Low-frequency variability of an Aquaplanet with a coupled atmosphere-ocean general circulation model

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Abstract and Motivation

The mean state and the variability of a coupled atmosphere-ocean climate system are analyzed in a long-term Aquaplanet simulation with a global atmospheric general circulation model (the Planet Simulator) coupled to an ocean circulation model (the Hamburg Large Scale Geostrophic model, LSG).

Different states of Aquaplanet climates have been found in previous studies. While *Smith et al. (2006)* analyzed a warm greenhouse climate, *Marshall et al. (2007)* and *Enderton and Marshall (2009)* investigated Aquaplanets with ice caps up to the mid-latitudes. *Ferreira et al. (2010)* present both a warm and a cold solution. In a following study (*Ferreira et al., 2011*) they discuss the multiple equilibria of an Aquaplanet. Even though multiple states in Aquaplanet simulations have been analyzed before, there is no previous study which describes an oscillation between cold and warm climates, as the one presented here.

A low-frequency oscillation is found in our Aquaplanet simulations: Warmer climates without polar sea ice cover and weaker oceanic overturning and cold climates with a sea ice cover up to 65°N/S and a stronger MOC alternate with a period of approximately 700 years. The oscillations occur in both hemispheres in-phase.

Model

The atmospheric GCM used in this study is the **Planet Simulator** (*Fraedrich et al., 2005*), which is coupled to the Hamburg Large Scale Geostrophic (**LSG**) ocean model (*Maier-Reimer et al., 1993*). Vegetation and terrestrial surface are not included in the Aquaplanet set-up.

Key features:
- portable
- fast
- open source
- parallel
- modular
- easy to use
- documented
- compatible

Information and downloads: ***http://www.mi.uni-hamburg.de/plasim***

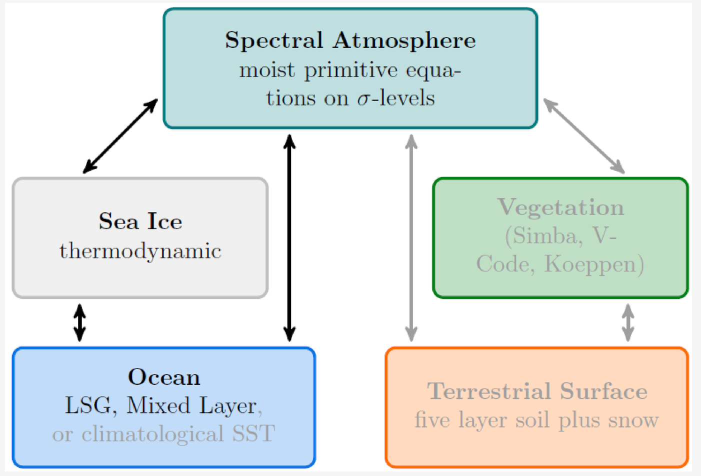

Fig. 1: Schematic diagram of model compartments of the Planet Simulator. For the Aquaplanet set-up only the atmosphere, the sea ice, and the ocean module are used.

Aquaplanet set-up

a planet, where the entire surface of the earth is covered by one ocean with a flat bottom and without any geometrical constraints

- idealized test environment
- zonally symmetric
- symmetric about the equator
- perpetual equinoctial conditions (no seasonality)

The coupled atmosphere-ocean model is run for 20,000 years. The time series is presented after 10,000 years of spin-up time and the years 15,001 to 20,000 are used for the EOF analysis and for the mean state.

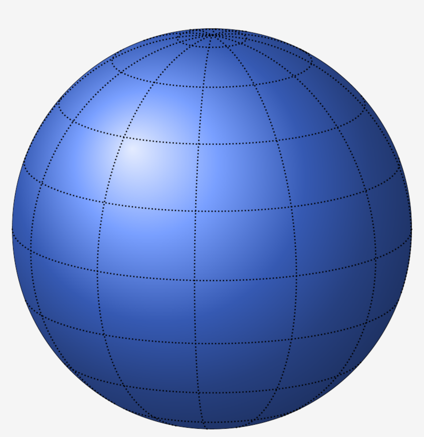

Fig. 2: Schematic picture of an Aquaplanet (without continents and entirely covered by one ocean)

Time Series and Low-frequency Variability

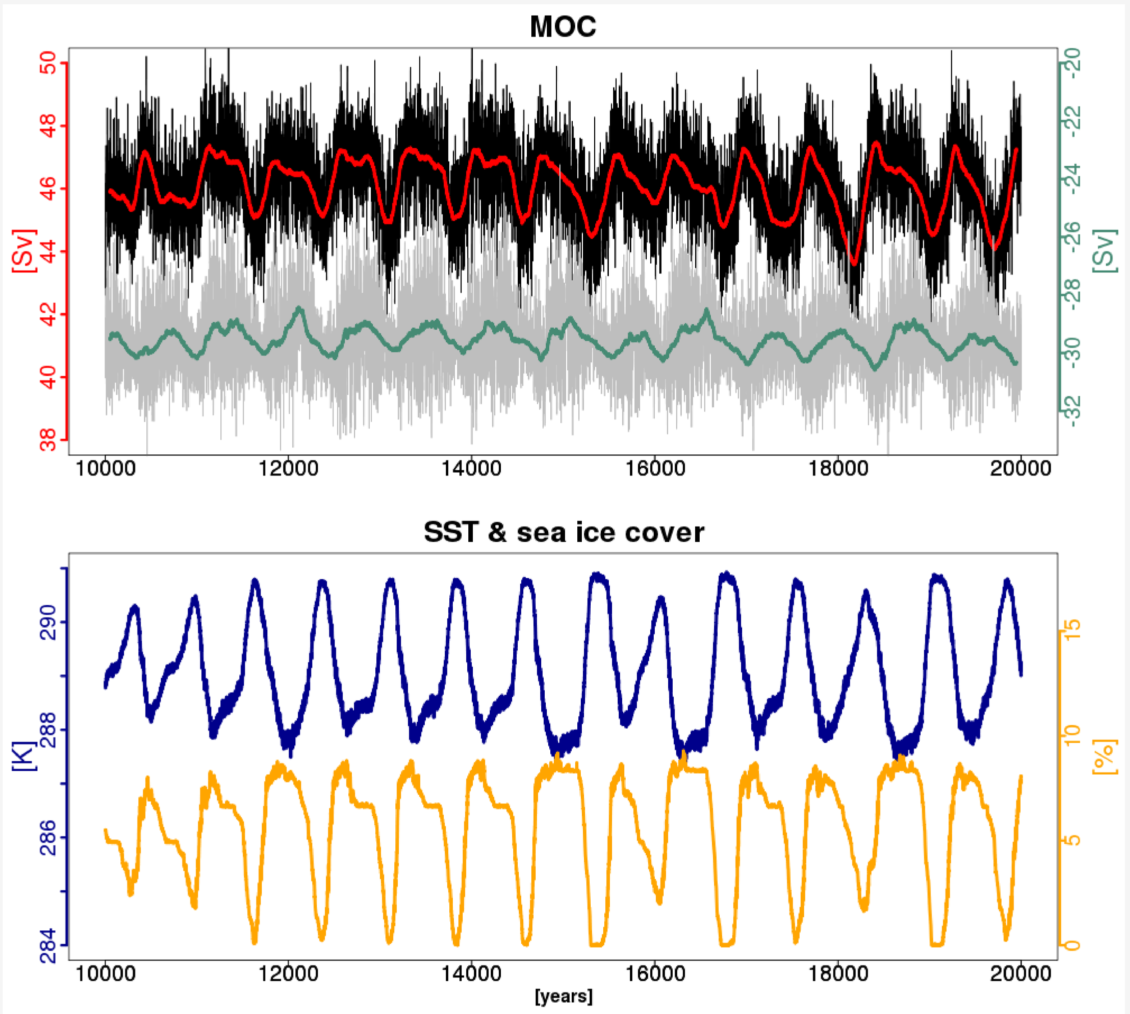

Fig. 3: Time series and 101-year running mean of the maximum of the MOC in the northern hemisphere's ocean are shown in the upper panel (red: tropical cell; green: extra-tropical cell). The global mean sea surface temperature (blue) and the sea ice cover (yellow) for the years 10,000 to 20,000 are presented below.

The time series of the maximum meridional overturning circulation (MOC) shows low-frequency variability with a period of approximately 700 years for both the tropical and the extra-tropical cell (figure 3, top). The global mean sea surface temperature (SST) and the global mean sea ice cover demonstrate similar oscillatory behavior (time series in figure 3, bottom).

An EOF (empirical orthogonal function) analysis is applied to the zonal mean temperature of the ocean. Together the first two EOFs explain more than 90% of the variability of the ocean's temperature.
The principal components (PC1 and PC2) are approximately 90° out of phase and their spectra also show maxima around 700 years (figure 5).
EOF1 and EOF2 show dipole patterns (figure 5). For a positive PC1, the first EOF has negative values at upper layers and in the tropics also at greater depths, while a positive pattern prevails close to the bottom, the poles, and the middle ocean in the mid-latitudes. EOF2 shows negative values throughout most of the ocean basin, but especially close to the sea floor and at the poles. In the tropics an area of positive values is located in upper and middle layers.

A linear regression with PC1 explains 63% of the variability of the zonal mean salinity and 40% of the variability of the MOC. In the atmosphere the linear regression with PC1 accounts for 54% of the temperature variability and 56% of the variability of the zonal wind.
The correlations between the first PC and other atmospheric and oceanic variables are high in most regions (salinity and atmospheric temperature in figure 6).

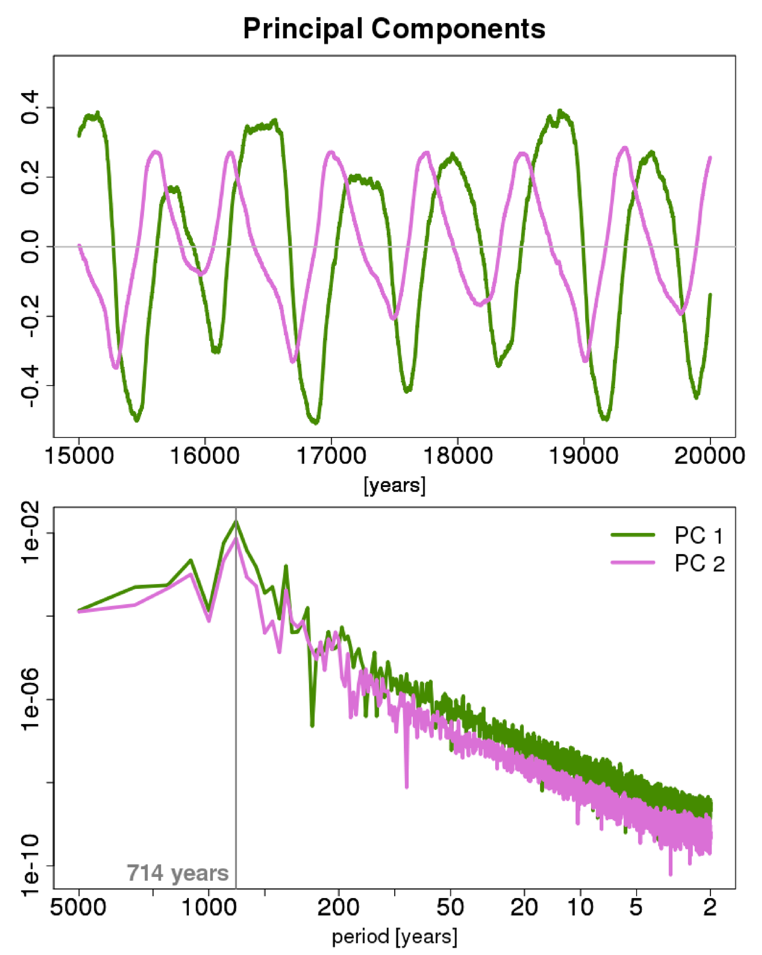

Fig. 4: The first and second principal component (PC) for the zonal mean ocean temperature. The time series is shown in the top panel and the spectrum of the time series is presented below. The maximum (714 for both PCs) is indicated with a gray line.

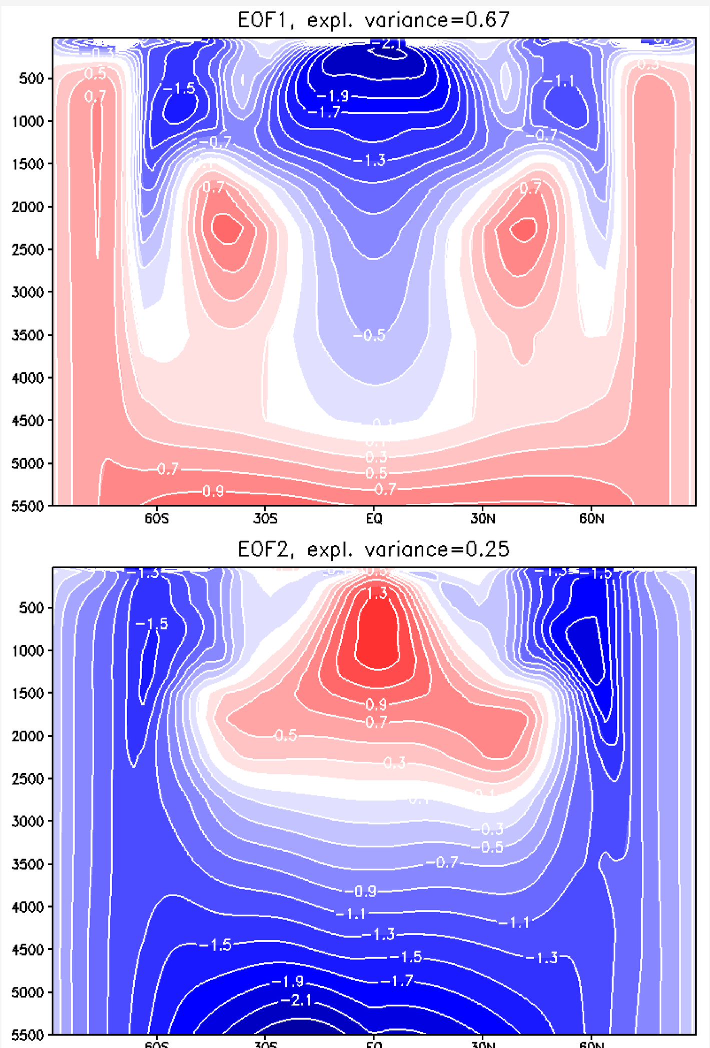

Fig. 5: The first two empirical orthogonal functions (EOF1 and EOF2) for the zonal mean ocean temperature.

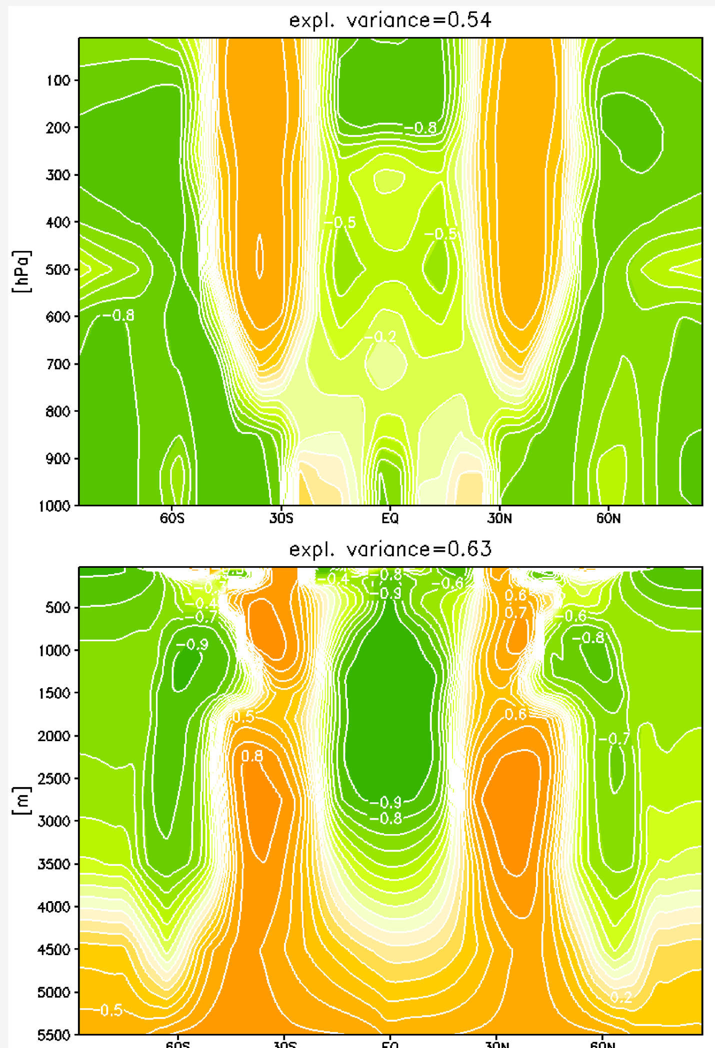

Fig. 6: Correlations between PC1 and the salinity anomalies in the ocean (bottom) and between PC1 and the atmospheric temperature anomalies (top).

Mean State

For the zonal mean climate the time averages over the last 5,000 years are shown. The differences between cold and warm states are minor and mostly restricted to higher latitudes. For colder climates with sea ice:
- the MOC reaches greater depths;
- MOC and zonal wind in the atmosphere are stronger;
- ocean temperatures and salinity differences are mostly restricted to upper layers;
- the atmosphere is dryer in polar regions;
- the ocean plays a weaker role in the meridional energy transports.

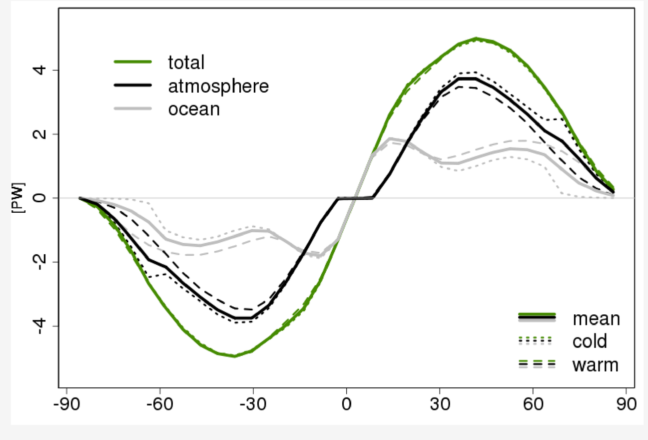

Fig. 9: Zonal mean meridional energy transport: transports conducted by the atmosphere only, the ocean only, and the combined total transport. The cold (warm) state is indicated by a dotted (dashed) line.

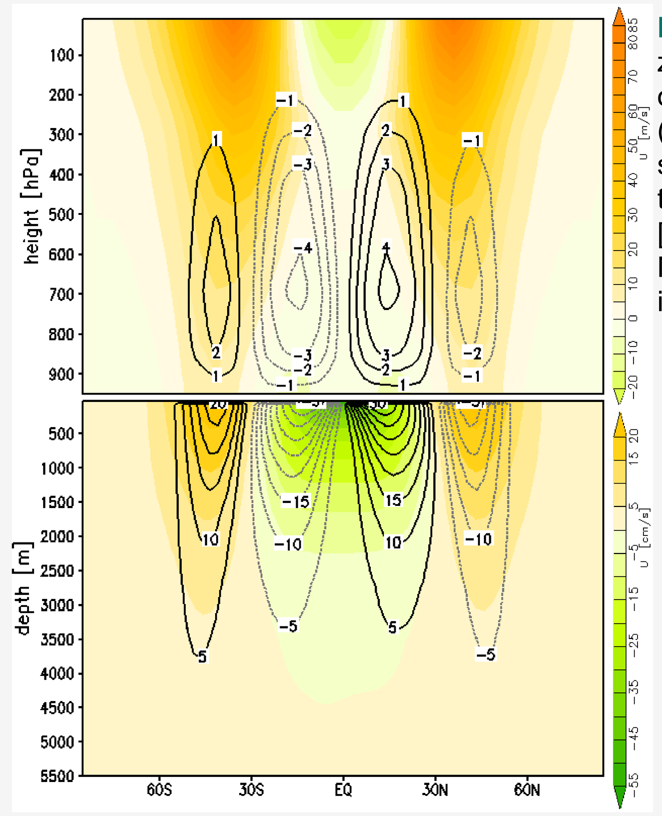

Fig. 7: Zonal mean zonal wind speed / ocean flow (shaded) and stream-function of the atmosphere in [10^{10} kg/s] and MOC of the ocean in [Sv] (contours).

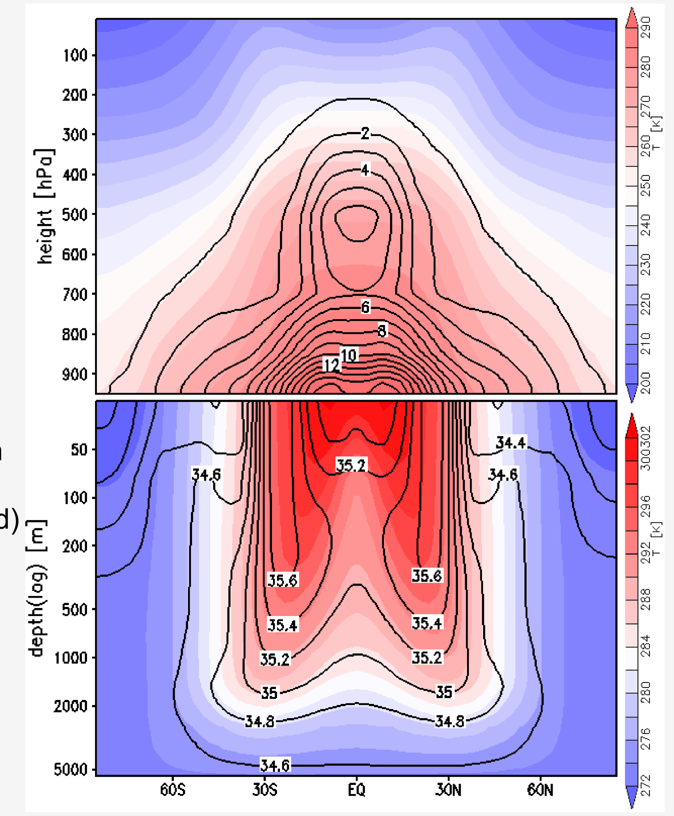

Fig. 8: Zonal mean temperature distribution (shaded) and atmospheric specific humidity in [g/kg] and oceanic salinity in [psu] (contours). The vertical axis of the ocean has a logarithmic scale.

Summary and Conclusion

A long-term coupled atmosphere-ocean simulation of an Aquaplanet has been conducted. A low-frequency oscillation develops on the Aquaplanet, which effects all the compartments: ocean, sea ice, and atmosphere. The MOC oscillates between stronger and weaker states with a period around 700 years. The temperatures in ocean and atmosphere alternate accordingly between cold and warm states, with and without sea ice cover.

The differences between cold and warm zonal mean climates are only significant in higher latitudes. The mean state resembles those of previous coupled Aquaplanet studies.

The first and the second EOF are sufficient to together explain over 90% of the variability of the zonal mean ocean temperature. EOF1 and EOF2 show dipole patterns and PC1 and PC2 are approximately 90° out of phase. Both oscillate with a period around 700 years. Linear regressions with the first PC show high correlations with other oceanic and also atmospheric variables.

The physical mechanisms behind this low-frequency oscillation need further analysis.

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