22. DESCRIPTION OF RESEARCH PROJECT

Monitoring the Atlantic Meridional Overturning Circulation at 26.5°N

a) Background: Objective 1 of the RAPID programme is “to establish a pre-operational prototype system to continuously observe the strength and structure of the Atlantic meridional overturning circulation (MOC)”. The MOC is commonly defined as the zonally integrated meridional flow, as a function of latitude and depth. While parts of the MOC are wind-driven, the basin-scale Atlantic MOC is largely buoyancy-forced. Hence, observing the Atlantic MOC is the fundamental observational requirement of a programme aiming to assess the role of the Atlantic thermohaline circulation (THC) in rapid climate change.

b) Rationale for observing the MOC at 26.5°N: While much of RAPID is focussed on the high latitudes, it is ultimately the ocean heat transport around 25°-35°N that is most relevant for climate. Much of the heat transported northward in the Atlantic is given off to the atmosphere over the Gulf Stream extension (e.g., Isemer et al., 1989), from where it is transported north-eastward toward Europe by the atmosphere. Two characteristics of ocean heat transport mechanisms are crucial: First, the ocean heat transport is mainly accomplished by the MOC (Hall and Bryden, 1982; Ganachaud and Wunsch, 2000). Second, fluctuations in heat transport (and, by implication, transports of other quantities such as freshwater and carbon) are expected to be dominated by fluctuations in the transporting velocity field, and only to a lesser extent by variability in heat (or property) content. For example, Jayne and Marotzke (2001) showed that in a global high-resolution model, heat transport variability equatorward of 40° arose almost exclusively because of velocity fluctuations advecting the mean temperature field. These two characteristics justify this programme’s emphasis on the MOC. As one consequence, the basic monitoring of the MOC should occur near the heat transport maximum. 26.5°N has the triple advantage of being close to the heat transport maximum in the Atlantic, of being the latitude of four modern hydrographic occupations, and of offering a long time series of boundary current observations not existing anywhere else (Baringer and Larsen, 2001; see below for the significance of this fact). We take as our starting point that it is not practical to obtain a quasi-continuous estimate of the MOC by constantly manning a hydrographic section, for personnel and financial limitations. This requires a radical re-thinking of how to obtain meridional transport estimates, for which hydrographic lines (top to bottom, coast to coast, ensuring a closed mass balance) have proven to be the most reliable strategy (e.g., Ganachaud, 1999).

c) Basic observational strategy: Our proposed strategy relies on a combination of moored arrays (temperature, salinity, currents, and pressure), hydrographic lines, satellite observations (sea level, winds), the opportunistic use of float data, cable measurements (Florida Strait transport), and modelling to synthesise the observations. The starting point lies in applying geostrophy: Geostrophic mass transport between any two points depends only on the pressure difference between these points; to estimate the MOC thus would require the continuous observation of density at eastern and western boundaries, plus the establishment of a reference level. This idea has been implemented in various ways, though not in a systematic attempt to observe the MOC continuously. Whitworth (1983) monitored Drake Passage transport; Lynch-Stieglitz et al. (1999) estimated Florida Strait transport during the Last Glacial Maximum; Lynch-Stieglitz (2001) used marginal density information to infer both modern and past integrated circulations; McPhaden and Zhang (2002) found a slowdown of the shallow low-latitude Pacific MOC by using boundary XBT profiles; Curry and McCartney (2001) estimated changes in subpolar gyre strength. Marotzke et al. (1999) tested endpoint monitoring ideas in their GCM, with some success, while Kanzow (2000) performed array design studies for moorings dedicated to monitoring integrated transports in the western North Atlantic. In part based on Kanzow’s findings, Send and co-workers from IfM Kiel deployed moorings at 16°N to observe the deep integrated flow west of the Mid-Atlantic Ridge, as a pilot study to an observing system for the entire MOC (U. Send, 2000, pers. comm.).

The 26.5°N section has the fundamental advantage that the western boundary current (flow through Florida Strait) can be measured relatively straightforwardly by cable (existing long-term programme by the US, e.g., Larsen, 1992; Baringer and Larsen, 2001) and regular calibration cruises. This makes the monitoring of the entire MOC equivalent to the task of monitoring the depth profile at which the flow through the Florida Straits returns southward. Currently, its contribution to the MOC returns southward at depths between 1000m and 4000m (e.g., Roemmich and Wunsch, 1985); dramatic shoaling of this return path would be equivalent to a collapse of the MOC (note that there is expected always to be wind-driven flow through the Florida Strait, as shown by the existence of the Kuroshio in the Pacific despite the absence of a deep sinking MOC cell in the North Pacific).

Over the past year, we have performed design studies to test our strategy; in particular, we have successfully tested our proposed antenna in two high-resolution models. Details are discussed below, following the presentation of our basic design.

d) Instrumentation: We propose to monitor continuously full-depth density profiles at and near the eastern and western boundaries. In total, we propose to deploy 8 full-depth moorings, six of which would be equipped with a McLane Moored Profiler (MMP) taking roughly one CTD profile every other day. This technology has just reached maturity (Morrison et al., 2001), and an SOC team has recently obtained 600 profiles over 25 days, to 700 m depth in the central Indian Ocean (A. New, 2002, pers. comm.). The use of profilers has the big advantage over individual, fixed-location CTD sensors that only a single instrument needs to be calibrated. Several moorings would be required near each boundary, for obtaining boundary current measurements through thermal wind, improving the signal-to-noise ratio, and as failsafe measures. We propose to use one conventional full-depth mooring at each end with fixed-depth CTDs. This serves as a fallback position, but it also provides the opportunity to add other instruments, such as current meters or the planned tracer autosamplers, which are intended to be put on one of our western moorings (A. Watson, 2002, pers. comm.). Based on Kanzow (2000), we conclude that 14 CTDs obtain sufficiently dense sampling in the vertical; the investment needed for these instruments equals that of the MMP. All moorings would be equipped not only with CTDs but also with bottom pressure sensors, and some with current meters. This gives added information for estimating the depth-independent part of the MOC that is not in thermal wind balance but is rather dominated by high-frequency barotropic dynamics (e.g., Jayne and Marotzke, 2001; Böning et al., 2001). To test the boundary array, two transoceanic sections would be required to obtain MOC estimates toward the beginning and the end of the deployment period, using an independent approach. The SOC James Rennell Division will perform a 26.5°N cruise as part of its Core Programme in 2004; we expect a second cruise to take place in 2008, after the RAPID programme has finished. Neither cruise is part of the current budget.

The presence of the Mid-Atlantic Ridge (MAR) complicates the endpoint monitoring of the MOC, because a pressure drop may exist across the ridge. Below the ridge crest, the sub-basins to the east and west therefore have to be monitored separately. We propose to use one MMP mooring on each side of the MAR, but the back-up fixed-depth CTD moorings will only reach to the ridge crest. The MMP moorings will tell us how the shallow Gulf Stream return flow is divided between eastern and western basins.

In addition to the full-depth sampling, we propose to instrument the sloping shelfbreak topography, from the deep water to shallow depths, with CTDs, bottom pressure recorders (BPR), and current meters (CM), to obtain continuous observations at fixed depths. This would provide an alternative vertical sampling strategy, and also help solve the bottom triangle problem (e.g., Whitworth and Peterson, 1985). It would be the continuous analogue to the sampling strategy employed by Lynch-Stieglitz et al. (1999) who used density information inferred from foraminiferal oxygen isotope data.

In summary, our design is based on the strategy that even the complete loss of any one mooring would not jeopardise the project as a whole.

e) Deployment details and budget considerations: The budget is based on the following (Fig. 1, which also contains the long-term averaged meridional velocity near the western boundary, Lee et al., 1996):

Western array at 26.5°N: **WB2** will be our pivotal mooring, as close to the western “wall” as possible, with a profiling MMP, a BPR, CM at top and bottom and, crucially, telemetry. **WB3** is the backup, conventional mooring, with 14 CTD and 6 CM instead of the MMP. *This mooring would not be required if the Johns & Baringer U.S. proposal is funded; their Mooring **B** would serve as the backup to our **WB2**, at a cost savings of £350K to this project.* **WB1** is similar to **WB2**, but without telemetry, and will be placed in about 2000m depth, to obtain thermal-wind shear estimates across the continental slope. **WBH1** and **WBH2** are HOMER moorings plus BPR, to obtain density profiles near the bottom, over 400 vertical metres. If HOMER is not available, we will purchase 5 SeaBird CTD instead for each HOMER. **WB4** is similar to **WB2**, but without telemetry, and will be placed at the outer edge of the DWBC core. It will obtain thermal-wind shear estimates across the strong current. Johns & Baringer propose one mooring further offshore of the DWBC (72°W, their Mooring **E**) to monitor the DWBC including its local recirculation. We propose to deploy an upward-looking **ADCP** (from the existing instrument pool) in 500m water depth, to capture the shallow Antilles current. Johns & Baringer propose a combined CM/ADCP mooring (their Mooring **A**) near our **WB1**. Together, these moorings would allow us to obtain thermal-wind shear across the entire boundary current. All our moorings would be serviced annually, using Miami as the base. We require one complete duplicate set of instruments for deployment years 2 and 4.

MAR array at 26.5°N: **MAR1** and **MAR4** are similar to **WB2**, with a profiling MMP and a BPR but without telemetry. Their backup moorings, **MAR2** and **MAR3**, need only cover the depths below the ridge crest and are therefore equipped with 10 CTDs each. The **MAR1** and **MAR4** MMPs will come out of SOC's equipment pool, at no equipment cost to this project. Consumables have to be included, however. Owing to the logistical difficulties of servicing MAR moorings regularly, we propose redeployment in every year of only **MAR2** and **MAR3**, whereas **MAR1** and **MAR4** would only be deployed in deployment years 1 and 3.

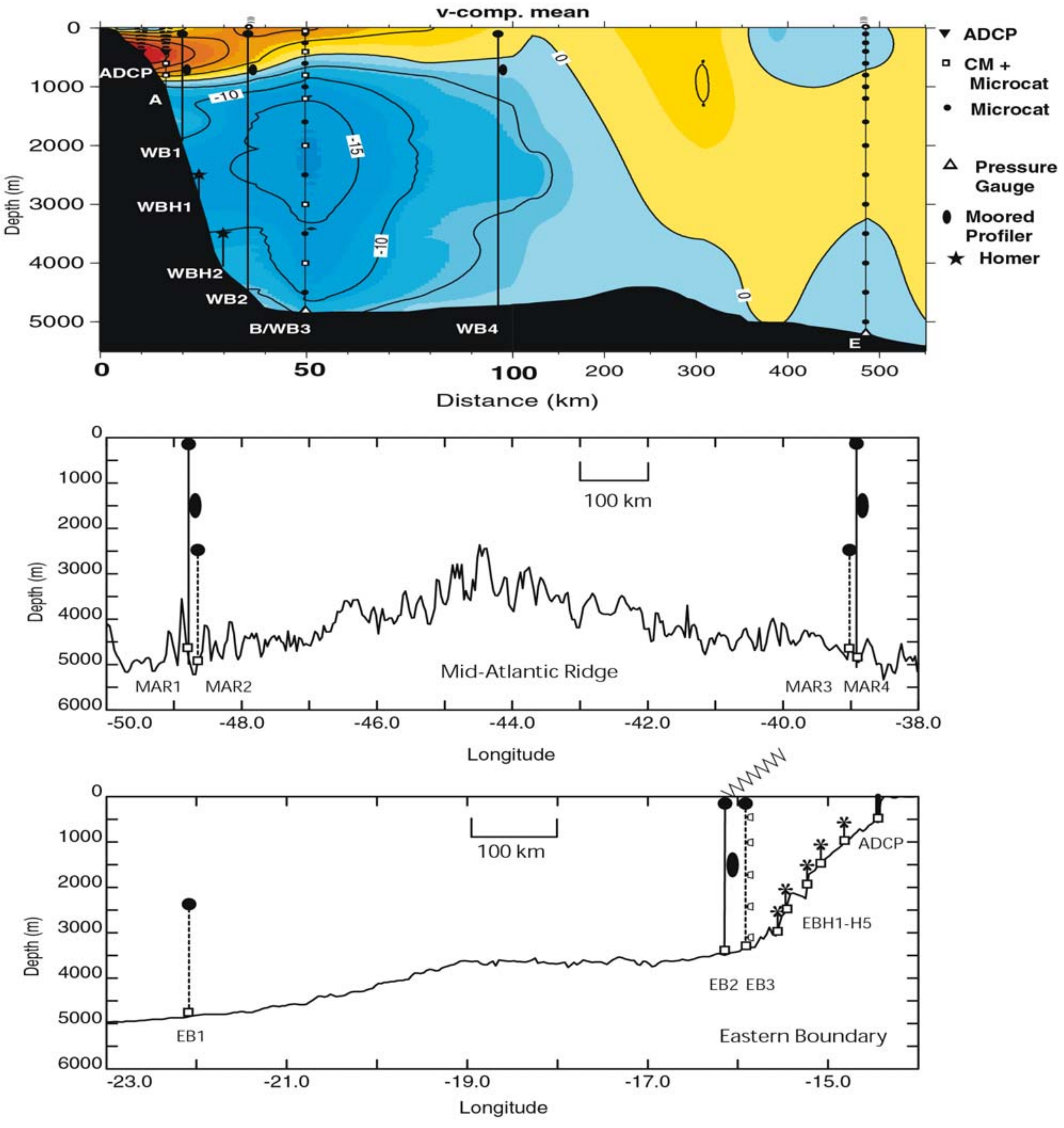

Figure 1: Mooring array for monitoring the Atlantic meridional overturning circulation at 26.5 N. a) Western boundary; b) Mid-Atlantic Ridge; c) Eastern boundary

Eastern array at 26.6°N: **EB2** would be our pivotal mooring – the counterpart to **WB2** – with its location chosen as a compromise between the desire for full water depth and nearness to the shelf break. **EB2** has a profiling MMP, a BPR, CM at the top and bottom, and telemetry. **EB3** is the backup, conventional mooring, with 10 CTD and 5 CM instead of the MMP. **EB1** is similar to **MAR3**, and serves to cover thermal-wind shear at depths greater than the bottom of **EB2**. Owing to the more gently sloping topography, compared to the western boundary, the potential of incurring a significant bottom triangle error even from slowly moving water is considerable. To minimise leakage, we propose moorings **EBH1** to **EBH5,** which are HOMER moorings plus BPR, to obtain density profiles near the sloping bottom, over 400 vertical metres. If HOMER is not available, we will purchase 5 SeaBird CTD instead for each HOMER. We propose to deploy an upward-looking **ADCP** (from the existing instrument pool) in 500m deep water, to capture shallow boundary currents. We require one complete duplicate set of instruments for deployment years 2 and 4.

f) Antenna design tests in numerical models: We have "deployed" the above-described array in two high-resolution ("eddy-permitting") numerical models, OCCAM (Webb, 1996; 1/4° resolution) and FLAME (e.g., Beismann and Redler, 2002; 1/3° resolution). Our reconstructions of the MOC are based on a superposition of Ekman and thermal wind contributions (similar to the approach of Lee and Marotzke, 1998). Knowing the wind stress allows the determination of the Ekman transport from theory. We assume that the Ekman transport is compensated by a spatially constant return flow across the section, so that there is no net meridional mass transport related to the zonal wind stress. The thermal wind balance allows us to calculate the vertical shear of the meridional velocity component between adjacent vertical density profiles, across the section. Integrating the shear from bottom to top yields a meridional velocity field. As for the Ekman transport a spatially (but not temporally) constant correction is applied to the velocity field in order to ensure zero net meridional mass transport. We assume that the vertical profile of mass transport across Florida Strait is known, (according to what cable measurements and profiling sections could provide in the real Atlantic).

Figure 2 shows the results of our standard design (8 full-depth moorings plus Mooring E of Johns & Baringer), for both models. The light shading in Fig. 2a indicates the parts of the section that are not covered by our array. Figs. 2b and 2c demonstrate that our reconstruction does an excellent job in recovering the time history of the maximum MOC, at 26°N. The FLAME analysis shows a slight bias of around 2 Sv, but the variability is very well reproduced. Fig. 2d shows that the reconstruction reproduces the vertical structure of the MOC, as well as the evolution of the maximum. Figs. 2e and 2f show that it is both contributions to the reconstruction, thermal wind and Ekman, that are required to capture the total MOC. In particular, the OCCAM run (Fig. 2e) shows a secular weakening of the MOC over 10 years, a result of model drift. This occurs despite forcing with climatological winds; the MOC weakening arises solely from the thermal wind contribution, and is very well reflected by our reconstruction.

We tested the sensitivity of our method to uncertainties in the Florida Strait transport, by adding noise (standard deviations of 1, 2, 5 Sv) to the Florida Strait transport simulated in OCCAM. The resulting uncertainty in the MOC reconstruction was of order one half of the assumed Florida Strait transport measurement error (Figure not shown), which we deem perfectly acceptable. We have also performed systematic tests leaving out parts of the array; because of space limitations, only the most salient results can be discussed here. Leaving out either the MAR moorings or covering the eastern boundary less densely only has a small effect on our reconstruction. However, we advise caution in taking the models literally on this point. At this resolution, the eddy kinetic energy is still considerably underestimated (e.g., Stammer et al., 1996), and we suspect that the models underestimate the vigour and variability of eastern boundary currents. We therefore rely on the strategy of sampling the eastern boundary to the extent we think is sufficient, with the possibility of reduction in future years. Also, we propose as part of our work plan for Year 1, to analyse output from the 1/12° OCCAM run that has recently been performed. Simulated time covers only a single year, but we expect important information concerning the 1/4° OCCAM's fidelity in reproducing boundary currents. Concerning the importance of the MAR moorings, both models underestimate the depth of the core DWBC, which shows up above the depth of the MAR, in contrast to observations. Again, we consider it prudent not to rely on the models being realistic at this stage.

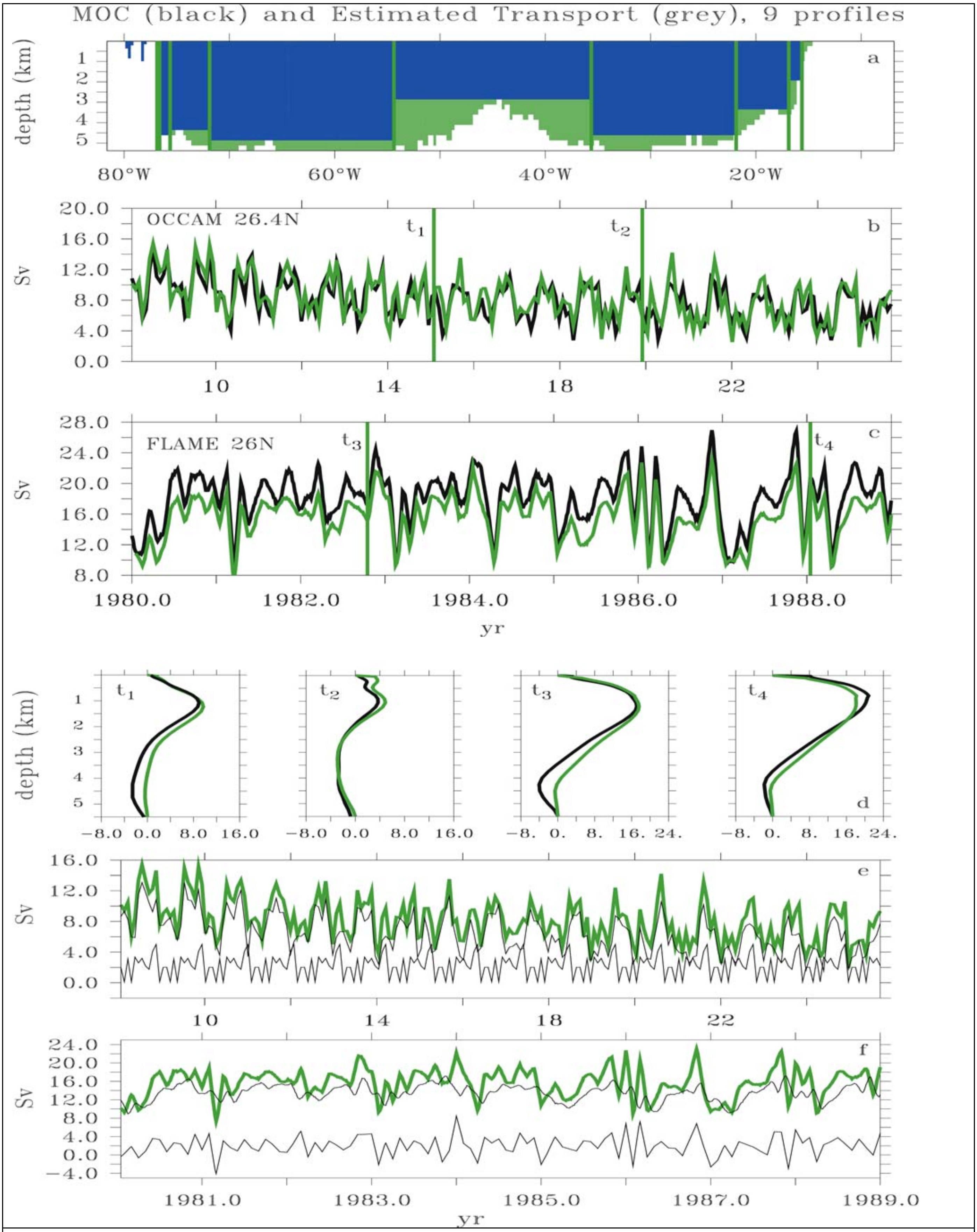

Fig. 2: Reconstruction of the MOC of two high-resolution numerical models, based on the proposed mooring design. (a) Location of the moorings. Dark shading marks areas across which thermal wind shear is captured by array; light shading marks “leakage” area. (b) Time series, maximum MOC (black) and maximum reconstruction (grey) for OCCAM. (c) Time series, maximum MOC (black) and maximum reconstruction (grey) for FLAME. (d) Vertical profiles of MOC (black) and reconstruction (grey), at times indicated in (b) and (c). (e) Decomposition of reconstruction (grey) into contributions from thermal wind (upper thin) and Ekman transport (lower thin), for OCCAM. (f) Decomposition of reconstruction (grey) into contributions from thermal wind (upper thin) and Ekman transport (lower thin), for FLAME.

We have also tested the scenario of having no observations at all outside the western boundary area, and here the changes are dramatic (Fig. 3). The reconstruction overestimates the MOC by a factor of two, and whereas there are periods when the variability appears to be captured reasonably well, there are also long periods of large disagreements. Also, the vertical structure is not reproduced well at all. Obviously, a western boundary array alone misses horizontal recirculations and their variability, and is therefore not a feasible strategy. It is essential to sample both the eastern and western boundaries.

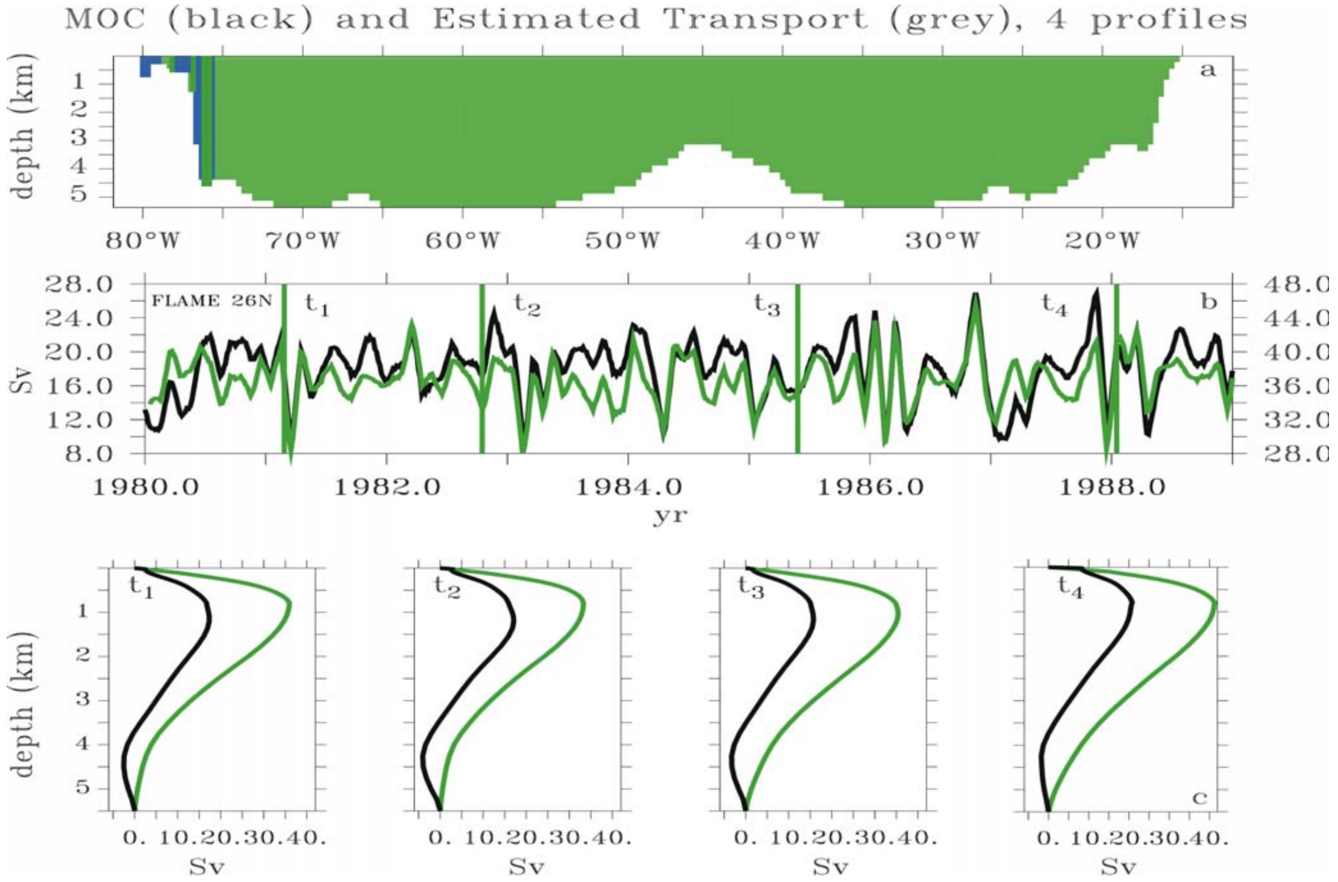

Fig. 3: Reconstruction of FLAME MOC, based only on western boundary profiles. See Fig. 2 for legend. Black and grey curves in the middle panel have the same vertical range but different offsets.

f) Scientific plan: The measurements are proposed primarily for monitoring the MOC, but we expect them to contain a wealth of information about quantities other than the MOC directly. The MOC is an integrated quantity, and much can be learned about its dynamics and its efficient monitoring by looking at its “constituents”. A partial list of science objectives is the following (other possibilities will open up as the project progresses):

i) The central time series to produce is that of the MOC profile. This would occur in three stages, according to the increasing volume and refinement of the data set. Stage 1 is based on the real-time density profiles from our moorings **WB2** and **EB2**, obtained through the telemetry**.** Together with wind observations that are available near real-time (http://podaac.jpl.nasa.gov/quikscat/), we can apply a simplified version of the method used for Figs. 2 and 3 (Hirschi et al., 2002). Stage 2 is based on the full density profiles available after mooring recovery, and we would follow exactly the procedure of Figs. 2 and 3. The final stage would occur after the synthesis of density profile, BPR, CM, and altimeter data (see below).

ii) We will compare the MOC estimate based on our deployment year 1 against that based on the 2004 hydrographic cruise. This will give us important clues concerning any potential bias in the array approach.

iii) We plan to investigate timescales of variability – internal waves, fast barotropic fluctuations (ca. 10 days timescale), seasonal cycle, interannual variability – in all our measurements. In particular, we will analyse the distribution of variability across the section, with a focus on how it can be filtered out where necessary (e.g., internal waves). The goal of this is to design an efficient monitoring system.

iv) We will analyse the data systematically for potential redundancy. For example, we have included two alternative ways of sampling density profiles near the eastern boundary: Through a few full-depth moorings, and through a series of HOMERs on the continental slope. We will both analyse the different sampling schemes for consistency, and test whether a reduction in sampling will change the estimated MOC.

v) We expect that variability in density near the western boundary is larger than near the eastern boundary, but we must analyse to what extent eastern boundary variability contributes to MOC variations. The potential for this exists, as shown by the sensitivity calculations of Marotzke et al. (1999). Simple models suggest rapid propagation of waves southward along the western boundary, the equator, and then northward along the eastern boundary (Kawase, 1987). If we can identify signals at the western and eastern boundaries that are coherent with a time-lag, this will hold important clues about the dynamics of MOC fluctuations. Important other information about signal propagation speed and coherence will come from Send's array at 16°N and from the proposed Hughes et al. RAPID deployments further north.

vi) We will compare altimeter data to sea level fluctuations inferred from the density and pressure information obtained from the moorings. Also, we will investigate propagating signals along 26.5°, determine their vertical (modal) structure, and compare the observed signals against theoretical predictions. Again, simple models suggest that planetary waves play a crucial role in setting up the WBC and hence the MOC (e.g., Kawase, 1987; Johnson & Marshall, 2002).

vii) In Year 1 of the project, we will refine our observational strategy using output from the 1/12° OCCAM run that has recently been executed at SOC. In particular, we will analyse errors incurred through the bottom triangle, and identify strategies that might be employed to control these errors.

viii) Based on the analysis of, and comparisons between, data sets from the various instruments and platforms, we will perform a synthesis of the data using a linear or nonlinear least-squares approach (e.g., Wunsch, 1996), which we will test on model output. From this synthesis, we will construct the most sophisticated version of the MOC time series as 26.5°N.

ix) We will compare our measured MOC variability against that simulated in a variety of models, such as OCCAM, FLAME, or the Hadley Centre coupled model. In collaboration with Stammer, we will use our 26.5°N MOC time series as a constraint in his global data assimilation model.

x) Based on all the analyses, we will assess whether the monitoring strategy we propose here is suitable for operational use.

g) Timetable: A project as complex and ambitious as this one requires efficient implementation for it to yield maximum benefit during the lifetime of RAPID. Time is of the essence, which is why we request a 1 January 2003 start date (as soon as possible after a funding decision has been made), so that equipment procurement can start immediately. We expect that the preparation of the first mooring deployment will require one year, and have requested shiptime in early 2004. During this proposal, we have referred to "deployment years", which are relative to a planned beginning of deployment in early 2004. Deployment Year 4 starts in early 2007 and will span into 2008, beyond the formal end of this project (Dec. 2007) and the RAPID programme. This is consistent with RAPID's objective to establish a *prototype* MOC monitoring system, implying that a successful demonstration will lead to follow-on funding.

h) Project management, personnel requirements, and data stewardship: All P.I.'s are at SOC, which greatly facilitates management of such a complex project. Marotzke will have the overall scientific oversight, while Cunningham will oversee the seagoing operations. Cunningham and Bryden will jointly take the lead on the data analysis. Travel has been budgeted for contacts with our overseas collaborators (Miami; Canaries). A project of this size and expected international visibility must be presented effectively at international conferences, for which we have budgeted. We have budgeted for UKORS personnel to manage the seagoing aspects of this project, which pose considerable challenges in terms of logistics. UKORS personnel for fieldwork has been fully costed.

We require 2 PDRAs for the full five years, one PGRA for three years, one tied student, and some programmer support, which is modest given the size of the project. The P.I.'s will play a strong role in the day-to-day work and contribute their time at no cost. One PDRA will work primarily with Cunningham on the preparation and execution of the monitoring array, the analysis of mooring data, and the comparison with the MOC estimate from the hydrographic section. Joel Hirschi (SOC, named PDRA) will work with Marotzke on refinement of the design, using the 1/12° OCCAM output (Year 1) and the synthesis of the different data, including least-squares techniques and collaboration with Stammer on assimilating the section data in the global model. The expertise required by single individual in modelling, data analysis, and inverse modelling means that an experienced researcher must be hired, at a grade above that of a standard PDRA. The tied student will work with Bryden on comparing altimeter data to sea level fluctuations inferred from the density and pressure information obtained from the moorings. In particular, the student will work on signal propagation along the 26°N line. Three years are requested, in Years 3-5, for a research assistant (PGRA) to work up the raw data into high-quality hydrographic, current, and pressure time series that will then be made available to the entire RAPID community. The PGRA will be supervised by Cunningham and Bryden. Two months of salary per year are requested for a programmer (John Stark) to provide general software support, especially for the modelling and the construction and maintenance of an effective web-based Live Access Server.

i) Place in RAPID: We believe that this project will provide a reference point for many if not all RAPID activities concerned with non-palaeo aspects of the programme. It will deliver a baseline set of observations that all models simulating the THC will be measured against. Moreover, this project will provide the conceptual framework for the more process-oriented work, in particular the proposed measurements along the western boundary by Hughes et al., Watson et al., and Heywood.

j) International collaboration: For our planned fieldwork near the western boundary, Miami appears to be the ideal base for mooring deployment and recovery. Johns and Baringer are preparing an NSF proposal, to be reviewed jointly with this one, to perform *i)* enhanced monitoring of the deep western boundary current (DWBC); *ii)* Florida Strait transport measurements, augmenting the cable measurements, which only give the total transport, with regular profiling information both for velocity and temperature. In addition, Johns and Baringer will request additional time on US ships to service our moorings. Should both proposals be funded as proposed, Johns's and Baringer's Mooring B will replace our WB3, at a saving of £350K to our project. Eastern boundary field work will be performed in collaboration with Parrilla, and will take place from a base on the Canaries. We will collaborate with Send to link our estimates of western basin deep transports to his, in particular with respect to signal propagation speed. We will collaborate with Stammer, both to compare our inferred MOC fluctuations to those he finds with his global data assimilation system, but also to use our observations as constraints in his model.

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