Interrogating the 'Great Conveyor': two questions; two flows

By Bob Dickson and Stephen Dye, CEFAS

The first question is relatively uncontentious: 'is the Atlantic Meridional Overturning Circulation (AMOC) of importance to climate?' These days, it would be generally accepted that through its northward transport of warm tropical waters, the AMOC contributes effectively to the anomalous warmth of northern Europe (Large and Nurser, 2001; see also Rhines and Hakkinen, 2003). The oceanic fluxes of volume, heat and salt that pass north across the Greenland-Scotland Ridge from the Atlantic to the Arctic Mediterranean have now been soundly established by direct measurement under the EC VEINS and ASOF/MOEN programmes, as have the corresponding fluxes to the Arctic Ocean (Ingvaldsen, Asplin, & Loeng, 2004 a,b; Schauer et al 2004). We now know that the 8.5 million cubic metres per second of warm salty Atlantic Water that passes north across this Ridge carries with it, on average, some 313 million megawatts of power (one watt is equal to a power rate of one joule of work per second of time) and 303 million kilograms of salt per second (Østerhus et al 2005). As it returns south across the Ridge in the form of the two dense overflows from Nordic Seas, its salinity has decreased from about 35.25 to 34.88 and its temperature has dropped from 8.5°C to 2.0°C or less. Not surprisingly, surrendering this amount of heat is of more than local climatic importance. When the AMOC is deliberately* shut down in the HadCM3 Atmosphere-Ocean General Circulation Model by artificially releasing a large pulse of freshwater in the northern North Atlantic (Wood, Vellinga and Thorpe 2003, Vellinga 2004; Wood et al 2006), the cooling of mean air temperature over the northern Norwegian Sea and Barents Sea 0-10 years after shutdown exceeds -15C, and some lesser degree of cooling is evident over the entire Hemisphere. (*note that this is a 'what if' experiment. No full-size model predicts it).

The obvious follow-up question is much harder to answer: is the AMOC actually slowing? Most computer simulations of the ocean system in a climate with increasing greenhouse-gas concentrations predict that the AMOC will weaken as the subpolar seas become fresher and warmer (eg Manabe and Stouffer 1995; Rahmstorf and Ganopolski 1999; Delworth and Dixon 2000; Rahmstorf 2003), but opinions are divided both on whether thermohaline slowdown is already underway or on whether any variability that we see is natural or anthropogenic. From the current literature for example, we have the report from HadCM3 Group (Wu, Wood and Stott, 2004) that the recent freshening of the deep N Atlantic has been accompanied by an *increase* in the AMOC, diagnostically associated with an increased north-south density gradient in the upper-ocean; from the Princeton Group (Delworth and Dixon, 2006) the idea that anthropogenic aerosols may actually have delayed a greenhouse-gas-induced weakening of the MOC; from the Kiel Group (Latif et al 2006), the suggestion that the expected anthropogenic weakening of the thermohaline circulation will be small, remaining within the range of natural variability during the next several decades; and from the Southampton Group (Bryden et al 2005), the claim that the AMOC has already slowed by 30% between 1957 and 2004. None of these opinions ---and there are others!---is controversial in the sense that they are all based on established and accepted techniques. But the more extreme are certainly controversial in their interpretation of events. Our observational series are simply too short or gappy or patchy to deal unambiguously with the complex of changes in space, time and depth that the Atlantic is exhibiting, and even the closely-observed line that Bryden et al rely on is not immune. Modelling the same Atlantic transect (26°N), Wunsch and Heimbach (2006 in press) find a strengthening of the outflow of North Atlantic Deep Water since 1992 (ie, in the layers and years where Bryden et al had observed their major decrease), and from the month-to-month variability that they encounter are forced to conclude that *'single section determinations of heat and volume flux are subject to serious aliasing errors'*. Such uncertainties in our observations are bound to feed through to our models. Thus in their recent assessment of the risk of MOC shutdown, Wood et al

(2006) can go no further than conclude that shutdown remains a '*high impact, low probability event*' and that '*assessing the likelihood of such an event is hampered by a high level of modeling uncertainty*'.

Two Fluxes: The fact remains that, understand it or not, current climate is changing. In their careful reassessment of the climatic record, Osborne and Briffa (2006) conclude that '*the most significant and longest duration feature during the last 1200 years is the geographical extent of warmth in the middle to late 20th Century'*. And despite the fact that Bryden et al report a decrease in the net northward oceanic heat flux through 25°N from 1.3-1.4 to 1.1 PW since 1957 (1PW=10^{15}W), the many time-series collated by the ICES WG on Oceanic Hydrography (ICES, 2006) show clearly enough that the Atlantic waters crossing over the Greenland-Scotland Ridge to the Nordic Seas and Arctic Ocean are generally at their warmest and saltiest since records began (see also Polyakov et al 2006). Reflecting this trend, Overpeck et al (2005) report that the Arctic system remains on trajectory to a new seasonally ice-free state, '*a state not witnessed for at least a million years'.*

Developing an understanding of the longer-term variability of the ocean-atmosphere-cryosphere system of subarctic seas is therefore critical to the continued development of our climate models. Together with partners at University of Hamburg and the Finnish Institute of Marine Research, CEFAS has focussed its attention on measuring two ocean flows off SE Greenland that seem of particular importance to the Earth's climate system. The cold, dense Denmark Strait Overflow, whose characteristics and variability are measured by the Slope array, drives the abyssal limb of the AMOC. The freshwater that flows south on the adjacent East Greenland Shelf ---the largest component of the freshwater flux that reaches the North Atlantic from the Arctic (Dickson et al in press) ---has been implicated in model experiments with slowing that circulation down.

Forty years on from Val Worthington's first heroic but unsuccessful attempt to deploy current meters across the violent flow through Denmark Strait in February-March 1967, the overflow array is now proven and fully-developed. A decade of continuous observations now reveals that the near-bottom flux at densities $\sigma\theta > 27.85$ is around 4 Sv, close to the 3.8 Sv predicted by Jack Whitehead (1998) on the basis of hydraulic constraints. Käse and Oschlies (2000) later used hydrographic observations and modelling to confirm that the strength of the DSO is, to first order, in hydraulic balance. However, as our observations have lengthened, they have moved us on a little from thinking of the DSO as an unchanging, hydraulically-controlled flow (eg Girton et al, 2001) to a hydraulically-controlled flow that can show interannual change. As Figure 1 below will show, the short term strengthening-then-weakening of overflow transport that we observed in our current meter array around 2000 is now neatly confirmed both by a model-optimised ADCP array close to the sill (Macrander et al 2005) and by transport estimates from satellite altimetry in the Denmark Strait (Köhl, Käse, Stammer and Serra, in press). There is no evidence yet of any long-period trend and no evidence of any co-variance in transport between Denmark Strait and Faroe Bank Channel overflows, as we had once supposed.

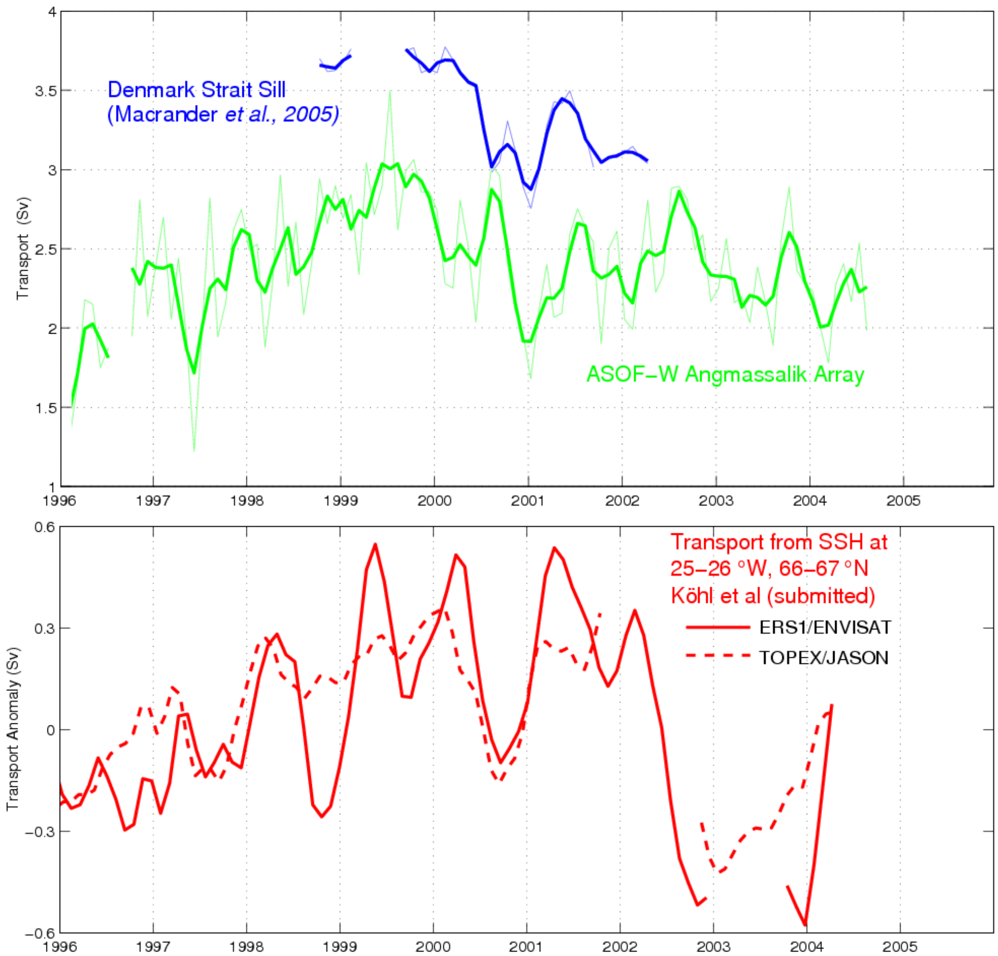

Figure 1. Strengthening-then-weakening of Denmark Strait Overflow transport around 2000, as revealed by three independent data-sets: a) direct observations of flow through the long-term CEFAS-UHH-FIMR moored current meter array on the East Greenland Slope off Angmagssalik (green curve); b) model-optimised estimates based on a discontinuous Acoustic Doppler Current Profiler (ADCP) array close to the sill (blue curve; see Macrander et al 2005); c) transport estimates from sea surface height as measured by TOPEX/Jason & ERS2/ENVISAT satellite altimetry close to Denmark Strait by Köhl, Käse, Stammer and Serra (red curve; submitted). Note that in the case of the Angmagssalik array we are emphasising the change in transport rather than its magnitude, so using the moorings with the longest continuous time-series from the core of the plume. When data from all moorings are considered, the transport of Denmark Strait Overflow Water (densities $\sigma\theta >$ 27.85) is around 4 Sv.

Curry and Mauritzen (2005) made the next logical step. Recognising that it is the density contrast across the Denmark Strait sill that drives the overflow and noting that both overflows have undergone a remarkably rapid and remarkably steady freshening over the past four decades (Dickson et al 2002), Curry & Mauritzen (2005) use Whitehead's hydraulic equation to ask how much more fresh water would have to be added to the western parts of the Nordic seas to produce significant slowdown. They find that's not going to happen anytime soon:- '*At the observed rate, it would take about a Century to accumulate enough freshwater (e.g. 9000 km*^{3}*) to substantially affect the ocean exchanges across the Greenland-Scotland Ridge, and nearly two Centuries of continuous dilution to stop them. In this context, abrupt changes in ocean circulation do not appear imminent*'. The fact that the freshening trend of both overflows at the sill has slowed to a stop over the past 10 years has merely reinforced this conclusion.

The Freshwater Flux array is at a much less advanced state of development. Set across the continental shelf of SE Greenland, it aims to use an array of fixed or profiling moored salinity sensors and current measurements to measure the major (and at present largely unmeasured) component of freshwater flux passing south from the Arctic Ocean to the N Atlantic under the ice of the East Greenland shelf. Our reliance on 'tube' moorings 35-45m long to carry the salinity sensors up to the ice-base, thus protected against strikes by drift ice on the principle of the knock-down-and-bounce-back 'Margaret Thatcher doll', has brought real advances, notably the recovery of continuous salinity records of up to 4 years duration. However the accelerated discharge of the glaciers at SE Greenland in 2005 reported by Rignot and Kanagaratnam (2006), including the increased mass-loss of the Kangerdlugssuak Glacier from 5-to 36 km^3 ice/yr between 2000 and 2005, has brought a major new and perhaps unsurvivable hazard. With grounded icebergs still present within 10 km of the array position when recovery was attempted in August 2005, it seems clear that the heavy losses we experienced then are likely to be due to this cause. Though the array we redeployed in 2005 was a rudimentary one, (one tube mooring with three Microcat sensors together with one ADCP), we plan once more to attempt to extend that small array towards its intended coverage in September 2006 with a 2nd tube mooring and a new Aanderaa RDCP-600 acoustic profiling current meter. The climatic importance of measuring this flux argues against withdrawing the array at our first reverse. But this will never be a safe site and only time will tell if our plans to re-extend the array across this dangerous shelf are justified or foolhardy. Val Worthington would have known the feeling!

References

Bryden HL, HR Longworth and SA Cunningham, 2005. Slowing of the Atlantic meridional Overturning Circulation at 25°N. Nature 438, 655-657.

Curry R and C Mauritzen, 2005. Dilution of the Northern North Atlantic Ocean in Recent Decades. Science. **308** (5729): 1772-1774.

Delworth TL and KW Dixon, 2000. Implications of the recent trend in the Arctic / N Atlantic Oscillation for the North Atlantic thermohaline circulation. J Clim, **13**, 3721-3727.

Delworth TL and KW Dixon, 2006. Have anthropogenic aerosols delayed a greenhouse gas-induced weakening of the North Atlantic thermohaline circulation? Geophys Res Lttrs., 33, LO2606, doi:10.1029/2005Glo24980,2006.

Dickson, R. R., I. Yashayaev, J. Meincke, W. Turrell, S. Dye, and J. Holfort. 2002. Rapid Freshening of the Deep North Atlantic over the past Four Decades. Nature lond, 416, 832-837.

Dickson R., B. Rudels, S. Dye, M. Karcher, J. Meincke and I.Yashayaev 2006. Current Estimates of Freshwater Flux through Arctic & Subarctic seas. Prog Oceanogr, (accepted).

Girton JB, TB Sanford and RH Käse, 2001. Synoptic sections of the Denmark Strait Overflow. Geophys Res Lett., 28, 1619-1622.

ICES(2006). ICES Report on Ocean Climate 2005 (editors. S. L. Hughes & N. P. Holliday), ICES Cooperative Research Report, No. 280. 47 pp

Ingvaldsen, R.B., Asplin, L., & Loeng, H. 2004a. Velocity field of the western entrance to the Barents Sea, *Journal of Geophysical Research*, *109*, C03021, doi:101029/2003JC001811.

Ingvaldsen, R.B., Asplin, L., & Loeng, H. 2004b. The seasonal cycle in the Atlantic transport to the Barents Sea during the years 1997–2001, *Continental Shelf Research*, *24*, 1015-1032.

Käse R and A Oschlies (2000) Flow through Denmark Strait. J. Geophys. Res. 10, 28527-28546.

Köhl A, R Käse, D Stammer and N Serra (2006). Causes of changes in the Denmark Strait Overflow. J Phys Oceanogr, (in press)

Latif M., C Boening, J Willebrand, A Bistoch, J Dengg, N Keenlyside, and U Schweckendiek, in press . Is the thermohaline circulation changing?

Large W G and A J G Nurser, 2001. Ocean surface water mass transformations, pp 317-335 In: G Siedler, J Church and J Gould (Eds) Ocean Circulation and climate. Academic Press International Geophysics Series, 77, 715 pp.

Macrander A, U Send, H Valdimarsson, S Jonsson, and RH Käse, 2005. Interannual changes in the overflow from the Nordic seas into the North Atlantic through Denmark Strait. Geophys res Lttrs., 32, L06606, doi:10.1029/2004GL021463, 2005

Manabe S and RJ Stouffer 1995. Simulation of abrupt climate change induced by freshwater input to the North Atlantic Ocean. Nature 378, 165-167.

Osborn TJ and KR Briffa 2006.The spatial extent of 20th-Century Warmth in the context of the past 1200 Years.

Østerhus S, WR Turrell, S Jonsson and B Hansen 2005. Measured volume, heat and salt fluxes from the Atlantic to the Arctic Mediterranean. Geophys Res Lttrs, 32, L07603,doi:10.1029/2004GL022188, 2005

Overpeck J and Co-authors, 2005. Arctic system on trajectory to new seasonally ice-free state. EOS, 86, 34, pp 309, 312, 313.

Polyakov I and co-authors, in press. 2005. One more step toward a warmer Arctic. Geophys. Res Lttrs. 32, L17605, doi:101029/2005GLO23740

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

Rahmstorf S 2003. Thermohaline Circulation: the current climate. Nature 421, 699

Rignot E and P Kanagaratnam, 2006. Changes in the velocity structure of the Greenland Ice Sheet. Science, 311, 986-990.

Rhines P and S Hakkinen, 2003. Is the Oceanic heat transport in North Atlantic irrelevant to the climate in Europe. ASOF Newsletter #2 13-17

Schauer U, E Fahrbach , S Østerhus and G Rohardt, 2004. Arctic warming through the Fram strait: Oceanic heat transports from 3 years of measurements. J . Geophys Res., 109, C06026, doi:10.1029/2003JC001823,2004

Vellinga M and RA Wood 2002. Global climate impacts of a collapse of the Atlantic Thermohaline Circulation. Climatic Change, 54, 251-267.

Vellinga M 2004. Robustness of climate response in HadCM3 to various perturbations of the Atlantic meridional overturning circulation. Hadley Centre Tech Note 48, unpaginated.

Whitehead JA, 1998. Topographic control of oceanic flows in deep passages and straits. Rev. Geophys 36, 423-440.

Wood R.A., M. Vellinga and R. Thorpe 2003 "Global warming and thermohaline circulation stability", Phil. Trans. R. Soc. Lond. (A), 361, pp 1961-1975

Wood, R.A., M. Collins, J. Gregory, G. Harris & M. Vellinga (2006) Towards a risk assessment for shutdown of the Atlantic Thermohaline Circulation. In '*Avoiding Dangerous Climate Change*', ed. H.J. Schellnhuber et al., Cambridge University Press, 392pp

Wu, P, R.A Wood and P Stott, 2004. Does the recent freshening trend in the North Atlantic indicate a weakening thermohaline circulation? Geophys Res Lttrs, 31, Lo2301, doi: 10.1029/2003GLO18584, 2004.

Wunsch C, and P Heimbach 2006 Estimated Decadal Changes in the North Atlantic Meridional Overturning Circulation and Heat Flux 1993-2004. J Phys. Oceanogr, (in press).