Collaborative Research: Cross-shelf Transport and Alongshelf Exchange Processes in Regions of Multiple Mesoscale Fronts

Dana K. Savidge[1], Glen Gawarkiewicz[2], Jay A. Austin[1], and James H. Churchill[2]

1 Introduction

Temperature, salinity, and density fronts on continental shelves are of interest for a variety of reasons. These density fronts may contain strong alongfront flows which fundamentally affect advective timescales, as well as strong secondary circulation with upwelling and downwelling cells. Frontal zones have an important influence on the transport of nutrients and biota into or out of the euphotic zone, on the aggregation of predators near fronts, and on the transport of carbon cycle constituents in the coastal ocean. One category of fronts that have been newly appreciated in the recent literature are persistent mesoscale fronts which are oriented across isobaths, found in regions where coastal water masses converge alongshelf. For example, on the continental shelf and slope near Cape Hatteras, Mid-Atlantic Bight (MAB) shelf water and South Atlantic Bight (SAB) shelf water converge from opposite directions alongshelf, carrying water of significantly different origin with large differences in T-S characteristics [*Pietrafesa et al.*, 1994; *Flagg et al.*, 2002; *Savidge and Bane*, 2001; *Berger et al.*, 1995]. This convergence supports a strong alongshelf gradient in temperature, salinity, and density known as the "Hatteras Front". A similar situation exists on the east coast of South America, where northward flowing shelf water of subantarctic origin and southward flowing shelf water of subtropical origin converge near ~35°S, resulting in large alongshelf gradients in temperature and salinity across the "Subtropical Shelf Front" [*Piola et al.*, 2000, see their figures 6 and 7]. These authors further suggest the alongshelf convergence on the shelf may be the shoreward extension of the convergence of the western boundary currents adjacent to the shelf, the Brazil/Malvinas Current Confluence. The Hatteras Front also coincides with a region of deep ocean convergence seaward of the continental slope (the Gulf Stream flowing northward and the nearshore limb of the Slope Sea Gyre flowing southward [*Csanady and Hamilton*, 1988]). From this one may reasonably speculate that alongshelf convergence on the shelf could potentially occur shoreward of other western boundary current convergence zones or separation points, subject to the details of local wind and buoyancy forcing on the shelf, making mesoscale cross-shelf oriented fronts of possible significance in a variety of locations.

The existence of the Hatteras Front has been recognized for many years [*Stefansson et al.*, 1971], but has only recently been implicated as an important conduit for both onshore and offshore transport near Cape Hatteras [*Churchill and Berger*, 1998; *Savidge*, 2002]. Interest in cross-shelf transport of shelf water and its constituents is acute in this region. Many commercially important species utilize the adjacent Albemarle and Pamlico Sounds for nurseries, while spawning offshore, requiring some physical transport mechanism to move the poorly motile eggs and larvae between the two regimes [see, for example, *Checkley et al.*, 1988]. Hatteras Front associated wintertime shoreward currents appear to be frequent and energetic enough to potentially account for that transport in winter [*Savidge*, 2002]. Transport of pollutants from the open ocean into those delicate Albemarle and Pamlico Sound ecosystems, as a result of proposed outer shelf commercial drilling for oil and gas or potential shipwrecks in the dangerous and crowded water off Cape Hatteras is also of concern. Further, the Cape Hatteras region has been identified as a major conduit for the transport of shelf-derived and terrestrial particulate matter to continental slope depocenters, some fraction of which consists of organic carbon [*Biscaye et al.*, 1994; *Lee et al.*, 1991]. Though it is clear that the shelf water convergent upon Cape Hatteras from both the north and the south must exit the shelf, the details of that seaward transport remain only sketchily understood. Both *Churchill and Berger* [1998] and *Gawarkiewicz et al.* [1996] propose mesoscale front related mechanisms to account for such export (discussed in Section 2).

Substantial observational effort has been expended in the past near Cape Hatteras, though much of it has been focused either northward or southward of the boundary between the MAB and the SAB, and not on the important transition region between the two. In the MAB, the second Shelf Edge Exchange Project (SEEP-II) of the Department of Energy (DOE) extended southward to 37 40'N [*Biscaye et al.*, 1994]. The more recent DOE Ocean Margins Project (OMP) reached south to 35°27'N, encompassing an area usually occupied by the alongshelf oriented northern portion of the Hatteras Front [*Kim et al.*, 2001; *Flagg et al.*, 2002], but seldom by the cross-shelf oriented portion of the front. In the SAB, the extensive DOE SAB project measurements of 1977-1991 did not extend northward past Cape Hatteras [*Atkinson et al.*, 1985], nor did the

[1]**Center for Coastal Physical Oceanography, Old Dominion University**
[2]**Physical Oceanography Department, Woods Hole Oceanographic Institution**

Frontal Eddy Dynamics Experiment (FRED) [*Glenn and Ebbesmeyer*, 1994a, b]. The South Atlantic Bight Recruitment Experiment (SABRE, 1991-1997) did encompass the boundary region between the MAB and the SAB in its purview, but the physical oceanography of the region was addressed primarily through modeling studies (which included no shelf or shelf edge frontal structures) [*Werner et al.*, 1999]. Field measurements (predominantly biological variables) were concentrated almost exclusively south of Cape Hatteras. In fact, to our knowledge, the only extensive observational program focused on the physical oceanography of the transition region between the MAB and the SAB, spanning the shelf both north and south of Cape Hatteras, was the North Carolina Field Program (NCFP) of 1992-1994, sponsored by the Minerals Management Service (MMS) [*Berger et al.*, 1995]. The transition zone focus of that experiment has yielded valuable insights thus far, including illustrating year-round alongshelf convergence near Cape Hatteras from both the north and south [*Savidge and Bane*, 2001], and indicating a variety of ways in which the requisite cross-shelf divergence (off-shelf export) depends on the Hatteras and Gulf Stream Fronts [*Churchill and Berger*, 1998; *Savidge and Bane*, 2001]. These findings will be discussed in Section 2. These studies have also illustrated the difficulty of examining front-related phenomena with moored instrumentation and the sparse resolution of typical shelf-scale hydrographic surveys.

The documented existence of mesoscale cross-shelf oriented fronts on the east coasts of both the U.S. and South America motivates further study of this type of front. If, in fact, such convergence zones occur preferentially in regions where energetic boundary currents separate from the shelf edge, as they do in the cases cited above, the possibility of frontal interactions also demands attention. Interactions between the Hatteras Front and the Gulf Stream Front seem quite likely (discussed below) [*Churchill and Berger*, 1998; *Savidge and Bane*, 2001]. Two additional mesoscale fronts on the shelf near Cape Hatteras are potentially in sufficient proximity to the Hatteras Front to also affect its circulation and transport: the MAB Shelf-Break Front [*Gawarkiewicz et al.*, 1996] and the newly recognized MAB Mid-Shelf Front [*Ullman and Cornillon*, 1999]. Frontal interactions have been documented involving the Shelf-Break and Gulf Stream Fronts [*Gawarkiewicz et al.*, 1996], and appear to be directly involved in the offshelf export of shelf water near Cape Hatteras [*Ford et al.*, 1952; *Gawarkiewicz et al.*, 1996; *Lozier and Gawarkiewicz*, 2001].

In the following, a field program is developed to examine the circulation and density fields associated with the Hatteras Front and its proximate fronts near Cape Hatteras. The primary observational strategy will be to deploy two research vessels equipped with ADCP, undulating-CTD sensors, and surface mapping CT sensors, to acquire repeated high resolution vertical sections and horizontal surface fields of velocity and density. Such an approach is ideal for locating these mobile features, measuring their horizontally compact (cross-front), vertically variable density and velocity fields at adequate vertical and horizontal scales to resolve them, and mapping their orientation and evolution under typical meteorological forcing. While standard current meter, salinity and temperature moorings have provided valuable evidence concerning the magnitude of the velocity associated with the Hatteras Front, and the salinity, temperature, and density contrasts across it [*Churchill and Berger*, 1998; *Savidge*, 2002], such moorings are not well-suited to defining frontal details, dynamics, variability or orientation in horizontal space. Hydrographic transects utilizing typical shelf station spacing of $\sim$10 km are inadequate to resolve the structure of the $\mathcal{O}$(15 km) wide front [*Churchill and Berger*, 1998; *Savidge*, 2002]. Standard CTD cast hydrographic sections at higher horizontal resolution require long periods of time to accomplish, compromising the synopticity of the sections and drastically reducing the time available to make repeat crossings to document frontal evolution. Modeling efforts of the area typically fail to include a realistic time-varying Gulf Stream density structure near the shelf edge, and do not include alongshelf density gradients in their initial conditions [*Werner et al.*, 1999]. Given the important role the Hatteras Front may play in cross-and alongshelf transport issues near Cape Hatteras, perhaps the most valuable first step will be to obtain a detailed understanding of frontal velocity and density structures along the front, and in regions where the Hatteras Front, the MAB Mid-Shelf Front, the Shelf-Break Front, and the Gulf Stream Front interact. This data-set will be important in establishing the spatial and temporal scales of fronts in the region, which is necessary for properly modelling the along-shelf and cross-shelf transport processes.

2 Background

Alongshelf transport is convergent north of Cape Hatteras to Duck, N.C., approximately 90% of the time, and 66% of the time south of Cape Hatteras to Ocracoke Inlet [*Savidge and Bane*, 2001]. The convergence of the cold, fresh, less dense MAB shelf water and the warm, salty, denser SAB shelf water defines the Hatteras Front (represented by the schematic bold grey line labelled "HF" in Figure 1). This front crosses the shelf near Cape Hatteras (the "nose" of the front), and extends northeastward along the shelf edge north of Cape Hatteras (the "seaward flank"). Cruise data from November 1992 shows the hydrography associated with the front (Figure 2), coarsely illustrating the large temperature (5-10 °C), salinity (2-5 psu), and density gradients (1-3 σ_t units) across it. Though the existence of the Hatteras Front has been known for decades [*Stefansson et al.*, 1971], its dynamical significance has been little appreciated, and it has not been well studied. For example, little is known about its cross-frontal structure, its temporal variability, its translation along and across isobaths, nor how it terminates or transitions at its offshore end. Three recent studies [*Churchill and Berger*, 1998; *Savidge and Bane*, 2001; *Savidge*, 2002], each based primarily on two years of continuous velocity, temperature, and salinity data from the MMS-sponsored NCFP mooring array on the Cape Hatteras continental shelf, indicate the dynamical significance of the Hatteras Front to mechanisms of cross-shelf transport there. These studies are summarized briefly below.

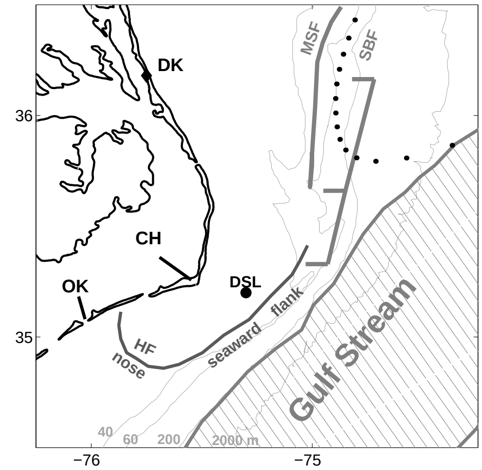

Figure 1: Map of the study region near Cape Hatteras, North Carolina. Schematic Hatteras Front (HF), Gulf Stream and Mid-Shelf Front (MSF) are shown. The approximate location of the Shelf-Break Front is illustrated by the drifter track (dots at daily intervals). The two export regions described by *Churchill and Berger* [1998] are shown with grey bars bracketing the limits. Duck (DK), Cape Hatteras (CH), Ocracoke Inlet (OK), and Diamond Shoals Light C-MAN station (DSL) are indicated.

2.1 The Hatteras Front and Cross-Shelf Advection

In an investigation of transport variability near Cape Hatteras, *Savidge and Bane* [2001] demonstrated robust alongshelf convergence at Cape Hatteras throughout all seasons of the year, with southward current predominating in the southern MAB, bringing fresh cool water southward year-around, and northward mean current in the northern SAB advecting warmer saltier SAB water northward. This scenario is clearly consistent with the existence of the Hatteras Front, and suggests it may be a fundamental feature of the hydrography in this region. This study also showed that while along-shelf transport variability was primarily wind-driven, along-shelf transport convergence (and cross-shelf transport) was highly correlated with Gulf Stream position offshore, with a more shoreward Gulf Stream position leading increased along-shelf convergence by a few days.

The observed alongshelf convergence at Cape Hatteras obviously requires cross-shelf divergence (offshelf export of shelf water) to satisfy continuity. From the OMP mooring data, *Kim et al.* [2001] found evidence for significant volume flux off the shelf to the north of Cape Hatteras, equalling roughly half of the volume transport entering the Hatteras Shelf (out to the 100 m isobath) off of Cape Henry. *Churchill and Berger* [1998] have examined mechanisms of export, focusing primarily on the MAB shelf water component of the convergent alongshelf water. They documented two export zones immediately north of Cape Hatteras, each associated with distinct mechanisms. In the southernmost zone, extending from 35°20'N — 35°40'N, offshelf export of MAB shelf water is associated with currents directed along the Hatteras Front near the shelf edge. Here, the Front is oriented obliquely at a 10-20° angle clockwise from the shelf edge. As the Hatteras Front advected shoreward, strong along-front currents were observed in the off-shelf direction, while seaward frontal motions showed weak evidence of along-front currents directed shoreward. *Savidge and Bane* [2001] speculated that the coherence they observed between Gulf Stream position and off-shelf export was due to the Gulf Stream influencing the motion of the Hatteras Front, and therefore modulating the *Churchill and Berger* [1998] export mechanism.

Along with predominantly convergent alongshelf transport at Cape Hatteras, periods of along-shelf divergence and shoreward cross-shelf transport exist which are associated with the Hatteras Front. South of Cape Hatteras, *Savidge* [2002] has identified energetic shoreward currents in the upper water column in winter. Shoreward velocities averaged ~12 cm/s, persisted from 0.5 to 4 days, occurred every 2.5-5 days, and were present ∼30% of the time from October through March. Flow along the Hatteras Front where it crosses the shelf appears to account for the shoreward currents, seen as temporal 'events' at the moorings as the Front advected alongshelf past the mooring locations. The alongshelf advection of the nose of the Hatteras Front depended both on winds and on the Gulf Stream proximity to the shelf edge, at temporal scales of days to weeks [*Savidge*, 2002]. Further, the alongshelf location of the Hatteras Front's nose appears to change seasonally, with southward rectification from September-May suggested by Advanced Very High Resolution Radiometry (AVHRR) satellite sea-surface temperature (SST) imagery, presumably due to the prevailing southwestward winter winds [*Savidge*, 2002]. Shoreward advection along the nose of the Hatteras Front was observed whether the front was advancing, retreating, or stationary over the mooring locations, in contrast to the observations of *Churchill and Berger* [1998] in the seaward flank of the Hatteras Front, where current direction along the front depended on the direction of frontal motion.

Seasonality in frontal density structure, circulation, and stability will likely exist, given the inherently seasonal variability in wind-forcing and water-mass T-S make-up in this region [*Berger et al.*, 1995; *Savidge and Bane*, 2001; *Flagg et al.*, 2002], and the near annual-period (pseudo-seasonal) Gulf Stream variability that has also been identified here [*Miller*, 1994; *Savidge and Bane*, 2001]. *Wright* [1976], *Houghton et al.* [1988], and *Lozier and Gawarkiewicz* [2001] all suggest some seasonality in the export of shelf water across the Shelf-Break Front in the MAB. The strength of along-front currents, cross-front density gradients, and frontal positions are all likely to vary accordingly in potentially dynamically important ways.

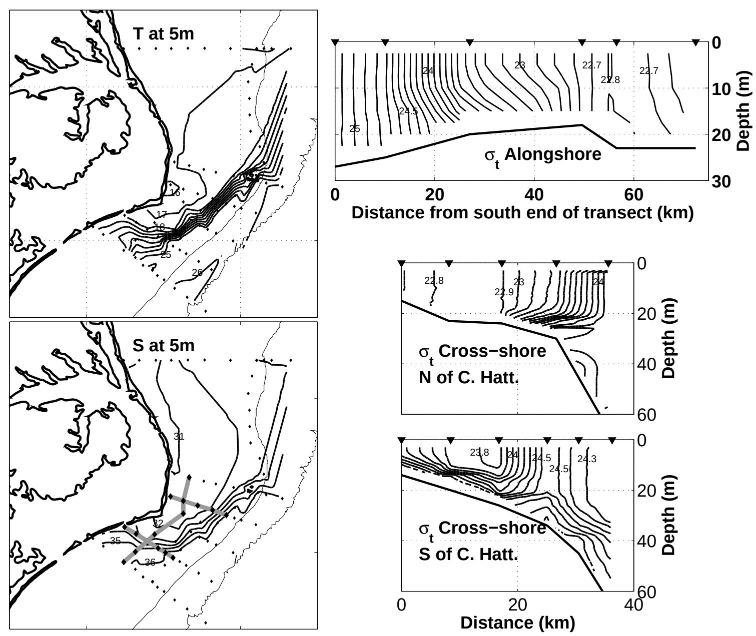

Figure 2: Hydrography from November 1992. Left panels: 5 m depth horizontal temperature (°C) and salinity (psu) maps. Station locations are shown as small diamonds. Right panels: vertical density section (σ_t) for one alongshelf transect and two cross-shelf transects. Locations of the sections are marked in bold grey lines on the lower left panel.

2.2 Frontal Interactions

The *Savidge and Bane* [2001] transport study linking Gulf Stream variability to alongshelf convergence and off-shelf export variability, and their suggestion that the source of the correlation was Gulf Stream/Hatteras Front interaction highlights the importance of interactions between the fronts that populate the Cape Hatteras region. At least four fronts potentially impinge on the shelf and shelf edge near Cape Hatteras: (1) the Hatteras Front, as discussed above; (2) the Gulf Stream Front [*Churchill and Cornillon*, 1991; *Glenn and Ebbesmeyer*, 1994a, b]; (3) the MAB Shelf-Break Front [*Gawarkiewicz et al.*, 1996], and (4) the recently identified MAB Mid-Shelf Front [*Ullman and Cornillon*, 1999]. Evidence indicating interactions between the Hatteras Front and the Gulf Stream Front was discussed in the preceding section. In this section, further indications of interactions among the family of fronts near Cape Hatteras are discussed.

In addition to the Hatteras Front-related export zone near Cape Hatteras discussed above, *Churchill and Berger* [1998] identified a second zone north of Cape Hatteras of off-shelf export from 35°40'N — 36°10'N, where diffuse export of shelf water occurred. The mechanism for export in this zone appeared to be entrainment into the Gulf Stream frontal circulation structure (meanders, filaments, and discharged Gulf Stream water). *Gawarkiewicz et al.* [1996] have investigated summer frontal structure of the Shelf-Break Front from 35°40'N — 36°50'N, overlapping and just northward of Churchill and Berger's second export zone. Using high-resolution circulation and density fields from ship-mounted ADCP and CTD casts, *Gawarkiewicz et al.* [1996] found evidence for Gulf Stream/Shelf-Break Front interaction, resulting in the export of MAB shelf water from the shelf to deeper waters. At least two modes of interaction were identified, and the possibility that such interactions could be altered by seasonal and Gulf Stream variability was noted. The Shelf-Break Front clearly participates in the delivery of northern origin water to the Hatteras Region, where floats entrained in the Shelf-Break Front circulation are routinely swept offshore along the Gulf Stream Front [*Lozier and Gawarkiewicz*, 2001; *Gawarkiewicz et al.*, 1996], further supporting a high probability of Gulf Stream Front/Shelf-Break Front interaction.

Despite the status of the Cape Hatteras region as a robust biogeophysical boundary between the MAB and the SAB, some exchange between the two regimes has been suggested in the literature. For example, *Pietrafesa et al.* [1994] suggest that water from the southern MAB resides as far south as Cape Fear (the second cape south of Cape Hatteras) as much as 10% of the time. Some evidence exists that there may be a pathway for exchange between the MAB outer shelf and the SAB inner-shelf associated with the frontal structure near Cape Hatteras. *Lozier and Gawarkiewicz* [2001] show at least one float that transits southward in the Shelf-Break Front, across Diamond Shoals (the shallow shelf region extending seaward from Cape Hatteras), and onto the mid-shelf in the SAB. J. Churchill, one of the co-PIs in this proposal, has also identified two drifter tracks that move from the MAB to the SAB. Recent findings from satellite imagery may be pertinent to this issue. Using an edge-detection algorithm based on image processing techniques, applied to 12 years of AVHRR SST imagery, *Ullman and Cornillon* [1999] have identified mid-shelf fronts in the MAB, located along approximately the 50 m isobath at locations from Cape Hatteras to the Bay of Fundy. These (not necessarily continuous) fronts appear primarily in winter SST imagery, situated shoreward of the Shelf-break Front, which is seaward of the 100 m isobath. On a November, 1999 cruise off New Jersey, *Rasmussen et al.* [2002] observed both fronts concurrently (Figure 3), with velocities in the Mid-Shelf Front of 30-40 cm s^{-1}. Interestingly, the Mid-Shelf Front appeared in the salinity fields, with no apparent surface temperature expression. This is consistent with *Ullman and Cornillon* [2001], who found salinity fronts at the 50 m isobath in historical hydrographic data. In the extreme southern MAB near Cape Hatteras, where the 50 and 200 m isobaths converge, it is difficult to discern two separate alongshelf-oriented fronts in the frontal loci plots of *Ullman and Cornillon* [1999]. These plots indicate high frontal probabilities following the shelf edge (representing presumably either the Shelf-Break Front, the Mid-Shelf Front, or some amalgamation of the two) extending southward in the MAB as far as the sharp bend in the 50 and 200 m isobaths (near 35°30'N) that is commonly a good marker of the Gulf Stream separation point. Though the preponderance of floats associated with the MAB Shelf-Break Front exit the shelf north of 36°N [*Gawarkiewicz et al.*, 1996], probably near the northern export site of *Churchill and Berger* [1998], it is possible that Mid-Shelf Front associated transport may feed the Hatteras Front from upstream, providing an exchange pathway from the MAB to the SAB.

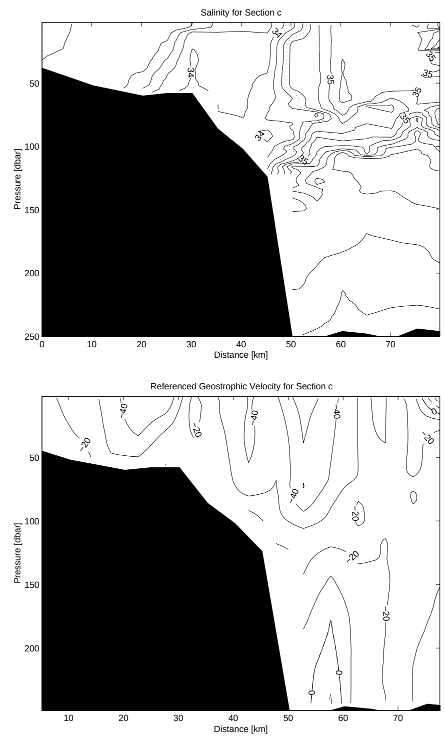

Figure 3: Salinity and referenced geostrophic velocity from the New Jersey shelf in November, 1999 [*Rasmussen et al.*, 2002]. Note the cross-shelf salinity gradient at x=20 km in the top panel, and the surface trapped jet at x=20 km in the bottom panel (maximum velocity >40cm/s).

It should be pointed out that radar, shipborne ADCP, and towed conductivity and temperature sensor arrays have also been used successfully within the Hatteras region to identify small-scale frontal structures and document interactions amongst them. *Marmorino et al.* [1994] studied a Gulf Stream filament with a horizontal scale of 8 km. *Marmorino and Trump* [1994] described a small-scale current rip with a horizontal scale of order 20 m. And an interesting case of frontal occlusion involving three different water masses was presented in *Marmorino et al.* [1998]. In general these studies have concentrated on smaller scale features than the larger and typically more persistent Hatteras, Shelf-Break, Mid-shelf, and Gulf Stream Fronts which we propose to study.

2.3 Tides and Inertial Variability Knowledge of the tidal and inertial variability in the region will be an important factor in utilizing ship-mounted ADCP velocity and undulating CTD density data to investigate mesoscale frontal processes on the Cape Hatteras continental shelf. The two-year MMS NCFP mooring dataset has allowed the tidal regime to be well characterized in the region [*Berger et al.*, 1995]. Barotropic tides are dominated by the semi-diurnal components. The M2 tidal velocities are of $\mathcal{O}$(5-10 cm s^{-1}), in phase both along and across the shelf. Diurnal currents are only a quarter as large, with southward phase propagation around Cape Hatteras [*Berger et al.*, 1995]. These magnitudes are small compared to the $\mathcal{O}$(40-50 cm s^{-1}) front-associated velocities expected [*Gawarkiewicz et al.*, 1996; *Churchill and Berger*, 1998; *Rasmussen et al.*, 2002]. Note that while *Savidge* [2002] found frontal velocities of $\mathcal{O}$(12 cm s^{-1}) in 24 hour-low-passed data, inspection of 3 hour-low-passed data from which the tides have been extracted indicate that velocities of $\mathcal{O}$(40-60 cm s^{-1}) can be expected in association with the nose of the Hatteras Front. Internal tide generation at the shelf edge does not appear to be a factor in this region of steeply sloping bathymetry, despite the documented presence of internal tides farther south at Frying Pan Shoals (the shoals off Cape Fear, two capes south past Cape Hatteras) [*Berger et al.*, 1995; *Ebbesmeyer et al.*, 1989]. This absence in Raleigh Bay and northward of Cape Hatteras is attributed to increased bottom slope along the narrow shelf and slope here, such that the bottom slope becomes less parallel with the slope of the 'internal wave tidal characteristic' of *Wunsch* [1969] (which depends on tidal frequency, the Coriolis parameter, and the Brunt-Väisälä frequency) [*Ebbesmeyer et al.*, 1989]. Internal wave variability at the inertial frequency also appears to be a relatively minor factor here, both at the mid-shelf [*Pietrafesa et al.*, 2002] and the shelf edge. Our own analysis of the MMS NCFP data indicates RMS values of 4 cm s^{-1} near the shelf edge.

2.4 Frontal Maintenance Mesoscale fronts such as the Hatteras or Shelf-Break Fronts must maintain some balance between processes acting to tighten spatial gradients in temperature, salinity, and velocity, and those that dissipate them. It is likely that synoptic-mesoscale processes (baroclinic or barotropic instabilities, interactions with Gulf Stream Rings and Filaments) dominate the dissipation [*Lozier and Gawarkiewicz*, 2001], especially in locations removed from Cape Hatteras, where the temporal and spatial scales of variability are large. Limited evidence concerning small scale mixing processes in either the Hatteras or Shelf-Break Fronts suggests that small-scale diapycnal mixing may not be important. *Gawarkiewicz et al.* [1996] found such high vertical density stratification in the summer Shelf-Break Front that sufficient vertical shear to mix the water column appeared unlikely, based on Richardson Number estimates. Coarsely defined vertical density gradients in the Hatteras Front would require larger vertical shears than those observed in the pointwise moored current meter data [*Savidge*, 2002]. *Grothues and Cowen* [1999] and *Grothues et al.* [2002] suggest relatively little mixing of water across the Hatteras Front, based on associating larval assemblages with T-S characteristics across the front. On the other hand, [*Flagg et al.*, 1994] suggest mixing is likely in salinity intrusions. Further, near Cape Hatteras, spatial scales of the dominant variability are potentially much smaller than elsewhere on the shelf [*Flagg et al.*, 2002]. Certainly the strong winds and shallow shelf water column over Diamond Shoals (the shallow shelf region off Cape Hatteras between the coast and the shelf-break) suggest that vertical mixing may become important. Therefore it becomes more difficult to discount the possibility that small scale mixing processes may be important there.

Recently it has become possible to make order of magnitude estimates of vertical mixing using simple and inexpensive instrumentation. The method, suggested to us by Dr. Ann Gargett of Old Dominion University, estimates vertical mixing in stratified water from CTD measurements [*Galbraith and Kelley*, 1996; *Ferron et al.*, 1998] by estimating the Thorpe Scale (L_T) [*Thorpe*, 1977] from density inversions. This measure of the overturning scale may be related to mixing properties by equating the Thorpe scale with the Ozmidov scale (L_O), which is related to the dissipation rate (ϵ) as $L_O = (\frac{\epsilon}{N^3})^{1/2}$ [*Ozmidov*, 1965]. N is the Brunt-Väisälä frequency. Dissipation estimates may then be used to estimate vertical eddy diffusivity using standard methods [*Osborn*, 1980]. Whether these CTD-based methods are able to resolve relevant overturning scales in any given oceanic regime depends on the stratification there, and on the depth, C and T resolution of the CTD instrument. *Galbraith and Kelley* [1996] found their methods useful in coastal regions with $N \simeq 0.03$ s^{-1}, using a CTD with 2 cm depth resolution and 0.001 kg m^{-3} density resolution. The Hatteras, Shelf-Edge, Mid-Shelf, and Gulf Stream Fronts near Cape Hatteras exhibit N in the 0.01-0.03 s^{-1} range [*Gawarkiewicz et al.*, 1996; *Savidge*, 2002; *Rasmussen et al.*, 2002; *Savidge et al.*, 1993], so should be ammenable to these methods using CTD instrumentation of equivalent resolution. While the dissipation estimates, and therefore the vertical eddy viscosity estimates obtained using CTD measurements are cruder than those obtained with expensive microstructure measurements, the CTD approach can provide order of magnitude estimates at an order of magnitude lower cost. We plan to include such measurements as a complement to our primary data collection (outlined in Section 4) near Cape Hatteras, to determine whether small scale mixing processes are relatively important in maintaining the frontal dynamical balance and will require future detailed attention, and to indicate possible seasonal variability in their contribution.

3 Science Questions

It is clear that the Hatteras Front, the MAB Shelf-Break Front, and the Gulf Stream Front each play a role in cross-shelf transport, both on and off-shore at Cape Hatteras. The recent identification of a Mid-Shelf Front in the southern MAB by *Ullman and Cornillon* [1999], and the *Rasmussen et al.* [2002] observation of the Mid-Shelf Front off New Jersey suggests that it too may dynamically affect the Cape Hatteras region. The critical role that fronts apparently play in cross- and along-shelf transport near Cape Hatteras motivates interest in details of circulation associated with the fronts. While previous observations of Shelf-Break Front/Gulf Stream interactions north of 35°40'N [*Gawarkiewicz et al.*, 1996] begin to address this issue, spatially dense observations of velocity and density across the Hatteras Front do not exist, across either its nose or seaward flank, or in regions where the Hatteras, Shelf-Break, Mid-Shelf, and Gulf Stream Fronts approach and interact with each other. A number of science issues need to be addressed for the region:

1. Kinematics and Dynamics of the Hatteras Front.
   (a) What are the magnitudes and spatial scales of the velocity and density fields associated with the nose and seaward flank regions of the Hatteras Front? Does the frontal circulation account for the shoreward currents documented by *Savidge* [2002]? How do circulation and density fields differ along the Front? Does the Front intersect the bottom along either the nose or seaward flank?
   (b) Is motion of the front a critical aspect of advection along the Front? How does ambient flow affect velocity and density field structures in the nose or seaward flank of the Front? Does the presence of a mean shelf flow opposing southward advection of the Hatteras Front affect its structure? Does vertical shear in the ambient flow affect Front density and velocity fields in either the nose or seaward flank of the Front? How do temporal or cross-shelf variations in the flow south of Cape Hatteras affect the motions and structure of the Hatteras Front?
   (c) What roles do vertical mixing and entrainment play in the nose of the Hatteras Front? Are there significant variations alongfront related to mixing, particularly as the flow crosses isobaths?
   (d) What are the leading terms in the cross-frontal dynamical balance? What ageostrophic terms are most important? Do seaward flank dynamics differ from those in the nose of the front? What aspects of ambient flow variability most affect the dynamical balances in the front?
2. Multiple Front Issues.
   (a) Are the MAB Mid-shelf and Shelfbreak Fronts distinct and detectable near Cape Hatteras? Does the Hatteras Front terminate to the northeast, or is it continuous with the MAB Shelfbreak or Mid-Shelf Fronts? Do pathways for exchange between the MAB and SAB shelves exist along the Hatteras Front?
   (b) Does the Gulf Stream interact with the Hatteras Front in dynamically important ways, as hypothesized by *Savidge and Bane* [2001], as it apparently does with the Shelfbreak Front [*Gawarkiewicz et al.*, 1996]? Can specific modes of interaction be identified? How does variability in the MAB Mid-shelf or Shelfbreak Front affect the Hatteras Front?
3. Frontal variability.
   (a) How do frontal density fields, circulation fields, and frontal interactions change with seasonal variability in water masses and wind forcing, and near-annual period Gulf Stream variability?
   (b) What are the important forces acting to maintain and destroy the fronts? Does vertical mixing play a role in this region of shallow water, strong winds, and spatially variable density gradients?

4 Proposed Observations

The primary observational strategy will be to utilize two research vessels equipped with ADCP, undulating-CTD sensors, and surface mapping CT sensors, to acquire high resolution vertical sections and horizontal surface fields of velocity and density. A relatively large ship (120 or 177 ft) will be deployed for the shelfbreak/upper slope work, while a smaller vessel will be used shoreward of the 40 m isobath. Large area rapid surveys, to define the location of the fronts of interest, will be combined with repeated high resolution across-front sections to examine the nose and seaward flank of the Hatteras Front, and to survey regions where the Hatteras Front, the MAB Mid-Shelf or Shelf-Break Front, and the Gulf Stream Front approach each other. Ship-board ADCPs and undulating-CTD sensors typically render horizontal resolution of about one kilometer after processing [*Munchow et al.*, 1992; *Gawarkiewicz et al.*, 2001], so should adequately sample the Hatteras, Shelf-Break, Mid-Shelf, and Gulf Stream Fronts, which are each typically several kilometers wide [*Savidge*, 2002; *Gawarkiewicz et al.*, 1996; *Glenn and Ebbesmeyer*, 1994b]. Two cruises are planned: one in winter (January, 2004), another in late summer (August, 2004).

4.1 Velocity, temperature, and salinity measurements

In order to sample effectively on the inner to middle shelf (where the Hatteras Front nose crosses over relatively shallow bathymetry) as well as over the shelfbreak and upper slope (where the Hatteras Front seaward flank, the Shelf-Break Front, the Mid-Shelf Front, and the Gulf Stream Fronts approach each other), an adaptive sampling strategy using two research vessels is envisioned. Most of the mid-shelf to shelf edge/slope mapping and section work will be conducted during continuous operation aboard either the 177 ft *R/V Oceanus* (in winter) or the 120 ft *R/V Cape Henlopen* (in summer). The *Henlopen* is equipped with shipmounted ADCP (RDI 300 and 1200 kHz), surface mapping Salinity, Temperature, Fluorescence, and Oxygen sensors, and a Danmark/Chelsea Scanfish MKII undulating CTD. The Scanfish routinely undulates to within 3 m of the bottom in shallow water during operations with the *Henlopen*, so that it will be useful for resolving the foot of the fronts. The *Oceanus* has been recommended (by the *Henlopen* Marine Operations Manager, Matt Hawkins) for the winter cruise, since its deeper draft and larger size should provide reasonable sea-keeping for the rough conditions expected at the shelfbreak in winter. Mr. Hawkins has agreed to provide the *Henlopen*'s Scanfish to us for use aboard the *Oceanus* winter cruise, to provide instrument consistency between cruises.

The shelfbreak grids north of Cape Hatteras will be aligned with the Hatteras Front seaward flank in the center of the cross-shelf transects (Figure 4). The cross-shelf length of the transects will be roughly 50 km, between the 40 m and 1000 m isobaths. Approximately four of the six cross-shelf transects shown can be covered in one day. We intend to focus primarily on the southernmost four, shifting our spatial coverage to the northern four as events allow. These overlapping study sub-sites will allow us to extend the spatial range of our observations, while still providing daily repetitions of the center two shelf edge transects in Figure 4. Note also that repeat sampling of the alongshelf-oriented segments along the upper slope will enable us to calculate variations in the offshelf heat, salt, and mass fluxes as the Shelfbreak Front tends offshore to the east, injecting "Ford water" into the Gulf Stream edge [*Ford et al.*, 1952; *Lillibridge et al.*, 1990]. Initially, along-shelf spacing of the cross-shelf transects will be 10 km. This is based on the correlation scales obtained near the Shelf-Break Front off New England [*Gawarkiewicz et al.*, 2002]. This will provide objective maps of the study area with small error estimates between sections. Temporally, we will repeat the grids at one day intervals. This interval is based on the anticipated temporal correlation scales. After performing the initial grid, we will evaluate the transect spacing to make sure we are appropriately resolving the observed features, and adjust the grid spacing as needed. Transmission of AVHRR SST imagery to the vessel will guide large scale mapping of the area, and facilitate the location of the Hatteras, Shelf-Break, Mid-Shelf, and Gulf Stream Frontal boundaries for the high resolution across-front sections.

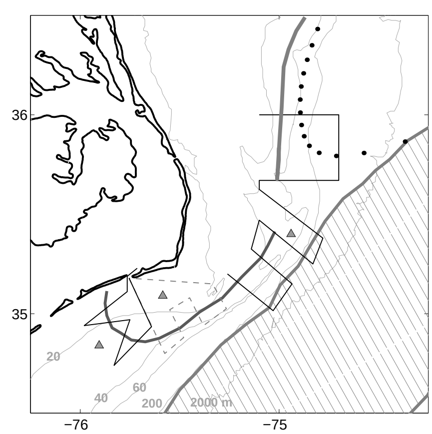

Figure 4: Map showing sample cruise tracks and schematic mooring locations (grey △). The Hatteras Front, Mid-Shelf Front, Shelf-Break Front are shown without labels - see Figure 1 for clarification.

Concurrently with the larger ship operations on the outer shelf, inner and middle shelf surveys will be made on the *R/V Slover*, Old Dominion University's new 55 ft research vessel. The *Slover* is instrumented with shipboard ADCP (RDI 600 kHz), surface mapping salinity, temperature, fluorescence, and Oxygen sensors, and two undulating CTD systems: a WS Ocean Systems (now WS EnviroTech) U-TOW (approximately the same size and capabilities as the more well known Chelsea Nu-Shuttle) and a Sea-Sciences Acrobat. The *Slover* will wait until good weather (low winds and waves) allows rapid deployment day-trips for surface mapping and high resolution sections across the nose of the Hatteras Front out to approximately the 40 m isobath. The *Slover* can travel in excess of 15 knots in calm seas, allowing it to transit rapidly from the coast out across the narrow shelf (only 40 km from the coast to the 40 m isobath) to the study site along the nose of the Hatteras Front. Monitoring of C-MAN Diamond Shoals station wind and wave data and National Weather Service radar information from nearby weather stations at Wakefield, Va. and Morehead City, N.C. will facilitate the identification of such windows of opportunity. At the start of each observational window, an alongshelf ADCP and surface mapping CT transect will be undertaken to establish the alongshelf location of the nose of the Hatteras Front. Undulating CTD and ADCP transects will then commence across the front. The *Slover*'s grids south of Cape Hatteras will be aligned with the nose region of the Hatteras Front in the center of the cross-front transects (Figure 4). The cross-front, approximately alongshelf oriented transects will be roughly 25 km long. Along-front spacing of the cross-front transects will be 10 km initially, as will those along the seaward flank. Grids will be repeated at one day intervals, with evaluation of the front location, transect spacing, and adjustment of the grid spacing as needed. If the weather allows and the mapping of the nose region procedes without significant difficulty, the transition region between the nose and seaward flank of the Hatteras Front will also be surveyed (see the dashed sample cruise track in Figure 4). As fuel and weather allow, large area ADCP and surface mapping will be accomplished at night to map the position and orientation of the nose of the front, in addition to the detailed ADCP and CTD profiling by the undulating vehicles during the day. Measurements of wind, position, and bottom depth will also be available from routine underway collection aboard the *R/V Slover*.

The U-TOW, an ~$40,000.00 instrument belonging to Carl Friedrichs and the Virginia Institute of Marine Sciences (VIMS) has been permanently loaned to Old Dominion University for use aboard the *R/V Slover*, so is available at no charge to the present proposal (see the letter of support from Dr. Friedrichs). The U-TOW is currently fitted with a WS Ocean Systems Marine Monitor CTD, which utilizes a Falmouth Scientific OEM-CT sensor. A transmissometer and an oxygen sensor will be added at relatively low cost. The vehicle has a pressure sensor, precision altimeter, and tilt sensors integrated into the towed platform, and will allow effective sampling from the surface to very near the bottom. As currently configured, the effective horizontal resolution should be several hundred meters when towed at 6 knots in 50 m of water. This should be more than sufficient to resolve frontal features. The *Slover* already has a winch and wire appropriate for this vehicle. ODU currently owns a smaller Sea-Sciences Acrobat undulating CTD which will serve as a back-up to the U-TOW. The Acrobat is similar in construction and operation to a Guildline MiniBAT, which Dr. J. Austin (a co-PI) has extensive experience with. The Acrobat is equipped with a FSI CTD, and oxygen and transmissivity sensors will be added.

The reasons behind the use of two research vessels are essentially twofold. First, the large range of shelf depths over which the study site extends requires careful consideration of the different ship/undulating CTD vehicle combinations to effectively observe the entire length of the Hatteras Front. For measurements of the seaward flank of the front, and regions over the outer-shelf and slope where the Hatteras Front may interact with the Gulf Stream or the Shelf-Break Front, the larger boat/Scanfish CTD combination should work well. The depth-range of the Scanfish will allow sampling of the fronts from near the surface to within 3-4 m of the bottom, or up to 200 m depth, whichever is shallower. The size of the *Henlopen* or *Oceanus* will allow continuous operation through moderately rough seas in deeper water than would be practical on a smaller vessel. Conversely, for inner to mid-shelf work off Cape Hatteras, where bottom topography is quite variable and shallow, with hard ridges over Diamond Shoals, the U-TOW/Acrobat combination is ideal. These instruments can be flown quite close to the seabed in water as shallow as 10 m without difficulty, making it possible to profile a large percentage of the shallow water column. The small size and manuverability of the *Slover* will also facilitate rapid stops or turns in the event of the instruments snagging on the bottom or other unforeseen difficulties. It has been the experience of researchers at ODU that deployment of small undulating CTD vehicles in shallow water from a large ship like the *Henlopen* can be problematic, due to the slower response time inherent in operations on a larger ship.

The second reason for deploying two ships is the large area of the study site. The shelf edge area south of Woods Hole studied by *Gawarkiewicz et al.* [2001] required two days of cruise time to sample an approximately 50 by 50 km area with the SeaSoar undulating CTD vehicle, completing four cross-shelf oriented transects at ~8 knots, with approximately 10 km or greater alongshelf spacing. The study site for this proposal, extending from about the 10 m isobath nearshore, along the Hatteras Front's nose, northward along the seaward flank to 35°40'N, and out across the Shelf-Edge and Gulf Stream Fronts constitutes an approximately 250 by 50 km area: roughly 5 times the lateral extent of the *Gawarkiewicz et al.* [2001] cruises. Using two ships will allow repeat sampling in under three weeks, and will improve the synopticity, permit larger areal coverage during good weather, and allow us to see contemporaneous shifts in frontal positions both north and south of Cape Hatteras.

Three current meter moorings are planned, utilizing bottom-mounted RDI Workhorse Sentinel units to measure tides for extraction from the shipboard ADCP records. The instruments selected for these moorings are capable of 1 m or better depth resolution at the depths at which they will be deployed. This will greatly enhance the utility of the shipborne ADCP measurements. One pair of moorings (600 kHz instruments) will bracket the nose of the Hatteras Front to the northeast and southwest along the 25 m isobath south of Cape Hatteras. Exact placement will be based on an early alongshelf transect by the *Slover*, with attention to optimal spacing for defining an empirically-based analytical model of the tides [*i.e.,Munchow*, 2000, methods]. The *Slover* will deploy and recover them prior to and after both the winter and summer observational periods. The scheduling flexibility of the *Slover* and its nearby homeport will allow this phase to proceed without interfering with operations concurrent with the *Henlopen/Oceanus.* The sampling rate will be high, to capture any potential phase lags that may occur in the tides as they progress through the large density gradients associated with the Front. The third mooring (a 300 kHz instrument) will be deployed at the shelf edge near the center of the larger vessel's survey area, near the Gulf Stream separation point (as estimated from AVHRR SST imagery and the MMS NCFP data set). One mooring should suffice to define tides at the shelf edge, where tidal velocities are quite low, and the signal has not been (potentially) modified by travelling across the shelf or around Cape Hatteras. This mooring, deployed and recovered from the *Oceanus* or *Henlopen* should thus supply quite local information for tidal extraction from the shipboard ADCP data. We will deploy a thermistor chain, a pair of near-top and near-bottom mounted SeaCats, and an anemometer at this mooring location as well, utilizing equipment presently at the PIs disposal. Placement of this mooring package must take into account local fishery activities, which often focus at the shelf edge.

Two sets of remotely-sensed near-real-time data will be assembled during the experiment to both enhance the daily planning of the next day's cruise tracks, and to complement the analysis of the ship and mooring data in the post-cruise analyses. The first of these is satellite AVHRR SST imagery. One excellent source for such imagery is the NOAA CoastWatch Southeast Region website (http://www.ccfhrb.noaa.gov — Dr. Jon Hare, regional node manager). We have also made arrangements with the Ocean Remote Sensing Group at the Johns Hopkins University Applied Physics Laboratory to provide high-resolution AVHRR SST imagery over a 3x4°region surrounding Cape Hatteras during the planned cruises, at no cost (see Dr. R. Gasparovic's letter of support). In addition to AVHRR SST imagery, surface velocity fields from shore-based long-range SeaSonde high-frequency radar north of Cape Hatteras will also be assembled. This radar array will be deployed in summer, 2003, by Dr. Harvey Seim and collaborators as part of the Southeast Atlantic Coastal Ocean Observing System (SEA-COOS). Coverage will include the region north of Cape Hatteras to the North Carolina border, out to the shelf edge, at ~6 km resolution (see Dr. Seim's letter of support). Both datasets will be available on the web in near-real-time.

4.2 Thorpe-Scale measurements

In order to estimate vertical mixing across the fronts, an additional set of measurements are proposed to measure vertical overturning scales: high vertical resolution temperature, salinity and density sections across the Fronts, taken with a free-falling CTD profiler. Determination of the Thorpe Scale, as described in Section 2.4, requires vertical CTD casts, so that CTD measurements from towed undulating vehicles would not be suitable for this approach. Dr. Ann Gargett has offered the use of her two OS200 CTDs, instruments with variable C, T ranges, allowing the finescale vertical resolution necessary for the sampling proposed here. To take advantage of this offer, development of a deployment capability will be necessary. The rough seas and shallow waters of the Cape Hatteras region suggest significant shipheave, which would not be damped by curvature in the in-water portion of the deployment cable, as it might be for deep water casts. These factors dictate the use of free-fall casts to deploy the CTDs. OS200 CTDs are light, small, and internally recording, so that the requirements of a free-fall deployment system are modest. Dr. Gargett estimates her instrument technician can devise a deployment system for ≃\$1500.00 per system, utilizing off-the-shelf parts from the local maritime outfitters. At that price, it is reasonable to instrument both the ships. We propose to buy one additional OS200 CTD profiler (\$7100) as a backup. These measurements will be taken as logistics allow in the Hatteras Front and associated fronts, if their presence is indicated. These measurements will render *in situ* order of magnitude estimates of vertical eddy diffusion coefficients in and near the fronts. We emphasize that Dr. Gargett has volunteered instrumentation, technical support, and data analysis/interpretation assistance for these measurements at no cost to the present proposal (see her letter of support). We view their inclusion as exploratory, to determine if future attention should be turned to vertical mixing in this region. While the entire experiment does not depend on their successful completion, we are excited about the opportunities for new insight they will provide. The proof of concept and development opportunity afforded by the inclusion of these measurements will potentially expand the toolbag of the typical synoptic-to-larger-scale observational physical oceanographer, allowing them to examine small-scale processes as they pertain to larger frontal to synoptic scale features. As further motivation for these measurements, Dr. Gargett's involvement is an ideal opportunity for the PIs in this proposal to develop expertise in examining small-scale processes as they pertain to the larger frontal to synoptic scale features that they more typically address. The costs in time and resources for these measurements are quite low, and the potential benefits are great.

4.3 Cruise Scheduling

To ascertain seasonal variability in frontal-related transport processes, with respect to the inherently seasonal variability in wind-forcing, water-mass T-S characteristics, and possible seasonality in frontal locations, two periods of ship-borne observations are proposed, one in late summer, another in winter. A two-week cruise is planned for the late summer deployment. This is consistent with areal coverage and repeat sampling requirements for the study site, as discussed above. A longer three-week cruise is planned for winter, to allow for the loss of several days to bad weather conditions, and to permit repeat sampling to capture the evolution and motion of the fronts over timescales at which they are expected to "oscillate". Both wind and Gulf Stream forcing typically vary in the 4-10 day band in this region [*Austin and Lentz*, 1999; *Savidge and Hamilton*, 2003], such that the motion and variability in structure of the fronts may be expected to vary over similar timescales. The mooring data examined by *Savidge* [2002] supports such timescales of variability in position for the Hatteras Front nose.

Scheduling of the cruises will be based on the following considerations. Steady summer NE winds prevail at the Diamond Shoals C-MAN station from June through mid-August [*Savidge and Bane*, 2001]. The annual minimum bottom water temperatures in June or July (advection of cold pool waters) [*Flagg et al.*, 1998], combined with the maximum in integrated surface heating of late summer suggests a late July-early August target date would provide a good window to observe established summer hydrographic conditions under typical summer wind conditions. Timing of the winter cruises should assure a late enough date that winter conditions on the shelf are established, without being so late that an unusually early Spring transition arrives before the cruise. Monthly climatologies of wind speed, significant wave height, and dominant wave period from long-term (1984-2001) data at the Diamond Shoals C-MAN station (DSLN7) suggest little appreciable difference among the months November through March, so that a January-early March target date for the study seems reasonable.

Operating conditions on the *Slover* on the shelf in winter are something of a concern. Dan Aspenleiter, Director of Marine Operations at the University of North Carolina-Wilmington and Captain of the R/V Cape Fear, estimates that off Hatteras Inlet, South of Cape Hatteras, we can expect every third day to be unacceptable for marine operations, with as many as half of our 21 scheduled days to be unmanagable in the worst years. Inspection of 15 years of hourly wind data from the Diamond Shoals C-MAN station supports this notion, indicating numerous two to three day periods in January every year when the winds do not exceed 10 m/s. Obviously safety is paramount, but we are cautiously optimistic about successful data-collection on the shelf for 10-14 days out of 21 in January-February. Winter operation in the Hatteras shelf-break region off a large vessel like the *Oceanus* has ample precedent: both the MMS-sponsored 1992-1994 NCFP experiment and the more recent OMP effort illustrate successful mooring deployment and recovery and transect-style data-collection.

5 Analysis

The observational program proposed will obtain high spatial resolution information on the circulation and density structures associated with the Hatteras Front and its proximate fronts near Cape Hatteras. In order for the transect data to be useful, of course, the velocity data must be adjusted for ship motion, and tidal and inertial effects must be removed. Standard procedures exist for quality control and conversion of ship-borne ADCP velocity measurements from a ship-based to a geographically-based frame of reference. For example, the CODAS system of Dr. Eric Firing and collaborators at Univ. of Hawaii [*Firing and Ranada*, 1995] is installed and operating at ODU.

The removal of tides (expected to be small — see Section 2.3) will be facilitated by the planned ADCP moorings for the experiment, and by the high quality characterization of the tides in the area provided by the two-year MMS NCFP mooring array data. Both data sets can be used to fit an empirically-based analytical three-dimensional representation of the tides to the ship-borne ADCP data using, for example, the methods of *Munchow* [2000]. Bracketing the nose of the Front with two ADCP moorings will be especially helpful in fitting such a model. Another approach to the removal of tides from shipboard ADCP data is to use tidal model predictions to define the tidal currents, for example the satellite altimetry based inverse model of *Egbert et al.* [1994]. Both model-based and empirical approaches will be investigated.

In order to remove inertial signals (also expected to be small) from the records, we will use a one-dimensional model of the mixed layer (such as the *Price et al.* [1986] model) which does a good job in deep water of capturing the variance within the surface mixed layer. The inertial response is more complicated in shallow water, where the lower layer can also be excited, producing a first baroclinic mode-type response, with opposing flows near the surface and bottom. A two layer response may be expected within several baroclinic Rossby radii of the coast. The planned mid-shelf ADCP moorings will be important in allowing us to determine whether the inertial response is confined to the surface mixed layer or whether a first baroclinic mode response is more evident. There are some existing theories for inertial response in shallow water [*Millot and M. Crepon*, 1981; *DeYoung and Tang*, 1990] which can be compared to the data from the three moorings. After doing this comparison, we will gauge the utility of further modelling to remove inertial band motions from the shipboard ADCP records.

The corrected high resolution across-front sections of velocity and density from ship-board ADCP and undulating-CTD sensors will then be analysed in conjunction with large-area rapid surveys of surface velocity and density fields to address the identified science issues. While transect data will not answer all of the science questions enumerated, there are significant aspects of the front-related processes here that will be well served by our efforts. While unanticipated findings will require a flexible analysis approach in the long run, the results of our first order analyses should address the following aspects:

Hatteras Front Structure — Inspection of the large number of cross-frontal transects will allow the $\mathcal{O}$(15 km) wide Hatteras Front velocity and density structures to be defined at $\sim$ 1 km resolution. We hope to define these fields over the length of the Front, over the relevant meterorological forcing cycles, in two distinctly different seasonal meterological forcing regimes and background density fields. Verification of large alongshelf velocities associated with the Front will validate its apparent importance in cross-shelf transport. Comparison of seaward flank transects with nose transects will explain apparent divergence along the Front, given the predominant shoreward surface flux described for the nose, and the seaward flow in the seaward flank. Seasonal comparisons will ascertain frontal existence and location in summer, and define first-order seasonal variability. Comparing fields of fronts in motion (southward vs. northward moving nose region or eastward vs. westward moving seaward flank) will illuminate the seaward flank's dependence on frontal motion that is apparently absent in the nose region. Cross-shelf velocities associated with advecting the seaward-flank of the Front shoreward or seaward will likely exhibit more vertical shear (changes of sign are not uncommon — see *Churchill and Berger* [1998], Figure 11) than the alongshelf velocities advecting the nose of the front, such that isopycnal slope in the seaward flank may depend more on the direction of frontal motion than it may in the nose of the Front. An important scientific goal of the analyses will be the comparison of the volume fluxes associated with the fronts obtained from highly resolved fields (spatially and temporally) with previous estimates obtained from more coarsely spaced mooring arrays which cannot resolve the fronts [e.g. *Churchill and Berger*, 1998]. Recent transport measurements of the Shelf-Break jet off New Jersey indicate transports as large as 1.3 Sv [*Rasmussen et al.*, 2002], much larger than previous estimates [*Beardsley et al.*, 1985], and so the direct measurement of heat, salt, and mass transports offshore north of Hatteras is extremely important in obtaining realistic budgets of these quantities for the Middle Atlantic Bight. Overall, we will be able to address Section 3 items 1a,1b, and 1c with significant confidence.

Multiple Front Interactions — There are a number of important issues regarding interaction of fronts that we will address. First, the surveys will enable us to examine the Shelf-Break Front structure north of Cape Hatteras and its proximity to a possible Mid-Shelf Front. As these fronts approach Diamond Shoals, two key interactions occur: the Gulf Stream entrains shelf water (with an unknown proportion taken from the Shelf-Break Frontal jet) and the shelf edge isobaths converge, potentially bringing the Mid-Shelf Front and the Shelf-Break Front into close proximity. It is unclear if remnants of the Shelf-Break Front cross Diamond Shoals, or if this occurs even intermittently, perhaps depending on Gulf Stream position. Another key issue is, what relation does the seaward flank of the Hatteras Front have with the shelf edge flows farther north. We are particularly interested in flow continuity across Diamond Shoals into the SAB, as well as the possibility of strong along-isobath gradients in this vicinity.

Second, the influence of the Gulf Stream on the Hatteras Front will also be examined. Since the Gulf Stream position affects the currents near the shelf edge, shoreward Gulf Stream displacements may lead to strong lateral shears near the seaward flank of the Hatteras Front. The Gulf Stream may also affect the ambient shelf currents that the nose of the Hatteras Front encounters. We will not be resolving the larger scale motions of the Gulf Stream, but the southernmost cross-shelf transects of the seaward flank surveys will extend offshore until the Gulf Stream is encountered, so that we will have local information on Gulf Stream proximity to the shelf edge. AVHRR imagery, though subject to degradation from cloud-cover, will also be helpful in determining proximity, as well as meander scales, as will the SEA-COOS high-frequency radar surface velocity fields of Dr. Seim. We are confident that we can answer questions 2a and 3a from Section 3. Question 2b will be more difficult, but we should have enough information on the Gulf Stream position to relate it to temporal shifts in the position of the Hatteras Front.

Dynamics — The surveys will enable us to obtain detailed information on both cross-frontal and alongfront gradients in the major fronts within this region. The cross-frontal momentum balance for shelf fronts is typically assumed to be geostrophic. However, a number of potential forcing agents may induce strong ageostrophic motions within this region. There is the possibility of strong advective effects (high Rossby number) particularly where ambient flows are in opposing directions. Because of the wide variety of water masses within the region, we anticipate high relative vorticities to appear. Frontal meandering and curvature are evident from AVHRR imagery. Ageostrophic velocities can be estimated using the gradient wind balance [*e.g.Pickart et al.*, 1999; *Gawarkiewicz et al.*, 2002]). Ageostrophic velocities within the Shelf-Break Front have been estimated to be as large as 30 cm s^{-1} in large meanders, making this is a potentially large signal. Potentially interesting ageostrophic motion could also result from lateral motions of the fronts. *Churchill and Berger* [1998] show a nice example of the passage of the Hatteras Front across a mooring on a time scale of 2 days. The most interesting task will be to determine the balances when large frontal excursions are occurring. These may involve Ekman transport and frictional effects, alongshelf pressure gradients imposed at the shelf edge, or downstream advection of alongfront gradients.

Recent theoretical work on buoyancy-driven currents will provide some direction for the initial analysis. The theories of *Yankovsky and Chapman* [1997] offer some insight into the relation between frontal transport and the cross-shelf position of a front. *Lentz and Helfrich* [2002] contains useful information on scaling buoyant plume velocities near the nose and seaward flank. We will undoubtedly encounter more complex flows, but these will serve as conceptual models for initially characterizing the fronts. In fact, numerous theoretical treatments on the dynamics of propagating fronts in the coastal ocean appear in the literature. While a review of that literature is beyond the scope of this proposal, the predictive power of relevant theories should be explored, and concise observation-based measures of their applicability developed. Once detailed measurements are in hand, relevant theory will be more easily identified. Section 3 items 1d, 2b, 3a and 3b will therefore be addressed, to the degree that transect data allow.

6 Significance of Research and Outreach

This experiment will provide important new information on the circulation and density fields associated with cross-shelf oriented mesoscale fronts and on interactions between proximate fronts of similar scale. Such fronts may play a central role in cross-shelf transport in the coastal ocean. We hope to verify that Hatteras Front related circulation constitutes a primary cross-shelf pathway near Cape Hatteras for both shoreward and seaward transport. These measurements will define transport mechanisms in a particularly energetic region of high offshelf export and considerable shoreward transport, and permit a dynamical analysis of frontal circulation features. Spatial and temporal correlation scales will be defined, thereby substantially informing future modeling efforts of this oceanographically complex region.

The proposed measurements of overturning scales in and near the fronts will directly address the dynamical balances of the maintenance of the mesoscale fronts near Cape Hatteras. Estimation of the vertical eddy viscosity associated with the fronts will also provide invaluable information for modeling studies. Further, they will support the development of economical turbulence measurement techniques, which will ultimately allow oceanographers who do not specialize in micro-scale measurements to obtain process-specific field measurements of turbulence (see Dr. Gargett's letter of support).

The onshore transport associated with the Hatteras Front may be extremely important in understanding recruitment dynamics for commercially important fish, many of which spawn on the outer shelf during the winter near Cape Hatteras and rely on physical mechanisms for larval transport to estuarine nursury areas. We will collaborate with Dr. Jon Hare, a fisheries specialist with NOAA-NMFS in Beaufort, N.C. (see his letter of support), who will coordinate larval fish surveys near Cape Hatteras to coincide with our winter observational program. We anticipate that our results will help lead to better understanding of environmental factors affecting recruitment dynamics near Cape Hatteras, particularly if we are able to identify new, rapid transport pathways connecting the fronts.

In addition, the Cape Hatteras region contains large numbers of marine mammals which appear to congregate near the fronts. We will work with Dr. Lance Garrison, a marine mammals specialist with the NOAA Southeast Fisheries Science Center in Miami, Fl. (see his letter of support), to better understand the spatial distribution of the bottlenose dolphin in relation to the various frontal systems. Dr. Garrison will conduct aerial surveys of marine mammal populations in the Cape Hatteras region, which he plans to coordinate with our winter and summer cruises. The combined physical and mammal population information should enhance NOAA's mammal mortality reduction efforts significantly.

Dr. Gawarkiewicz will also use this data for two ONR-sponsored programs with societal relevance. He is currently involved in the "Capturing Uncertainty in the Tactical Environment" ARI, which is an attempt to quantify the uncertainty of sonar performance (including transmission loss) in marine environments. Frontal variability that we observe will be used in propagation calculations to see what effect multiple fronts have on such uncertainty. Dr. Gawarkiewicz has also been involved in the ONR-sponsored program "Effects of Sound in the Marine Environment" to model the impact of various Navy sonar systems on marine mammals. Establishing spatial distributions of marine mammals through our work with Dr. Garrison will be useful in establishing environmental factors on bottlenose dolphin distributions (one target species of the initial studies).

The findings of this study will be disseminated through the scientific community through presentations at national meetings and articles published in refereed journals. We will involve two graduate students during the cruise periods to collect and assess AVHRR SST imagery, high frequency radar data, and evolving weather conditions, and to participate as science crew on the *Slover* cruises. We will also recruit an undergraduate student to participate in the cruises (no cost), through ODU's participation in NSF's Research Experience for Undergraduates (REU) program. Outreach to the K-12 community will be possible at both the primary and secondary grade levels. Dr. Savidge has been involved in the National Ocean Sciences Bowl (a question and answer contest for high-schoolers organized by the Consortium for Oceanographic Research and Education (CORE)), serving on the Bowl's technical advisory panel for questions, and acting as moderator and judge for the Virginia regional Bowl. A series of questions based on results from this study will be developed and submitted to CORE Headquarters in Washington, D.C.. Dr. Gawarkiewicz will continue to visit Falmouth public schools to talk about oceanography. He has averaged 3 one hour talks per year in the school system over the past few years. In addition, he was recently added to the Board of Directors of the Children's School of Science in Woods Hole, and he is working with the teacher of the Oceanography and Marine Biology courses to incorporate current research results into the curriculum.

7 Results from prior NSF Support

Dana K. Savidge has no prior NSF support.

Glen Gawarkiewicz Co-P.I with D. Chapman NSF OPP94-22292: *Dense Water Transport Off Arctic Continental Shelves: Numerical Studies of Shelf-Basin Interaction* (period: 04/15/95-03/31/98; amount: $434,506). Processes by which dense water formed beneath an Arctic coastal polynya moves offshore and into the deep Arctic basins were studied, using a 3-D, primitive-equation numerical model in idealized settings to isolate the fundamental dynamics. The ocean response beneath a steady coastal polynya was examined with prescribed geometry and surface buoyancy forcing to represent brine rejection accompanying ice production. We found that the dense water is carried offshore by energetic, small-scale (15-25 km) eddies. With continued ice production in the polynya, a balance is achieved between the surface buoyancy input and the offshore buoyancy flux by eddies. Scaling arguments produced simple algebraic expressions for the maximum density anomaly achievable and the time needed to reach this maximum [*Chapman and Gawarkiewicz*, 1997]. The importance of spatial variations in the surface buoyancy flux was examined [*Chapman*, 1998], and the results were applied to a two-layer fluid to explain some recent laboratory results [*Chapman*, 1997]. These results have been generalized in a theoretical study of the efficiency with which baroclinic eddies can transport heat (or density) across a narrow front [*Spall and Chapman*, 1998]. The steady-polynya results have been extended to the time-dependent case by incorporating a model for the polynya size and surface buoyancy flux based on atmospheric conditions [*Chapman*, 1999]. The behavior of the eddies when they reach the shelf edge has been examined [*Gawarkiewicz*, 2000]. An inverse model was used to study the importance of shelf processes on the overall structure of the Arctic circulation and formed the basis of a Ph.D. dissertation and two subsequent papers [*Goldner*, 1998, 1999a, b]. The three-dimensional adjustment of a stratified flow over a sloping bottom has been examined [*Chapman and Lentz*, 1997] to show the effects of density advection in the bottom boundary layer. Finally, a review article has summarized our present understanding of the influence of sea ice processes on Arctic shelves [*Gawarkiewicz et al.*, 1998].

Jay A. Austin P.I. NSF OCE-0136559: *Collaborative Research: Dye Tracer and Modeling Investigations of Cross-Shelf Circulation during Coastal Upwelling* (period: 2/1/02-1/31/05; amount: $106,634). This field program commenced in summer 2002, and is a collaborative effort with A. Dale and others at Oregon State University. Preliminary results from two successful cruises over the past summer were reported in December, 2002 in a departmental seminar at ODU. Dr. Austin has no other prior NSF support.

James H. Churchill P.I. NSF OCE-9712889: *Examining Sediment Transport and Dynamics as Part of the Lake Superior Kites Project* (award period: 03/01/98 to 02/28/03; amount of award: $1,003,135). Churchill is currently involved in a number of projects with NSF support. These include a study of processes affecting harmful algal blooms in the Gulf of Maine, a project investigating physical processes over Georges Bank, and a study of near-shore fluid and sediment dynamics in Lake Superior. Of relevance to this proposal is the Lake Superior study. The field work of this project included acquisition of data from moored sensors, ship-board surveys of water mass and suspended sediment distribution and Lagrangian studies using GPS-Argos drifters. Thus far, analysis of the data acquired has focused on the dynamics of the Ontonagon River plume, the principle source of terrigeneous material to the study region, the mechanisms responsible for cross-margin sediment transport, and water mass exchange between Lake Superior and an embayment. Findings have been presented at three national meetings (2000 & 2002 Ocean Sciences, 1999 ASLO). A paper describing the Ontonagon River plume dynamics is in press [*Churchill et al.*, 2002b], and a paper dealing with lake-embayment exchange has recently been submitted for publication [*Churchill et al.*, 2002a]. In addition, two papers dealing with near-bottom sediment and fluid dynamics off the Keweenaw Peninsula are in preparation.