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Towards measuring the meridional overturning circulation from space

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Abstract

We present a step towards measuring the meridional overturning circulation (MOC), i.e. the full-depth water mass transport, in the North Atlantic using satellite data. Using the Parallel Ocean Climate Model, we simulate satellite observations of ocean bottom pressure and sea surface height (SSH) over the 20-year period from 1979–1998, and use a linear model to estimate the MOC. As much as 93.5% of the variability in the smoothed transport is thereby explained. This increases to 98% when SSH and bottom pressure are first smoothed. We present initial studies of predicting the time evolution of the MOC, with promising results. It should be stressed that this is an initial step only, and that to produce an actual working system for measuring the MOC from space would require considerable future work.

1 Introduction

Heat transported northwards in the Atlantic by the thermohaline circulation (THC) produces a warmer climate in Western Europe than would otherwise be the case. Modelling studies suggest that with global warming the THC will slow down or even shut off (Rahmstorf and Ganopolski, 1999; Wood et al., 1999; Stocker et al., 2001).

Some studies suggest that a slowdown of the North Atlantic THC might already be occurring (Häkkinen, 2001; Hansen et al., 2001). According to Häkkinen and Rhines (2004), in the last two decades there has been an increase in sea surface height (SSH) in the North Atlantic subpolar gyre and a reduction in the strength of the North Atlantic subpolar gyre in the 1990s. However, because of the lack of SSH data prior to 1978, there is uncertainty as to whether or not this feature is a decadal cycle or a long-term trend. Levermann et al. (2005) show the usefulness of SSH observations in monitoring the strength of the THC.

To detect the early onset of rapid climate change, the THC needs to be monitored. Separating the density-driven THC (the thermal wind component of ocean circulation) from the wind-driven ocean circulation is impossible due to lack of data. However, measuring the THC by indirect methods is feasible. This can be achieved by using the meridional overturning circulation (MOC) as a proxy for the THC. The MOC is defined as the mass transport of water as a function of latitude and depth. As part of the UK Natural Environment Research Council's RAPID programme, an array has been deployed near 26° N to monitor the MOC from which measurements of temperature, salinity, currents and bottom pressure are obtained. Combining this information with satellite observations, cable measurements in the Florida Strait and ocean circulation models will enable a true 'observed' estimate of the MOC (Hirschi et al., 2003). An alternative strategy is to monitor the strength of the MOC from routine observations, including satellite data. We present the results of a feasibility study that adopts this latter approach.

The Gravity Recovery And Climate Experiment (GRACE) satellite mission enables bottom pressure to be estimated monthly to an accuracy of ~0.1 mbar, and thus to determine bottom pressure gradients (Tapley et al., 2003, 2004a, b). We could therefore, in principle, infer bottom velocity currents using GRACE (Wahr and Molenaar, 1998). Just two physical parameters, ocean bottom pressure and sea surface height, could effectively yield the total (i.e. the sum of the barotropic and baroclinic components) geostrophic flow, and thus allow an estimate of the full-depth mass transport of the MOC.

As there are currently insufficient satellite-derived bottom pressure data, we simulate satellite observations of bottom pressure using the Parallel Ocean Climate Model (POCM). We do the same for SSH. Our initial task is to test how well the MOC could be estimated using satellite observations alone. The basic method is to use a linear model to predict the MOC from the simulated satellite observations of bottom pressure and SSH.

We emphasise that this paper is a feasibility study showing that it is possible to estimate the strength of the MOC from space, but it does not demonstrate an actual working system. It will take considerable follow-up work, and an improved resolution gravity mission, before such a system can be produced.

2 Meridional overturning circulation

2.1 Introduction

The MOC is defined as the mass transport of water as a function of latitude and depth. The MOC stream function, Ψ, is:

$$\Psi(y, z_0, t) = \int_{-H}^{z_0} \int_{0}^{L} v(x, y, z, t)dxdz \tag{1}$$

where $v=v(x, y, z, t)$ is the meridional velocity; $H=H(x, y)$ is the water depth; $L=L(y, z)$ is the zonal width of the basin; x, y, z and t are the longitude, latitude, depth and time coordinates; and z_0 is the sea surface elevation.

2.2 Model description

Our proposed method of monitoring the MOC is tested here using output from POCM-4C, a global eddy-permitting model (Semtner and Chervin, 1992). This is an established and realistic ocean model covering a multi-decadal time period. Its MOC has average values of around 20 Sv (1 Sverdrup or Sv = 10^6 m^3/s), consistent with observations (Marsh et al., 2005); whereas, in some other ocean models such as OCCAM (Ocean Circulation and Climate Advanced Modelling Project; Webb, 1996), the MOC is rather weak (around 6–10 Sv; see Hirschi et al., 2003).

POCM is on a Mercator geographical grid with a longitudinal resolution of 0.4° and a latitudinal resolution of $0.4^\circ \times \cos(\phi)$, where ϕ is latitude, yielding an average spatial resolution of 0.25°. The bottom topography is derived from the 5-min of arc resolution grid of the Earth Topography dataset (ETOPO5). The model is forced with atmospheric fluxes (wind stress, freshwater and heat) using the European Centre for Medium-Range

Weather Forecasts (ECMWF) twenty-year reanalysis (ERA-20) data (Matano et al., 2002). The model run extends from January 1979 to December 1998, inclusive. The model is initialised from a prior ten- year simulation (POCM-4B).

POCM has twenty depth levels, and a free surface consistent with the formulation of Killworth et al. (1991). A description of the POCM equations and algorithms can be found in Stammer et al. (1996). The geographical region from which POCM output is extracted here is 0° to 68° N, 0° to 90° W. We use temperature, salinity, zonal (u) and meridional (v) velocities, as well as density.

3 Methodology

3.1 Description of the statistical method

Our aim is to see if the MOC can be estimated from simulated SSH and bottom pressure data from POCM output. Obtaining SSH is straightforward as it is output directly by the model. Bottom pressure, p_H, is obtained from:

$$p_H \cong g\rho_0\zeta + g\int_{-H}^{0} \rho dz + p_a \tag{2}$$

where ζ is SSH and p_a is the atmospheric pressure. We use an average of four grid points for SSH and bottom pressure. Thus our bottom pressure data does not simulate the current GRACE satellite observations, but a future higher resolution mission instead.

Rather than use complex non-linear fitting procedures, such as neural networks or support vector machines (Hastie et al., 2003), we use a linear model. Our statistical model is given by:

$$\mathrm{MOC}_i = \sum_{j=1}^{p} \alpha_j X_{ij} + \varepsilon_i \tag{3}$$

where MOC_i is the value of the MOC at the ith timestep, X_{ij} $(j=1,p)$ are the linear predictors, and ε_i is an error term such that:

$$\varepsilon_i \sim N(0,\sigma^2) \text{ and } E(\varepsilon_i \varepsilon_j)=0, i \neq j \tag{4}$$

The variables to be used as predictors in Eq. (3) need to be determined. Two sets of predictors are used: (1) a "geostrophic" set comprising SSH and bottom pressure values at either end (79° W and 15° W), of the 26° N basin transect, and also at one point in the middle (45° W); and (2) a "gyre" set comprising the first three empirical orthogonal functions (EOFs) for both SSH and bottom pressure anomaly (BPA) over the whole basin, as well as north and south of 26° N. The rationale for the former is clear. For the latter, we exploit the suggestion by Häkkinen and Rhines (2004) that EOFs provide a measure of the gyre strength. Using EOFs north and south of 26° N, as well as for the whole basin, allows us to distinguish the subpolar and subtropical gyres, albeit in a crude way. Equivalently, we may regard 26° N as the line of zero windstress curl, to a rough first approximation.

In the statistical model we allow interaction between the various SSH terms and between the various BPA terms. However, for simplicity, we do not allow interactions between the SSH and BPA terms. Similarly, we do not allow interactions between the geostrophic terms and the gyre terms, or between the north, south or total gyre terms. Häkkinen and Rhines (2004) investigated the possible role of the North Atlantic Oscillation (NAO) in the strength of the MOC. Therefore, we also include an NAO index in the model.

Our model notation in Eq. (5) follows that of Wilkinson and Rogers (1973). Thus, "*" includes the interaction terms whilst "+" does not. Therefore, A*B+C, for example, means the terms A+B+A.B+C; and A*B*C indicates A+B+C+A.B+A.C+B.C+A.B.C. Our initial model is:

$$\begin{aligned}\mathrm{MOC}=&\mathrm{Constant}+\mathrm{NAO}\\ &+\mathrm{Wssh}*\mathrm{Mssh}*\mathrm{Essh}+\mathrm{Wbpa}*\mathrm{Mbpa}*\mathrm{Ebpa}\\ &+\mathrm{Bssh\_1}*\mathrm{Bssh\_2}*\mathrm{Bssh\_3}+\mathrm{Bbpa\_1}*\mathrm{Bpa\_2}*\mathrm{Bpa\_3}\\ &+\mathrm{Nssh\_1}*\mathrm{Nssh\_2}*\mathrm{Nssh\_3}+\mathrm{Nbpa\_1}*\mathrm{Npa\_2}*\mathrm{Npa\_3}\\ &+\mathrm{Sssh\_1}*\mathrm{Sssh\_2}*\mathrm{Sssh\_3}+\mathrm{Sbpa\_1}*\mathrm{Sbpa\_2}*\mathrm{Sbpa\_3}\end{aligned} \tag{5}$$

where ssh is sea surface height, bpa is bottom pressure anomaly, the prefixes W, M, and E refer to the west, middle and east of the 26° N transect, respectively. The number at the end of the term denotes the *x*th EOF. The prefix B means the EOF covers the whole basin, N is north of 26° N and S is south of 26° N. The results are presented in Sect. 4.

3.2 EOF analysis

As explained above, to obtain the linear predictors needed for Eq. (3) we require an EOF analysis of the two POCM datasets. These are sea surface height anomaly (SSHA) and BPA. SSHA is calculated with respect to the time-mean sea surface of the model.

The EOF principal components (i.e. the time series associated with each EOF) are used as inputs for the linear regression model. We calculate EOFs of SSHA for the complete North Atlantic basin using POCM output. We repeat for the area north of 26° N and also the area south of 26° N. There is a secular trend in SSHA principal component mode 1 (not shown), indicative of typical model drift. We address this below.

4 Results

Figure 1a shows the monthly strength of the MOC in Sv over the years 1979–1998 (black line). There is strong month-to-month variability. Our primary interest is in the long-term variation of the MOC, with most interest in early warning of an imminent shutdown in the thermohaline circulation, rather than inter-month variation; therefore these MOC values are smoothed appropriately. We apply a simple spline smoother (smooth.spline in the R language (R Development Core Team, 2004)). The smoothed MOC is shown as the solid line in Fig. 1. The long-term behaviour of the MOC is apparent: after an initial rise, the MOC strength falls almost linearly until 1997 when it recovers close to its earlier maximum strength of 20 Sv. The reasons for this variability are as yet unknown.

We now fit the statistical model described in Sect. 3 to the data shown in Fig. 1. We use a standard F-test for the linear model (Venables and Ripley, 2002) to see which terms are significant. Note that we do not fit the terms sequentially; we simply fit the most complex model described in Sect. 3. The input variables for the model are smoothed using the spline smoother. The statistical model explains 93.5% of the variability prior to smoothing the inputs, and 98% following smoothing. In none of our fits is the NAO significant. This is consistent with the finding of Häkkinen and Rhines (2004) that the NAO is not a significant factor in the subpolar gyre weakening observed in the 1990s.

To test the strength of this model, we use the first half of the data as a training set to predict the MOC for the second half of the data. The resulting fit explains 99% of the variability in the half of the data used for the fitting, but does not give a good prediction of the second half of the data (Fig. 1a). The mean square error of this prediction is $2.02\,\mathrm{Sv}^2$.

We believe this relatively poor prediction arises from drifts in the model output. POCM-4B, like most ocean general circulation models, conserves volume rather than mass (McDougall et al., 2002). This means that it is possible for the model to gain mass, which seems to be happening here. To correct for this model drift we use EOFs 2 to 4 for SSH, as the first EOF appears to be the linear trend (Fig. 1b). The mean square error of this prediction is 0.63 Sv^2.

As this study aims to simulate satellite data, 2 cm of noise was added to the SSH model inputs, and increasing amounts of noise were added to the BPA data. The results, using 0.02 mb of noise for bottom pressure, are shown in Fi. 1c. The mean square error for this prediction is 0.93 Sv^2. When the noise for the bottom pressure exceeds 0.05 mb the prediction of the MOC seems to be overestimated and the mean squared error exceeds 1.8 Sv^2.

Intriguingly, detrending the data before calculating the EOFs gives a worse prediction than detrending the EOFs themselves. In the latter case we remove a separate trend for each grid point. This is probably removing relevant local information. Working with the EOFs will tend to remove the large-scale trends that we expect to be caused by non-conservation of mass. Our model with the best predictive skill, shown in figure 1b, has the terms:

$$\begin{aligned}\text{MOC}=&\text{Constant} + \text{Wssh}_s + \text{Nssh\_3}_s + \text{Nssh\_4}_s\\ &+\text{Bssh\_2}_s.\text{Bssh\_4}_s + \text{Nssh\_2}_s.\text{Nssh\_3}_s + \text{Sssh\_2}_s.\text{Sssh\_3}_s\\ &+\text{Sssh\_3}_s.\text{Sssh\_4}_s + \text{Wssh}_s.\text{Essh}_s + \text{Wssh}_s.\text{Mssh}_s.\text{Essh}_s\\ &+\text{Bbpa\_2}_s + \text{Bbpa\_3}_s + \text{Sbpa\_1}_s + \text{Bbpa\_1}_s.\text{Bbpa\_2}_s\\ &+\text{Bbpa\_2}_s.\text{Bbpa\_3}_s + \text{Nbpa\_1}_s.\text{Nbpa\_2}_s + \text{Sbpa\_1}_s.\text{Sbpa\_3}_s\\ &+\text{Bbpa\_1}_s.\text{Bbpa\_2}_s.\text{Bbpa\_3}_s + \text{Wbpa}_s.\text{Ebpa}_s\end{aligned} \tag{6}$$

To test whether the model can produce the same result without bottom pressure, the model was run using only SSHA terms and used to predict the MOC for the second half of the data. The results can be seen in Figure 1d. The mean square error is 1.74 Sv^2. Thus omitting the bottom pressure terms gives a significantly worse prediction.

5 Discussion and future work

Our study suggests that it is possible to monitor the meridional overturning circulation (MOC) using a combination of sea surface height and bottom pressure measurements. The eventual aim of this work is an early warning system for collapse of the North Atlantic thermohaline circulation. The considerable month-to-month variability means that we need to extract carefully the trend from the signal; otherwise many false alarms would be triggered.

The linear regression method explains 98% of the variability in the smoothed MOC when the inputs are smoothed. In fitting the regression we assumed that the residuals were uncorrelated. This is true for the unsmoothed data but the smoothing adds correlation and non-white residual noise. This noise has a rather complex structure and our attempts to model it using ARMA noise models have so far been unsuccessful. However, the successful prediction of the second, unfitted, half of the data shows that our model is robust, although the estimated errors are likely too low.

We have used the Parallel Ocean Climate Model (POCM) in this paper. It would clearly be useful to test the proposed method on other models also, such as HYCOM (Chassignet et al., 2003) or HadCM3 (Gordon et al., 2000), and also by exploiting high-resolution gravity data from space, probably from a follow-up GRACE mission. Once the MOC monitoring array near 26° N has been fully operational for some time we hope to compare it with our satellite-based method. Such a test will only be useful once a sufficiently long time series becomes available: perhaps ∼10 years, as suggested by our prediction testing. We intend to repeat our studies at other latitudes to test whether our methodology can be applied to monitor the MOC at locations other than that of the RAPID array, thus complementing and extending the array's capability.

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References

Chassignet, E. P., Smith, L. T., Halliwell, G. R., and Bleck, R.: North Atlantic simulation with the HYbrid Coordinate Ocean Model (HYCOM): Impact of the vertical coordinate choice, reference density, and thermobaricity, J. Phys. Oceanogr., 33, 2504–2526, 2003.

Gordon, C., Cooper, C., Senior, C. A. , Banks, H. T., Gregory, J. M., Johns, T. C., Mitchell, J. F. B., and Wood, R. A.: The simulation of SST, sea ice extents and ocean heat transports in a version of the Hadley Centre coupled model without flux adjustments, Climate Dyn., 16, 147–168, 2000.

Häkkinen, S.: Variability in sea surface height: A qualitative measure for the meridional overturning in the North Atlantic, J. Geophys. Res., 106, 13 837–13 848, 2001.

Häkkinen, S. and Rhines, P. B.: Decline of Subpolar North Atlantic Circulation During the 1990s, Science, 304, 555–559, 2004.

Hansen, B., Turrell, W. R., and Østerhus, S.: Decreasing overflow from the Nordic seas into the Atlantic Ocean through the Faroe Bank channel since 1950, Nature, 411, 927–930, 2001.

Hastie, T., Tibshirani, R., and Friedman, J.: The Elements of Statistical Learning: Data Mining, Inference and Prediction, Springer, 2003.

Hirschi, J., Baehr, J., Marotzke, J., Stark, J., Cunningham, S., and Beismann, J.-O.: A monitoring design for the Atlantic Meridional Overturning Circulation, Geophys. Res. Lett., 30(7), 1413, doi:10.1029/2002GL016776, 2003.

Killworth, P. D., Stainforth, D., Webb, D. J., and Patterson, S. M.: The development of a free-surface Bryan-Cox-Semtner ocean model, J. Phys. Oceangr., 21, 1333–1348, 1991.

Levermann, A., Griesel, A., Hofmann, M., Montoya, M., and Rahmstorf, S.: Dynamic sea level changes following changes in the thermohaline circulation, Climate Dyn., 24, 347–354, 2005.

McDougall, T. J., Greatbatch, R. J., and Lu, Y.: On conservation Equations in Oceanography: How Accurate are Boussinesq Ocean Models?, J. Phys. Oceangr., 32, 1574–1584, 2002.

Marsh, R., de Cuevas, B. A., Coward, A. C., Bryden, H. L., and Alvarez, M.: Thermohaline circulation at three key sections in the North Atlantic over 1985–2002, Geophys. Res. Lett., 32, L10604, doi:10.1029/2004GL022281, 2005.

Matano, R. P., Beier, E. J., Strub, P. T., and Tokmakian, R.: Large-scale forcing of the Agulhas variability: The seasonal cycle, J. Phys. Oceangr., 32, 1228–1241, 2002.

R Development Core Team: R: A language and environment for statistical computing, R Foundation for Statistical Computing, Vienna, Austria, http://www.R-project.org, 2004.

Rahmstorf, S. and Ganopolski, A.: Long-term global warming scenarios computed with an efficient coupled climate model, Clim. Change, 43, 353–367, 1999.

Semtner, A. J. and Chervin, R. M.: Ocean general circulation from a global eddy-resolving model, J. Geophys. Res., 97, 5493–5550, 1992.

Stammer D., Tokmakian, R., Semtner, A., and Wunsch, C.: How well does a 1/4° global circulation model simulate large-scale oceanic observations?, J. Geophys. Res., 101(C10), 25 779–25 811, 1996.

Stocker, T. F., Knutti, R., and Plattner, G.-K.: The Future of the Thermohaline Circulation – A Perspective, in: The Oceans and Rapid Climate Change: Past, Present and Future, edited by: Barron, E. J. and Seidov, D., American Geophysical Union, Geophysical Monograph., 126, 277–293, 2001.

Tapley, B. D., Chambers, D. P., Bettadpur, S., and Ries, J. C.: Large scale ocean circulation from the GRACE GGM01 Geoid, Geophys. Res. Lett., 30(22), 2163, doi:10.1029/2003GL018622, 2003.

Tapley, B. D., Bettadpur, S., Watkins, M., and Reigber, C.: The gravity recovery and climate experiment: Mission overview and early results, Geophys. Res. Lett., 31, L09607, doi:10.1029/2004GL019920, 2004a.

Tapley, B. D., Bettadpur, S., Ries, J. C., Thompson, P. F., and Watkins, M. M.: GRACE Measurements of Mass Variability in the Earth System, Science, 305, 503–505, 2004b.

Venables, W. N. and Ripley, B. D.: Modern Applied Statistics with S, Springer, New York, 2002.

Wahr, J. and Molenaar, M.: Time variability of the Earth's gravity field: Hydrological and oceanic effects and their possible detection using GRACE, J. Geophys. Res., 103(B12), 30 205–30 229, 1998.

Webb, D. J.: An ocean model code for array processor computers, Comput. Geosci., 22, 569–578, 1996.

Wilkinson, G. N. and Rogers, C. E.: Symbolic description of factorial models for analysis of variance, Appl. Statist., 22, 392–399, 1973.

Wood, R. A., Keen, A. B., Mitchell, J. F. B., and Gregory, J. M.: Changing spatial structure of the thermohaline circulation in response to atmospheric CO_2 forcing in a climate model, Nature, 399, 572–575, 1999.

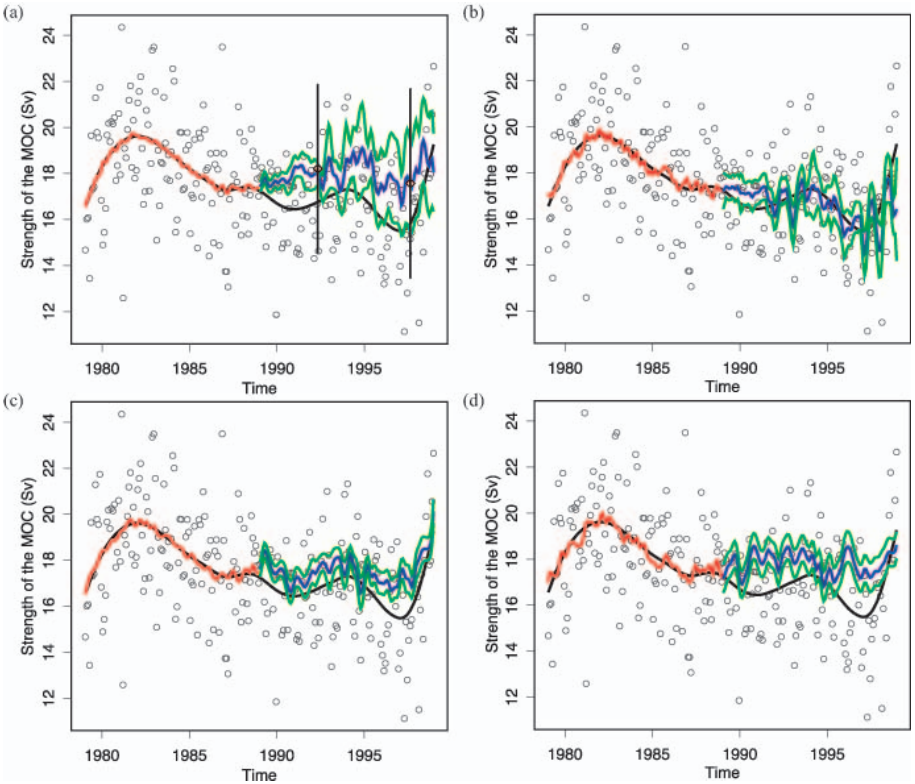

Fig. 1. The strength of the meridional overturning circulation in Sv at 26° N in POCM (circles; black line is smoothed MOC: see text for details). Linear model fit (red line) for the training data, and predictions (blue line) with 95% standard errors of the prediction (green line) for **(a)** the simplest regression model; **(b)** using smoothed and partially detrended inputs for the model; **(c)** adding satellite-equivalent noise to the inputs; and **(d)** using smoothed and detrended SSHA only. The diamonds in (a) represent actual observations, with the lines representing their error bars (Marsh et al., 2005).