

Defining an early warning method for an AMOC collapse based on ensemble statistics

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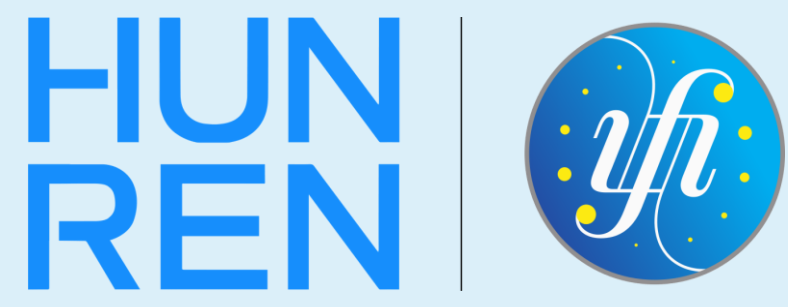
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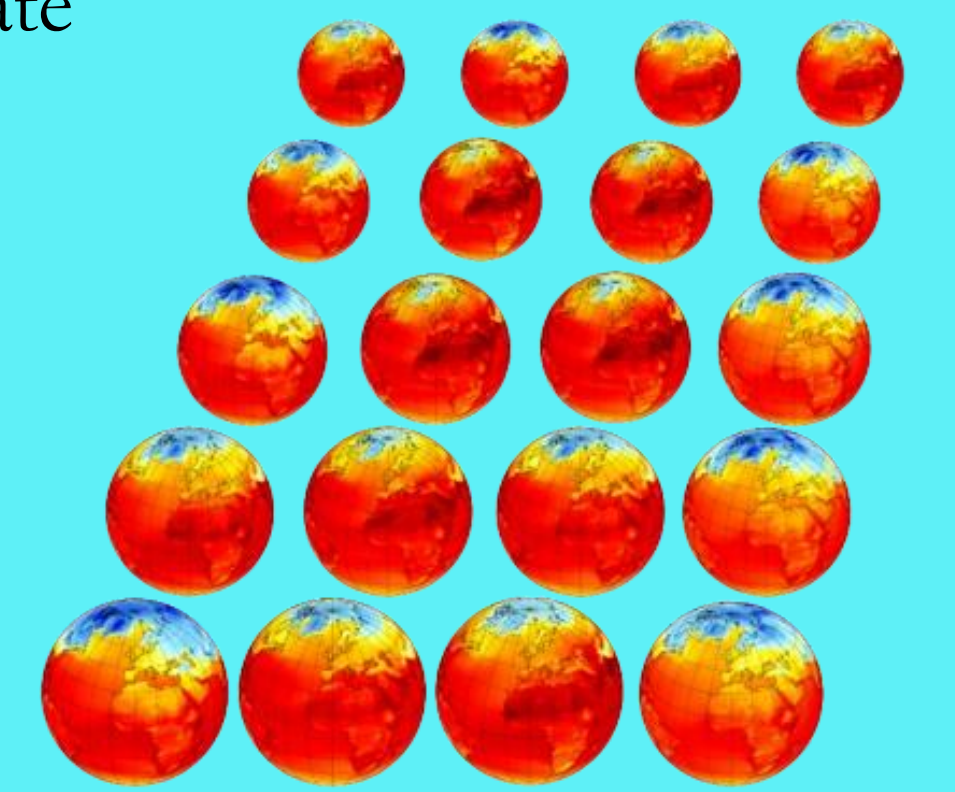


Background

- The **Atlantic Meridional Overturning Circulation (AMOC)** is a system of ocean currents critical in maintaining global climate stability [1]
- Its **potential collapse** due to climate change is a central question of climate science, as it would have severe consequences, e.g. strong cooling in Northern and Central Europe
- We develop a **new early warning method** for the AMOC collapse under climate change, based on so-called **parallel climate realizations**
- We demonstrate this early warning in the low-dimensional **Lorenz84-Stommel model**, and the fully coupled **ACCESS-ESM1.5 model**

Parallel climate realizations

- In the language of **dynamical systems theory**, climate change means that the **system is non-autonomous**
- In these systems, investigating **only one simulation** (time series) is **not statistically representative**
- Instead, **an ensemble of simulations** have to be studied within the same system
- These are the so-called **"parallel climate realizations"**: Earth replicas developing independently under the same physics [2]



AMOC collapse in the Lorenz84-Stommel model

Lorenz84-Stommel model [3]:

$$\varepsilon_f \dot{x} = -\Delta - ax + aF + aF_1 T$$

$$\varepsilon_f \dot{y} = xy - bxz - y + G$$

$$\varepsilon_f \dot{z} = bxy + xz - z$$

$$\dot{T} = -\frac{1}{\varepsilon_a}(T - T_s) - T - \mu|\Psi|T$$

$$\dot{S} = S_s - S - \mu|\Psi|S$$

where: $T_s = \theta + \theta_1 \frac{x - \bar{x}}{\sqrt{\varepsilon_f}}$

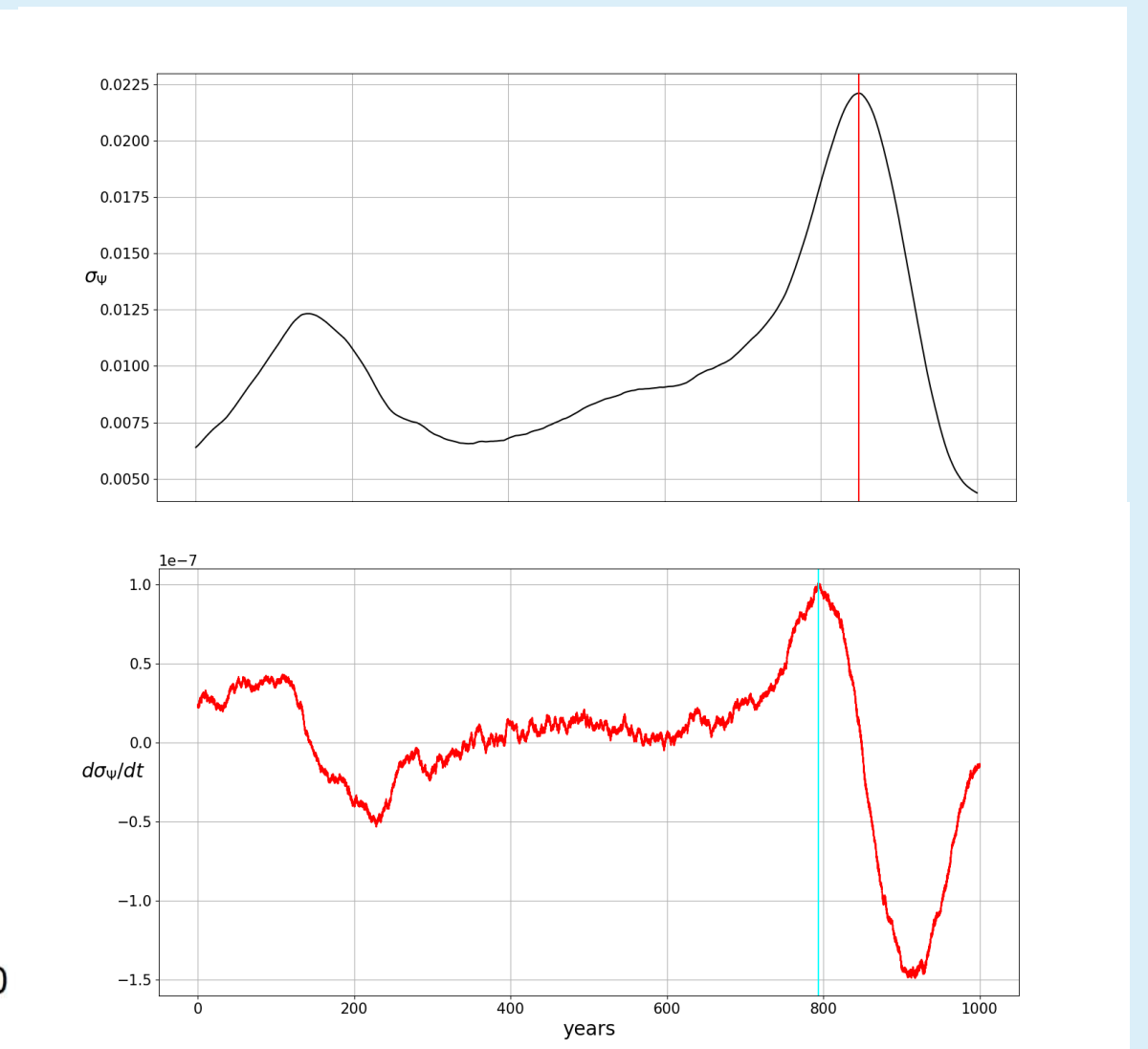
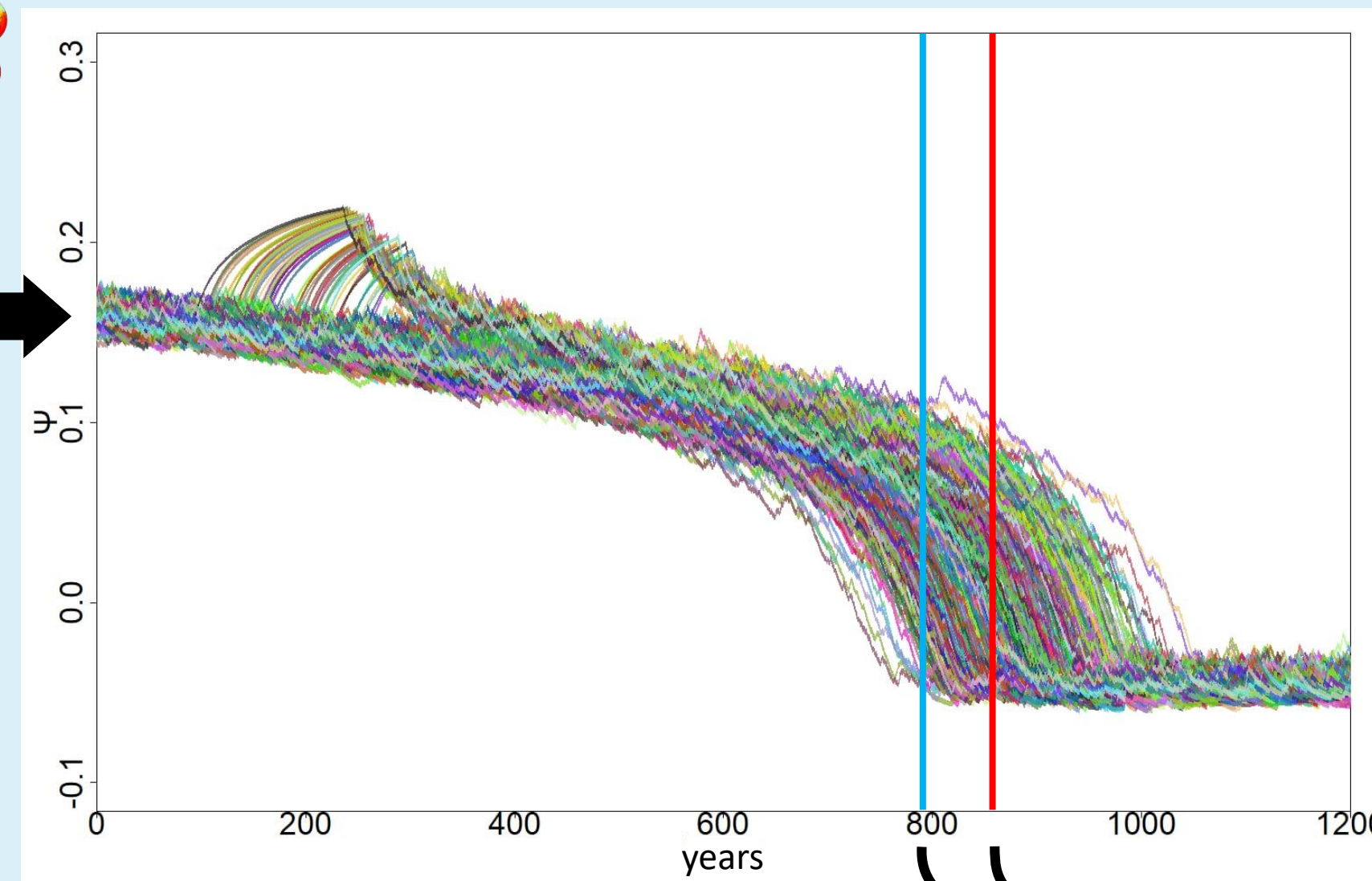
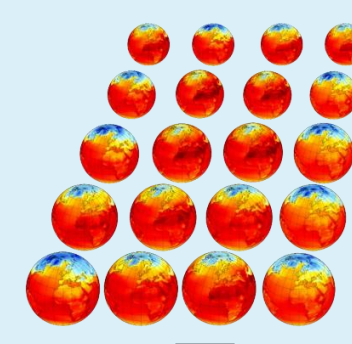
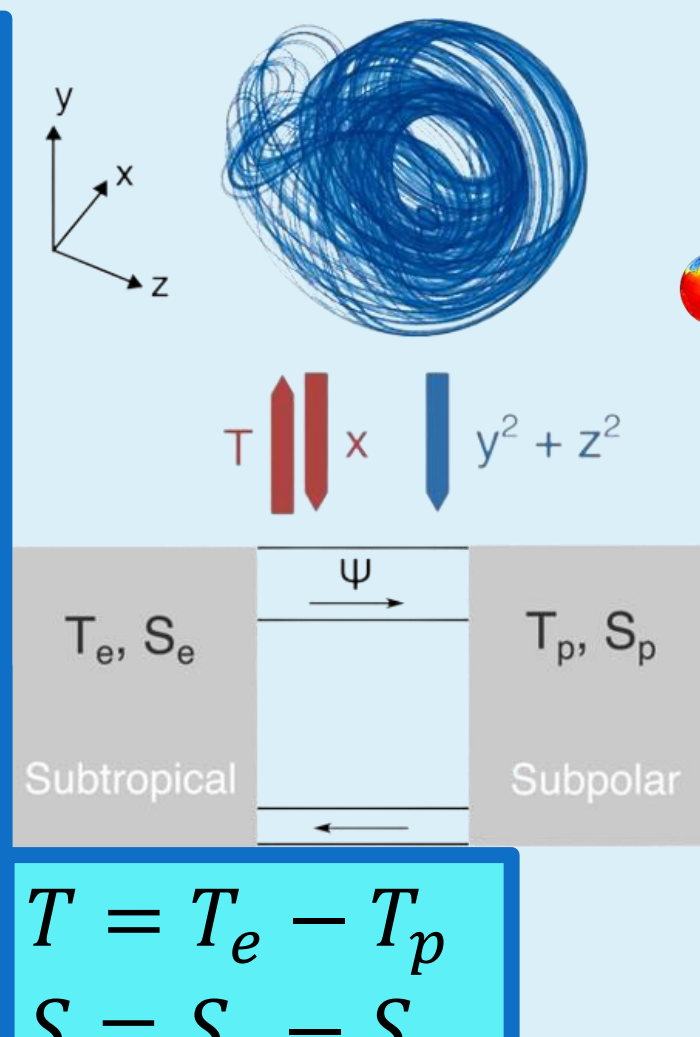
$$S_s = \zeta + \zeta_1 \frac{\Delta - \bar{\Delta}}{\sqrt{\varepsilon_f}}$$

$$\Delta = y^2 + z^2$$

AMOC flux: $\Psi = T - S$

$F \sim$ pole-to-equator temperature contrast

$\zeta \sim$ surface freshwater flux



Climate change:

$$F(t) = F_0 - \alpha t$$

$$\zeta(t) = \zeta_0 + \beta t$$

Initial conditions are generated through the "spin-up" method

The $\sigma_\Psi(t)$ variance over the parallel climates diverges near the critical transition

The **inflection point precedes the transition** by several decades

The early warning signal (EWS) is the maximum of the derivative of the variance:
EWS = max(σ'_Ψ)

Variance derivative maximum at 793 yrs

Collapse (variance maximum) at 849 yrs

EWS in the ACCESS-ESM model

The fully coupled ACCESS-ESM1.5 model [4] is one of the few ESMs that:

- Shows AMOC collapse
- Uses parallel climate realizations

10 realizations with SSP-8.5 until year 2300

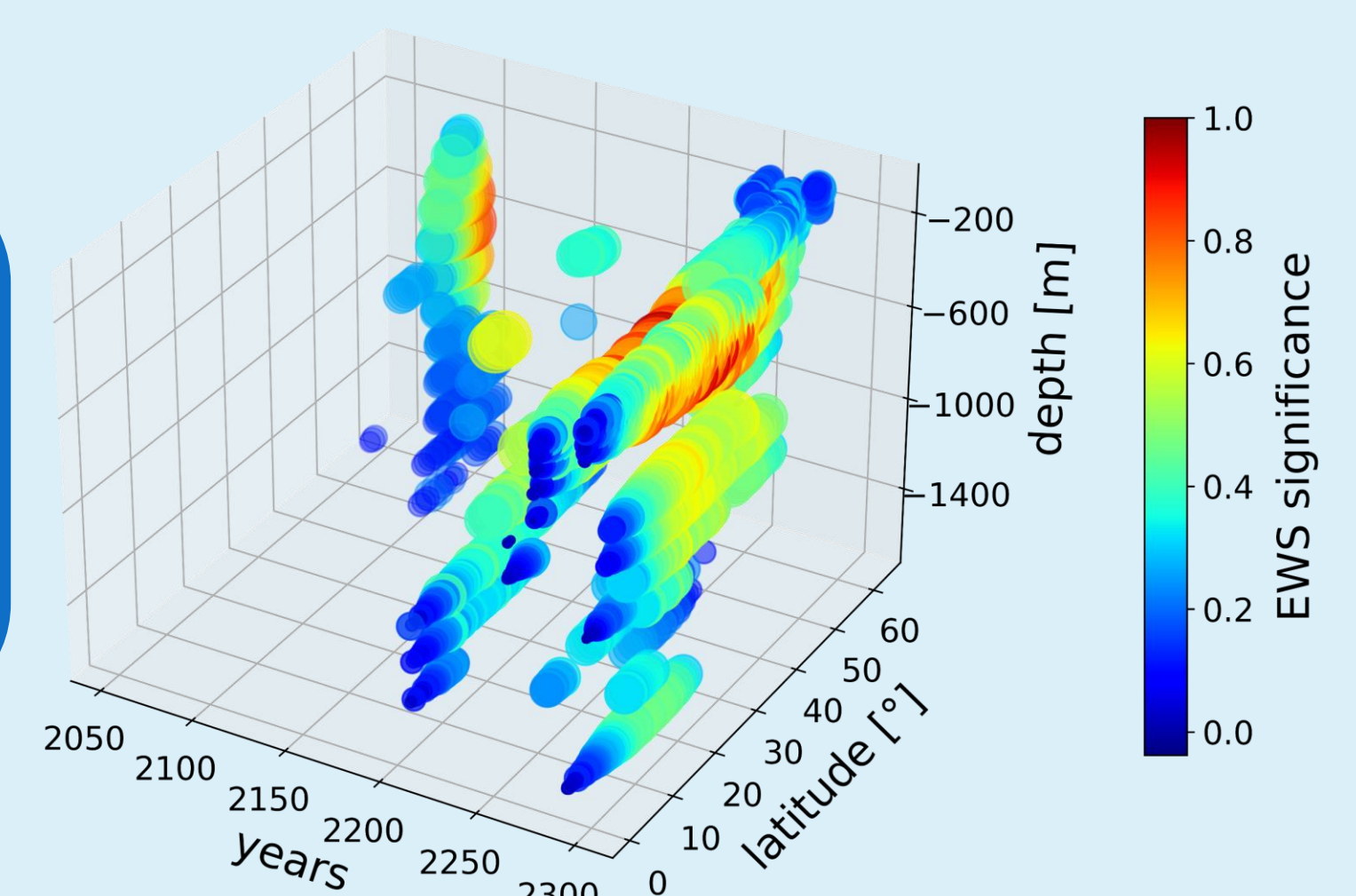
The EWS now depends on the spatial coordinates: $EWS(\varphi, z) = \max_t(\sigma'_\Psi(t, \varphi, z))$

EWS significance:

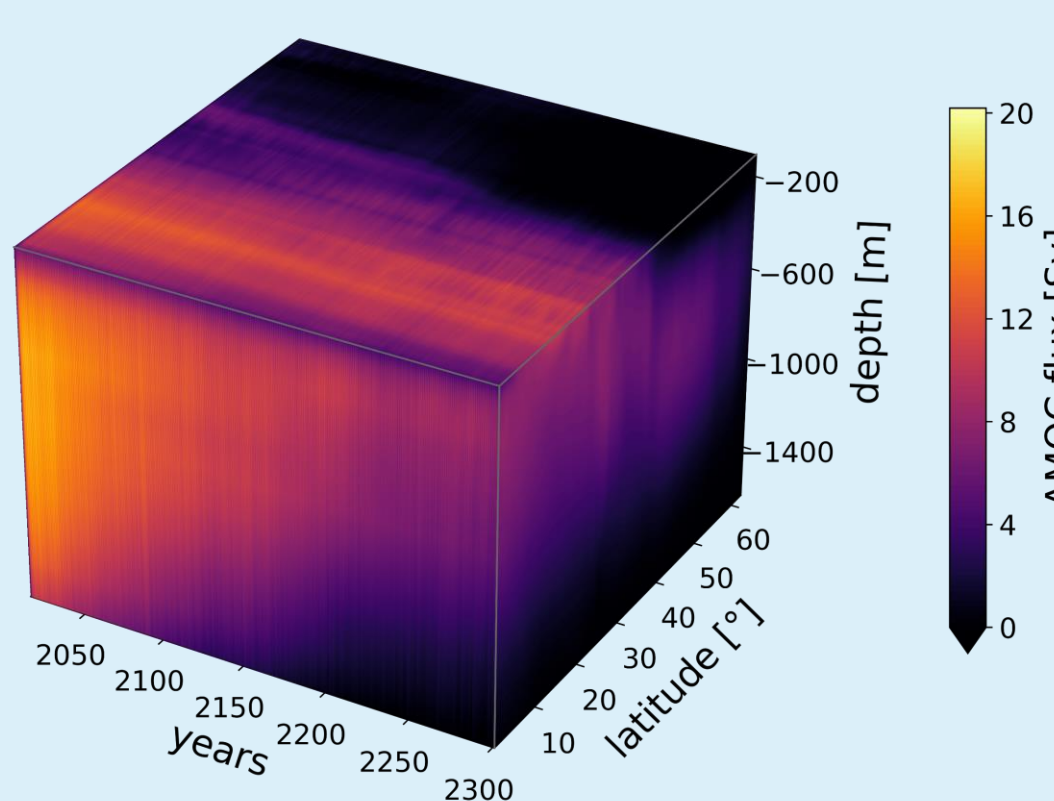
$$\xi_{EWS}(\varphi, z) = \left\| EWS - \max(\{\sigma'_\Psi = 0\} \setminus EWS) \right\|$$

Significant EWS points:

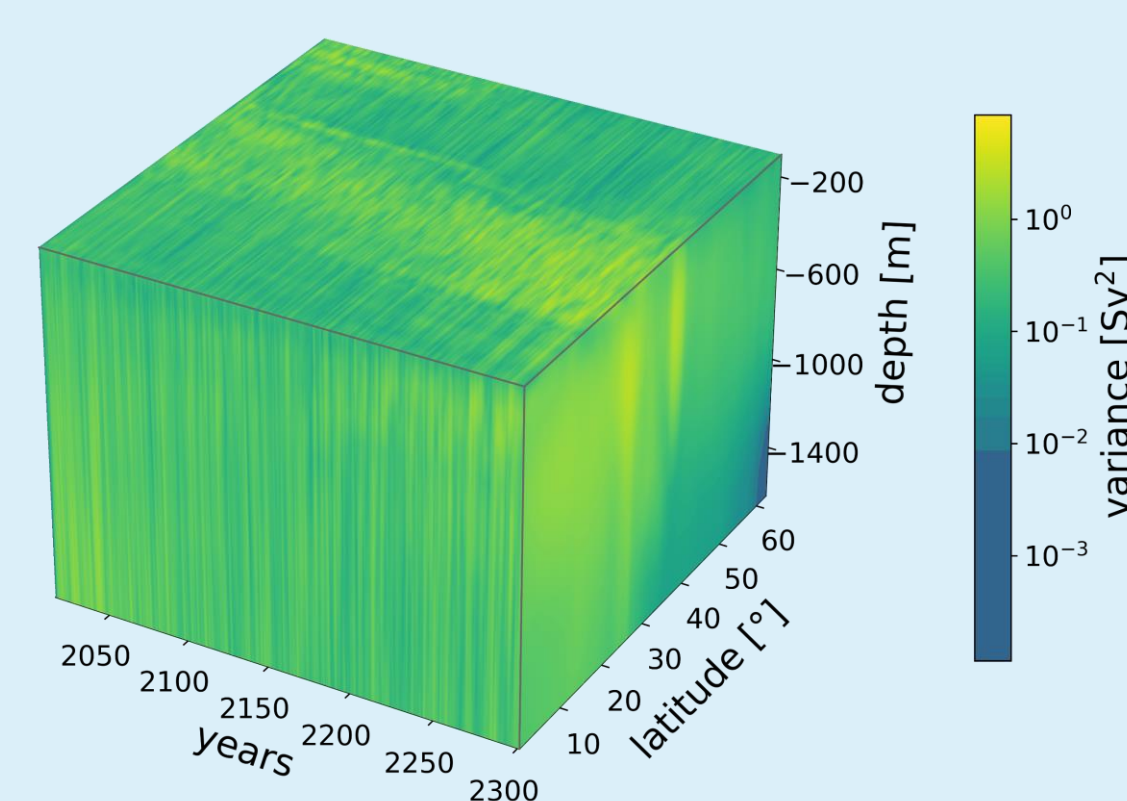
- 2090, 60°, 400-700m
- 2270, 10°-50°, 200-600m
- 2290, 10°-30°, 200m



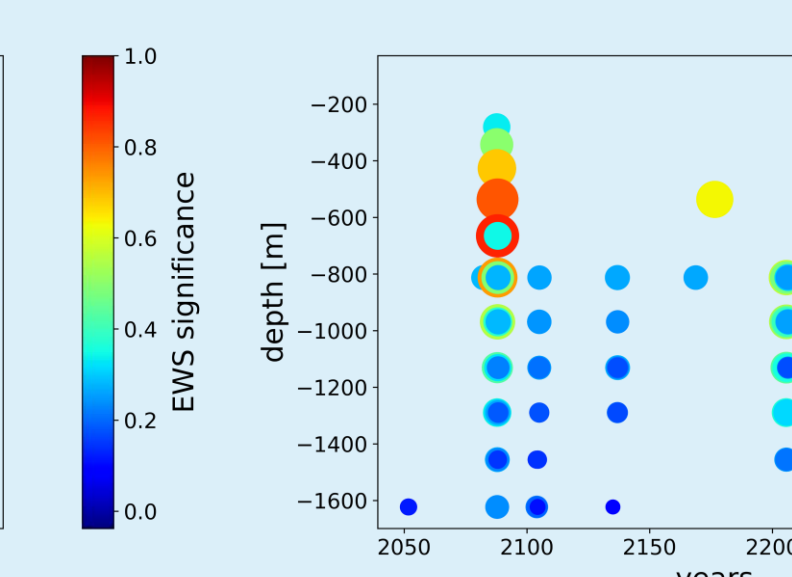
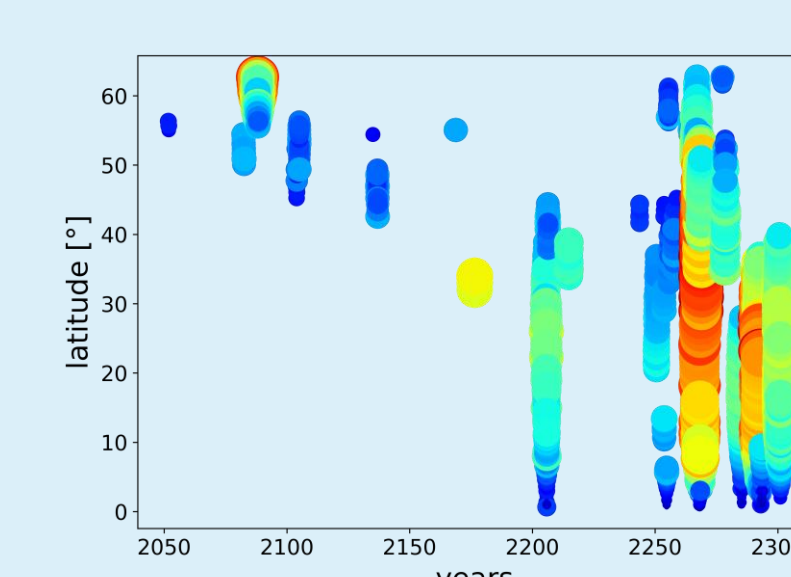
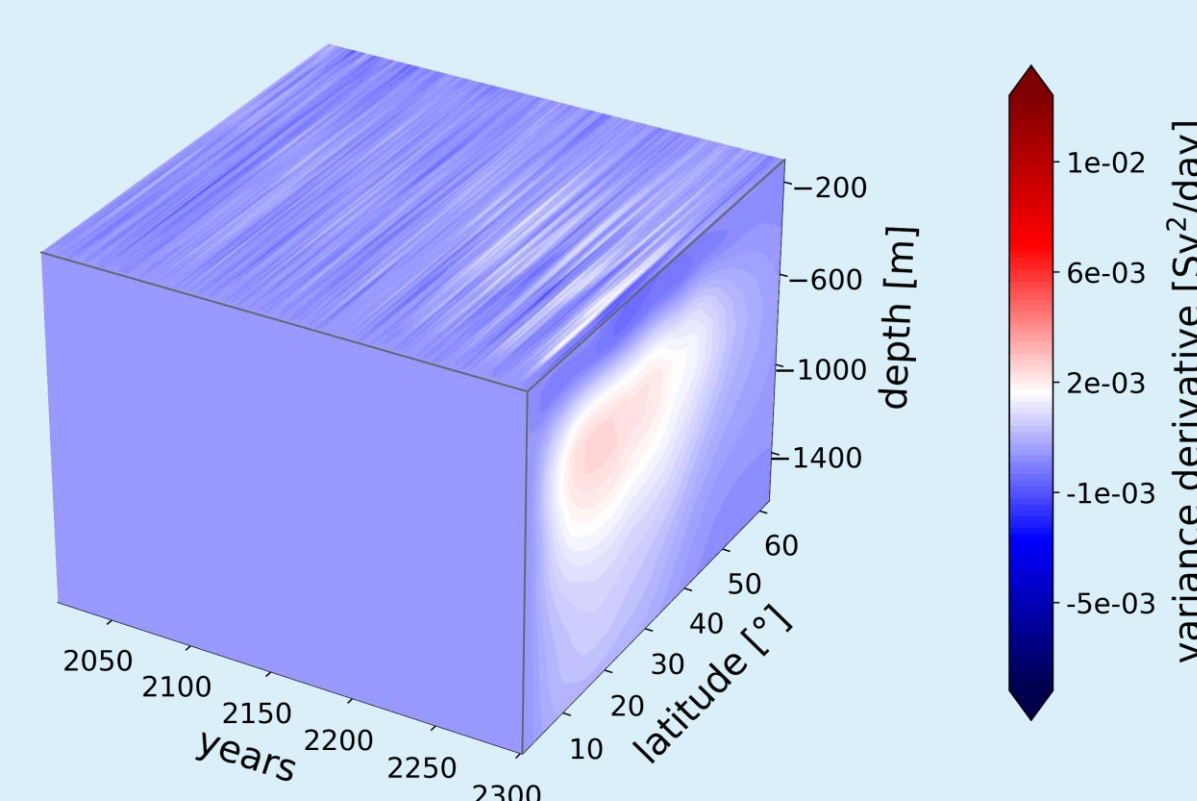
$\bar{\Psi}(t, \varphi, z)$



$\sigma_\Psi(t, \varphi, z)$



$\sigma'_\Psi(t, \varphi, z)$



References

- [1] Johns et al., Journal of Climate 24, pp. 2429-2449 (2011)
- [2] Herein et al., Scientific Reports 7, 44529 (2017)
- [3] Mehling, Börner and Lucarini, Physica D 459, 134043 (2024)
- [4] Ziehn et al., Journal of Southern Hemisphere Earth Systems Science, 70(1), 193-214 (2020)

Acknowledgments

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