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Estimating proximity to the AMOC tipping point using Machine Learning

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Introduction

- The **Atlantic Meridional Overturning Circulation (AMOC)** is a key part of the climate system, transporting heat and salt northward.
- Evidence suggests it may be **multi-stable**, with a strong and a weak or collapsed state, linked by the **salt-advection feedback**. When **freshwater forcing** is applied in the North Atlantic, it freshens the surface, **weakens deep-water formation**, and reduces **northward salt transport**, which further weakens the AMOC.

Our contribution

- We develop a **CNN-based approach**, combined with a **normalized distance index** d_f ,to estimate the **distance to the AMOC tipping point** directly from **oceanic variables**. The method **does not rely on proxy data**, **requires no prior knowledge of the forcing rate**, and **generalizes across models of varying complexity**.

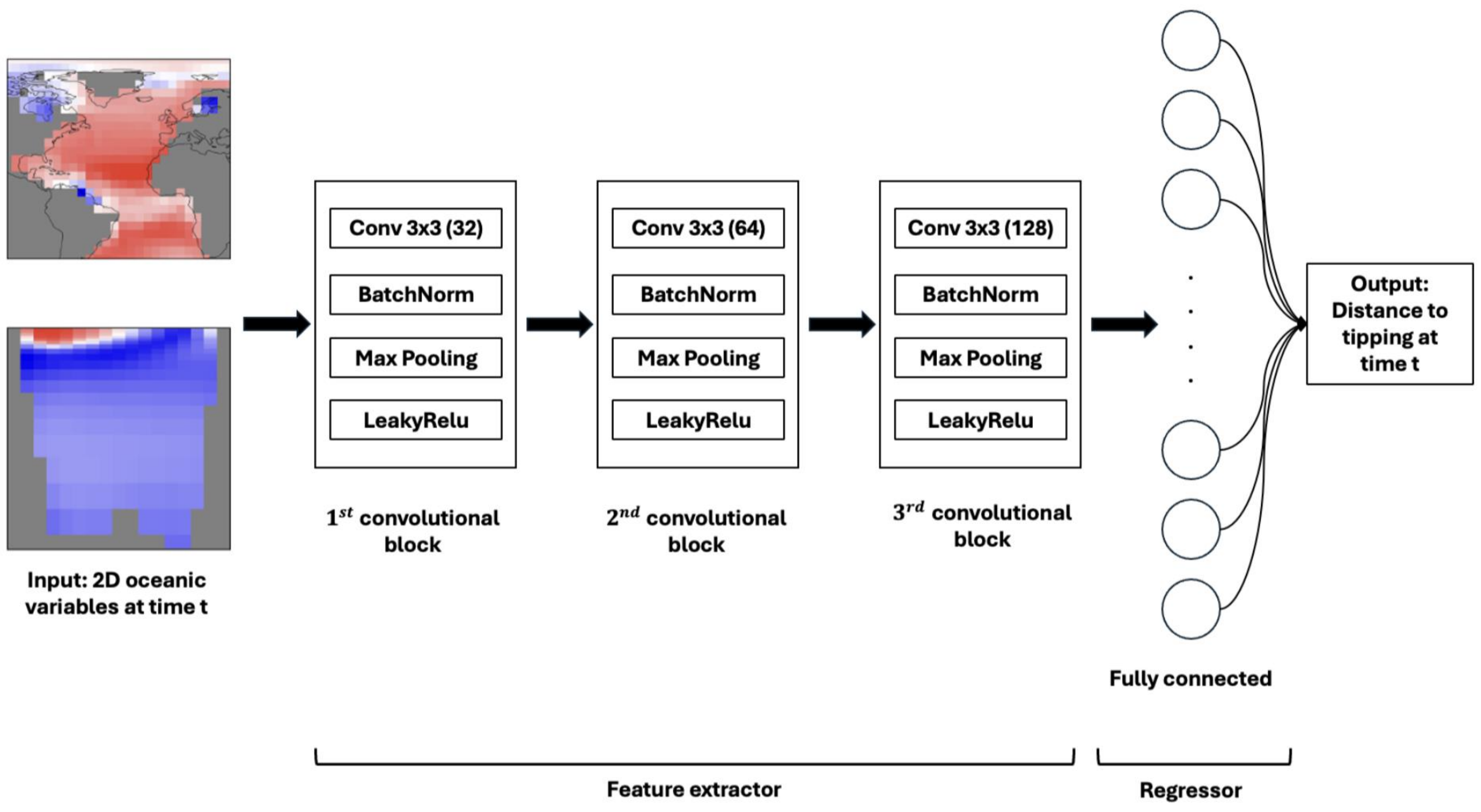


Figure 1
Architecture of the Convolutional Neural Network (CNN) employed for AMOC tipping prediction.

Input data and normalized index definition

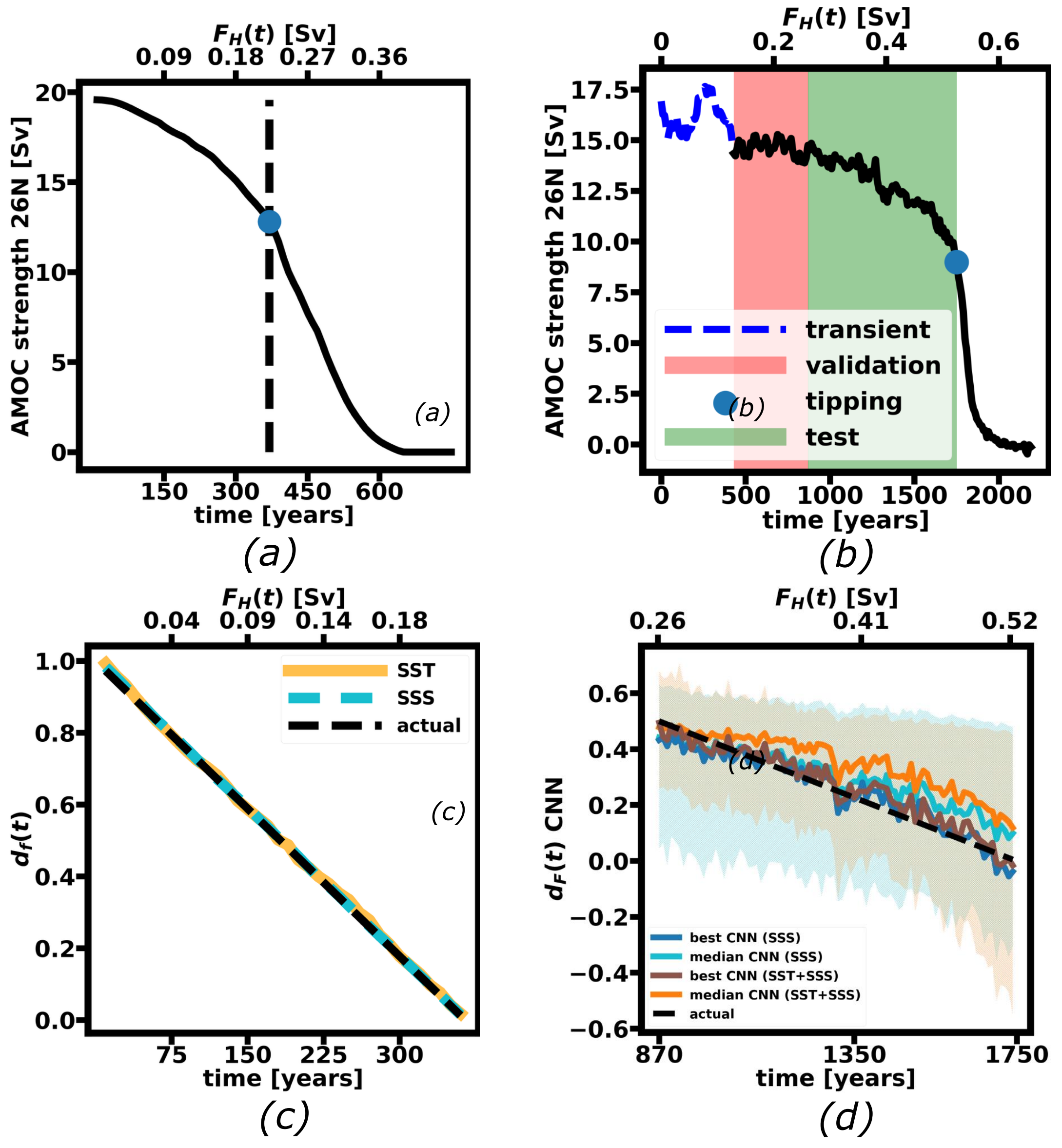
- **Inputs:**
  - Sea Surface Temperature fields **(SST)** (90°N–35°S, Atlantic)
  - Sea Surface Salinity fields **(SSS)** (90°N–35°S, Atlantic)
  - **Full-depth salinity section** at 35°S
- **Output:** Normalized distance-to-tipping index

$$d_f(t) = \frac{FH(t_p) - FH(t)}{FH(t_p)}$$

- $FH(t)$:freshwater forcing at time t
- $FH(tp)$:freshwater forcing at tipping

Results

- CNN first **trained and evaluated** on 7 AMOC collapse simulations (different forcing rates r_f). from intermediate complexity **CLIMBER-X model.**
- For **generalization**, trained on CLIMBER-X and then **tested on the CESM collapse run** obtained in [1].
- **Outcome:** near-perfect fit on CLIMBER-X and strong performance on CESM.



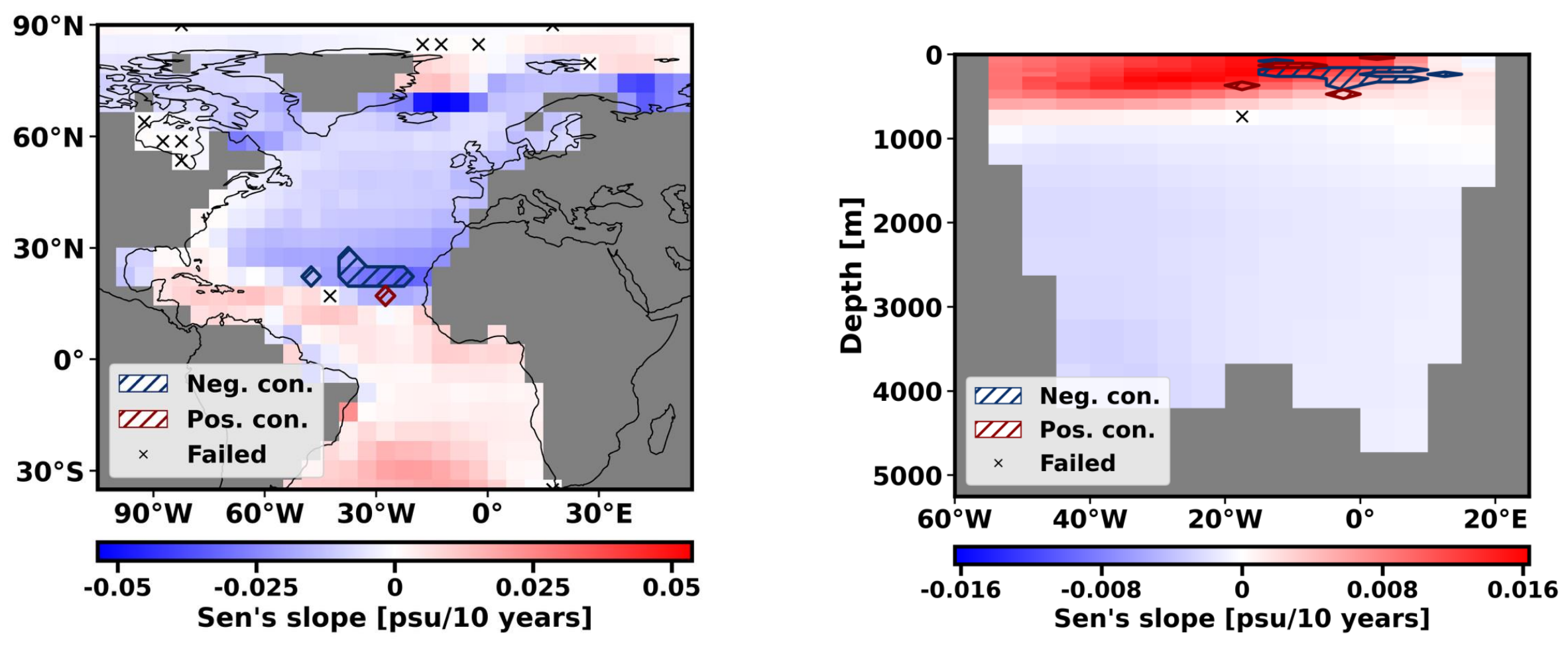
(a) (b)

(c) (d)

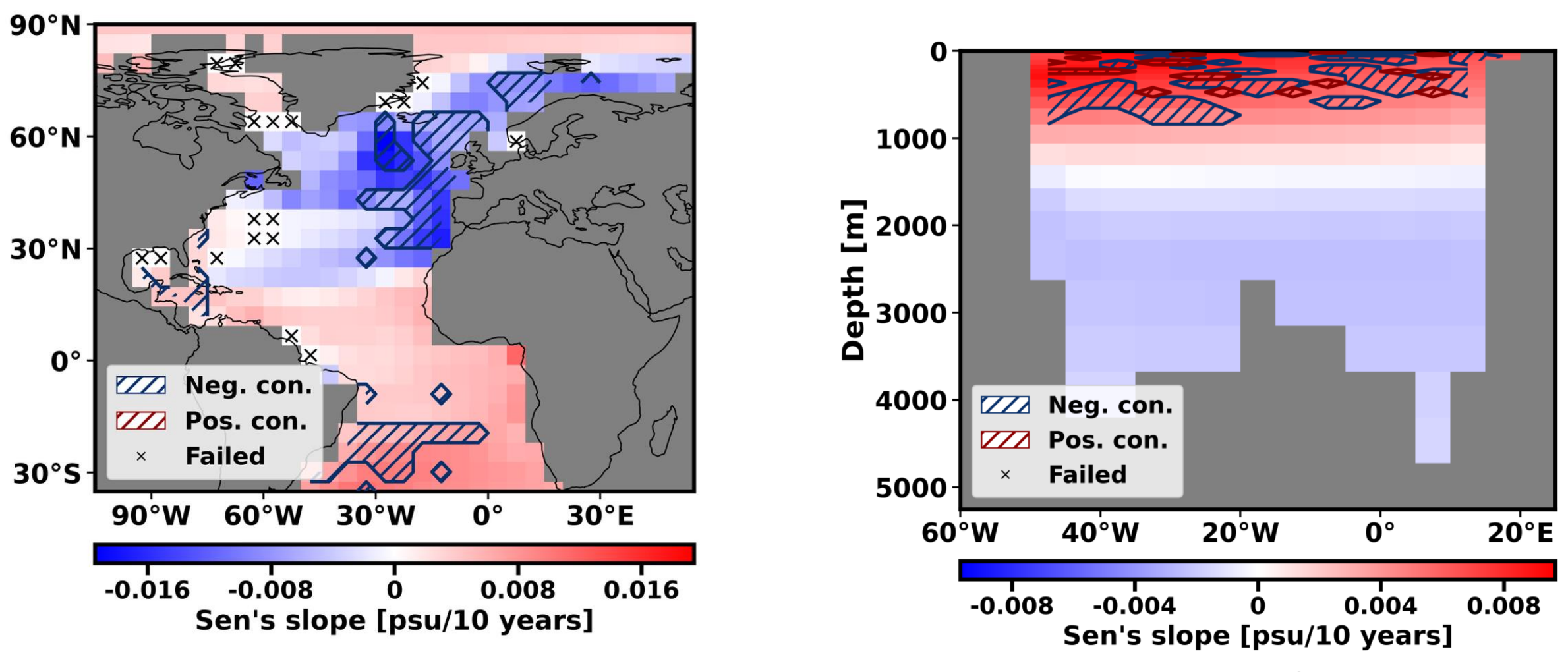
Figure 2.
(a) Temporal evolution of AMOC strength at 26°N in CLIMBER-X under freshwater forcing rate r_F = 6×10⁻⁴ Sv yr⁻¹.
(b) AMOC evolution for the simulation obtained in [1].
(c) CNN predictions vs. true distance to tipping (trained on SST or SSS).
(d) Distribution of 500 CNN predictions for CESM (SSS; SST+SSS).

Explainability

- SHAP values quantify input contributions relative to an AMOC-on state; negative (positive) values indicate destabilizing (stabilizing) effects.
- **Outcome:** The CNN identifies coherent large-scale patterns of AMOC destabilization across CLIMBER-X and CESM.



(a) SSS (b) S_z^{35S}



(c) SSS (d) S_z^{35S}

Figure 3.
(a) Temporal trends of SSS in CLIMBER-X under freshwater forcing rate r_F = 6×10⁻⁴ Sv yr⁻¹; contours indicate regions most relevant to the CNN output.
(b) As in (a), for S_z^{35S}.
)c–d) Same as (a–b), but for CESM data.

Conclusions

- CNN predicts AMOC tipping distance directly from ocean fields, without proxies, and generalizes from CLIMBER-X to CESM.
- SHAP confirms physical consistency, revealing that the CNN captures coherent large-scale patterns.

References

1.“Physics-based early warning signal shows that AMOC is on tipping course” Van Westen et al.