# CHAPTER 1. Conclusions

The basic understanding of the baroclinic processes in the coastal ocean has improved significantly in recent years. The development of coastal ocean observing and prediction systems is providing and will continue to provide additional invaluable knowledge of these processes. The availability of long-term systematic and sustained observations of the coastal ocean is starting to allow the study of processes that vary on in a range of time scales from daily to annual and interannual.

In this study, several developments associated with coastal ocean observing and prediction systems were used to improve our understanding of the baroclinic process in coastal oceans. A data assimilative hindcast of the frontal system on the Southern Flank of Georges Bank and its implications to the transport and retention of particles was developed in Chapter 2. Available atmospheric and hydrographic observations were analyzed in Chapter 3 to determine the conditions and forcing mechanisms associated with a cold water event during the summer of 2003 in the South Atlantic Bight. The spatial and temporal variability of an approximation to the work balance of mixing and buoyant forces in the South Atlantic Bight was presented in Chapter 4. The development and initial results of a model study of the forcing mechanisms that triggered and controlled the cold water event of 2003 was presented in Chapter 5.

The previous chapters constitute recent developments in understanding of the baroclinic processes relevant in two specific regions of the coastal ocean. The main focus was to explore the relevant processes that controlled two events: the response of the frontal system on Georges Bank to the passage of a storm system, and the presence of anomalously cold water over most of the shelf in the South Atlantic Bight. These two events represent examples of the complex and highly dynamic baroclinic processes in coastal systems. As in most research, by trying to answer some questions of these systems, a new set of interesting questions surfaced. The magnitude of the remaining questions is substantial and some of those questions might not be addressed in the near term, but they open the doors to new and exciting approaches to understanding the coastal ocean.

The two regions studied (Georges Bank and South Atlantic Bight) present important similarities: the extreme seasonal changes in baroclinic structures and associated stratification levels, the fundamental influence of tidal dynamics and mixing and the rapid response to passage of atmospheric systems. The differences between the systems are associated with their characteristic topographic features, the lack of river influences in Georges Bank and the direct influence of the Gulf Stream in the SAB.

## 1.1 Applications and Future Directions

### 1.1.1 Georges Bank Frontal Study

Chapter 2 showed the usefulness of data assimilative techniques to the improvement of the prediction of baroclinic features and their associated dynamics. This work was an extension of previous work in the same area (*Lynch et al.*, 2001; *Lynch and Naimie*, 2002), but added the application to a concrete event and studied the secondary circulation associated with the tidal front and its repercussions on laval retention on the Bank.

Georges Bank remains a region of intense interest and study. The continuing effort of projects like U.S. GLOBEC ensures the maintenance of intense research in this area both currently and in the near future. Some of the work currently underway looks at the biological implications of the tidal-front circulation focusing on the growth of Atlantic cod larvae (*Lough et al.*, 2005).

A limiting factor in the simulations presented in Chapter 2 is still the proper specification of initial conditions. Improvements may be achieved by using ensemble smoother assimilation techniques (*Evensen*, 1994; *van Leeuwen*, 1999) to estimate optimal initial conditions from prognostic simulations and T-S observations (e.g., CTD, satellite SST). This method is computationally expensive but provides additional useful fields such as error statistics.

### 1.1.2 2003 Event Observational Study in the SAB

The 2003 SAB upwelling event was a complex combination of upwelling-favorable winds, stratification on the shelf and intrusion of cold water from the Gulf Stream associated with the meanders and frontal eddies of the Stream. Chapter 3 showed the need to compile information from all available sources to understand complex events such as the one described. The importance of considering the feedback mechanisms between the different forcings was recognized as a fundamental factor to achieve understanding of processes on the SAB shelf.

The effect of intraseasonal oscillations detected during the summer of 2003 on the SAB shelf water level signal needs to be determined. Our understanding of such oscillations in the ocean is only partial and the characterization of the governing processes and their effects is starting to be achieved (*Bane et al.*, 2005).

The contributions of several open ocean effects on the SAB processes, such as transport contributions from the Florida and Antilles Currents, remains incompletely understood. The relationship between low-frequency Gulf Stream transport and coastal water level in the SAB (*Noble and Gelfenbaum*, 1992) is currently being studied using HYCOM products.

The description of the intrusion process in 2003 in the mid-shelf with data from the R2 tower also needs to be completed. The evolution of the anomalously cold water over the shelf as well as the determination of the dominating temporal and spatial scales of the intrusion process needs to be completed. The comparison of the dynamical differences between two intrusions, one during May and another one in June, still needs to be completed. The 2003 stratification had severe implications on several other shelf processes, like the appearance and propagation of internal waves in the SAB (Catherine Edwards, personal communication).

The importance of a complete long-term monitoring system of the coastal ocean is evident from this study. The lack of consistent, sustained observations for most of the shelf makes the interpretation of events like the one during 2003 only partially successful. Coastal ocean observing systems like SABSOON (*Seim*, 2000) and SEACOOS are therefore invaluable.

### 1.1.3 Work Balance in the SAB

The energetics of the shelf region of the SAB remain only partially understood. The potential use of energetics and $h/u^3$ parameterizations for prediction of frontal positions in the coastal frontal zone needs to be studied. The implications of the peculiar characteristic of the cross-shelf distribution of critical $h/u^3$ in the SAB needs to be determined.

One substantial improvement to the basic parameterization described in Chapter 4 is the formulation by *Aken* (1986) and *Blanton et al.* (1989) to include advective processes and river discharge in the energy balance of the SAB. The main assumption in their study is that horizontal advection of density is predominantly in the cross-shelf direction and Ekman driven. This formulation allows the characterization of the effects on stratification by upwelling- and downwelling-favorable winds.

Another goal would be to study the dynamical processes associated with the frontal zone of the SAB applying the knowledge aquired from the Georges Bank experiment (Chapter 2), including the spring-neap cycle, increased mixing due to wind events, and seasonal variations. During fall and winter, jet-like structures have been observed that suggest substantial advection of inner-shelf water across the shelf (Figure 1). Currently, there is a strong interest in the processes controlling these jet-like features associated with the inner shelf frontal system and work in this topic is underway (*Li et al.*, 2003).

### 1.1.4 Model Study during 2003

The results presented in Chapter 5 were preliminary model simulations. The complete set of simulations for 2003 needs to be finalized and the study of the implications for the 2003 event. A rigorous validation of the model results is needed. Even considering the limitations, the characterization of complex processes, such as the intrusion of 2003, can be approximated.

Several remaining modeling improvements in the 2003 study are needed to evaluate questions raised in Chapters 3 and 5. The primary need is to extend the domain size to include the shelfbreak and Gulf Stream region from at least Cape Canaveral, Florida to Cape Hatteras, North Carolina. This future simulation will allow the representation of several processes: 1) the influence of changes in Gulf Stream transport on shelf dynamics and coastal water level; 2) the contribution of the Antilles Current to the SAB dynamics; and 3) the evolution of intrusions through the shelfbreak by the passage of Gulf Stream meanders and frontal eddies.

As in Chapter 2, the initial conditions used in these simulations need to be improved. A possible approach might be to update the climatological fields with observations available during 2003 (e.g., CTD, NDBC stations, satellite SST) using Objective Analysis (*Hendry and He*, 1996; *Lynch and McGillicuddy*, 2001). This approach would allow the development of covariance fields for the SAB shelf that can be used for several other studies. Another approach is the use of ensemble smoother techniques (*Evensen*, 1994; *van Leeuwen*, 1999) to estimate optimal initial conditions and surface boundary conditions from prognostic simulations and observations of the temperature and salinity fields. A final approach is to extract the initial conditions from basin-scale simulations like HYCOM, NLOM and NCOM. Currently, a rigorous evaluation of the character of the HYCOM solution in the SAB shelf is underway (Brian Blanton, personal communication).

The connection between the basin-scale model (HYCOM) and the shelf-scale simulations (QUODDY) needs to be improved. A possible approach is the use of a set of nested simulations, transitioning from the basin-scale HYCOM solution, to a SAB-scale domain that would include the shelfbreak, and then to the shelf-scale Quoddy simulation. Initially, the approach will be to use one-way nesting. The possibility of transferring information from the shelf-scale model to the basin-scale is interesting but presents considerable challenges.

This study suggests several possible additions to the currently available SAB coastal ocean predic-

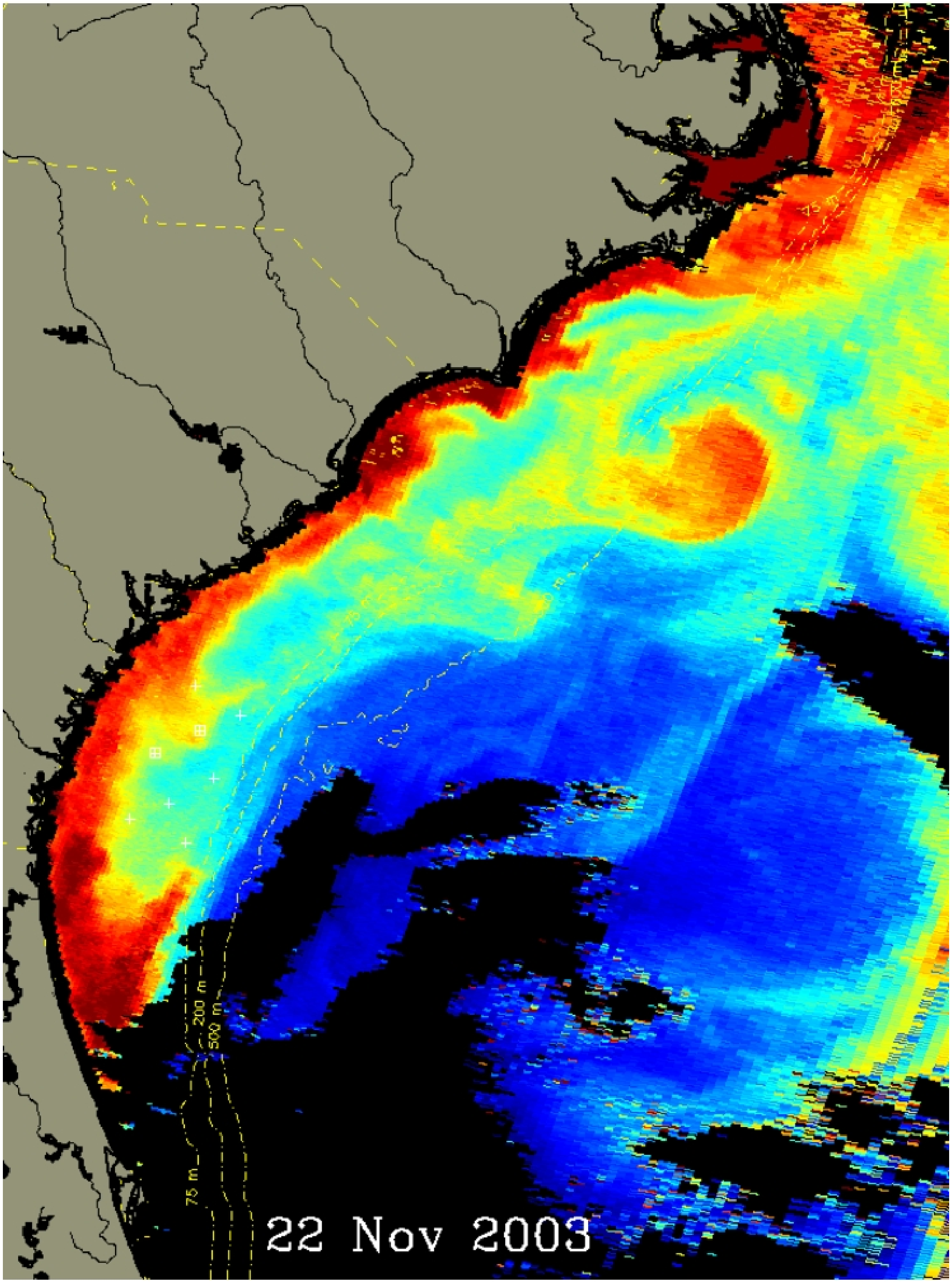

Figure 1: SeaWifs image of ADCM for 22-Nov-2003 showing jet-like features in the SAB shelf.

tion system (SEACOOS). The inclusion of adequate mass fields and baroclinic features in the operational simulations is a fundamental need to predict the coastal ocean appropriately.

## 1.2 Potential Climate Change Effects on Coastal Stratification

A thorough discussion of the effects associated with environmental changes in the SAB was presented by *Windom et al.* (1993). They discussed changes in several physical, chemical, and biological processes under recent climatic changes and some potential future implications. One of the effects of climate change in the SAB is the possible increase in annual precipitation. From studies of the long-term precipitation time series in the southeastern United States (*Sheridan and Knisel*, 1989; *Erhardt*, 1989; *Plummer*, 1989), there appears to have been an approximate 10 % increase in average rainfall during the last 100 years. The increased freshwater discharge will decrease salinity in coastal areas and enhance lateral flux of buoyancy in the inner-shelf. The combined effect of projected increases in runoff and temperature for the SAB will augment the strength of the vertical stratification. Considering the described consequences of increased stratification during upwelling events (Chapter 3 and 5), in the near future we might expect an increase in the frequency of cold water events such as the one described for 2003. The economical (decreased tourism income due to the presence of cold waters at the beach) and ecological (cold stunning of turtle hatchlings, fish kills) impacts of these events need to be considered.

The increased stratification will change the circulation in the inner- and mid-shelf and therefore the fate of particles in the shelf. Two aspects of this effect are the change of the fate of pollutants in the SAB shelf and a possible change in the distribution of larvae with severe implications for the design and management of Marine Protected Areas. Preliminary studies to address the interaction of shelf dynamics and larval dispersal are under way (*Edwards et al.*, 2005).

Considering that the tidal and wind forcings are not expected to change significantly, the increased river discharge and rising temperatures will enhance the buoyancy of the coastal areas. Considering the effects presented in Chapter 4, the resulting work balance will cause a displacement of the location of the stable tidal front to off-shore positions. The magnitude of this change will be directly associated with the increased runoff. Under normal circumstances, a large displacement would not be expected, but considering the specific characteristics of the SAB with regard to cross-shelf distribution of $h/u^3$ parameter (Chapter 4), “severe” displacements might occur. Future work will try to evaluate this potential displacement.

Buoyancy changes are expected in the Georges Bank region as well, even considering the lack of direct river discharge. The change in heat flux input in the bank will displace the position of the tidal front on-bank, which, in turn, may have significant effects on larval retention on the Bank.

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