6 Summary and Conclusions

The impact of midlatitude ocean variability on the overlying atmosphere is not well understood, in part because the effects are subtle. The role of midlatitude air-sea interaction on climate variability is examined in this research using a mixed layer model (MLM) of the North Atlantic ocean (20-60˚N) and NCAR's (National Center for Atmospheric Research) atmospheric general circulation model, CCM1 (Community Climate Model version one). The MLM is composed of horizontally independent column models of the upper ocean, which includes prognostic mixed layer physics and a convective-diffusive model below the mixed layer. Flux corrections of heat and salt are included in the model formulation to prevent climate drift. The MLM is forced in an uncoupled integration with CCM1 control fields and the heat (salt) flux corrections are calculated as the amount of heat (salt) needed each day to match the predicted to the observed ocean temperature (salinity). To calculate the corrections, the MLM is forced with daily values of CCM1 radiation and momentum fluxes and with latent and sensible heat fluxes calculated from CCM1 air temperature, mixing ratio, winds, and MLM predicted ocean temperatures. The control case 256 of CCM1 is a 10 year atmospheric model integration with a specified annual cycle of observed global climatological SSTs of Alexander and Mobley (1976) in all the ocean basins as the lower boundary condition. Flux corrections do not influence the atmosphere but act to maintain mean MLM temperatures and salinities that are consistent with the SST climatology of the CCM1 and the observed salinity climatology of Levitus (1982), respectively. Identical flux corrections are used in all of the model simulations. A series of numerical simulations are performed to understand better the processes that are important in midlatitude air-sea interaction.

The primary mode of model and observed interannual variability in the North Atlantic is characterized by a north-south oriented dipole in surface air temperature and ocean temperature. The corresponding atmospheric circulation is consistent with the notion of the atmosphere forcing the ocean. Examining natural variability in the model is relevant, because of the similarity between observed and model dipole patterns. This research focuses on the impact of air-sea interaction on the natural variability on monthly to interannual time scales with an emphasis on interannual variability during the fall and winter months of September to March.

6.1 Conclusions

6.1.1 Oceanic Response to Atmospheric Forcing

The response characteristics of the ocean model are examined in a series of uncoupled simulations, in which the MLM is forced with observed atmospheric anomalies during 1950-1988 from the Comprehensive Ocean and Atmospheric Data Set (COADS). In the partially coupled (PC) method of connecting the ocean to the atmosphere, the MLM is forced with surface sensible and latent heat fluxes that are calculated using CCM1 atmospheric temperature, moisture, and winds and the mixed layer model predicted ocean temperature. Therefore, in PC simulations the heat and momentum forcing on the MLM is modified by the predicted ocean temperature. Compositing techniques to combine winters that are characterized by warm (cold) northern and cold (warm) southern ocean temperature anomalies respectively, are used to examine the oceanic response to atmospheric anomalies of the dipole mode.

These simulations indicate that surface heat fluxes account for 75% of the seasonal to interannual variability in the observed SST anomalies and that specifically sensible and latent heat fluxes are comparable in the northern part of the domain. Latent heat flux anomalies dominate the total heat flux forcing in the southern part of the ocean basin, consistent with previous observational (Cayan, 1992c) and modeling (Alexander, 1990b) studies. Radiative fluxes generally vary in the same sense as the surface heat fluxes but are significantly smaller in magnitude. Sensitivity experiments indicate that air temperature and moisture anomalies are essential to the heat flux anomalies that lead to SST anomalies. However, anomalous wind speed has a negligible effect on the heat fluxes as well as the SST anomalies. The secondary role of anomalous wind speed in generating large-scale SST anomalies was also noted in Haney et al. (1983).

For the dipole mode of variability, we estimate that anomalous Ekman advection of the mean temperature gradient accounts for 20% or less of the SST anomalies generated by the surface heat fluxes (Battisti et al., 1995). This result is consistent with Delworth (1995), who finds that anomalous currents play a secondary role in the variability of SST on interannual time scales in a 1000 year integration of the GFDL (Geophysical Fluid Dynamics Laboratory) general circulation model coupled to an ocean general circulation model. Luksch (1995) examines variability in the North Atlantic in an ocean general circulation model by prescribing observed COADS winds during the period 1950-1979. The heat flux parameterization involves an atmospheric advection term, which moves air temperature anomalies in a manner consistent with the atmospheric winds. In contrast, Luksch (1995) finds that advection (mainly Ekman) is responsible for about 50% of the heat flux variance of the surface heat fluxes. One possible explanation for this discrepancy is that in Luksch's model, there are no continental air temperature anomalies over North America. This may underestimate the influence of air temperature anomalies on the oceanic anomalies, which would manifest in smaller anomalous surface heat fluxes.

6.1.2 Impact of Coupling on Atmospheric Anomalies

The CCM1 is coupled to the MLM in the North Atlantic and integrated for 31 years. The annual cycle of SSTs is specified according to the observed climatology of Alexander and Mobley (1976) outside of the North Atlantic basin. A parallel 31 year long control simulation of CCM1 is integrated, using as a lower boundary condition, the globally specified climatological annual cycle of sea surface temperatures of the coupled simulation. The results of the coupled and control simulations are examined using simple statistical measures: regressions, correlations, EOFs and epoch analysis. The analysis focuses on interannual variability during the autumn and winter months of September to March.

The mean wintertime (December to February) climatologies of air temperature, atmospheric mixing ratio, surface heat flux, precipitation, and surface heat flux are essentially unchanged with coupling. However, there is a statistically significant increase in the variance of wintertime surface air temperatures (greater than a factor of 2) and a decrease (factor of 2) in the variance of surface heat fluxes with coupling. The variance of the wintertime surface mixing ratio is over twice as large in the coupled than the control simulation in the southern part of the basin.

Turbulent heat fluxes strongly damp air temperature anomalies in the presence of no ocean temperature anomalies (Frankignoul, 1985) and conversely, allowing for interaction between the ocean and the atmosphere leads to decreased ‘thermal damping’ of atmospheric anomalies. Barsugli (1995) found that coupling enhances air temperature variance through decreases in thermal damping in a 50 meter slab global ocean coupled to a two-level global GCM, with perpetual January radiation conditions. This idea of decreased ‘thermal damping’ with coupling is consistent with the increase of variance of air temperature and the concurrent decrease of heat flux variance. This can be illustrated by the following example: a positive atmospheric air temperature forces a positive ocean temperature anomaly, and consequently, the net heat flux anomaly will be smaller than that in an uncoupled simulation where the ocean is not able to respond.

Autocorrelations of air temperature are statistically significant at lags of 1-2 months in the control and 3-4 months in the coupled simulation, indicating an increase in the persistence of seasonal anomalies. It is expected that monthly anomalies of air temperature persist longer when the strength of the temperature damping by the heat fluxes decreases.

6.1.3 Role of Entrainment on Mixed Layer Temperature Persistence

In the northern part of the ocean basin, significant autocorrelations (statistically significant at the 95% level or greater) of air and ocean temperature are found between one winter and the following winter in the coupled simulation (Section 5-1). The 'Re-emergence' mechanism (Namias and Born, 1970, 1974) is consistent with these autocorrelations that are separated by almost a year. During late winter (February-March) when mixed layer depths are at their annual maximum, ocean temperature anomalies penetrate to great depths. The mixed layer reforms closer to the ocean surface during spring and the wintertime temperature anomalies are sequestered below the shallow summer mixed layer. These anomalies re-emerge into the mixed layer the following fall when the mixed-layer begins to deepen. February mixed layer temperatures are uncorrelated with ocean surface temperatures during the following summer but are strongly correlated (0.9) with temperatures between 50 and 120 meters the following summer.

A series of one-way forced (OWF) experiments were performed using MLM in the North Atlantic. In addition to the prescribed fluxes from the coupled integration, a small linear damping term is added to the mixed layer temperature tendency equation. The total forcing of the ocean in these sensitivity experiments is surface heat, momentum, and freshwater fluxes from the coupled simulation. In a sensitivity experiment where anomalies in entrainment heating and mixed layer depth are suppressed, the autocorrelations of mixed layer temperature between one winter and the next are very weak. This suggests that the reemergence of temperature anomalies through entrainment is a likely mechanism to explain the strong autocorrelations of ocean temperatures from one winter to the next. 'Re-emergence' does not play an important role in the southern region of the ocean model. Autocorrelations of observed air and ocean temperature from one winter to the next fall are strong (weak) in the northern (southern) part of the basin, in agreement with model results.

Other researchers have also found the importance of the re-emergence mechanism depends on the oceanic location. Alexander and Deser (1995) find that the re-emergence mechanism is more clearly visible at Ocean Weather Station (OWS) C (53˚N, 35˚W) than at OWS E (35˚N, 48˚W) in the North Atlantic. Miller et al. (1994) find that the importance of the ‘Re-emergence’ mechanism in the North Pacific varies throughout the basin in a numerical study using a bulk mixed layer model coupled to an isopycnal representation of the deep ocean.

The strength of re-emergence is overestimated in the MLM of the North Atlantic Ocean, as can be seen in the weaker winter-to-winter autocorrelations in the observations than in the coupled model (see Figure 5-8a and c). This is likely due to the absence in our model of ocean currents which, in nature, will advect sub-mixed layer temperature anomalies.

A schematic of the role of air-sea interaction on climate variability in the midlatitude North Atlantic (Figure 6-1) highlights the primary processes examined in this research. The spatial scale of the dipole mode of variability is determined by the atmosphere, and the integrated affects of the atmospheric forcing results in a lower frequency response in the ocean. The feedback of the ocean on the atmosphere is subtle and alters the variance and persistence of the atmospheric dipole anomalies. The role of anomalous entrainment overall acts to enhance the dipole mode of variability in SST anomalies, particularly in the northern part of the domain. Hence, the model results indicate that both ‘Re-emergence’ and ‘Thermal Damping’ play important roles in the changes of midlatitude climate variability associated with air-sea interaction.

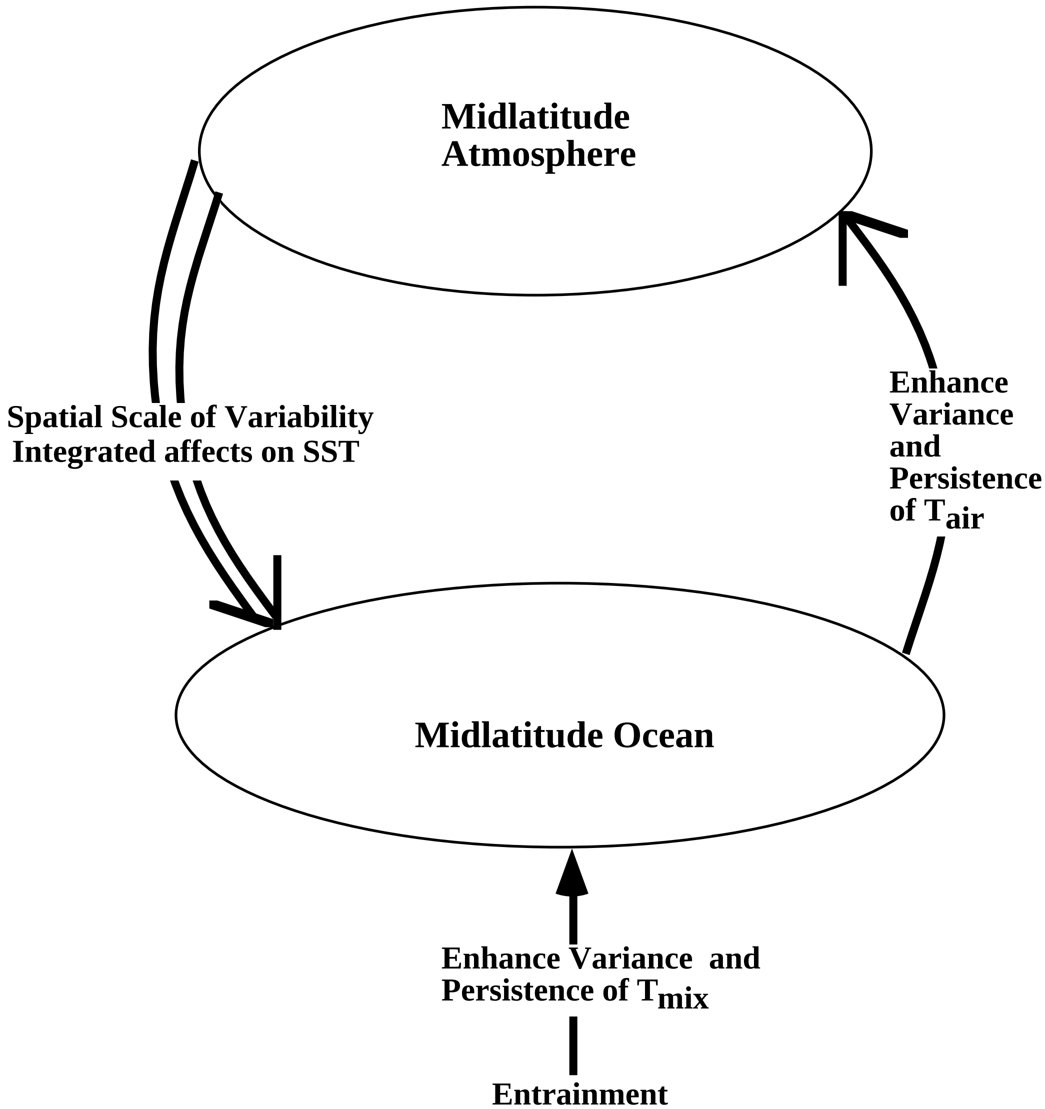

Figure 6-1. Schematic of the relationship between the ocean and the atmosphere in the midlatitude North Atlantic with particular reference to the dipole mode of variability. The atmosphere determines the spatial scale of the interannual variability in the ocean. The ocean feedback to the atmosphere is more subtle and acts to influence the variability and persistence of atmospheric fields. Entrainment of water from below the ocean surface layer acts overall to enhance the variance and to increase the persistence of ocean temperature anomalies.

6.2 Implications

Mixed layer physics on the seasonal to interannual time scale does a good job at representing the zero order variability of the midlatitude oceans. The experiments in this study using the variable depth mixed layer model capture the role of entrainment in the strong autocorrelations of temperature anomalies from one winter to the next. The model results nicely parallel the observations. The demonstration of the importance of entrainment in interannual variability indicates that it is preferable to use a variable depth mixed layer model over a slab mixed layer ocean. The increase in computer requirements is negligible compared to the atmospheric model requirements. However, it is somewhat more difficult to establish causalities in variable depth mixed layer model than a fixed slab model, because of the complex partitioning of the energy input to the mixed layer.

The atmospheric response to midlatitude SST anomalies is very sensitive to the polarity of the imposed SST anomaly (Kushnir and Lau, 1992; Peng et al., 1995 and others). In general, it has been difficult to establish the atmospheric response to midlatitude SST anomalies. Since the presence of midlatitude SST anomalies is associated with the climatological features of the model such as the storm tracks and the jet (Palmer and Sun, 1985), specifying observed SST anomalies, may yield confusing results unless the observed and model climatological features are collocated. To examine the atmospheric response to midlatitude SST anomalies in climate models, it would be more fruitful to perform both coupled and uncoupled modeling simulations. The coupled simulation will clearly establish the preferred locations of SST anomaly development in a particular climate model. Once the preferred locations are known, SST anomalies placed strategically can be used to examine the atmospheric response to a specified SST anomaly. Druyan (1991) successfully applied such a two step procedure to examine the impact of South Atlantic SST anomalies on Sahel rainfall. Recently, Latif and Barnett (1994) examined the atmospheric response to midlatitude North Pacific SST anomalies by combining coupled and imposed SST climate simulations. Gallimore (1995) has employed this method to examine the life cycle of midlatitude climate anomalies in the North Pacific.

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