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Meridional coherence of the North Atlantic meridional overturning circulation

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[1] The North Atlantic Meridional Overturning Circulation (MOC) is associated with deep water formation at high latitudes, and climatically-important ocean-atmosphere heat fluxes, hence the current substantial effort to monitor the MOC. While it is expected that, on sufficiently long time scales, variations in the MOC would be coherent across latitudes south of the deep water formation region, it is not clear whether coherence should be expected at shorter timescales. In this paper, we investigate the coherence of MOC variations in a range of ocean models. We find that, across a range of model physics, resolution, and forcing scenarios, there is a change in the character of the overturning north and south of about 40°N. To the north the variability has a strong decadal component, while to the south higher frequencies dominate. This acts to significantly reduce the meridional coherence of the MOC, even on interannual timescales. A physical interpretation in terms of an underlying meridionally coherent mode, strongest at high latitudes, but swamped by higher frequency, more localised processes south of 40°N is provided. **Citation:** Bingham, R. J., C. W. Hughes, V. Roussenov, and R. G. Williams (2007), Meridional coherence of the North Atlantic meridional overturning circulation, *Geophys. Res. Lett.*, *34*, L23606, doi:10.1029/2007GL031731.

1. Introduction

[2] It has been shown that the collapse of the North Atlantic MOC could have dramatic consequences for northern hemisphere climate, particularly for Northwest Europe [*Vellinga and Wood*, 2002; *Wood et al.*, 2003]. Even a more gradual slow down, as predicted by most climate models [*Cubasch et al.*, 2001] would have a significant impact on regional patterns of climate change. For this reason, a large effort is being made to monitor the Atlantic MOC, and there has been a great deal of interest in the suggestion of *Bryden et al.* [2005] that observations at 26°N show a substantial slowing of the MOC since the 1950s.

[3] However, in speaking of "the" MOC, there is an implicit assumption that changes in the overturning occur at all latitudes south of the deep water formation region, at essentially the same time. For an MOC defined in terms of zonally-integrated transports between density surfaces, it is possible for the MOC to change at one latitude and not another if there is an accumulation of water in particular density classes and a loss in other classes, over the intermediate latitudes. At some long timescale, such that the inflation of density layers reaches equilibrium, a meridionally-coherent overturning must be established. For an MOC defined in terms of zonally-integrated northward flow at constant depth, even the latter equilibrium state may in principle include local overturning cells, although in practice it is also expected to be meridionally coherent.

[4] The purpose of this paper is to investigate the meridional coherence of MOC variability. We use three models, two *z*-coordinate models and a density coordinate model with three forcing scenarios, and in each case find there is substantial variability south of about 40°N, which is not clearly connected to the variability further north. This suggests that optimal detection of a meridionally coherent change in the MOC would require measurements from both north and south of this latitude.

2. Model Descriptions

[5] The main results of this paper are based on an analysis of two z-level numerical models. The first is the Hadley Centre coupled atmosphere-ocean model HadCM3. The oceanic component of HadCM3 has a horizontal resolution of 1.25°, and has 20 depth levels, which vary in thickness from 10 m near the surface to 500 m at the bottom. Results are presented from an analysis of a 100 year control run of HadCM3, with atmospheric aerosols set at preindustrial levels. The second z-level model is the Ocean Circulation and Climate Advanced Modelling project model (OCCAM) run at the National Oceanography Centre, Southampton. It is a global, free surface model with a rotated grid over the North Atlantic, and is forced with 6-hourly ECMWF atmospheric data. The run we are considering (run 202) is at 0.25° resolution, with 66 vertical levels, and covers the 19-year period 1985–2003, with an initial 4 years of spin-up [*Coward and de Cuevas*, 2005].

[6] The results from OCCAM and HadCM3 are assessed against several runs of an isopycnic model, version 2.7 of the Miami Isopycnic Coordinate Ocean Model MICOM 2.7 [*Bleck and Smith*, 1990], with a formulation similar to that employed by *Roussenov et al.* [2006]. For every run the model has 15 σ_2 isopycnal levels in the vertical plus a surface layer with variable density. The model domain is the North Atlantic from 35°S to 65°N, with a horizontal resolution of either 0.23° or 1.4°. The model is spun up with climatological forcing for 150 years and then run for a further 20 years with either climatological or interannual forcing, depending on the experiment. It is this final 20 year period that is analysed.

3. Analysis of MOC variations

[7] The mean North Atlantic overturning stream functions in HadCM3 and OCCAM are shown in Figures 1a and

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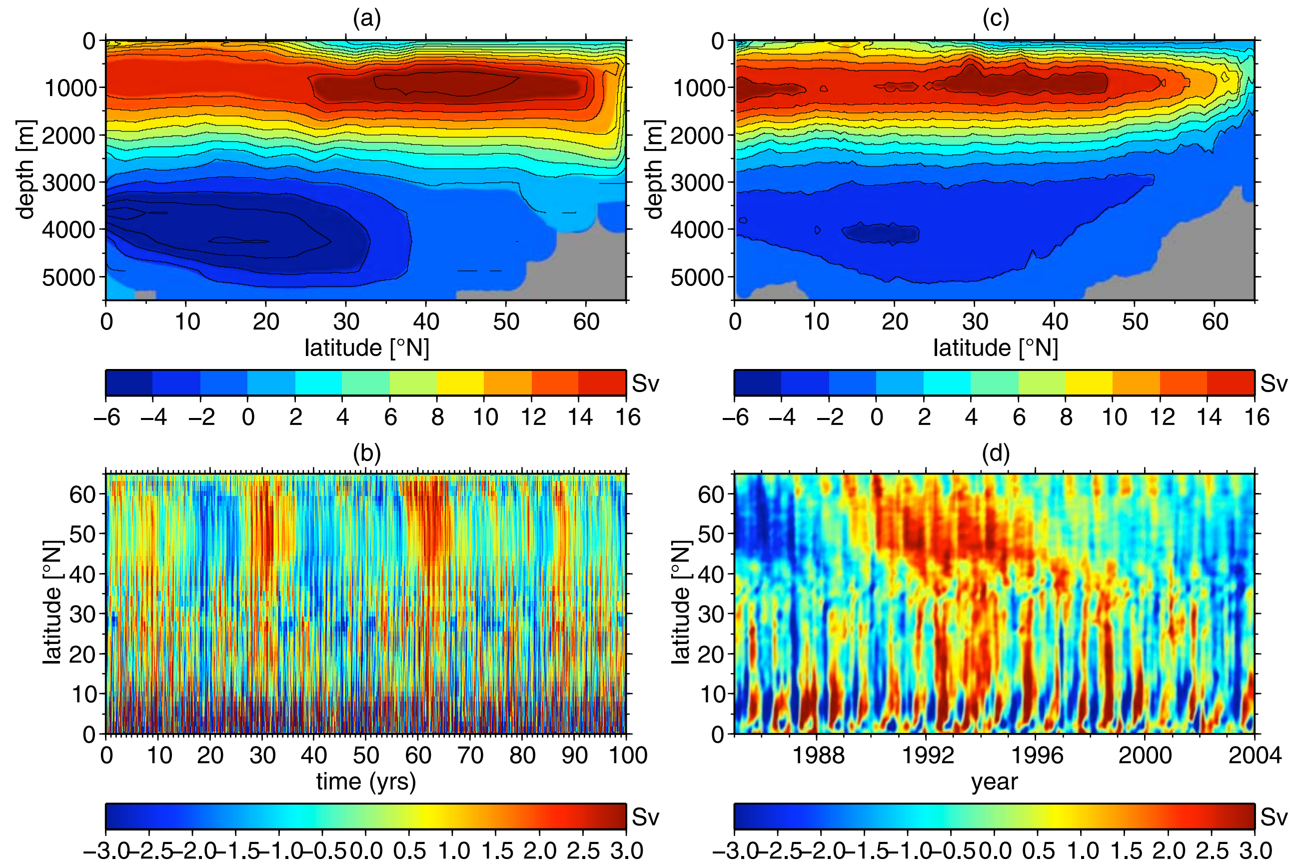

Figure 1. (a) The (a) HadCM3 and (c) OCCAM time-averaged overturning stream function. The (b) HadCM3 and (d) OCCAM northward transport anomaly between 100 m and 1000 m depth.

1c. The MOC of both models comprises an upper and a lower cell. While the maximum northward transport in the upper cells of approximately 20Sv for HadCM3 and 18Sv for OCCAM, occurring near 40°N, are consistent with observations, the lower cells, particularly for HadCM3, appear somewhat stronger than expected from observations [*Bryden et al.*, 2005]. Given the almost constant 1000 m depth of the stream function maximum in each case, we characterise the MOC as the total northward transport between 100 m and 1000 m, thereby excluding the Ekman transport, which reflects the meridional coherence of the wind forcing.

[8] Thus defined, the temporal and latitudinal structures of the MOC from HadCM3 and OCCAM are revealed in Figures 1b and 1d. The most prominent feature in both models is a decadal mode of variability with an amplitude of about 2Sv which is seen clearly at latitudes above 40°N, but not at lower latitudes where the MOC is dominated by annual and higher frequency signals. A similar change in the nature of the MOC variability between low and high latitudes can also be seen in results from the same run of OCCAM presented by *Marsh et al.* [2005].

[9] While much of the higher frequency variability is localised or only coherent over some interval south of 40°N, close inspection of the OCCAM MOC (Figure 1d) shows there are also signals spanning the meridional extent of the domain. These signals appear slightly tilted, suggestive of a signal propagating rapidly from high to low latitudes. Applying the radon transform method to the displayed data gives a southward propagation speed of 1.84 ms^{-1} and a time of 56 days for the signal to reach the equator from 65°N. These signals are perhaps generated by a seasonal deepening and shoaling of the mixed layer and corresponding change in the rate of deep water production at high latitudes. The discrepancy between the propagation time of 30 days reported by *Johnson and Marshall* [2002] could easily be due to the highly idealised configuration of their model domain which produces only Kelvin waves rather than the coastally trapped waves that occur when topography is included. Unfortunately, its monthly resolution does not permit a similar analysis of the HadCM3 data.

[10] From the perspective of climate regulation, short-term fluctuations of the MOC are not so important and so we now focus on interannual variability of the MOC by removing the mean seasonal cycle and applying a low-pass filter with a 13-month box-car filter to remove the remaining intra-annual variability. The degree to which interannual MOC variations are correlated between latitudes is quantified in Figure 2. From the simple picture of adjustment to changes in deep water formation mediated by boundary waves we would expect, on these timescales, a high degree of correlation between MOC variations at all latitudes. Yet, as Figure 2 shows, this is not the case. For HadCM3 (Figure 2a) while latitudes north of 40°N are well correlated with each other, they are generally not well correlated with more southerly latitudes, and the mutual correlation between latitudes south of 40°N is high only over a range of about 15° at most. This shows that variability at any

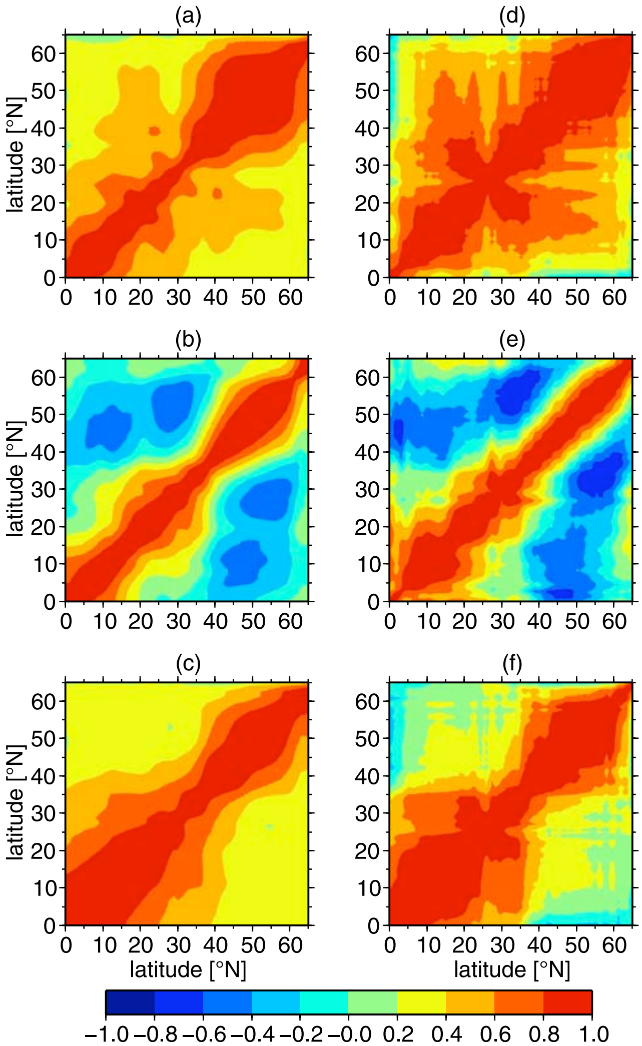

Figure 2. Cross correlation between interannual depth integrated (left) HadCM3 and (right) OCCAM transport at each latitude: (a) and (d) 100–1000 m, (b) and (e) 0–100 m Ekman, and (c) and (f) 0–1000 m.

particular latitude is generally not representative of variability at other latitudes. For OCCAM (Figure 2d) there is a greater correlation between the variability north and south of 40°N. However, with far fewer degrees of freedom this is not necessarily significant.

[11] In our analysis we have excluded the effect of Ekman transport by not including transport above 100 m. The cross correlation matrices due to this surface transport, and those due to the total transport between the surface and 1000 m, are shown in Figures 2b, 2c, 2e, and 2f. We see that the effect of the transport variability in the upper 100 metres is to somewhat increase the correlation length between the equator and 40°N, although only a little, and to reduce still further the correlation between variability north and south of 40°N.

[12] Although the cross correlation matrices in Figure 2 show that much of the interannual MOC variability is rather localised, even for HadCM3 the correlations are always positive, perhaps reflecting an underlying mode of MOC variability that is meridionally coherent. We explore this possibility for HadCM3 by calculating Empirical Orthogonal Functions (EOFs) of the low-pass filtered zonally-integrated northward transports as a function of depth.

[13] The first two EOFs, expressed as stream functions, are illustrated in Figure 3, with the percentage of variance explained by each EOF shaded. The leading EOF (explaining 25% of total variance) represents a coherent overturning cell that spans the meridional extent of the North Atlantic from the equator to 65°N. The overturning mode is most vigorous to the north of 40°N, where it accounts for most of the variance between 100 m and 1000 m and between 2500 m and 4000 m. The EOF evolves primarily on a decadal timescale, accounting for the decadal nature of the MOC variability at these latitudes. Because, as Figures 1 and 2 show, latitudes south of 40°N have much more high frequency, small scale variability, EOF1 is weaker at these latitudes and accounts for much less of the variance. EOF1 represents meridionally coherent transport fluctuations with an RMS of 0.8Sv, and with the most dramatic change being a fluctuation of 4Sv over a period of 8 years. The 2nd EOF (explaining 12% of total variance) contributes significantly to the mid latitude, mid-depth flow, but contributes little to the flow above 1000 m. It represents meridionally coherent transport variations between the equator and 40°N, but with an RMS value of only 0.2Sv.

4. Isopycnal Model Experiments

[14] In order to the test the robustness of the above analysis to different model formulations and forcing scenarios the following experiments were performed with the MICOM isopycnal model: (E1) The model was run with a resolution of 0.23 degrees on a Mercator grid, and was forced by winds and surface fluxes from ECMWF; (E2) The model resolution was reduced to 1.4 degrees, with forcing as in E1; (E3) The model resolution was as in E1, but was forced with monthly climatological winds and surface fluxes from ECMWF, repeating each year. The northward transport integrated over layers 1 to 8, where layer 1 is the mixed layer, and the bottom of layer 8 lies at about 1000 m, is used to characterise the MOC variability. Again we only consider interannual variability. Here Ekman transport is included, but as shown in the above analysis it only makes a small difference to overall MOC coherence at interannual timescales. The results are shown in Figure 4.

[15] The first point to note is that despite the differences in model formulation and forcing, all of the runs show a distinction between variability north and south of about 40°N, similar to that seen in HadCM3 and OCCAM. This indicates that results of this study are general and not peculiar only to z-level models. Second, for both runs with interannual forcing (E1 and E2) the variability to the north of 40°N has longer timescales than that to the south of 40°N. This does not appear to be the case for the climatologically forced run, suggesting that atmospheric forcing plays a crucial role in setting the timescale of the variability in the north. Yet, for experiment E3, it is still the case that the variability to the south of 40°N is to a large extent independent of that to the north. Given that for experiment E3 the filtering removes any direct oceanic response to the atmosphere, ocean dynamics must play a role in creating a discontinuity in MOC variations at 40°N. Finally, just as we

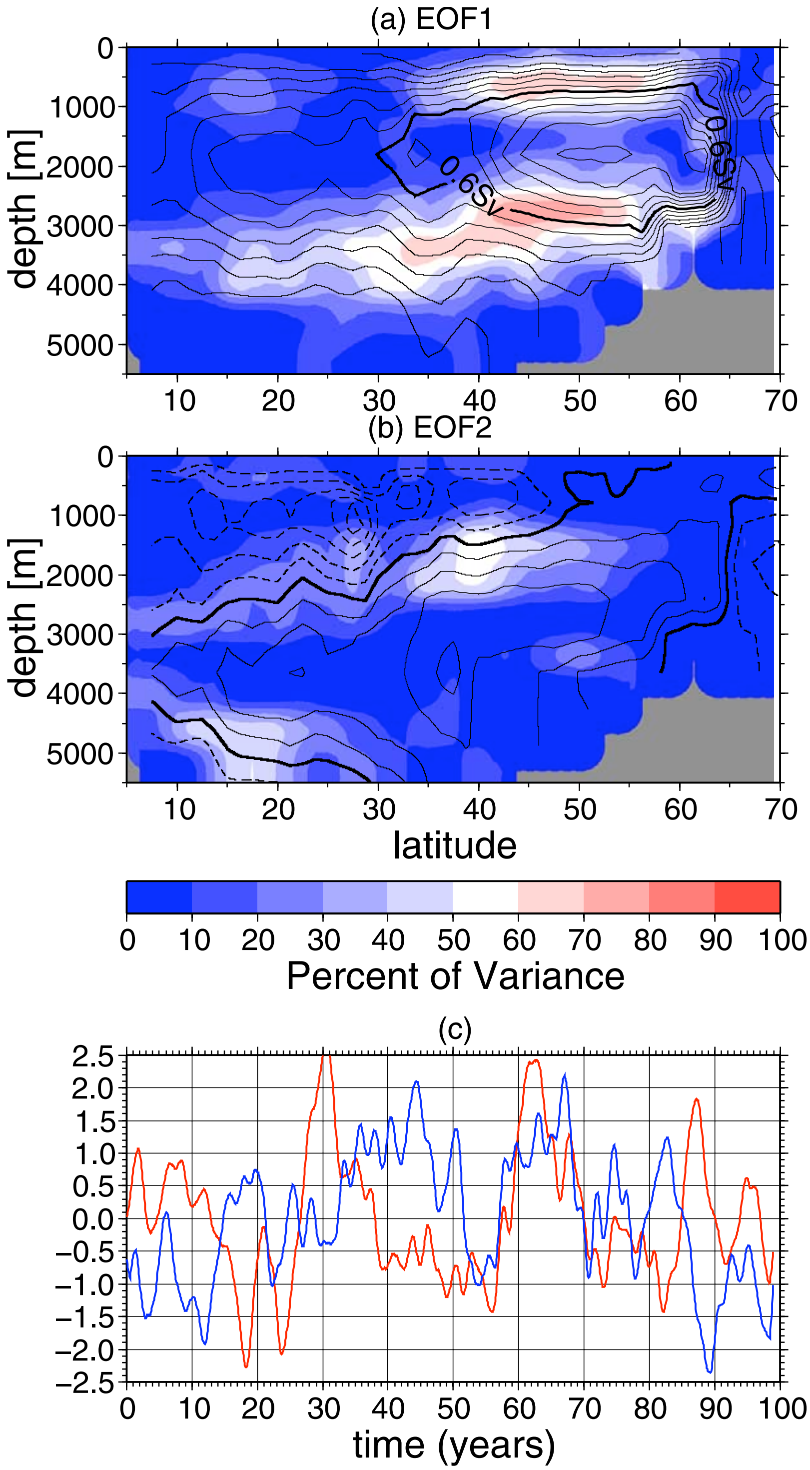

Figure 3. Results of an EOF analysis of the interannual zonally integrated northward transport in HadCM3: (a) the stream function of the leading EOF contoured (interval 0.2Sv) and colours representing the percentage of the total low frequency variance accounted for by the mode, (b) as in Figure 3a but for EOF2 and with contour interval 0.1Sv the heavy contour at 0Sv, and (c) the temporal functions of EOF1 (red) and EOF2 (blue).

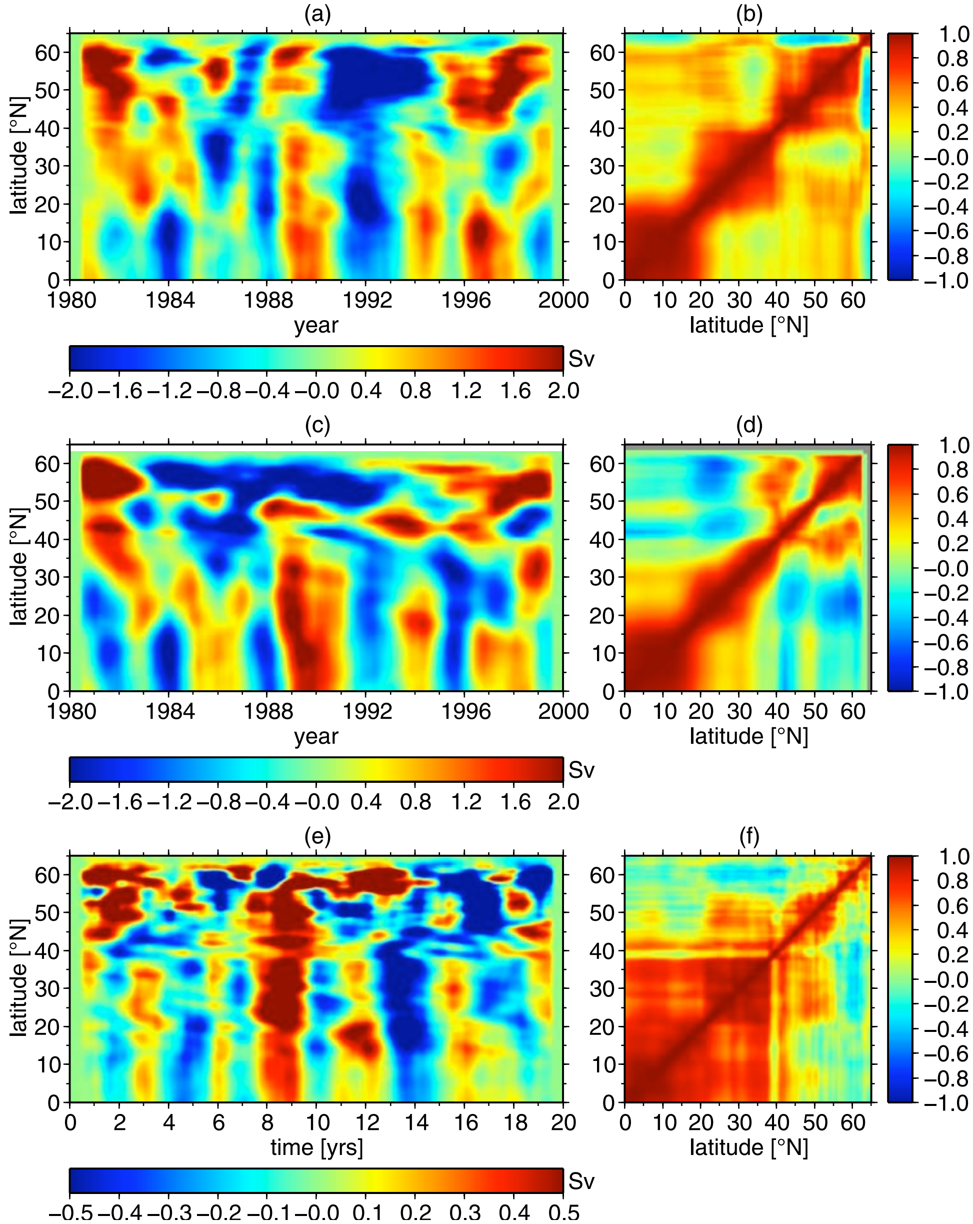

Figure 4. Analysis of several runs of the MICOM model: (left) the interannual northward transport anomaly integrated over layers 1 to 8 and (right) the cross-correlation of the transport shown for (a)–(b) experiment E1, (c)–(d) experiment E2, and (e)–(f) experiment E3. Note that in Figure 4e the range is one quarter of that in Figures 4a and 4c since the variability is internal only, rather than forced and internal. (See text for descriptions of experiments.)

saw for the z-level models, comparison of experiments E1 and E2 shows that the differences north and south of 40°N do not depend on whether the model has the ability to permit eddies, although the discontinuity does appear to be sharper at higher resolution. This suggests that the intergyre boundary, less well defined in course resolution models, may play a role in creating the discontinuity.

5. Discussion and Conclusions

[16] A physical interpretation of the above statistical analysis is of an underlying mode of MOC variability which is meridionally coherent on interannual timescales, the variability being driven by changes in deep water production at higher latitudes and mediated by the southward propagating coastal waves as detected in the unfiltered OCCAM data. This mode agrees with the picture of rapid basin wide adjustment of the MOC to changes at high latitude as seen in the idealised model experiments of *Johnson and Marshall* [2002]. In addition to this, are many processes not represented by an idealised model, that result in higher frequency, more localised changes in the MOC, which greatly reduce the meridional coherence of the MOC, even at interannual timescales. One possible reason that this high frequency variability is much reduced north of 40°N is that, due to weak stratification in the subpolar gyre, Rossby waves do not propagate as freely as they do to the south.

[17] *Eden and Willebrand* [2001] (hereinafter referred to as EW) claim that the strength of the MOC is largely

determined by the strength of the NAO (North Atlantic Oscillation). Figure 6 of EW shows the MOC at 52°N increasing in strength from the late 1980s until the mid-1990s when it begins to decrease; the rise and fall in strength of the MOC in OCCAM north of 40°N has similar timing, although with twice the amplitude (see Figure 1d). EW relate the changing strength of the MOC to a deepening and then shoaling of the mixed layer in the Labrador Sea, resulting from the increasing and then decreasing strength of the NAO. These results seem to indicate that it is the NAO, or rather how the subpolar ocean responds as a low-pass filter to the NAO, that sets the timescale of the MOC variability seen north of 40°N. However, analysis of the 100 year HadCM3 control run does not reveal such an obvious relationship between the low frequency MOC variability north of 40°N and the NAO, nor, for that matter, with the higher frequency variability to the south. This suggests a more complex relationship between the MOC and the NAO than the former responding passively to the latter, where MOC variability results from natural advective timescales of the ocean, as suggested our experiment E3 and by *Griffies and Bryan* [1997], and processes, such as dense water overflows, not represented by the model used by EW.

[18] These model diagnostics clearly have implications for monitoring changes in the MOC. In particular, caution should be exercised when interpreting MOC variations recorded at any one latitude. At subtropical latitudes records may be affected by localised interannual variability making the detection of meridionally coherent changes in the MOC difficult, particularly with short or intermittent observations. On the other hand, measurements north of 40°N, while less affected by higher frequency variability, will over-estimate the amplitude of the coherent MOC variability. Our analysis thus suggests that measurements of the MOC north and south of the 40°N would be complementary, and in combination give the best estimate of meridionally coherent MOC variability.

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