North Atlantic Modeling of the Low Frequency Variability
in Mode Water Formation

Afonso M. Paiva[1,2] and Eric P. Chassignet[1]

Several studies have been carried out in order to investigate the mechanisms responsible for the observed sea surface temperature (SST) variability (e.g., Bjerknes, 1964; Deser and Blackmon, 1993; Kushnir, 1994; Delworth, 1996). These studies were motivated in part by the important role played by SST in the coupling between ocean and atmosphere, and were made possible by the availability of observational data sets representing the SST variability on interannual and longer time scales. Since water mass formation takes place in regions of intense heat loss to the atmosphere, and since the properties of newly formed water masses are related to those of the wintertime mixed layer, a numerical investigation was carried out to find out if whether, and to what extent, realistic wintertime surface heat flux anomalies can generate the observed variability in the water mass renewal in the western North Atlantic basins for these time scales.

Observations of long term subsurface variability in the North Atlantic are sparse (both in space and in time), and evidence of the associated forcing mechanisms is not yet conclusive. Levitus (1989) used historical hydrographic data to suggest that the observed changes in the intermediate layers (500 to 1300 m) between the 1955-1959 and 1970-1974 pentads may be related to variations in the magnitude of the wind stress curl (and therefore in the intensity of the Ekman pumping and/or of the gyre transport). On the other hand, New and Bleck (1995) have proposed, based on analysis of the trends simulated during the spin-up phase of an ocean model integration, that these changes were caused by subduction from a cooler than average mixed layer.

A few locations in the North Atlantic have been continuously monitored, providing long term records of water mass properties. Based on analysis of data from the Panulirus station ($32^o10'N$, $64^o30'W$), variability on interannual to near-decadal time scales in the formation rates and properties of Subtropical Mode Water (STMW), or 18^o water, has been shown to occur (Talley and Reymer, 1982; Joyce and Robbins, 1996). STMW is formed by subduction through the base of the winter mixed layer, in a region of strong surface heat loss. Expecting the observed variability to be caused by changes in surface forcing, and consequently in convective activity, Jenkins (1982) and Talley and Reymer (1982) were however unable to strongly correlate this variability to surface heat flux anomalies. Notwithstanding these results, Marsh and New (1996) were able to simulate the changes in potential vorticity (PV) observed to occur in the STMW core in the 1960s and 1970s by forcing a numerical model with idealized heat flux anomalies. Long term records from the Bravo station (latitude $56^o30'N$, longitude $51^o00'W$), in the central Labrador Sea, demonstrate that the formation rates and properties of the Labrador Sea Water (LSW) also have non-stationary characteristics (Lazier, 1981; Talley and McCartney, 1982; Lazier, 1988). The thickness and potential temperature of LSW have been shown to possess negatively correlated near-decadal variations (Curry et al., 1998). Low production of LSW corresponds to periods of weak surface heat loss in the Labrador Sea (McCartney and Talley, 1982), and also to the occurrence of intense freshwater surface anomalies that enhanced the vertical stratification and reduced convection (Lazier, 1981).

It has been noted (Dickson et al., 1996; Houghton, 1996; Joyce et al., 1999) that the decadal variability in convective activity in the North Atlantic western subtropical gyre and in the Labrador Sea have near opposite phases. Dickson et al. (1996) suggest that this asynchronicity is imposed by the spatial and temporal scales of the atmospheric forcing, which can be characterized by referring to the North Atlantic Oscillation (NAO). When the NAO index (the pressure difference between the Azores high and Iceland low atmospheric systems) is high, the heat loss is intense in the Labrador Sea due to strong westerlies and cold air advection, but is low in the western subtropical gyre due to the inflow of warm and moist air (Cayan, 1992); when the NAO index is low, the westerlies shift southward, intensifying the storminess (Dickson and Namias, 1976; Rogers, 1990) and the outbreaks of cold and dry continental air over the western subtropics, thus enhancing the heat loss in that region and reducing it in the Labrador Sea.

With atmospherically forced variability, the Miami Isopycnic Coordinate Ocean Model (MICOM), configured for the North Atlantic ($28^o S$-$65^o N$), was able to reproduce quite well the potential vorticity and isopycnal depth anomalies associated with STMW at Bermuda (Fig. 1). Heat storage and preconditioning of the convective activity were found to be the important factors for the generation of STMW variability, with persistence of cold or warm conditions, associated with anomalous heat loss over the western subtropics, being more significant for the generation of the simulated variability than strong anomalous events in isolated years. The PV anomalies were generated to the northeast of Bermuda, near the Gulf Stream front, and were advected within a large area in the western subtropics and the Sargasso Sea.

In the Labrador Sea, under anomalous heat flux forcing, the model was able to capture the phase and order of magnitude of the observed near-decadal variability in the convective activity, if not its maximum amplitude. The differences between the simulated and observed variability (Fig. 2) were attributed to the lack of significant fresh water anomalies in the model, representing the Great Salinity Anomalies. These anomalies, which were originated at higher latitudes outside the model domain and were advected into the Labrador Sea, increased the stability of the upper ocean reducing convection. The present simulations demonstrate that the heat flux variability represent also an important factor in controlling the convective activity in the Labrador Sea.

The simulated (as well as observed) PV anomalies in the western subtropics are out-of-phase with those in the Labrador Sea. PV anomalies in the western subtropics and in the Labrador Sea were found to correlate well with the NAO at near-decadal time scales, with the oceanic response lagging the NAO by $\sim 2-3$ years (Fig. 3). These results support the idea that the variability in water mass formation in the western North Atlantic can be attributed, to a large extent, to changes in the pattern of the large scale atmospheric circulation, which generate sensible and latent heat flux variability by modifying the strength and position of the westerly winds and the advection of heat and moisture over the ocean. To the best of our knowledge, this is the first time that the interannual and near-decadal subsurface variability associated with STMW and LSW, and its relationship to the NAO, has been simulated in an ocean general circulation model.

Acknowledgements: This research was supported by the National Science Foundation through grant OCE-9531852. AMP was also supported by a graduate student fellowship from the Brazilian Research Council (Conselho Nacional de Desenvolvimento Cientifico e Tecnologico - CNPq).

[1] RSMAS/MPO, University of Miami, 4600 Rickenbacker Causeway, Miami, FL, 33149-1098, USA

[2] Now at COPPE/PENO, Universidade Federal do Rio de Janeiro Cidade Universitaria - CT - Bloco C - Sala 203, Rio de Janeiro, RJ, 21945-970, Brasil

References

Bjerknes, J. (1964). Atlantic air-sea interaction. In H. E. Landsberg and J. Van Mieghem (Eds.), *Advances in Geophysics*, Volume 10, pp. 1–82. Academic Press.

Cayan, D. R. (1992). Latent and sensible heat flux anomalies over the northern oceans: driving the sea surface temperature. *J. Phys. Oceanogr. 22*, 859–881.

Curry, R. G., M. S. McCartney, and T. M. Joyce (1998). Oceanic transport of subpolar climate signals to mid-depth subtropical waters. *Nature 391*(5), 575–577.

Delworth, T. L. (1996). North Atlantic interannual variability in a coupled ocean-atmosphere model. *J. Climate 9*, 2356–2375.

Deser, C. and M. L. Blackmon (1993). Surface climate variations over the North Atlantic ocean during winter: 1900-1989. *J. Climate 6*, 1743–1753.

Dickson, R., J. Lazier, J. Meincke, P. Rhines, and J. Swift (1996). Long-term coordinated changes in the convective activity of the North Atlantic. *Prog. Oceanogr. 38*, 241–295.

Dickson, R. R. and J. Namias (1976). North american influences on the circulation and climate of the North Atlantic sector. *Mon. Wea. Rev 104*(10), 1255–1265.

Houghton, R. W. (1996). Subsurface quasi-decadal fluctuations in the North Atlantic. *J. Climate 9*, 1363–1373.

Huang, R. X. and J. Pedlosky (1999). Climate variability inferred from a layered model of the ventilated thermocline. *J. Phys. Oceanogr. 29*, 779–790.

Jenkins, W. J. (1982). On the climate of a subtropical ocean gyre: decade time scale variations in water mass renewal in the Sargasso Sea. *J. Mar. Res. 42(S)*, 265–290.

Joyce, T. M., C. Deser, and M. A. Spall (1999). On the relation between decadal variability of subtropical mode water and the North Atlantic Oscillation. Submitted to *J. Phys. Oceanogr.*

Joyce, T. M. and P. Robbins (1996). The long-term hydrographic record at Bermuda. *J. Climate 9*, 3121–3131.

Kushnir, Y. (1994). Interdecadal variations in North Atlantic sea surface temperature and associated atmospheric conditions. *J. Climate 7*, 141–157.

Lazier, J. R. N. (1981). Oceanographic conditions at O.W.S. Bravo. *Atmos.-Ocean 18*, 227–238.

Lazier, J. R. N. (1988). Temperature and salinity changes in the deep Labrador Sea, 1962-1986. *Deep Sea Res. 35*, 1247–1253.

Levitus, S. (1989). Interpentadal variability of temperature and salinity at intermidiate depths of the North Atlantic ocean, 1970-1974 versus 1955-1959. *J. Geophys. Res. 94*, 6091–6131.

Marsh, R. and A. L. New (1996). Modeling 18^oC water variability. *J. Phys. Oceanogr. 26*(6), 1059–1080.

McCartney, M. S. and L. D. Talley (1982). The subpolar mode water of the North Atlantic ocean. *J. Phys. Oceanogr. 12*, 1169–1188.

New, A. L. and R. Bleck (1995). An isopycnic model study of the North Atlantic - Part 2: Interdecadal variability of the subtropical gyre. *J. Phys. Oceanogr. 25*(11), 2700–2714.

Rogers, J. C. (1990). Patterns of low-frequency monthly sea-level pressure variability (1899-1986) and associated wave cyclonic frequencies. *J. Climate 3*, 1364–1379.

Sturges, W. and B. G. Hong (1995). Wind forcing of the Atlantic thermocline along 32^oN at low frequencies. *J. Phys. Oceanogr. 25*, 1706–1715.

Talley, L. D. (1996). North Atlantic circulation and variability reviwed for the CNLS conference. *Physica D 98*, 625–646.

Talley, L. D. and M. S. McCartney (1982). Distribution and circulation of Labrador Sea Water. *J. Phys. Oceanogr. 12*(11), 1189–1205.

Talley, L. D. and M. E. Reymer (1982). Eighteen degree water variability. *J. Mar. Res. 40, Supp.*, 757–775.

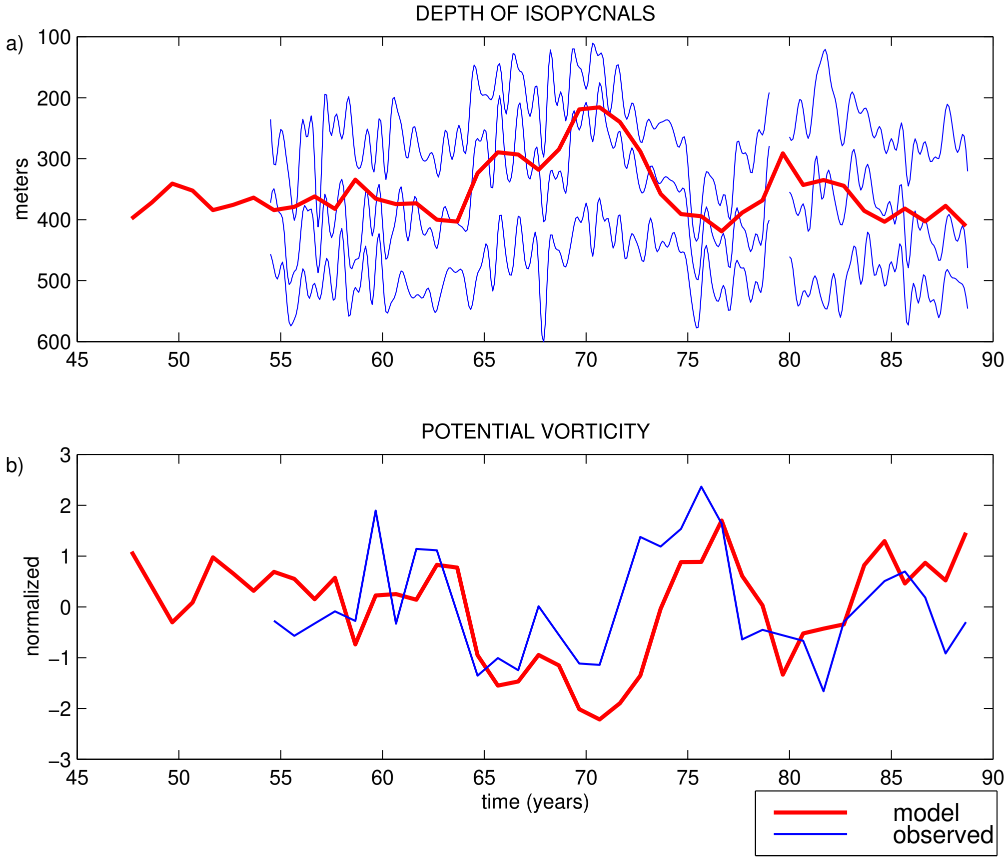

Figure 1: Time evolution at Bermuda for: a) depth of model interface 6 in September (thick red line) and observed depth of the 26.4, 26.5 and 26.6 (from top to bottom) σ_θ surfaces (thin blue lines), from Talley (personal communication); and b) potential vorticity anomaly from the model (thick line), and from observations (thin line) at the 200-400 db depth range (Joyce and Robbins, 1996), normalized by their respective standard deviations.

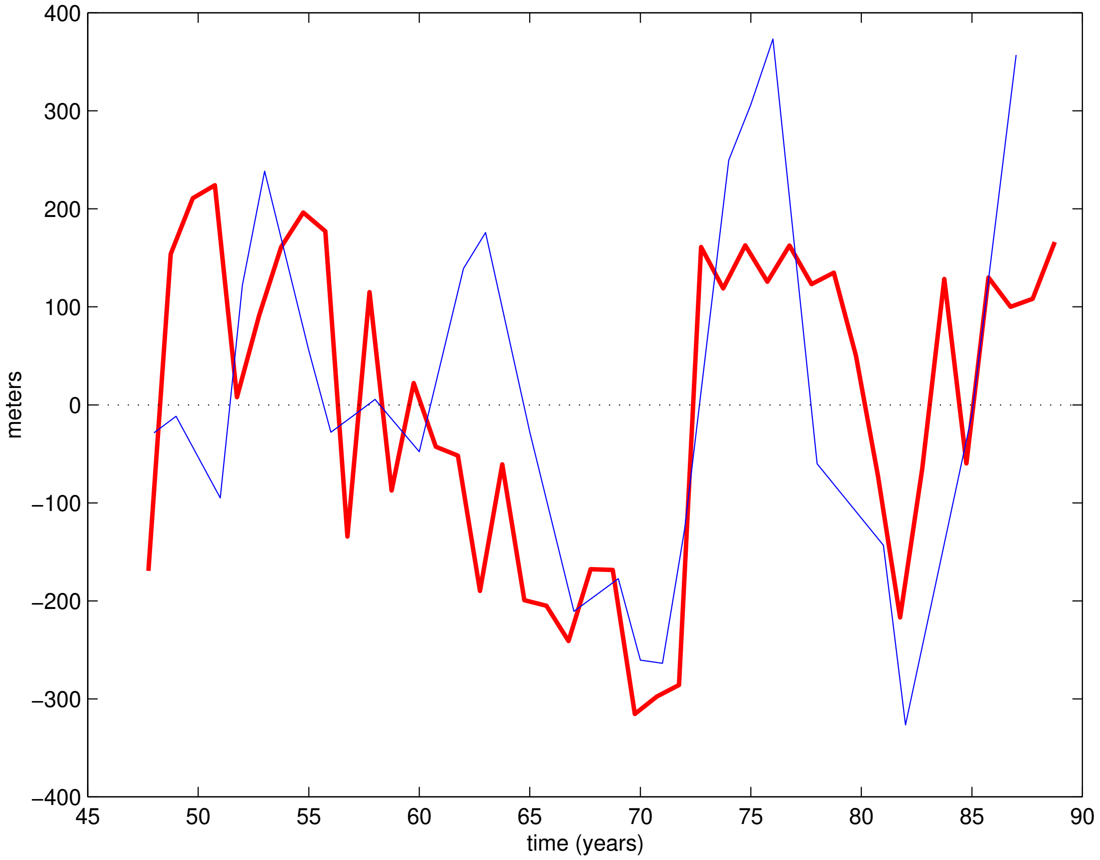

Figure 2: Time evolution of model layer 12 thickness anomaly in the Labrador Sea (solid line), and of the thickness of the observed LSW core (dashed line, redrawn from Curry et al., 1996).

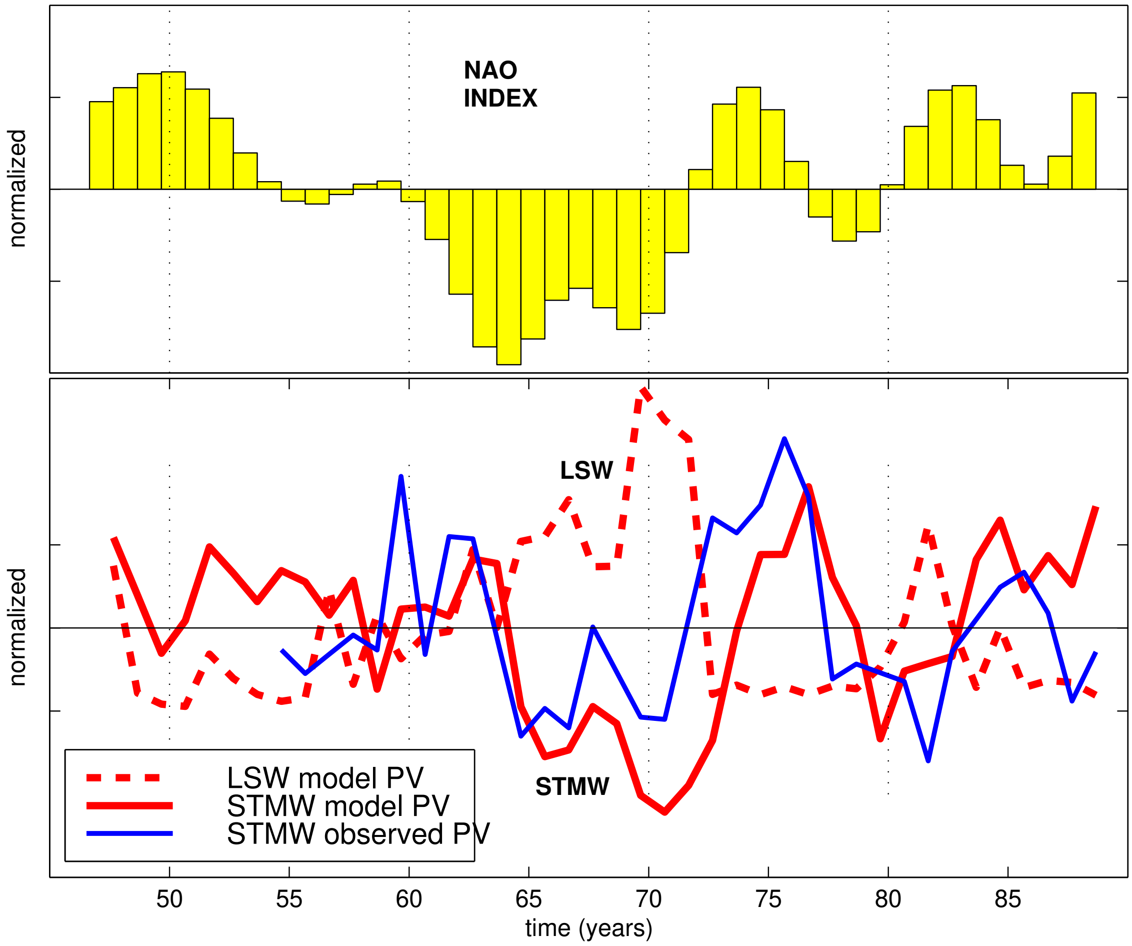

Figure 3: Comparison between the NAO index of Hurrell (1999, personal communication), the model LSW (dashed red line) and STMW (solid red line) PV anomalies, and the observed PV anomaly (solid blue line). All curves are normalized by their respective standard deviations.