North Atlantic circulation in a 1000 year climate model

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Abstract

The North Atlantic meridional overturning circulation (MOC) is important for ocean heat transport in the Atlantic, so it is widely monitored and modelled. Previous work based on a few decades of model simulations has shown that the overturning north of about 40°N is quite different from that further south, and that changes in the circulation can be accurately monitored using pressure measurements at the western boundary, and reasonably well using tide gauge data. Here, we extend these analyses to 1000 years of data from the HadCM3 climate model Control run. In the northern band we find a decadal mode of variability, whilst to the south higher frequencies dominate, and the signal becomes coherent with the northern mode (with a few years lag) only at periods longer than about 10 years. In the deeper waters, especially at lower latitude and for the first few centuries of the model run, the signal is dominated by longer term trends. There is initially a strong increasing trend in the deep water overturning cell, which stabilises after several centuries. Spatial patterns associated with the transient are quite different from those produced by natural variability later in the run.

Introduction

HadCM3 is a climate model from the Hadley Centre with a resolution of $1.25^\circ \times 1.25^\circ$ in the ocean[1]. The control run spans over 1000 years, so can be used to examine very long term climate patterns. We examined the data from 1850 to 2849. The MOC is defined by the zonal integral across the Atlantic of the total northwards velocity, and the streamfunction defined as the integral from a given depth to the surface. The colours in figure 2 show the mean MOC streamfunction over time, which indicates a peak of about 16Sv between 500–1000m depth. There is northwards flow at all latitudes above 500m and the main overturning cell returns between 1000 and 3000m. There is also a deep overturning cell south of 40°N , flowing north at the ocean bottom and south at about 3000m.

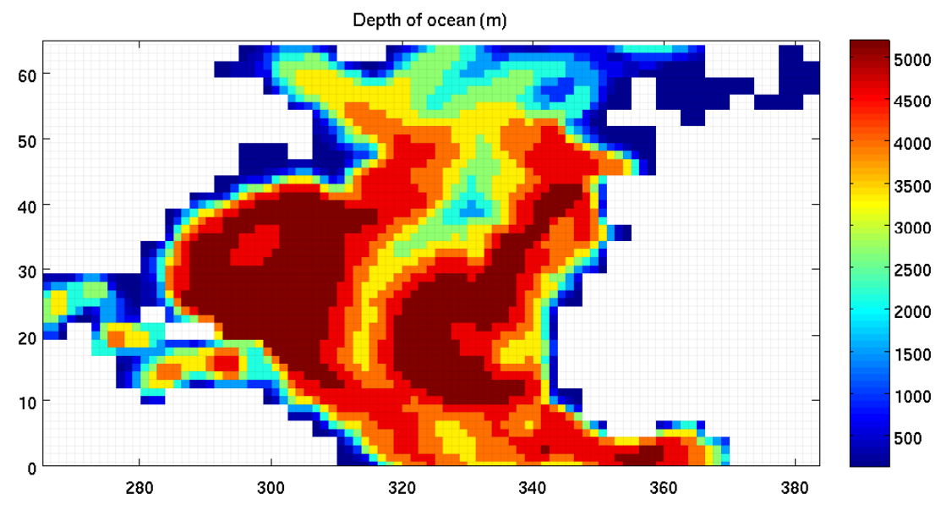

Figure 1: Bathymetry of North Atlantic in HadCM3

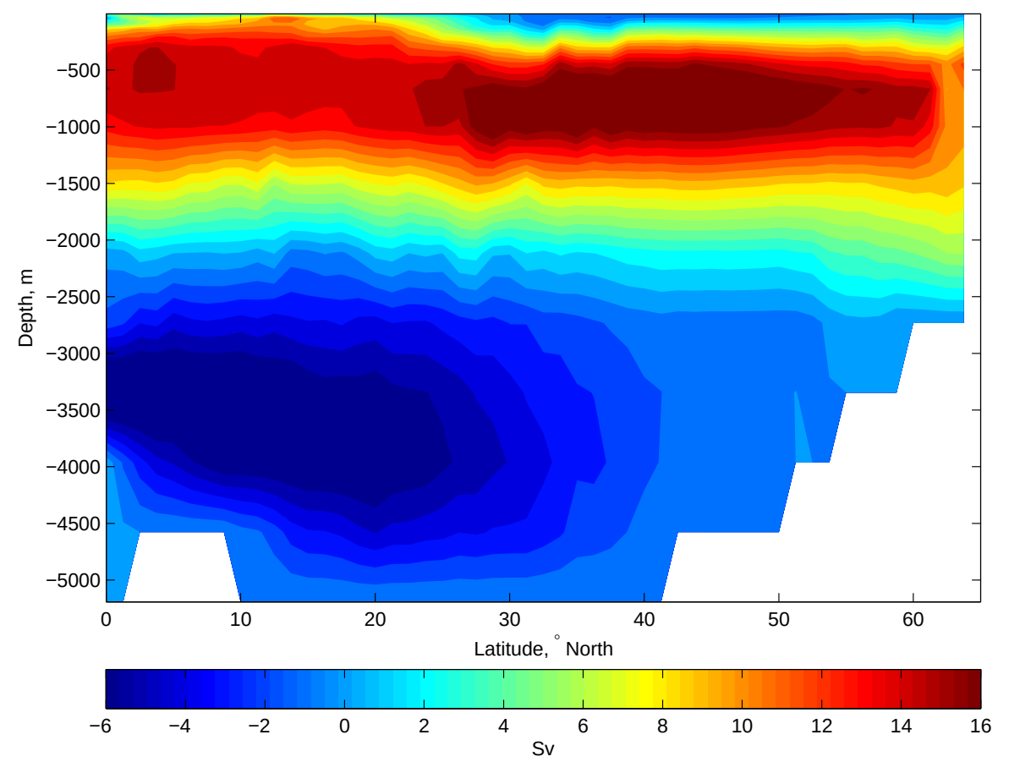

Figure 2: MOC streamfunction, averaged over 1850–2849

Coherence across latitudes

Figures 3 to 5 show time-dependent behaviour of the model for three depth bands, 96–996m, 996–3347m, and 3962–4577m. The figures show anomalies in the total northwards flow from the time-mean at the same latitude and depth band. There is a coherence in the signal across latitudes north of 40°N and south of 28°N . However in the deeper waters, especially at lower latitude and for the first few centuries of the model run the signal is dominated by longer term trends. There is initially a strong increasing trend in 996–3347m and decreasing trend in 3962–4577m, that is a weakening of the deep-water overturning cell, which stabilises after about 2400. It might be that HadCM3 takes this long for the deep waters to recover from spin-up conditions.

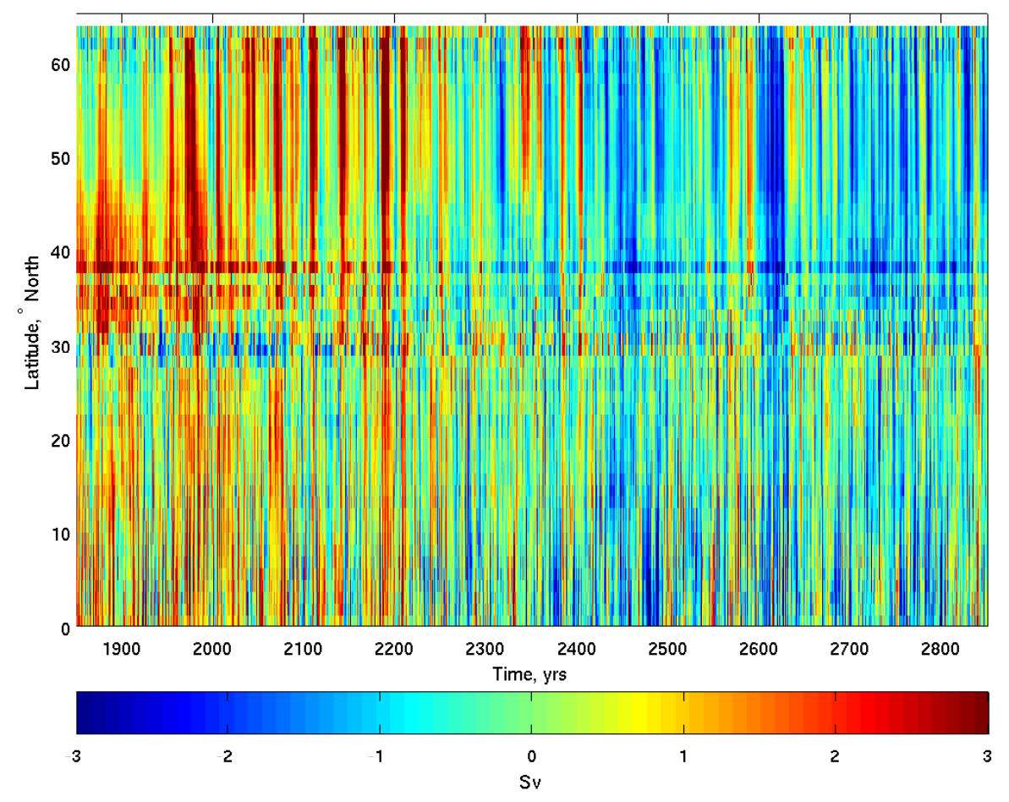

Figure 3: Northwards flow anomalies in 96–996m, HadCM3

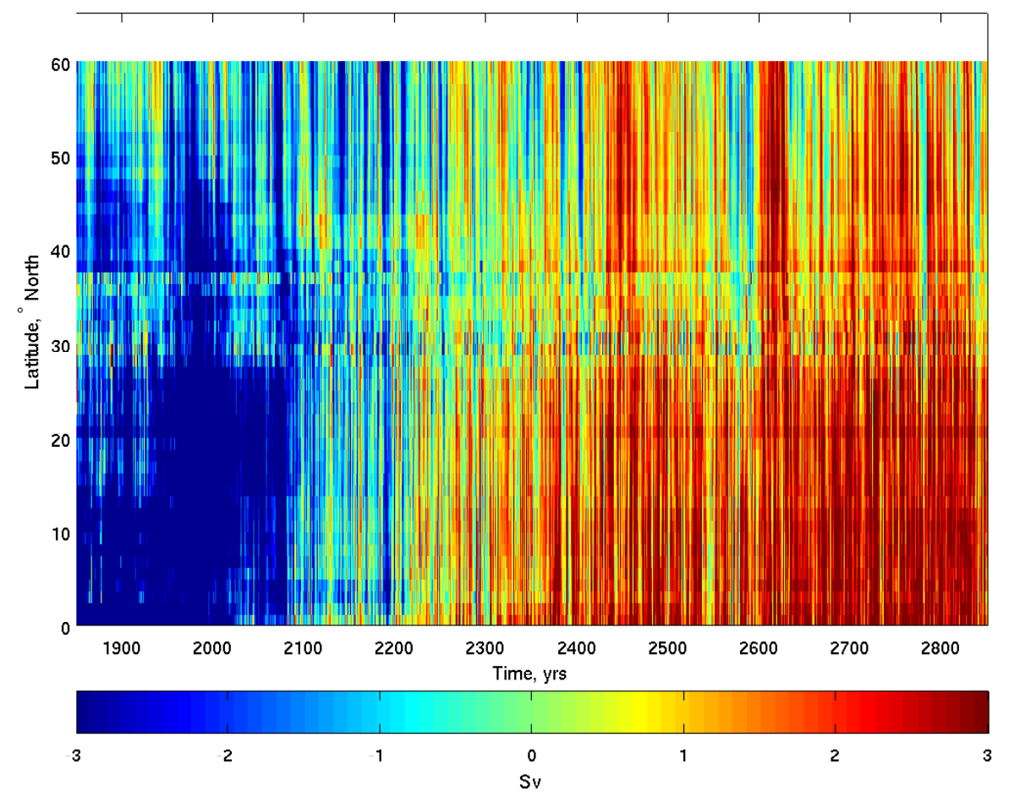

Figure 4: Northwards flow anomalies in 996–3347m, HadCM3

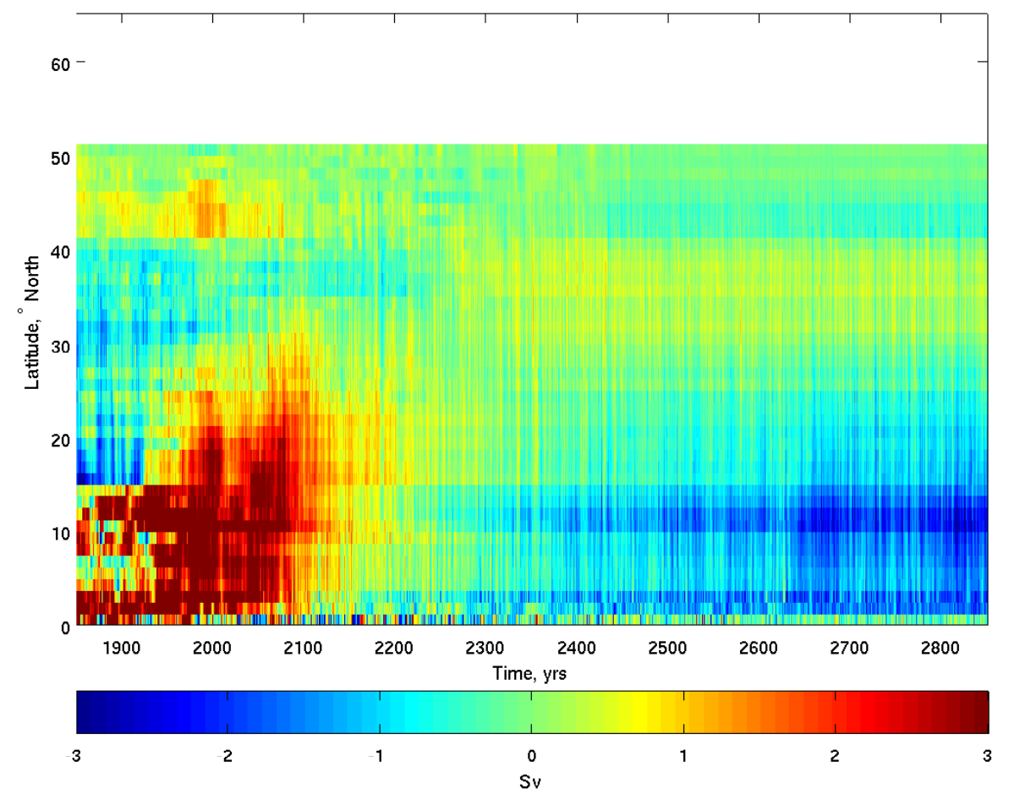

Figure 5: Northwards flow anomalies in 3962–4577m, HadCM3

Frequencies

Frequency analysis of the upper depth band (96–996m) at two latitude ranges (45-50°N and 10-20°N) reveals that there are lower-frequency oscilations further north (figure 6). Both signals have strong annual and semi-annual components. Windowing the data (figure 7) emphasises that in the northern band there are more oscillations of longer than 10 years, whilst in the southern band there are more oscillations shorter than 10 years. This is consistent with an earlier study of 100 years of HadCM3 and 10 years of OCCAM data[2].

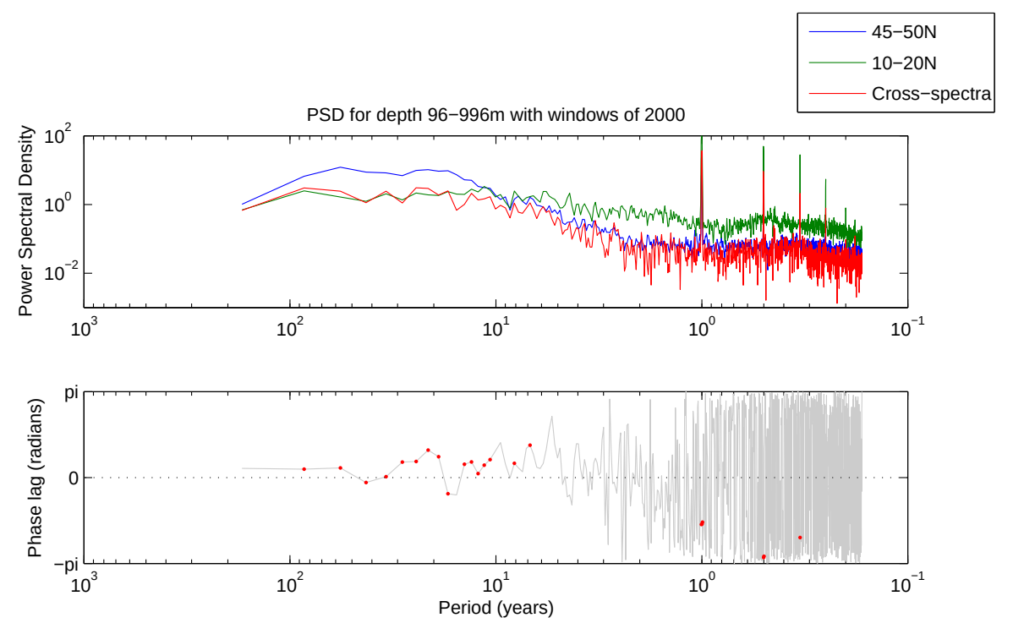

Figure 6: Power spectral density of flow in 96–996m at 45-50°N (blue) and 10-20°N (green), and cross-spectra (red), and phase lag of signal at 10-20°N behind 45-50°N .

Red points on the phase-lag data are those for which cross-spectral density is greater than 1. The phase data indicates that most signals have a lag from north to south, although the annual signal and its harmonics have a lag from south to north.

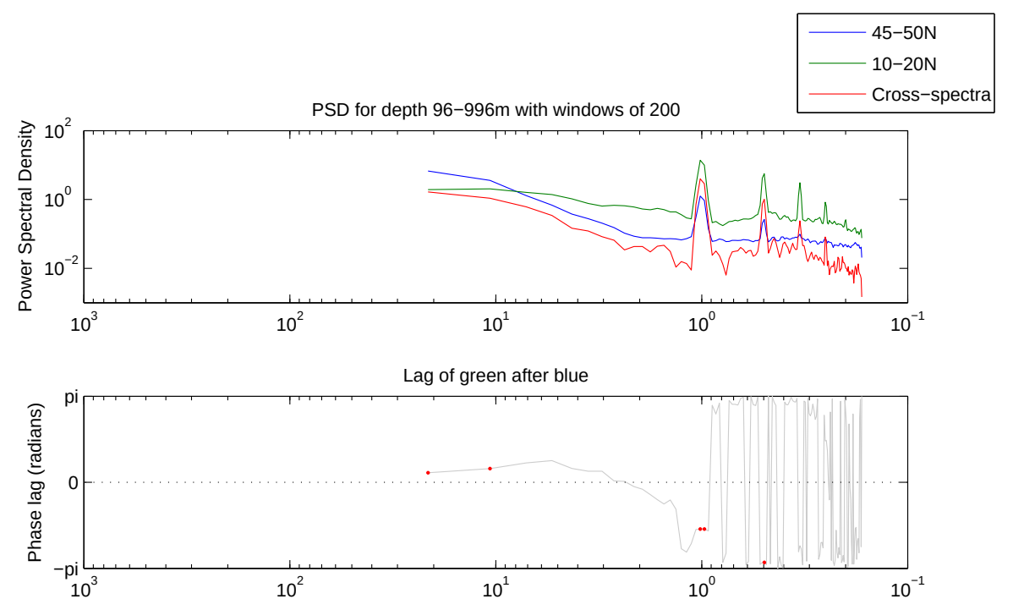

Figure 7: As previous figure, but with shorter windowing.

Modes of variability

We can capture the primary modes of the meridional flow by plotting empirical othogonal functions (EOFs). In the second half of the HadCM3 control data set, years 2400 to 2849, with a decadal filter, the first EOF is as expected, dominated by the overturning cell about 50°N . The second mode is weak, with little variability, but the third mode is dominated by the deep overturning. With a 50 year filter (not shown) the deep cell appears in the second EOF. In figures 8 to 10 are shown the first three EOFs; contours indicate the EOF of the streamfunction and the colours the percentage of variance explained.

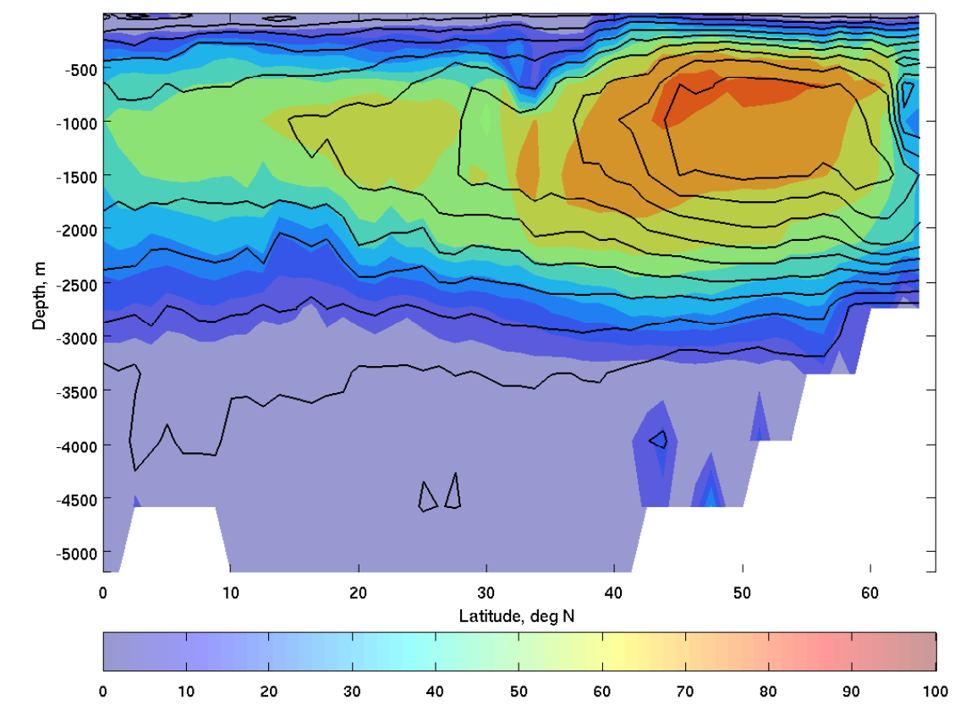

Figure 8: EOF1 of MOC, years 2400 to 2849. Contour interval 0.01.

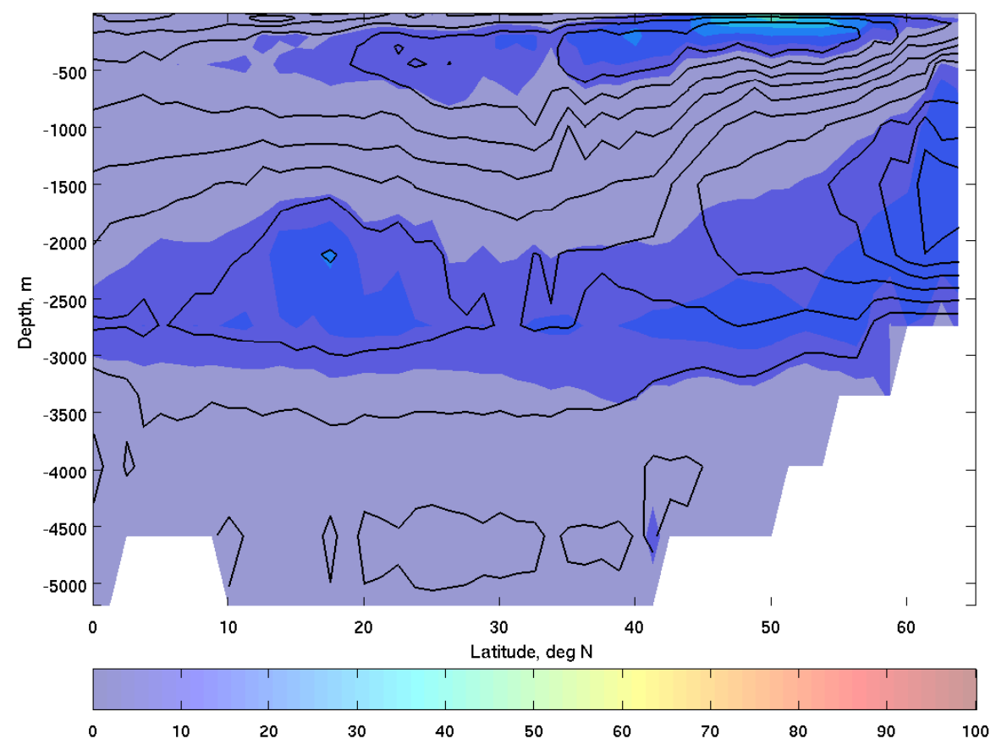

Figure 9: EOF2 of MOC, years 2400 to 2849. Contour interval 0.02.

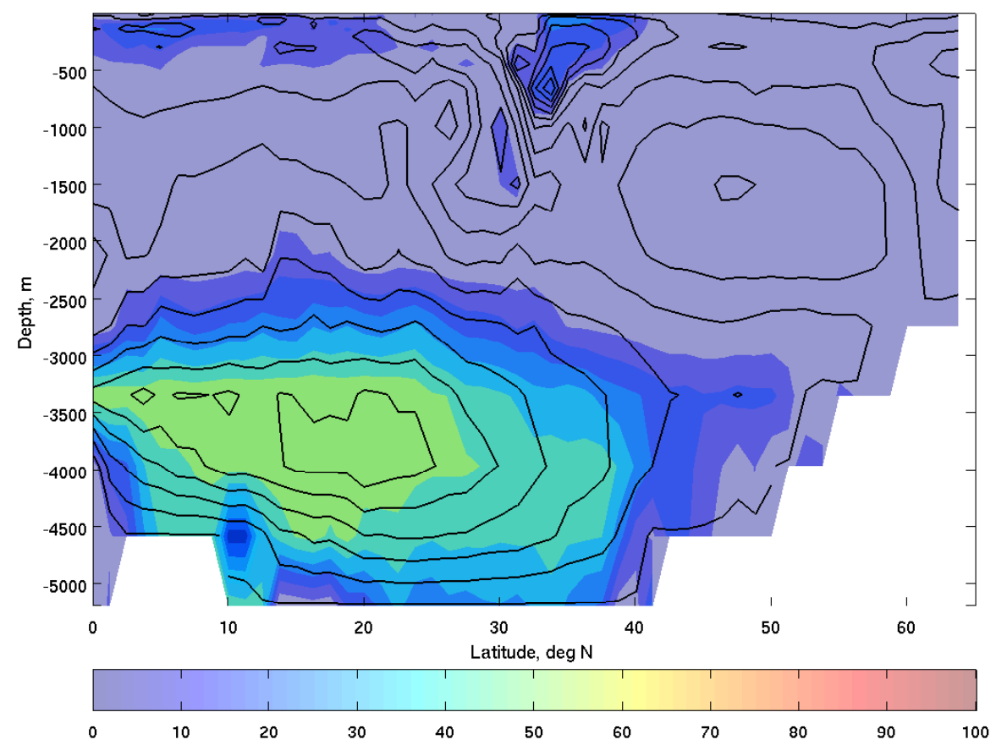

Figure 10: EOF3 of MOC, years 2400 to 2849. Contour interval 0.02.

Figure 11 shows the first EOF for each century of data and shows how there is initially more variation in the deep waters. It is not until after 2150 that the dominance of the North Atlantic overturning cell emerges, and during the century 2450–2550 this is broken again.

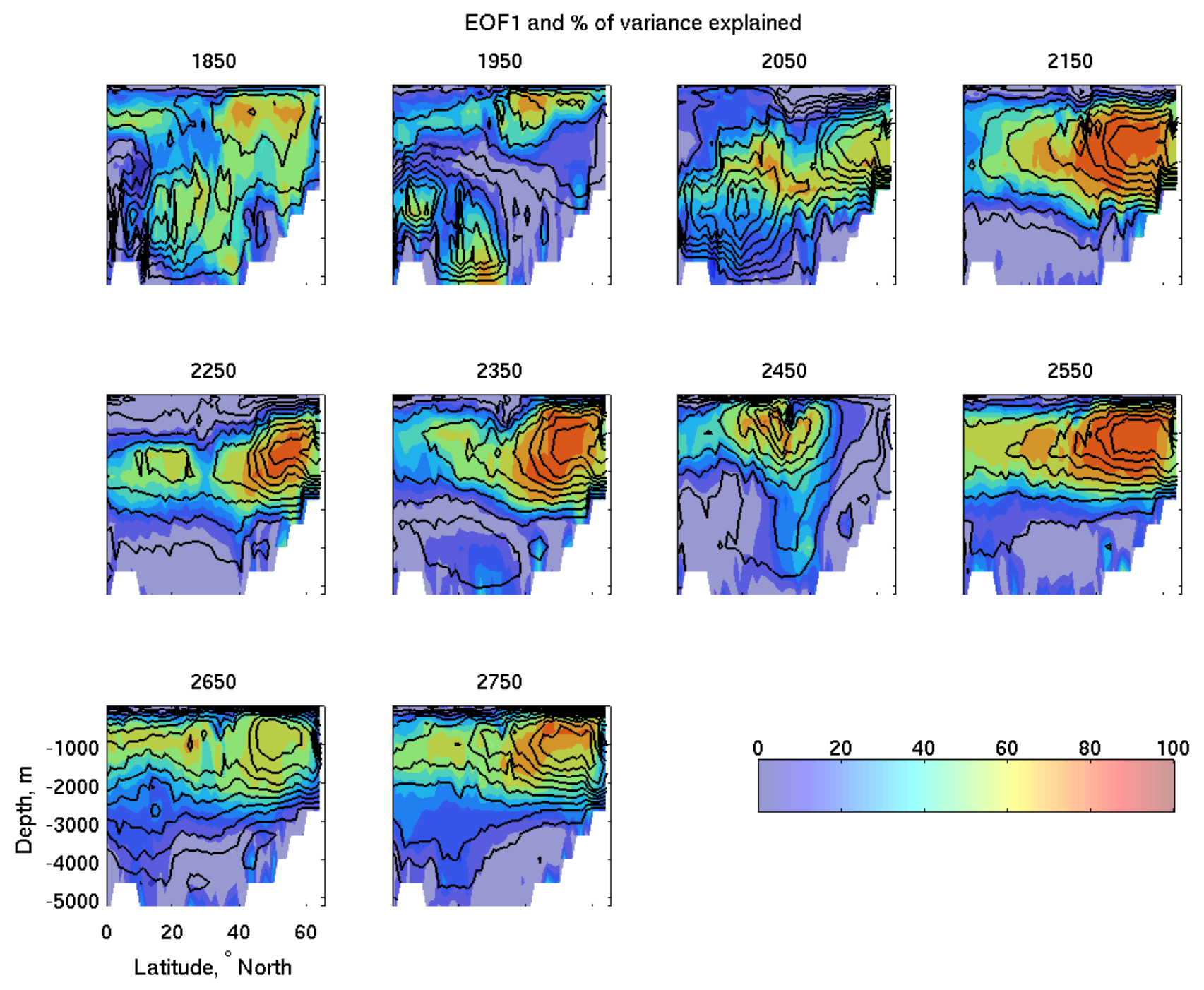

Figure 11: EOF1 of MOC by century, 1850 to 2849

Comparison with HadGEM1

HadGEM1 is a more recent Hadley Centre model[3], with significant changes to atmosphere, ocean and sea-ice models. It has 3.75 times as many ocean grid points as HadCM3. We examined Atlantic data from -35 to 70 °N in the control run for model years 1860–2099. Figure 13 shows the MOC streamfunction. The main overturning circulation is of similar magnitude to that in HadCM3, but the deep-water cell does not extend so far north.

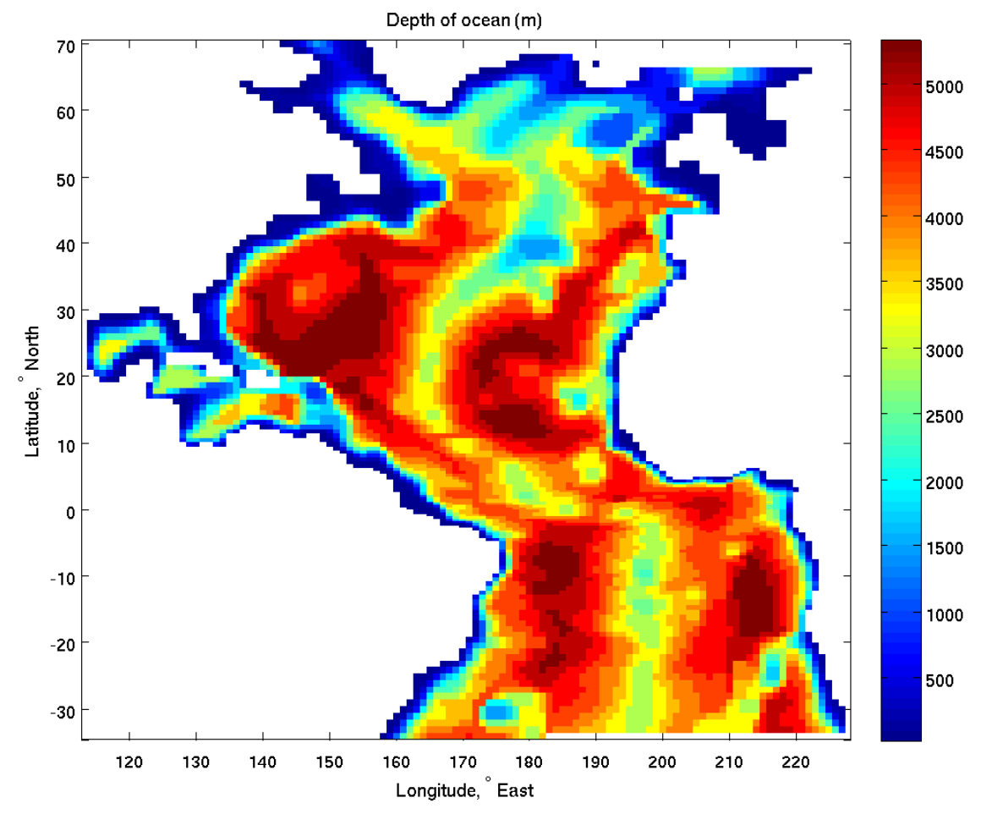

Figure 12: Bathymetry of Atlantic in HadGEM1

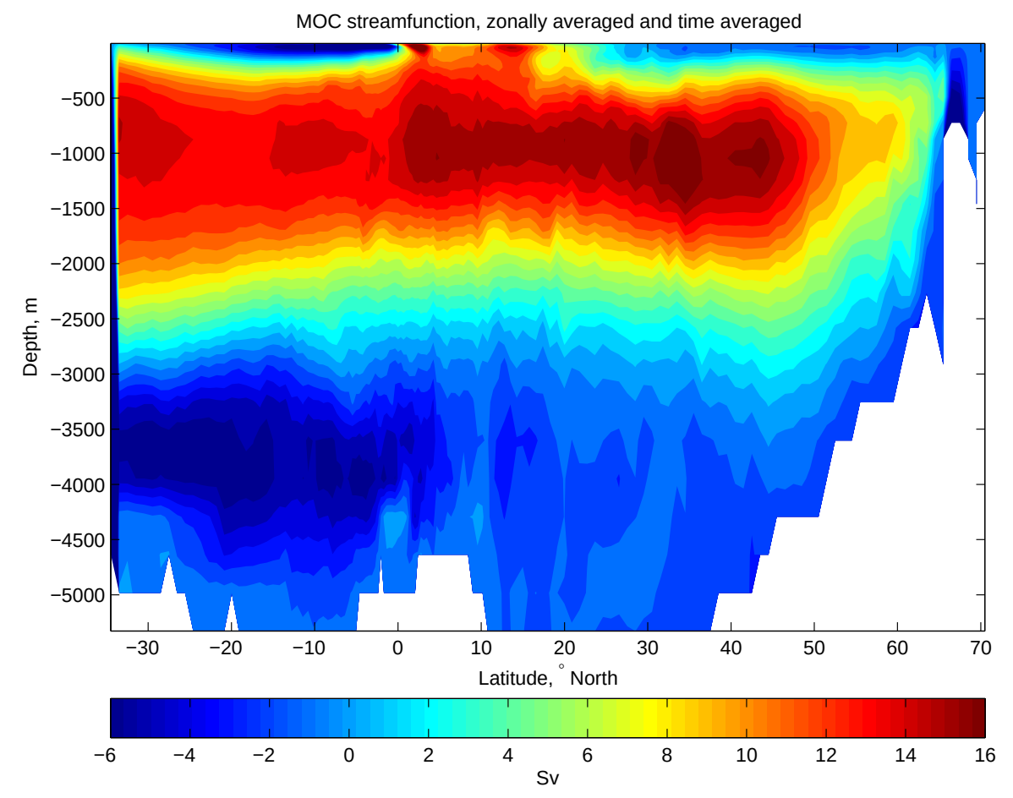

Figure 13: MOC streamfunction in HadGEM1 Control, averaged over 1860–2099.

Figures 14 to 16 show the time-dependent behaviour in three depth bands. As in HadCM3, there is strong coherence of the signal across latitudes north of about 35°N and between -30 to 30°N , with some interference at 0–5°N .

Unlike in HadCM3 this coherence persists to the deeper water, and there is no latitude-dependent transient seen, although there is a slight increasing trend in the deepest band. Again there is less variance in periods shorter than 10 years north of 35°N than further south, whereas for periods longer than 10 years all latitudes are similar.

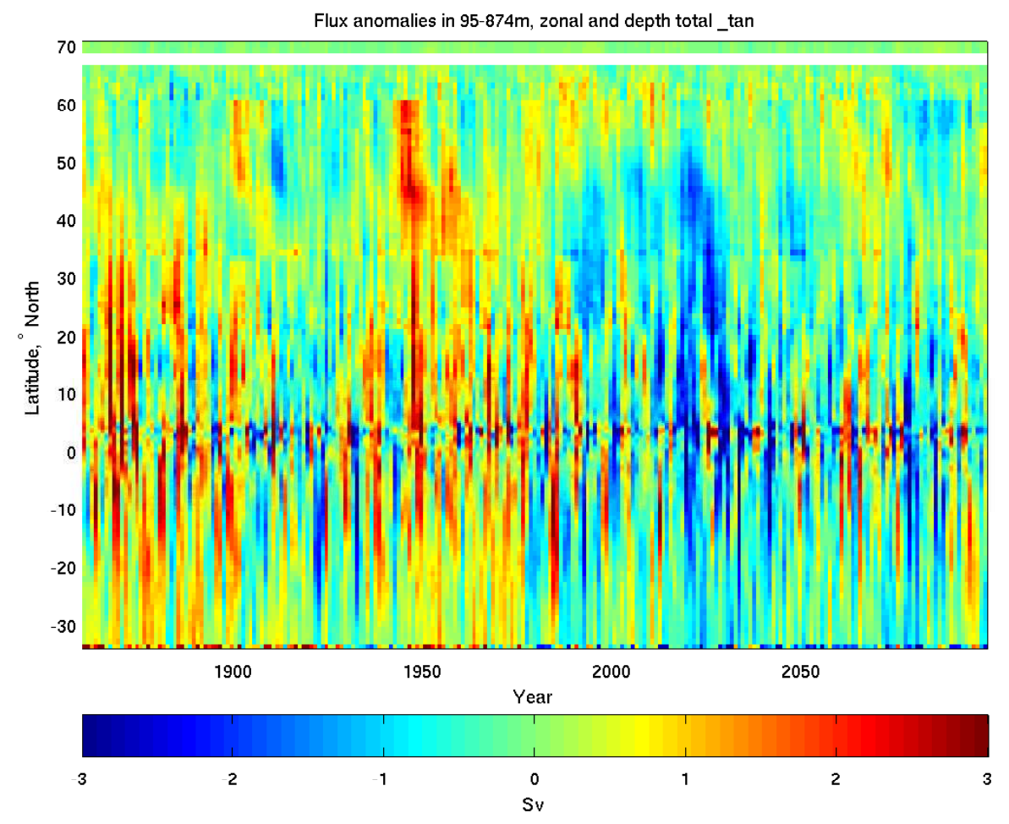

Figure 14: Northwards flow anomalies in 94–874m, HadGEM1

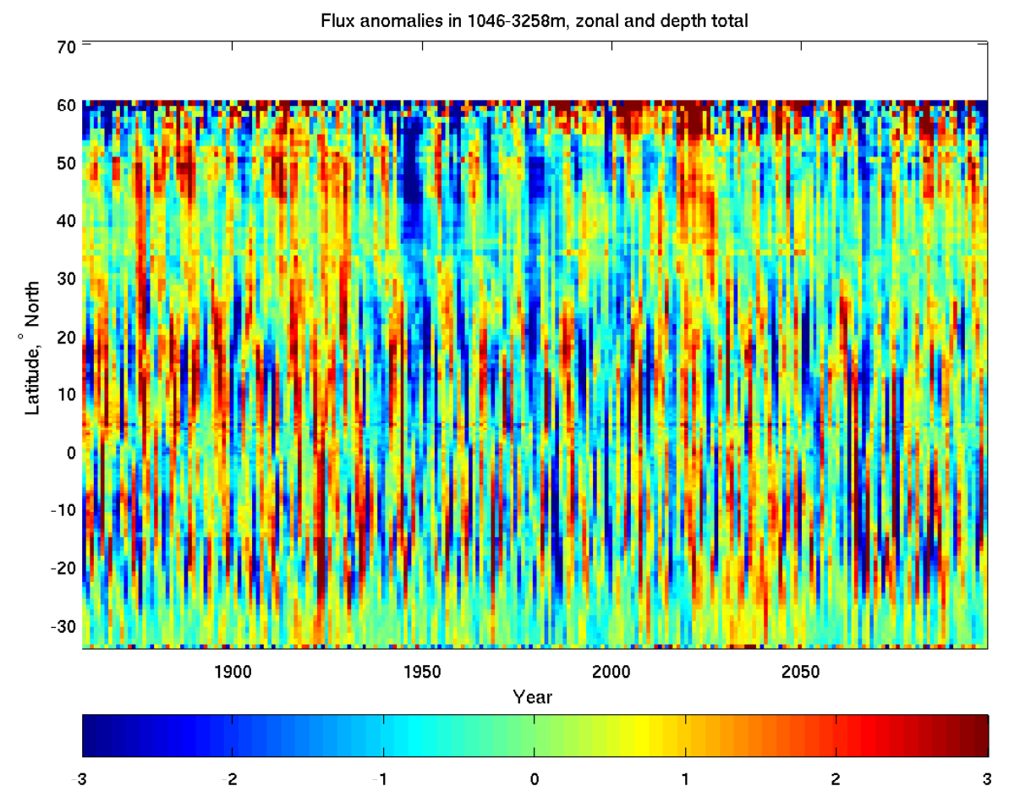

Figure 15: Northwards flow anomalies in 1046–3258m, HadGEM1

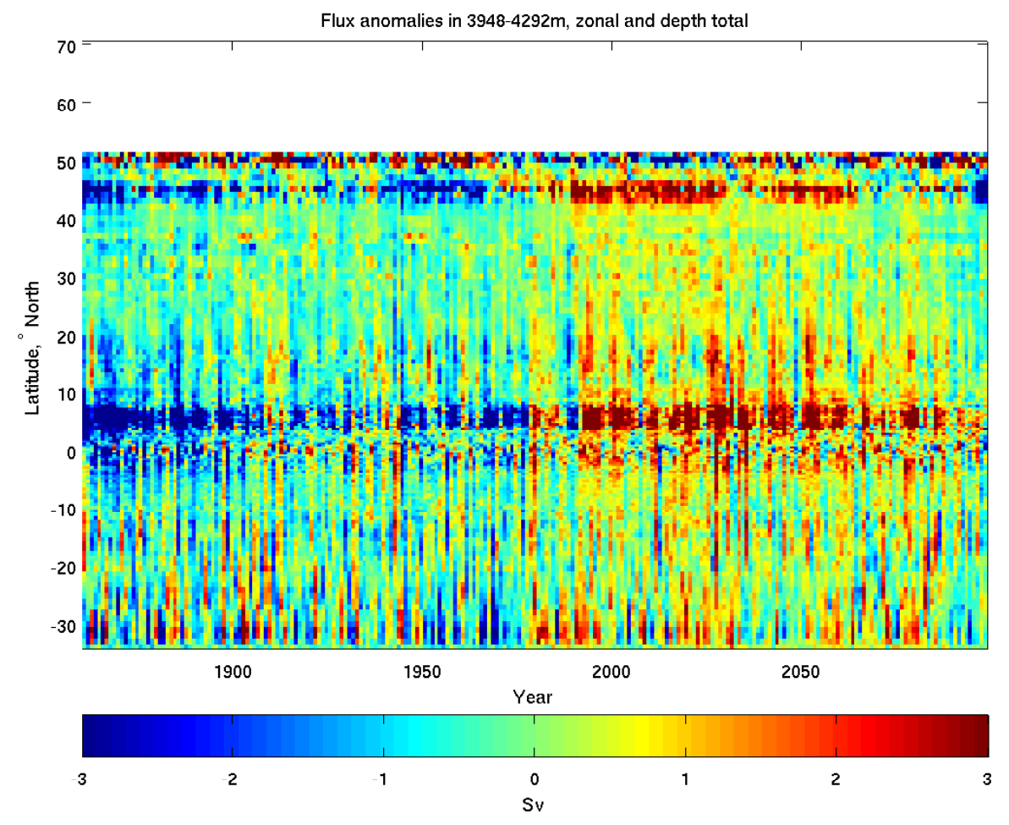

Figure 16: Northwards flow anomalies in 3948–4292m, HadGEM1

References

[1] UK Meteorological Office, Hadley Centre. HadCM3 Control Run Model Data, [Internet]. British Atmospheric Data Centre, 2006–2009. Available from http://badc.nerc.ac.uk/data/hadcm3-control.

[2] R. J. Bingham, C. W. Hughes, V. Roussenov and R. G. Williams (2007) *Geophys. Res. Lett. 34* L23606

[3] UK Meteorological Office, Hadley Centre. HadGEM1 Control integration, [Internet]. British Atmospheric Data Centre, 2006–2009. Available from http://badc.nerc.ac.uk/data/hadgem1.