# Evolution and Variability of Ocean Circulation in a Transient Holocene Simulation

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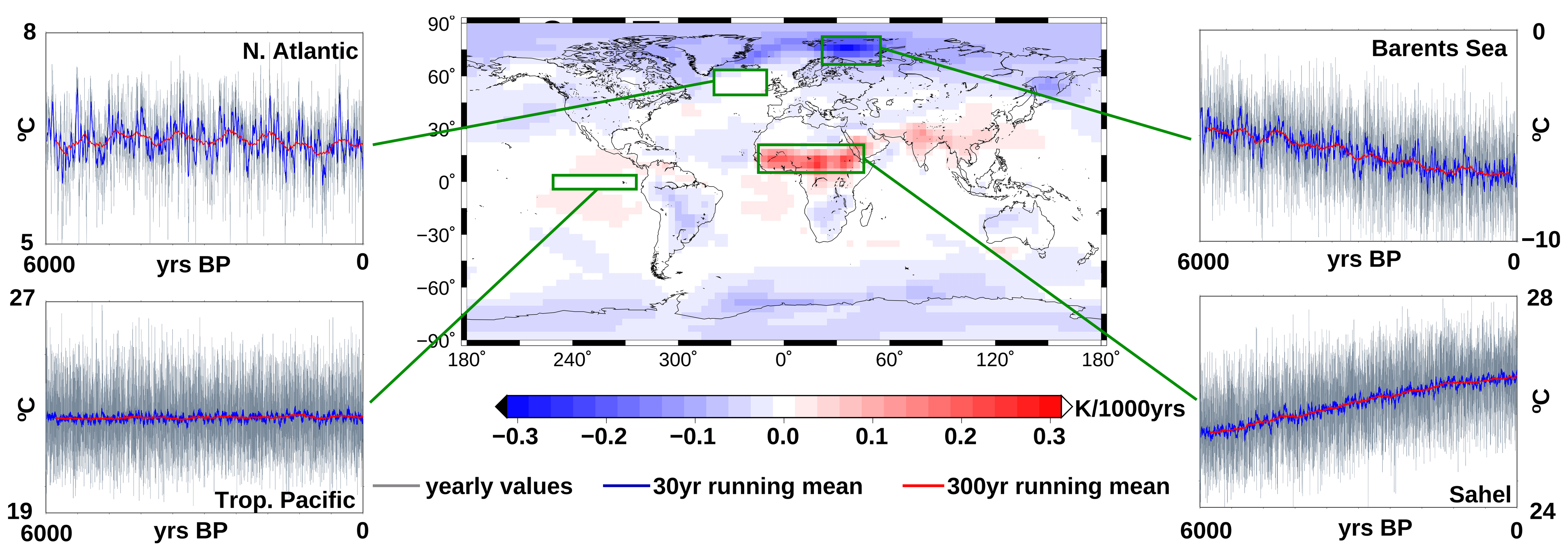
## 1 Introduction

- In the Atlantic, ocean circulation transports large amounts of heat from low- and mid latitudes to high latitudes which leads to comparably high temperatures in northern Europe.
- This heat transport is connected to the Atlantic meridional overturning circulation (AMOC), which brings warm and saline water from the tropics to high latitudes.
- Sparse temporal and spatial measurements of the AMOC limit a thorough understanding of its driving mechanisms.
- We approach the problem by analyzing results from a transient Earth-system-model experiment.

## 2 Experimental Set-Up

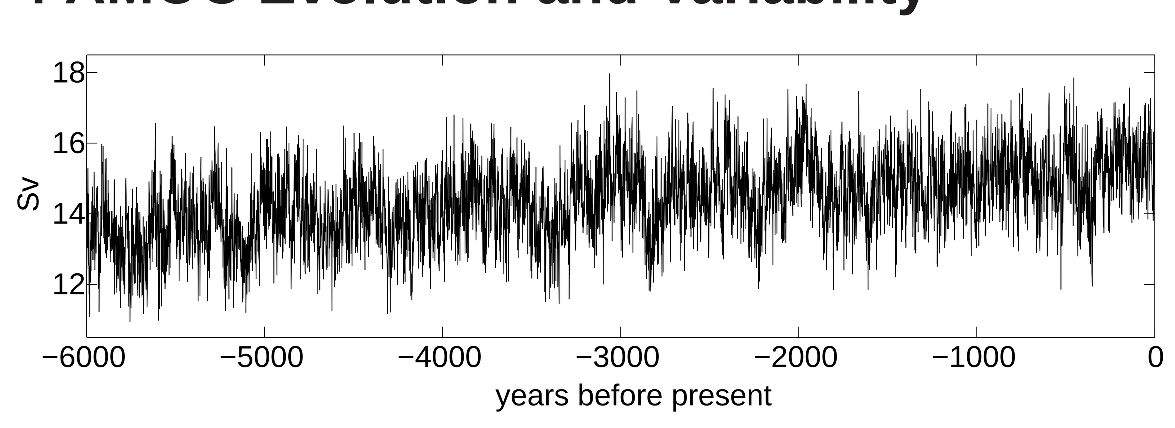
- We perform a transient simulation of the last 6,000 years from the mid-Holocene to today.
- We use a coupled atmosphere-ocean general circulation model including a land surface model (ECHAM5/JSBACH/ MPI-OM) with applied orbital forcing.
- The model resolution is 3.75° in the atmosphere and ≈3° in the ocean component, respectively.
- We investigate how changes in insolation forcing affect the overall AMOC strength and on what time-scales and amplitudes ocean circulation variability occurs.

## 3 Surface Temperature Response to Insolation Changes

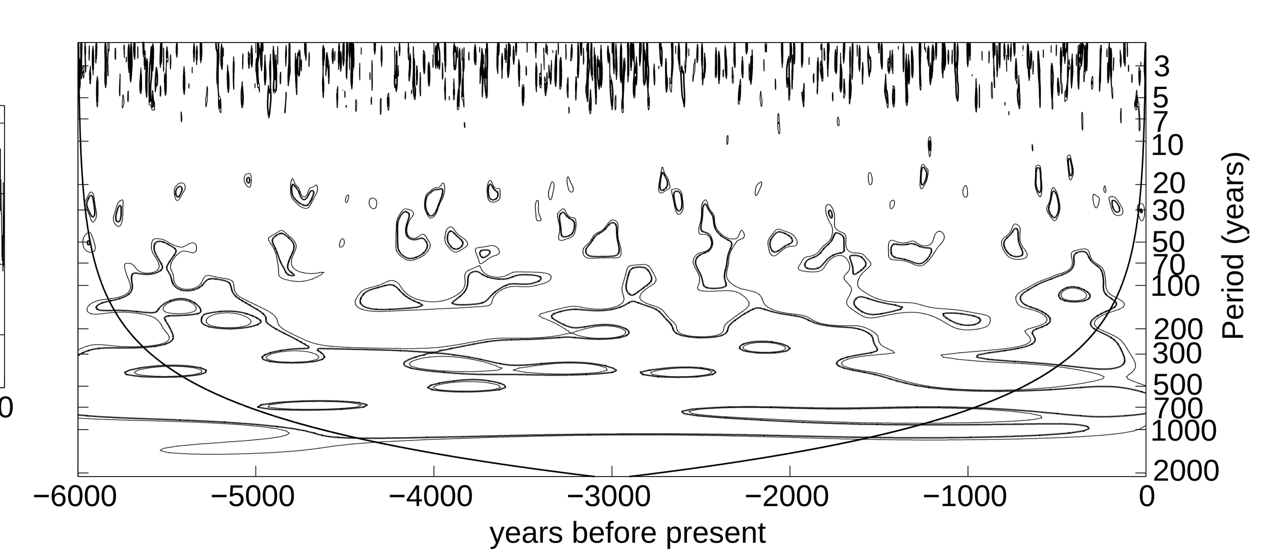



The surface temperature trends over the simulation period show a general cooling in the high latitudes and a warming in the low latitudes. Regionally, these signals are enhanced due to local effects, e.g., over the Sahel region (decrease in Monsoon activity) and the Barents Shelf (increase in sea-ice cover). The temperature time-series over regions influenced by the Atlantic meridional overturning circulation (AMOC) show strong variability on multi-decadal and centennial time-scales, as opposed to the tropical Pacific and the Sahel region.

## 4 AMOC Evolution and Variability

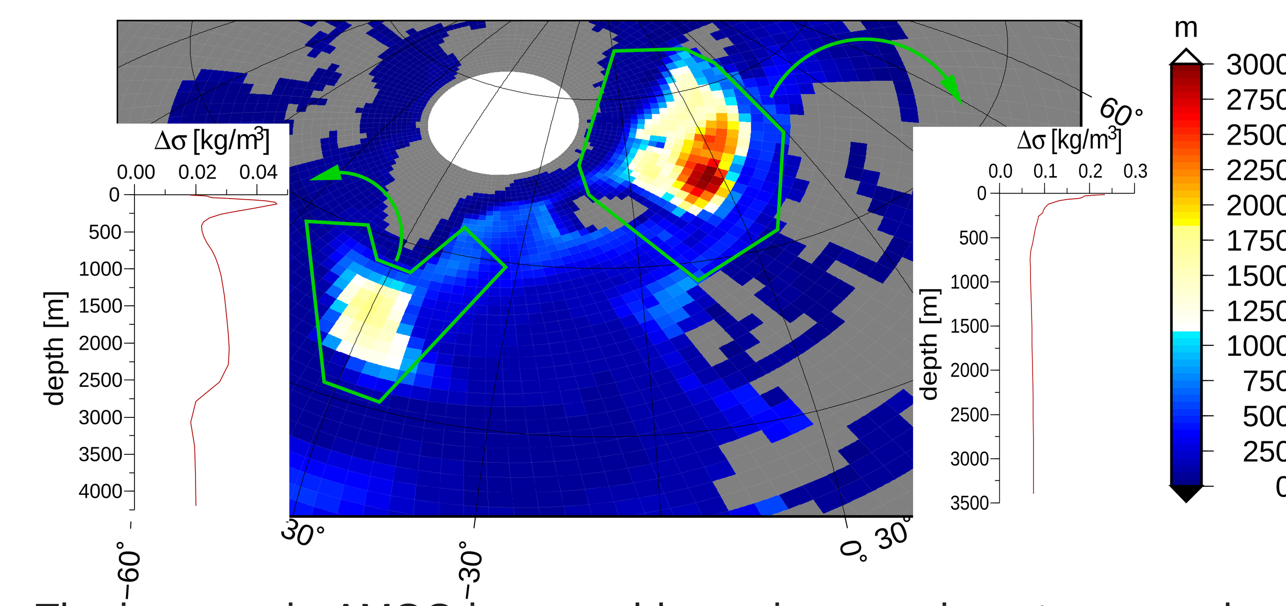



The time-series of AMOC at 30°N, 1000 m depth shows an overall increase from 14 to 16 Sv and variability from annual to multi-centennial time-scales.



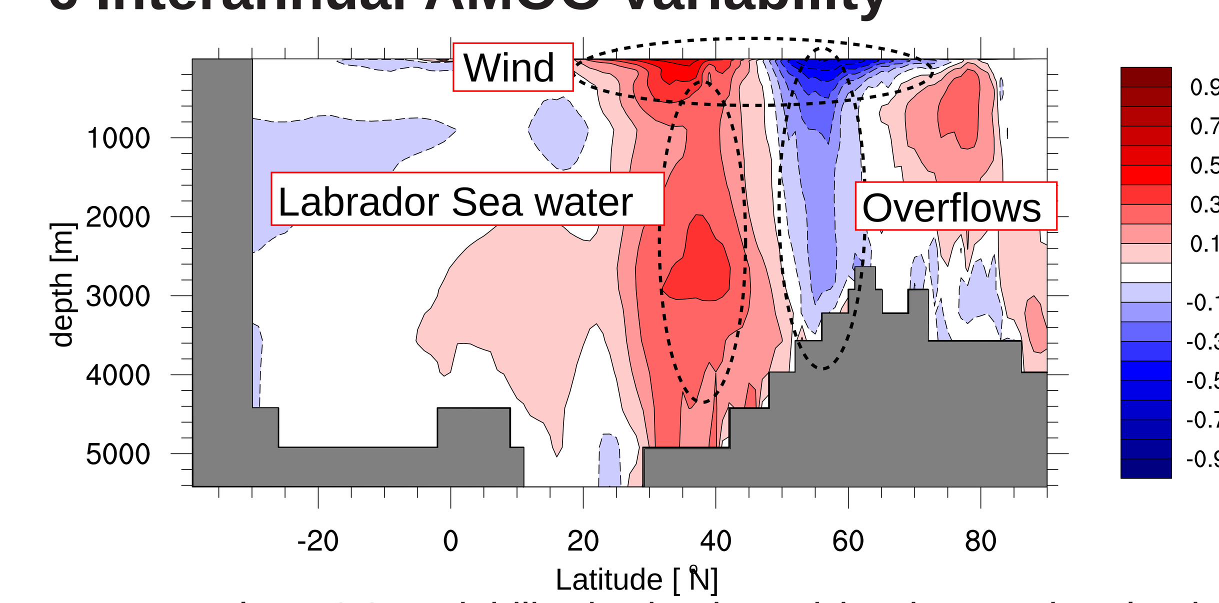

The wavelet transform shows continuous significant variability (95% significance indicated by solid lines) on interannual and multi-centennial time-scales.

## 5 AMOC Increase



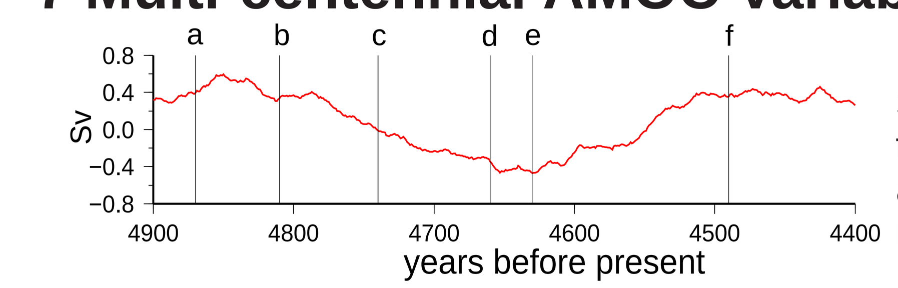

The increase in AMOC is caused by an increase in water mass density in the deep water formation regions in the Nordic Seas and the Labrador Sea region (green areas). The xy-plots show the density difference between the first and the last 1,000 years of the simulation in the depicted areas.

## 6 Interannual AMOC Variability

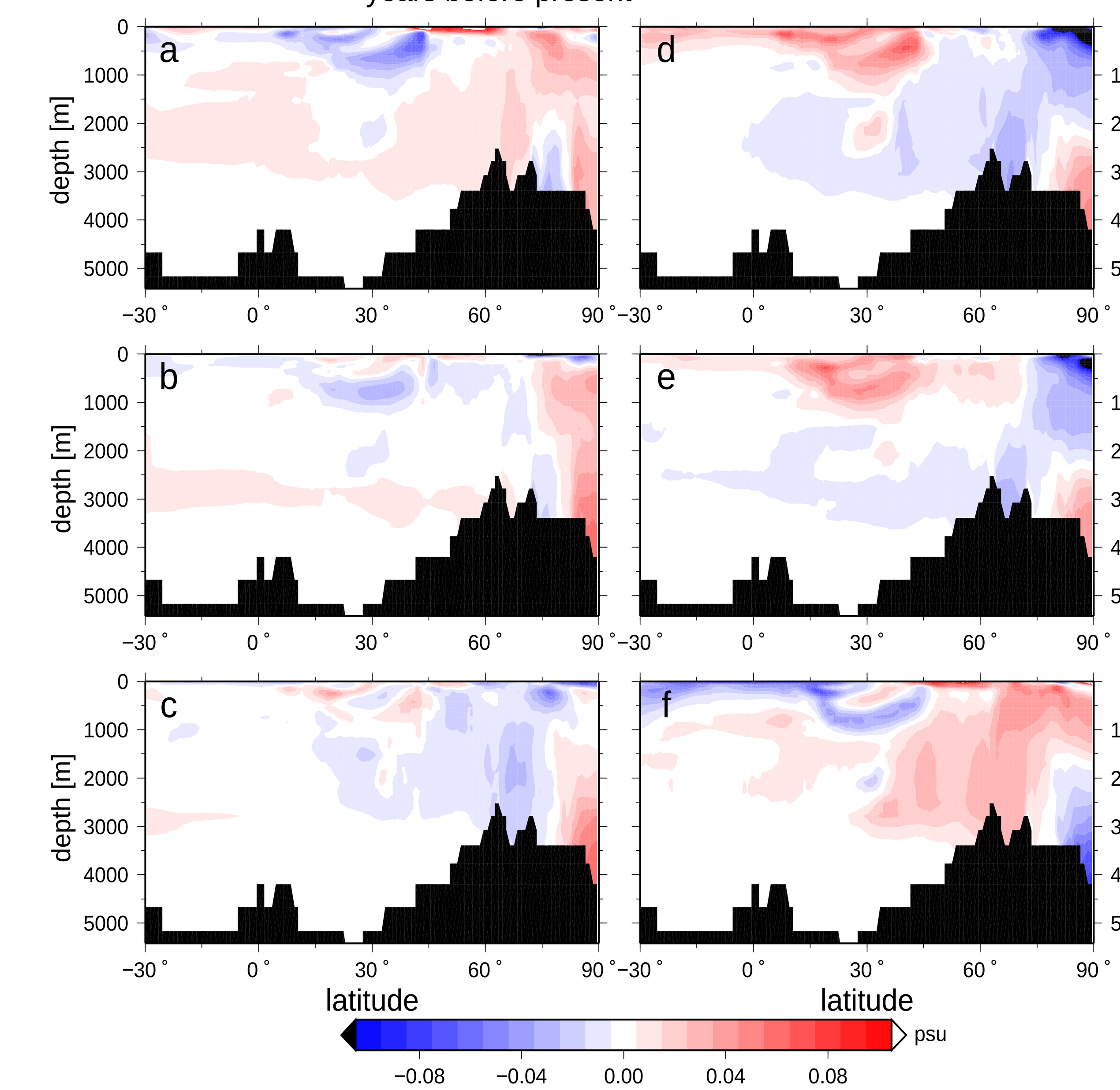



Interannual AMOC variability is dominated by the North Atlantic Oscillation (NAO). The Figure shows the correlation between the NAO-index and the 2D-streamfunction in the Atlantic basin at lag zero. At the surface between 30° and 60°N wind anomalies associated with the NAO+ phase strengthen the northern limb of the sub-tropical gyre and weaken the southern limb of the sub-polar gyre. Cold conditions over the Labrador Sea enhance winter convection causing a positive AMOC response around 35°N, whereas relatively fresh and warm conditions over the Nordic Seas cause a negative response of the overflow's contribution to AMOC at 60°N.

## 7 Multi-centennial AMOC Variability




Section of the AMOC-time-series detrended and with a 100-year running-mean applied.




The figure shows zonal mean salinity anomalies (100-year running mean) of the Atlantic basin at different snapshots marked from a to f in the timeseries above. During a strong state of the AMOC positive salinity anomalies prevail in the deep water formation regions and are advected southwards in the deeper ocean. At the same time negative anomalies accumulate in the sub-tropical gyre region (a). After reaching a threshold these negative anomalies reach the deep water formation regions (b) and are convected to the deeper ocean (c) which leads to a slowdown of the AMOC. Now, positive anomalies accumulate in the sub-tropical gyre (d) that again reach the deep water formation region (e) and complete the cycle (f).

## 8 Conclusions

In a first transient AO-GCM study of mid-Holocene, we can assess AMOC evolution and variability and identify the corresponding mechanisms:
An increase in AMOC throughout the experiment can be explained by an increase in water-mass density in the deep water formation regions. In the Labrador Sea, a density increase of the convected deep water is due to increased salinity advection from the eastern North Atlantic. In the Nordic Seas, lower temperatures cause a substantial density increase and result in enhanced overflows.

The AMOC exhibits persistent significant variability on interannual and multi-centennial timescales. The interannual variability is dominated by the NAO the multi-centennial variability by accumulating salinity anomalies. The amplitude and period of the multi-centennial variability depends on the interplay of various processes in different ocean basins.
Our findings add to the understanding of ocean circulation obtained from simpler model set-ups and are supported by paleo reconstructions of AMOC strength and variability.

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