Is the Atlantic Ocean circulation on the brink of a collapse?

ERC project TAOC group
René M. van Westen
Jelle Soons
Elian Vanderborght
Sven Baars
Emma Smolders
Valérian Jacques-Dumas
Lucas Esclapez
Henk A. Dijkstra (PI)
Amber Boot

The Atlantic Ocean circulation plays a key role in the global climate by redistributing heat through the global ocean. This large-scale ocean circulation transports relatively warm surface waters to Western Europe, which explains the relatively mild climate there compared to other regions at the same latitude (e.g. Canada).

The warm surface currents flow further northward to Greenland, where they cool, sink and flow southward at greater depth (Figure 1). This conveyor belt of water is important for the global climate and influences storm-track activities, large-scale precipitation patterns and the regional sea level.

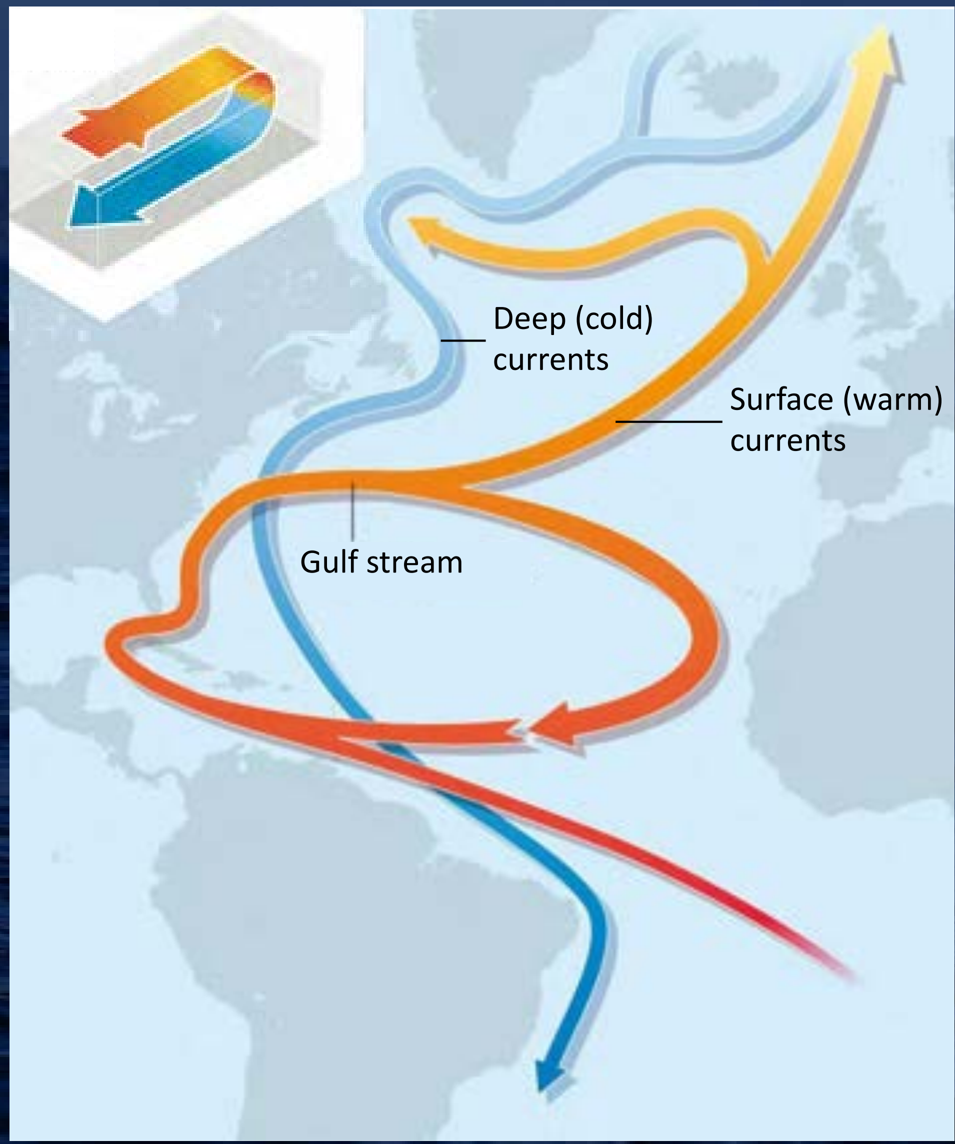

Figure 1: Sketch of the present-day Atlantic Ocean circulation, with warm water flowing northward in the upper ocean (red), sinking near Greenland and returning as a deep cold flow (blue).

Tipping element

There are reasons for concern about the strength of the Atlantic Ocean circulation under future climate change, as it has been labelled as a tipping element in the climate system. Tipping behaviour is induced by positive feedback loops in which an initial perturbation is amplified. Under a strong enough forcing of freshwater in the North Atlantic, the present-day circulation may undergo a transition to a much weaker or even fully collapsed and/or reversed circulation. Positive freshwater anomalies in the North Atlantic Ocean increase the vertical stratification, reducing the sinking near Greenland and the Atlantic Ocean circulation strength. Such a weakening would have regional and global impacts on top of the anthropogenic-induced climate change. Current climate projections indicate a consistent weakening of the circulation strength over the twenty-first century, and recent work (Ditlevsen and Ditlevsen, 2023) suggests a collapse in the near future. There is strong evidence from sediment records that such transitions have occurred in the geological past.

The research community is somewhat confused about the tipping aspect of the Atlantic Ocean circulation. Some believe that tipping is only a theoretical concept as such behaviour is only found in highly idealised climate models (Stommel, 1961), where a lot of relevant feedback is not captured. The modern complex climate models, in which this additional feedback is included, do not show a fully collapsed circulation. These latter results, however, do not align well with the evidence from sediment records.

The ERC-funded **TAOC** project (**T**ipping of the **A**tlantic **O**cean **C**irculation, PI: H.A. Dijkstra) studies the probability that the present-day Atlantic Ocean circulation will undergo a collapse before the end of the century. This project uses a hierarchy of climate models, from conceptual climate models to modern complex climate models. The conceptual climate models help to understand the core dynamics and feedback mechanisms of tipping, and these models require only limited computational resources compared to the complex climate models. Simulating a tipping event with a complex climate model, including all relevant feedback, is a crucial milestone for the TAOC project.

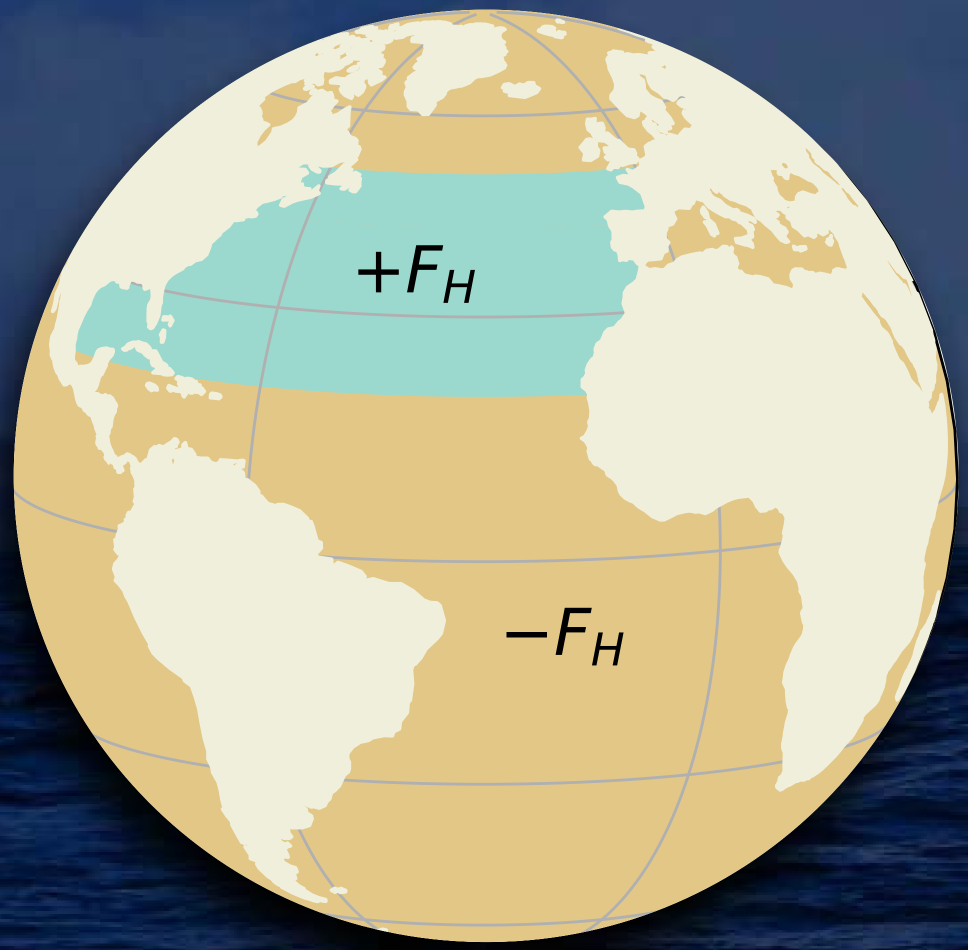

Figure 2: Typical set-up of a hosing experiment where fresh water is added in the North Atlantic Ocean (cyan region), and freshwater is removed from the remaining ocean surface to conserve the total ocean salinity.

Finding the collapsed circulation state

A recent analysis (van Westen and Dijkstra, 2023) within the TAOC project shows that complex climate models have persistent biases. The largest model bias is that the Indian Ocean becomes too fresh, which is related to ocean-atmospheric feedback that is not well captured. The Indian Ocean salinity bias eventually influences the salinity fields in the Atlantic Ocean. The strength of Atlantic Ocean circulation and the possibility of tipping are particularly sensitive to the Atlantic Ocean salinity content. These persistent salinity biases likely explain why tipping in complex climate models is difficult to find.

It is possible to adjust the model by imposing freshwater fluxes that correct the various salinity biases, a so-called hosing experiment. A typical procedure is to add fresh water to the surface over the North Atlantic Ocean and remove this fresh water from the remaining ocean areas to conserve the total ocean salinity (Figure 2). Slowly increasing the freshwater forcing may eventually induce a tipping event, as was demonstrated in more idealised climate models. Previous studies have performed experiments with modern climate models under very strong freshwater-forcing conditions. In these simulations, however, the strong decrease in the circulation strength is mainly due to the large forcing. The intrinsic feedback, which controls the tipping, is strongly masked by the forcing. Simulations with complex climate models under a slowly-varying freshwater forcing have not been conducted due to the large computational resources required. The TAOC project plans to perform such long computational simulations with such a complex climate model.

Predicting the tipping event

The collapsed circulation state is expected to also exist in complex climate models, once model biases are corrected. When such a tipping event is found, it answers a long-standing climate science problem: is Atlantic Ocean circulation tipping possible in complex climate models? The next step is to identify early warning signals of the forthcoming tipping event in the model and to connect them to the observed Atlantic Ocean circulation. These early warning signals indicate the resilience of the present-day Atlantic Ocean circulation and help to quantify whether the circulation is on the brink of collapse, as has been suggested by previous work (Ditlevsen and Ditlevsen, 2023).

The existence of a collapsed state would also motivate the analysis of the probability of such a tipping event. Transitions in the Atlantic Ocean circulation can appear randomly under the influence of noise, for example, by salinity anomalies induced by precipitation differences. The transition probabilities are expected to be low (Castellana *et al.*, 2019), but we know from sediment records that these events have occurred in the geological past. Moreover, it is expected that climate change may enhance the risk of tipping.

The impacts of a tipping event

Tipping of the Atlantic Ocean circulation has major consequences for global heat redistribution. The large-scale circulation exchanges heat between the two hemispheres. When it collapses, the Northern Hemisphere cools while the Southern Hemisphere warms. Under a tipping event, the European continent would receive substantially less heat from the ocean, and it is expected that the climate there would cool by 5 °C to 10 °C (Orihuela-Pinto, England and Taschetto, 2022). The large-scale precipitation patterns, the trade winds and tropical cyclones are also expected to shift and change under a tipping event (van Westen, Dijkstra and Bloemendaal, 2023).

The study of Orihuela-Pinto, England, and Taschetto (2022) clearly demonstrates severe global climate impacts under a strong weakening of the Atlantic Ocean circulation by applying a very strong freshwater forcing to the model. The strong forcing dominates the circulation responses, and the approach of the TAOC project focuses on the intrinsic feedback by applying a slow-varying forcing. It is expected that this approach will give similar large-scale responses as reported in Orihuela-Pinto, England, and Taschetto (2022). The advantage, however, is that the transient responses can be adequately studied. The transient responses under a circulation collapse strongly determine how fast society can adapt to these changes. The present-day global mean surface temperature changes by about 0.2 °C per decade and is already affecting society. It is possible that an Atlantic Ocean circulation collapse induces even stronger temperature changes and climate impacts.

Within the TAOC project, we are now conducting the first simulations with a complex climate model, and the results look very promising. We are on track to assess the resilience of the present-day Atlantic Ocean circulation and whether this circulation is on the brink of a collapse.

References

Castellana, D., Baars, S., Wubs, F.W. and Dijkstra, H.A. (2019) 'Transition probabilities of noise-induced transitions of the Atlantic Ocean circulation', *Scientific Reports*, 9(1), 20284. doi: 10.1038/s41598-019-56435-6.

Ditlevsen, P. and Ditlevsens S. (2023) 'Warning of a forthcoming collapse of the Atlantic meridional overturning circulation', *Nature Communications*, 14(1), pp. 1–12. doi: 10.1038/s41467-023-39810-w.

Orihuela-Pinto, B., England, M.H. and Taschetto, A.S. (2022) 'Interbasin and interhemispheric impacts of a collapsed Atlantic Overturning Circulation', *Nature Climate Change*, 12(6), pp. 558–565. doi: 10.1038/s41558-022-01380-y.

Stommel (1961) 'Thermohaline convection with two stable regimes of flow', *Tellus*, 13(2), pp. 224–230. doi: 10.1111/j.2153-3490.1961.tb00079.x.

van Westen, R.M. and Dijkstra, H.A. (2023) 'Persistent Climate Model Biases in the Atlantic Ocean's Freshwater Transport', *EGUsphere*, 2023, pp. 1–29. doi: 10.5194/egusphere-2023-1502.

van Westen, R.M., Dijkstra, H.A. and Bloemendaal, N. (2023) 'Mechanisms of tropical cyclone response under climate change in the community earth system model', *Climate Dynamics*, 61, pp. 1–16. doi: 10.1007/s00382-023-06680-3.

PROJECT NAME

TAOC (Tipping of the Atlantic Ocean Circulation)

PROJECT SUMMARY

The TAOC project aims to determine the probability that the Atlantic Ocean circulation will collapse under climate change before the year 2100. A hierarchy of ocean-climate models will be used to which we will apply modern rare event techniques.

PROJECT PARTNERS

We collaborate with many other groups in other (H2020 and Horizon Europe) projects.

PROJECT LEAD PROFILE

Dr Hendrik Dijkstra secured a PhD in mathematics from the University of Groningen (the Netherlands) and is currently Professor of Dynamical Oceanography at the Institute for Marine and Atmospheric Research Utrecht (IMAU), Department of Physics, Utrecht University, Utrecht, the Netherlands. Dijkstra holds a PIONIER award from the Dutch Science Foundation and a Lewis Fry Richardson Medal from the European Geosciences Union for his outstanding work in developing the nonlinear dynamical systems approach to oceanography and for his study of the role of ocean circulation in (palaeo)climate.

PROJECT CONTACTS

Dr Hendrik Dijkstra

https://webspace.science.uu.nl/_dijks101

FUNDING

This project has received funding from the European Research Council (ERC) under the European Union's Horizon 2020 research and innovation programme under grant agreement No. 101055096.