

POSTERS

Johanna Baehr*

Testing the RAPID 26N concept for continuous monitoring of the meridional overturning circulation in the South Atlantic

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We investigate if and how the monitoring strategy for the meridional overturning circulation (MOC) implemented at 26N in the Atlantic can also be applied at a latitude in the South Atlantic. Here, we focus on the ability of the 'deployed' array to capture long-term trends in the MOC. We simulate a monitoring array akin to the RAPID array at 26_N in the global coupled climate ECHAM5/MPI-OM, forced with the IPCC scenario A1B. We find that the monitoring strategy can provide reliable estimates of the MOC in the South Atlantic, but the latitude needs to be carefully chosen to ensure adequate coverage of the variability arriving from both the north and the south. The limitations in the North Atlantic apply in the South Atlantic, however, we find that direct boundary current observations and bottom velocity measurements are of lesser importance for the time-mean value and the variability than in the North Atlantic. However, western boundary observations and bottom velocity measurements are crucial in capturing the vertical structure of the MOC correctly. We suggest that basin-wide MOC monitoring based on the RAPID strategy at 26N be conducted only where boundary currents do not hit steep topography, and where bottom velocities are small.

Molly Baringer*

The relationship between heat transport, heat content and net surface heat fluxes in the Atlantic Ocean

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Various estimates of components of the heat budget in the Atlantic Ocean derived through insitu observations and models have been made. This paper examines the relationship between heat transport time series made using expendable bathythermograph measurements near 30N and 35S with surface heat flux products and gridded estimates of heat content. Heat transport estimates have been made using XBT data resulting in time series dating since 1995. Three different gridded time series of heat content are used including the Levitus data, gridded Argo data and a merged Argo/altimetry estimate. Surface heat fluxes used includes Turbulent flux estimates from WHOI, NCEP, ECMWF and various other model derived products.

Tania Casal*

Reanalysis of historical observations of the convective formation of AAIW in the SE Pacific

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It has been 30 years since McCartney (1977) introduced a different mechanism for the formation of Antarctic Intermediate Water (AAIW) where AAIW was the densest variety of Subantarctic Mode Water (SAMW) produced in the Pacific as opposed to cold and fresh Antarctic Surface Water sinking to intermediate depths at the Polar Front circum-polarly (Sverdrup et al., 1942; Piola and Georgi, 1982). Despite this knowledge, SAMW and AAIW characteristics are still largely unknown at its source. For this reason, we revisited a 1980 austral late winter/early spring survey (17 September to 15 October) in the southeastern Pacific Ocean and Drake Passage, where conductivity-temperature-depth (CTD) observations were obtained in a total of 6 sections between [45-61]°S and [90-62]°W. (NP) Results show that immediately below the deepest convective (SAMW) layers a downward (diapycnal) influence into denser levels (AAIW) from vertical (diapycnal) mixing. The PV (salinity) minimum associated with the SAMW (AAIW) core was centered at $\sigma_\theta = 27.03$ ($\sigma_\theta = 27.11$) at the western most section and

deepening to 27.08 (27.13) before it entered the southern Atlantic. (NP) Geostrophic transport calculations (using a LNM at 2000 db) show clearly both northwestward and eastward pathways of SAMW/AAIW, with maximum transport at 27.08-27.10 in the Drake Passage sections.

Beth Curry*, Craig M. Lee, Brian Petrie, Jason I. Gobat

Volume, freshwater and heat transport through the Davis Strait, 2004-2005.

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The Canadian Arctic Archipelago (CAA) and Fram Strait are the two main pathways for freshwater leaving the Arctic Ocean en route to the Atlantic Ocean. Flow through the Davis Strait captures the Arctic Ocean outflow that has passed through the CAA and includes terrestrial runoff and water mass modifications made within Baffin Bay. Quantifying the flow through the Davis Strait is a significant step in closing the volume and freshwater budgets of the Arctic Ocean and Baffin Bay. We present the flux estimates from the first year of a six year moored array, measuring currents, temperature and salinity, deployed across Davis Strait. The 2004-2005 array has improved spatial coverage over an earlier array deployed in 1987-1990. Year-long temperature, salinity and velocity measurements are obtained on the shelves, as well as ADCP velocity profiles in the upper 100 m across the entire Strait for the first time. To estimate fluxes more accurately and constrain errors, salinity, temperature and velocity are objectively mapped. Annual estimates of volume (-2.65 ± 0.73 Sv), freshwater (-124 ± 34 mSv) and heat (19 ± 9 TW) fluxes through the Davis Strait are not significantly different from estimates based on the 1987-1990 array. Transport in the upper 100 m represents 35% (-0.94 Sv) of the total volume flux and 48% (-60 mSv) of the total freshwater flux. The contributions to the volume and freshwater fluxes are generally small for the shelf areas. Over the broad West Greenland Shelf, 0.31 Sv of volume and 12 mSv of freshwater are transported northward while the steep Baffin Island Shelf transports 0.11 Sv of volume and 7 mSv of freshwater southward.

Ruth Curry*

Abyssal circulation and water mass transformation in the interior western North Atlantic Ocean

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A detailed investigation of observed water mass properties and stratification in the western North Atlantic Ocean is combined with existing theory to describe the geometry and dynamical underpinnings of the interior abyssal circulation and transformation of cold, dense bottom waters of Antarctic origins (AABW) into warmer overlying layers of lower North Atlantic Deep Water (LNADW). This upward transfer of mass and buoyancy occurs in five identifiable stages between the equator and 40°N along a pathway that spirals cyclonically around the western basin, rising vertically in depth and density space along the way. Each stage involves a dynamically distinct, topographically constrained, cyclonic circulation cell that appears to be forced by locally enhanced diapycnal mixing and vortex stretching. Several lines of evidence suggest that these highly structured interior flows are remarkably vigorous. Between 20-35°N in the western basin, ~ 7 -8 Sv of waters colder than 1.75°C flowing poleward at depths > 5000 m upwell across that isotherm to feed the warmer NADW components flowing equatorward at depths shallower than 5000 m in the deep western boundary current.

Although this buoyancy forced abyssal circulation and upwelling are fundamentally important to the AMOC and to ocean budgets of mass, heat and tracers, the structure, strength and variability of these interior flows -- and the diapycnal forcing that feeds them -- remain inadequately quantified. As a consequence, these are poorly represented in climate models. In particular, direct measurements from which the structure of the turbulent

mixing field can be assessed are required to improve parameterizations of mixing that will enable climate models to reproduce the observed state of the ocean and to evolve with a changing climate system.

Gokhan Danabasoglu*, J. Tribbia, P. R. Gent, S. Yeager, and H. M. Hsu

Contrasting the AMOC variability in Version 3 and Version 4 of the Community Climate System Model (CCSM)

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The pre-industrial and present-day control simulations as well as the 20th Century ensemble integrations with the CCSM version 3 (CCSM3) all showed multi-decadal variability in their Atlantic Meridional Overturning Circulations (AMOCs). Using this particular version of the model, a 30-member ensemble of the A1B future scenario experiments revealed similar oscillatory behavior in their AMOC time series, indicating potential predictability of the AMOC and some related fields on decadal time scales. In contrast, a discernible oscillatory behavior on decadal time scales is absent in some of the control simulations using preliminary versions of the next generation of the coupled model (CCSM4). In addition, the initial AMOC adjustment time scale appears to be much longer in these new simulations (more than 250 years) compared to the older CCSM3 experiments (about 150 years). The lack of an oscillatory behavior is expected to have an adverse effect on predictability. Indeed, a series of experiments initialized in the ocean component using data sets from either an assimilation integration or a hindcast simulation do not show any predictability beyond the first few years. We also attempt to compare the AMOC time series from the hindcast, assimilation, and 20th Century coupled simulations for the latter half of the 20th Century. This comparison reveals significant sensitivity of the AMOC to the specification of freshwater flux boundary conditions in the hindcast simulations.

Kathleen Donohue*, T. Rossby, C. Flagg

Gulf Stream mean structure and variability: a perspective from the 16-year Oleander Project

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Beginning in late 1992, high-horizontal resolution upper-ocean velocity has been sampled by an acoustic Doppler current profiler (ADCP) mounted in the hull of the container vessel CMV Oleander that operates on a weekly schedule between New Jersey and Bermuda. In September 2004, a RD Instruments 75 kHz Ocean Surveyor replaced the original RD Instruments 150 kHz narrowband and this has enabled profiling to greater depths. The Oleander measurements provide a view of ocean-current variability over a very wide range of spatial and temporal scales. With a nearly 16-year dataset, we revisit earlier analyses of the structure and variability of the Gulf Stream system. Not surprisingly, at 75-m depth, the double exponential structure of the Gulf Stream emerges with scale widths of 20 and 40 km on the cyclonic and anticyclonic sides, respectively. The Gulf Stream appears as a rigid meandering stream. In the 16-year data set, while the core of the Gulf Stream varies over nearly 2 degrees latitude, the mean velocity maximum is 2.02 m/s with a standard deviation of 0.25 m/sec. Although mean and eddy statistics from standard mapped satellite altimeter products are generally weaker compared to the Oleander, similar patterns emerge. In particular, both data sets indicate diffluent cross-stream flow away from the Gulf Stream core and a convergence of momentum fluxes towards the core. Cross and along-stream velocity wavenumber spectra analysis is examined after a canonical Gulf Stream is removed from each section. Both components have similar magnitude and a remarkably well-defined spectral slope of k^{-3} . No statistically significant trend or low-frequency variability appears in Gulf Stream transport. This contrasts against its low-frequency path variability. A parallel XBT program has recently been expanded so that sampling occurs at mesoscale resolution across the breadth of the New Jersey to Bermuda transect. Together with the deep-reaching ADCP, the Oleander project will have the frequency and duration to quantify temperature fluxes in the upper-ocean including the mixed layer in the Gulf Stream system.

Paula Fratantoni* and Michael S. McCartney

Freshwater export from the Labrador Current to the North Atlantic Current at the Tail of the Grand Banks of Newfoundland.

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At the Tail of the Grand Banks of Newfoundland the major branches of the wind-driven and thermohaline circulations collide. The warm Gulf Stream approaches from the west and splits into several distinct branches, one flowing north to feed the North Atlantic Current. The cold Labrador and Deep Western Boundary Currents approach the Tail from the north and bifurcate with some fraction retroreflecting offshore. While the North Atlantic Current, Deep Western Boundary Current, and Labrador Current have each been thoroughly studied both up and downstream of the Tail of the Grand Banks, to this day the details of the cold retroreflection pathways near the Tail of the Banks remain obscure. In this study, 100 years of historical hydrographic data are used to investigate these pathways. We show, using salinity anomaly as a tracer, that the Labrador Current does not simply bifurcate at the Tail, but that freshwater is advected offshore along the full length of the boundary between Flemish Cap and the Tail of the Banks. The retroflected Labrador Current water returns north as an identifiable component of the western North Atlantic Current. Knowledge of the mean freshwater pathways in this region is crucial to understanding the propagation and significance of anomalies associated with climate transients.

Paula Fratantoni*, Michael McCartney, and Kathleen Donohue

Poster-Tale of two currents: The collision of the Gulf Stream and Deep Western Boundary Current at the Tail of the Grand Banks of Newfoundland

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The Tail of the Grand Banks of Newfoundland is a dramatic topographic ridge that protrudes southeastward from the continental shelf in the western North Atlantic. It is a critical location for the North Atlantic circulation because here the major branches of the wind-driven and thermohaline circulations meet, with dramatic changes in the currents' pathways. The Gulf Stream approaches from the west, splitting into four recognized branches at the Tail. A critical branch turns north, crossing the Tail to feed the North Atlantic Current. The Labrador and Deep Western Boundary Currents approach from the north. At the Tail the cold currents bifurcate, branching westward and retroreflecting northward, and eventually come into contact with the warm branches offshore. Here we analyze all available post-1948 hydrographic data together with satellite derived sea surface height observations to characterize the meeting of the Gulf Stream Branch, the retroflecting Labrador Current Branch, and the Deep Western Boundary Current over the southern part of the Tail of the Grand Banks. Based on the geometry of the vertical superposition of the oppositely flowing currents, we hypothesize that the path of the DWBC is not determined by the Tail's topography alone, but by the orientation of the Gulf Stream Branch crossing over the Tail and the Deep Western Boundary Current.

Zulema Garraffo*, S Z. Garzoli, S. Dong, M. Baringer

South Atlantic pathways from a high resolution global model

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Results for the South Atlantic from 1/12 deg global simulations, respect to pathways for the upper and deep flow, are presented and discussed, based on particles launched using the model solutions, during one year of the simulations.

Geoffrey Gebbie**Centennial and Millennial Scale AMOC Variability as Inferred from Sediment Core Data*Harvard University, gebbie@eps.harvard.edu

Instrumental records are too short to capture the centennial and millennial timescale variability of the Atlantic Meridional Overturning Circulation (AMOC). Carbon and oxygen isotope ratios recorded by foraminifera in sediment cores have been used to extend the data record, and to infer Atlantic Ocean transport rates during the Little Ice Age and the Last Glacial Maximum, shedding the first observational light upon low frequency variability of the AMOC. Specifically, it has been reported that transport in the Florida Current was reduced by 10% during the Little Ice Age. In the South Atlantic, oxygen isotope observations show that upper-ocean cross-basin differences were weaker during the Last Glacial Maximum (LGM, 22,000 years ago) than the present, possibly indicating a reduced LGM cross-basin density difference and, via the thermal wind relation, a reduced vertical shear. But such a dynamical interpretation depends critically upon a number of assumptions. In this work, I use a geostrophic inverse model to show that previous methods of inferring past MOC rates are subject to uncertainties due to the difference between geostrophic shear and total water column transport, as well as the complex relationship between oxygen isotope ratios and density. To resolve these uncertainties, I apply a water-mass decomposition technique which was developed in the context of modern-day tracer climatologies of temperature, salinity, phosphate, nitrate, and oxygen. When applied to sediment core data, the water-mass information allows a better estimate of density from oxygen isotope ratios, and thus, a better estimate of the vertical profile of transport in the Atlantic. The result is an estimate of the MOC transport that pre-dates the instrumental record, along with a thorough categorization of the assumptions that go into the estimate, and an estimate of the uncertainty.

George Halliwell*, Carlisle Thacker, Haoping Yang*Observing System Simulation Experiments for the Atlantic Meridional Overturning Circulation**NOAA/AOML/PhOD, george.halliwell@noaa.gov

We report on initial efforts associated with a new project supported by NOAA and the National Oceanographic Partnership Program to quantitatively evaluate observing system strategies for the purpose of monitoring the AMOC. The primary strategy is to use Observing System Simulation Experiments (OSSEs) to evaluate the impact of new and planned observing systems, and also to use Observing System Experiments (OSEs) to evaluate the impact of existing observing systems. The procedure for evaluating a proposed observing system using an OSSE is straightforward: (1) the proposed observations are sampled from an ocean model simulation known as the "nature run" that is assumed to represent the true ocean; (2) noise is added to make the observations more representative of what might actually be observed with actual instruments; (3) the observations are assimilated into a different ocean model, known as the operational model, to correct it with respect to the nature run; (4) an ocean forecast initialized with the corrected fields of the operational model is performed; and then (5) the quality of the forecast is evaluated against the nature run. We discuss our plans for developing and validating an ocean OSSE capability at NOAA/AOML and the University of Miami over the next 1-2 years. During this development period, our initial effort in the AMOC project is focused on evaluation of a multi-model ensemble to quantify the significant errors in the representation of the AMOC that exist in present-day ocean models, and also on identifying the best choice for use as a nature run. Error covariances determined from this analysis will be used to perform "virtual" OSSEs, which enable evaluation of the potential impact of observations without actually having to actually sample observations from a nature run and assimilate these into the operational model.

Feng He*

The Nature of the Decadal Variability of Atlantic Meridional Overturning Circulation -- Coupled Ocean-Atmosphere-Sea Ice Interaction Organized by Damped Ocean Mode

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The nature of the observed 11~14-year decadal variability of the surface climate over the North Atlantic Ocean is investigated using the Fast Ocean Atmosphere Model (FOAM) and its data-atmosphere configuration. A 14~16-year damped ocean mode, characterized by the decadal variability of Atlantic Meridional Overturning Circulation (AMOC) and southward-moving western boundary low frequency waves, is found to be able to organize coupled atmosphere-ocean-sea ice interaction in the North Atlantic and produce the decadal variability of the surface climate in this region. In the North Atlantic, the coupled simulation produces a faithful simulation of the observed decadal variability in terms of the pattern and periodicity of the main variability of sea surface temperature (SST), surface air temperature (SAT) and sea level pressure (SLP). Moreover, the coupled simulation also bears the observed dipole pattern of dynamic topography in West North Atlantic and the Great Salinity Anomaly (GSA)-like decadal salinity signature in the subpolar gyre. These connections between the coupled simulation and observations suggest coupled ocean-atmosphere-sea ice interaction organized by damped ocean mode is a plausible explanation for the observed decadal variability in this region.

In the coupled simulation, two physical processes, namely SAT-convection feedback and sea ice-convection feedback, were found to be critical for the decadal variability of AMOC. The SAT-convection feedback is the local effect of SAT on oceanic convections in the Labrador Sea. Under cold episodes of surface climate in the North Atlantic, the damped ocean mode is pushed to its "positive" mode when the cold air induces stronger convective activity in the Labrador Sea. The stronger convections produce more vigorous AMOC and the trough of western boundary low frequency waves in the subpolar gyre. The clockwise circulation associated with the trough of western boundary low frequency waves induces more heat transport into the subpolar North Atlantic and generates warmer SST and SAT. This gives rise to the warm episodes of surface climate in the North Atlantic and a new cycle starts. The sea ice-convection feedback is the effect of salinity anomaly on oceanic convections in Labrador Sea due to nonlocal sea ice melting/growing. The aforementioned warmer SAT induces more sea ice melting and results in low sea surface salinity (SSS) in the northern subpolar gyre, especially in Irminger Sea. After the low salinity is transported into Labrador Sea, it suppresses local convective activity and acts jointly with SAT-convection feedback to switch the damped ocean mode into its "negative" mode.

The damped ocean mode was uncovered in the stochastic atmospheric simulation and found to be responsible for the decadal time scale in the coupled simulations. The stochastic atmospheric simulation also reproduces the southward propagation of western boundary low frequency waves and the decadal variability of AMOC, but fails maintaining the decadal variability of ocean temperature and salinity in the North Atlantic both at surface and subsurface. This discrepancy between the coupled and stochastic atmosphere simulation underscores the critical role of coupled ocean-atmosphere-sea ice interaction in simulating the decadal variability of surface climate in the North Atlantic. In the coupled simulation, the atmospheric response to the subpolar SST substantially enhances the variability of the damped ocean mode on decadal time scales: when the subpolar SST is warmer, the warm-ridge dynamic response of the atmosphere provides the positive feedback by inducing northward Ekman transport to further increase the warming of SST; the local SAT-convection feedback and the remote sea ice-convection feedback act jointly to provide the delayed negative feedback in coupled ocean-atmosphere-sea ice interaction. In fact, on one hand, the ocean is driven by the atmospheric variability in the subpolar region; on the other hand, the atmosphere derives the decadal time scale from the ocean. Therefore it is coupled ocean-atmosphere-sea ice interaction organized by the damped ocean mode that generates the decadal variability of AMOC.

Alonso Hernández-Guerra*, Terrence M. Joyce, Eugenio Fraile-Nuez, and Pedro Vélez-Belchí
Using Argo data to investigate the Meridional Overturning Circulation in the North Atlantic

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Using a variety of oceanographic data, including direct volume transports in the Florida Strait, and Argo float profiles and drift velocities at 24 and 36N in the North Atlantic, inverse calculations are presented in which the net meridional transport, down to a depth of approximately 1600 m, is estimated at both latitudes for a five year period 2003-2007. The upper ocean is divided into 7 layers using neutral density, and mass conservation constraints have been applied to a closed box bounded by these latitudes, including the Florida Strait. Ekman layer transports have been included in the top-most layer, and the inverse calculation has solved for changes from the initial reference velocities, Ekman and Florida Strait transports, given *a priori* estimates on the accuracy of each of these quantities. Solutions with and without transformations due to Mediterranean Water (MW) formation are made. Our results indicate that 1) time-averaged transport estimates derived from Argo have significant less eddy noise than individual hydrographic sections, 2) Argo drift velocities provide information to the inverse solution for the ocean interior, and 3) comparison of the total integrated interior mass transports in the thermocline waters for the period 2003-2007 with the previous estimates based on trans-ocean hydrographic sections shows that the Meridional Overturning Circulation has not significantly changed since 1957.

Boyin Huang*, Yan Xue, David Behringer and Arun Kumar

Atlantic Meridional Overturning Circulation Simulated by NCEP GODAS

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The Atlantic meridional overturning circulation (AMOC) was estimated using the NCEP operational Global Ocean Data Assimilation System (GODAS), which assimilates observed temperature and synthetic salinity profiles down to 750m. The averaged (1982-2004) AMOC is 17 Sv at 26N, consistent with other observed analyses and model simulations.

The AMOC was also estimated from two experimental GODAS runs, one that is identical to the GODAS except assimilating observations down to 2200m (GODAS_deep) and the other assimilating observed temperature and Argo salinity profiles down to 750m from 2001 to 2006 (GODAS_Argo). The GODAS_deep AMOC drifted upward for about 5 years from its initialization in 1979 provided by GODAS, and then became stationary until the Argo data became available in 2000 when the upward drift started again. The averaged (1982-2004) AMOC in the GODAS_deep is 26 Sv, about 9 Sv stronger than that of GODAS. However, the strength of the GODAS_Argo AMOC is similar to that of the GODAS. The results suggested that the strength of AMOC can be reasonably assimilated by a shallow data assimilation scheme, and the quality of AMOC simulation was not necessarily improved by using a deep data assimilation scheme. Impacts of Argo salinity on the AMOC strength appear small.

Since AMOC is density-driven, it is critical to analyze the features of temperature and salinity, and their contributions, to density. We analyzed the features of temperature and salinity in the GODAS and compared them with observations. We also explored utility of GODAS in simulating the coherent surface-subsurface fingerprints of AMOC and the lead-lag relationship between the subpolar North Atlantic and subtropical North Atlantic as revealed in observations. The linear trend of AMOC is also investigated.

Boyin Huang* and Vikram M. Mehta

Assessing the role of Amazon River on AMOC, salinity, and temperature in MIT OGCM

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The role of the Amazon River runoff in the Atlantic Meridional Overturning Circulation (AMOC), salinity, and temperature was assessed using the global ocean general circulation model (OGCM) developed at the Massachusetts Institute of Technology. The changes in AMOC, salinity, and temperature were compared between two ideal scenarios with and without Amazon River runoff. The blocking of the Amazon River runoff first resulted in a salinity increase near the river mouth. The saltier and, therefore, denser water was then transported to higher latitudes in the North Atlantic by mean currents near the surface. The subsequent density contrasts between North and South Atlantic resulted in changes in AMOC. The anomalous AMOC lead to significant temperature changes by anomalous heat transports. The current and temperature anomalies created by the blocking the Amazon River runoff propagated from the Atlantic to the Pacific via coastal and equatorial Kelvin waves. This study suggests that the Amazon River runoff may be playing an important role in oceanic salinity, temperature, and circulations.

Bohua Huang*, Zeng-Zhen Hu, Edwin K. Schneider, Zhaohua Wu

The Atlantic Meridional Overturning Circulation Simulated by the NCEP Climate Forecast System

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In this study, we examine the meridional overturning circulations simulated by the Climate Forecast System (CFS), a state-of-the-art coupled ocean-atmosphere general circulation model currently being used for operational climate prediction at the National Centers for Environmental Prediction (NCEP). A 101-year CFS integration was conducted at the Center for Ocean-Land-Atmosphere Studies from the initial condition for January 1, 1985 derived from the NCEP Global Ocean Data Assimilation System (GODAS) analyses and Atmospheric Reanalysis II. Our study is concentrated on the seasonal and lower-frequency variability of the Atlantic Meridional Overturning Circulation (AMOC) as well as its climate effects in this simulation.

Our results show that CFS produces a realistic AMOC, with its northward volume transport around 14 Sv at 30oN, which is close to the value calculated from the 25-year (1979-2004) GODAS analysis and compatible with other estimates based on observations. An empirical orthogonal function (EOF) analysis further shows that the AMOC variations in both CFS and GODAS are dominated by a strong out-of-phase fluctuation between the tropics and mid-latitudes on seasonal time scales. In addition, the CFS mean AMOC is perturbed actively by the 2nd EOF mode structured as a pair of deep anti-symmetric cells with respect to the equator, which extends to 30o latitudes in both hemispheres and fluctuates on a range of time scales, possibly resulting from the AMOC interaction with the subtropical and equatorial shallow cells. This mode also bears some resemblance to the 2nd EOF from the GODAS data. Due to the non-polar domain of the CFS oceanic component, the model AMOC strength, as well as its variability, is generally weaker than that of GODAS in high latitudes. However, the CFS northward volume transport at 30oN still shows distinctive oscillations on both interannual and decadal time scales, based on the ensemble empirical mode decomposition (EEMD) of the 101-year time series. The EEMD also delineates a nonlinear trend, attributable to the model climate drift. The effects of the surface momentum, heat, and freshwater fluxes on the AMOC's seasonal, interannual, and decadal fluctuations are analyzed. The potential connections of the AMOC to the climate variability in the Atlantic sector are also examined.

Carlos Cruz and **Barry A. Klinger***

Time-dependent North Atlantic SST and overturning response to a Southern Ocean wind perturbation

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We use an ocean model with simplified three-basin geometry to look at the response to switched-on Southern Ocean and compare cases with strong and weak Haney-type surface restoring boundary conditions. Weak restoring provides a simplified model with which to study the effect of Atlantic circulation changes on the climate through warming or cooling of the atmosphere. The increases in wind-driven meridional overturning and northward heat transport warms SST in the North Atlantic and cools it in the Southern Ocean. The North Atlantic SST warm anomaly has a similar magnitude to that in a coupled general circulation model (Delworth and Zeng, 2008) when the difference in wind perturbation strength is taken into account. We characterize the time-dependence of the overturning and SST anomalies in the weak-restoring run and compare the overturning response to the response with strong restoring.

Michael McCartney*

Measurement of the Guiana Abyssal Gyre recirculation and the reversed overturning cell within the cold limb of the MOC in the western North Atlantic

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I report results from an extensive current meter array near 16°N across the Guiana Basin of the western tropical North Atlantic, the Guiana Abyssal Gyre Experiment (GAGE). The goal for GAGE purpose was to measure the combination of southward flow of the Deep Western Boundary Current (DWBC) and hypothesized northward recirculation to its east that comprise a Guiana Abyssal Gyre. GAGE was done at the same location as, and with shared resources with, the Meridional Overturning Variability Experiment (MOVE, U. Send and T. Kanzow), whose goal was testing a monitoring system for deep flow in the AMOC. The combined array of 10 moorings spanning the Guiana Basin provided 73 current meter records for two years, and enabled the detection and quantification of the Guiana Abyssal Gyre below 1600 m, the upper sampling level for most of the array. The southward DWBC average flow was 31 Sv, opposed by 19 Sv northward interior flow, for a net southward flow of 12 Sv. These measurements fully sampled AABW, LNADW MNADW but only partial sampling of UNADW. That confirms the underlying basis for the Guiana Abyssal Gyre: the estimates for DWBC transport from hydrography, current meters and floats have been typically two or three times the estimated AMOC cold lime net transport, requiring substantial recirculation to have consistency. The second part of the Guiana Abyssal Gyre hypothesis was also confirmed. Before this experiment's measurement of absolute flow, all that could be done to estimate the recirculation was reference level-based geostrophic transport. In order to have such an estimate provide a northward interior transport of this magnitude, ~ 20 Sv, with the observed interior shear and temperature distributions, a large contribution of northward flow of water with $\Theta \leq 1.8^\circ\text{C}$ was geostrophically estimated. That temperature typically is associated with AABW. Hall, McCartney and Whitehead (1997) measured the transequatorial inflow to the Guiana Basin as only 2 Sv.

The second part of the Guiana Abyssal Gyre hypothesis was that this small entering flow of AABW, with average $\Theta \approx 0.9^\circ\text{C}$, warmed by entrainment of recirculating LNADW as it flowed northward in the interior of the Guiana Abyssal Gyre. The entrainment would inflate the transport of the AABW. The same data summarized for the above Gyre strength estimates, can be integrated across the Guiana Basin in temperature classes. The total net deep transport of 12 Sv to the south is found to be the residual difference between a larger 20 Sv of southward deep flow ($\Theta \geq 1.8^\circ\text{C}$), and a northward 8 Sv cold flow ($\Theta \leq 1.8^\circ\text{C}$).

The quantification of a reversed overturning cell in the tropical abyss I find a pleasing result, for it indicates a degree of symmetry between the northern and southern originating dense water plumes. DSOW and AABW feed two abyssal plumes that are isolated from each other for $\Theta \leq 1.75^\circ\text{C}$, and have first contact at that temperature in the deep Gulf Stream near 40°N . Both dense plumes are initiated by entry into the western North Atlantic with very cold temperatures, and transports of a few Sv (2.9 Sv DSOW and 2.0 Sv AABW). They both warm by entrainment of overlying deep water, and have their volume transports considerably inflated. There is no lateral exit from the western North Atlantic for waters that cold, so their fate (Luyten, McCartney, Stommel, Dickson and Gmitrowicz, 1992) is to warm “up” into the LNADW – which is the deep water dominating the low latitude DWBC and deep water export from the North Atlantic.

There is an element of significant eastern concentration to the northward interior limb of the Guiana Abyssal Gyre. Does this persist farther north? There has been a tendency to think of the equatorial estimate of 2 SV AABW transport as setting an upper bound on the transport of this cold class farther north. GAGE shows that to be incorrect, that instead the transport grows through entrainment. We know that at 26°N , the various Abaco arrays also show the large DWBC that requires northward interior flow to compensate given the AMOC estimated deep flow. Does the RAPID array have adequate sampling in what might be the critical area for such compensation, the western flank of the Mid-Atlantic Ridge?

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Seeking AMOC signals in satellite data

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Global satellite data sets now include multi-decadal time series of sea surface temperature from infrared radiometers, and surface wind speeds and the ice edge from microwave radiometers. During the period spanned by these measurements there have been several generations of satellite sensors, but recently reprocessed data sets are believed to minimize, as far as possible, the artifacts that result from changing sensors and orbital drift.

A targeted analysis of long time series of satellite data sets over the Atlantic Ocean is being conducted to lay the foundation for the identification of signatures of changes in the AMOC. Focus is being directed to areas of deep water formation, and to the region of the MOCHA-RAPID array at 26.5°N . Our analyses will result in new climatologies of satellite-derived parameters, with determinations of the seasonal and interannual variations. Covariance with the North Atlantic Oscillation will be derived. These analyses are necessary to allow future detection of signals from a changing AMOC independent of those from other causes. Additional foci will include episodic effects, such as Polar Lows and Greenland Tip Jets, to determine their likely roles in triggering deepwater formation, as changes in such forcing functions as a response to a changing climate may be a more sensitive indicator of a change in the intensity of the AMOC than seeking direct signals in the satellite measurements. Additional shorter data sets, such as vector winds and microwave sea surface temperatures, as well as modeled NWP fields, will be used to enhance the scientific merit of the analyses.

Edwin Schneider*

Weather Noise Forcing of AMOC Variability

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The role of weather noise forcing of AMOC variability (i.e. extending the Hasselmann mechanism) is diagnosed in model simulations, and inferred from atmospheric and SST analyses. Simulations with Interactive Ensemble (IE) CGCM (AGCM ensemble coupled to OGCM and land) are used to evaluate the AMOC variability with weather

noise forcing filtered out. Weather noise surface fluxes are evaluated as the difference between observed/analyzed/simulated surface fluxes and the feedbacks to boundary forcing evaluated from AMIP-type AGCM ensemble simulations. IE CGCMs are then forced by the weather noise surface fluxes.

The procedure is applied using data from long model simulations and from reanalyses. AMOC variability in the simulation of the current climate by the COLA CGCM and preliminarily, by CCSM3, is found to be predominantly weather noise forced. The COLA IE CGCM is then forced by weather noise from the NCEP reanalysis to estimate the AMOC variability in the latter half of the 20th century. The results, however, highlight systematic errors in the reanalysis.

Jeffery Scott*

Ensemble 20th century behavior of the MOC in a coupled climate model of intermediate complexity

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The behavior of the MOC is examined in an ensemble of runs using a coupled model of intermediate complexity. Climate “parameters” varied are the climate sensitivity, the aerosol forcing, and the strength of ocean heat uptake. Variations in the latter were accomplished by changing the strength of the oceans’ background vertical mixing, which in turn affects the strength of the AMOC. Although our ensemble tested a wide range of climate sensitivities and aerosol forcings, it is more difficult to create such variation in heat uptake while maintaining a realistic ocean circulation. In our model, the AMOC maximum increases slightly before 1900, and exhibits a general decreasing trend over 1900-2000, particularly in the last two decades. However, the spread among ensemble members is on the order of 5-10 Sv at the end of the century, which is less than the typical decrease in specific ensemble members that correlate well with observed changes in surface air temperature. Each parameter combination is tested with four different initial conditions, which has only minor effect on the climate behavior. The model has explicit representation of the solubility and biological pumps of carbon in the ocean, and the air-sea exchange of carbon dioxide induced by these pumps. The 20th century ensemble showed a range of the air-sea flux of anthropogenic CO₂ into the ocean that compare favorably to the means and error bars of direct and indirect estimates from observations.

Uwe Send*, M. Lankhorst, T. Kanzow

Variability of the Atlantic Meridional Overturning Circulation Observed at 16 N

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The Atlantic Meridional Overturning Circulation has been observed continuously since early 2000 by the “MOVE” (Meridional Overturning Variability Experiment) ocean observatory located near 16 N. It uses a scaled-down array which assumes that it is sufficient to observe only the southward (NADW) branch of the MOC, and that most of that flow passes west of the Mid-Atlantic Ridge. Data are available until summer 2008, i.e. for more than eight years. The southward volume transport of the overturning circulation is measured in three components: a continental slope contribution observed directly with current meters, an internal geostrophic part obtained from end-point moorings measuring dynamic height, and an external part observed with bottom pressure measurements. Results discussed will be the intraseasonal variability of all three components, and interannual variability in the former two. In particular, the internal plus boundary part contains a significant trend towards reduced circulation over the observing period. Such a trend is expected by climate models in an anthropogenic greenhouse scenario, but may also occur naturally as part of low-frequency variability. The observations are intended to provide additional constraints for climate models, and an emphasis will be on how we interpret the observed trend and assess its uncertainty.

Benjamin Shaw* and William Johns

A comparison of model-simulated vs. observed MOC variability at 26.5°N

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Climate model projections suggest that the strength of the Atlantic meridional overturning circulation (MOC) will decline in association with global warming. A monitoring system for the MOC at 26.5°N in the Atlantic has now been in place for over four years, within the framework of the joint U.K.-U.S. Rapid Climate Change (RAPID)-Meridional Overturning Circulation & Heat Flux Array (MOCHA) Program. One of the goals of the RAPID-MOCHA program is to understand the variability spectrum of the MOC so that trends in the MOC can be discerned from the shorter term variability representing the background noise in the system.

This poster discusses the ability of two numerical models, a high-resolution forced ocean GCM and a coarse-resolution fully-coupled model, to accurately reproduce the strength and variability of the RAPID-MOCHA timeseries. The variability characteristics of the modeled and observed MOC fluctuations are compared, as are the meridional structure and correlation scales of the modelsimulated MOC. The two models studied are (i) the Parallel Ocean Program (POP) model run 14b, at 0.1° resolution, forced with daily ECMWF winds, and (ii) the Community Climate System Model version 3 (CCSM3) run gx1v3.210, at 1° nominal ocean resolution.

At 26.5°N, the CCSM3 and POP 14b models have a generally realistic MOC strength of 20.3 Sv and 16.2 Sv respectively, compared to the RAPID-MOCHA observed MOC strength of 18.5 Sv. Additionally, both models show significant intraseasonal variability, but with a smaller amplitude than the observed MOC. The variance of the RAPID-MOCHA timeseries (23.8 Sv (1 Sv = 1e6 m³/s)) is about a factor of two greater than either the CCSM3 (11.2 Sv) or the POP 14b (12.7 Sv) models. A comparison of the MOC spectra at 26.5°N shows that the coupled model variability is weaker throughout the entire intraseasonal band, while POP is weaker mainly at periodicities less than 40 days. The meridional decorrelation scales of the model MOC variability in subtropical latitudes are about 12° for the coupled model and 4-6° for the POP OGCM. Mechanisms of internal variability that lead to the intraseasonal MOC fluctuations in the models are also investigated.

Caihong Wen*

Effect of Atlantic Meridional Overturning Circulation Changes on Tropical Atlantic Sea-Surface Temperature Variability: A 2-1/2 layer Reduced Gravity Ocean Model Study

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Coupled climate model simulations reveal that a dipole like SST pattern with cooler (warmer) temperature over the north (south) tropical Atlantic emerges in response to a slow-down of the Atlantic Meridional Overturning Circulation (AMOC). Using a 2-1/2 layer reduced gravity ocean model, we conducted a systematic investigation into oceanic processes controlling tropical Atlantic sea-surface temperature (SST) response to AMOC changes by varying the strength of northward mass transport at the open boundaries. It is found that a prominent equatorial warming occurs when the AMOC is weakened below a threshold value. This nonlinear behavior is attributed to an interaction between the Atlantic thermohaline circulation and the wind driven subtropical cells. A dynamic mechanism is proposed to explain how the AMOC change can affect the SST variability in the tropical Atlantic sector. The sensitivity of the mechanism on oceanic parameters is further examined.

Josh Willis*

Changes in the Upper-Ocean Circulation of the North Atlantic

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In the far North Atlantic, at latitudes north of the boundary current separation, much of the meridional overturning circulation is confined to the ocean interior. Away from the steep ocean boundaries, the Argo array of profiling floats provides absolute velocity at depth and hydrographic data from the surface to 2000 m. By combining float data with altimeter data, sampling error can be reduced and accurate estimates of time-averaged, three-dimensional geostrophic velocity can be determined. With more than 8 years of data from Argo and several years of pre-Argo data from the mid-1990s, decadal and interannual changes in the upper ocean circulation can now be computed. Results will include interannual to decadal changes in the upper ocean circulation of the far North Atlantic. In addition, changes in the strength northward limb of the overturning circulation will be presented along with estimates of the heat and freshwater transport.

Xiaobiao Xu*, William Schmitz Jr., Harley Hurlburt, Eric P. Chassignet

Comparison of simulated AMOC in a high-resolution, basin scale model to observations

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Numerical outputs from a high-resolution, basin scale simulation are compared to various observations to evaluate the simulated Atlantic Meridional Overturning Circulation (AMOC) and to recognize the main issues the model has. For the southward flowing deep western boundary current, the simulation shows about 5 Sv of dense water (with $\sigma_\theta > 27.80$) flowing out of the Greenland-Scotland Ridge through the Denmark Strait and the Faroe Bank Channel, and the volume transport of this dense water increases to ~10 Sv around the Labrador Sea. Only part of this dense water flows around the Grand Banks into the Subtropic North Atlantic Ocean, while part of it recirculates back into the Labrador Sea and the Irminger Sea. The deep boundary current at 26.5°N compares with observation quite well. For the northward flowing upper branch of the AMOC, the simulation shows about 30 Sv Florida current at 27N; the volume transport of the Gulf Stream increases to ~60 Sv at 73°W, to ~80 Sv at 68°W, but decreases to ~40Sv further downstream at 55°W. The main issues of the model appear to be (1) no Antarctic bottom water (AABW) contributes into the lower deep water; (2) the overflow water is too fresh and cold; and (3) Gulf Stream it is not inertial enough so that the transport increase is less than observed and a significant part recirculates southwestward west of 55W.

Igor Yashayaev*

Origin and Variability of the Deep and Abyssal Waters of the Northwest Atlantic

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The two dense water overflows that cross the Greenland–Scotland Ridge via the Denmark Strait and Faroe–Shetland Channel form the Denmark Strait Overflow Water and Northeast Atlantic Deep Water, respectively, filling the deep and abyssal reservoirs of the subpolar North Atlantic. Changes at depths greater than the limits of open-ocean deep convection (2300 m or so) are primarily controlled by the processes involved in the formation and subsequent modification of these waters, starting with the overflows themselves. Each of the constituent water masses that form the original overflows will carry with them the imprint of time-varying climatic forcing in their source regions and of modifications en route. Their properties will also be subject to alteration by the processes of horizontal and vertical exchange from their spillways to the Labrador Basin and further downstream. The purpose of this presentation is to identify from the hydrographic record those locations that are of primary importance for the transfer of ocean climate ‘signals’ into and between the two spreading overflow plumes, and if

possible to trace the influence of these changes downstream to the Newfoundland Basin and beyond in the Deep Western Boundary Current.

Igor Yashayaev*, Michael Dunphy

Hydrographic sections of the North Atlantic from Argo data (ArgoBrowser)

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Argo floats provide real-time monitoring of temperature and salinity in the upper 2000 m layer in critical basins of the world ocean. In the northern North Atlantic, and particularly in the Labrador Sea, the continuous Argo observations resolve seasonal cycle of key seawater properties and reveal major water-mass developments.

Regional time series of vertical temperature and salinity distribution based on the Argo measurements are extremely useful for analysis of convective processes. These series clearly show how convection progresses during a cooling season and how it changes its strength and duration from year to year. The Argo observations are also used to identify the spreading pathways and transit times of newly-formed water masses.

We also demonstrate our approach to constructing trans-basin hydrographic sections from the Argo data and compare and combine these sections with shipboard and moored measurements in order to better resolve key water mass developments and variability in the North Atlantic.

TALKS

Johanna Baehr*

Optimization of an observing system for the North Atlantic Meridional Overturning Circulation

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Two methods are analyzed for the design of ocean observing systems to monitor the meridional overturning circulation (MOC) in the North Atlantic. Specifically, a continuous monitoring array similar to the RAPID 26N array is 'deployed' into a numerical model at both 26N and 53N. We compare array design methods guided by (i) physical intuition (heuristic array design), and (ii) global optimization.

Global optimization always outperforms the heuristic array design in terms of minimizing the root mean square error. However, whether the results are physically meaningful is not guaranteed: At a location where the proposed monitoring strategy does not have the ability to reproduce the MOC at 1000 m (i.e., 53°N), global optimization finds profiles with lower root-mean-square errors than the heuristic design, but the suggested setup is not physically meaningful.

At a location where the proposed monitoring strategy has the ability to reproduce the MOC at 1000 m (i.e., 26°N), global optimization has the potential to yield results of comparable quality to the heuristic array design. Overall, global optimization technique can recover the true global solution for the analyzed array design. Provided the solution's physical robustness is tested, global optimization can therefore help to formally identify optimal number and location of instruments for a large-scale monitoring array.

Amy Bower*

Some Observations of the Connectivity (or not) of the Atlantic Meridional Overturning Circulation

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The global Meridional Overturning Circulation (MOC) is often referred to as the Great Conveyor (Broecker, 1987). This analogy, and some of the schematic diagrams of the MOC that go with it, can conjure up images of a very steady circulation pattern with smooth, continuous connections between oceans and between basins. As recently stated by Richardson (2008) in his history of MOC schematics, the simplicity of the analogy is both its greatest strength and its greatest weakness. It beautifully captures the process by which water is cooled at high latitudes, spreads throughout the deep ocean basins where it slowly upwells and warms before returning to high latitudes to begin the cycle again. But if taken too literally, there is the danger of drifting into thinking of the Atlantic MOC in particular as consisting of pipelines that transport warm and cold water continuously over large meridional distances. In this presentation, we will review observations of the connectivity (or lack thereof) of the AMOC between subpolar and subtropical latitudes, with a focus on Lagrangian measurements.

Ping Chang*, Ben P. Kirtman, Xiuquan Wan and Duke Min

Role of "Weather Noise" in the Atlantic Meridional Overturning Circulation (AMOC)

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Ping Chang, Recent studies suggest that in the North Atlantic the primary (internal) source of predictability on decadal timescales is the AMOC. In many coupled climate models the AMOC exhibits decadal oscillations, although the time scale of these oscillations varies considerably. These oscillations, if they indeed exist in nature, can be considered as one possible physical basis for decadal climate prediction. However, there is as yet no clear

understanding of the causes for the AMOC oscillations in either the models or observations. A recent debate is centered around whether the AMOC oscillations are sustained by air-sea feedbacks or maintained by “weather noise”. The issue is highly pertinent to the understanding of decadal climate predictability and to the discussion of the role of oceans in climate change, and thus should be adequately addressed. We recently took a critical look at this issue in the framework of the Community Climate System Model (CCSM). Through the use of a novel noise-filtering algorithm, called interactive ensemble (IE), developed by Kirtman and Shukla (2002) and recently implemented to CCSM by Kirtman et al. (2009), we are able to show unequivocally that “weather noise” has a dominant impact on both the variability and mean strength of the AMOC.

Stuart Cunningham*, Torsten Kanzow, William Johns, Joel Hirschi, Molly Baringer, Chris Meinen, Darren Rayner, Maria Paz Chidichimo, Lisa Beal, Harry Bryden, Julie Collins, Jochem Marotzke

Sub-seasonal to seasonal variability of the Atlantic Meridional Overturning Circulation at 26.5 N

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The RAPID-WATCH/MOCHA array for monitoring the Atlantic meridional overturning circulation (AMOC) at 26.5°N has been in continuous operation since April 2004. It is both a practical and cost effective method for monitoring the AMOC. Here we present a 3.5 year timeseries of its strength and variability from observations obtained between April 2004 and October 2007.

The 26.5°N section is separated into a Florida Strait section west of the Bahamas where the Gulf Stream transport is monitored from cable voltage measurements and a mid-ocean section from the Bahamas to Africa. Variability in the wind-driven surface-layer Ekman transport is derived from QuikScat satellite-based observations. Mid-ocean flow is monitored by an array of moored instruments along the section. The basic principle of the array is to estimate the zonally integrated geostrophic profile of northward velocity on a daily basis from time-series measurements of temperature and salinity throughout the water column at the eastern and western boundaries and on either side of the mid-Atlantic Ridge. Inshore of the most westerly measurements of temperature and salinity, the transports of the Antilles current and deep western boundary current are monitored by direct velocity measurements.

The mean AMOC strength is 18.5 ± 4.9 Sv and has substantial sub-seasonal and seasonal variability. Fluctuations in Gulf Stream, Ekman and mid-ocean transports are independent and so their variability translates directly into AMOC variability.

The sub-seasonal variance (periods between 10 and 90 days) of the Ekman transport exceeds that of the Gulf Stream and mid-ocean, dominating fluctuations of the AMOC. However, the seasonal variance (periods > 180 days) of both the Gulf Stream and mid-ocean transports exceed the Ekman transport variance, dominating seasonal fluctuations of the AMOC. The standard deviation of seasonal variations in the AMOC is ± 3.5 Sv [7 Sv peak-to-peak] with maxima in early Autumn and minima in early Spring. A strong seasonal cycle in eastern boundary densities from the surface to 1000 dbar dominates the upper mid-ocean seasonal cycle and appears to be driven by seasonal variations of the eastern boundary wind stress curl.

Thomas Delworth*, H.-C. Lee, R.C. Pacanowski, T.Rosati, F. Zeng, R.Zhang

Simulated AMOC response to climate change in a high resolution global coupled climate model

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Our best assessment of the future behavior of the AMOC comes from global coupled climate models. Typical resolutions of models used in the IPCC AR4 were approximately 100 Km in the ocean and 200 Km in the atmosphere. The ocean components of these models were relatively viscous, with weaker than observed ocean currents. In order to assess the robustness of AMOC simulations, we present results of simulated AMOC variability and change from a newly developed global coupled climate model of very high resolution. This global model has an oceanic resolution that varies from 25Km in the Tropics to 9 Km at high latitudes, along with a 100 Km atmospheric resolution. The ocean component incorporates very accurate, non-dissipative numerics, very low viscosity, no parameterization of mesoscale eddies, and no explicit diffusion.

With this fine scale ocean resolution and less viscous physics, the model simulates energetic and realistic oceanic mesoscale eddies over most of the World Ocean, including such features as eddies shed from the Gulf Stream as well as eddies breaking off from the Loop Current in the Gulf of Mexico. Vigorous boundary currents are present, with simulated current speeds well in excess of 1 meter per second. We use this new model to assess the robustness of the response of the AMOC to climate change, as well as the sensitivity of simulated AMOC variability to model formulation and resolution. Specifically, we perform a multi-century control integration, and two sets of perturbation experiments with this new model: a doubled CO₂ experiment, in which CO₂ rises at 1% per year until doubling, and a water hosing experiment in which a massive amount of fresh water is injected into the North Atlantic. We find that for both perturbation simulations the primary results from lower resolution studies carry over to the high resolution model, suggesting a certain level of robustness to previously reported results. AMOC changes have a hemispheric to global scale impact on climate. Interestingly, the time scales of response are also similar between the low and high resolution models, although the variability characteristics are different.

Shenfu Dong*, Silvia Garzoli, Molly Baringer, Christopher Meinen, Gustavo Goni

The Atlantic Meridional Overturning Circulation and its Northward Heat Transport in the South Atlantic

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The variability of the Atlantic Meridional Overturning Circulation (AMOC) and its effect on the northward heat transport in the South Atlantic are examined using observations from a transbasin expendable bathythermograph (XBT) high-density line nominally along 35°S (AX18). The time-mean AMOC is 17.7 Sv with a standard deviation of 2.1 Sv based on the twenty completed occupations during the period 2002 to 2008. Although 91% of the time-mean AMOC is contributed by the geostrophic transport, both geostrophic and Ekman transports are important in explaining the variability in the AMOC. The contributions of geostrophic and Ekman transports to the AMOC show annual cycles, but they are out of phase with each other, which results in weak seasonal variability in the AMOC. The contributions of geostrophic and Ekman transports to the AMOC show annual cycles, but they are out of phase with each other, which results in weak seasonal variability in the AMOC at 35°S. The variability of the northward heat transport across AX18 is significantly correlated with the strength of the AMOC, where a large northward heat transport is associated with a strong AMOC, and vice versa. A 1 Sv increase in the AMOC would yield a 0.055 ± 0.012 PW increase in the northward heat transport. Separation of transport into western and eastern boundaries and interior indicates that transport variability in the interior is comparable with variability near the eastern and western boundaries, suggesting that it is critical to monitor all three regions in order to quantify changes in the AMOC and total northward heat transport.

Charles Eriksen*

Prospects for Transport & Flux Estimation using Deepgliders

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Deepgliders are a powerful new tool to make hydrographic repeat surveys over the entire water column in missions covering up to 10,000 km lasting as long as 18 months. Longer missions are feasible in 'virtual mooring' mode. All data is transmitted in near real time. Total per mission cost is under \$50K.

These autonomous underwater gliders record temperature, salinity, and dissolved oxygen with vertical resolution finer than 1 m, as desired, from the sea surface to depths as great as 6000 m. Measurements are collected while both diving and climbing along a saw-tooth path with user-determined slopes as high as 1:1 or as gentle as 1:3 to give horizontal resolution between 12 and 36 km in 6 km deep water. Deepgliders dive to within a few meters of the sea floor, detected acoustically, before returning to the sea surface. By comparing dead-reckoned horizontal displacement with GPS fixes acquired before and after a dive cycle, an estimate of depth-averaged current is obtained, suitable for reference of geostrophic shear. Data and commands are sent via Iridium satellite telemetry.

Deepgliders build upon the success of Seagliders, which have demonstrated their ability to monitor boundary currents in the top 1 km. Seagliders have surveyed the eastern boundary current system over the continental slope offshore Washington for over 5+ years to describe seasonal and interannual variability. These 220-240 km long repeat sections repeated fortnightly show that upper 1 km transports vary by more than 20 Sv on time scales of a few months. This variability is linked by along-slope advection to water mass alternations between waters of sub-tropical and sub-polar origin. Annual period temperature and salinity variations beneath the surface mixed layer take the form of waves propagating offshore at ~ 1 cm/s, perhaps topographic Rossby waves forced by coastal upwelling circulation at the shelf break. The maiden Deepglider transects in the same region were able to detect geothermal heating in the bottom hundred meters or so in addition to property surface tilts throughout the water column and robust depth averaged currents.

Possible uses of Deepgliders include making repeat sections across western boundary current systems and across the Antarctic Circumpolar Current in the Drake Passage.

Alexey Fedorov* and F. Sévellec

Stability of the Atlantic Meridional Overturning Circulation: the effects of freshwater forcing, wind stress and diapycnal diffusion

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We study the stability of the Atlantic Meridional Overturning Circulation (AMOC) in an idealized 2-dimensional (zonally-integrated) ocean model. The basin of the model extends from northern high latitudes to Antarctica and includes an implicit representation of a periodic circumpolar channel in the Southern ocean. The ocean circulation is driven by buoyancy fluxes (via mixed surface boundary conditions) and wind forcing. To describe ocean mixing, we employ both diapycnal and isopycnal diffusivities, and the Gent-McWilliams parameterization to represent eddy fluxes. Under the standard surface boundary conditions taken from the observations, the model reproduces a realistic ocean thermal and salinity structure with realistic meridional overturning circulation. The model is very efficient computationally, which allows us to conduct sensitivity experiments in a broad parameter range. The structure, intensity, and stability of the AMOC is then extensively studied using three control parameters: the strength of the westerly wind stress over the Southern Ocean, the magnitude of surface freshwater fluxes imposed in the Northern Atlantic, and the strength of diapycnal diffusion. In particular, we show that the intensity

of the overturning increases only slightly when the wind stress over the Southern Ocean intensifies. However, a weakening of the wind stress can lead to a strong reduction of the AMOC intensity and, potentially, to its shutdown. Ultimately, our calculations produce stability maps for the AMOC that can be used, for example, to interpret results obtained by comprehensive general circulation models exhibiting different sensitivity to freshwater forcing, and to understand abrupt climate changes in the paleorecord that involve rapid reorganization or a shutdown of the AMOC.

William M. Smethie, Jr., **Rana A. Fine***, Deborah A. LeBel

Monitoring the Formation Rate of North Atlantic Deep Water Components using Tracer Inventories

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The accumulation of man-made tracers- chlorofluorocarbons (CFCs) and Sulfur Hexafluoride (SF₆) in subsurface water masses is directly related to their formation rates, and the water mass formation rates can be calculated from their CFC and SF₆ inventories. The technique is an effective means for continuing to monitor the Atlantic Meridional Overturning Circulation (AMOC), as it can be applied to data collected in the CLIVAR and post-CLIVAR periods. Furthermore, rather than presenting a snapshot, the tracer inventory method integrates over a multi-year time scale, thus providing longer term trends and a means for monitoring temporal variability in water mass formation rates. We present CFC-11 inventories between 65°N and 10°S that calculated using data collected primarily between 1996 and 1998 as part of the World Ocean Circulation Experiment (WOCE) for the components of North Atlantic Deep Water (NADW). CFC-11 inventories for individual water masses are 10.5 million moles for Upper Labrador Sea Water (ULSW)(4.6 million moles south of 42°N), 23.4 million moles for Classical Labrador Sea Water (CLSW), 10.4 million moles for Iceland-Scotland Overflow Water (ISOW), and 8.3 million moles for Denmark Strait Overflow Water (DSOW). The estimated error for these inventories is about ± 9%. The sum of the NADW components (ULSW, CLSW, ISOW, DSOW) is 53.2 million moles which is about half of the total CFC-11 inventory, 103.8 million moles, in the North Atlantic Ocean. Maps of water column inventories are illustrative of the formation mechanisms and spreading pathways within these water masses. The inventories directly reflect the input of newly formed water in the North Atlantic over the time scale of the CFC transient, about 3 decades. The interior regions of the North Atlantic contain most (75-80%) of the CFC-11 inventory in NADW indicating strong recirculation and mixing of newly formed NADW from the DWBC into the interior with a time scale of 2-3 decades. Average water mass formation rates between 1970 and 1997 are: 3.3 Sv for EDW, 3.5 Sv for ULSW (2.0 Sv from the central Labrador Sea and 1.5 Sv from the southern Labrador Sea), 8.2 Sv for CLSW, 5.7 Sv for ISOW, and 2.2 Sv for DSOW. Estimated errors are ±20% for CLSW and ±16% for the other water masses. The total for NADW which forms the deep limb of the (AMOC), is 19.6 Sv. An extensive test of the effects of temporal variability on the average formation rate calculated from the CFC inventory indicates that the error introduced by the assumption of a constant water mass formation rate is no greater than 15% for CLSW and 10% for the other water masses.

Stefan Gary*, Susan Lozier, Claus Böning, and Amy Bower

An eddy-driven mechanism for partitioning the AMOC deep limb into the DWBC and an interior pathway

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Since the work of Stommel (1958), it has been assumed that the principal pathway for the deep limb of the AMOC is the Deep Western Boundary Current (DWBC). However, recent observations of Lagrangian drifters and modeling studies have shown that the DWBC is not necessarily a unique or continuous pathway (Bower et al., submitted). A significant portion of the export from the subpolar to the subtropical gyres follows a pathway through the interior of the Newfoundland and subtropical Basins, sandwiched between the western boundary and the western flank of the MidAtlantic Ridge. Here, we investigate the hypothesis, first inferred from hydrographic

data (Lozier, 1997), that deep eddydriven recirculation gyres are a mechanism for partitioning the deep limb of the AMOC into the DWBC and this interior pathway. We perform Eulerian and Lagrangian analyses of ocean general circulation models at eddyresolving, eddypermitting, and noneddy permitting resolutions. We conclude that the eddydriven recirculation gyres in the eddyresolving and eddypermitting models are similar to recirculations observed in hydrographic data and that the effect of eddies is an important factor in shaping the export pathways of deep water from the subpolar to the subtropical gyres.

Silvia Garzoli*, Shenfu Dong, Molly Baringer and Zulema Garraffo

AMOC variability and connectivity in the South Atlantic

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The AMOC variability in the South Atlantic is described using both available observations and a non data-assimilative simulation of the AMOC with the aim of defining the importance of variations in inter-ocean and inter-basin exchange and the connectivity of the AMOC. One of our tasks is to examine the heat budget in a box in the South Atlantic. Our ultimate goal of heat budget in this box is to examine the role of inter-ocean exchanges in northward heat transport and air-sea heat exchanges. We first evaluate how well the heat budget in the box closes on time-mean and seasonal time scale with currently available data, what uncertainty we would expect, and the relationship between transport across each boundary, air-sea heat flux, and heat storage rate. The seasonal heat budget in the box is also examined using output from the global eddy-resolving Hybrid Coordinates Ocean Model (HYCOM) for a data-model comparison. We next explore the interannual variability of the heat transport across each boundary and heat content in the box for the period 1992 to the present to understand the effects of the transport across the two chokepoints (Drake Passage and South of Africa) on the AMOC northward heat transport across the northern boundary and their effects on the variability of heat content and air-sea heat fluxes.

Sirpa Hakkinen* and Peter Rhines

Shifts in North Atlantic warm water pathways, a sign of AMOC changes?

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We review the North Atlantic upper ocean current changes as seen from altimetry and surface drifters 2001-2007 and update with the present state. Penetration of subtropical waters, north to the subpolar gyre, is emphasized. Variability of the subpolar gyre's circulation appears to have far-reaching effects on the meridional circulation, and to facilitate the decadal warming observed throughout the northeastern Atlantic and Nordic Seas. We implement simple tracer models tracking in these 'observed' velocity fields and compare the tracer evolution with similar fields from available ocean state estimates as well as from prognostic ocean models. We use also direct evaluation of the velocity fields from the models. Our goal is to establish any possible relationship (or lack of) between the changes in the warm water surface pathways and AMOC from the modeling results. The models and ocean state analyses used are: prognostic POM/GSFC, POM-Z/GSFC, and ocean state analyses: ECCO-KF/JPL, SODA/UMD, and GMAO/GSFC. The surface forcing changes will be analyzed to gain understanding of the role of local atmospheric forcing versus remote forcing.

Patrick Heimbach* and C. Wunsch

Implications for Atlantic MOC Observing Systems of Adjoint Model Sensitivities

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Sensitivities of the AMOC to a variety of oceanic and atmospheric state variables are analyzed in the framework of the ECCO-GODAE state estimation infrastructure. The use of the adjoint model, which furnishes full geographical information of AMOC sensitivities to each of these variables at each instant in time, combined with prior uncertainty estimates, enables the inference of regions of comparable influence on time scales of years to decades. Analogous calculations are possible for any physical variable or property. On decadal time scales, remote regions of the ocean conspire to affect AMOC variability. To enable a description and understanding of the dynamical causes of AMOC variability it is thus imperative to have available continuous ocean (and improved atmospheric) measurements covering at least most of the Atlantic basin. If multi-decadal processes are of interest, the measurements must extend much further away.

Aixue Hu*, Gerald A. Meehl, Weiqing Han, and Jianjun Yin

Transient Response of the MOC and Climate to Potential Melting of the Greenland Ice Sheet in the 21st Century

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The potential effects of Greenland Ice Sheet (GrIS) melting on the Atlantic meridional overturning circulation (MOC) and global climate in the 21st century are assessed using the Community Climate System Model version 3 with prescribed rates of GrIS melting. Only when GrIS melting flux is strong enough to be able to produce net freshwater gain in upper subpolar North Atlantic does the MOC weaken further in the 21st century. Otherwise this additional melting flux does not significantly alter the MOC relative to the simulation without this added flux. The weakened MOC doesn't make the late 21st century global climate cooler than the late 20th century, but does reduce the magnitude of the warming in the northern high latitudes by a few degrees. However, the additional dynamic sea level rise due to this weakened MOC could potentially aggravate the sea level problem near the northeast North America coast.

T. Kanzow, **Helen L. Johnson***, D. P. Marshall, S. A. Cunningham, J. J-M., Hirschi, A. Mujahid, H. L. Bryden and W. E. Johns

Basin-wide integrated volume transports in an eddy-filled ocean

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Western boundary regions coincide with the fastest ocean currents, and are associated with elevated levels of eddy kinetic energy and dynamic height variations. Based on moored density measurements along 26.5N in the Atlantic we show that the amplitude of dynamic height variability peaks between 500 and 100 km east of the Abaco shelf (Bahamas) with values between 9.1 and 11.0 dyn. cm rms. It then rapidly decays westward to 5.9 and 3.9 dyn. cm rms at 40 and 16 km east of the shelf, respectively. Sea surface height variability observed by satellite altimetry shows a similar decline toward the shelf. Consequently, the meridional upper mid-ocean transport (i.e., transport shallower than 1000 m integrated between Morocco and Abaco) displays variations of 3.0 Sv rms, whereas the integral between Morocco and a station 500 km east of Abaco varies by 10.7 Sv rms, and the integral between Morocco and a station 40 km east of Abaco varies by 6.0 Sv rms. A numerical model simulation is presented, suggesting that boundary trapped waves may account for the observed decline in variability in the coastal zone since they provide a mechanism for fast equatorward export of transport anomalies associated with eddies impinging on the western boundary. A theory based on linear dynamics successfully describes the reduction of thermocline thickness variations on the boundary compared to open-ocean conditions. The results

suggests that the impact of eddy-boundary-impingement on upper mid-ocean transport estimates at 26.5N is too small to mask possible decadal trends in the Atlantic meridional overturning circulation.

Torsten Kanzow and S. A. Cunningham

Large-amplitude fluctuations of deep transports over sloping bathymetry: Impact on the vertical structure of the Atlantic Meridional Overturning Circulation at 26.5°N

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The time-variable barotropic flow over the continental rises of the eastern and western boundaries of the Atlantic projects on the vertical structure of the Atlantic meridional overturning circulation (AMOC) streamfunction. This AMOC component is invisible to density measurements, and is therefore difficult to quantify by observations. The RAPID/MOCHA array has provided daily estimates of the vigor of the AMOC at 26.5°N since April 2004, based on simultaneous observations of (i) Gulf Stream transports using cable measurements across the Straits of Florida, (ii) Ekman transports inferred from satellite scatterometry, and (iii) mid-ocean baroclinic transports derived from density profiles taken at the Moroccan and Bahamas continental slopes. Time-variable reference transports for the baroclinic mid-ocean transports - required to estimate the daily strength of the AMOC – have previously been estimated indirectly, via the imposition of a physically plausible, integral zero-net-transport constraint at each time step (Cunningham et al., 2007). This constraint has been implemented in the form of a spatially uniform compensation velocity field. Using geostrophic reference transports inferred from deep bottom pressure measurements carried out on the eastern and western boundaries at 26.5°N, Kanzow et al. (2007) showed that the AMOC strength was highly correlated with that using the integral transport constraint. At the same time AMOC related abyssal, basin-wide integrated meridional rms transport fluctuations using the former approach exceeded those relying on the transport constraint by a factor 3.

Based on an analysis of bottom pressure records collected between April 2004 and October 2007 we show that abyssal, zonally integrated transport variations at 5000 m show pronounced seasonal variability, and that the amplitude of the observed fluctuations exceeds that at any other level below the thermocline, in contrast to the transport constraint solution. The reason for this are intense time-variable flows over the eastern continental rise, as revealed by the bottom pressure records, that vary out of phase with the integrated transports over the remaining part of zonal extent of the 6000 km wide section, thereby reducing basin-wide integrated transport on shallower levels. The presence of the large-amplitude abyssal transport variability is puzzling from an energetics point of view, as it clearly exceeds the level of variability required for a barotropic compensation of Gulf Stream and Ekman transports. Overall, our results reveal that the external mode exhibits a pronounced zonal structure. This suggests that a modification of the spatially invariant compensation flow field (required to estimate mid-ocean reference transports) to incorporate a simple approximation to the zonal structure inferred from the bottom pressure measurements, yields a much more realistic representation of the deep, time-variable, vertical structure of the AMOC.

Kathryn Kelly*, LuAnne Thompson

Assessing Meridional Transports in the North Atlantic Ocean

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The Atlantic Meridional Overturning Circulation (AMOC) transports heat from the subtropical gyre to the subpolar gyre. Changes in the poleward heat transport are commonly associated with changes in the strength of the circulation, especially changes in the Gulf Stream, following the "ocean heat conveyor" conceptual model. Assuming a degree of coherence in circulation anomalies between the gyres, the AMOC is currently monitored in

the subtropical gyre near 26N. For changes in the large-scale ocean circulation to explain observed decadal anomalies of ocean heat and freshwater, there must be a robust mechanism to move water properties across the boundaries between subtropical and subpolar gyres. However, the conveyor paradigm has been challenged by recent observations showing little connectivity between the subtropical and subpolar gyres: floats deployed near the gyre boundary rarely cross that boundary. Fifteen years of observations from satellite altimeters reveal that anomalies in transport into the subpolar gyre (the North Atlantic Current) result from the Gulf Stream switching flow from one gyre to the other, rather than from transport anomalies in the Gulf Stream itself, as the conveyor model suggests. Higher sea surface temperatures at the gyre boundary do correspond to a stronger NAC. The switching appears to be controlled by winds related to the North Atlantic Oscillation. Changes in Gulf Stream transport are, however, associated with changes in the convergence of heat transport and with air-sea flux anomalies. This relationship suggests an alternative scenario for the Gulf Stream to influence the higher latitudes: heat anomalies injected into the atmosphere over the Gulf Stream may be transported poleward by the atmosphere.

Janina Körper*, Ulrich Cubasch

The importance of salinity for AMOC variations in an undisturbed and anthropogenic influenced climate

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The fully coupled ocean-troposphere-stratosphere model EGMAM is employed to investigate the role of salinity for the variability of the AMOC. First, the long periodic internal variability of the salinity in the Labrador Sea as a trigger of AMOC variations is analyzed in a simulation with constant preindustrial conditions. Second, the role of salinity for AMOC response to increasing greenhouse gas concentrations is investigated in the SRES A1B- and B1-scenario with stabilization of greenhouse gas concentrations thereafter as well as in a simulation with concentrations held constant at year 2000 values.

In the preindustrial simulation salinity and sea-ice-concentrations in the Labrador Sea and the AMOC show long-periodic variability. Spectral density of these parameters passes the 95%-significance level above red noise with peaks between 10 and 75 years. Wavelet-analysis reveals that there are different episodes in the simulation with different frequencies of long periodic variability. Cross-correlationanalysis shows that salinity anomalies in the Labrador Sea and AMOC variations are significantly correlated with maximum correlation at salinity leading the AMOC by two years. In the simulations with greenhousegas increase and stabilization thereafter analysis of the thermosteric and halo-steric contributions to the North Atlantic density gradient show that salinity plays an important role for the long term response of the AMOC to the anthropogenic greenhouse gas increase. During the greenhouse gas increase thermo-steric and halo-steric contributions are about equal and counteract each other. After stabilization of concentrations the saline effect exceeds the thermal effect, which prevents the AMOC from recovery.

Implications for a potential predictability of the AMOC from salinity measurements will be discussed.

Mojib Latif*

Multidecadal MOC Variability: Atmospheric Response and Coupled Feedbacks

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The temperature record of the last 150 years is characterized by a long-term warming trend, with strong multidecadal variability superimposed. The multidecadal variability is also seen in other (societal important) parameters such as Sahel rainfall or Atlantic hurricane activity. The existence of the multidecadal variability makes

climate change detection a challenge, since Global Warming evolves on a similar timescale. The ongoing discussion about a potential anthropogenic signal in the Atlantic hurricane activity is an example. A lot of work was devoted during the last years to the understanding of the dynamics of the multidecadal variability, and external as well as internal mechanisms were proposed. The paper discusses the different mechanisms, with special emphasis given to the Atlantic Multidecadal Oscillation/Variability (AMO/V). Specific attention is given to the role of the Meridional Overturning Circulation (MOC) in the Atlantic. Model studies show a strong connection between multidecadal MOC changes and changes in surface air temperature, regionally and globally.

Craig Lee*, Brian Petrie, Beth Curry and Jason I. Gobat

Davis Strait Transport and Freshwater Fluxes

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Arctic freshwater enters the North Atlantic through the major gateways of the Davis Strait/Canadian Arctic Archipelago (CAA) and Fram Strait, making these convenient locations for quantifying temporal and spatial variability of the critical upstream boundary for deep water formation regions to the south. Davis Strait integrates flows from the smaller passages of the CAA (Nares Strait, Heel Gate and Cardigan Strait, Wellington Channel and Barrow Strait) to provide a measure of net CAA fluxes after modification by mixing, terrestrial runoff and atmospheric inputs experienced during the southward transit.

Hydrographic sections occupied by ship-based surveys and by autonomous underwater gliders supplement year-round current, temperature and salinity measurements collected by a moored array that, for the first time, spans both Baffin and West Greenland shelves and extends to the ice-ocean interface. We summarize four years of autumn sections and moored measurements contrasted against climatological conditions derived from historical measurements spanning 1928 – 2004. Autumn snapshots show a small increase in net southward freshwater flux over the measurement period, beginning with volume and freshwater fluxes derived from the 2004 – 2005 moored measurements that are not statistically different from those calculated from moored measurements collected between 1987 – 1990. The 2004 – 2005 measurements indicate that the upper 100 meters account for 40% of the volume and over half the freshwater fluxes, while the two shelves carry roughly 17% of the total freshwater flux.

Tong Lee*

Consistency of AMOC estimates from global ocean data assimilation products

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As part of the CLIVAR/GODAE global ocean reanalysis evaluation effort, the state of the Atlantic Meridional Overturning Circulation (AMOC) estimated by over a dozen ocean data assimilation (ODA) products from the US, Europe, and Japan are compared. The goals of the comparison are: (1) to examine the consistency of the ODA products; (2) to evaluate their ability to detect climate signals; (3) to determine the accuracy of observational estimate of AMOC needed to distinguish or effectively constrain the ODA products; and (4) to identify potential causes for the consistency or discrepancy among these products. This presentation focuses on the meridional transport stream function (MTSM). Regardless of latitude and depth, the temporal variability of the estimated MTSF (“signal”) is generally larger than the r.m.s. difference among different ODA products (“noise”). This “signal-to-noise” ratio decreases with depth. The difference among the products is substantially larger for intraseasonal than for seasonal-interannual variability. For intraseasonal, seasonal, and interannual time scales, the r.m.s. differences are all larger in the tropical Atlantic than at higher latitudes. At 26N, the r.m.s. difference of MTSF variability (for all time scales) at 1000-m depth (1.8 Sv) is smaller than the averaged variability in various products (2.7 Sv). For

decadal and longer time scales, however, the discrepancy among the products is as large as the variability itself. The implications to AMOC observing systems will be addressed.

W Timothy Liu* and Xiaous Xie

Spacebased Observations of Atlantic Meridional Water and Heat Transport

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Significant improvement in estimating surface momentum, heat and water fluxes using a new generation of spacebased sensors and techniques allows better estimation of the mean meridional fresh water and heat transport, and surface Ekman transports in the Atlantic. Time varying ocean heat and mass storage has been derived from radar altimeter and Gravity Recovery and Climate Experiment; the time varying meridional transports could also be studied. The meridional transport derived from spacebased data compares favorably with those derived from numerical model with assimilation of altimeter data.

L. Czeschel, **David. P. Marshall***, H. L. Johnson

Oscillatory sensitivity of Atlantic overturning to high-latitude forcing

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Under anthropogenic greenhouse forcing, the Atlantic meridional overturning circulation is expected to weaken over the next century due to high-latitude warming and freshening. However, the ongoing global warming as seen in the upper North Atlantic ocean has not been monotonic. Departures from a steady warming on decadal timescales are well established and it is widely accepted that the meridional overturning circulation (MOC) plays an important role in driving these decadal near-surface temperature variations. Here, using the MITgcm and its adjoint in an 1 degree global configuration, we show that the Atlantic MOC exhibits an oscillatory sensitivity to anomalous forcing at high-latitudes. This leads to the counter-intuitive result that a positive Atlantic overturning anomaly can emerge as a result of, although some years after, anomalous warming at high latitudes. Our study suggests that the variability of the MOC is sensitive to changes in the buoyancy fluxes and SST in the North Atlantic of at least the last four decades. This longterm memory makes it extremely challenging to detect secular change in the MOC through short observational time series. We also discuss the time lag between highlatitude buoyancy forcing and the response in the MOC at different latitudes.

Michael McCartney* and Paula S. Fratantoni

MOC issues at the Tail of the Grand Banks

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We describe several interconnected circulation elements near the Grand Banks of Newfoundland, posing a series of circulation and dynamics puzzles and questions connected to the structure of the midlatitude AMOC, and relevant to its function in transporting heat and freshwater. We suggest a large new program including a regional scale field experiment and parallel process modeling and regional simulations.

The Tail of the Grand Banks of Newfoundland is a dramatic topographic ridge that protrudes southeastward from the continental shelf. It is a critical location for the North Atlantic circulation because here the major branches of the wind-driven (Gulf Stream GS and Labrador Current LC) and thermohaline circulations (Deep Western Boundary Current DWBC) meet, with dramatic changes in each current's pathway. The Tail of the Grand Banks is one of two locations where the GS and DWBC are forced to contend with one another, the other being Cape

Hatteras. Both locations have been implicated by Zhang and Vallis (2007) as critical points in setting the basin scale pathways for the GS and adjacent recirculations through the interaction of thermocline flow and the DWBC.

Northwards from 35°N, the GS leaves the western boundary, moving from the upper continental slope out over the much deeper abyssal plain, and crossing the DWBC as it does so. The crossunder of the GS by the DWBC off Cape Hatteras has been the target of a variety of field experiments and analytical and numerical process studies. In ocean circulation and climate numerical model simulations, a benchmark of simulation performance has been getting the GS separation “right” (leaving the coast at the observed location, and angle, with a subsequent pathway settling into an eastward trajectory near 40°N). While various technical aspects like vertical and lateral resolution and process parameterizations play a role in a model’s quality of GS replication, the interaction of the GS with the DWBC has been implicated in setting the location of the GS separation and its subsequent pathway and downstream strengthening. Our program intends to answer the basic question of “what happens next?” in the GS system by measurements of the flow system with time and space resolution adequate to ask and answer questions about the mean circulation and its dynamics, and with parallel process modeling and regional simulation studies.

The GS encounters the DWBC a second time at the Tail of the Grand Banks. The 150 Sv GS approaches the Tail as a full-depth (5200 m), unidirectional eastward current near 40°N. Ahead stands the Tail cresting near 4000 m. There is evidence that the GS sheds a large fraction of the 150 Sv into recirculations to the north and south of the GS path, leaving a smaller GS Branch (20-80 Sv) to continue eastward across the Tail. At the Tail the baroclinic front of the GS Branch abruptly turns north. The current, now called the North Atlantic Current (NAC), grows in transport until at 43°N it is a full water depth (4700 m) unidirectional northward current near 43°N, with about 140 Sv transport.

Between the NAC and the Grand Banks is a belt of southward flow over the continental slope and shelf of the Grand Banks. This includes the DWBC and the Labrador Current. The Tail forces the DWBC, at the same location where the mean GS Branch pathway crosses the Tail and turns north, the lower DWBC oppositely crosses the Tail crest turning from south to west. The turning path of the GS Branch at the Tail appears to reflect its encounter with the rapidly shoaling topography and with the counter-flowing DWBC pivoting beneath it. However, it is highly likely that the pathway distortions of both currents are a coupled phenomenon. The northward strengthening of the NAC is achieved through entrainment from offshore, the Mann Eddy recirculation cell, and from onshore, the Labrador Current and DWBC partially retroflecting into the strengthening NAC instead of crossing the Tail to flow west.

Rym Msadek*

Multidecadal variability of the AMOC and its impact on climate

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The influence of the natural variability of the Atlantic Meridional Overturning Circulation (AMOC) on climate is investigated in a control simulation of the IPSL coupled model. The low frequency fluctuations of the AMOC are mainly controlled by the East Atlantic Pattern (EAP) through a northward anomalous advection of salinity that drives oceanic deep convection in the subpolar gyre and leads to an intensification of the AMOC. This induces an interhemispheric SST anomaly that resembles the model Atlantic Multidecadal Oscillation (AMO) and is shown to have a significant influence on the atmosphere. The climate impacts induced by the AMOC fluctuations are strongest during summer and are quite similar to those following a corresponding phase of the AMO. The atmospheric response is global in scale and projects onto the EAP over the North Atlantic, suggesting a weak positive feedback on the AMOC. Sensitivity experiments with the atmospheric component of the climate model

coupled to an oceanic mixed layer reproduce a consistent signal but point to a strong non linearity of the summer response linked to transient eddy activity. During winter, the AMOC has a NAO-like influence on the atmosphere but the signal to noise ratio is smaller in the coupled run.

Ernesto Munoz*, Silvia Garzoli and Molly Baringer

Varied representation of the South Atlantic MOC across ocean reanalysis

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The variability of the South Atlantic Meridional Overturning Circulation (SAMOC) and its climate fingerprint is being analyzed from several ocean reanalysis. One of the goals of this study is to determine the extent to which the interannual variability of the AMOC contributes to the Atlantic meridional heat transport. The analyses from global ocean reanalysis (and models) is paramount to provide a basinwide view of the variability associated with changes in the SAMOC. Among the global ocean reanalysis being used are the GFDL, the SODA and the GECCO ocean reanalysis. A SAMOC index is obtained by determining the maximum meridional stream function at 32°S from each reanalysis. The variability of the SAMOC index is analyzed with respect to circulation and thermodynamic fields. Just like in its northern counterpart, the SAMOC index is not in agreement among reanalysis. In fact, in the South Atlantic there is greater divergence in the SAMOC representation (with a range of values between 11 Sv and 22 Sv). From the correlation of the SAMOC index with sea surface temperature (SST) anomalies it can be observed that whereas in the Pacific and Indian Oceans the SST fingerprint is similar among products, in the Atlantic it is not. This varied representation can also be appreciated from the relation between SAMOC and the Atlantic meridional heat transport at different latitudes.

Doron Nof

Will Europe cool or warm due to a slowing Atlantic Meridional Overturning Cell?

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The atmospheric response to a potential slow-down of the AMOC is described using the nonlinear analytical approach (for Heinrich events) introduced by Sandal and Nof (2008, SN, hereafter). Our interest in the problem stems from recent suggestions that the AMOC may slow down in the future due to an increased Arctic fresh-water flux into the North Atlantic. Virtually all numerical-global-climate models predict that Europe should cool in response to increased fresh water fluxes (“hosing”) that slow the AMOC down. Interestingly, in contrast to the numerical predictions, the analytics suggest that a region in the immediate vicinity of the Atlantic convection [up to a distance of ~o(1000km)] will warm, not cool (roughly 1.2°C for 20% mass-transport reduction). Here, we do not only apply the SN solution to present day conditions; we also place the SN results on a firmer ground by examining in detail its closure condition and the most critical assumption adapted by SN. The first has to do with the ratio of the atmospheric and oceanic mass transports (assumed unity in SN) and the second involves up-to-date maps of the ocean-atmosphere heat-fluxes.

Monika Rhein

AMOC heat and volume transports in the subpolar North Atlantic

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The ocean plays an important role in the past and present climate and very likely in future climate change by the long-term variability of the oceanic meridional mass, heat and freshwater transport. Most climate models envision a weakening of the MOC under a global warming scenario, with significant consequences to the climate,

particularly in the North Atlantic and for Western Europe. The strength of today's MOC and its decrease in the 21st century, however, differ significantly between the climate models, and little observational evidence exists of the strength and modulation of the MOC. I propose to deploy an AMOC array in one of the key regions of the MOC, the subpolar North Atlantic. The array will not only monitor the temporal, vertical and spatial volume transport fluctuations, but also -- by high resolution measurements of the total velocity and temperature field --, the total mean MOC volume and heat transport. These time series will be crucial to understand the links between the strength of the AMOC in the subpolar North Atlantic and atmospheric and oceanic processes: Are changes in water mass transformation and gyre circulation linked to the MOC? What are the mechanisms causing MOC modulations on different time scales from <1 year to interannual? What is the role of MOC pathways in the ocean's interior for the mean transport and the fluctuations? How is the correlation between the AMOC transports in the subpolar and subtropical North Atlantic? The array will be accompanied by other measurements: Continuous time series of the variability of the NAC and LSW transport when crossing the Mid Atlantic Ridge, and biannual time series of the production rates of LSW.

Anthony Rosati*, S. Zhang, Y. Chang, T. Delworth

The Non-Stationary Nature of the Observing Systems and the Potential Predictability of the AMOC

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It is likely that decadal climate predictions will be substantially improved by Argo data. However, quantifying any improvement is complicated by the fact that Argo data have only been available for a few years. One possible way to evaluate the relative capability of the XBT network and Argo network is to conduct synthetic observing system experiments using a perfect model scenario. Zhang et al 2007 use a coupled model simulation of the 20th century as "truth", and assimilating "observations" from that "truth" experiment into a second, independent experiment using a Coupled Data Assimilation system (CDA) based on an Ensemble Kalman filter. "Observations" are taken from the model at places and times where real observations were taken. These observations are then assimilated into a coupled model ensemble that is subjected only to preindustrial forcings. The assimilation is able to successfully reconstruct twentieth-century ocean heat content variability and trends in most locations. However, the Atlantic Meridional Overturning Circulation (AMOC) was difficult to constrain using the twentieth-century observational network (XBT). The AMOC is only successfully reproduced when the Argo observing system is simulated. These results indicate that Argo profiles are critical for developing a nowcasting capability for the AMOC.

From these perfect model analyses we are able to run ensembles of coupled model experiments to investigate the potential predictability of variations of AMOC on decadal time scales and their dependence on the observing system network. Additionally, their source of the predictability is investigated.

In addition to the predictability experiments, results of the CDA using real observations highlight the sensitivity of the AMOC simulation to the non-stationary nature of the observing system. In particular the assimilation shows a marked increase in the background AMOC strength as we enter the Argo era. This result seems to be attributed to the increased depth of the Argo profiles as well as the high volume of salinity data.

Mirosław (Meric) Srokosz*

The UK RAPID programme

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The RAPID programme collected in-water measurements of the Atlantic Meridional Overturning Circulation (MOC) from 2004-2008. In concert work was carried out on modelling and palaeo aspects of rapid climate change. Here results from the across programme will be presented. Subsequent funding has allowed the observation programme to be extended to 2014, thus eventually providing a decade of Atlantic MOC observations. In addition, further work is being funded to examine the predictability of the MOC and whether the data being obtained, in conjunction with other measurements, can be used to improve decadal forecasting. This later work is being carried out in conjunction with the UK Met Office Hadley Centre. These new developments will also be briefly described.

Fiammetta Straneo*, David A. Sutherland, Stephen Dery

Fresh water transport into the North Atlantic: the contribution from Hudson Strait

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Hudson Strait is the third largest net contributor of fresh water to the North Atlantic, after Fram and Davis Straits, due to a large river input in the upstream Hudson Bay System and to the inflow of fresh water from the Arctic Ocean. The fresh water exported from Hudson Strait flows into the Labrador Current: a fresh-water-laden current which strongly influences the shelf-slope waters of the entire North American coast and, even more importantly to the AMOC, contributes to the stratification and dense water formation process of the Labrador Sea. Variations in the fresh water exported from Hudson Strait, either due to changes in the upstream sources or to fresh water storage and release in the extensive Hudson Bay are, therefore, likely to impact the AMOC. Here we present the first estimates of the fresh water outflow from Hudson Strait and its variability from a moored array deployed from 2004 to 2007. The observed interannual variability is discussed in the context of recent changes in the hydrologic cycle of the Arctic region.

John Toole*, R.G. Curry, T.M. Joyce, B. Peña-Molino, W.M. Smethie Jr. and J.N. Smith

Line W: A sustained measurement program sampling the North Atlantic Deep Western Boundary Current and Gulf Stream about 39°N 70°W

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Begun in spring 2004, a sustained measurement program - Line W - is returning high-resolution observations of the North Atlantic's Deep Western Boundary Current (DWBC) southeast of New England. The study focuses on the cold limb of the AMOC near the boundary between the subpolar and subtropical gyres. The field study consists of a 6-element, continental-slope-spanning moored array on a line underlying an altimeter satellite ground track, and periodic reoccupations of a full-depth hydrographic section along the line extending from the continental shelf towards Bermuda. As of this writing, data from the first 4 years of the array installation are in hand, along with 10 realizations of the section (starting with the CLIVAR repeat of WOCE Line A22 in November 2003). The array, a mix of Moored Profiler and conventional fixed-depth discrete instrument moorings, has to date returned temperature, salinity and horizontal velocity data for the period 12 May, 2004 to 11 April, 2008. After averaging to filter inertial, tidal and other high-frequency motions, the combined moored data has a lowest common temporal resolution of 5-days (the nominal burst sample interval of the Moored Profiles). The fixed sensors logged at the much higher rate of 2 to 4 samples per hour, albeit with much less vertical resolution: 250-500 m vs 2 m. Temperature, salinity, dissolved oxygen, tracer chemical concentrations and direct velocity (SADCP, LADCP) data

were acquired on the hydrographic cruises. Program details and data are available on the web site:
<http://www.whoi.edu/science/PO/linew/index.htm>

The 2004-2008 estimated time-mean meridional transports of intermediate (Upper and Classical Labrador Sea Waters) and deep waters (Iceland-Scotland and Denmark Strait Overflow Waters) across Line W are:

gamma-n=27.8
ULSW: -3.07 Sv
gamma-n=27.897
CLSW: -8.10 Sv
gamma-n=27.983
ISOW: -6.15 Sv
gamma-n=28.066
DSOW: -5.16 Sv
gamma-n=28.125

total mean : -22.5 Sv

with 5-day 4-layer-summed transport samples ranging between -0.9 and -56.5 Sv. Based on the estimated 10-d integral time scale, 95% confidence bounds on the total mean transport estimate are +/- 1.6 Sv. (All quoted transport estimates represent integrations of cross-line velocity within density layers from the continental shelf break to the maximum in southward transport streamfunction over the extent of the moored array.) We find intriguing suggestion at marginal correlation that the DWBC equatorward transport and Gulf Stream position co-vary, with poleward transport anomalies leading southward displacement of the North Wall by 20-60 days. Changes in Labrador Sea winter convection products are manifested in Line W intermediate water salinity, PV and CFC within approximately 5 years. Interpreting 129I observations in terms of simple boundary current models composed of an advectively transported "core" region and a stationary "shoulder" region with mixing or recirculation permitted between the two, we infer comparable transit times for the overflow waters between Labrador Sea and Line W in the range of 5-8 years. With continuing support from the NSF, we plan to continue the Line W measurement program to 2014. The PI's welcome opportunities for collaborative data analyses, comparisons with simulated fields and to use Line W data to constrain assimilative models.

Chunzai Wang*, Shenfu Dong, and Ernesto Munoz

Has the AMOC Weakened or Strengthened over the Past Five Decades?

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Seawater property changes in the North Atlantic Ocean affect the Atlantic meridional overturning circulation (AMOC), which transports warm water northward from the upper ocean and contributes to the temperate climate of Europe, as well as influences climate globally. Previous observational studies have focused on salinity and freshwater variability in the sinking region of the North Atlantic, since it is believed that a freshening North Atlantic basin can slow down or halt the flow of the AMOC. Here we use available data to show the importance of how density patterns over the upper ocean of the North Atlantic affect the strength of the AMOC. For the long-term trend, the upper ocean of the subpolar North Atlantic is becoming cooler and fresher, whereas the subtropical North Atlantic is becoming warmer and saltier. On a multidecadal timescale, the upper ocean of the North Atlantic has generally been warmer and saltier since 1995. The heat and salt content in the subpolar North Atlantic lags that in the subtropical North Atlantic by about 8-9 years, suggesting a lower latitude origin for the temperature and salinity anomalies. Because of the opposite effects of temperature and salinity on density for

both long-term trend and multidecadal timescales, these variations do not result in a density reduction in the subpolar North Atlantic for slowing down the AMOC. Indeed, the variations in the meridional density gradient between the subpolar and subtropical North Atlantic Ocean suggest that the AMOC may have become stronger over the past five decades. These observed results are supported by and consistent with some oceanic reanalysis products.

Josh Willis

The Day after Yesterday: Good Science, Bad Movies and the Ugly Truth about the AMOC's Role in Global Climate

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The Atlantic Meridional Overturning Circulation has been blamed for causing Europe's mild winters, past abrupt climate change and a disaster movie starring Dennis Quaid. In some ways, the modern-day AMOC is well understood. Its volume transport, heat transport, and even variability, have been observed and modeled and its basic physical forcing is well known. However, the importance of the AMOC in regulating regional atmospheric temperatures and the potential for changes in the AMOC to affect global climate remain matters of some debate. An assessment of recent work on the impact of the AMOC on global climate will be presented. The discussion will include work on future projections under IPCC scenarios, simulations of past climate change and paleoclimate evidence. Dennis Quaid, however, is not expected to attend.

Igor Yashayaev*, Yongsheng Wu , John Loder , Charles Tang , Simon Prinsenber

Variability of Deep Convection in the Labrador Sea in Recent Years

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The causes, strength and consequences of the deep convection that produces Labrador Sea Water (LSW) are analyzed by interpreting hydrographic, moored and profiling float measurements in conjunction with ocean-ice model simulations with realistic atmospheric forcing. Significant changes in the winter atmospheric forcing over the Labrador Sea are (or appear to be) able to explain most of the observed variability in the properties and volumes of the newly-formed year classes of LSW. The evolution of this water mass along its exit pathways and the associated signal transfer/transit rates will be described.

High-resolution model runs simulating the changes in sea ice and convection will be analyzed and used to examine the relative effects of variable freshwater flux and variable winter air temperature and winds on the simulated ice cover, convective mixing and water mass production in the Labrador Sea. Preliminary results suggest that both increased ice cover and enhanced LSW production in the winter of 2007-2008 were caused by high surface heat losses associated with extremely low air temperatures. That winter was indeed reported as the coldest regionally and globally over at least 7 years preceding 2008. We will also report on anomalously fresh near-surface water in the Labrador Sea in the second half of 2008 and examine its origin and impact on subsequent convection.

Rong Zhang*

Fingerprints of Atlantic Meridional Overturning Circulation (AMOC) Variability

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To reconstruct the past variability of the AMOC when no direct observations have been made, as well as to evaluate AMOC impacts, it will be very useful to develop fingerprints for the AMOC variations. The

fingerprints need to be quantities that can be derived from both climate models and observations. The development of fingerprints of the AMOC would link the circulation with variables that are observed extensively. The identification of such fingerprints will contribute to the interpretation of AMOC variations, and improve assessments of the impacts of AMOC variability on global climate. The talk will review previous studies on the fingerprints of AMOC variability, such as the Atlantic sea surface temperature (SST) anomalies, and pycnocline depth fluctuation at the western boundary, etc. An example fingerprint of AMOC variability using satellite altimeter sea surface height (SSH) and subsurface temperature data will be discussed in detail. The satellite altimeter SSH data is highly correlated with instrumental subsurface ocean temperature data in the North Atlantic, and both show opposite signs between the subpolar gyre and the Gulf Stream path. Such a dipole pattern is a distinctive fingerprint of AMOC variability, as shown for the first time by a 1000-year coupled ocean-atmosphere model (GFDL CM2.1) simulation. Satellite SSH data shows a weakening of the North Atlantic subpolar gyre during the 1990s, which is previously thought as an indicator of a slowdown of the AMOC. However, whether the recent slowing subpolar gyre is a decadal variation or a long-term trend remains unclear. The fingerprint using modeled and observed SSH/subsurface temperature data suggests that, contrary to previous interpretations, the recent slowdown of the subpolar gyre is a part of a multidecadal variation and suggests a strengthening of the AMOC. The dipole pattern in SSH and subsurface ocean temperature is an identifiable and measureable AMOC fingerprint that could be used to compare with other observations of AMOC variations. The ongoing satellite and subsurface temperature measurements (ARGO floats) could be used to monitor future AMOC variations sensitively.

Dongxiao Zhang* and Michael J. McPhaden

Tracking the Phase of AMOC with the North Brazil Current

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While climate models all predict a weakening AMOC during this century under global warming, there is a large spread in terms of both mean and variations for the 20th century. State-of-the-art ocean data assimilations also diverge on the low frequency variability of the AMOC over the last several decades. Diagnosing the AMOC historical variability is challenged by the lack of adequate basin-wide ocean observations that needed to define the overturning rate. This lack of understanding of AMOC in the past limits our knowledge about the current phase of the AMOC, even with a highly successful program RAPID monitoring the current state of the AMOC.

The North Brazil Current (NBC) flowing northward in the tropical south Atlantic, is one of the strongest western boundary currents in the world ocean. It's unique location, straddling the tropical Atlantic where currents are predominately zonal, suggests that it is the major pathway for the upper branch return flow of the AMOC. Here, we calculate an NBC transport time series based on 5 decades of observations near the western boundary off the coast of Brazil. Results reveal a large magnitude NBC variation on multidecadal time scales. The NBC is coherent with the Atlantic Multidecadal Oscillation in sea surface temperature, multidecadal swings in Sahel Drought and Atlantic hurricane activity, as well as the subtropical and subpolar upper ocean salinity anomalies. All of these multidecadal variations have been linked to the AMOC in a number of modelling studies. We will discuss the possibility of using the NBC variations to track the phase of the AMOC based on the observational evidence and numerical model results, and address the question about whether the slowdown of the AMOC has already occurred under global warming.