Tipping Points: towards a quantitative understanding?

Corentin Herbert

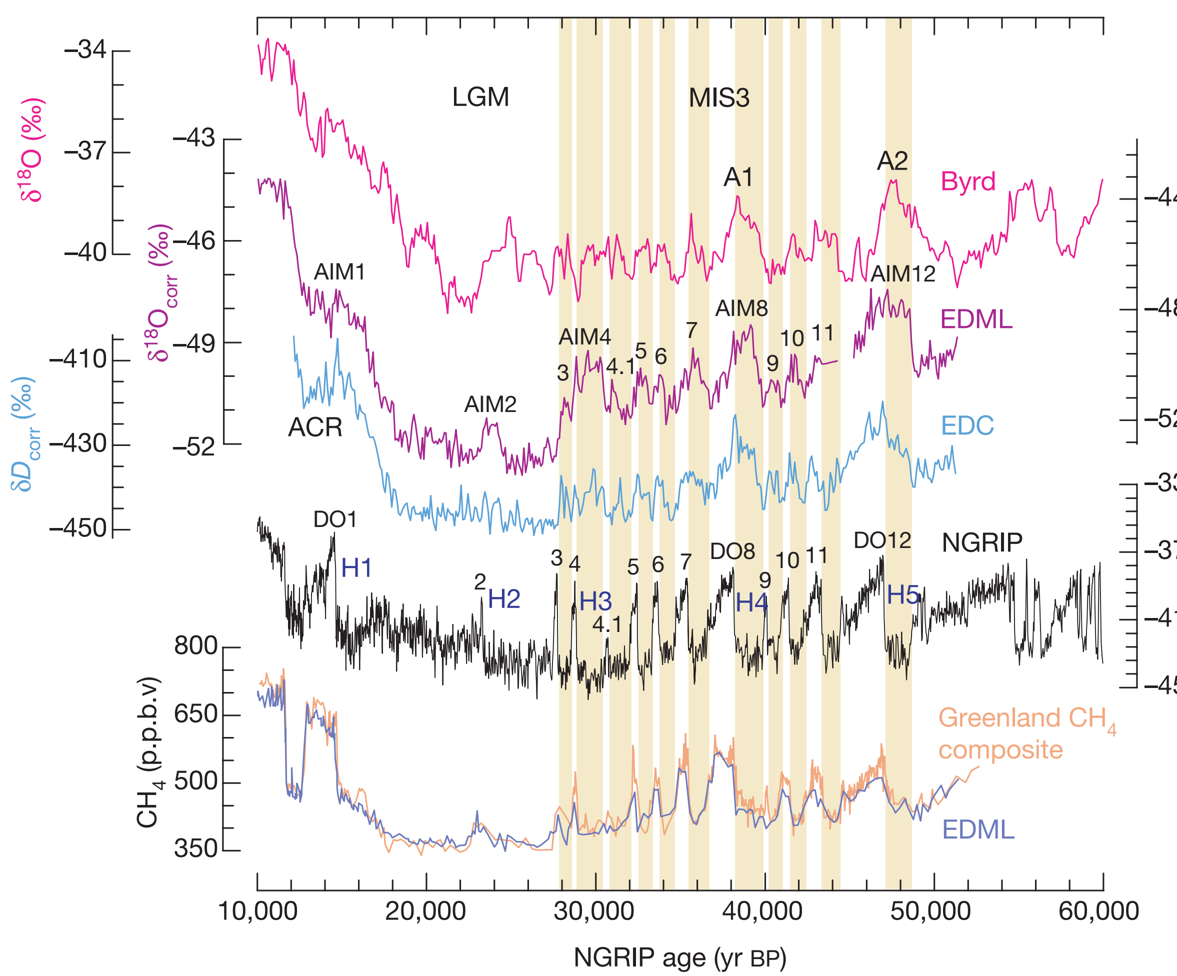
Picture from R. Saravanan's blog

cnrs
ENS DE LYON
anr agence nationale de la recherche AU SERVICE DE LA SCIENCE

cnrs GDR Groupement de recherche Défis Théoriques pour les sciences du climat

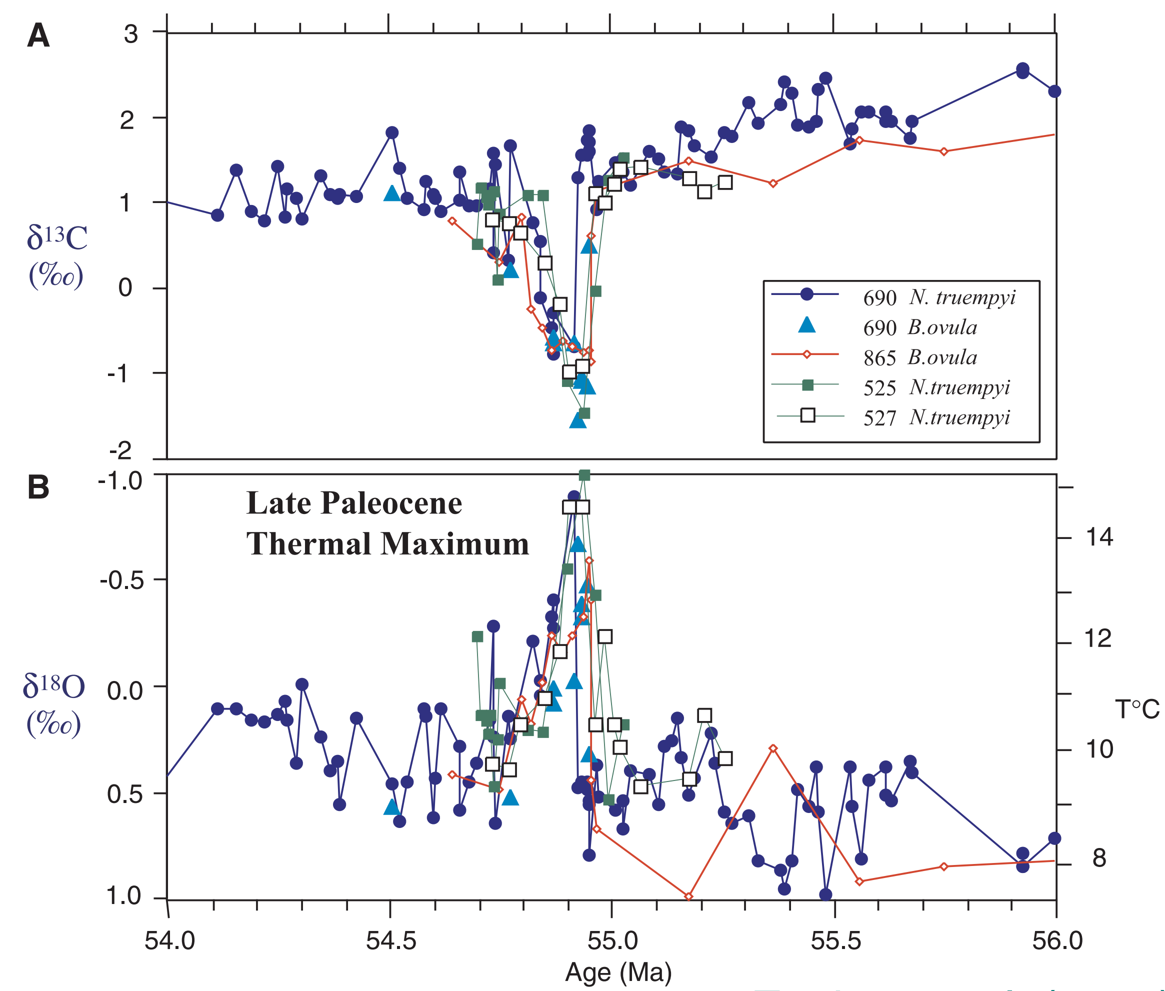
Can climate change abruptly?

Abrupt events recorded in paleoclimate data for the last glacial period…



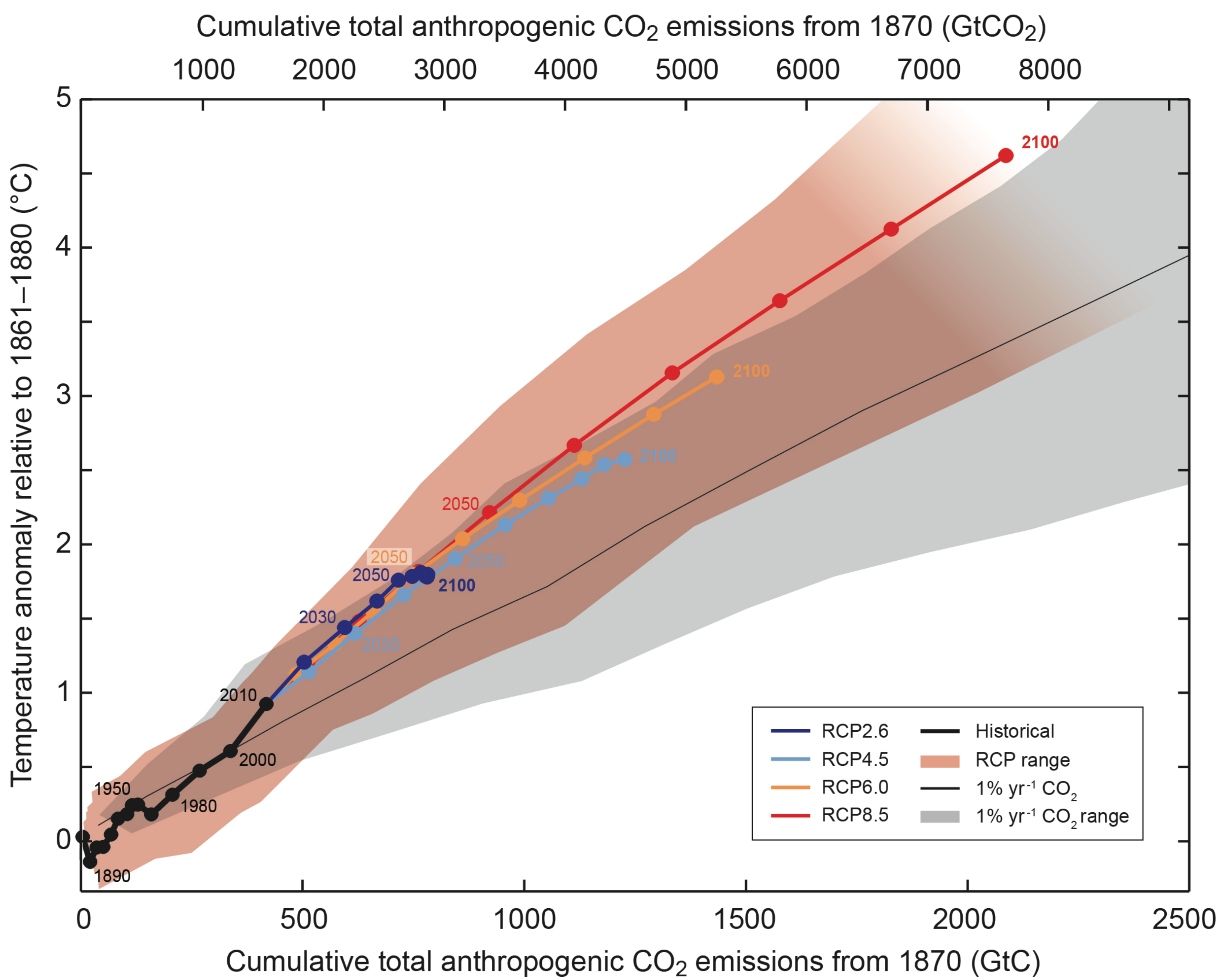
Barbante et al. (2006)

…and at the Paleocene-Eocene Thermal Maximum



Zachos et al. (2001)

Can climate change abruptly?



IPCC AR5

Model projections for 21st century do not exhibit abrupt changes

Main questions

- **Which physical mechanisms can lead to abrupt climate change?**
- **Are they represented reliably in climate models?**
- **If abrupt climate changes are controlled by external parameters, do we know the thresholds?**
- **If abrupt climate changes are due to internal fluctuations, can we estimate their probability?**
- **Are abrupt climate changes predictable?**

Outline

I. **Tipping points in current models: state-of-the-art and limitations**

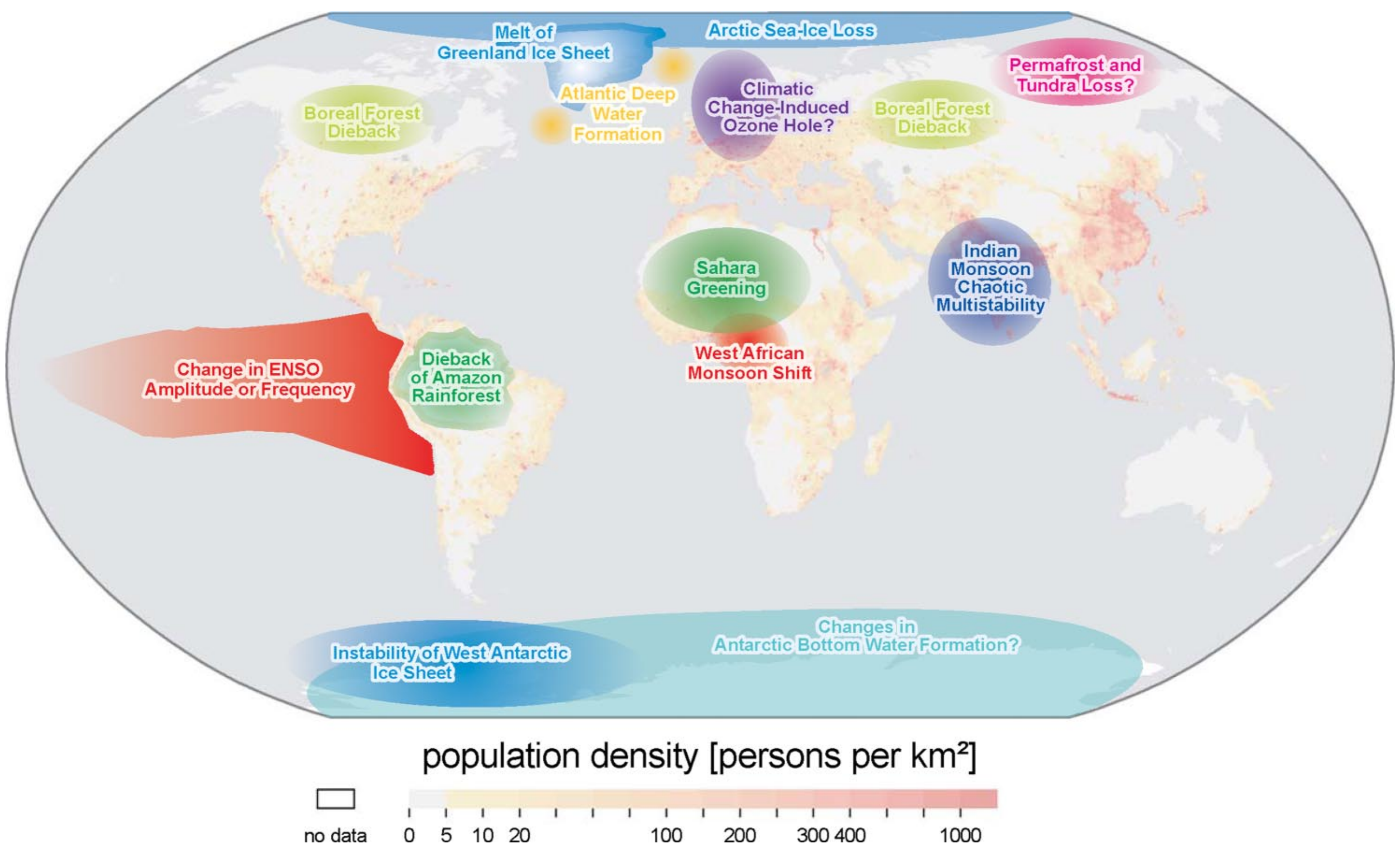
II. Towards a quantitative study of tipping points

   1. Transitions in turbulent flows

   2. New theoretical tools

III. Conclusions

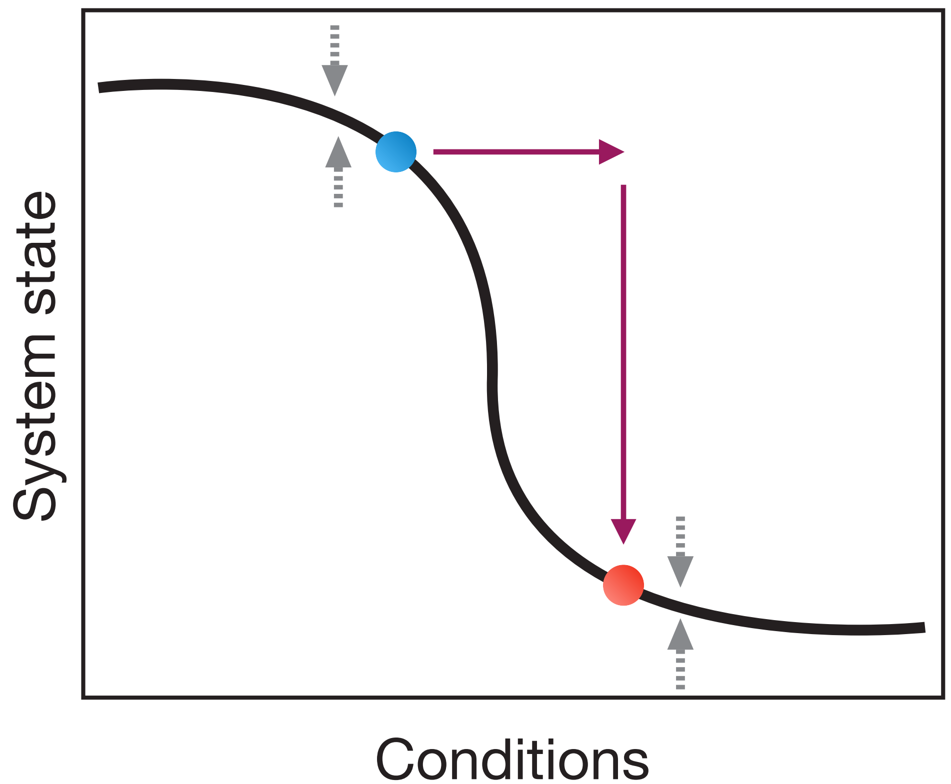
Potential climate tipping points

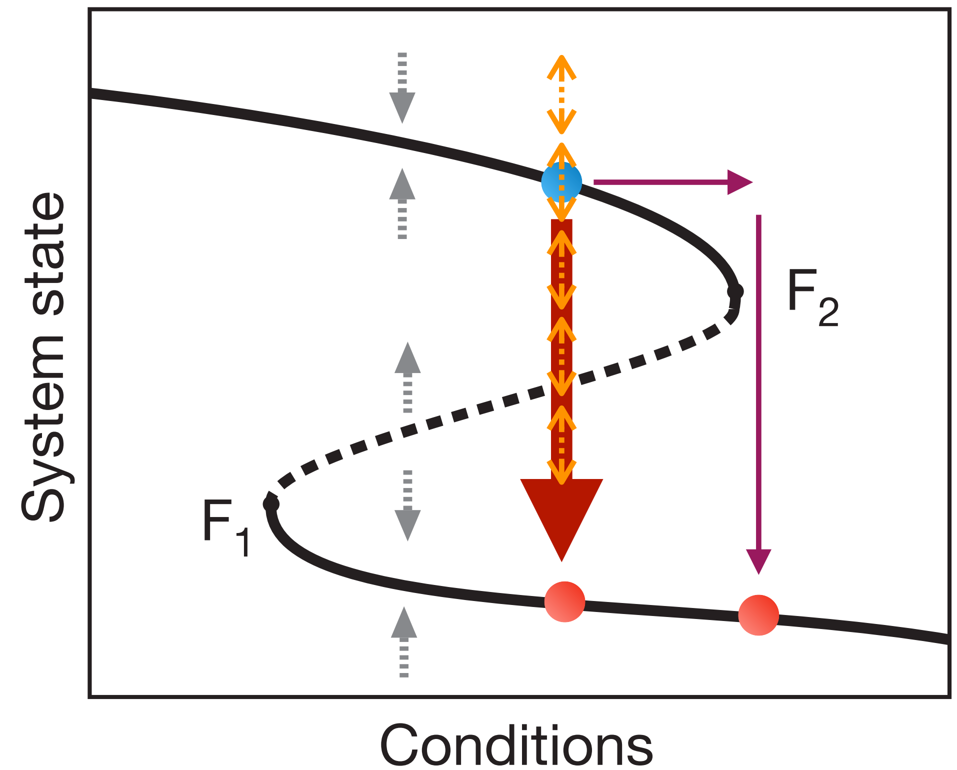


Lenton et al. (2008)

- Some of these tipping points are found in climate models (known knowns)
- Other tipping points might exist but are not represented in current models (known unknowns)
- Yet others might exist but are not found in climate models due to inaccurate representation of physical processes (unknown unknowns)

Bifurcations and noise-induced transitions

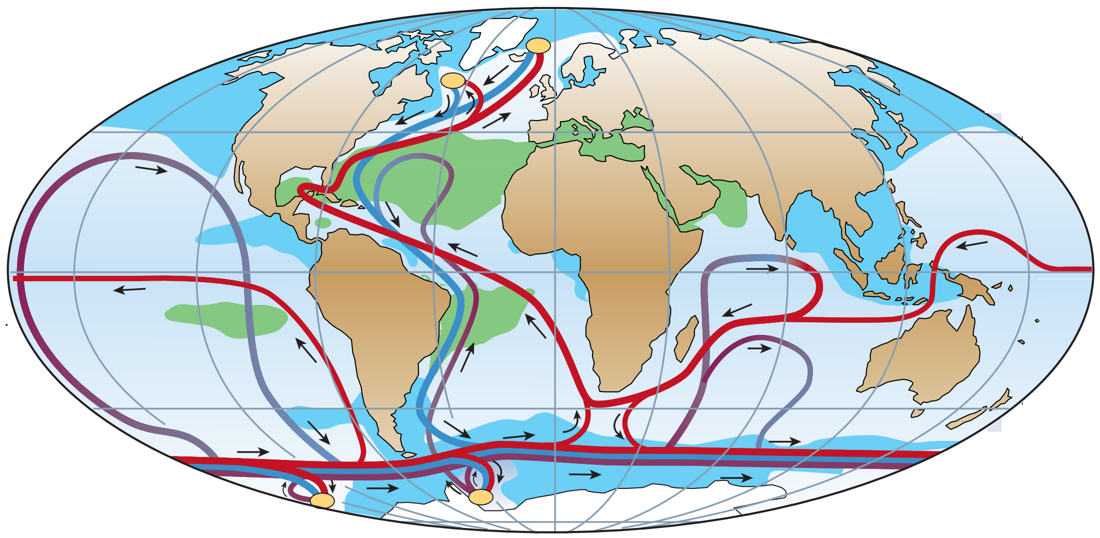


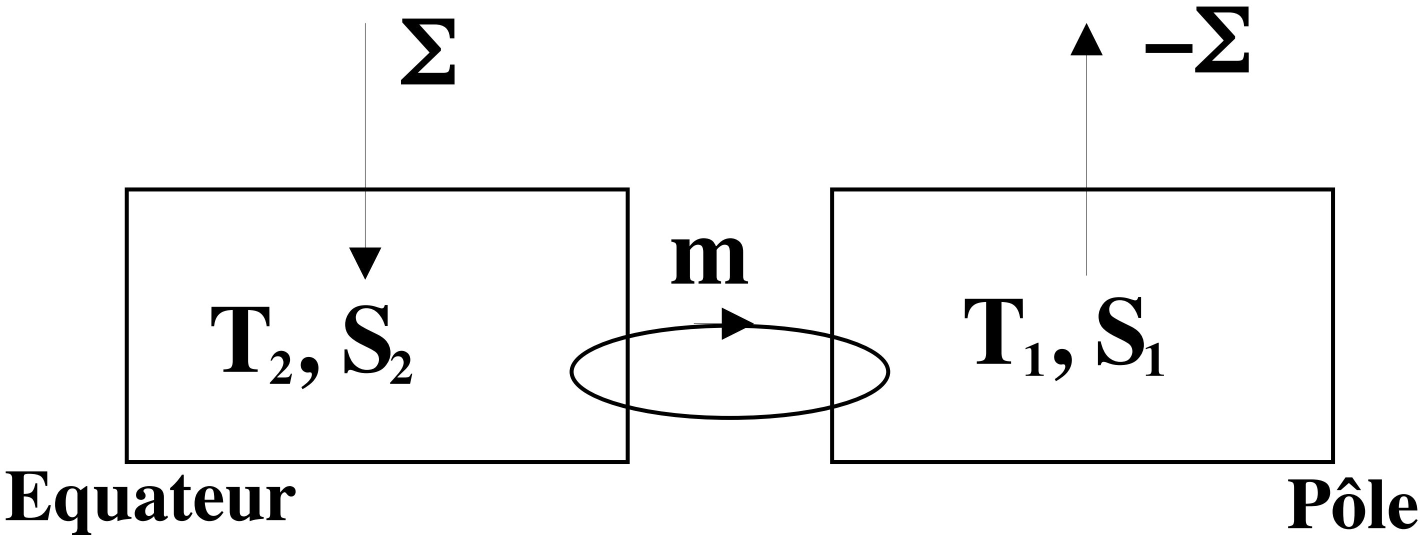


- Transition due to loss of stability when external parameter changes (bifurcation). Irreversibility of the transition (hysteresis).
- Transition due to external forcing across the separatrix (shock) in the bistability regime.
- Transition due to internal fluctuations (noise) in the instability regime.
- More sophisticated behaviors are also possible (Hopf bifurcation, noise-induced transitions between chaotic attractors,…)

See Dijkstra (2013) or Lucarini and Ghil (2022) for reviews

AMOC bistability in box models



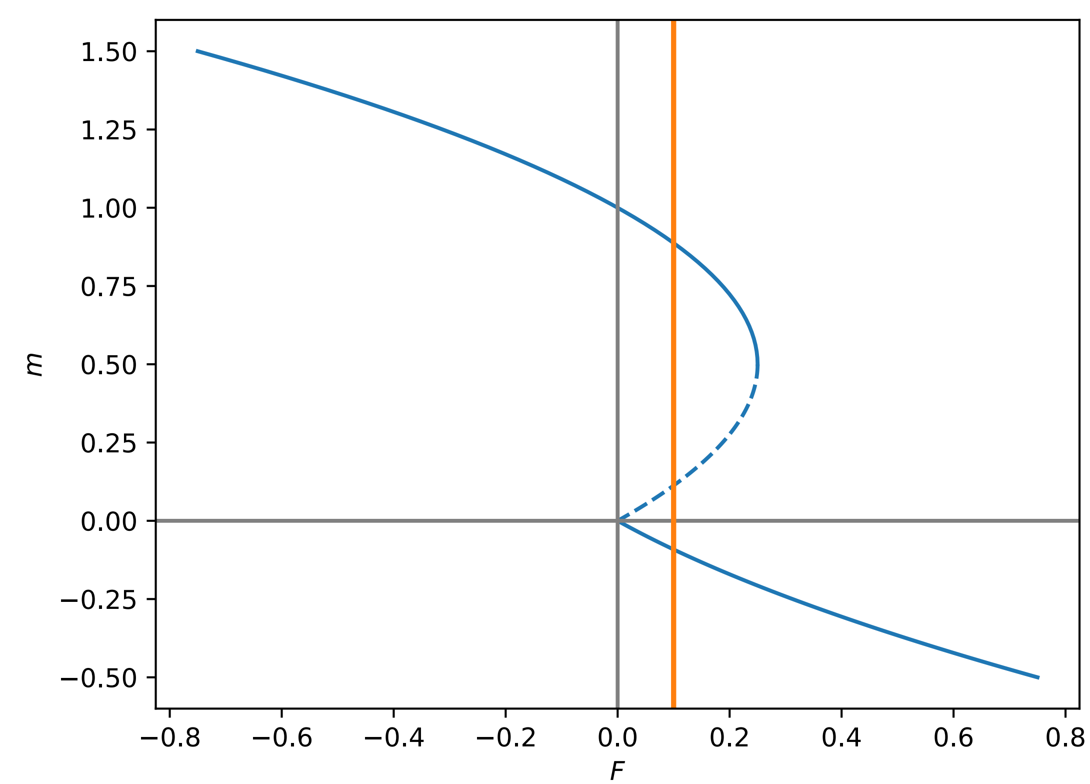


$$
\begin{aligned}
m &= \mu(\rho_1 - \rho_2) \\
&= \mu(\alpha(T_2 - T_1) - \beta(S_2 - S_1)) \\
&= \mu(\alpha \Delta T - \beta \Delta S)
\end{aligned}
$$

Steady state:

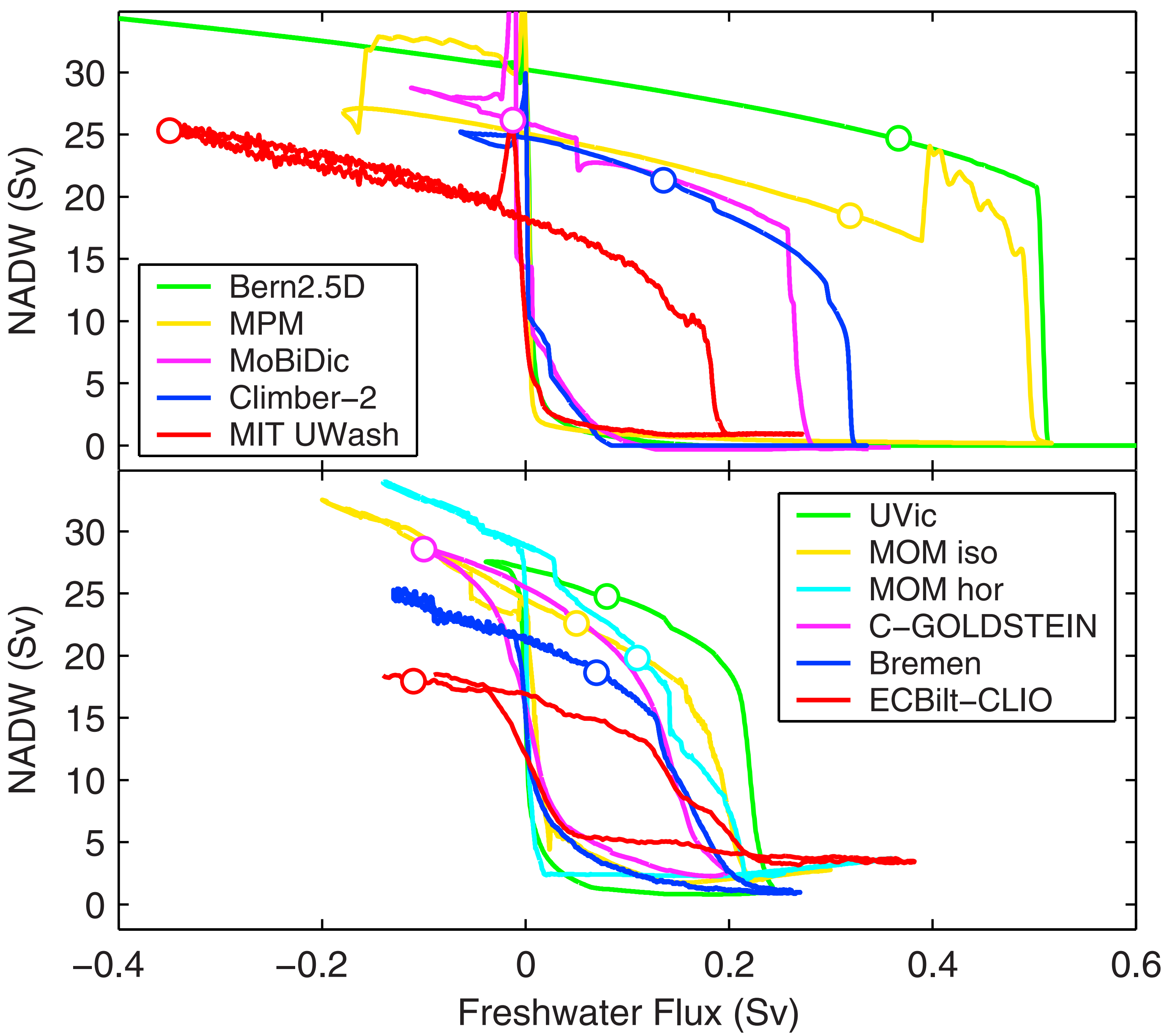
$$\Sigma = \mu \,|\, \alpha \Delta T - \beta \Delta S \,|\, \Delta S,$$

$$F = |\, 1 - x \,|\, x, \quad F = \frac{\Sigma \beta}{\mu (\alpha \Delta T)^2}, x = \frac{\beta \Delta S}{\alpha \Delta T}$$



Stommel, *Tellus* (1961)

AMOC bistability in many intermediate complexity models



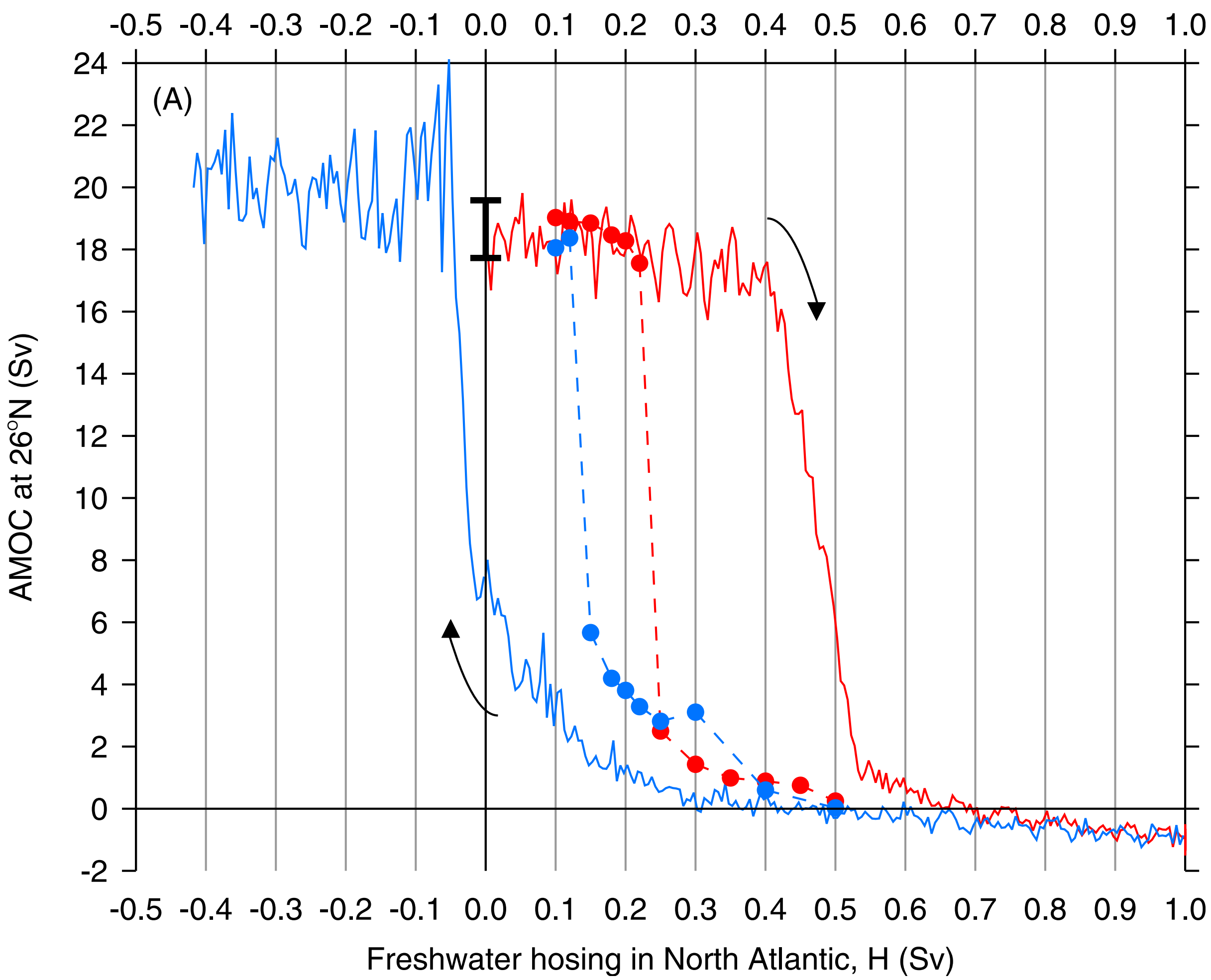
Model Name	Ocean Component	Atmosphere Component
Bern 2.5D	zonally averaged, 3 basins	zonally averaged energy moisture
Bremen	large-scale geostrophic	energy balance
Climber-2	zonally averaged, 3 basins	statistical-dynamical
ECBilt-CLIO	3D primitive equations	quasi-geostrophic
C-GOLDSTEIN	3D simplified	energy-moisture balance
MIT_UWash	3D prim. equations, square basins	zonally averaged
MoBiDic	zonally averaged, 3 basins	zonally averaged
MOM-hor	3D primitive equations (MOM)	simple energy balance
MOM-iso	as above, with isopycnal mixing	simple energy balance
MPM	zonally averaged, 3 basins	energy-moisture balance
UVic	3D primitive equations (MOM)	energy-moisture balance

- **All models exhibit hysteresis**
- **They disagree about the position of the bifurcation**
- **Is present day climate mono-stable or bistable?**

Rahmstorf et al. (2005)

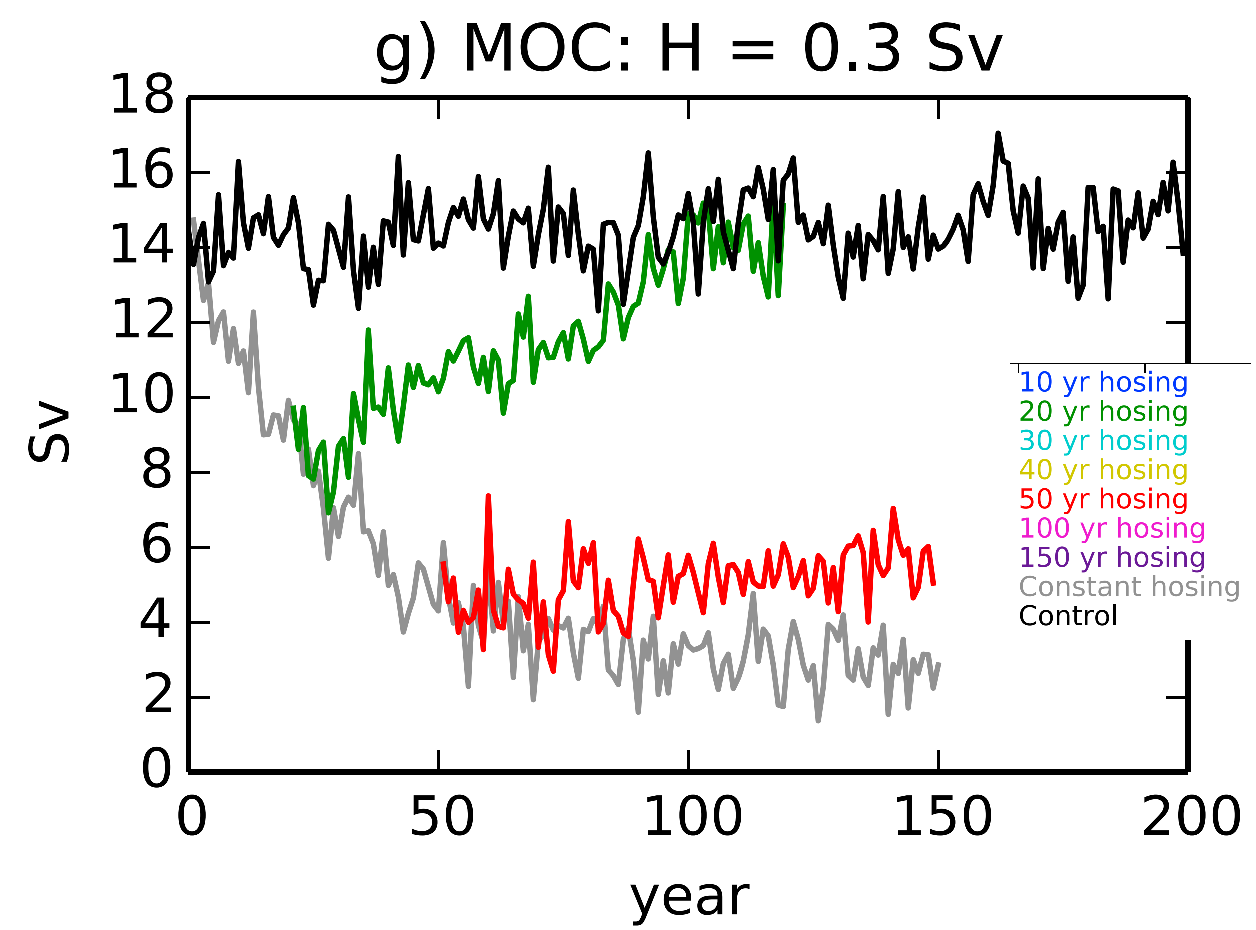
AMOC bistability in ocean GCMs

low-resolution GCM (FAMOUS)



Hawkins et al. (2011)

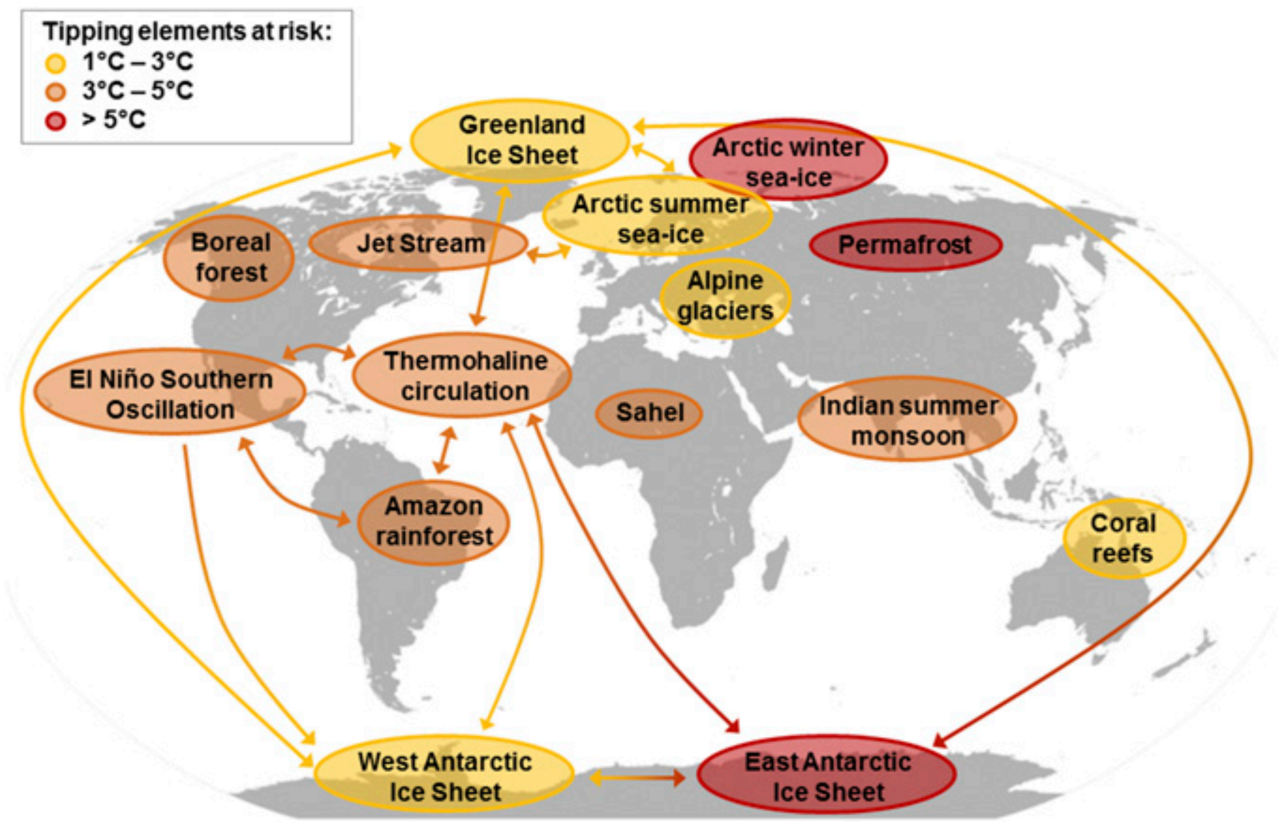
Eddy-permitting model (HadGEM3-GC2)



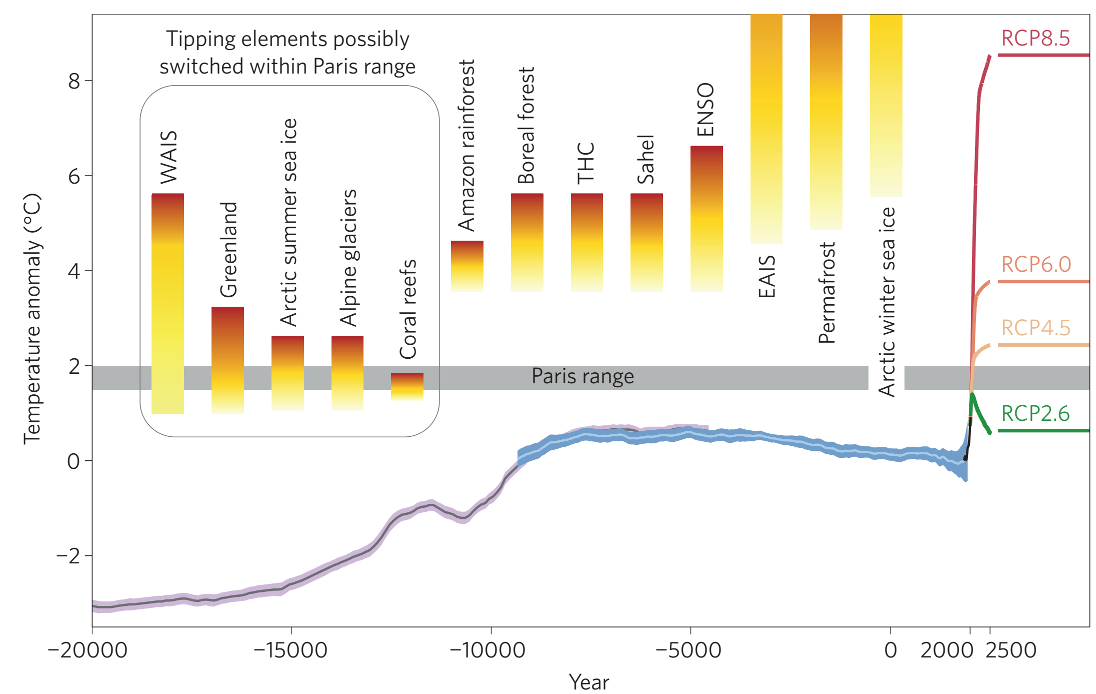
Jackson & Wood (2018)

- **Some GCMs exhibit AMOC bistability, but not all of them**
- **For those which do, it depends on details of the experiment**

Thresholds for Tipping Points



Steffen et al (2018)

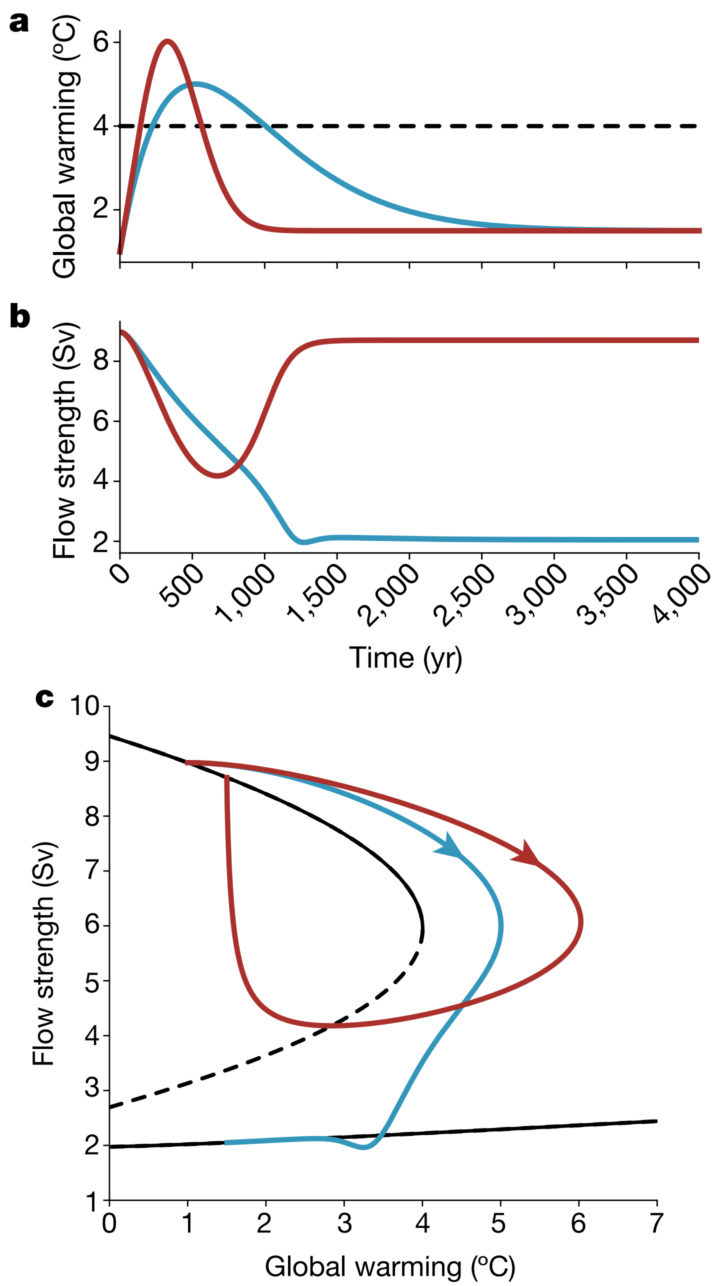


Schellnhuber et al. (2016)

- **These are "expert elicitations", not direct simulation results**
- **Uncertainties are large**
- **Tipping points studied separately with idealized forcing, while they are coupled in reality *(tipping cascades)***
- **Timescale of forcing matters (e.g. *overshooting*)**

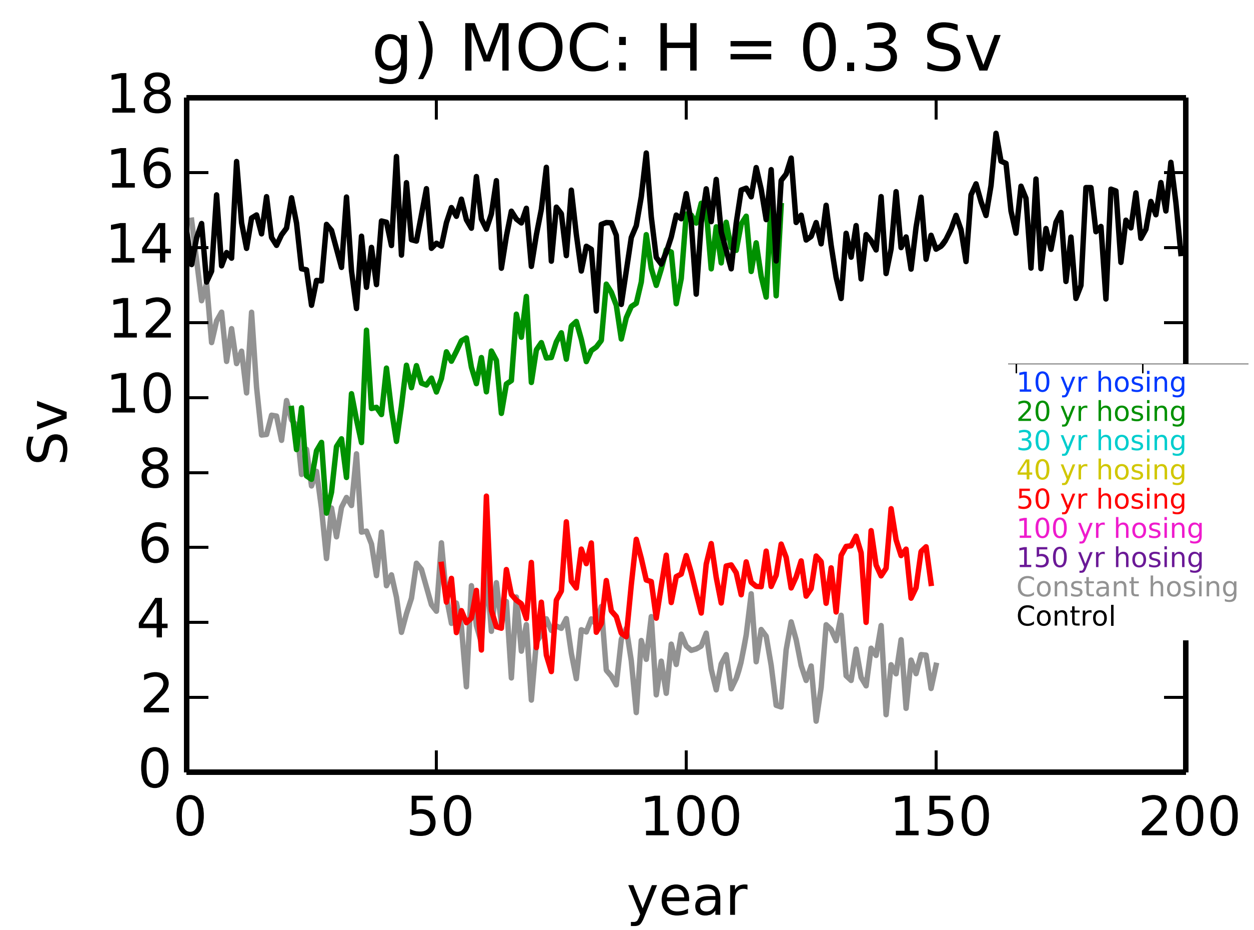
Overshooting

Can we safely overshoot tipping points if we go back below the threshold sufficiently fast?



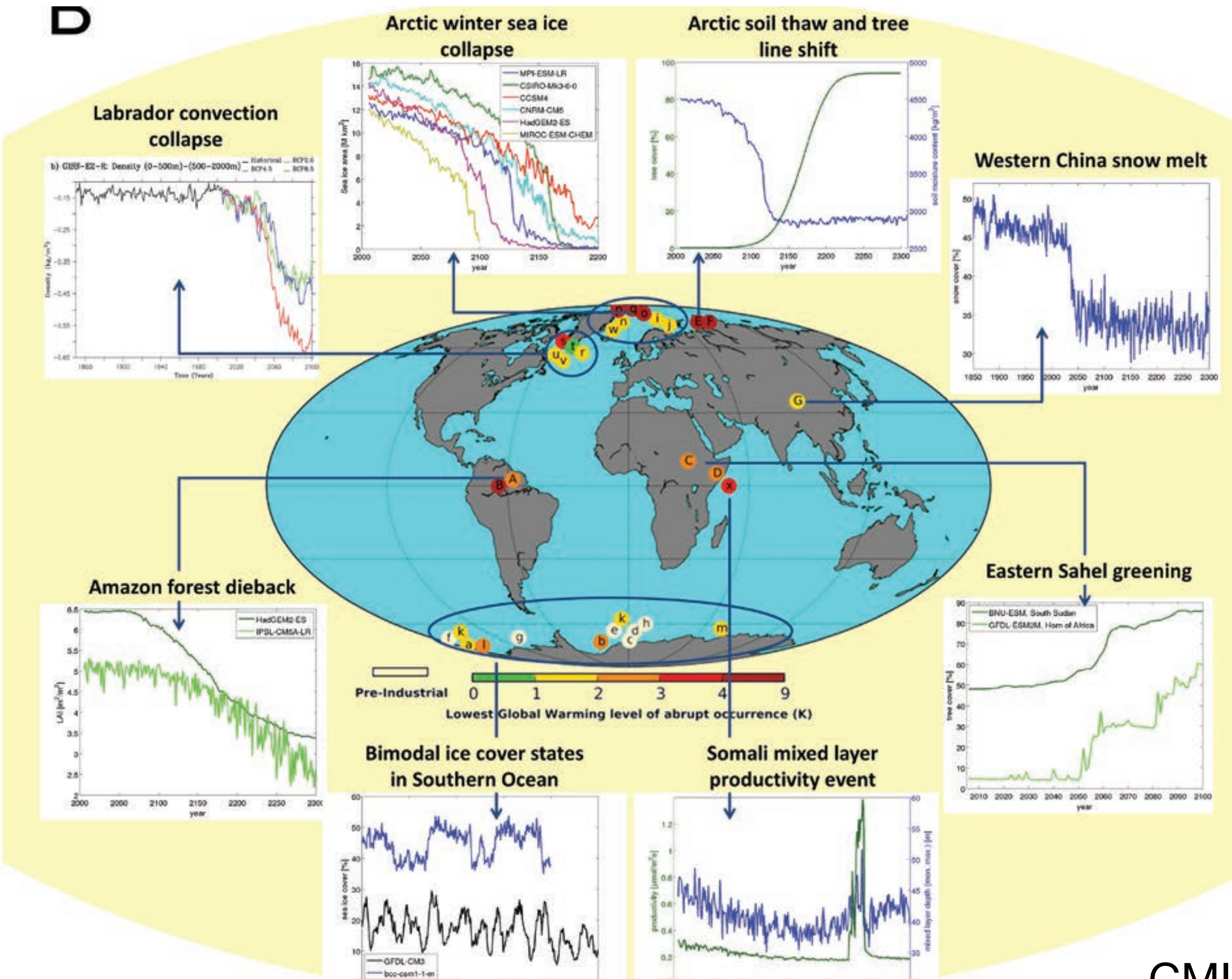
Ritchie et al (2021)

Eddy-permitting model (HadGEM3-GC2)



Jackson & Wood (2018)

Spontaneous transitions in climate models

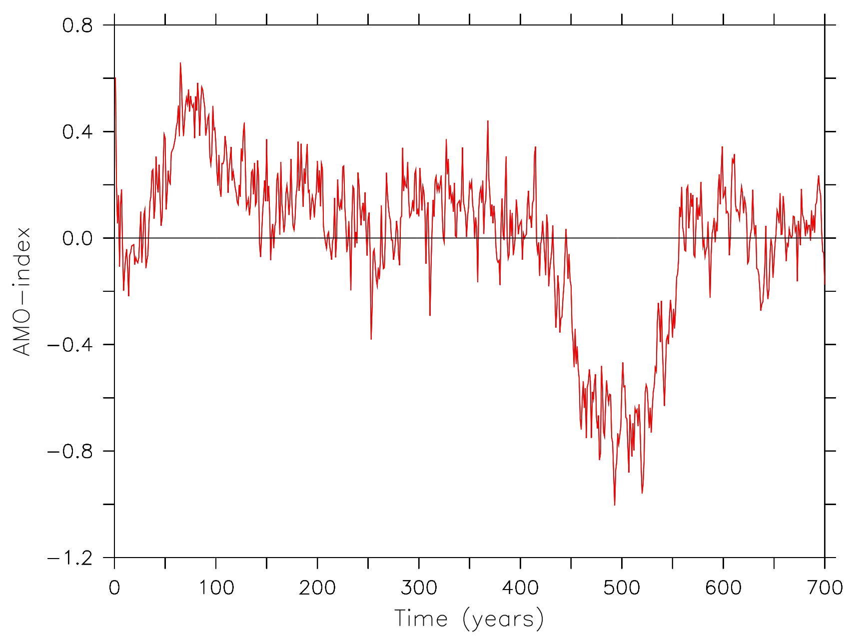


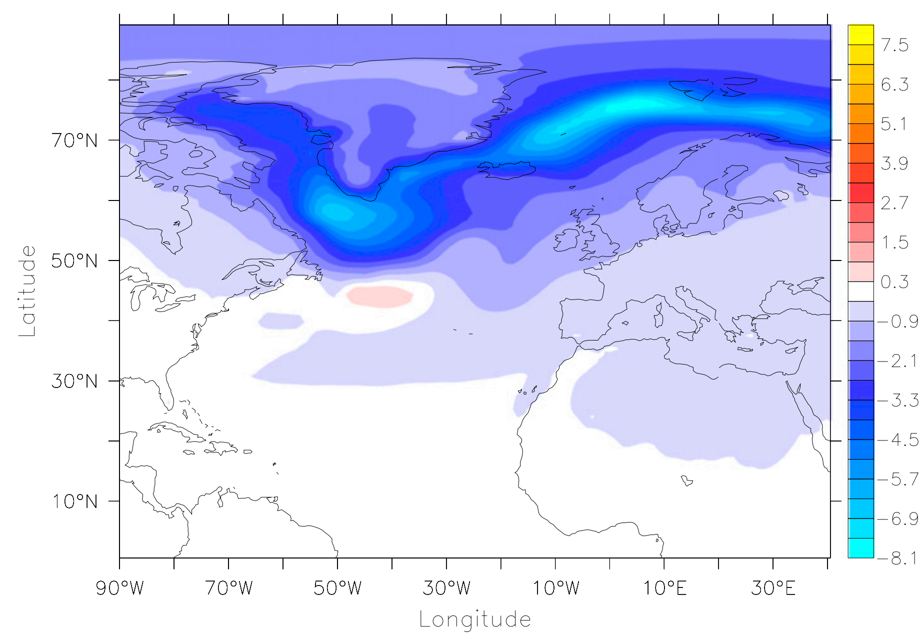
CMIP5 simulations

Bathiany et al. (2016), after Drijfhout et al. (2015)

Spontaneous transitions in climate models

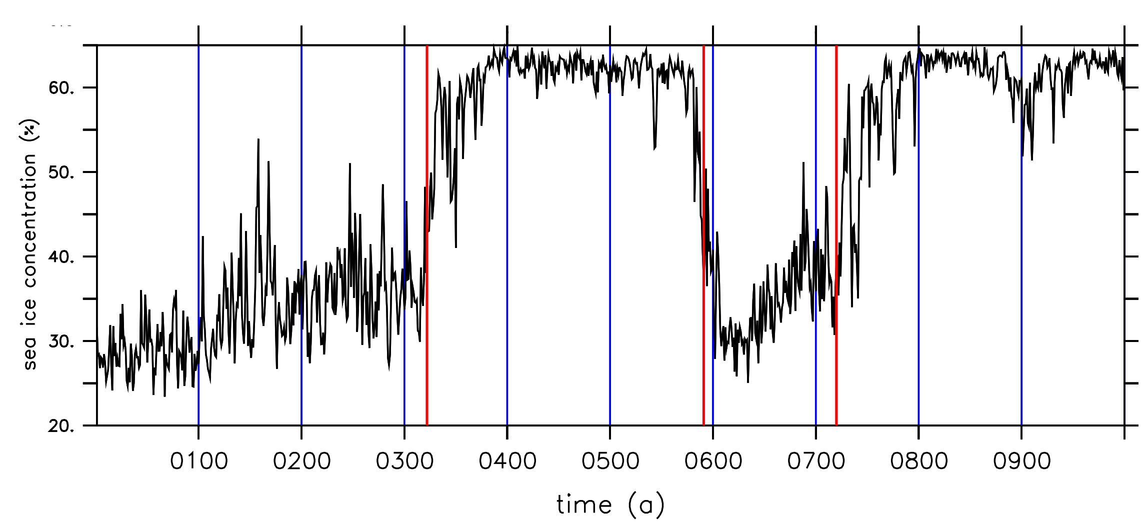
Abrupt events reported in pre-industrial control runs:





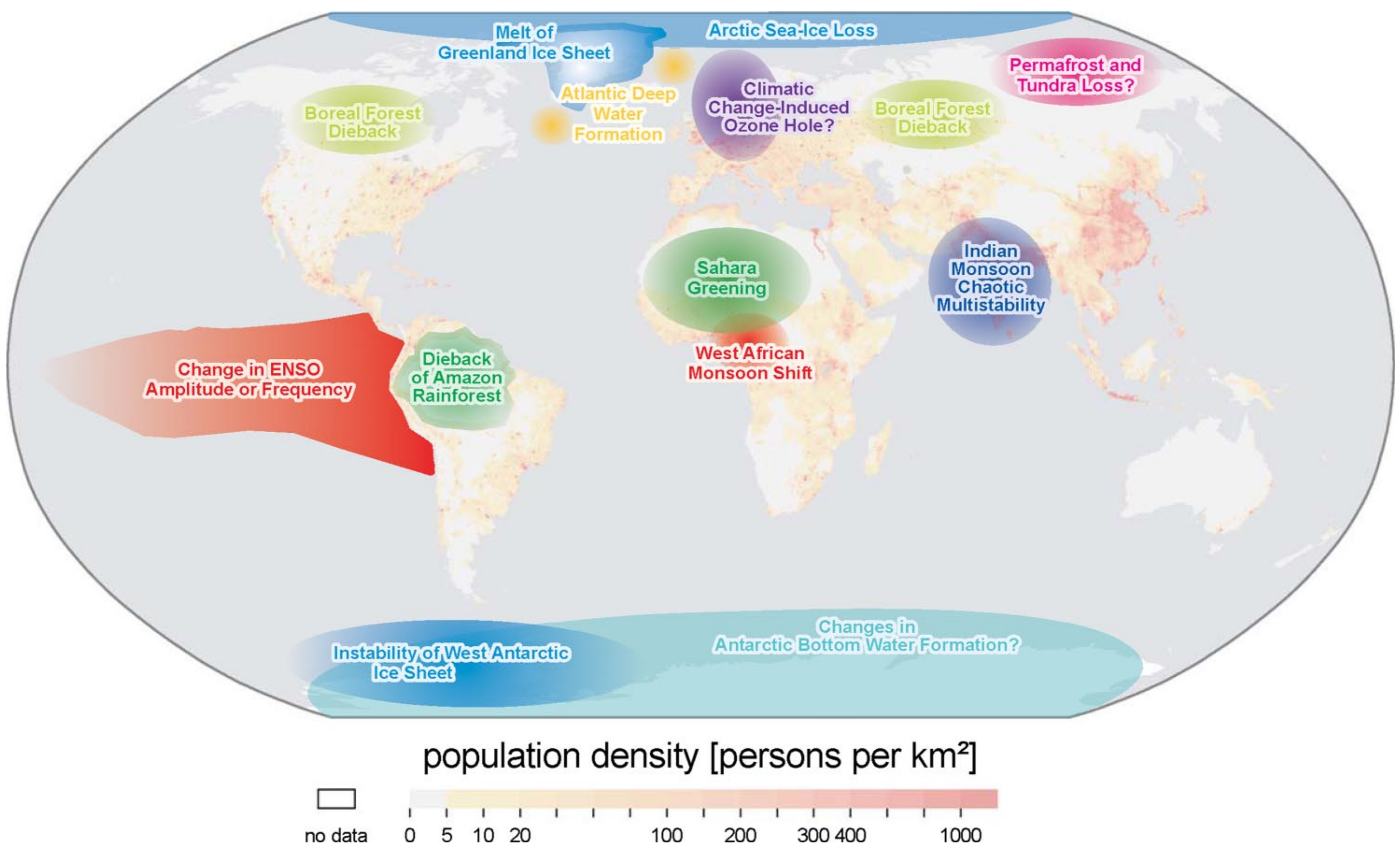
SAT anomaly
y 450-550

Drijfhout et al. (2013), EC-Earth



Kleppin et al. (2015), CESM

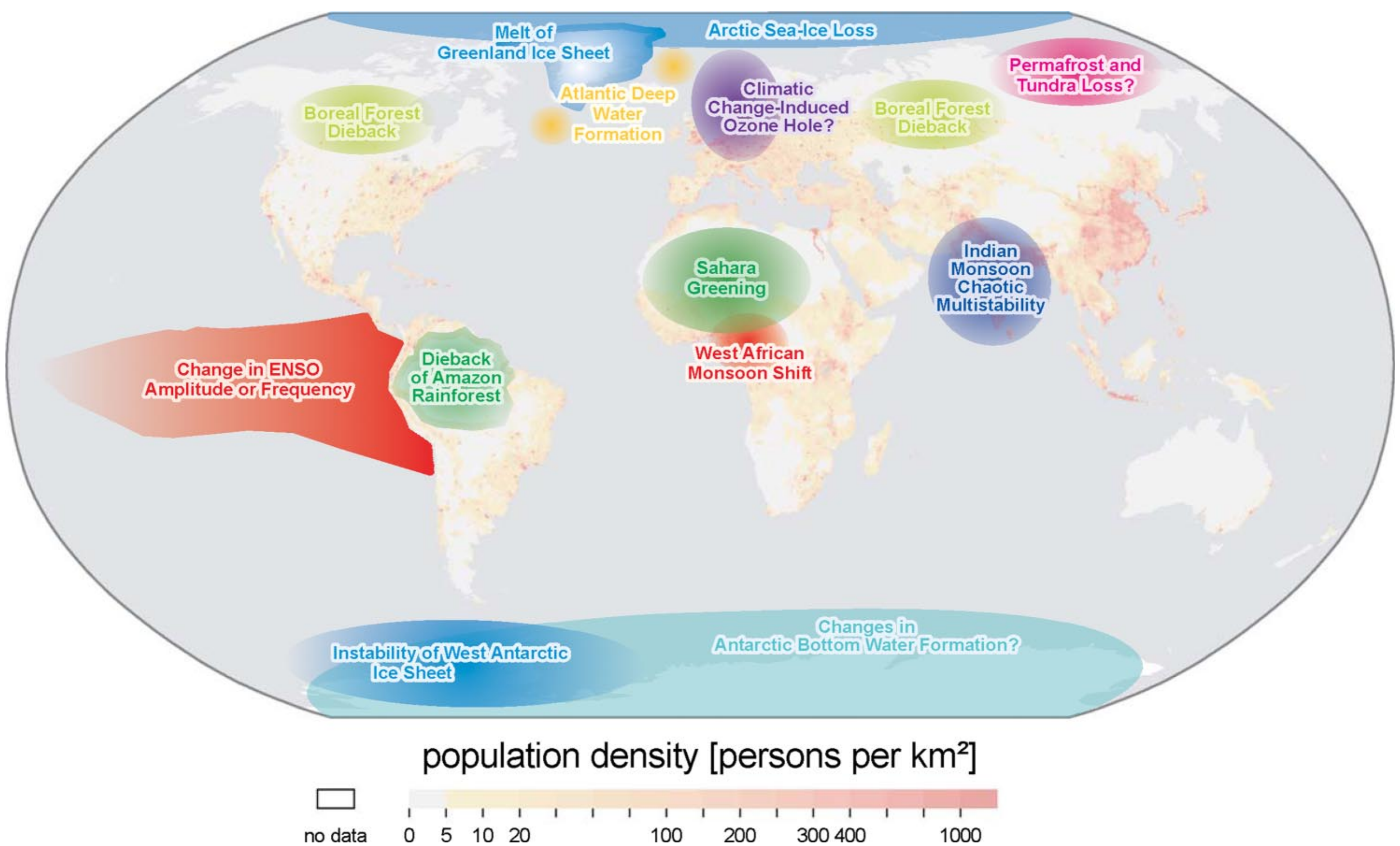
Potential climate tipping points



Lenton et al. (2008)

- **Some of these tipping points are found in climate models (known knowns)**
- **Other tipping points might exist but are not represented in current models (known unknowns)**
- **Yet others might exist but are not found in climate models due to inaccurate representation of physical processes (unknown unknowns)**

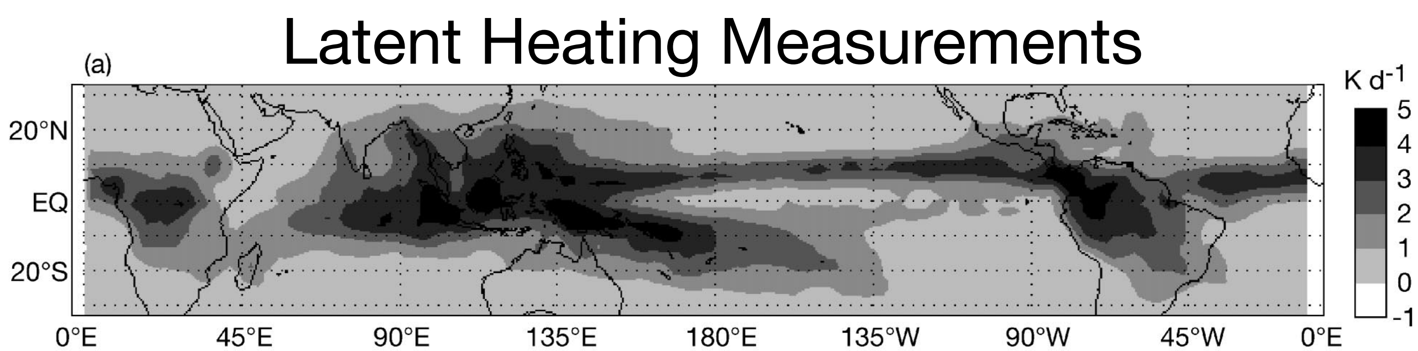
Potential climate tipping points



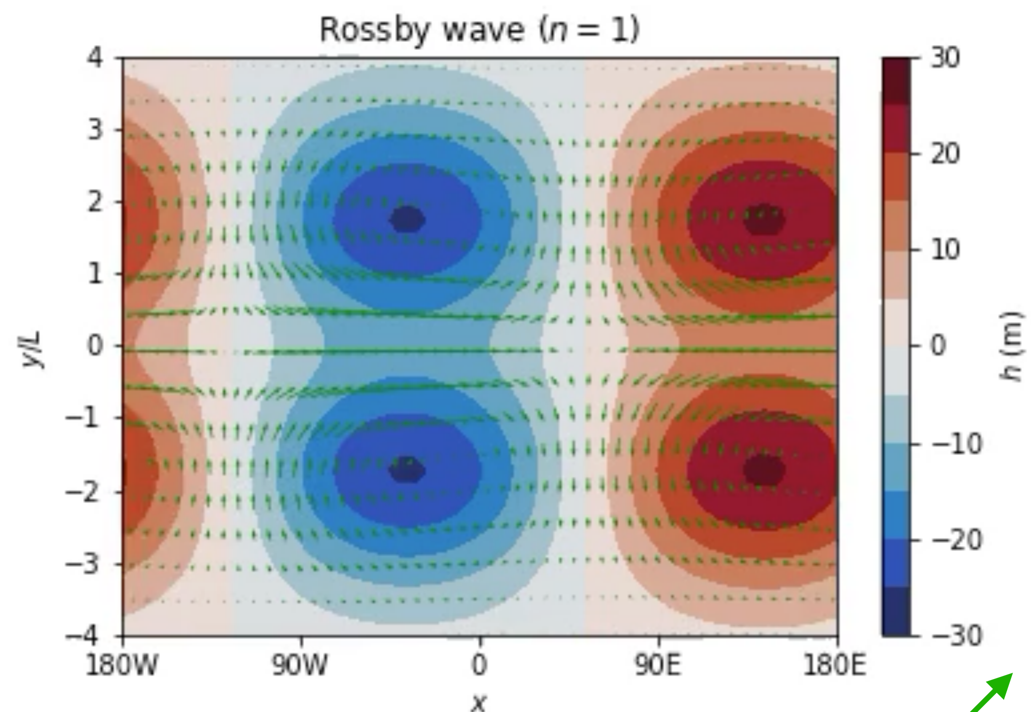
Lenton et al. (2008)

- **Some of these tipping points are found in climate models (known knowns)**
- **Other tipping points might exist but are not represented in current models (known unknowns)**
- **Yet others might exist but are not found in climate models due to inaccurate representation of physical processes (unknown unknowns)**

Tipping points in the large-scale atmospheric circulation?



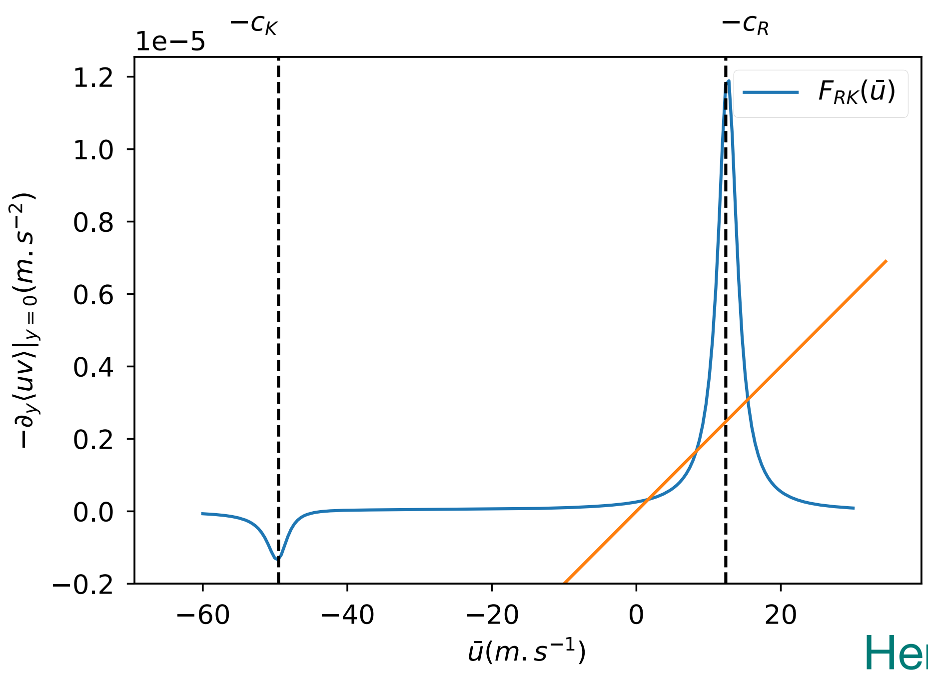
Schumacher et al (2004)



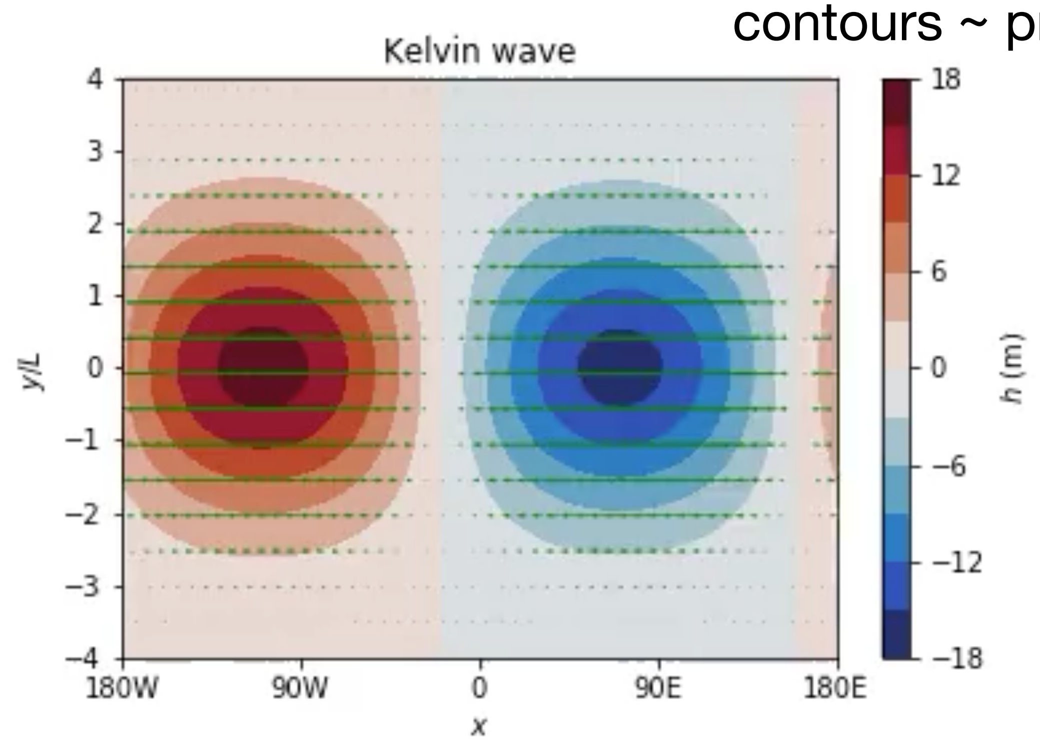
Tropical convection generates waves which interact with the underlying mean-flow

wind

contours ~ pressure



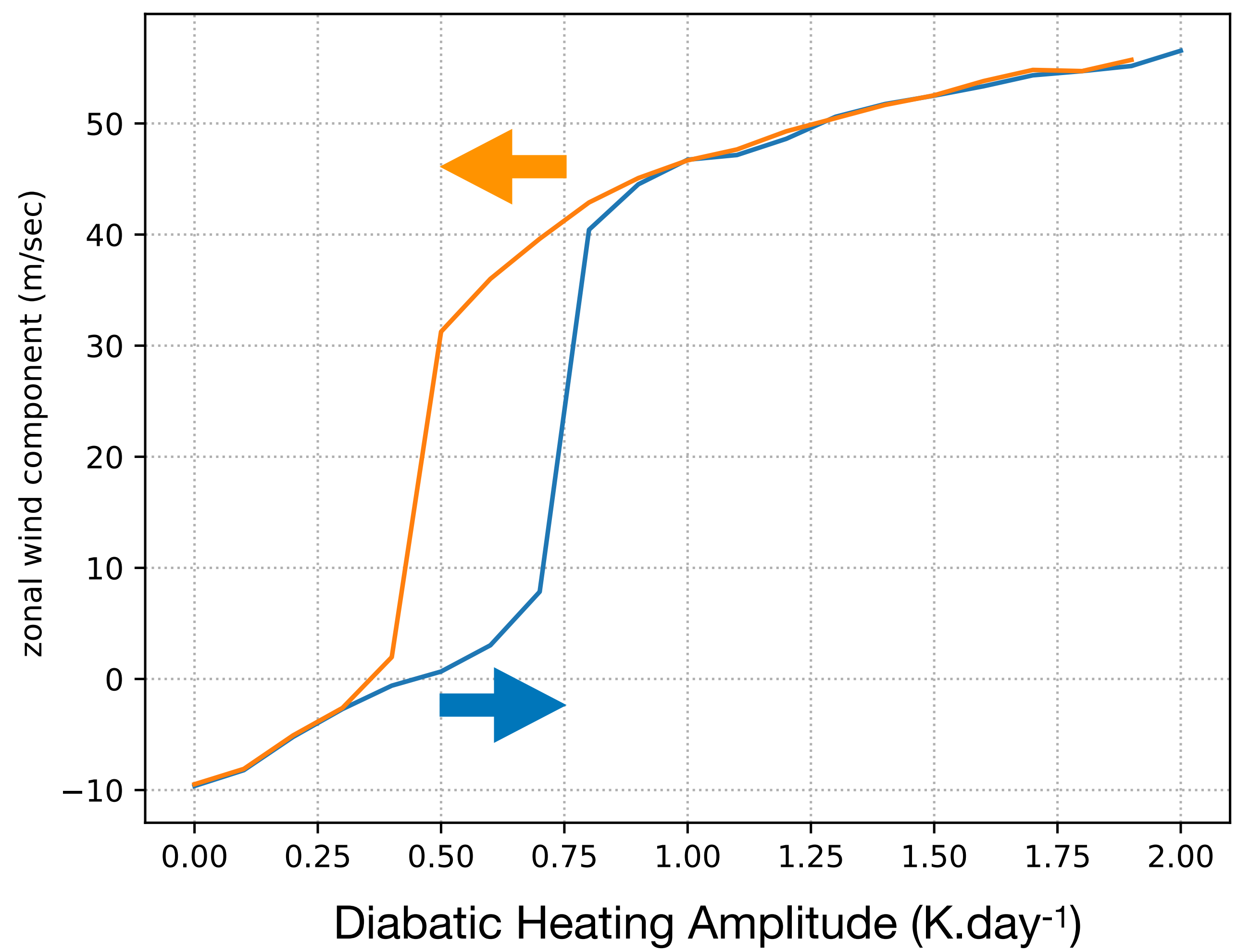
Herbert et al (2020)

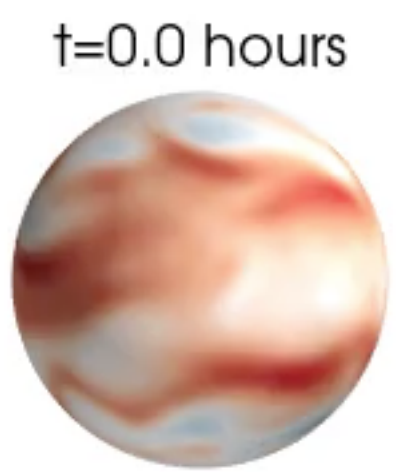


Simple model for bistability

Tipping points in the large-scale atmospheric circulation?

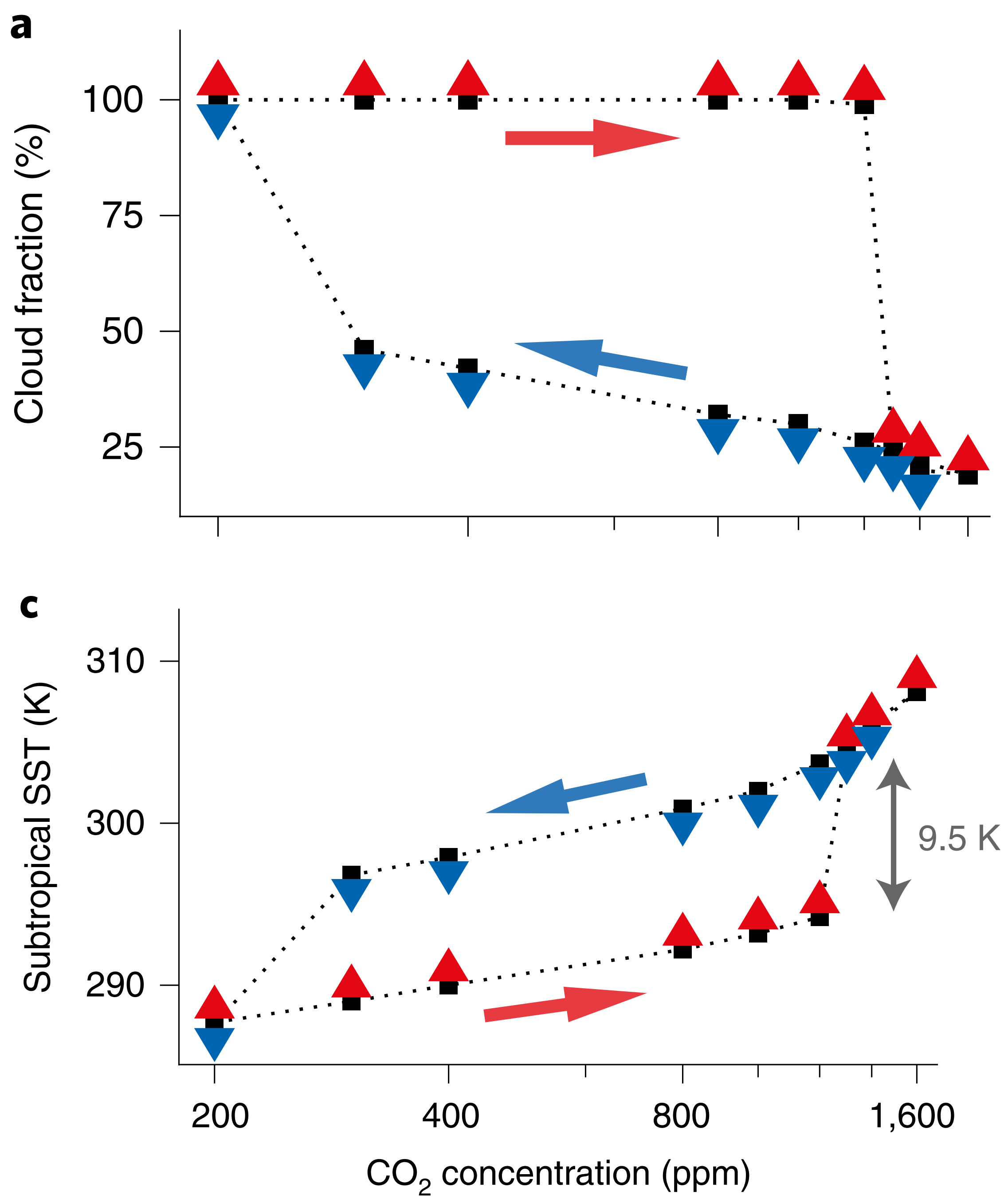
Transition driven by diabatic heating in the tropics

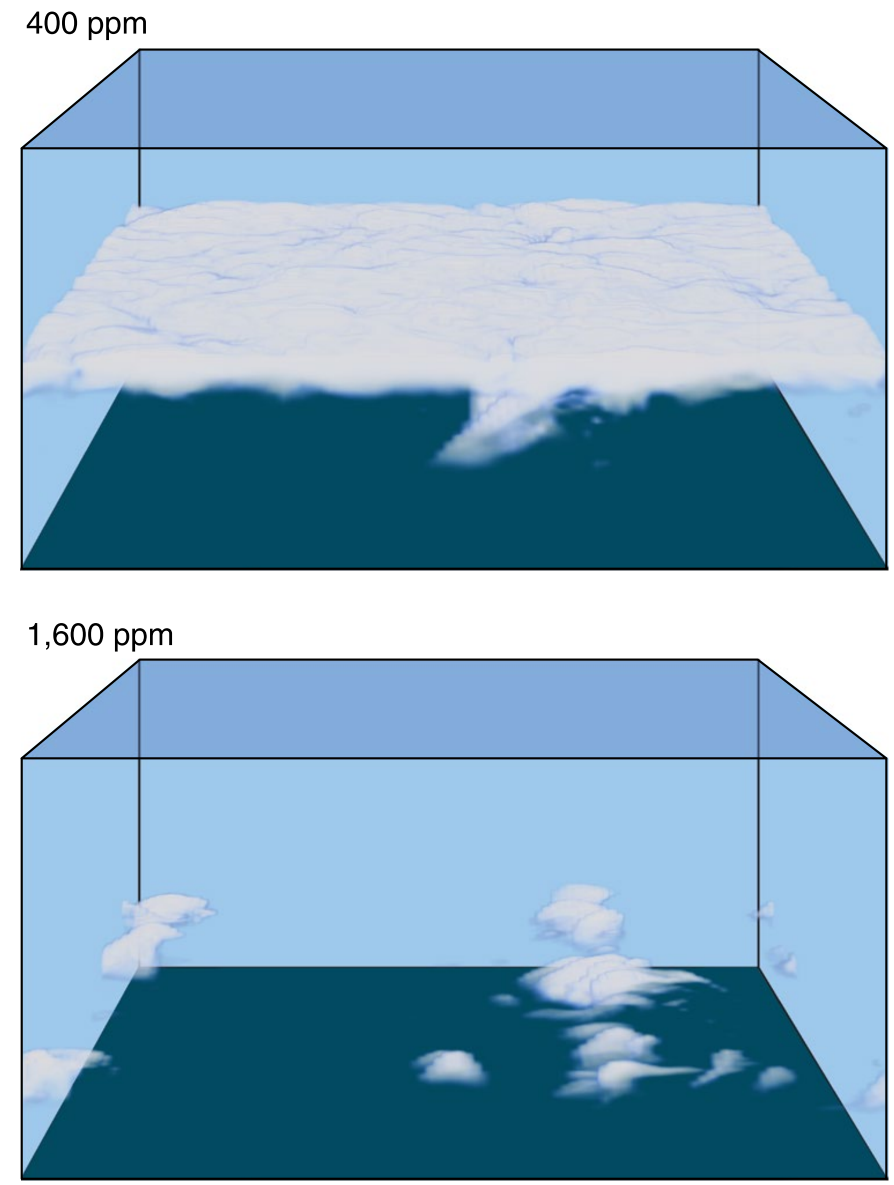




3D dry primitive equations exhibits hysteresis between conventional circulation and superrotating state in some parameter regimes (weak baroclinicity or weak boundary layer friction)

Clouds and turbulence





Abrupt breakup of stratocumulus decks in coupled cloud LES/ tropical atmosphere column model

Schneider et al (2019)

Outline

I. Tipping points in current models: state-of-the-art and limitations

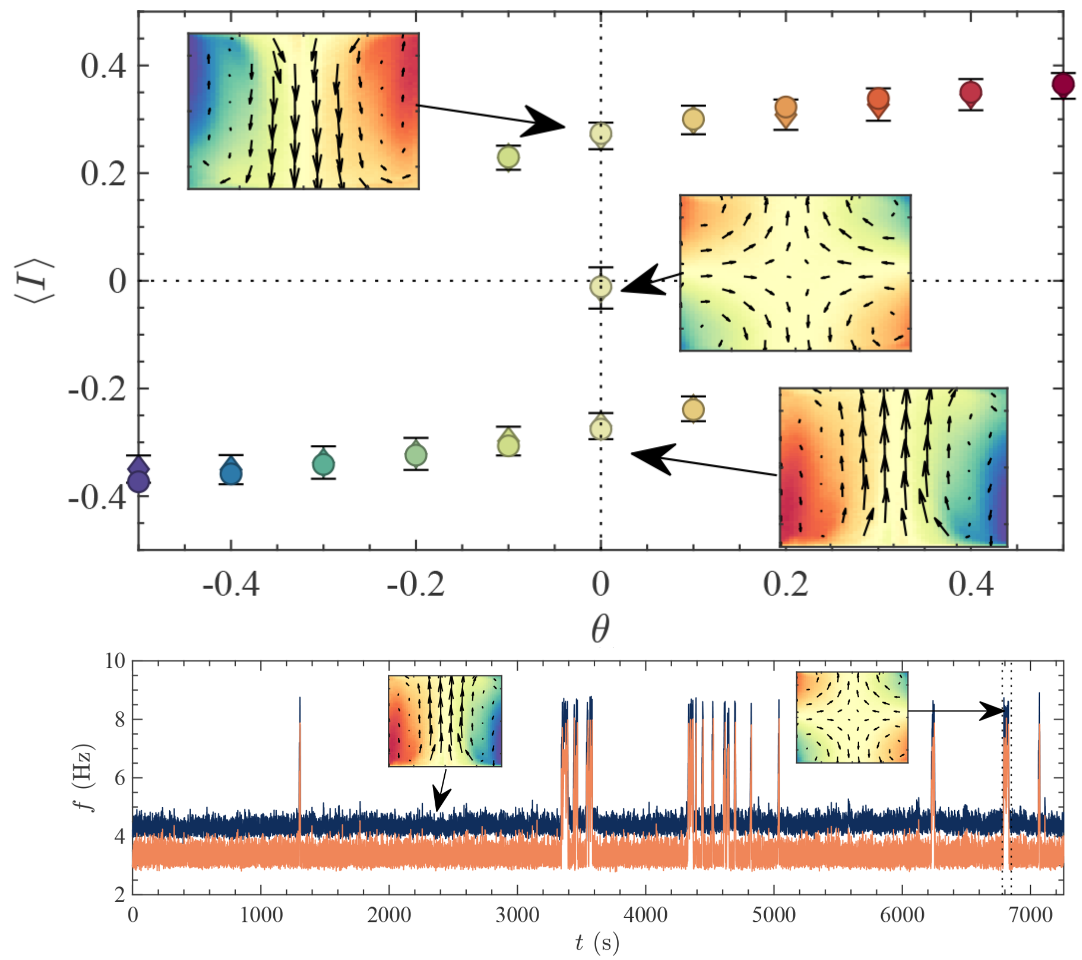
II. Towards a quantitative study of tipping points

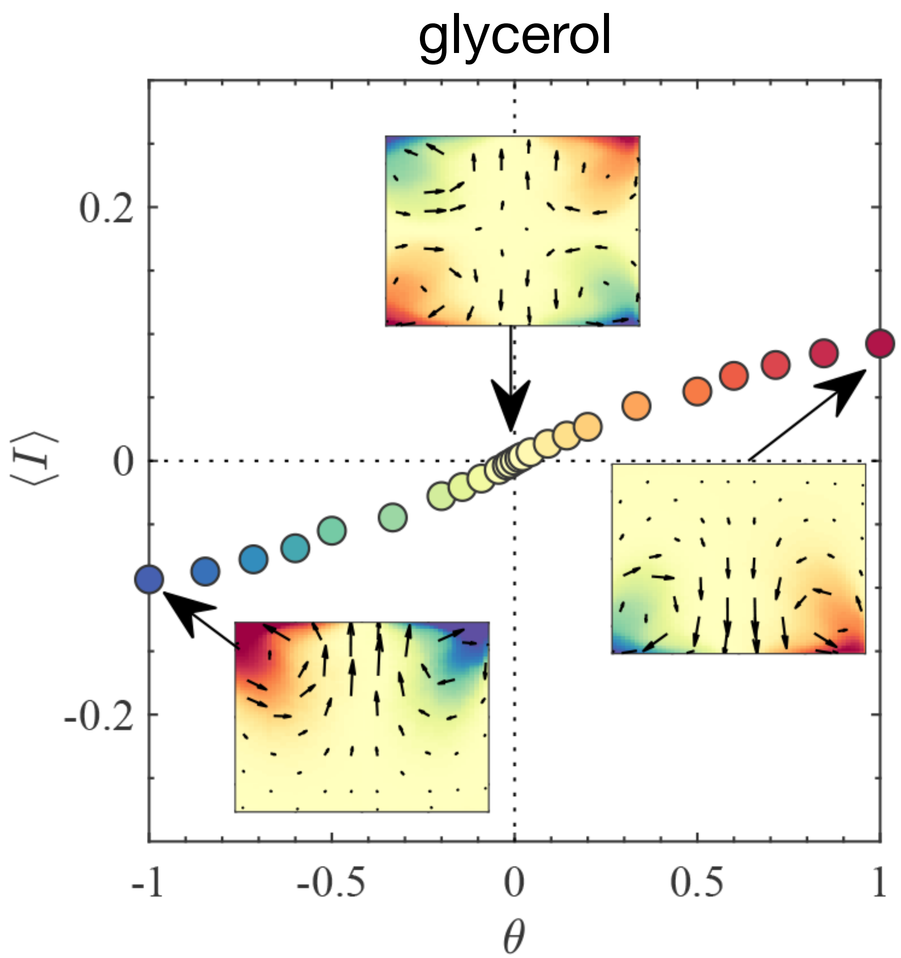
1. **Transitions in turbulent flows**

2. New theoretical tools

III. Conclusions

Von Karman Flow



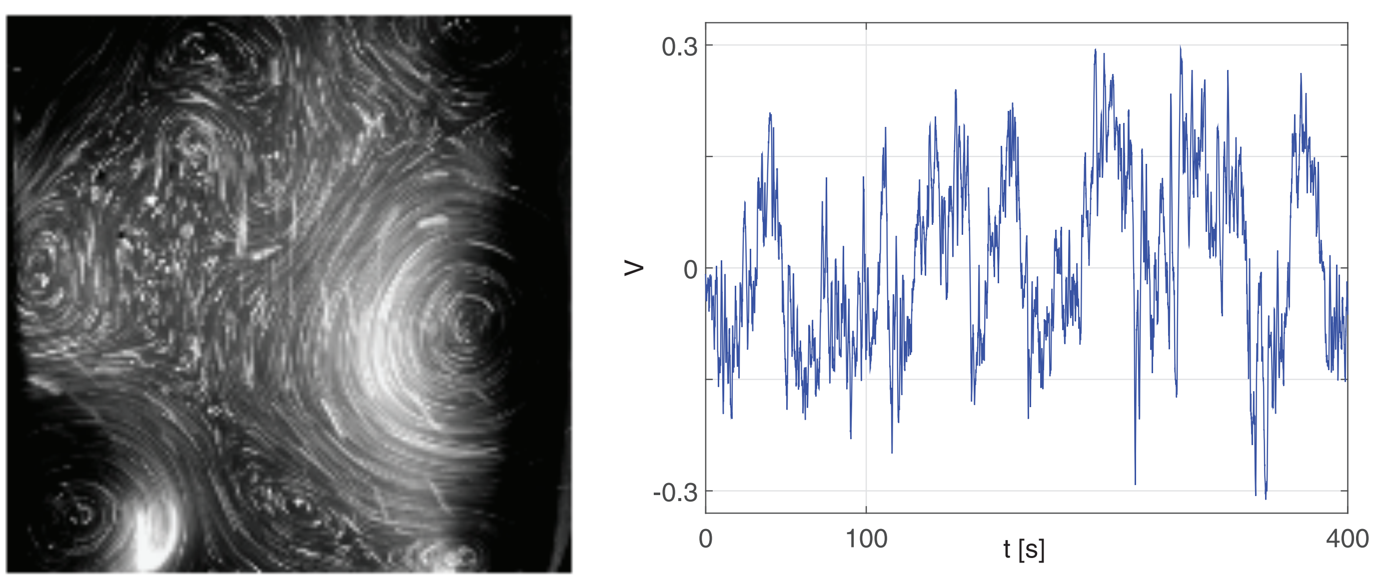


- **Hysteresis and spontaneous transitions observed in turbulent flow**
- **The nature of the transition depends on the viscosity**
- **Fluctuations at very-small scales (sub-Kolmogorov) might matter for those transitions**

Ravelet (2005)
Torre & Burgete (2007)
Berhanu et al. (2007)
Saint-Michel et al. (2013)
Dubrulle et al. (2022)

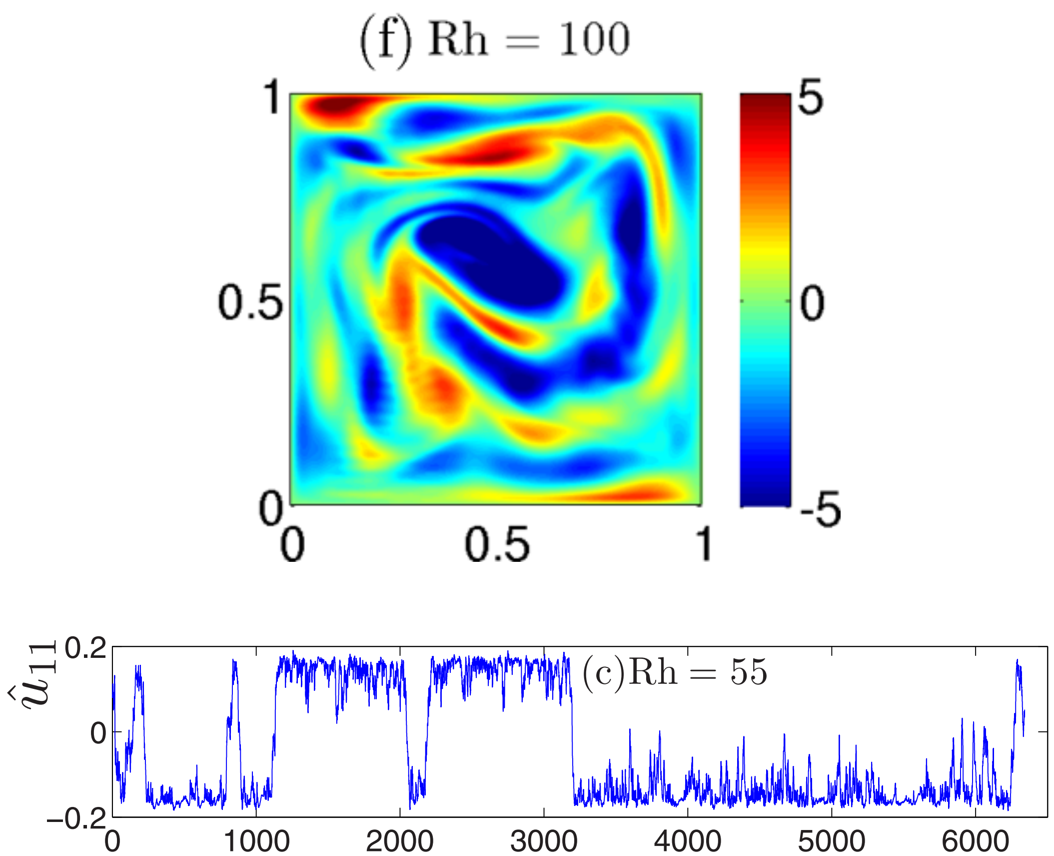
Quasi-bidimensional flow

Experiment



Michel et al. (2016)

Numerical Simulations



Mishra et al. (2015)

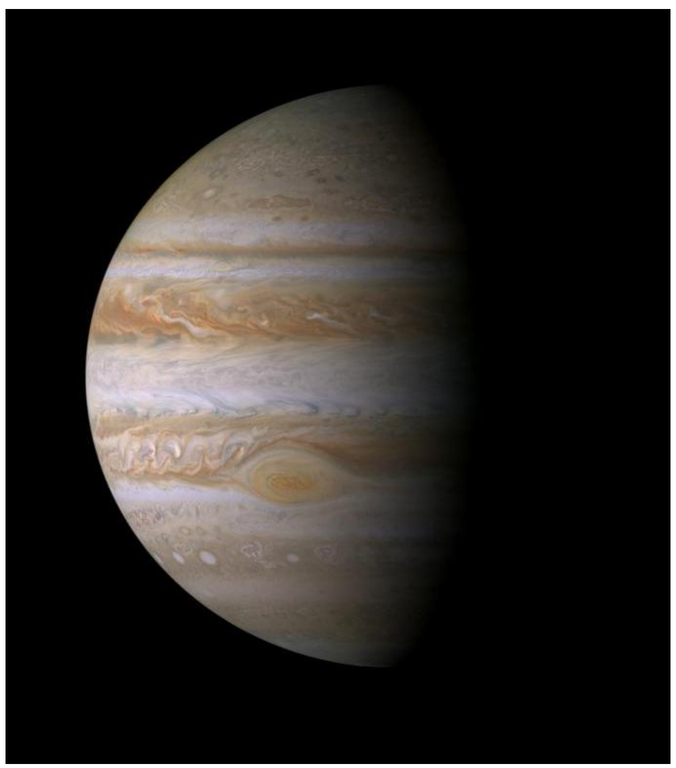
- **Random reversals of large-scale flow in electromagnetically forced thin fluid layer**
- **Bifurcation structure studied in details**
- **Both large-scale friction and molecular viscosity matter**

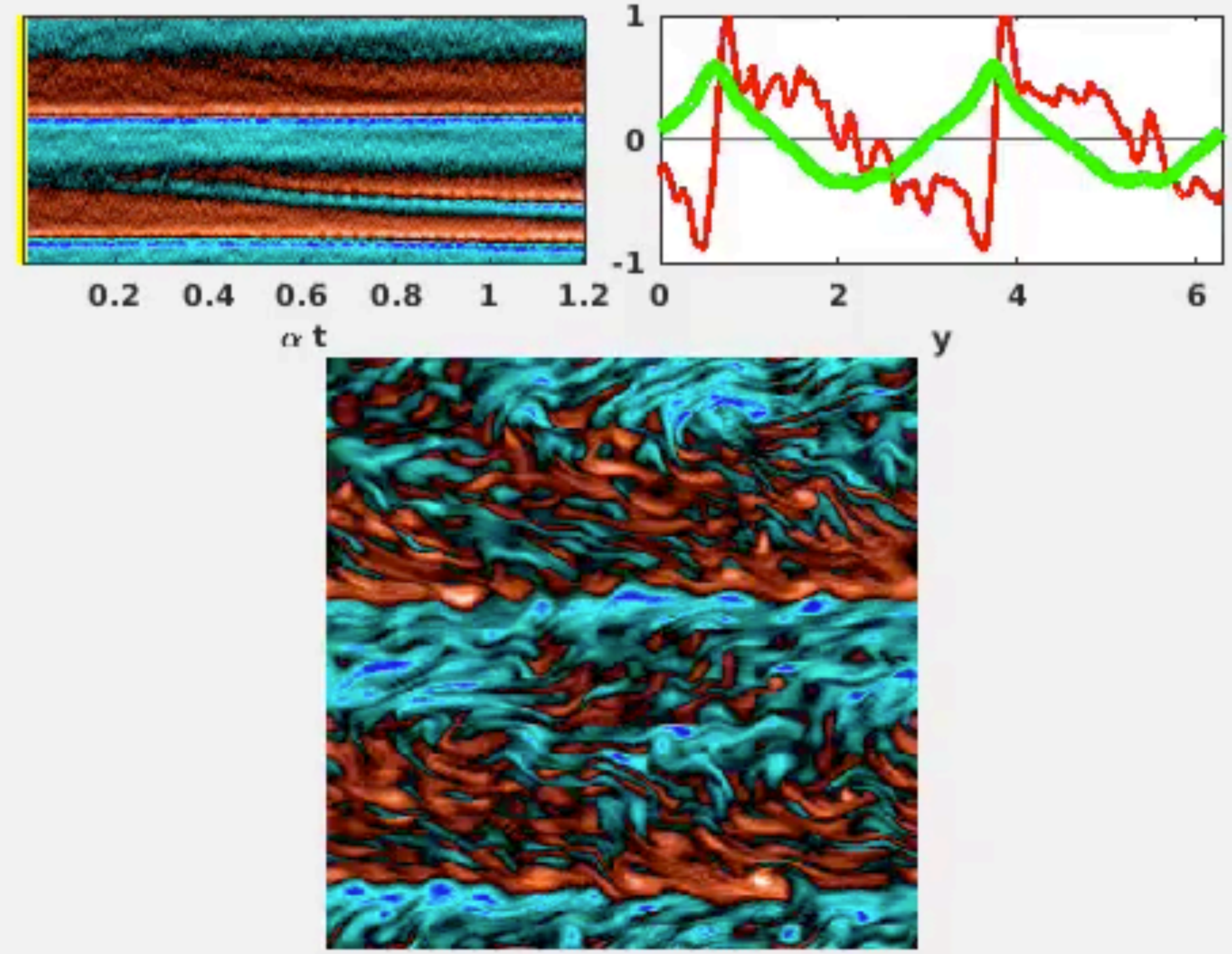
See also Herault et al. (2015), Shukla et al. (2016), Pereira et al. (2019), Dallas et al. (2020)

Barotropic Jets

Model for Jupiter jets

$$\partial_t \omega + \mathbf{u}\nabla\omega + \beta v = \nu\Delta\omega - \alpha\omega$$





Rare jet nucleation and merging

Bouchet et al. (2019)
Simonnet et al. (2021)

Outline

I. Tipping points in current models: state-of-the-art and limitations

II. Towards a quantitative study of tipping points

1. Transitions in turbulent flows

2. **New theoretical tools**

III. Conclusions

Towards a quantitative study of transitions

Many new theoretical and numerical tools have been developed over the past years and used to study precise properties of transitions in complex systems.

Conceptual issues

What are the relevant statistical quantities?
Which properties of abrupt transitions are generic and predictable?

Large deviation theory, Transition path theory…

Practical issues

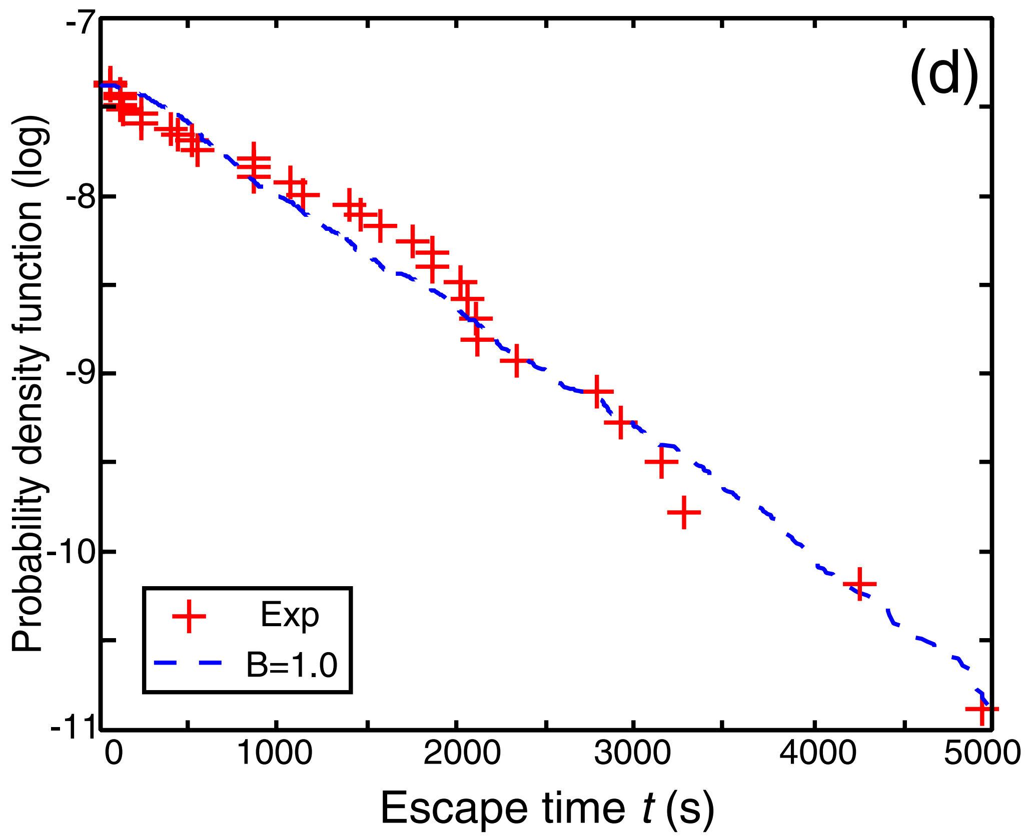
How to sample events of interest, which are rare, with costly numerical models?
How to make an optimal use of the available data?

Rare event algorithms, data-based methods (including machine learning)…

Transition time statistics

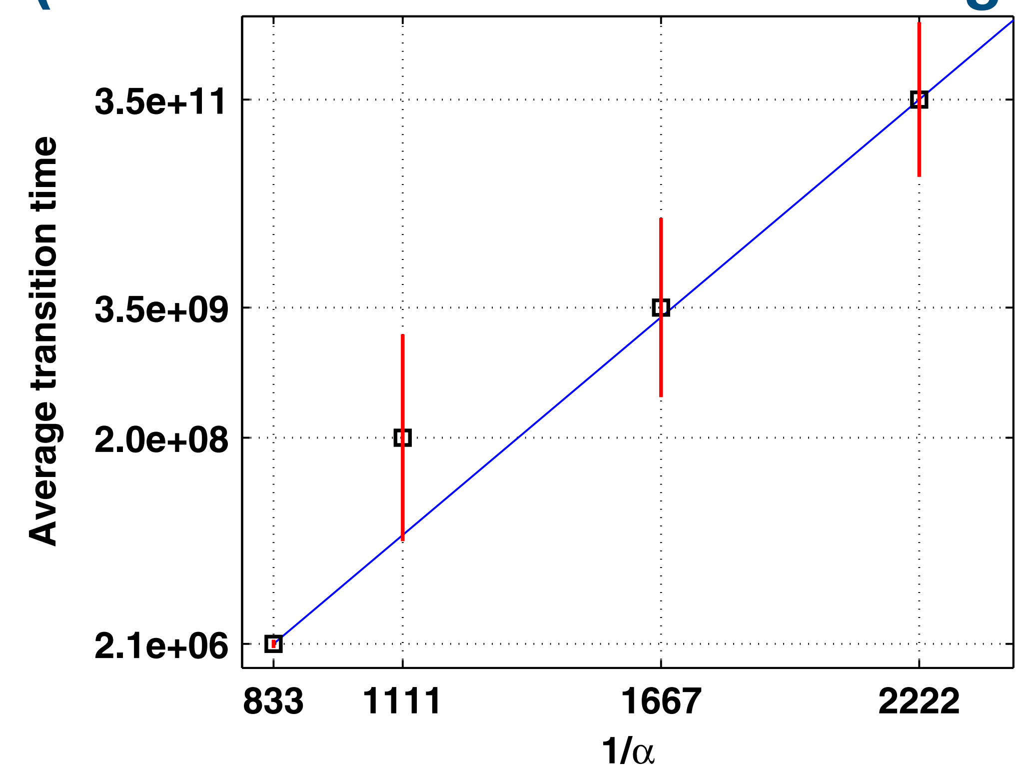
Goal: estimate the probability/return time of transitions

Von Karman Flow (experiment)



Torre & Burgete (2007)

Barotropic Jets (simulation with a rare event algorithm)



Bouchet et al. (2019)

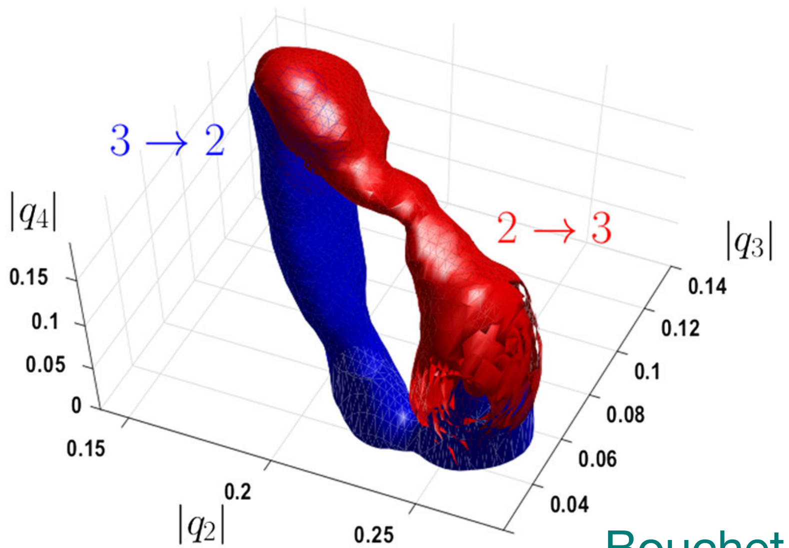
Phenomenology similar to classical results (Kramers, Eyring…)

- **Transitions form a Poisson point process**
- **Arrhenius law:** $\mathbb{E}[\tau] \propto e^{\Delta V/\varepsilon}$

Instanton-like behavior

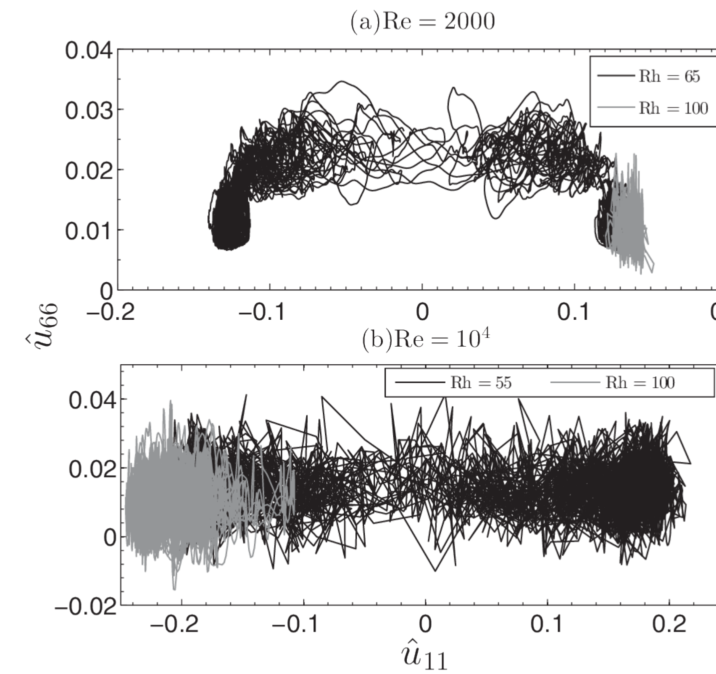
Goal: characterize the dynamics of the transition

Barotropic Jets



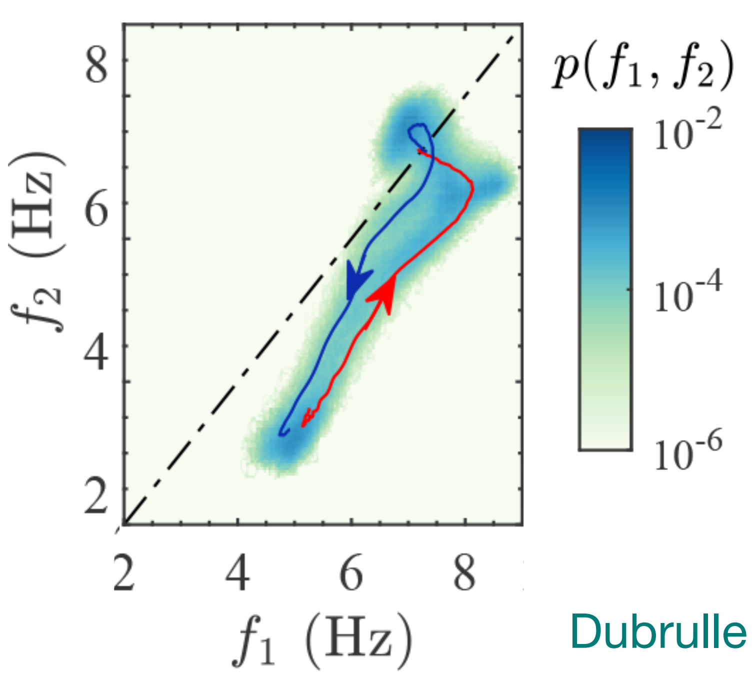
Bouchet et al. (2019)

2D vortex condensate



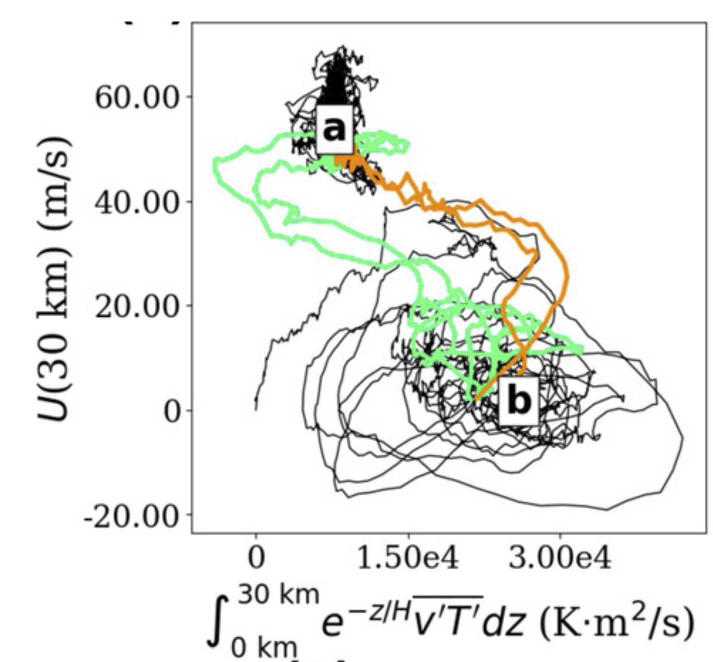
Mishra et al. (2015)

Von Karman Flow



Dubrulle et al. (2022)

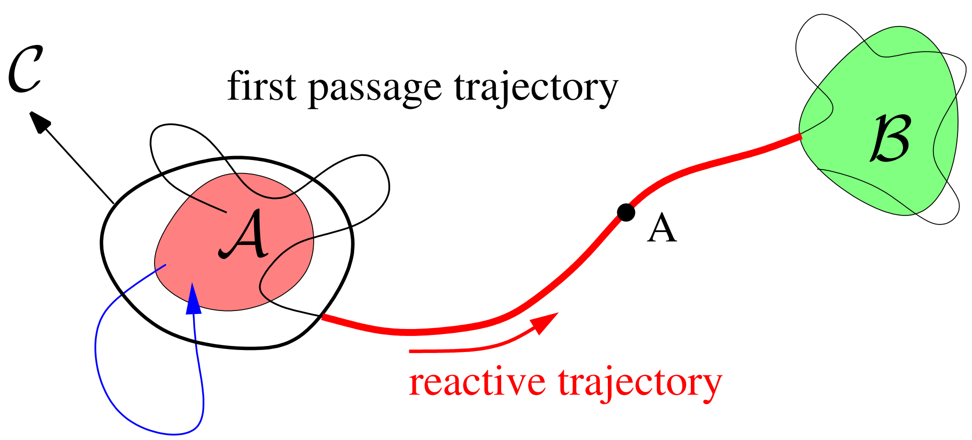
Sudden Stratospheric Warmings



Finkel et al. (2021)

Committor Functions

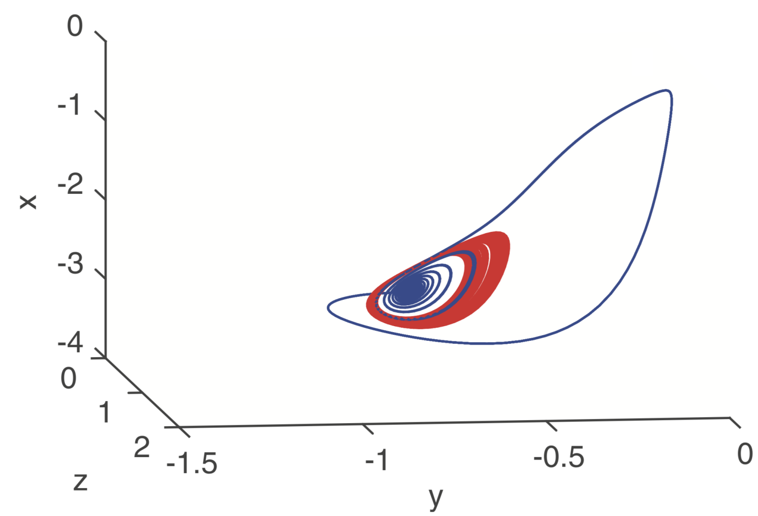
Definition

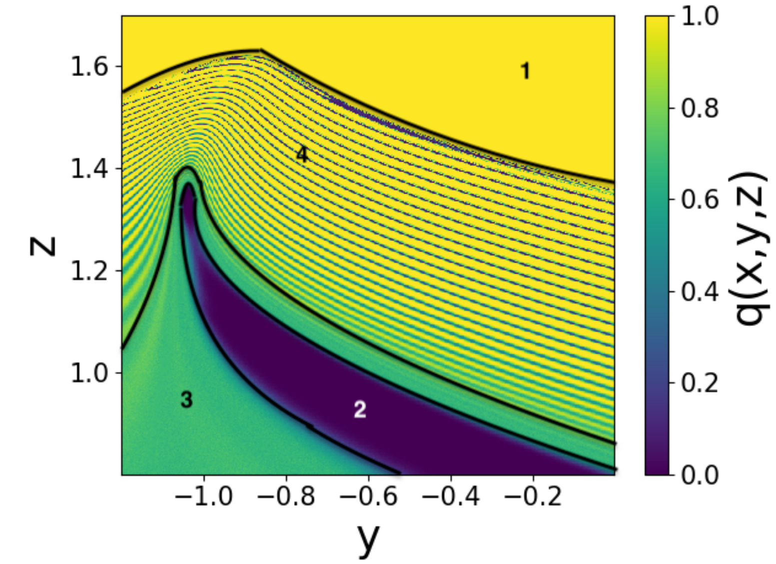


$$q(x) = \mathbb{P}[\tau_{\mathscr{B}} < \tau_{\mathscr{A}} \,|\, X_0 = x]$$

$$\tau_{\mathscr{C}} = \inf\{t > 0 \,|\, X_t \in \mathscr{C}\}$$

Exemple: committor function for toy model of El Niño





Lucente et al. (2022)

Several groups are currently developing tools to compute committor functions in complex systems such as climate models. Lucente et al. (2019), Thiede et al. (2019), Khoo et al. (2019), Finkel et al. (2021), Jacques-Dumas et al. (2022), Lucente et al. (2022)

Applications:

- **early-warning signal, prediction problems**
- **Improving efficiency of rare-event algorithms for complex systems**

Conclusions

Tipping points are one of the fundamental aspects of the climate system, important for past and future climates, which are still lacking proper understanding

Modelling challenges

- Some tipping points are seen in climate models but are still marred by large uncertainties
- There are probably many other tipping points which are not currently represented in models
- Tipping points are still studied mostly independently from one another

Prospects for a quantitative study of tipping points

- Improved representation of dissipative processes, convection, clouds, etc in models
- Insight from controlled turbulence experiments
- Leveraging new theoretical and numerical tools