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Structure and Variability of the North Atlantic Meridional Overturning Circulation from Observations and Numerical Models

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UNIVERSITY OF MIAMI

STRUCTURE AND VARIABILITY OF THE NORTH ATLANTIC MERIDIONAL OVERTURNING CIRCULATION FROM OBSERVATIONS AND NUMERICAL MODELS

By

Benjamin Stuard Shaw

A THESIS

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STRUCTURE AND VARIABILITY OF THE NORTH ATLANTIC MERIDIONAL OVERTURNING CIRCULATION FROM OBSERVATIONS AND NUMERICAL MODELS

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This study presents an analysis of observed Atlantic Meridional Overturning Circulation (AMOC) variability at 26.5°N on submonthly to interannual time scales compared to variability characteristics produced by a selection of five high- and low-resolution, synoptically and climatologically forced OGCMs. The focus of the analysis is on the relative contributions of ocean mesoscale eddies and synoptic atmospheric forcing to the overall AMOC variability.

Observations used in this study were collected within the framework of the joint U.K.-U.S. Rapid Climate Change (RAPID)-Meridional Overturning Circulation & Heat Flux Array (MOCHA) Program. The RAPID-MOCHA array has now been in place for nearly 6 years, of which 4 years of data (2004-2007) are analyzed in this study. At 26.5°N, the MOC strength measured by the RAPID-MOCHA array is 18.5 Sv.

Overall, the models tend to produce a realistic, though slightly underestimated, MOC. With the exception of one of the high-resolution, synoptically forced models, standard deviations of model-produced MOC are lower than the observed standard deviation by 1.5 to 2 Sv. A comparison of the MOC spectra at 26.5°N shows that model variability is weaker than observed variability at periods longer than 100 days.
Of the five models investigated in this study, two were selected for a more in-depth examination. One model is forced by a monthly climatology derived from 6-hourly NCEP/NCAR winds (OFES-CLIM), whereas the other is forced by NCEP/NCAR reanalysis daily winds and fluxes (OFES-NCEP). They are identically configured, presenting an opportunity to explain differences in their MOCs by their differences in forcing. Both of these models were produced by the OGCM for the Earth Simulator (OFES), operated by the Japan Agency for Marine-Earth Science & Technology (JAMSTEC). The effects of Ekman transport on the strength, variability, and meridional decorrelation scale are investigated for the OFES models.

This study finds that AMOC variance due to Ekman forcing is distributed nearly evenly between the submonthly, intraseasonal, and seasonal period bands. When Ekman forcing is removed, the remaining variance is the result of geostrophic motions. In the intraseasonal period band this geostrophic AMOC variance is dominated by eddy activity, and variance in the submonthly period band is dominated by forced geostrophic motions such as Rossby and Kelvin waves. It is also found that MOC variability is coherent over a meridional distance of ~8° throughout the study region, and that this coherence scale is intrinsic to both Ekman and geostrophic motions.

A Monte Carlo-style evaluation of the 27-year-long OFES-NCEP timeseries is used to investigate the ability of a four year MOC strength timeseries to represent the characteristics of lengthier timeseries. It is found that a randomly selected four year timeseries will fall within ~1 Sv of the true mean 95% of the time, but long term trends cannot be accurately calculated from a four year timeseries. Errors in the calculated trend
are noticeably reduced for each additional year until the timeseries reaches ~11 years in length. For timeseries longer than 11-years, the trend's 95% confidence interval asymptotes to 2 Sv/decade.
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Chapter 1: Introduction

1.1 Motivation

The global ocean is known to play a significant role in the earth's climate system. In the North Atlantic Ocean, heat transport is dominated by the Atlantic meridional overturning circulation (AMOC). The most recent climate model projections suggest that the strength of the AMOC will decrease by 25% in the next century as a result of global warming (Intergovernmental Panel on Climate Change [IPCC], 4th Assessment Report). This forecast would have a significant impact on global heat transport and on the climates of geographical regions such as Northwestern Europe that are directly affected by the Atlantic Ocean's heat transport.

Although there are many differing viewpoints on the subject, global warming and rapid climate change (anthropogenic or otherwise) have the potential to cause wide-reaching problems, from sea level change and flooding to desertification and drought. The AMOC's significant role in global climate change has not been lost on world leaders and policy makers. In response to the international demand for explanations and predictions of future climate change, the AMOC has become a focal point of study.

Because of the AMOC's large spatial and temporal scales, observation and quantification of its characteristics are difficult. In the past, estimates of the AMOC's strength and variability were based on sparse data from trans-basin hydrographic sections. In 2004, the joint US-UK Rapid Climate Change–Meridional Overturning Circulation & Heatflux Array (RAPID-MOCHA) Program deployed a series of moorings
across the Atlantic Ocean at 26.5°N to collect observations of the strength and structure of the Atlantic MOC, and to assess the role of thermohaline circulation in rapid climate change. The RAPID-MOCHA program is composed of scientists from the National Oceanography Centre (NOC) in Southampton, U.K., the University of Miami's Rosenstiel School of Marine and Atmospheric Science (UM-RSMAS), and the National Oceanographic and Atmospheric Administration's Atlantic Oceanographic and Meteorological Laboratory (NOAA-AOML). As of writing, the RAPID-MOCHA array has already provided more than four years of continuous AMOC and meridional heat transport observations, and funding for the project is expected to continue until 2014.

The purpose of this study is to compare the strength, variability, and vertical structure of the observed MOC against MOCs produced by a variety of numerical models. Using model-produced MOC data, this study will also describe the MOC's meridional coherence and representativeness of longer timeseries.

1.2 Background

1.2.1 MOC & THC

Because of its particular importance in terms of the global climate, the MOC has been subject to rigorous study in the past two decades. Although many people use the terms “thermohaline circulation” (THC) and “meridional overturning circulation” (MOC)
interchangeably, THC refers to those circulations associated only with surface fluxes of heat and fresh water, whereas MOC refers to any circulation in the meridional-vertical plane.

Explained simply, the global THC is a process in which water, heated at low latitudes in the Atlantic Ocean, is transported northward to higher latitudes where it loses energy to the atmosphere. Freed of its energy, the water becomes colder and denser, sinks, and flows southward at depth. Upon reaching the Antarctic Circumpolar Current (ACC), it is distributed to the Indian and Pacific Oceans where it eventually upwells and returns to the Atlantic Ocean so the process can begin again. It is a very slow circulation, and may take upwards of 200 years for a parcel of water to complete the entire loop.

Overturning circulations exist in all ocean basins, but special importance is attached to the Atlantic MOC (AMOC) because its percentage contribution to the global meridional heat transport (MHT) is much larger than either the Indian or Pacific Ocean's heat transport. At 25.4°N, Lavin et al. (1998) calculated heat transport in the Atlantic Ocean to be 1.27 +/- 0.26 PW; Johns et al. (2010, submitted) showed that the mean meridional heat transport between 2004 and 2007 at 26.5°N is 1.33 +/- 0.12 PW, approximately 70% of the net poleward heat flux carried by the global oceans at this latitude. In contrast, several studies of the Pacific Ocean show that its heat transport values are significantly lower than that of the Atlantic Ocean, and that heat transport in the Pacific Ocean is principally associated with shallow wind-driven Ekman dynamics. Ganachaud & Wunsch (2000), for example, calculated the Pacific Ocean heat flux to be 0.53 +/- 0.24 PW at 24°N, and Macdonald (1998) calculated it to be 0.45 +/- 0.26 PW.
The Atlantic MOC is stronger than either the Pacific or Indian Ocean overturning circulations due to deep water formation sites located in the Greenland, Iceland, and Norwegian (GIN) Sea in the northernmost reaches of the North Atlantic. Convection in the Labrador Sea (2-4 Sverdrups; [1 Sverdrup = 1 Sv = $10^6$ m$^3$/s]) and turbulent geostrophic gravity currents through the steep overflows and bottom topography of the Denmark Strait (2.4-2.9 Sv) and Faroe Bank Channel (2.4-2.7 Sv) generate comparable amounts of North Atlantic Deep Water (NADW), some of the deepest water found in the global ocean (Kuhlbrodt et al. 2007). Pickart & Spall (2007), however, suggest that convection in the Labrador Sea generates only 1 Sv of sinking water, and does not significantly affect the North Atlantic MOC.

1.2.2 Global Thermohaline Circulation Theory

There are two major theories regarding the path taken by the global THC. The “warm route” is described in detail in Gordon (1986). In the warm route, NADW, formed in the Labrador Sea and GIN Sea, flows southward at depth in the Atlantic Ocean into the Antarctic Circumpolar Current. From there, it is exported into both the Indian and Pacific Oceans while upwelling into the thermocline layer. Once the NADW has upwelled into the thermocline, it then flows from the Pacific Ocean into the Indian Ocean via the Indonesian through-flow. From the Indian Ocean, the global THC continues around the southern tip of Africa and then back into the South Atlantic as part of a branch of the
Agulhas Current that does not participate in the Agulhas retroflection. Once back in the South Atlantic, water flows northward through the subtropical gyre, across the equator, and back to the North Atlantic as upper ocean waters.

In his warm route paper, Gordon (1986) asserted that cold water from the Drake Passage could contribute only 25% of the total global THC flow returning to the North Atlantic. Rintoul et al. (1991), however, using an inverse model and historical hydrographic data, found that water from the Drake Passage was primarily responsible for transporting return flow to the Atlantic Ocean. The study also concluded that the import of Indian Ocean waters to the South Atlantic Ocean does not play a significant role in the global overturning circulation associated with the formation of NADW.

Since the publication of the seminal Gordon (1986) and Rintoul (1991) “cold route vs. warm route” studies, several observational (e.g. Macdonald, 1993; van Ballegooyen et al., 1994; Schmitz, 1995, etc.) and modeling (e.g. Matano & Philander, 1993; Doos, 1995; Thompson et al., 1997) efforts have been made to determine which route is the dominant global THC pathway. According to de Ruijter (1999), however, none of them have come to a common conclusion.

1.3 The Atlantic MOC and its Components

In the subtropical North Atlantic, the mean meridional flow is composed of the following main components: the northward flowing Florida Current/Gulf Stream (intense western boundary current); the basin-wide northward-flowing surface-intensified wind-driven Ekman transport; the southward-flowing Deep Western Boundary Current
(DWBC); and the broad, slow, southward-flowing transport associated with the North Atlantic subtropical gyre. When summed together, these flows yield the net MOC. Until recently, comprehensive observations of the MOC had never been possible, although several experiments devoted to the study of individual aspects of the MOC were conducted in recent decades.

1.3.1 The Florida Current

The Gulf Stream, commonly known as the Florida Current (FC) as it passes through the Straits of Florida, is possibly the most heavily studied of all ocean currents in the world. Records indicate the first FC transport estimates were made in the 1880s by John Elliott Pillsbury (Pillsbury, 1887; 1890). The first detailed direct transport estimates of the FC were made using dropsondes in the 1960's (Schmitz & Richardson, 1968).

Today, a continuous volume transport timeseries exists for the Florida Current dating back to 1982, thanks to simple electromagnetic theory. Electromagnetic theory states that when charged particles pass through a magnetic field, a voltage is induced perpendicular to the flow of the charged particles. In the case of the FC, salt ions in the seawater flow through the earth's magnetic field inducing a voltage in an abandoned telecommunications cable that spans the Straits of Florida. The strength of the FC can then be estimated because it is linearly proportional to the magnitude of the observed cable voltage (Larsen and Sanford, 1985). Measurements of this voltage, calibrated with direct current measurements, have been successfully used to provide transport estimates of the FC for the last 25 years.
1.3.2 Ekman Transport

The Ekman layer is a thin, horizontal boundary layer of approximately 100m in depth, wherein water is transported at right angles to the direction of the wind acting on it. This wind-driven transport is known as the Ekman transport. In the subtropical North Atlantic, generally speaking, easterly winds cause a northward volume transport. Basin-wide Ekman transport is derived from surface wind stress data collected by satellite scatterometry and is calculated by zonally integrating the following equation from Abaco, Bahamas to the African coast:

\[ T_{ekman}(t) = -\int \left[ \tau_x(x, t) / \rho f \right] dx \]  
(Equation 1-1)

where \( T_{ekman} \) is the Ekman transport, \( \tau_x \) is the zonal surface wind stress, \( \rho \) is density, and \( f \) is the Coriolis parameter.

1.3.3 Deep Western Boundary Current Transport

The Deep Western Boundary Current (DWBC) is a southward-flowing cold-water current that makes up part of the Atlantic Ocean's strong western boundary current system. As its name suggests, the DWBC is a subsurface current and is typically found at depths below 1000m. Water in the DWBC is made up of NADW that is formed both by dense overflows in the GIN sea and by deep convection in the subpolar gyre (Schmitz and McCartney, 1993). Early theoretical work by Stommel (1957) and Stommel and Arons (1960a,b) predicted that deep-water mass formation in the high northern latitudes would lead to intensified southward flow along the basin's western boundary.
1.3.4 Interior Ocean Transport

The term “interior ocean transport” refers to the northward geostrophic transport integrated between the Bahamas and Africa. In the RAPID-MOCHA program, it is calculated by zonally integrating the geostrophic profile of northward velocity from temperature and salinity data collected by “dynamic height” moorings located at the zonal limits of the Atlantic basin. The density profiles measured by these endpoint moorings are used to calculate the net geostrophic flow (relative to a level of reference) between the two endpoints. The absolute geostrophic horizontal velocity \( U \) can be deduced from horizontal pressure \( P \) gradients in the ocean by the equation

\[
2 \Omega \times U = \frac{1}{\rho} \nabla_P P \tag{Equation 1-2}
\]

where \( \Omega \) and \( \rho \) denote the earth’s angular velocity and reference ocean density, respectively (Kanzow et al., 2009). For further details, the reader is referred to Kanzow et al. (2007, 2009).
Chapter 2: Objectives

The goal of this study is to explore and describe the AMOC's mean state, variability, mechanisms of variability, and meridional coherence using a combination of numerical model output, historical data, and observations collected from the RAPID-MOCHA Array. Using the RAPID-MOCHA dataset as a basis, I want to investigate how model formulation and configuration (e.g. climatologically vs. synoptically forced, high-vs. low-resolution) affects the models' ability to simulate observed MOC variability. Also, lengthy model simulations can help to define how representative the available (now 4 years long) RAPID-MOCHA timeseries is, and explore physical mechanisms of variability on various time scales.

The strength of the MOC is calculated at any given latitude \( y \) by taking the horizontal and vertical integral of the ocean's meridional velocity component \( v \):

\[
\Phi(z) = \int_{-H}^{z} \int_{x_w}^{x_e} [v(x, z)] dx \, dz = \int_{-H}^{z} V(z) \, dz' \tag{Equation 2-1}
\]

and the overall strength of the MOC is given by the maximum value of \( \Phi(z) \):

\[
\Phi_{max} = \max \left[ \Phi(z) \right] \tag{Equation 2-2}
\]

where \(-H\) is the depth of the sea floor; \( x_w \) and \( x_e \) are the zonal position of the western and eastern boundaries of the Atlantic Ocean; and \( V \) is the meridional volume transport per unit depth (units of m\(^3\)/s). Volume transport is often reported in units of Sverdrups (1 Sv = 10\(^{6}\) m\(^3\)/s).
In this thesis, I will extend Cunningham et al. (2007)'s analysis of the strength, structure, and variability of the Atlantic MOC by examining observations collected from the RAPID-MOCHA array, and then by comparing those observations to output from numerical models. This thesis will attempt to answer the following questions:

1. What is the strength and variability of the North Atlantic MOC, and are models able to reproduce this?
2. Are numerical models able to accurately reproduce the vertical structure of the MOC at 26.5°N?
3. How do the modeled spectra of MOC variability compare with observations?
4. Are the dominant modes of variability of $\Phi(z)$ well simulated?
5. What are the mechanisms by which the MOC variability is forced?
6. What part of the MOC variability is due to random internal variability not obviously related to forcing?
7. How representative is the existing MOC timeseries of long-term MOC variability?
8. How well are MOC trends resolved, given the statistical nature of the modeled (and observed) MOC variability?
9. What is the meridional coherence scale of the MOC fluctuations?
Chapter 3: Data Sources

3.1 Observations: The RAPID-MOCHA Array

In 2004, in response to the IPCC’s report suggesting the likelihood of a weakening AMOC in the near future, researchers at UM-RSMAS and NOAA-AOML in the United States joined forces with scientists from the University of Southampton in the United Kingdom to establish the RAPID-MOCHA program. The program is a joint effort to monitor the strength and variability of the AMOC. This thesis focuses on a 4 year timeseries of RAPID-MOCHA data that stretches from April 2004 through April 2008.

Each element of AMOC has its own observation system, the data from which are then combined to form the complete RAPID-MOCHA dataset. Details of these observations systems are provided in the following four sections. For detailed information on the design and implementation of the RAPID-MOCHA array, the reader is referred to Hirschi et al. (2003) and Cunningham et al. (2007).

3.1.1 Florida Current Observations

The cable used by the RAPID-MOCHA program to estimate FC strength is located at approximately 27°N, stretching from West Palm Beach, Florida to Grand Bahamas Island, Bahamas. Voltage differences in the cable are measured once per minute, then 3-day lowpass filtered using a 2nd order Butterworth filter passed both
forward and backward to remove tides and magnetic field variations (Meinen et al., 2010). Cable voltage is calibrated against dropsonde and direct current profiling data from repeat hydrographic sections across 27°N. These calibration cruises are performed 6-10 times per year (Johns et al. 2010). Results from the cable study show that the FC's long term mean is 32.2 Sv with a standard deviation of 3.3 Sv (Meinen et al., 2010). For a more comprehensive explanation of the FC cable study, the reader is referred to Meinen et al. 2010.

The FC's contribution to the AMOC requires knowledge of its vertical distribution, but the cable voltage only provides estimates of the total volume transport. Transport per-unit-depth profiles of the FC were computed by projecting the FC volume transport onto the first vertical mode of meridional transport per unit depth. The first vertical mode was determined by an empirical orthogonal function analysis of the meridional velocity measurements from 64 historical Pegasus sections across the Straits of Florida. The analysis shows that the first vertical mode contains 87% of the variance (Kanzow et al., 2007 [Supporting Online Material]).

3.1.2 Ekman Transport Observations

As described in Section 1.3.2, Ekman transport observations ($T_{ekman}$) integrated across the Atlantic Ocean basin, are estimated from the equation

$$T_{ekman}(t) = -\int \left[ \tau_x(x, t) / \rho f \right] dx$$

(Equation 3-1)
where $\tau_x$ is the zonal surface wind stress, $\rho$ is ocean density, and $f$ is the Coriolis parameter. The zonal wind stress $\tau_x$ is estimated from space-borne Quikscat scatterometer measurements. Scatterometers are active microwave sensors that transmit a series of microwave pulses and measure the returned echo power. This allows for determination of the normalized radar backscattering cross section of the ocean surface and, subsequently, the ocean wind speed and direction (Graf et al., 1998). Daily gridded scatterometer data from Quikscat, available from CERSAT, IFREMER (France), are used for the $T_{e_k}$ calculation.
Calculated values of $T_{ekman}$ are then distributed evenly over the top 100m of the water column, the approximate thickness of the Ekman layer, to obtain vertical transport per-unit-depth profiles for each timestep. The meridional strength of the Ekman transport during between April 2004 and October 2007 ranges from approximately 13 Sv to -5 Sv (Kanzow et al., 2010 [submitted]).

Figure 3-2: Summary of previous western boundary wedge studies (from Bryden et al., 2005)

3.1.3 Observations of the Deep Western Boundary Current

Between 1986 and 1997, three decades after the theory behind the DWBC had been proposed, a series of observational programs began collecting measurements of the DWBC at 26.5°N. These programs were the SubTropical Atlantic Climate Study (STACS), the Western Atlantic Thermohaline Transport Study (WATTS), and the
Atlantic Climate Change Project (ACCP). Seven current meter mooring deployments were made, each of which lasted from 12 to 25 months. In total, these three programs produced an eleven year DWBC timeseries (Bryden et al., 2005).

Following the termination of the STACS, WATTS, and ACCP programs in 1997, observations of the western boundary region continued in a limited fashion. Then, in 2004, the RAPID-MOCHA program was launched. In March and April of 2004 seven moorings were deployed in the western boundary region at 26.5°N. Johns et al. (2008) describes the DWBC system in detail using data collected from RAPID-MOCHA between the initial deployment date through May 5, 2005 (the first results from the RAPID-MOCHA program). During this time period, the DWBC’s mean core position was approximately 50km from the east coast of Abaco, Bahamas at a depth of 2000m, and observed northward transport values ranged from 0 Sv to -60 Sv. These findings confirm the results of previous studies, though meanders in the current were capable of displacing the DWBC core as far east as 25km from Abaco and as far west as 125km from Abaco (Lee et al., 1996).

3.1.4 Observations of the Atlantic Ocean's Interior

Although continuous observations of FC transport and Ekman transport are available from previously established observation systems (submarine cable voltage and Quikscat satellite scatterometry measurements, respectively), there is no simple way to collect data from the ocean's interior. Within the last ten years, some progress has been made to collect continuous measurements of the ocean interior. For example, since 2000
the Argo program has developed and maintained a broad-scale, global ocean array of
over 3,000 profiling floats that collect temperature and salinity data in the upper ocean
(Roemmich et al., 2009; Roemmich & Gilson, 2009). However, focused, full-depth
measurements of the ocean’s interior have been limited to infrequent snapshots collected
during repeat hydrographic sections (Bryden et al., 2005). Continuous observations using
this same repeat hydrography approach would require a dedicated fleet of ships
constantly collecting data, the operational costs of which would be impossibly large.

Rather than suffer the limitations of repeat hydrography, under the direction of the
RAPID-MOCHA program a trans-basin mooring array was experimentally designed,
successfully tested in model studies (Hirschi et al., 2003), and then deployed across the
Atlantic at 26.5°N in 2004. The purpose of the array is to collect daily measurements of
salinity and temperature throughout the water column at the eastern and western
boundaries of the Atlantic Ocean. From this data, daily estimates of the zonally integrated
geostrophic profile of northward velocity can be made.

In its entirety, the trans-basin mooring array consists of 15 moorings. “Dynamic
height” moorings at the eastern and western limits of the basin collect measurements of
the basin-wide geostrophic shear; moorings on the Bahamian continental margin are
positioned to resolve the Deep Western Boundary Current (DWBC); and moorings on
either side of the Mid-Atlantic Ridge (MAR) are positioned to resolve flows in both sub-
basins. The moorings are equipped with current meters and hydrographic sensors that
collect data at 10-15 minute intervals. As of writing, the array has been in the water for
over six years.
The RAPID-MOCHA data used in this study was processed by the National Oceanography Centre (NOC) in Southampton, UK and downloaded from the NOC's RAPID-MOC website (http://www.noc.soton.ac.uk/rapidmoc/). The data has been 2-day lowpass filtered using a six-pole Butterworth filter to remove tidal and inertial oscillations, and then subsampled onto a 12-hour sampling grid (Kanzow et al., 2007).

Figure 3-3: Overview of RAPID-MOCHA mooring locations (from Kanzow et al., 2007)

### 3.2 Numerical Models

Below is a description of the five different numerical models used in this study. A summary of their characteristics is provided in Table 3-1 at the end of the section. In this study, the investigation of the models listed below is focused on the subtropical North Atlantic, between 15°N and 40°N.
3.2.1 Climatologically Forced OFES (OFES-CLIM)

The Ocean General Circulation Model For the Earth Simulator (OFES), based on the Modular Ocean Model (MOM3) developed at Geophysical Fluid Dynamics Laboratory/National Oceanographic and Atmospheric Administration (GFDL/NOAA), was developed and run by the Japan Agency for Marine-Earth Science and Technology (JAMSTEC) Earth Simulator (Sasai et al. 2004). The Atmosphere and Ocean Simulation Research Group at JAMSTEC uses their Earth Simulator supercomputing facility to perform atmospheric and oceanic dynamical research by running global simulations with extremely high resolutions. The OFES-CLIM global simulation is forced by climatological monthly mean wind stresses averaged from 1950 to 1999 from NCEP/NCAR reanalysis data. It is run at a horizontal resolution of 1/10° degree and is a level-coordinate model with 54 layers. Vertical layer thicknesses vary from 5 meters at the surface to 330 meters at depth. There are 8 years of daily sampled data available, and the model's meridional range goes from 75°S to 75°N, though this study focuses on every tenth gridpoint (~1.0°) of the OFES model output between 15°N and 40°N.

3.2.2 NCEP-NCAR Forced OFES (OFES-NCEP)

This model was also developed and run by JAMSTEC using OFES. Its horizontal and vertical resolutions are identical to the climatologically forced version mentioned above. However, instead of being forced by a monthly climatology, this simulation was
forced by NCEP-NCAR daily winds (OFES-NCEP) from 1950 to 2003 and sampled every three days. The length of the MOC timeseries available for this model is 27 years, and data extends meridionally from 75°S to 75°N.

3.2.3 POP 14b

Data from the Parallel Ocean Program (POP) model run 14b (POP14b, described in detail in Smith et al., 2000 and Bryan et al., 2007) allows for further comparison of the effect of resolution and forcing on MOC characteristics. POP14b is a high resolution (0.1°), level-coordinate North Atlantic model with 40 vertical levels and layer thicknesses that vary from 10m at the surface to 250m at depth. The model is forced by daily averages of ECMWF TOGA surface analyses. Three years of model output are available in 10-day snapshots between March 1, 1998 and February 23, 2001, extending from 20°S to 72°N.

3.2.4 Peacock, Bryan, and Maltrud Model

The Peacock, Bryan, and Maltrud (PBM) model is a level-coordinate POP model with a horizontal resolution of 0.1°, 42 vertical levels, and layer thicknesses that vary from 10m at the surface to 250m at depth (Maltrud et al., 2010). The atmospheric state of the model is based on the repeat annual cycle Coordinated Ocean Reference Experiment (CORE) forcing dataset with 6-hourly forcing averaged to monthly. Four years of daily
data from this model run were graciously provided by Dr. Mathew Maltrud of Los Alamos National Laboratory (LANL). This data extends meridionally from 23°N to 28°N at 0.45° intervals.

3.2.5 **CCSM3 POP**

To provide a base for comparison to the high-resolution models presented above, this study also examines a low-resolution (1.0°) global model. The model is POP version 1.4 which is used as the ocean component of the Community Climate System Model (CCSM3), version 3 (Yeager and Large, 2007). In CCSM3 POP the north pole is displaced over Greenland, so although its horizontal grid is different than a standard latitude/longitude grid, its horizontal resolution is nominally 1.0°. It is a level-coordinate model with 40 vertical levels and layers thicknesses that vary from 10m at the surface to 250m at depth. The model is forced by a repeating 43-year cycle of NCEP-NCAR 6-hourly winds (from 1958 to 2000). Model years 0130 to 0145 (16 years of data) were downloaded from earthsystemgrid.org for use in this study which correspond to years 1958 through 1973 from the fourth cycle of the 1958-2000 NCEP-NCAR forcing. Data is available in 4-day averages, and extends meridionally from 27°S to 70°N.
Table 3-1: Summary of models examined in this study

<table>
<thead>
<tr>
<th>Name</th>
<th>Resolution</th>
<th>Forcing</th>
<th>Length of Dataset</th>
<th>Sampling</th>
<th>Meridional Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>OFES-CLIM</td>
<td>0.1°</td>
<td>NCEP-NCAR monthly mean climatology (1950-1999)</td>
<td>8 years</td>
<td>1-day samples</td>
<td>15°N–40°N</td>
</tr>
<tr>
<td>OFES-NCEP</td>
<td>0.1°</td>
<td>NCEP-NCAR daily averages</td>
<td>27 years (1980-2006)</td>
<td>3-day snapshots</td>
<td>15°N–40°N</td>
</tr>
<tr>
<td>POP 14b</td>
<td>0.1°</td>
<td>ECMWF daily averages</td>
<td>3 years (2005-2007)</td>
<td>10-day snapshots</td>
<td>20°S–70°N</td>
</tr>
<tr>
<td>PMB</td>
<td>0.1°</td>
<td>Repeat annual cycle (normal-year)</td>
<td>4 years</td>
<td>1-day samples</td>
<td>23°N–28°N</td>
</tr>
<tr>
<td>CCSM3 POP</td>
<td>1.0°</td>
<td>NCEP-NCAR 4-hourly</td>
<td>16 years (1958-1973)</td>
<td>4-day averages</td>
<td>27°S–70°N</td>
</tr>
</tbody>
</table>
Chapter 4: AMOC Characteristics at 26.5°N

Four years of MOC data have been collected thus far by the RAPID-MOCHA array. A timeseries of this length is insufficient to make meaningful statements about climate-timescale variability. However, with the assistance of lengthier numerical models, it is possible to determine whether or not the characteristics of these four years are representative of longer datasets. But before a representativeness study can be performed, the numerical models listed in Section 3.2 must be assessed.

Chapter 4 begins by describing the calculation of the MOC, then investigates its strength, structure, and variability by comparing observations collected during the RAPID-MOCHA program to the series of numerical models. The model data is then compared to the observational estimates.

4.1 MOC Calculation

The strength of the MOC is calculated in three steps. First, the meridional velocity is zonally integrated along a given latitude to yield $V(z)$, the transport per unit depth (units: m$^2$/s). $V(z)$ is then vertically integrated to form the vertical streamfunction $\Phi(z)$. The strength of the MOC is defined as the maximum value of $\Phi(z)$, indicated by the red arrow in the integration demonstration diagram (Figure 4-1).
Vertical integration of $V(z)$ begins at the surface ($\Phi(0) = 0$) and ends at the ocean floor. Ideally, $\Phi(\text{bottom}) = 0$ too, but net imbalances can exist on short timescales. To remove these imbalances, a zero-net-flow constraint is imposed by adding a compensating barotropic profile at each timestep, similar to Kanzow et al. (2007). The MOC strengths for each of the models were calculated for this study from meridional velocity model output data. Calculations of the RAPID-MOCHA MOC were performed by Kanzow et al. (2007).

$$\Phi(z) = \int V \, dz$$

Figure 4-1: Diagram showing the method by which the strength of the MOC is calculated. On the left is RAPID-MOCHA's mean vertical profile of transport per unit depth at 26.5°N (in units of m²/s), and on the right is $\Phi(z)$, its vertical integral (in units of Sv). The strength of the MOC is given by the maximum northward value of $\Phi(z)$. 
4.2 The MOC at 26.5°N

4.2.1 Mean Strength and Vertical Structure of the MOC

Although the meridional extent of numerical model output spans a wide range, RAPID-MOCHA observations are limited to a single line of latitude at 26.5°N. Therefore, comparison of observations to the models can only be performed at this latitude. Figure 4-2 compares RAPID-MOCHA’s long-term $\Phi(z)$ mean to each of the models at 26.5°N.

![Mean Vertical Streamfunction Comparison](image)

*Figure 4-2: Mean MOC vertical streamfunction at 26.5°N*

At first glance, the modeled vertical streamfunction profiles have roughly the same shape. In the upper ocean, the surface intensified northward Ekman Transport and northward flowing Gulf Stream are partly balanced by the gyre’s southward interior
Sverdrup transport, but the residual flow is northward. Between a depth of 1000m and ~4500m, flow is dominated by southward flow of NADW via the DWBC, and below ~4500m flow switches again due to northward flowing Antarctic Bottom Water (AABW). These flows divide the ocean vertically into an upper ocean cell and a lower ocean cell. Because of the large temperature contrast between the northward upper ocean flow and deep return flow of NADW, the northward heat transport in the North Atlantic is governed primarily by the strength of the upper ocean overturning cell. The OFES models tend to have a thinner upper-ocean cell and a thicker lower-ocean cell than any of the other datasets (note that the RAPID-MOCHA observations do not collect data on the AABW, instead assuming a climatological AABW value).

At 26.5°N, the mean strength of the RAPID-MOCHA observations is 18.7 Sv. The OFES-CLIM, OFES-NCEP, and POP 14b models exhibit slightly weaker mean MOC strengths than observations (2.5-3.5 Sv weaker). Mean MOC strength in the CCSM3 POP model is very similar to the mean strength of observations (only 0.3 Sv stronger), and the PMB model has the strongest MOC of all models, nearly 7 Sv stronger than observations. For latitudes adjacent to 26.5°N, the modeled strength of the MOC tends to be weakest at lower latitudes and strongest from 30-35°N. North of 35°N, MOC strength tends to weaken as latitude increases poleward. This results is consistent for all of the models examined.
The mean strengths and variances of the observations and models at 26.5°N are presented in Table 4-1. To the first order, it appears that modeled MOC variability is more sensitive to the type of wind forcing applied than to model resolution. Synoptically forced models tend to have higher MOC variability than climatologically forced models. However, there is no clear relationship between forcing, resolution, and mean strength.

Table 4-1: MOC Statistics for the full timeseries at 26.5°N. Mean and variance, calculated from their full-length respective timeseries, are presented here for the RAPID-MOCHA observations and the 5 models investigated in this study.

<table>
<thead>
<tr>
<th>Data Source</th>
<th>Mean</th>
<th>Standard Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>RAPID-MOCHA (4 year timeseries)</td>
<td>18.7 Sv</td>
<td>5.1 Sv</td>
</tr>
<tr>
<td>OFES-CLIM (8 year timeseries)</td>
<td>16.4 Sv</td>
<td>2.9 Sv</td>
</tr>
<tr>
<td>OFES-NCEP (27 year timeseries)</td>
<td>15.6 Sv</td>
<td>4.2 Sv</td>
</tr>
<tr>
<td>POP 14b (3 year timeseries)</td>
<td>17.0 Sv</td>
<td>3.1 Sv</td>
</tr>
<tr>
<td>PMB (4 year timeseries)</td>
<td>25.1 Sv</td>
<td>2.5 Sv</td>
</tr>
<tr>
<td>CCSM3 POP (16-year timeseries)</td>
<td>19.1 Sv</td>
<td>3.0 Sv</td>
</tr>
</tbody>
</table>

4.2.2 MOC Variability at 26.5°N

In Figures 4-3 and 4-4, 20-day lowpass filtered one-year-long Hovmöller diagrams provide additional insight into the vertical structure and strength of $\Phi(z,t)$. These figures are consistent with Figure 4-2, which indicates that the OFES and POP 14b models underestimate the MOC's observed mean strength, whereas CCSM3 slightly overestimates it, and PMB is significantly stronger than observations. Note that the
RAPID-MOCHA data overlaps in time only with the POP 14b model. The rest of the models are aligned so that their yeardays coincide with observations. The RAPID-MOCHA Hovmöller diagram shows data from 2006 whereas the OFES-NCEP Hovmöller diagram shows data from 2005, CCSM3 POP from 1958, and the PMB and OFES-CLIM models are forced by repeating monthly climatological wind stresses that have no analogous date.

![Figure 4-3: 1-year-long Hovmöller diagrams of 20-day lowpass filtered \( \Phi(z) \) for RAPID-MOCHA (top), OFES-CLIM (middle), and OFES-NCEP (bottom). All diagrams show a full year (from January through December) but not necessarily the same year. OFES-NCEP shows data from 2005, RAPID-MOCHA shows data from 2006, and OFES-CLIM is forced by a monthly climatology that has no analogous date.](image-url)
Figure 4-4: Continuation of previous figure. Shown here are 20-day lowpass filtered 1-year-long Hovmöller diagrams of CCSM3 POP (top), POP 14b (middle), and PMB (bottom). As mentioned before, the model dates do not necessarily overlap. All diagrams show a full year (from January through December) but not necessarily the same year. CCSM3 POP data is from 1958; POP 14b is from 1999; and PMB data is forced by a forcing cycle with no real-time analogue.

The largest values seen in Figures 4-3 and 4-4 at each timestep are considered the strength of the MOC. A 4-year-long timeseries of these maximum values are shown in Figure 4-5 for each model and the RAPID-MOCHA observations. As before, yeardays for the models that don't overlap in time are matched against yeardays from the observations.

Except for PMB's mean strength, which is 6.6 Sv stronger than the observed MOC, the mean strengths of the models are within 3 Sv of observations. The variance (26.0 Sv²) of the RAPID-MOCHA observations is significantly higher than any of the models. The model with the next highest variance is the synoptically forced 0.1°-
resolution OFES-NCEP model (20.3 Sv²), followed by the 0.1°-resolution POP (13.7 Sv²) and 1.0°-resolution CCSM3 (10.2 Sv²), the other synoptically forced models. As expected, the two climatologically forced models (PMB and OFES-CLIM) have the smallest variance (6.3 Sv² and 8.4 Sv² respectively).

From Figure 4-5, it is obvious that the RAPID-MOCHA observations have an annual cycle, but the presence of annual variability is less clear in the models. Figure 4-6 presents a monthly climatology of MOC strength at 26.5°N for each of the datasets. The RAPID-MOCHA annual MOC signal has a peak-to-trough amplitude of 7.7 Sv with maxima tending to occur during the second half of the year (between July and January),
and minima tend to occur during February, March, and April. May and June are transitional months between the peaks and troughs. As in the observations, OFES-CLIM, OFES-NCEP, CCSM3, and POP all tend to have lower MOC strength in the first half of the year and higher strength in the second half of the year. However, their peak-to-trough amplitudes are all smaller. PMB annual signal is much weaker, and its orientation is opposite the observations and other models at best, such that it is higher in the spring and lower in the fall. A standard error analysis of the models and observations indicates that all datasets except for the PMB model have significant annual cycles.

![MOC Monthly Climatologies](image)

**Figure 4-6: Monthly climatologies of observations and models**

The variability associated with the annual signal was determined by interpolating the monthly climatology in Figure 4-6 to a daily timeseries and subtracting it from the original timeseries. The variances of the original timeseries were then compared to the
variances of each timeseries with the annual signal removed. Table 4-2 presents a summary of the total MOC variance, variance of the MOC's annual signal, and percentage of variance belonging to the annual signal. RAPID-MOCHA has the largest annual signal with annual variance of 7.5 Sv$^2$, followed by the two high-resolution, synoptically forced models. The annual signal is less pronounced in the rest of the models.

Table 4-2: Variance of the MOC strength: total variance, variance of the annual signal, and percentage of variance contained within the annual signal.

<table>
<thead>
<tr>
<th>Dataset</th>
<th>MOC Variance (Sv$^2$)</th>
<th>Variance of MOC's annual signal (Sv$^2$)</th>
<th>% Variance in annual signal</th>
</tr>
</thead>
<tbody>
<tr>
<td>RAPID-MOCHA</td>
<td>26.0</td>
<td>7.5</td>
<td>28.9</td>
</tr>
<tr>
<td>OFES-CLIM</td>
<td>8.4</td>
<td>1.6</td>
<td>19.6</td>
</tr>
<tr>
<td>OFES-NCEP</td>
<td>20.3</td>
<td>3.5</td>
<td>17.0</td>
</tr>
<tr>
<td>CCSM3</td>
<td>10.2</td>
<td>2.4</td>
<td>23.4</td>
</tr>
<tr>
<td>POP</td>
<td>13.7</td>
<td>6.9</td>
<td>50.6</td>
</tr>
<tr>
<td>PMB</td>
<td>6.3</td>
<td>1.0</td>
<td>15.4</td>
</tr>
</tbody>
</table>

4.3 Power Spectral Density Analysis of MOC at 26.5°N

A power spectral density analysis was performed on the full records of observations and models to compare the spectrum of energy present in each timeseries. Variance preserving spectra are presented in Figure 4-7. The spectra are based on Welch's periodogram method using a 730-day-wide Hamming window with a 365-day overlap between consecutive data segments. RAPID-MOCHA observations have higher energy
than all the models at time periods shorter than 25 days and longer than 140 days. The observed spectrum also has a maximum at 35 day periods which is absent from any of the models.

Figure 4-7: Variance preserving spectral analysis of MOC signal at 26.5°N. RAPID-MOCHA observations are compared to each of the models. The spectra are based on Welch’s periodogram method using a 730-day-wide Hamming window and 365 days overlap between consecutive data segments.

OFES-NCEP has more energy at all periods than the other models at periods less than 65 days, including a relative maximum at 45 day periods, a feature which is not present in observations or other models. POP 14b has a relative maximum at 73 days. As expected, the climatologically forced models (OFES-CLIM and PMB) both have significantly less power at submonthly periods than either observations or the synoptically forced models. For periods of 120 days, the models all converge to
approximately the same energy as observations, but observations have the highest energy at periods longer than 120 days, consistent with the annual signals presented in Figure 4-6.

![Ekman Transport at 26.5°N: Variance-preserving spectral comparison](image)

**Figure 4-8:** As in Figure 4-7, but for Ekman transport.

The 35-day peak in the observations is partly explained by a corresponding 35-day peak in observed Ekman variance. As seen in Figure 4-8, the observed 35-day maximum in Ekman transport is found only in the POP 14b model, and even then the peak has less than half of the power seen in the observations. It is possible that this 35-day peak is a feature particular to RAPID-MOCHA’s 2004-2008 period of observations, and will be investigated in future work.
Oddly, there is no peak in the observed MOC spectrum corresponding to the secondary peak in Ekman transport at periods of 45-60 days. Instead, there is a broad spectral peak at periods of 50-90 days that partially overlaps the secondary Ekman peak. These differences may partly reflect the large uncertainties in the spectral density estimates for relatively short records such as the observations (4 years) and POP 14b (3 years), where uncertainties in individual spectral estimates are approximately +/-50%. Conversely, the larger OFES-NCEP record (27 years) shows a closer correspondence between the shape of the MOC and Ekman transport spectral density functions, with a broad co-located peak at 40-60 days.

4.4 Bandpass Filtered Analysis

The PSD analysis technique shown in Figure 4-7 is one way to examine MOC energy at different periods. To condense these results, in this section the variance of the MOC signal is bandpass filtered into four period bands. As in the PSD analysis, the goal of this step is to identify the timescales responsible for MOC variance. In this case, a Butterworth filter is used to break the MOC signal's variance into four different period bands: 1-30 days (submonthly), 31-120 days (intraseasonal), 121-420 days (seasonal), and 421-2918 days (interannual).

This information is presented in Figure 4-9. From left to right, the five clusters of bar graphs represent unfiltered, submonthly, intraseasonal, seasonal, and interannual variance of the MOC strength. Variance in each dataset is represented by two like-colored bars. The first bar is variance as described the previous paragraph. The second
bar shows MOC variance at 26.5°N when direct Ekman forcing is removed, as will be discussed in detail in Chapter 5. Explained briefly, when direct Ekman forcing is removed from observations and models, the MOC variance that remains is the result of a combination of the ocean's internal dynamics (eddies) and the ocean's non-Ekman response to wind forcing (e.g., Rossby and Kelvin waves). The difference between the Ekman-included and Ekman-removed variance bars in Figure 4-9 is a measure of the wind's direct influence on the MOC through Ekman transport variability.

Also included in Figure 4-9 is data from Hirschi et al. (2007). In their study, a similar method was adopted to investigate the variability of the ¼° horizontal resolution Ocean Circulation and Climate Advanced Modelling Project (OCCAM) model. Forcing in the OCCAM model consists of 6-hourly NCEP-NCAR data, simulating the ocean circulation for the years 1985-2003. Hirschi et al. (2007) broke down MOC strength variability at four latitudes (10°N, 26°N, 36°N, and 45°N) into three period bands: 1-5 months, 5-23 months, and 23 months to the length of the OCCAM timeseries (18 years). Although Hirschi et al. (2007)'s filter bands do not match up exactly with those used in this study, their standard deviation values were included in the closest approximate category in Figure 4-9 (intraseasonal, seasonal, and interannual, respectively). It should be noted that Hirschi et al. (2007) provides no analogue for the submonthly timescale.

In the unfiltered (left-most) cluster, RAPID-MOCHA observations have the most variance (25.9 Sv²) of all timeseries. Removing the direct influence of Ekman from observations reduces its variance by 33% to 17.2 Sv². Among the models, OFES-NCEP has the highest unfiltered variance (18 Sv²). Without Ekman, its variance drops by 53%
to 8.5 Sv\(^2\), a sharp variance reduction similar to that seen in RAPID-MOCHA. Variance in POP 14b, the other high resolution, synoptically forced model, drops by 87%, the largest reduction in any of the datasets. The low-resolution, synoptically forced CCSM3 POP model only drops by 16%. OFES-CLIM only experiences a slight 20% drop in variance, from 8.7 Sv\(^2\) to 6.9 Sv\(^2\). PMB has the lowest unfiltered variance of all models, and removing Ekman from it seems to have little effect.

Figure 4-9: Variance of the bandpass-filtered MOC Strength at 26.5°N for RAPID-MOCHA observations and each of the models. From left to right, the bar graph clusters represent variance of bandpass filtered MOC strength: unfiltered, 1-30 days, 31-120 days, 121-420 days, and 421-2918 days, respectively. Each data source is represented by a pair of identically colored bars, the second of which shows the Ekman-removed variance. Also included in this figure are variances from the OCCAM model examined in Hirschi et al. (2007).
RAPID-MOCHA variance is higher in all period bands than model MOC variance. Among the models, the high-resolution, synoptically forced models (OFES-NCEP and POP 14b) tend to have the highest variance in each of the filtered period bands, and are most strongly affected by the removal of Ekman forcing. Although its variance is less than OFES-NCEP and POP 14b, the $\frac{1}{4}^\circ$ synoptically forced OCCAM model is also strongly affected by the removal of Ekman forcing. The low-resolution synoptically forced model (CCSM3 POP) and the high-resolution climatologically forced models (OFES-CLIM and PMB) have roughly the same amount of total variance, and are less affected by the removal of the direct influence of Ekman forcing.

Variance in the interannual period band is less than in any of the other three period bands, but calculation of interannual variance is only significant for the lengthy (8- and 27-year) OFES datasets. The rest of the models and RAPID-MOCHA are only ~4 years long, and variances calculated from them, though insightful, are not as robust.

4.5 Empirical Orthogonal Function (EOF) Analysis

An empirical orthogonal function (EOF) analysis was performed on the vertical streamfunction, $\Phi(z, t)$, of the RAPID-MOCHA dataset and all five of the models to determine the dominant modes of vertical MOC structure and variability. This analysis is often used in oceanography to conveniently reduce large space- and time-varying datasets into smaller series of spatial patterns, or EOFs. The analysis is performed by
diagonalizing the covariance matrix obtained by removing the temporal mean, and the result is $\Phi_i(z)$, a set of modes that explain fractions of temporal variance in the data (Borzelli & Ligi, 1999).

Modes of variability are ranked in order of their explained variance, but the EOFs can not provide any information on the physics that describe them. Although the uncovered patterns of variance can sometimes be attributed to well-known and better-understood phenomena, as in the case of EOFs of equatorial Pacific sea surface temperature that resemble El Nino, this is not always the case. And although the first EOF may be responsible for the most variability, important information can be contained within modes of either high or low statistical significance. For example, Kelly (1985) performed a temporal EOF analysis of Advanced Very High Resolution Radiometer (AVHRR) images of the Northern California coast. The study found that the first two modes explained a vast majority (80%) of the total variance and were associated with large scale sea surface temperature (SST) variability. However, the third mode, which was responsible for only 4% of the total variance, was associated with important features related to mesoscale SST variability.

Below are several figures representing EOFs of the observed and modeled MOCs, both with and without the influence of Ekman. The influence of Ekman transport is removed as will be discussed in Chapter 5.

Figure 4-10 shows the distribution of variance as a function of mode number. In all datasets, the first mode overwhelmingly explains the highest percentage of variance and is well-separated from all other modes. Each subsequent mode is responsible for a
much smaller percentage of the total variance. RAPID-MOCHA’s first mode explains approximately 88% of its variance, slightly less than that of CCSM3 but higher than any of the other four models. RAPID-MOCHA’s second mode explains about 9% of its variance, slightly larger than CCSM3’s second mode variance (7%) and equal to POP 14b and OFES-NCEP’s percentages. In contrast, the first mode of the climatologically forced PMB and OFES-NCEP models explains the least amount of variance (68% and 73%, respectively) among all first modes; their second modes explain more variance (~17%) than the other models and RAPID-MOCHA observations.

The distribution of variance changes slightly when the direct influence of Ekman transport is removed (Figure 4-11). The PMB curve changes most, its first mode variance dropping by ~10% and its second mode increasing by ~12%. The first mode variances of OFES-NCEP and POP 14b drop by ~8-12%, most of which is compensated for by increases in second mode variance. Variances in the first five modes of RAPID-MOCHA, CCSM3, and OFES-CLIM are relatively unaffected by the removal of direct wind forcing. Figures 4-10 and 4-11 are summarized in Table 4-3.

Figure 4-12 shows a timeseries of the principal components (PCs) of each of the datasets. These PCs contain the dimensional variance of \( \Phi(z) \), whereas the vertical modes, which are normalized to unit variance, contain the vertical structure of \( \Phi(z) \). When multiplied and summed together, the PCs and vertical modes yield the original MOC timeseries. Figure 4-12 is a bit messy, but it is apparent that the first mode of RAPID-MOCHA observations and OFES-NCEP carry more total variance than any of the models.
Figure 4-10: Percentage of variance explained by modes #1-5 of observations and models (with the direct influence of Ekman transport included).

Table 4-3: Summary of MOC’s percent variance explained by modes 1, 2, and 3. Modes 4 and 5 contribute much less variance than the first three modes and are not shown here.

<table>
<thead>
<tr>
<th>Dataset</th>
<th>Percent Variance: 1st Mode</th>
<th>Percent Variance: 2nd Mode</th>
<th>Percent Variance: 3rd Mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>RAPID-MOCHA</td>
<td>87.9</td>
<td>9.2</td>
<td>2.3</td>
</tr>
<tr>
<td>OFES-CLIM</td>
<td>73.4</td>
<td>16.4</td>
<td>5.9</td>
</tr>
<tr>
<td>OFES-NCEP</td>
<td>83.3</td>
<td>10.1</td>
<td>4.1</td>
</tr>
<tr>
<td>CCSM3</td>
<td>90.1</td>
<td>6.4</td>
<td>1.4</td>
</tr>
<tr>
<td>POP</td>
<td>82.5</td>
<td>8.7</td>
<td>5.3</td>
</tr>
<tr>
<td>PMB</td>
<td>68.1</td>
<td>17.5</td>
<td>10</td>
</tr>
</tbody>
</table>
Figure 4-11: As in Figure 4-9 but with the direct influence of Ekman transport removed.

Table 4-4: As in Table 4-3, but without Ekman.

<table>
<thead>
<tr>
<th>Dataset</th>
<th>Percent Variance: 1st Mode</th>
<th>Percent Variance: 2nd Mode</th>
<th>Percent Variance: 3rd Mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>RAPID-MOCHA</td>
<td>84.9</td>
<td>12.3</td>
<td>1.9</td>
</tr>
<tr>
<td>OFES-CLIM</td>
<td>68.1</td>
<td>20</td>
<td>7.2</td>
</tr>
<tr>
<td>OFES-NCEP</td>
<td>74.3</td>
<td>15.5</td>
<td>4.6</td>
</tr>
<tr>
<td>CCSM3</td>
<td>90.4</td>
<td>6.8</td>
<td>1.7</td>
</tr>
<tr>
<td>POP</td>
<td>69.1</td>
<td>18.5</td>
<td>5.6</td>
</tr>
<tr>
<td>PMB</td>
<td>55.8</td>
<td>31.3</td>
<td>8.3</td>
</tr>
</tbody>
</table>
This perception is confirmed by the variance-preserving power spectral density analysis in Figure 4-13. OFES-NCEP's first mode variance is generally greater than any of the models, and RAPID-MOCHA's first mode variance is comparable to the models except at 35-day periods and for periods longer than 150 days. In general, the spectral density functions in Figure 4-13 are similar in appearance to their counterparts in Figure 4-7, which is to be expected since the first modes account for a large fraction of the total MOC variation.
When Ekman forcing is removed, variability in all of the first modes is greatly reduced. RAPID-MOCHA’s variance by approximately 50% throughout the spectrum, and OFES-NCEP’s first mode no longer stands out from the rest of the models (Figure 4-14). A PSD analysis of the Ekman-removed first mode timeseries shows that the first mode power is reduced in all periods for the observations and all models except CCSM3, which remains unaffected (Figure 4-15). The peak in observations at 35-day periods is still present, but at approximately half the amplitude of the Ekman-included first mode timeseries. The fact that it persists even though the ocean's Ekman response to wind forcing has been removed indicates that the ocean continues to respond to the wind via forced geostrophic motions such as Rossby or Kelvin waves.
Figure 4-14: Timeseries of first principal components for observations and models (without direct Ekman transport).

Figure 4-15: Variance-preserving power spectral density analysis of the first principal component (without direct Ekman transport).
Figure 4-16 shows normalized vertical transport profiles of the first mode. These profiles represent the structure of the dominant mode of variability for each dataset. The RAPID-MOCHA, OFES-CLIM, OFES-NCEP, and POP 14b profiles appear to represent the vertical structure of a surface intensified, first baroclinic mode. Their first mode vertical profiles reflect northward transport above ~1100m and southward transport below ~1100m. The two high-resolution, synoptically forced models (OFES-NCEP and POP 14b) follow approximately the same structure. RAPID-MOCHA and OFES-CLIM have similar first mode transport profiles, but their southward transport at depth is stronger. The CCSM3 POP model’s first-mode vertical transport structure appears to represent a strong northward Ekman layer close to the surface on top of a weakly southward quasi-barotropic profile. The PMB model’s first mode vertical structure is unique and seems to indicate the presence of physics not found in any of the other models. For this reason, further analysis of the PMB model will not be discussed here.

Figure 4-17 shows the normalized first mode vertical transport profiles for the Ekman-removed case. When the influence of Ekman forcing is removed, there is little difference in OFES-CLIM. However, without Ekman forcing, the first mode vertical transport profiles of OFES-NCEP and POP 14b (the two synoptically forced, high resolution models) and RAPID-MOCHA all begin to look more like the OFES-CLIM profile. All of these now have vertical structures that are strongly reminiscent of a first baroclinic mode structure, with zero crossings between about 1200-1800m. CCSM3 POP’s first mode transport profile, on the other hand, appears unaffected by the absence of Ekman forcing.
Figure 4-16: Vertical transport profiles of the first principal component of observations and models (with Ekman).

Figure 4-17: Vertical profiles of the first principal component of observations and models (without Ekman).
Chapter 5: Attribution of MOC Variability

5.1 MOC Variability Due to Ekman Transport

In this study, the elimination of high frequency energy associated with Ekman transport is used as an important analytical tool. In order to explore the role that wind forcing has on the MOC, the ocean's direct response to Ekman forcing was removed from the RAPID MOCHA observations and each of the models. When the ocean's response to Ekman forcing is removed, all remaining variability must be attributed to either 1) forced geostrophic motions, such as Rossby or Kelvin waves, or 2) internal ocean variability, such as mesoscale eddies. This analysis is based on the assumption that Ekman Transport fluctuations are balanced quasi-instantaneously by a uniform, depth-independent, compensatory velocity anomaly as shown by Jayne & Marotzke (2001).

Ekman transport anomalies are calculated in the following steps. First, the wind stress at each grid point is calculated from the specific wind forcing field associated with each model via the following equation (from Josey et al. 2002):

$$\tau_x = \rho \cdot C_d \cdot u \cdot \sqrt{(u^2 + v^2)}$$  \hspace{1cm} (Equation 5-1)

where $\tau_x$ is the zonal component of the sea surface wind stress; $\rho$ is the density of air; $u$ and $v$ are the zonal and meridional components of the wind speed, respectively; and $C_d$ is the 10-m neutral drag coefficient relationship of Smith (1980) given by

$$10^3 \cdot C_{D10n} = 0.61 + 0.063u_{10n}$$  \hspace{1cm} (Equation 5-2)
Then, the Ekman Transport is calculated (Equation 1-1) and decomposed into its mean and perturbation quantities by

\[
T_{ekman}(y,t) = -\int \left[ \tau_x(x,y,t)/\rho f \right] dx
\]

(Equation 5-3)

and

\[
T_{ekman}(y,t) = T'(y,t) + \bar{T}(y,t)
\]

(Equation 5-4)

where \( T_{ekman}(y,t) \) is the Ekman Transport as a function of time; \( T'(y,t) \) is the Ekman Transport anomaly; \( \bar{T}(y) \) is the mean Ekman Transport; \( \rho \) is the density of seawater, and \( f \) is the Coriolis parameter. The barotropic compensatory transport anomaly \( E'(y,z,t) \) is then calculated using the calculated value for \( T'(y,t) \) in the equation

\[
E'(y,z,t) = \frac{T'(y,t) \ast L(y,z)}{\int [L(y,z)] dz}
\]

(Equation 5-5)

where \( L(y,z) \) is the total width of the ocean at each depth. Each Ekman anomaly is distributed over the top 100m of the water column (the approximate depth of the Ekman layer). Next, both the Ekman anomalies and depth-independent compensatory anomalies are then removed from \( V(y,z,t) \), the zonally integrated transport-per-unit-depth profile. Finally \( V(y,z,t) \) is vertically integrated to produce an Ekman-removed vertical streamfunction

\[
\phi_{(no\ Ekman)}(y,z,t) = \int [V(y,z,t) - E'(y,z,t) + T'(y,z,t)] dz
\]

(Equation 5-6)

the maximum value of which at each timestep is the MOC strength timeseries

\[
MOC\ Strength_{(no\ Ekman)}(y,t) = \max[\phi_{(no\ Ekman)}]
\]

(Equation 5-7)

As seen in Figure 5-1, and compared to Figure 4-6, removing the direct influence of Ekman transport generally acts to reduce the energy at all periods. Although energy in RAPID-MOCHA is cut nearly in half at all periods, the maximum at 35 days is still
present. The fact that it persists even though the ocean's direct response to Ekman forcing has been removed indicates that the ocean continues to respond to the wind via forced geostrophic motions such as Rossby or Kelvin waves.

Large reductions in energy are also seen in OFES-NCEP, but energy in POP 14b, the other high resolution synoptically forced model, seems unaffected by the removal of the ocean's Ekman response. Except for a very slight reduction in variance, the Ekman-removed CCSM3 POP, OFES-CLIM, and PMB models are virtually identical to their Ekman-included counterparts.

Figure 5-1: As in Figure 4-6, but without the direct influence of Ekman
5.2 Evaluating the Influence of Ekman Transport in OFES

In Section 4.5 each of the timeseries at 26.5°N were bandpass filtered, and in Section 5.1 the influence of Ekman transport at 26.5°N was removed. In this section, both of these tools are applied to the OFES-NCEP and OFES-CLIM models for latitudes between 15°N and 40°N. The OFES models were selected over the other models for this analysis because their MOC characteristics are most similar to RAPID-MOCHA’s characteristics.

5.2.1 OFES Total Variance as a Function of Latitude and Period Band

Figures 5-2 through 5-8 present a series of bar graphs that summarize the OFES model variances at each latitude and period band. In these figures, as in Figure 4-7, the leftmost cluster of bar graphs shows the variance at each latitude for the unfiltered timeseries, and the four remaining bar graph clusters represent the variance for the other period bands.

Figures 5-2 and 5-3 represent the total variance of the OFES-CLIM and OFES-NCEP models respectively. One of the most striking features of these bar graphs is the consistent pattern of variance from latitude to latitude that is apparent in both models. In OFES-CLIM, a plateau of lower variance exists from 16°N-23°N, increases to a variance maximum at 34°N-36°N, then drops off to the north. In OFES-NCEP the pattern is nearly identical, except for the addition of a local maximum at 22°N and a local minimum at 27°N. As expected because of its climatological forcing, variance in OFES-CLIM is
significantly less than in OFES-NCEP for the unfiltered and submonthly period bands at all latitudes. Although there is less difference between the models in the intraseasonal, seasonal, and interannual period bands, OFES-NCEP's variance is still slightly higher in those period bands.

When the direct influence of Ekman forcing is removed from the OFES models, as described in Section 5.1, all that remains is “geostrophic” MOC variability. When this geostrophic MOC variability is subtracted from the total MOC, what remains is related only to direct Ekman forcing. Bar graphs of OFES-CLIM's Ekman and geostrophic variance are presented in Figures 5-4 and 5-5 respectively, as a function of latitude and period band. Similar bar graphs of OFES-NCEP's Ekman and geostrophic variance are shown in Figures 5-6 and 5-7, respectively.

Figure 5-4 shows that virtually all Ekman variance in OFES-CLIM is the result of variance in the seasonal period band. No Ekman variance is present in the submonthly, intraseasonal, or interannual bands. This is as expected, as this model is forced by a repeating monthly climatology.

Unlike OFES-CLIM's variance breakdown, OFES-NCEP's total variance appears to be divided evenly between Ekman variance (Figure 5-6) and geostrophic variance (Figure 5-7) and evenly among the submonthly, intraseasonal, and seasonal period bands. Less variance exists in the interannual period band, but it is still divided approximately evenly between Ekman and geostrophic variance.
Figure 5-2: OFES-CLIM model variance as a function of latitude and bandpass filtered period band.

Figure 5-3: OFES-NCEP model variance as a function of latitude and bandpass filtered period band.
Figure 5-4: OFES-CLIM Ekman variance as a function of latitude and bandpass filtered period band.

Figure 5-5: OFES-CLIM geostrophic variance as a function of latitude and bandpass filtered period band.
Figure 5-6: OFES-NCEP Ekman variance as a function of latitude and bandpass filtered period band.

Figure 5-7: OFES-NCEP geostrophic variance as a function of latitude and bandpass filtered period band.
OFES-NCEP's Ekman variance is strongest (unsurprisingly, because of its synoptic forcing) in the submonthly period. However, Ekman variance in the other period bands is only slightly weaker. Although Ekman variance in OFES-NCEP's interannual period is the weakest of all, it is still greater than OFES-CLIM's interannual Ekman variance, which is unsurprising as OFES-CLIM has no interannual Ekman forcing.

5.2.2 Attribution of Geostrophic Variance

As mentioned in Section 1.3.4, the RAPID-MOCHA mooring array estimates the interior ocean transport by measuring density profiles at the eastern and western boundaries of the North Atlantic Ocean. As such, eddy-induced fluctuations in the density profiles at the eastern and western boundaries will result in changes in the basin-wide geostrophic shear, and cause short-term variations in the AMOC strength. It was proposed in Wunsch (2008) that variability associated with eddy activity along the boundaries in the North Atlantic was large enough to obscure any possible climate change-related trends in the AMOC. However, it has since been shown by Kanzow et al. (2009) that although eddies do contribute to AMOC variability, their amplitude is greatly reduced at the boundaries. It was found that as eddies and Rossby waves impinge on the western boundary, they excite fast, equatorward boundary waves that propagate pressure anomalies along the boundary, and that these pressure anomalies are significantly weaker than the open-ocean eddy variability.
For the purposes of this study, ocean dynamics are assumed to behave linearly, meaning that energy is not transferred from one period band to another. For example, Ekman forcing in OFES-CLIM exists only in the seasonal period band. This means that the non-Ekman forced response would also be contained entirely within the seasonal period band. Figure 5-5 shows that geostrophic variance exists in all four filtered period bands for OFES-CLIM; however, variance in the submonthly, intraseasonal, and interannual bands should not be the result of the non-Ekman forced geostrophic motions such as Rossby or Kelvin waves, rather it should result from instabilities in the model's internal dynamics, or eddies. In the seasonal period band, both forced geostrophic motions and unforced internal variability (eddies) should be present. For this reason, the two sources of variance can not be distinguished from each other in this band.

Because OFES-CLIM and OFES-NCEP are identically formulated, one can make a second assumption: the internal dynamics between the two models are essentially identical, and any variability resulting from spontaneous internal modes is the same in both models. Combined with the linear ocean assumption mentioned above, Figure 5-5 can now be viewed as a measure of the eddy variance present in both OFES models (except in the seasonal period band, as discussed above). Comparing Figure 5-5 with Figure 5-7, it can be seen that in the submonthly band the internal “eddy” variance in Figure 5-5 accounts for only a small part of the total geostrophic variance in Figure 5-7, whereas in the intraseasonal band the internal variability accounts for most of the
geostrophic variance. This suggests that geostrophic AMOC variance in the intraseasonal period band is dominated by eddy activity, and variance in the submonthly period band is dominated by forced geostrophic motions such as Rossby and Kelvin waves.

Eddy variance is present in the submonthly and interannual bands, although it is most prominent in the intraseasonal period band (no attempt will be made to describe seasonal eddy variance). In the submonthly period band, eddy variance tends to have lower values (0-1 Sv²) in the south (15°N-29°N) and higher values in the north (30°N-40°N) of the study area, with a relative maximum occurring around 35°N. The intraseasonal period band has the most eddy variance, averaging 2.5 Sv² in the south and reaching a maximum of 8 Sv² at 36°N. Interannual eddy variance is small and varying between 1 and 2 Sv² throughout the study region. It is not surprising that the location of greatest eddy variance in the OFES models occurs around 37°N. This latitude is coincident with the location of the Gulf Stream extension and the North Atlantic's highest eddy kinetic energy values (Richardson, 1983).

In the OFES-NCEP model, direct Ekman forcing is roughly equal in the submonthly, intraseasonal, and seasonal period bands (Figure 5-6), and for this reason the ocean's forced geostrophic motions are also evenly distributed over these periods (Figure 5-7). Compared to its climatologically forced counterpart, OFES-NCEP has much more Ekman variance in the submonthly and intraseasonal period bands, and one would expect this difference to be reflected in their geostrophic variances. OFES-NCEP's submonthly
geostrophic variance is certainly higher than in OFES-CLIM, but despite the large difference in intraseasonal Ekman variance, there is hardly any difference in the intraseasonal geostrophic variance between the two models.
Chapter 6: Representativeness of the RAPID-MOCHA Dataset

As discussed in the introduction to Chapter 4, this chapter investigates the extent to which four years of data, such as the RAPID-MOCHA dataset, are able to represent the characteristics of longer timeseries. Because the OFES-NCEP dataset compares reasonably well to the RAPID-MOCHA timeseries, and because its dataset is of sufficient length (27 years long), it will be the subject of a Monte Carlo-style evaluation to determine its representativeness.

6.1 Monte Carlo-Style Evaluation

“Monte Carlo-style evaluation” refers to a statistical analysis method wherein random subsamples are repeatedly extracted from a timeseries, analyzed, and then compared to properties of the full dataset (the “truth”). In this particular case, random four-year subsamples are selected from the 27-year OFES-NCEP timeseries. The MOC variance and mean of each subsample is then compared to the MOC variance and mean of the full 27-year OFES-NCEP timeseries (the “true variance” and the “true mean”). The results of this comparison are indicative of how well the subsampled data represents the truth.
Four-year subsamples are created by randomly selecting and aggregating four one-year-long segments from the 27-year OFES-NCEP timeseries into four-year-long segments for latitudes from 15°N to 40°N. Years begin with the first day of January, and each year can be selected only once (no repetition). Four years randomly sampled from a 27-year timeseries (without repetition, irrespective of order) can be combined in 17,550 unique ways. The means and variances of these 17,550 randomly selected four-year combinations are then calculated and compared to the true variance and mean.

A histogram of the differences between the subsamples and the truth at 26.5°N is presented in Figure 6-1. The histogram of differences between subsampled means and the true mean is shown in blue, and that of differences in variance is shown in red. The blue histogram is normally distributed about the origin, indicating that means calculated from the four-year subsamples are very representative of the true mean. The red histogram, however, exhibits a positive bias. Because the differences were calculated by subtracting subsampled variances from the true variances, a positive bias means that true variance is larger than subsampled variance.

In addition to aggregations of four randomly selected individual years, these calculations were repeated for consecutive four-year subsamples of OFES-NCEP data. In this case, there are only 24 possible consecutive four-year subsamples (allowing for overlap) and seven possible consecutive four-year subsamples (if overlapping years are not permitted) the sample size is much smaller than 17,550. For the 24 consecutive overlapping cases, the results obtained were similar to the four-year aggregations of randomly selected individual years (Figure 6-2).
Figure 6-1: Histogram of the differences between the “true” means and variances (27-year values) and the means and variances from each of the 17,550 randomly selected 4-year subsamples.

Figure 6-2: Histogram of the differences between the “true” means and variances (27-year values) and the means and variances from each of the 24 possible consecutive 4-year subsamples.
That a positive bias exists in the difference in variances is an expected result. A 27-year timeseries will contain variance at periods longer than four years, whereas aggregations of four randomly selected individual years will not. The bias is simply indicative of variance that exists in the truth at time periods not resolved by a four year subsample.

When all 17,550 subsampled mean and variance biases are averaged at each latitude in the study region (Figure 6-3), it is apparent that the biases seen in Figure 6-1 are representative of a region-wide trend. When averaged over all latitudes in the study region (the average of the blue line in Figure 6-3), the bias of differences in mean is virtually zero \( O(10^{-4}) \). Even though the bias in variances tends to be larger north of 34°N, the bias of variance averaged over all latitudes (average of the red line in Figure 6-3) is 0.32 Sv².

But what are the possible sources of this 0.32 Sv² variance in periods longer than four years? Thanks to the availability of direct measurements of the FC and Ekman transport, the variance of two of the MOC's components can be calculated.

In Meinen et al. (2010), a near-continuous 16-year FC transport timeseries at 27°N was band pass filtered using a method similar to the one described in Section 4.4. The period bands used in Meinen et al. (2010) are one month to 11 months, 11 to 13 months (annual), 13 to 42 months (interannual), and longer than 42 months. FC variance at periods longer than 42 months was calculated to be 0.8 Sv², or roughly 8% of the FC's total variance.
Figure 6-3: Average biases of differences and variances between the truth and 4-year subsamples.

Ekman transport variance was calculated with the same 27 year timeseries of NCEP-NCAR synoptic forcing as used by the OFES-NCEP model. As seen in Figure 6-4, for periods longer than four years, Ekman transport variance ranges from 0.1 Sv$^2$ at 25°N to 0.73 Sv$^2$ at 35°N with an average value of 0.34 Sv$^2$.

Assuming that the difference between variances at periods longer than 42 months (as used in Meinen et al. (2010)) and variance at periods longer than four years is very small, it appears that the FC and Ekman transport are each partly responsible for the variance bias at 27°N seen in Figure 6-1.
Figure 6-4: Ekman transport variance in the study region as a function of latitude.

Figure 6-5: Root mean square (RMS) of the differences between the "truth" (27-year timeseries values) and the result of 17,550 randomly selected 4-year chunks. RMS differences between means are shown in blue, and RMS differences between variances are shown in green.
In Figure 6-5, the RMS of the 17,550 differences between the truth and each subsample is calculated and presented as a function of latitude (note the difference in the scale of the abscissae). The RMS of the difference in means and difference in variances follow similar trajectories as a function of latitude: there are maxima near 25°N and 35°N, and minima near 18°N, 29°N, and 38°N. It is not obvious what causes the elevated RMS values between 23°N and 26°N, but the western boundary current passes through the Gulf of Mexico as the Loop Current at these latitudes before flowing northward into the Straits of Florida as the Gulf Stream. It is possible that this region of elevated variance is associated with the Loop Current system’s signature and its eventual transition into the Straits of Florida. In general, both curves in Figure 6-5 indicate that the southern half of the study region has lower RMS values than the northern half. This seems to indicate one of two things. Either

1. four year subsamples do a better job of predicting the truth at low latitudes, meaning there is less variance at periods longer than four years at low latitudes, or

2. there is less total variance at lower latitudes.

But which of these two potential answers is right?

As is seen in Figure 6-4, four-year low pass filtered Ekman transport variance in the southern half of the study region is less than in the northern half. On average, variance in the northern half of the study region is greater than variance in the southern half by 0.3 Sv². This supports the idea that there is less variance at periods longer than four years in the southern half of the study region.
On the other hand, Figure 6-6 shows both the true variance and the RMS of the difference in variances as a function of latitude. Both curves have lower variances in the southern half of the study area, supporting the idea that there is less total variance at lower latitudes.

Based on these findings, it appears that both proposed explanations are partly responsible for the lower RMS variance differences in the southern half of the study area seen in Figure 6-3.

**Figure 6-6: True MOC variance (in blue), and the RMS of the differences between the true variance and the variance of all of the 17,550 randomly selected 4-year chunks (in green).**
6.2 Representativeness of a 4-year Timeseries

6.2.1 Representativeness of Mean and Variance

Because the difference in means (Figure 6-3, blue line) shows no bias, the RMS of the differences in means at 26.5°N (Figure 6-5, blue line) is essentially a measurement of its standard deviation, the 67% confidence level, $\sigma$. Averaged over the study region, $\sigma = 0.57$ Sv. This means that the averages of randomly selected four-year subsamples will fall within 0.57 Sv of the true mean 67% of the time. At the 2$\sigma$ (95%) confidence level, randomly subsampled four-year means will fall within 1.14 Sv of the true mean 95% of the time. In Kanzow et al. (submitted), the RAPID-MOCHA timeseries was found to have a standard (1$\sigma$) error of 0.8 Sv, which is 0.23 Sv larger than OFES-NCEP’s 1$\sigma$ error of 0.57 Sv. This is expected, because the standard deviation of the observations is 0.9 Sv more than OFES-NCEP’s standard deviation (see Table 4-1). This suggests that with respect to the long term mean, the error estimate of random four-year OFES-NCEP subsamples is comparable to the observational error estimate, considering the model’s slightly lower variance.

6.2.2 Representativeness of Trends

The four-year RAPID-MOCHA timeseries is the longest continuous dataset of the North Atlantic MOC, but because of the magnitude of its variability, four years of data is not enough for scientists to uncover significant trends. To demonstrate this point, take for
example the 27-year OFES-NCEP timeseries. When calculated in a least squares sense, it has a trend of 0.09 Sv/decade with a 95% confidence interval of 0.11 Sv indicating that this trend is not statistically different from zero. When the 27-year trend is removed, and the detrended timeseries is subsampled as in Section 6.1, the magnitude of trends calculated from random and sequential four-year subsamples are almost always higher than the true trend of 0.09 Sv/decade. In fact, as illustrated in Figure 6-7 for the case of random subsamples, the magnitudes of 4-year-long subsampled trends are greater than the 4-year RAPID-MOCHA trend (1.18 Sv/decade) more than 85% of the time. This means that the observed trend is not qualitatively different from trends produced by error associated with random sampling. Similar results were found when trends were calculated from sequential four-year subsamples taken from the detrended OFES-CLIM timeseries.

A four-year timeseries may be too short to detect a 1 Sv/decade trend, but increasing the length of the timeseries by a few years tends to greatly reduce the uncertainty of a trend. Another Monte Carlo-style evaluation was performed on the OFES-NCEP timeseries. In this evaluation 26 continuous 15-year segments (with a 14-year overlap) of the full OFES-NCEP dataset were used. Trends were initially calculated from only the first year of data in each 15-year segment. Subsequent years were then added one-by-one, and trends were calculated each time a year was added until trends were calculated from the full 15-year timeseries.
Figure 6-8 and Figure 6-9 show the trends and 95% confidence intervals respectively, as a function of segment length. One-year trends have magnitudes as large as 60 Sv/decade, but as more years are included in the calculation, the trend limits and confidence intervals begin to decay exponentially. For four-year-long segments, trends range from 0-5 Sv/decade, with a 95% confidence interval of 13 Sv/decade, indicating that trends calculated from the four-year RAPID-MOCHA dataset are essentially meaningless. For 11-to-15-year-long timeseries, the magnitude of the trends is steady, ranging from 0-2.5 Sv/decade. The 95% confidence interval is also steady for 11-15-year-long datasets with a value of ~2 Sv/decade. This suggests that as the RAPID-MOCHA dataset becomes longer than 11 years, the addition of new observations will not act to significantly reduce uncertainty in the MOC strength trend.

Figure 6-7: Histogram of the magnitude of trends calculated from Monte Carlo analysis of randomly selected four year subsamples taken from the detrended OFES-NCEP timeseries.
Figure 6-8: Monte Carlo-style evaluation of OFES-NCEP trends, as a function of dataset length.

Figure 6-9: Confidence levels for trends calculated from OFES-NCEP as a function of dataset length.
Chapter 7: Meridional Structure & Coherence of AMOC

During the course of this study, the ability of several models to accurately represent the observed MOC was investigated. Because the OFES-CLIM and OFES-NCEP models present a solid opportunity for intercomparison based on identically formulated models (differing only in their forcing scheme), this chapter will focus on data from the OFES-based models. In this way, differences in the MOCs produced by these two models can be more directly linked to differences in their forcing.

In this chapter, the meridional structure and coherence of the MOC are investigated in the OFES-CLIM and OFES-NCEP models. Little is known about the MOC’s connection between latitudes. Aside from the RAPID-MOCHA data, there are no other comprehensive timeseries observations of the MOC in the Atlantic against which to compare model data. In situations like this, models are often used to fill in the data gaps. For example, during the planning stages of the RAPID-MOCHA array, scientists used the OCCAM and FLAME models to evaluate the proposed mooring array’s ability to observe the North Atlantic MOC (Hirschi et al., 2003). Likewise, scientists planning to deploy an observing system for the South Atlantic MOC (analogous to the RAPID-MOCHA array) have used numerical models to provide insight on the most appropriate latitude for the system (Baehr et al., 2009; Perez et al., submitted).
7.1 Meridional AMOC Structure

The OFES models are run at 0.1-degree horizontal resolution with a meridional range from 75°S to 75°N. This study examines output from both OFES models at every tenth meridional gridpoint (~0.1°) between 15°N and 40°N, and at 26.5°N, in the North Atlantic Ocean. The time mean vertical streamfunctions of the OFES models are visualized as latitude-depth contour maps in Figures 7-1 and 7-2. The OFES-CLIM and OFES-NCEP models have similar long-term mean MOC structures. In both models, maximum MOC values occur at approximately 33°N and a depth of 1000m.

By subtracting the long-term OFES-NCEP mean from the long-term OFES-CLIM mean and plotting the result on a separate contour map, the initial impression that differences between the two models are fairly small is confirmed. The biggest difference between models exists at 40°N, where OFES-CLIM is 3-4 Sv stronger than OFES-NCEP. It is an intriguing question why the AMOC strength in this region should be smaller in a synoptically forced experiment, but this question is beyond the scope of the present work. Instead, we focus on the meridional coherence scale of the AMOC fluctuations and the factors controlling this coherence scale.
Figure 7-1: OFES-CLIM 8-year mean vertical streamfunction, as a function of depth and latitude.

Figure 7-2: OFES-NCEP 27-year mean vertical streamfunction, as a function of depth and latitude.
7.2 Meridional Coherence of the AMOC

7.2.1 Calculation of Meridional Coherence of AMOC

Here, the meridional coherence of the MOC variability in both OFES models is investigated to determine the distance over which changes in the MOC at one latitude are “felt” by MOC variability at surrounding latitudes. The integral time scale method described in Emery and Thompson (2001) is here adapted to determine the characteristic length scale beyond which the MOC is no longer correlated. First, correlation coefficients \( C(\tau) \) are calculated between the MOC timeseries at one latitude and the MOC timeseries at all other latitudes. The integral length scale is then calculated by integrating \( C(\tau) \) for all distance lags \( \tau \) and taking its maximum value:
\[ L = \int C(\tau) d\tau \]  
(Equation 7-1)

\[ MDLS = \max(L) \]  
(Equation 7-2)

where \( L \) is the integral length scale, and the maximum value of \( L \) is considered the meridional decorrelation length scale (MDLS) in units of degrees of latitude.

This method is applied to the unfiltered and bandpass filtered MOC timeseries, both with and without the influence of Ekman forcing. Figure 7-4 shows selected \( C(\tau) \) correlation functions calculated from the Ekman-removed OFES-NCEP model. Each line represents the correlation coefficient (y-axis) between the MOC at a specified latitude and the MOC at a certain distance away (x-axis). It can be seen in Figure 7-4 that there are two distinct regimes of the \( C(\tau) \) curves for distances between 0-10 degrees. The \( C(\tau) \)
curves with higher correlation values between 0-10 degrees were calculated from MOC strength timeseries in the southern half of the study region. The $C(\tau)$ curves with lower correlation values between 0-10 degrees were calculated from MOC strength timeseries in the northern part of the study region, which is known to be the location of intense eddy activity corresponding to the location of the Gulf Stream’s separation from the coast.

![Graph](image)

**Figure 7-5**: OFES: Decorrelation distance (in units of degrees of latitude) as a function of latitude. At 26.5N, the MOC signals are correlated over a meridional distance of 6-7 degrees of latitude.

Integration of the correlation functions in Figure 7-4 produces the decorrelation length scales shown in Figure 7-5 for unfiltered OFES-CLIM and OFES-NCEP, with and without Ekman. South of 21°N, the removal of the ocean's direct response to Ekman forcing from OFES-CLIM tends to increase the decorrelation length scale by 1-4°. North
of 32°N, removal of the ocean's direct response to Ekman forcing results in a decrease of 1-2°. Between 21°N and 32°N, the MOC decorrelation length scale is virtually unaffected by the removal of the direct Ekman response.

The bandpass filtered decorrelation length scale for OFES-CLIM and its Ekman-removed counterpart are presented in Figure 7-6 and Figure 7-7, respectively. In general, the decorrelation scale is largest for the seasonal band, and tends to be smaller in the other bands, especially the submonthly band. In the seasonal period band south of 25°N, the Ekman-removed OFES-CLIM decorrelation length scale is longer than the Ekman-included scale. From 25°N to 33°N, there is very little difference between the two curves, and north of 33°N, the Ekman-removed decorrelation length scale is 1-3° shorter than the Ekman-included scale.

Unlike OFES-CLIM, OFES-NCEP has Ekman variability at all period bands. For the Ekman-included case, the decorrelation scale is nearly independent of latitude in the submonthly, intraseasonal, and seasonal period bands, with an average decorrelation length between 6° and 8°. The interannual period band appears to exhibit some meridional dependence, with meridional decorrelation length scales extending as far as 14° south of 20°N, but it has less variability than all other periods. Without Ekman, the meridional decorrelation scales of the submonthly and intraseasonal period bands are uniformly shorter than the Ekman-included cases by 1-2°. The meridional decorrelation scale of OFES-NCEP's seasonal period band behaves very similarly to OFES-CLIM's seasonal period band. It tends to lengthen by as much as 4° (compared to OFES-CLIM's increase of as much as 8°) south of 25°N when Ekman forcing is removed.
Based on the meridional decorrelation analysis of both OFES models, it appears that including the influence of Ekman forcing in the submonthly and intraseasonal period bands causes the meridional decorrelation length scale to increase slightly (by 1-2°) for all latitudes in the study region. On the other hand, the inclusion of Ekman forcing in the seasonal period band acts to reduce the meridional decorrelation length scale significantly (by as much as 4-8°), but only for latitudes south of 25°N. The importance of Ekman forcing in the interannual period band is limited as a result of the small amount of energy it contains in both models.

Figure 7-6: OFES-CLIM decorrelation diagram.
Figure 7-7: Ekman-removed OFES-CLIM decorrelation diagram.

Figure 7-8: OFES-NCEP decorrelation diagram.
7.2.2 Meridional Coherence of Ekman Transport

This section investigates whether or not the MOC's meridional coherence is affected by wind forcing. Because the meridional coherence of Ekman transport is directly proportional to the zonal wind stress, Ekman transport is used here as a proxy for the wind's meridional coherence, and is calculated as described in the previous section. The meridional coherence of the wind is compared to the MOC's meridional coherence, with and without Ekman as seen in Figure 7-5, in Figure 7-10 and Figure 7-11 for OFES-CLIM and OFES-NCEP respectively. Because OFES-CLIM is only affected by wind forcing in the seasonal period band, only the meridional decorrelation length scale of the seasonal Ekman transport is presented in Figure 7-10. OFES-NCEP's Ekman forcing is
divided evenly among the submonthly, intraseasonal, and seasonal period bands, so the unfiltered Ekman transport is presented in Figure 7-11. The green curve in both figures represents the ratio of Ekman variance to geostrophic variance, and is calculated from the variances described in Figures 5-4 through 5-7. For ratio values greater than one, Ekman variance dominates; for values less than one, geostrophic variance dominates.

OFES-CLIM's Ekman transport coherence curve (dashed line, black triangles, Figure 7-10) tends to be lowest in the middle of the study region and highest at the northern and southern limits of the region. This curve is roughly mirrored in shape by the Ekman/geostrophic variance ratio. Geostrophic variance is more important than Ekman variance at all latitudes in the study region for OFES-CLIM. However, the region of Ekman variance's greatest relative importance (north of 32°N) is coincident with the region of OFES-CLIM's largest Ekman transport coherence. For this reason, when Ekman is included (solid blue line), OFES-CLIM's MOC is coherent over a longer distance than when Ekman is removed (dashed blue line). South of 20°N in the study region, the opposite is true. The importance of Ekman variance increases at the southern limit of the study region, but here Ekman coherence scale is less than the coherence scale of the MOC's geostrophic variability. Therefore, when Ekman variability is included, it acts to reduce the MOC's meridional coherence scale in this region.

In the case of OFES-NCEP, the meridional coherence of Ekman transport (dashed black line with triangles) is virtually independent of latitude, with an average meridional decorrelation distance of approximately 8° throughout the study region. Ekman variance is larger for latitudes south of 20°N and north of 37°N, and geostrophic variance is larger
everywhere else, but their ratio is much closer to 1 than was the case for OFES-CLIM, varying between about 0.8-1.2. For latitudes north of 22°N, the MOC’s geostrophic meridional decorrelation distance (dashed red line) is ~2-3° shorter than the Ekman transport meridional decorrelation distance. Therefore, when Ekman is included (solid red line), the MOC’s meridional coherence increases by ~1°. The opposite is true south of 18°N, as was the case for OFES-CLIM. In this region, the MOC’s Ekman-removed coherence is slightly larger than the Ekman transport's coherence, so the Ekman-included MOC coherence is reduced.

In summary, both OFES models follow the same pattern: the wind's meridional coherence acts to extend the MOC's meridional coherence in the north of the study region and reduce it in the south. Ekman dynamics are more important at the upper and lower limit of the study region than in the middle latitudes for both OFES models. This is consistent with the observed wind pattern. The boundaries of the subtropical gyre are located not far from 15°N and 40°N, the location of maximum wind stress curl and significant Ekman variance, and winds tend to be weaker in the center of the gyre where geostrophic variance dominates.
Figure 7-10: OFES-CLIM: comparison of the MOC’s meridional decorrelation to the bandpass filtered Ekman transport meridional decorrelation.

Figure 7-11: OFES-NCEP: comparison of the MOC’s meridional decorrelation to the bandpass filtered Ekman transport meridional decorrelation.
Chapter 8: Discussion and Conclusions

The MOC is a complex large-scale oceanographic feature whose importance has been linked to global climate change. Before the 2004 deployment of the RAPID-MOCHA array, few observations had been made of the MOC, but now the program has already collected more than four years of MOC data. We revisit here the main questions posed in this study, and the insights that have resulted from our investigation.

1. What is the strength, structure, and variability of the North Atlantic MOC and are models able to reproduce this? Are numerical models able to reproduce the vertical structure of the MOC at 26.5N?

The North Atlantic MOC is found to have a mean strength of 18.7 Sv, with a standard deviation of 5.1 Sv. The models used for comparison to the observations in this study generally underestimated the observed mean MOC by 2-3 Sv, although CCSM3 POP and PMB overestimated the mean by 0.4 Sv and 6.4 Sv respectively. Similarly, all of the models underestimated the observed variability. The modeled standard deviations ranged from 2.5-4.2 Sv, with the climatologically forced models tending to have smaller standard deviations than the synoptically forced models.

The vertical structure of the observed MOC is divided into two cells. The time mean vertical profile indicates that a broad, upper ocean cell stretches from the surface to a depth of ~4250m, with its maximum strength occurring at a depth of ~1000m. A thinner, reverse, deep ocean cell exists between 4250m to the sea floor with its maximum
strength occurring at a depth of ~5250m. The models are generally able to reproduce this structure, although they tend to have much narrower upper ocean cells, and much broader deep ocean cells.

2. How does the model spectra of MOC variability compare with observations?

RAPID-MOCHA observations have higher energy than all the models at time periods shorter than 25 days and longer than 140 days. The observed spectrum also has a maximum at 35 day periods which is absent from the models, much of which results from a peak in observed Ekman variance at this period. OFES-NCEP has more energy than the other models at periods less than 65 days, including a relative maximum at 45 day periods, a feature which is not present in observations or other models. As expected, the climatologically forced models (OFES-CLIM and PMB) both have significantly less power at submonthly periods than either observations or the synoptically forced models. At 120 day periods, the models all converge to approximately the same energy as observations, but observations have the highest energy for periods longer than 120 days, consistent with the monthly climatologies presented in Figure 4-6.

3. Are the dominant modes of variability of \( \Phi(z) \) well simulated?

The dominant modes of MOC variability were investigated by an EOF analysis of the models and observations. In all datasets, the first mode overwhelmingly explains the highest percentage of variance, and is well-separated from all other modes. Each subsequent mode is responsible for a much smaller percentage of the total variance. The vertical transport profiles for RAPID-MOCHA, OFES-CLIM, OFES-NCEP, and POP 14b appear to represent the vertical structure of a surface intensified, first baroclinic
mode. Their first mode vertical profiles reflect northward transport above ~1100m and southward transport below ~1100m. The two high-resolution, synoptically forced models (OFES-NCEP and POP 14b) appear to be more barotropic than the other models. RAPID-MOCHA's and OFES-CLIM's first mode transport profiles are similar to the rest of the models, but their southward transport at depth is stronger. The CCSM3 POP model's first-mode vertical transport structure appears to represent a strong northward Ekman layer close to the surface on top of a weakly southward quasi-barotropic profile. The PMB model's first mode vertical structure is unique and seems to indicate the presence of physics not found in any of the other models.

Without Ekman forcing, OFES-CLIM's normalized first mode vertical transport profile is not very different than when Ekman is included. However, without Ekman forcing, the first mode vertical transport profiles of OFES-NCEP and POP 14b (the two synoptically forced, high resolution models) and RAPID-MOCHA all begin to look more like the OFES-CLIM profile. Their southward transport in the deep ocean increases, and their northward transport follows roughly the same pattern as OFES-CLIM. CCSM3 POP's first mode transport profile appears unaffected by the absence of Ekman forcing.

4. What are the mechanisms by which the MOC variability is forced? What part of the MOC variability is due to random internal variability not related to forcing?

The OFES models were used to investigate the mechanisms by which MOC variability is forced. OFES-CLIM's variance due to Ekman forcing is confined to the seasonal period band, and its geostrophic variance is contained within the intraseasonal and seasonal period bands. OFES-NCEP's Ekman and geostrophic forcing are distributed
evenly among the period bands. Assuming that the two OFES models have identical internal dynamics and the ocean functions quasi-linearly, the geostrophic variance can be broken down into variance due to eddies and variance due to the ocean's non-Ekman response to wind forcing (e.g., Rossby and Kelvin waves). As seen in Figure 5-5, eddy variance on the order of 2.5-8 Sv$^2$ is concentrated in the intraseasonal period band, with higher values located near 35°N. This latitude is coincident with the location of the North Atlantic's highest eddy kinetic energy, and is associated with large meanders of the Gulf Stream. This suggests that AMOC variance in the intraseasonal period band is dominated by eddy activity, and variance in the submonthly period band is dominated by forced geostrophic motions such as Rossby and Kelvin waves.

5. How representative is the existing MOC timeseries of long-term MOC variability?

The averages of randomly selected four-year subsamples from the most realistic model (OFES-NCEP) will fall within 1.14 Sv of the true mean 95% of the time. In Kanzow et al. (submitted), the RAPID-MOCHA timeseries was found to have a standard (1σ) error of 0.8 Sv, which is 0.23 Sv larger than OFES-NCEP's 1σ error of 0.57 Sv. This is expected, because the standard deviation of the observations is 0.9 Sv more than OFES-NCEP's standard deviation (see Table 4-1). This suggests that with respect to the long term mean, the error estimate of random four-year OFES-NCEP subsamples is comparable to the observational error estimate, considering the model's slightly lower variance.
6. How well are MOC trends resolved, given the statistical nature of the modeled (and observed) MOC variability?

Not surprisingly, four years of data is not enough to reveal significant trends. The trends calculated from random and sequential four-year subsamples taken from the detrended OFES-NCEP model are often higher than OFES-NCEP's and RAPID-MOCHA's true trends. In fact, trends of random subsamples are greater than both the 27-year OFES-NCEP trend (0.09 Sv/decade) and the 4-year RAPID-MOCHA trend (1.18 Sv/decade) more than 50% of the time. This means that the true trend is not qualitatively different from trends produced by error associated with random sampling.

One-year trends have magnitudes as large as 60 Sv/decade, but as more years are included in the calculation, the trend limits and confidence intervals begin to decrease exponentially. For four-year-long segments, trends range from 0-5 Sv/decade, with a 95% confidence interval of 13 Sv/decade, indicating that trends calculated from the four-year RAPID-MOCHA dataset are essentially meaningless. For 11-to-15-year-long timeseries, the magnitude of the trends is steady, ranging from 0-2.5 Sv/decade. The 95% confidence interval is also steady for 11-15-year-long datasets with a value of ~2 Sv/decade. This suggests that as the RAPID-MOCHA dataset becomes longer than 11 years, the addition of new observations will not act to significantly reduce uncertainty in the calculated trend.
7. What is the meridional coherence scale of the MOC fluctuations?

OFES-CLIM’s MOC meridional coherence ranges from a distance of 6-9°, with maximum coherence occurring around 20°N and minimum coherence around 35°N. OFES-NCEP’s MOC meridional coherence is almost independent of latitude, with maximum values near 8° between 15°N and 20°N to a minimum of 6° around 38°N. Both OFES models follow the same pattern: the wind's meridional coherence acts to extend the MOC’s meridional coherence in the north of the study region and reduce it in the south. Ekman dynamics are more important at the northern and southern limits of the study region than in the middle latitudes for both OFES models. This is consistent with the observed wind pattern. The boundaries of the subtropical gyre are located not far from 15°N and 40°N, the location of maximum wind stress curl and significant Ekman variance, and winds tend to be weaker in the center of the gyre where geostrophic variance dominates. However, for the most realistic model (OFES-NCEP), we find that the meridional coherence scale of both Ekman forced MOC variations (associated with the meridional coherence scale of zonal winds) and the geostrophic MOC variations (associated with either eddies or forced motions) are quite similar, ranging from about 5°-8° of latitude. Therefore, neither mechanism is dominant in controlling the overall meridional coherence scale of the MOC fluctuations. We conclude for this study that MOC fluctuations separated by ~10° of latitude in the subtropics should be essentially independent from one another on time scales shorter than annual.
References


Pillsbury, J. E. (1887). Gulf Stream Explorations – Observations of Currents 1887

Pillsbury, J. E. (1890). The Gulf Stream – A Description of the Methods Employed in the Investigation, and the Results of the Research


