The Effect of Lower Sea Level on Geostrophic Transport through the Florida Straits during the Last Glacial Maximum

A Thesis
Presented to
The Academic Faculty

By

Dana A. Ionita

In Partial Fulfillment
Of the Requirements for the Degree
Master of Science in the
School of Earth and Atmospheric Sciences

Georgia Institute of Technology
December, 2008

The Effect of Lower Sea Level on Geostrophic Transport through the Florida Straits during the Last Glacial Maximum

Approved by:

Dr. Jean Lynch-Stieglitz, Advisor
School of Earth and Atmospheric Sciences
Georgia Institute of Technology

Dr. Emanuele Di Lorenzo, Co-Advisor
School of Earth and Atmospheric Sciences
Georgia Institute of Technology

Dr. Robert Black
School of Earth and Atmospheric Sciences
Georgia Institute of Technology

Dr. Annalisa Bracco
School of Earth and Atmospheric Sciences
Georgia Institute of Technology

Date Approved: September 30th, 2008

ACKNOWLEDGEMENTS

For invaluable help and advice with this thesis, I thank my advisors, Dr. Jean Lynch-Stieglitz and Dr. Emanuele Di Lorenzo. I also thank all my committee members, who took the time to read and approve this thesis.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

LGM = Last Glacial Maximum

NCEP = National Centers for Environmental Prediction

QuickSCAT = Quick Scatterometer, earth-observing satellite that provides wind speed and direction information over oceans

Sv = Sverdrups

SUMMARY

We investigate the effect of a 120 meter sea level drop on transport through the Caribbean Sea and the Florida Straits during the Last Glacial Maximum (LGM) relative to the present, using the Regional Ocean Modeling System (ROMS). A geostrophic transport estimate for the Florida Straits suggests the LGM Florida Current was weaker than today by one third, inferring a likely decrease in the North Atlantic overturning circulation by 12-15 Sv. A possible impact of a shallower LGM Florida Straits sill depth on the Florida Current has been suggested. Our model results show that the volume transport through the Florida Straits is slightly reduced in a lower sea level model simulation when compared to a control sea level simulation (34.8 ± 2.0 Sv vs. 39.8 ± 2.3 Sv). The difference in transport is of the order of 5 Sv, representing a maximum limit to the LGM flow reduction due to sea level change. Therefore the change in sill depth between the LGM and the present is unlikely to have been a cause of the entire observed flow reduction.

1. INTRODUCTION

The modern North Atlantic surface circulation (shallower than 1 km) consists of a wind-driven clockwise subtropical gyre superimposed on the surface component of the meridional overturning circulation (MOC), which flows northward along the western boundary and is compensated by a southward deep water flow.

Water flowing westward and northward through the Caribbean Sea and the Florida Straits includes components of both the wind-driven gyre (~17 Sv) and the surface compensation for North Atlantic deep water export (~14 Sv). Both components enter the Caribbean Sea through the Antilles Islands channels, pass through the Yucatan Channel, and exit through the Gulf of Mexico and the Florida Straits [*Johns et al.*, 2002]. This adds up to ~ 31 Sv net transport through the Florida Straits. Observations show 18.4 $\pm$ 4.7 Sv entering the Caribbean through the Lesser Antilles, 3.0 $\pm$ 1.2 Sv through the Mona Passage and 7 - 8 Sv through the Windward Passage [*Bulgakov et al.*, 2003], resulting in a total Caribbean inflow of 28.4 Sv [*Johns et al.*, 2002]. Approximately 3 - 4 Sv enter the Florida Straits from the NW Providence and Santaren channels [*Leaman et al.*, 1995], adding up to around 32 Sv of water flowing northward through the Florida Straits [*Baringer and Larsen,* 2001, *Hamilton et al.*, 2005], above a sill depth of about 760m.

During the last glacial maximum (LGM), approximately 21,000 years ago [e.g. *Bard et al.,* 1990, *Yokoyama et al.*, 2000], the North Atlantic MOC was markedly different from today. There is evidence of a shallower LGM overturning [e.g. *Curry and*

Oppo, 2005], but the strength of the overturning has not yet been definitively established [*Lynch-Stieglitz et al.*, 2007].

A geostrophic transport estimate through the Florida Straits during the LGM suggests that flow was weaker by one-third relative to today [*Lynch-Stieglitz et al.*, 1999b]. This estimate is based on oxygen-isotope ratios of benthic foraminifera from the margins of the Florida Current. A geostrophic velocity profile, referenced to the bottom of the straits, can be calculated from cross-channel horizontal density gradients. Since the $\delta^{18}O$ of foraminifera shells is a proxy for the density of the water in which they formed, geostrophic transport can be estimated from foraminifera $\delta^{18}O$ measurements on the sides of the strait. The reduced LGM Florida Current is consistent with a decrease in the Atlantic overturning circulation, but it is necessary to rule out other possible factors, like a shallower Florida Straits due to a lower LGM sea level or a significant change in wind-driven circulation.

Our focus here is limited to the effect of a shallower Florida Straits. Sea level reconstructions estimate a sea level lower by about 120 meters during the LGM [e.g. *Alley et al.,* 2005, *Bassett et al.,* 2005, *Bard et al.*, 1990, *Lambeck and Chappell*, 2001], which reduced the Florida Straits sill depth of 760 m [*Malloy and Hurley*, 1970] to 640 m. The sea level drop could either have a negligible effect on the Florida Current transport – the flow increases either its vertical shear or bottom velocity, transporting the same amount of water as today – or block transport of water flowing below 640 m at present. Since the modern-day Florida Current extends down to the sill, it is important to test whether the geostrophic LGM Florida Current reduction observed in *Lynch-Stieglitz et al.* [1999a,b] may have been due to a shallower sill depth as well as a likely reduced

MOC. It is safe to assume that the topography of the Florida Straits has remained constant since the LGM, since the elapsed time is much shorter than geological time scales and the sediment records appear undisturbed. In addition, sea level analyses based on Barbados shoreline history [*Peltier and Fairbanks*, 2006] already take local isostatic adjustments into account.

In this study, we test the sensitivity of the volume transport through the Florida Straits to a sea level drop of 120 m. For this purpose, we use two runs of the Regional Ocean Modeling System (ROMS), one with modern-day bathymetry and another with the bathymetry raised by 120 m to simulate lower sea level conditions during the LGM. We also verify using modeled data that the geostrophic method used in *Lynch-Stieglitz et al.* [1999b] gives accurate estimates of the entire transport, provided that the cores extend deep enough on the respective margins to capture the entire geostrophic flow.

2. METHODS

2.1 Model

The Regional Ocean Modeling System (ROMS) is a high resolution, bathymetry-following ocean model. ROMS solves free-surface, hydrostatic, eddy-resolving primitive equations on a grid of stretched, terrain-following coordinates in the vertical and orthogonal curvilinear coordinates in the horizontal [*Shchepetkin and McWilliams*, 2005; *Haidvogel et al.,* 2007]. In the Intra Americas Seas (IAS) configuration the model grid has a horizontal resolution of 10 kilometers with 30 vertical levels, more closely distributed toward the surface. The grid covers the Caribbean Sea, the Gulf of Mexico, and the Florida Straits. The model bathymetry is derived from the *Smith and Sandwell* [1997] bathymetric map with a 2 arc minute cell size. Smoothing is applied to minimize pressure gradient model errors associated with strong topographic slopes, however particular care is given to insure the sill depths of all important passages and straits are accurately represented.

2.2 Boundary Conditions and Forcing Functions

The model has two open boundaries. At these boundaries, a radiation condition is applied to the model state variables (temperature, salinity, velocity and free-surface) [*Marchesiello et al.,* 2001], along with nudging to monthly climatological conditions derived from a ROMS simulation of the North Atlantic (*Levin et al., personal communication*). Configuration parameters for the open boundary conditions and mixing are similar to the ones used in *Di Lorenzo* [2003] and *Marchesiello et al.* [2003]. At the surface the model is forced with climatological monthly mean wind stresses derived from the 2000 - 2004 QuickSCAT winds blended with the NCEP reanalysis [*Milliff and Morzel*, 2001].

2.3 Experiments

We perform two model integrations of 16 years length each. The first integration uses the control (modern) bathymetry. For the second integration, the bathymetry is raised by 120 meters to simulate lower sea level conditions of the LGM [*Peltier and Fairbanks*, 2006], while all other parameters remain unchanged. In both runs, the bathymetry at the open boundaries is blended with the North Atlantic model bathymetry through a gradual transition over a buffer zone to ensure the same boundary mass flux.

We did not conduct experiments to test directly the sensitivity of model transports to different strengths of the overturning circulation. These experiments require different specifications of the mass flux at the model open boundary that cannot be realistically derived without data from a large-scale model of the entire North Atlantic that exhibit a slower overturning. Therefore our model experiments are limited to studying the sensitivity of flow in this region to changes in sea level alone.

3. RESULTS AND DISCUSSION

3.1 Control Run

The model streamfunction shows a net flow from the equatorial Atlantic Ocean into the Caribbean Sea and the Gulf of Mexico, and toward the North Atlantic through the Florida Straits (Figure 1), thus agreeing overall with observations [*Johns et al.*, 2002]. The control run indicates a total transport of 39.5 Sv through the Florida Straits, which is consistent both at the entrance from the Gulf of Mexico and at the exit into the North Atlantic. This transport is higher than the measured 32 Sv transport [e.g. *Baringer and Larsen*, 2001]. The model exhibits flow of 2.2 Sv out of the straits through the Old Bahama channel, compensated by an inflow of 2.5 Sv through the NW Providence channel, which is comparative to the 1.2 Sv observed inflow [*Leaman et al.*, 1995] (Figure 2, Table 1). The Old Bahama channel outflow is opposite to the observed 2 Sv Santaren Channel flow into the straits [*Leaman et al.*, 1995].

The volume entering the Florida Straits (39.5 Sv) is balanced by the volume exiting the Florida Straits (39.8 Sv), and the 0.3 Sv difference is the difference between the Old Bahama Channel outflow (2.2 Sv) and the NW Providence Channel inflow (2.5 Sv). Transport measurements across numerous model sections indicate that transport tends to be conserved within 1%, an error that could be due to changes in the free surface elevation on time scales of a few days [*Hamilton et al.*, 2005].

The control run tends to exhibit a 6-8 Sv higher transport on average than observed. This difference may most likely reflect an incorrect specification of the mass flux open boundary condition derived from the North Atlantic model, which was calibrated for a lower resolution bathymetry. Nevertheless, the goal of this study is not to reproduce the absolute transport through the straits but rather to capture the sensitivity of the transport to the different sea level conditions during the LGM. Because the relative transport across the various straits in the model is comparable in size to the observed, we assume that the model simulations are adequate to explore the sea level sensitivity.

3.2 Sensitivity to Lower Sea Level

The lower sea level run streamfunction has a similar appearance to the control (Figure 1), indicating that a 120 meter sea level drop does not induce any major circulation change in the Caribbean Sea and the Florida Straits. There is a 37.1 Sv flow entering the Florida Straits between Cuba and the Dry Tortugas and 34.8 Sv exiting the straits into the Atlantic Ocean north of the Bahamas (Figure 2, Table 1). The flow is around 2.5 Sv less than the control at the straits entrance and around 5 Sv less at the exit, with the difference exiting through the Old Bahamas (2 Sv) and the NW Providence (0.5 Sv) channels. This reduces the NW Providence channel inflow to 2.0 Sv and increases the Old Bahama channel outflow to 4.2 Sv. These numbers suggest that the sill depth can have an effect on transport, albeit a small one for a sea level change of 120 meters. Since the great majority of the transport is in the upper 600 meters of the straits in our model (36.7 Sv according to Figure 3) just as in observations [*Leaman et al.*, 1989], it makes sense that blocking the straits below 640 meters would not impact the flow significantly.

Our sensitivity study indicates that the effect of a shallower Florida Straits can be two-fold: (1) blocking the throughflow of water deeper than the sill, indicated by a 2.5 Sv reduction of flow entering the straits, and (2) the shoaling of deep water flowing through, which can flow either directly along the Florida shore or out through the (shallower than

500 meters) Old Bahama Channel (2.5 Sv). The latter effect is indicated by the additional reduction of flow at the straits' exit. In the control run, water exiting through the Old Bahama Channel flows contrary to observed modern-day 2 Sv inflow through this channel. This is probably due to the higher model transport through the straits (39.8 Sv vs. 32 Sv), which reverses the much weaker flow through the shallower (~ 500 m) side channel. It is likely that the 39.5 Sv model transport at the Dry Tortugas section extends deeper and is affected more by a shallower bathymetry than the observed 28.4 Sv transport, thus making the net 5 Sv flow reduction between the control and lower sea level runs an upper limit rather than an estimate. Out of the approximately 12 – 15 Sv geostrophic reduction from modern flow to LGM flow inferred in *Lynch-Stieglitz et al.* [1999a,b], this study suggests that at most 5 Sv could have been due to a sea level change.

3.3 Geostrophic Transport

Geostrophic transport is calculated across various sections throughout the straits based on (a) the model's absolute geostrophic currents and (b) two density profiles along the bottom layer (straits margins) as in *Lynch-Stieglitz et al.* [1999a,b]. The model geostrophic calculation (a) is calculated from the density and sea surface height of the model output and uses the same model numerics computing the pressure gradient term on the terrain-following coordinate system. The straits margins (b) calculation, referenced to the bottom, indicates that a non-zero bottom layer velocity constitutes a significant part of the model transport, unlike the observed flow, which is close to zero at the bottom.

The model differentiates between bottom velocity, which is defined to be zero, and bottom layer velocity, which is the average velocity of the (at least) 100 meter thick bottom-most layer and is located half-way between the layer's vertical boundaries . Adding the bottom layer velocity as reference level velocity in the straits margins method (b) brings the geostrophic transport close to the total transport everywhere (Table 1). The margins method (b) has two sources of error in this case: (1) loss of half of the bottom layer cross-sectional area while interpolating density in order to calculate horizontal density gradients and (2) sampling error (local ageostrophic velocity fluctuations at the sampled point multiplied by a very large cross section). Both error sources become more significant when the bottom layer velocity is non-zero, which adds an uncertainty of ± 3 Sv to the geostrophic calculation. When applied to actual density measurements, the margins method (b) does not encounter either error, since it does not deal with a bottom layer or bottom velocity data.

The 39.5 Sv total transport at the Dry Tortugas section, where bottom velocity is nearly zero, is within error in geostrophic balance, according to the (a) margin density transport of 40.5 Sv and the (b) model's geostrophic transport of 37.5 Sv (Table 1). The flow in the straits exhibits significant horizontal velocities in the bottom layer (Figure 3b), especially at and right after the more restricted sections, e.g. between Florida and the Cay Sal Bank. The geostrophic flow calculated at these locations without the bottom layer velocity (column 5 in Table 1) considerably underestimates the model flow. The geostrophic transport referenced to zero bottom velocity at 27ºN, the sill location, is 31.3 Sv, which becomes 38.4 Sv with the added transport due to bottom velocity. The fact that the model can handle a total transport as high as 40 Sv through the straits indicates that depth is not a definite limiting factor in the total Florida Straits transport and there is room for considerable transport variations. However, the geostrophic transport is affected by sill depth through the large bottom velocity variations in the shallower sections of the straits.

3.4 Core locations

Of special interest are the core locations of *Lund et al.* [2006], just west of the Dry Tortugas and off the Great Bahama Bank. Although these locations, chosen for their high Holocene sediment accumulation rates, are not exactly across the strait from each other, these high resolution cores have been used to assess flow variability over the last 1000 years and longer cores collected at the same locations can be used for a more precise constraint on the LGM transport through the Florida Straits. In Figure 4, we show model potential density profiles at sections incorporating the core locations, indicating that any vertical redistribution of transport through the Florida Straits is associated mainly with density changes along the Florida margin and not the Cuba/Bahamas margin, since the potential density profiles along the Cuba and Bahamas sides are nearly identical, except for the top 100 meters.

While *Lund et al.* [2006] assume a reference level at a depth of 850 meters, the model velocity approaches zero closer to a depth of 1000 meters (Figure 3) at the Dry Tortugas section. Geostrophic model transport referenced to 850 meters at the Dry Tortugas is 36.2 Sv, 4 Sv less than the 40.6 Sv referenced to the bottom. Much of the difference is due to the fact that the model transport of 39.5 Sv likely has a deeper vertical distribution compared to the observed 28.4 Sv. Observations across a 1050 meter deep Florida Straits section show velocity approaching zero at 1000 meters and a small ($<$ 0.05 m s^{-1}) velocity component at 850 meters [*Leaman et al.*, 1995], corresponding to a geostrophic transport increase of about 2 Sv. Since the Great Bahama Bank section is about 850 meters deep, any deeper transport at the Dry Tortugas section or barotropic transport due to bottom velocity at the Great Bahama Bank section, if there is any, will not be recorded by this method. In order to take into account any deeper flow in the LGM geostrophic calculation, data points deeper than the Great Bahama Bank cores would have to be collected on the Cuban margin. Our model indicates, just as observed density profiles do, that the Great Bahama Bank and the Cuban margins have similar potential density profiles (Figure 4), thus supporting the idea that interchanging or combining the two does not greatly affect the geostrophic calculation.

Table 1
Transport in Sverdrups (10^6 m^3/s) for observations, the control run (Control), and the lower sea level run (Lower sea level), across sections illustrated in figure 1. Model error is 1 standard deviation.

		Control (Run 1) transport (Sv)				**Lower sea level (Run 2)**
	Observed transport (Sv)	**Total**	**Geostrophic (model)**	**Geostrophic (margins only)**	**Geostrophic (margins + bottom v)**	**Total transport (Sv)**
1. Dry Tortugas	28.4	39.5 ± 4.7	37.5 ± 5.9	40.6	40.6	37.1 ± 4.2
2. Old Bahama Channel	- 1.9	2.2 ± 3.2	2.0 ± 2.9	1.4	2.1	4.2 ± 2.7
3. Great Bahama Bank	N/A	37.1 ± 2.1	40.3 ± 3.1	32.9	39.8	32.9 ± 2.1
4. NW Providence Ch.	- 1.2	-2.5 ± 1.3	-2.5 ± 1.0	- 2.1	- 2.1	-2.0 ± 1.0
5. Bahamas 27N	31.5	39.8 ± 2.3	39.6 ± 2.3	31.3	38.4	34.8 ± 2.0

4. CONCLUSION

Our results show that the effect of a 120 meter sea level drop on the Florida Current transport is twofold: some of the water (2.3 Sv) flowing below 640 m at present is blocked by the sill and never reaches the Florida Straits, while some (2.5 Sv) shallows out and is diverted through the 500 m deep Old Bahama Channel (due to the Cay Sal Bank sill) with a reduced NW Providence Channel inflow (due to the 27ºN sill) to rejoin the Gulf Stream north of the Florida Straits. The total flow deflection of 5 Sv is a maximum limit rather than an estimate, due to the larger than observed Florida Straits flow (39.5 Sv). Out of the approximately 12 – 15 Sv geostrophic reduction measured in *Lynch-Stieglitz et al.* [1999a,b], it is unlikely that more than 5 Sv could have been due to a sea level change.

The Florida Straits flow can be accounted for by our margin geostrophic calculation within error (Table 1), and the geostrophic calculation depends on properly accounting for the bottom velocity. When the bottom velocity is non-zero (e.g. Great Bahama Bank section, Figure 3), uncertainties are introduced, thus making the deep Dry Tortugas section the preferred location to calculate geostrophic transport, due to a safe assumption of zero bottom velocity. The method used in *Lund et al.* [2006] does a good job of calculating geostrophic transport, but due to lack of cores deeper than 850 meters the results of this study cannot rule out variability in geostrophic transport referenced below this depth. By calculating the Dry Tortugas geostrophic transport relative to a reference level closer to 1000 meters, as in the model, rather than 850 meters, as in *Lund et al.* [2006], we can make sure we eliminate any non-zero reference-level velocity. The

Lund et al. [2006] cores are from the Dry Tortugas shelf on the Florida side and from the Great Bahama Bank instead of Cuba's shore, which is steeper and more difficult to reach. However, since our model indicates that the potential density profiles are nearly identical off Cuba and the Great Bahama Bank (Figure 4), the two profiles can be used interchangeably and sediment cores can be combined for a deeper high resolution profile on the Bahamas/Cuba side of the straits. Sediment cores from the Cuban margin deeper than the Great Bahama Bank cores will allow us to take into account any deeper flow in future studies.

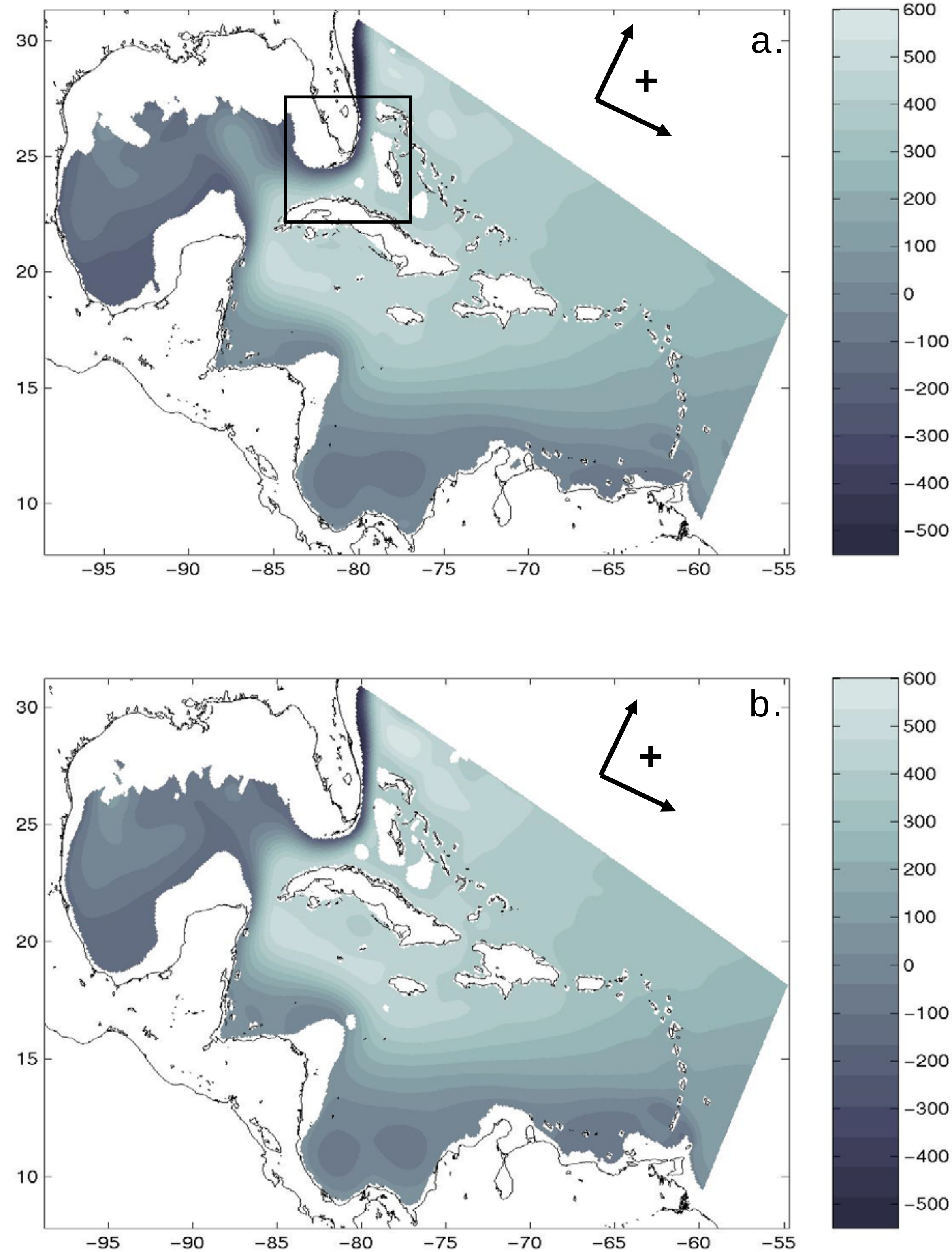

Figure 1 Streamfunction of the average model flow at density σ = 25.5 psu for **a.** the control run and **b.** the lower sea level run. Strong gradients indicate high velocities. Black arrows indicate direction of positive transport. The black rectangle indicates the location of figure 2.

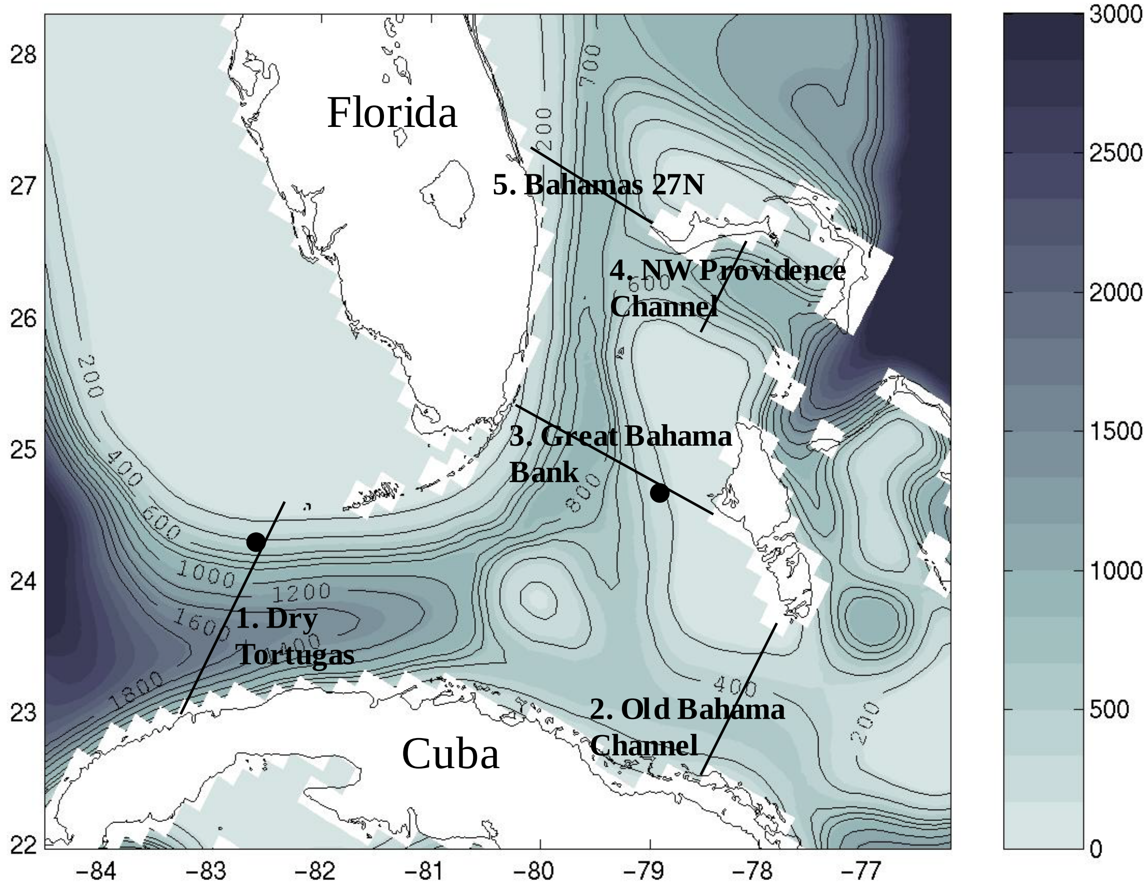

Figure 2 Florida Straits bathymetry and locations of sections across which transport in Table 1 is measured. The black dots indicate the *Lund et al*. [2006] core locations.

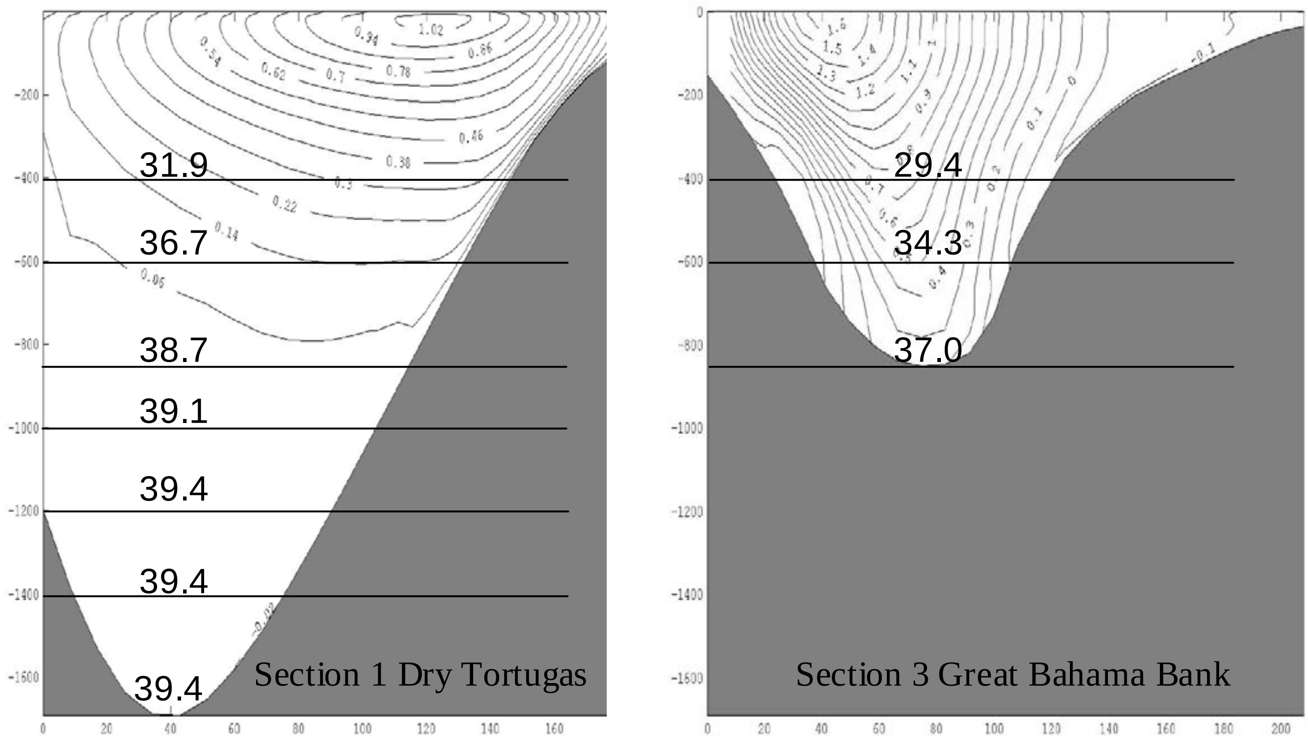

Figure 3 Contoured are the velocity (m s^{-1}) profiles across **a.** the Dry Tortugas section (section 1 in Figure 2) and **b.** the Great Bahama Bank section (section 3 in Figure 2). The numbers in each section indicate total transport (Sv = 10^6 m^3 s^{-1}) above the solid horizontal line reference levels.

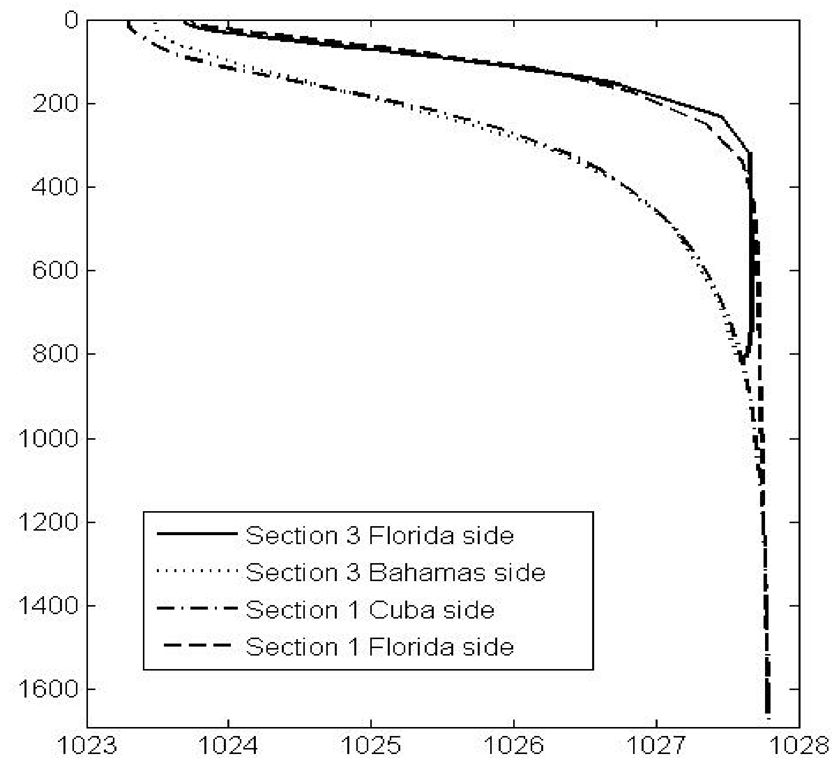

Figure 4 Potential density profiles (kg m^{-3}) from the straits margins across the Dry Tortugas section (section 1 in Figure 2) and the Great Bahama Bank section (section 3 in Figure 2) for the control run.

5. REFERENCES

Alley, R. B., Clark, P.U., Huybrechts, P., Joughin, I. (2005), Ice-Sheet and Sea-Level Changes, *Science*, *310*, 456-460.

Bard, E., Hamelin, B., Fairbanks, R.G., Zindler, A. (1990), Calibration of the ^{14}C timescale over the past 30,000 years using mass spectrometric U-Th ages from Barbados corals, *Nature*, *345*, 405-410.

Baringer, M. O., Larsen, J.C. (2001), Sixteen Years of Florida Current Transport at 27o N, *Geophysical Research Letters*, *28*, 3179-3182.

Bassett, S. E., Milne, G.A., Mitrovica, J.X., Clark, P.U. (2005), Ice Sheet and Solid Earth Influences on Far-Field Sea-Level Histories, *Science*, *309*, 925-928.

Bulgakov, S. N., Bulgakov, N.P., Ivanov, V.A. (2003), A comparison of direct observations of velocity and transport in the Windward Passage, *Geofisica Internacional*, *42*, 115-129.

Curry, W. B., Oppo, D.W. (2005), Glacial water mass geometry and the distribution of $\delta^{13}C$ of ΣCO_2 in the western Atlantic Ocean, *Paleoceanography*, *20*.

Di Lorenzo, E. (2003), Seasonal dynamics of the surface circulation in the Southern California Current System, *Deep-Sea Research II*, *50*, 2371-2388.

Haidvogel, D. B., H. Arango, W.P. Budgell, B.D. Cornuelle, E. Curchitser, E. Di Lorenzo,
K. Fennel, K. Hedstrom, W.R. Geyer, A.J. Herman, L. Lanerolle, J. Levin, J.C. McWilliams, A.J. Miller, A.M. Moore, T.M. Powell, A.F. Shchepetkin, C.R. Sherwood, R.P. Signell, J.C. Warner, J. Wilkin (2008), Ocean forecasting in terrain-following coordinates: Formulation and skill assessment of the Regional Ocean Modeling System, *Journal of Computational Physics*, in press.

Hamilton, P., Larsen, J.C., Leaman, K.D., Lee, T.N., Waddell, E. (2005), Transports through the Straits of Florida, *Journal of Physical Oceanography*, *35*, 308-322.

Johns, W. E., Townsend, T.L., Fratantoni, D.M., Wilson, W.D. (2002), On the Atlantic inflow to the Caribbean Sea, *Deep-Sea Research I*, *49*, 211-243.

Lambeck, K., Chappell, John (2001), Sea Level Change through the Last Glacial Cycle, *Science*, *292*, 679-686.

Leaman, K. D., Johns, E., Rossby, T., 1989: The average distribution of volume transport and potential vorticity with temperature at 3 sections across the Gulf Stream. *Journal of Physical Oceanography, 19*, 36-51.

Leaman, K. D., Vertes, P.S., Atkinson, L.P., Lee, T.N., Hamilton, P., Waddell, E. (1995), Transport, potential vorticity, and current/temperature structure across Northwest

Providence and Santaren Channels and the Florida Current off Cay Sal Bank, *Journal of Geophysical Research*, *100*, 8561-8569.

Lund, D. C., Jean Lynch-Stieglitz, William B. Curry (2006), Gulf Stream density structure and transport during the past millenium, *Nature*, *444*, 601-604.

Lynch-Stieglitz, J., Curry, W.B., Slowey, N. (1999a), A geostrophic transport estimate for the Florida Current from the oxygen isotope composition of benthic foraminifera, *Paleoceanography*, *14*, 360-373.

Lynch-Stieglitz, J., Curry, W.B., Slowey, N. (1999b), Weaker Gulf Stream in the Florida Straits during the Last Glacial Maximum, *Nature*, *402*, 644-648.

Lynch-Stieglitz, J., Jess F. Adkins, William B. Curry, Trond Dokken, Ian R. Hall, Juan Carlos Herguera, Joel J.-M. Hirschi, Elena V. Ivanova, Catherine Kissel, Olivier Marchal, Thomas M. Marchitto, I. Nicholas McCave, Jerry F. McManus, Stefan Mulitza, Ulysses Ninnemann, Frank Peeters, Ein-Fen Yu, Rainer Zahn (2007), Atlantic Meridional Circulation During the Last Glacial Maximum, *Science, 316*, 66-69.

Malloy, R.J., Hurley, R.J. (1970), Geomorphology and Geologic Structure: Straits of Florida, *Geological Society of America Bulletin, 81,* 1947–1972

Marchesiello, P., McWilliams, J.C., Shchepetkin, A. (2001), Open boundary conditions for long-term integration of regional oceanic models, *Ocean Modeling*, *3,* 1-20.

Marchesiello, P., McWilliams, J.C., Shchepetkin, A. (2003), Equilibrium Structure and Dynamics of the California Current System, *Journal of Physical Oceanography*, *33*, 753-783.

Milliff, R. F., Morzel, J. (2001), The Global Distribution of the Time-Average Wind Stress Curl from NSCAT, *Journal of the Atmospheric Sciences*, *58,* 109-131.

Peltier, W. R., Fairbanks, R.G. (2006), Global glacial ice volume and Last Glacial Maximum duration from an extended Barbados sea level record, *Quaternary Science Reviews*.

Shchepetkin, A. F., James C. McWilliams (2005), The regional oceanic modeling system (ROMS): a split-explicit, free-surface, topography-following-coordinate oceanic model, *Ocean Modelling*, *9*, 347-404.

Smith, W. H. F., Sandwell, D.T. (1997), Global Sea Floor Topography from Satellite Altimetry and Ship Depth Soundings, *Science*, *277*, 1956-1962.

Yokoyama, Y., Lambeck, K., De Deckker, P., Johnston, P., Keith Fifield, L. (2000), Timing of the Last Glacial Maximum from observed sea-level minima, *Nature, 406*, 713-716.