistical properties of extreme events in weather and climate depend on the meridional temperature contrast?

**Partial answers:**

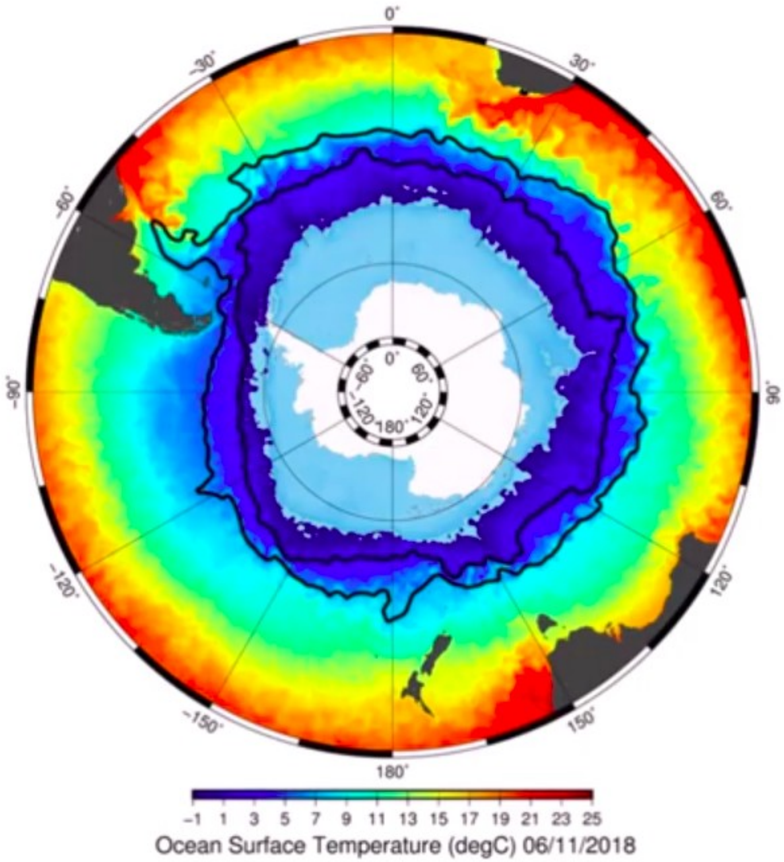
**If only Rossby wave dynamics was involved (minimum mid-latitude atmosphere), a marked polar amplification would yield**

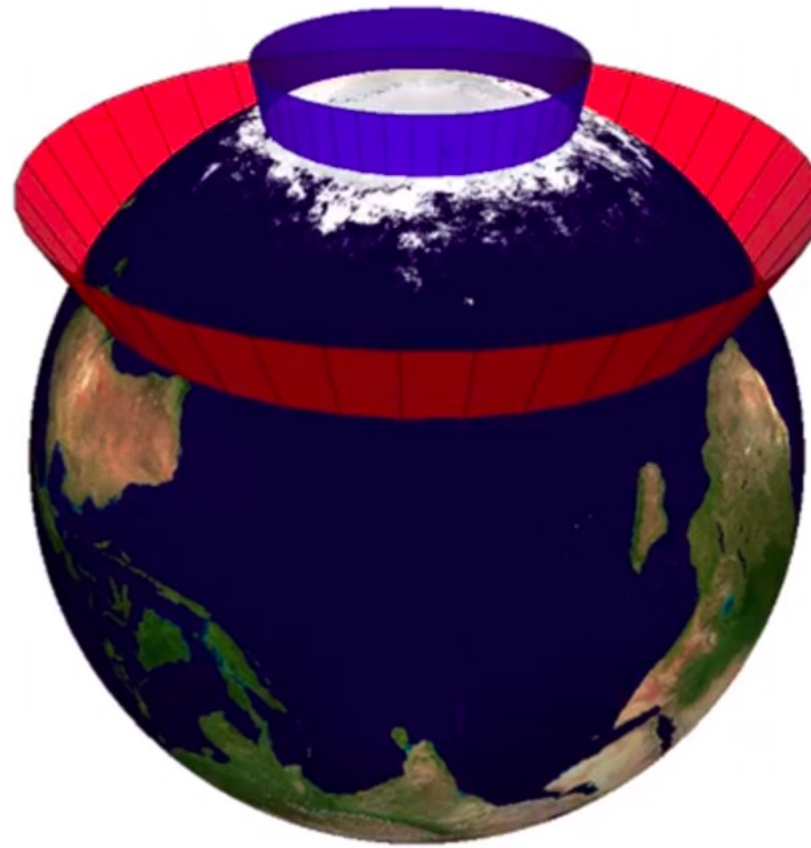
• a narrower distribution of temperature fluctuations, whose width **scales with $\sim \Delta T$**

• generally smaller “jumps” in temperature, **scaling with $\sim \Delta T^2$**

• the correlation timescale (“persistence”) of the weather would significantly increase, **scaling with $\sim 1/\Delta T$**

# The present-day ACC: temperature field

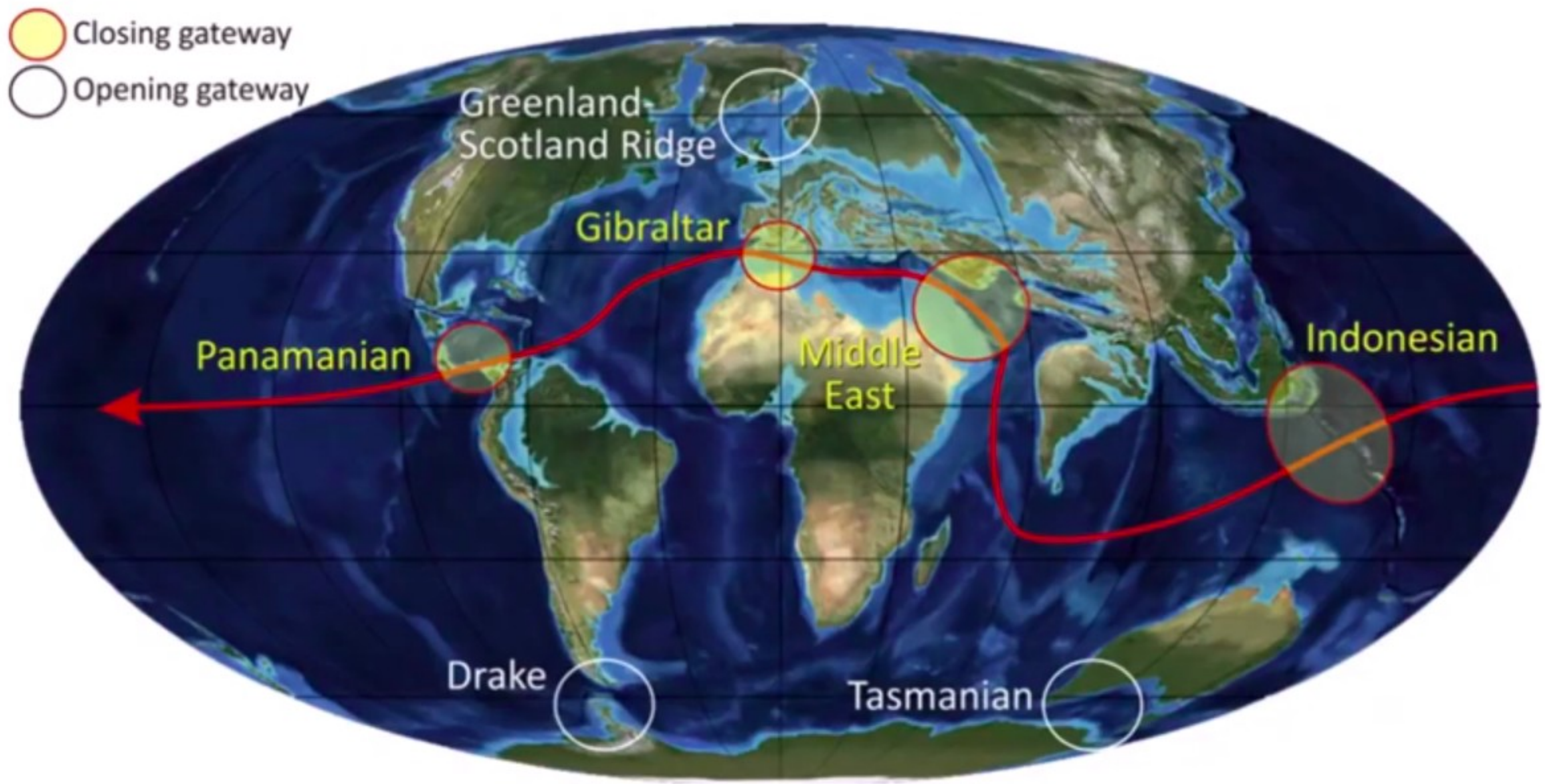


Large meridional SST gradient, accompanying the eastward geostrophic current.

The "minimalistic approach" to the lateral thermal boundary conditions – differential heating (in reality the scale of the ACC jet is set by the β-effect: Rhines scale)

# Motivation: The eocene-oligocene transition (EOT) ~ 34 Mya




M. Rebesco et al., Marine Geology 352 (2014)

# Motivation: The eocene-oligocene transition (EOT)

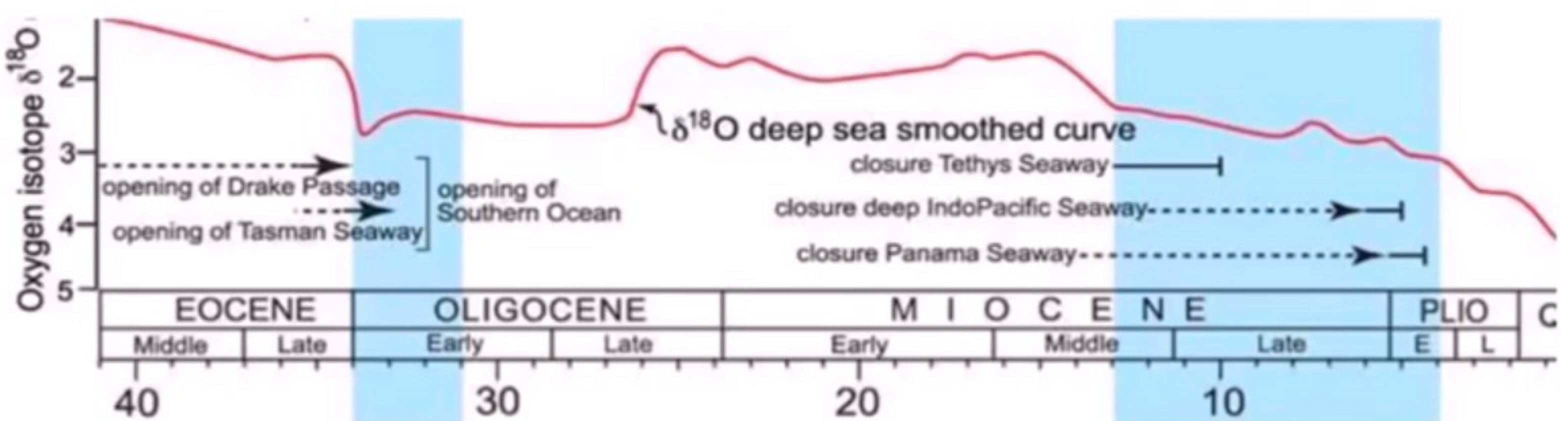
- Rapid onset of glaciation of Antarctica ca. Mya (Coxall et al., 2005)

- Kennett (1977): this major cooling episode was triggered by the opening of Drake Passage. (DP opening → ACC → isolating Antarctica)

- This has been challenged since then: maybe long-term decrease in atmospheric CO2 level was the main driver of Antarctic glaciation (DeConto and Pollard, 2003, Pearson et al., 2009)

- Impact events! (Ivany et al., 2000)

- **What do we do?** Experimental minimal modeling ("toy model") of the pre-EOT overturning of the Southern hemisphere.




Steerman et al., Syst. Biol. 58(6):573–585, 2009

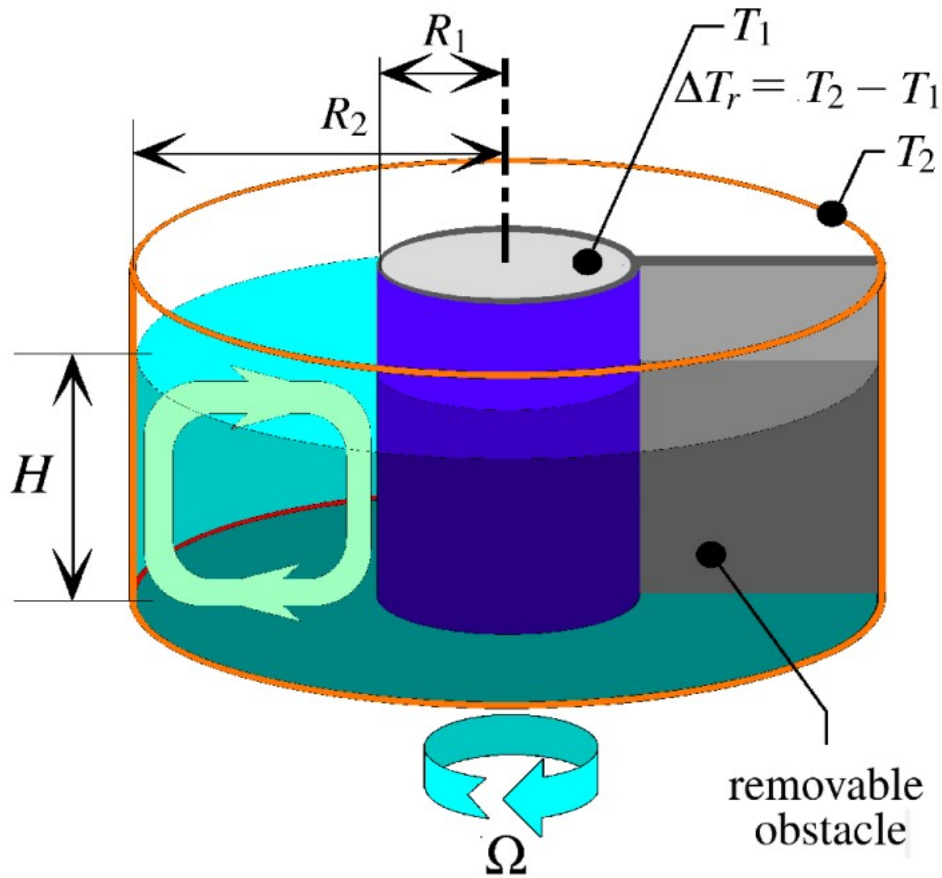
“Closing the Drake Passage” with a removable radial barrier

$R_1 = 4.5$ cm

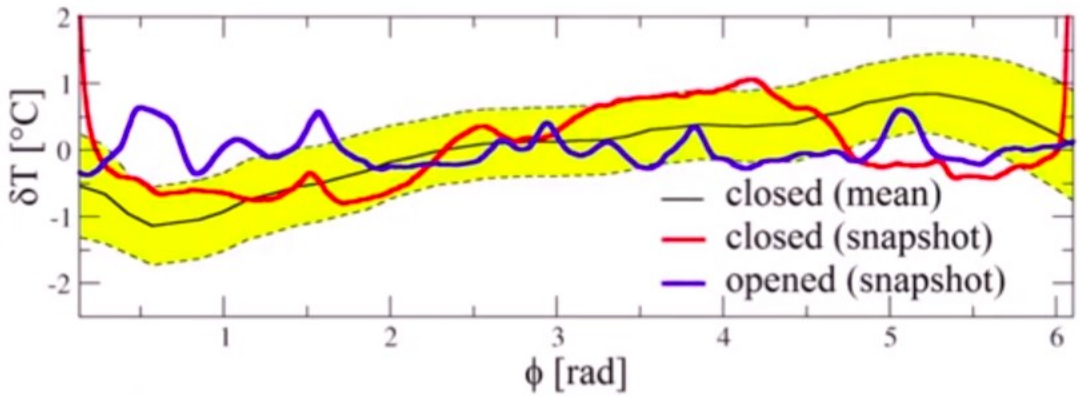
$R_2 = 12$ cm, $15$ cm

$H = 5$ cm

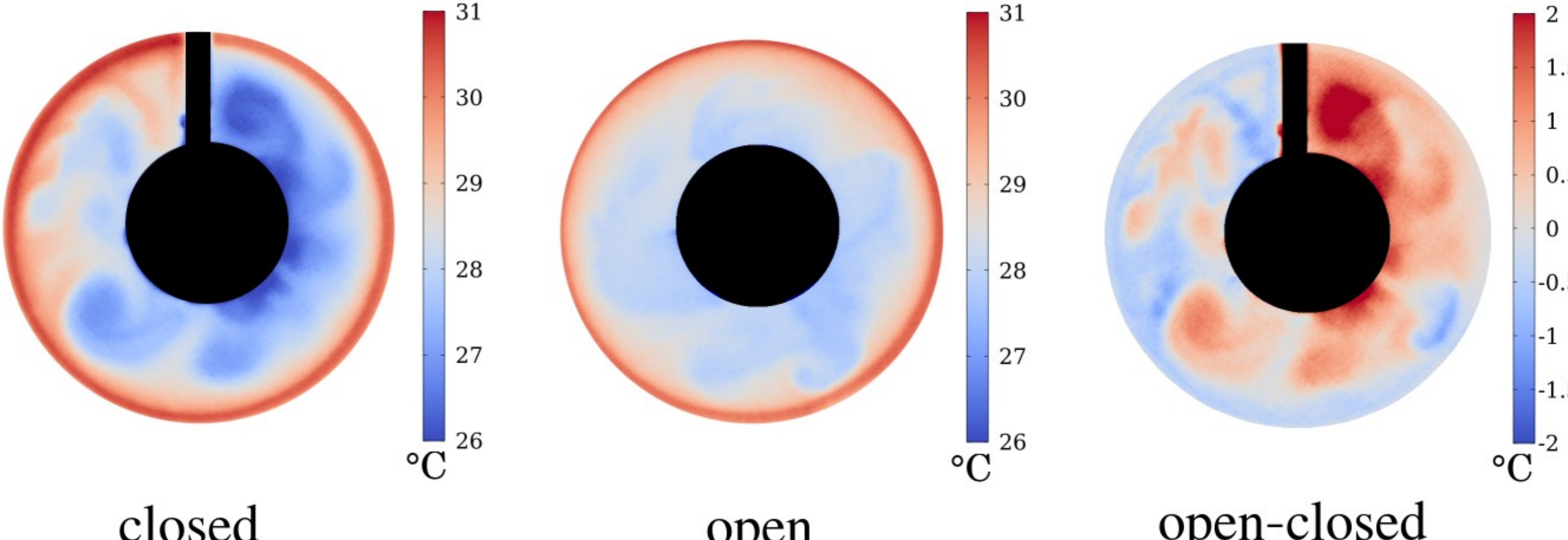
$\Omega = 2.0$ rad/s



# Surface temperature patterns (IR)




Bozóki, T. et al. (2019),
Deep Sea Res. II., 160, 16-24.



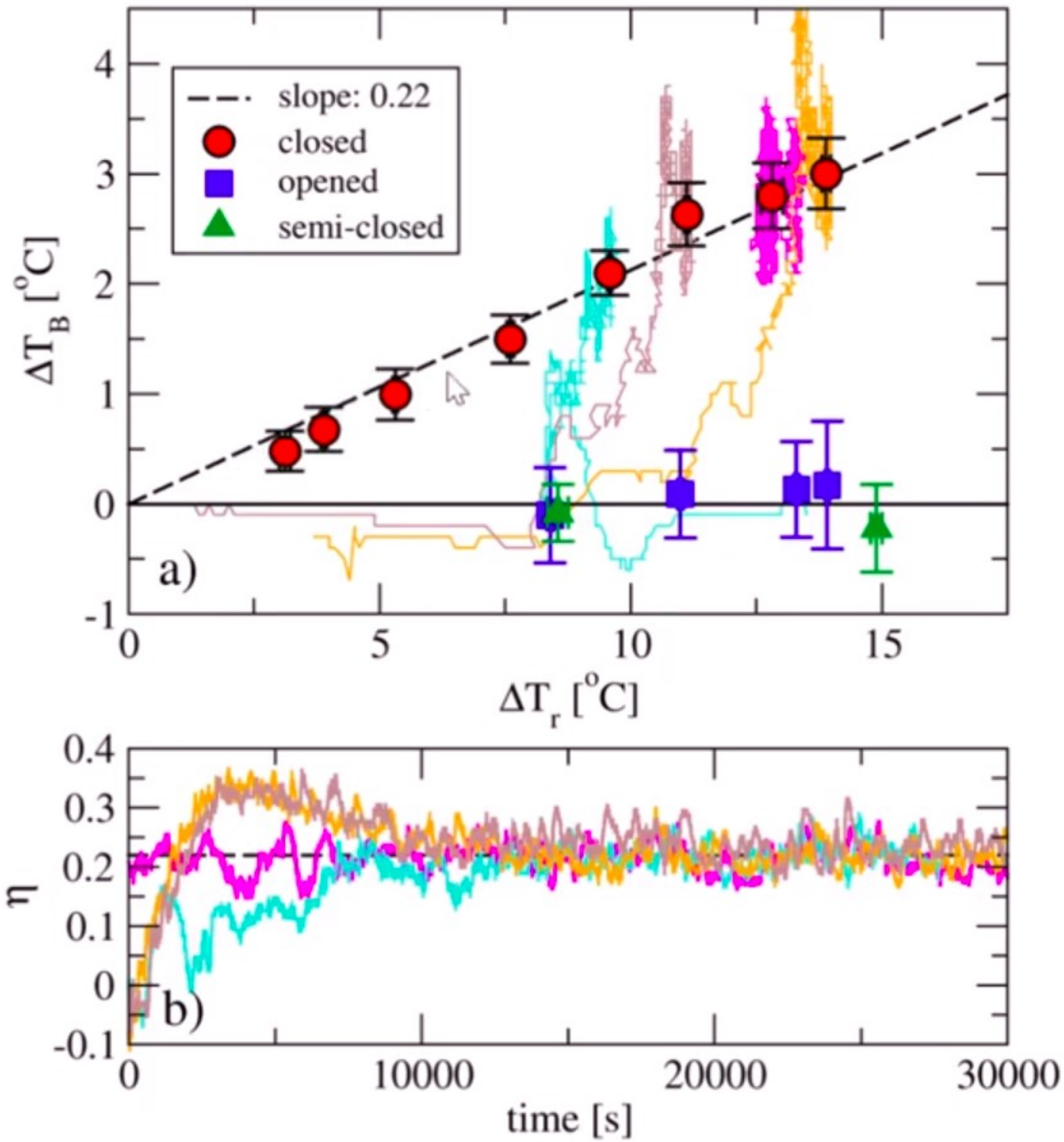
# Scaling properties

A linear scaling between the azimuthal and radial temperature contrast for the closed experiment runs.

$$\langle \Delta T_B \rangle \sim \langle \Delta T_r \rangle$$

$$\eta(t) = \Delta T_B / \Delta T_r$$

$$\eta_0 = 0.22$$

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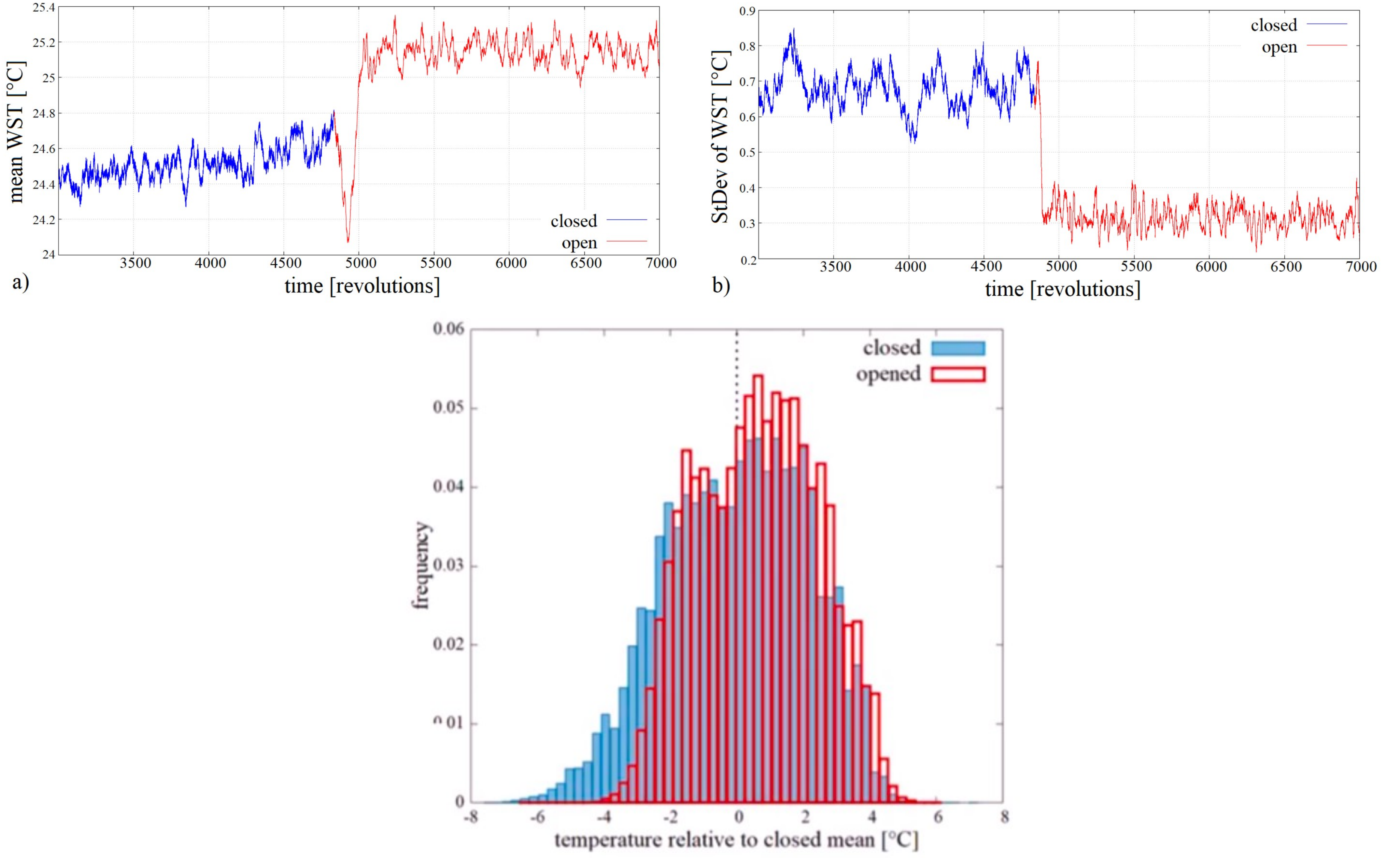
# The effect of opening on the zonal spatio-temporal variability



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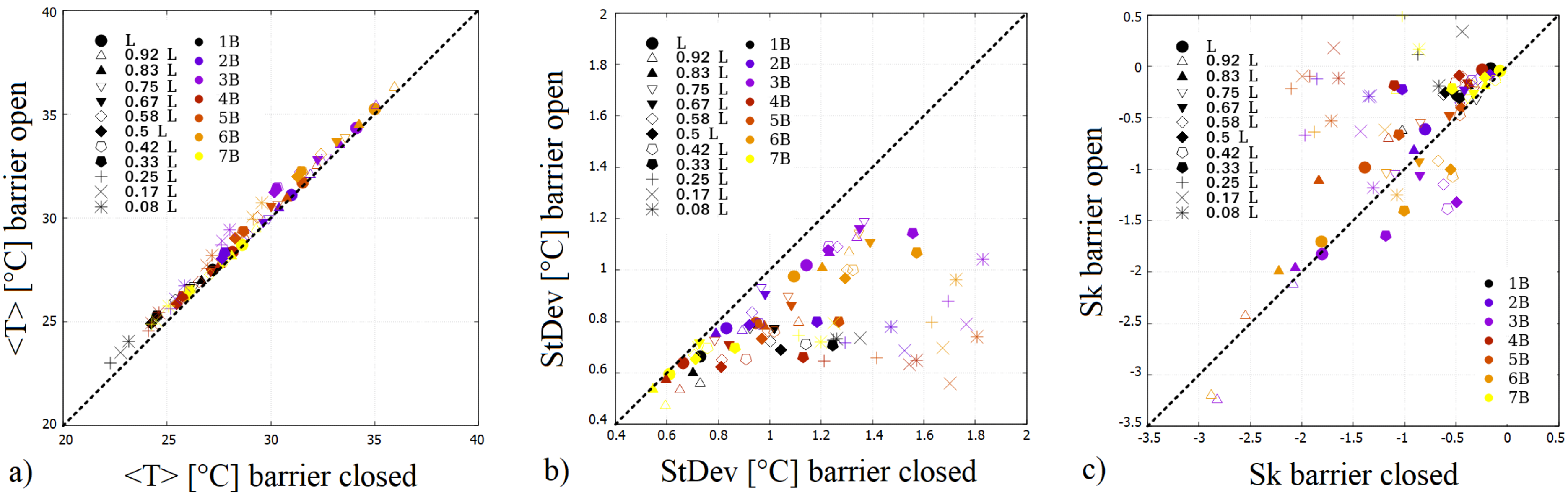
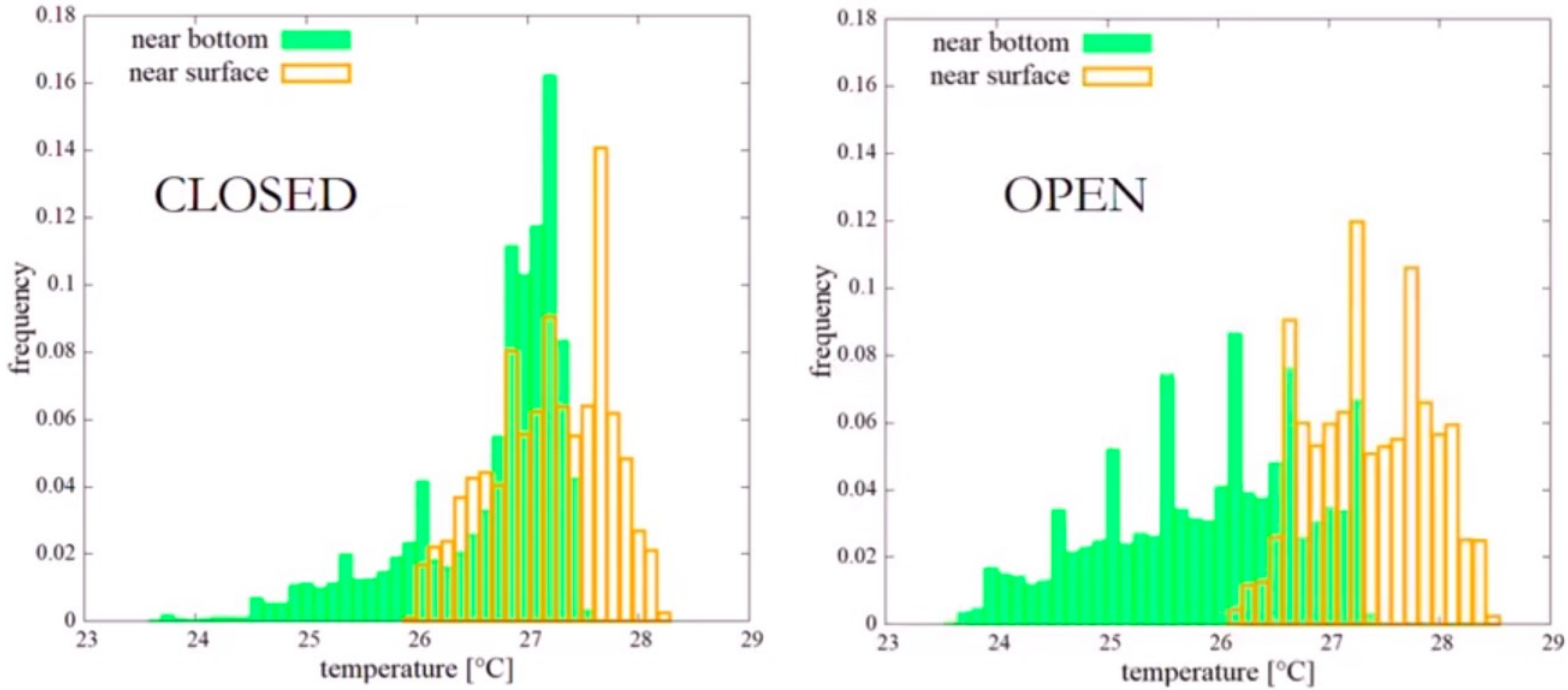


# Increasing mean "SST" in the Southern ocean following the opening – an apparent contradiction with paleoclimate. Why?

Control experiments with thermometers (Cottbus tank)

Larger thermal separation between the surface and the bulk in the open configuration!



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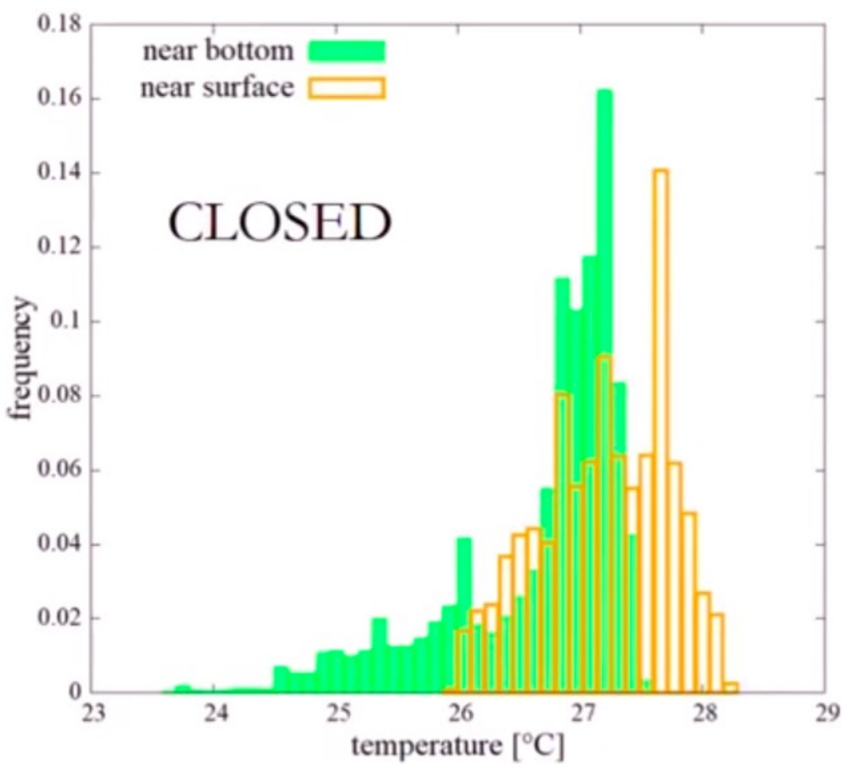
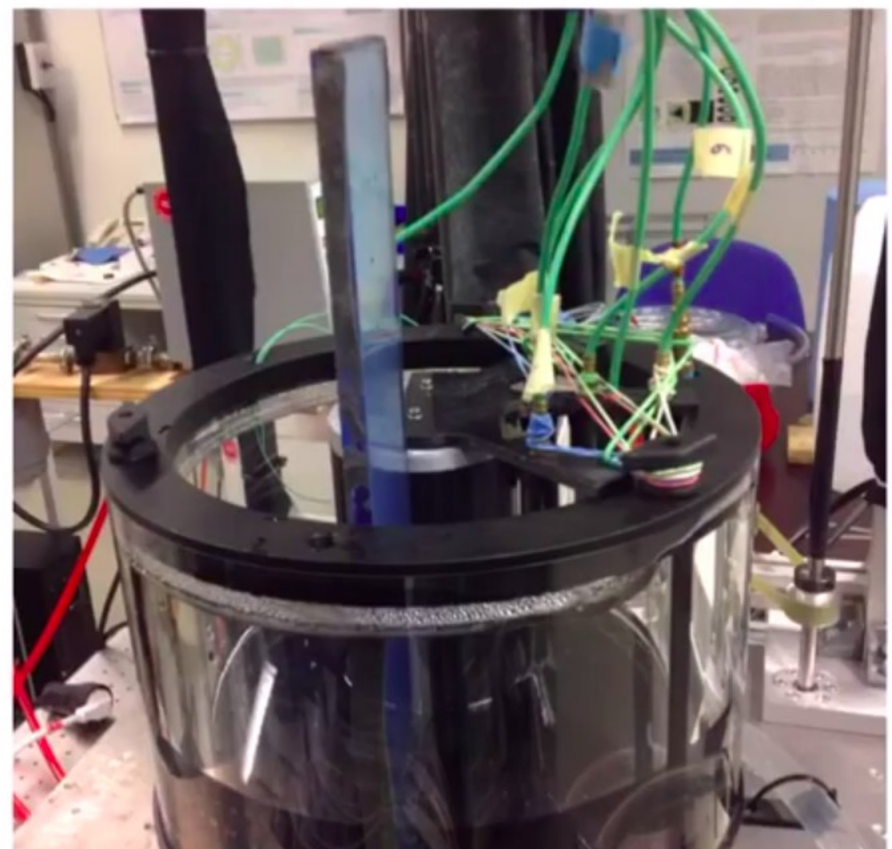


Increasing mean "SST" in the Southern ocean following the opening – an apparent contradiction with paleoclimate. Why? – NUMERICS!

- T21 PlaSim + LSG ("large scale geostrophic") ocean module (22 layers, resolution: $4^\circ \times 4^\circ$)
- 1000 years of simulation
- Topography, orography and ocean topography modiefied (not real paleogeography, only a ca. 100 km-wide meridional "dam" inserted into the Drake passage for the "closed" runs)

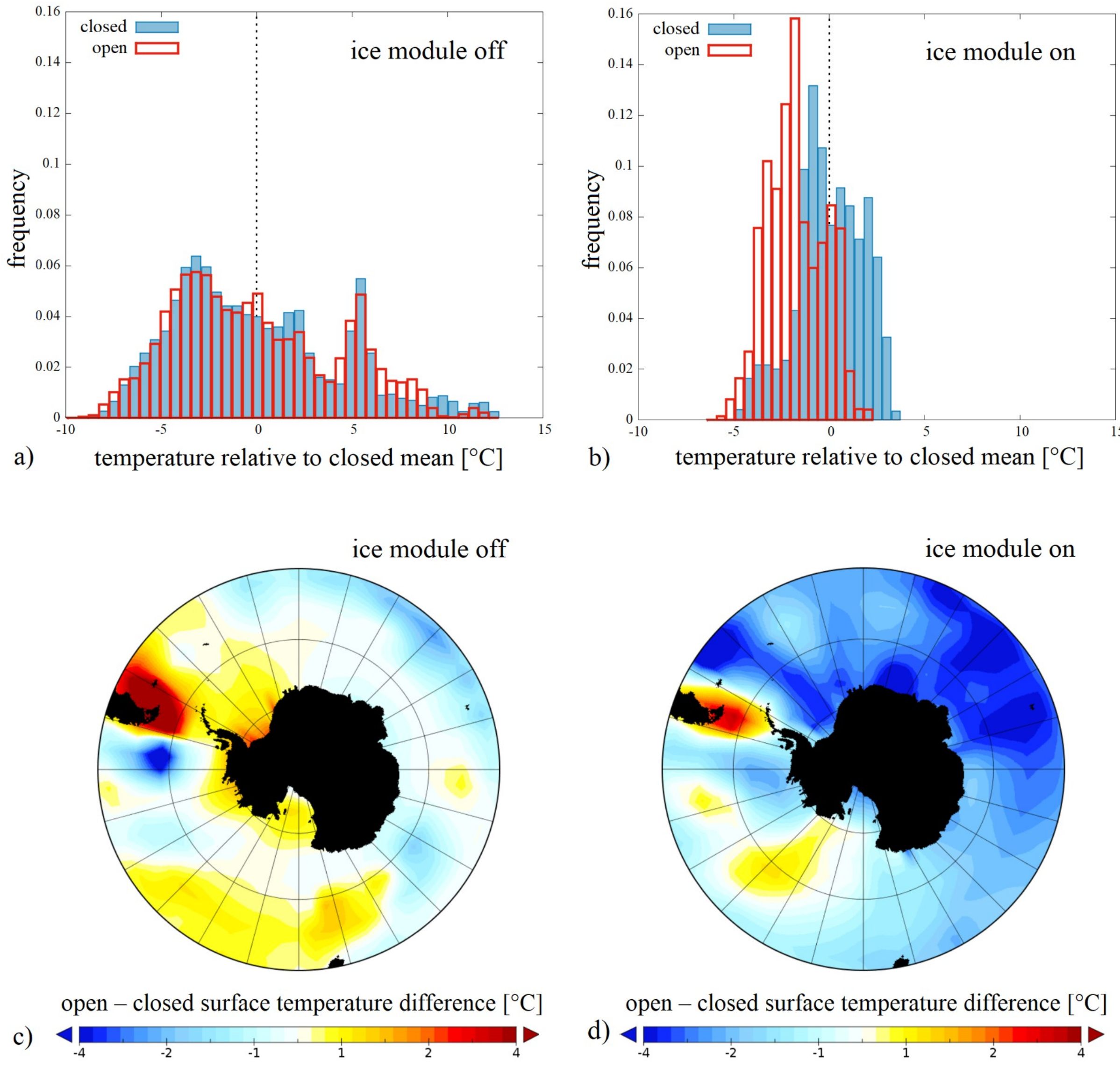
4 runs (Drake passage open/closed × two different configurations):

- $CO_2$: 750 ppm (as 34 Mya) & sea ice + land ice ON
- $CO_2$: 750 ppm (as 34 Mya) & sea ice + land ice OFF

PlaSim (UH Met. Institute) – a "medium complexity" GCM

https://www.mi.uni-hamburg.de/en/arbeitsgruppen/theoretische-meteorologie/modelle/plasim.html

# Significant cooling in the Southern ocean – only when the sea ice module (albedo feedback) is ON!



## Summary & Conclusions

- Minimalistic laboratory "toy model" of the closed Drake passage setting before and after EOT (*very* conceptual).
- In the closed case a temperature contrast can develop between the 'Atlantic' and 'Pacific' side, that is ca. ¼ of the meridional temperature difference in the domain
- After opening the passage, mean SST in the set-up slightly *increases*, and the cold extremes (long left tail) disappear.
- Turns out (from PlaSim simulations) that without active sea-ice dynamics, the Souther Ocean's mean SST would not decrease either, pointing to the importance of ice albedo feedback in the EOT.

*Thank you for your attention!*