Tidal and Wind Mixing versus Thermal Stratification in the South Atlantic Bight.

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Short title: WHITE PAPER:

SAB STRATIFICATION ENERGETICS

DRAFT: June 26, 2005

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Abstract. Controls on vertical density stratification are explored using a potential energy formulation for the South Atlantic Bight (SAB). The efficiency of wind and tidal mixing remained poorly understood. Wind and heat flux data from 2003 is used to evaluate some preliminary spatial and temporal estimates of the work balance in the SAB. The tidal information is provided by the most recent database available for the SAB. During the fall and winter, all the different forcing mechanisms combined to provide conditions favoring mixing over the entire shelf. The use of this simple parameterization, as well as h/u^3, estimates for frontal prediction in the SAB is discussed. The resulting fields suggest the presence of a front in the near-shore region around the 10-m isobath during spring and summer. The character of the SAB shelf produces large fluctuactions in the position of the front with small changes in forcing.

1. Introduction and Background

Seasonal fluctuations in the intensity of stratification in the water column are common in mid-latitude shelf regions. In the South Atlantic Bight (SAB) these fluctuations are controlled by the cycles of tidally forced mixing, heat flux, wind and river discharge. During spring, river discharge is large enough to produce sustained stratification in the inner- and mid-shelf [*Blanton and Atkinson*, 1983]. During summer, stratification is primarily determined by variations in the surface temperature resulting from increased solar radiation [*Atkinson and Blanton*, 1986]. Additionally, the summer intrusion of cold water from the Gulf Stream significantly increases stratification in the outer- and mid-shelf [*Atkinson et al.*, 1987; *Aretxabaleta et al.*, 2005]. Breakdown of stratification during fall occurs because of the combined effect of wind events,tidally-driven mixing, and associated with heat loss. Of these processes, wind mixing and heat loss are the most variable, being driven primarily by the passage of meteorological systems [*Blanton et al.*, 1987]. Turbulent mixing due to tidal forcing is relatively constant on seasonal scales with the most energetic inputs being localized to shallow banks and shelves and associated with the Estuaries and Tidal Inlet Complex (ETIC) in the SAB [*Blanton et al.*, 2004].

The classic works on the topic of stratification and work balance were first developed for tidal mixing front locations in the Celtic and Irish Seas by *Simpson and Hunter* [1974]; *Fearnhead* [1975]; *Simpson and Bowers* [1981]; *Simpson* [1981]. The usefulness of these methods has been demonstrated in several regions: Gulf of Maine [*Garrett et al.*, 1978; *Garrett and Loder*, 1981; *Loder and Greenberg*, 1986], North Sea [*Elliott and Clarke*, 1991;

Nielsen and St.John, 2001], Patagonia [*Rivas and Piola*, 2002].

In the SAB there have been two main previous studies addressing stratification and the processes that modify it. *Blanton and Atkinson* [1983] looked at the effects that tidal mixing can have on stratification caused by fresh water input in the frontal zone of the inner-shelf. They suggested that during spring and summer "buoyancy flux caused by river discharge overcome the tendency for tidal power to produce a well-mixed system". Additionally, they expressed some concerns about the uncertainties associated with the values of bottom drag coefficients (C_{Db}) and tidal efficiency (ε_b). *Atkinson and Blanton* [1986] presented a more thorough study of the processes that affect stratification in shelf waters of the SAB. Their work included most of the processes that control stratification: heat flux, evaporation-precipitation, fresh water input, wind stress work, bottom tidal work, and advective processes are discussed. The main limitations of their work were the estimation of heat flux input from monthly temperature data and the derivation of the wind and tidal work from the friction velocities, u_*, instead of using explicit efficiency models.

In this paper, the basic potential energy argument is introduced and some preliminary estimates of the work balance on the SAB shelf will be presented. The potential use of this approach in the prediction of frontal locations is discussed.

2. Data Sources

The tidal velocity data for this study was extracted from the latest ADCIRC tidal database (TDB, *Blanton et al.* [2004]). The TDB includes information for the Estuaries and Tidal Inlet Complex (ETIC) in the SAB, which extends from the Florida-Georgia border to North

Carolina. The TDB data consists of depth-averaged velocity for the relevant tidal constituents. In the current study only five tidal constituents are used: M_2, S_2, N_2, $O_1$and K_1. The M_2 depth-averaged speed for the central SAB region is presented in Figure 1.

Figure 1.

The heat flux and wind velocity data for 2003 is extracted from the NCEP operational meteorological solutions (Eta Data Assimilation System, EDAS). The EDAS product has a temporal resolution of 6 h (four solutions daily) and a spatial resolution of 32km. Figure 2 presents the net heat flux comparison between EDAS data and observations for 2003 at the R2 SABSOON tower. The skill of the EDAS product (RMS$\sim$ $150\ W/m^2$) is adequate for this study, but the recovery of the daily cycle was not achieved partly because of the temporal resolution. In Figure 3 the monthly heat flux cycle for 2003 is presented. Comparison with previous years suggest higher net heat flux values during 2003 than in previous years (not shown).

Figure 2.

Figure 3.

3. Method

3.1. Basic formulation

The potential energy at a location in the water column can be defined as $pe(z) = -\beta\, z$, where z is the vertical distance from some reference level (the obvious choice being mean sea level, $z = 0$). β is the buoyancy per unit volume:

$$\beta = -g \left(\frac{\nabla \rho}{\rho_0} \right) \sim \frac{-g}{\rho_0} \frac{\partial \beta}{\partial z} \tag{1}$$

where g is the acceleration due to gravity, ρ is water density and ρ_0 is a reference density. The evolution equation for buoyancy is:

$$\frac{\partial \beta}{\partial t} + (\mathbf{u} \cdot \nabla)\, \beta = \kappa \nabla^2 \beta \tag{2}$$

where $\mathbf{u}$ is the three-dimensional velocity vector and κ is a diffusion coefficient. The evolution of potential energy is:

$$\frac{d(-\beta z)}{dt} = -z\frac{d\beta}{dt} - \beta\frac{dz}{dt} = -z\frac{d\beta}{dt} - \beta w \tag{3}$$

where w is the vertical velocity. Then substituting from the buoyancy evolution equation 2:

$$\left(\frac{\partial}{\partial t} + \mathbf{u} \cdot \nabla\right)(-\beta z) = -\beta w + \kappa \nabla^2 (-\beta z) + 2\kappa \frac{\partial \beta}{\partial z} \tag{4}$$

Using Reynolds averaging to separate mean and turbulent fluxes ($\mathbf{u} = \overline{\mathbf{u}} + \mathbf{u}'$ and $\beta = \overline{\beta} + \beta'$), the evolution of the mean potential energy is:

$$\left(\frac{\partial}{\partial t} + \overline{\mathbf{u}} \cdot \nabla\right)\left(-\overline{\beta} z\right) = \nabla\left(\overline{\mathbf{u}'\beta' z}\right) + \kappa \nabla^2 \left(-\overline{\beta} z\right) + 2\kappa \frac{\partial \beta}{\partial z} - \overline{\beta}\,\overline{w} - \overline{\beta' w'} \tag{5}$$

The first term of equation 5 corresponds to turbulent transport of potential energy. The second term is the diffusive flux of potential energy. The third term describes the conversion of internal to potential energy. The fourth and fifth terms correspond to the exchange to potential energy from mean kinetic energy (MKE) and eddy kinetic energy (EDE) respectively.

In previous studies [*Simpson and Bowers*, 1981; *Atkinson and Blanton*, 1986], most of those terms were neglected and a balance between the temporal change of potential energy and the turbulent transport of potential energy was considered.

$$\frac{\partial}{\partial t}\left(-\overline{\beta} z\right) = \frac{\partial}{\partial z}\left(\overline{w'\beta' z}\right) \tag{6}$$

The potential energy of the entire water column, PE, is the vertically integrated potential energy for every depth:

$$PE = \int_{-h}^{0} -\beta\, z\, dz \; = \int_{-h}^{0} \frac{g}{\rho_0}\frac{\partial \beta}{\partial z}\, z\, dz \qquad (7)$$

Therefore, integrating equation 6, we obtain the evolution equation of the potential energy of the water column.

$$\frac{\partial PE}{\partial t} = \overline{\beta' w'}\,|_0 - \overline{\beta' w'}\,|_{-h} \qquad (8)$$

The first term in the right hand side is the buoyancy flux through the surface and the second term is the buoyancy flux associated with the bottom. Several terms can be included with this formulation: heat additions (insolation, sensible heat, convection, latent heat of evaporation); loses through latent heat of evaporation; river runoff additions; loses through wind stress mixing, and tidal induced mixing. Positive inputs of PE occur through surface cooling, wind and tidal mixing. Negative inputs (increasing stratification) result from surface heating and, in some areas, from river discharge and precipitation. Parameterizations are necessary to include these terms in the equation and several earlier studies provided some of these parameterization for the coastal ocean [*Simpson and Bowers*, 1981; *Atkinson and Blanton*, 1986; *Csanady*, 1990].

3.2. Simplifications and Parameterizations

In the classical work by *Simpson and Bowers* [1981]; *Simpson* [1981] for the British Isles shelf, the change in potential energy was parameterized as:

$$\frac{\partial PE}{\partial t} = -\frac{\alpha g Q h}{2C_p} + \varepsilon_b C_{Db}\rho\overline{|u_b|^3} + \varepsilon_s \rho_a \gamma C_{Ds} W_{10}^3 \qquad (9)$$

where h is the water column depth, Q is the net heat flux gain, ε_b is the tidal mixing efficiency, ε_s is the wind mixing efficiency, C_{Db} is the bottom drag coefficient, C_{Db} is the surface drag coefficient, γ is the ratio of the wind-induced surface current to the wind speed, $\overline{|u_b|}$ is the tidal stream amplitude near the bottom averaged over a tidal cycle and W_{10} is the wind speed at 10-m.

Simpson and Bowers [1981] studied the parameter spectrum of the efficiencies (ε_b and ε_s). They first started with constant efficiency models and then considered the fact that efficiencies may be influenced by the existing level of stratification. The basic argument is that increasing stability reduces the efficiency, so they developed efficiency models with feedback. In the current study, only the constant efficiency models are considered.

A different parameterization of the wind and tidal work was given by *Atkinson and Blanton* [1986]. They included the work done by the wind from the friction velocity estimation.

$$Work_W = \rho u_*^3 = \rho \left[\left(\frac{\rho_a}{\rho} \right) C_{Ds} \right]^{3/2} W_{10}^3 \tag{10}$$

where ρ_a is the air density and u_* is the frictional velocity. The underlying assumption of this parameterization is a relationship between the efficiencies of wind mixing and the frictional velocity:

$$\varepsilon_s = \frac{\rho \left[\left(\frac{\rho_a}{\rho} \right) C_{Ds} \right]^{3/2}}{\rho_a \gamma C_{Ds}} \tag{11}$$

Using published values from *Atkinson and Blanton* [1986], the assumed efficiency of the wind work is $\varepsilon_s \sim [0.03, 0.05]$. These values are not that different from the ones used by *Simpson and Bowers* [1981]; *Blanton and Atkinson* [1983] $[0.01, 0.02]$. A similar parameterization was obtained for the tidal work. In that case, the tidal efficiency is related to the bottom drag coefficient by $\varepsilon_b = C_{Ds}^{1/2}$. This results on efficiencies around 5 % (5×10^{-2}) much larger than the values in the literature (*Simpson and Bowers* [1981], 4×10^{-3}; *Fearnhead* [1975], 10^{-2}).

In the SAB, the effects of the river discharge need to be included at least during spring and summer months. The simplest approach is to modify equation 9, neglecting buoyant effects of precipitation and evaporation, but including river discharge. The resulting expression can be written as:

$$\frac{dPE}{dt} = -gh\left[\frac{\alpha Q}{2C_p} + F\right] + \varepsilon_b C_{Db}\rho\overline{|u_b|^3} + \varepsilon_s \rho_a \gamma C_{Ds} W_{10}^3 \qquad (12)$$

where F is the freshwater flux. In the current study the effect of the river discharge is not considered due to the difficulties of the evaluation of appropriate river fluxes for the entire SAB region. *Blanton and Atkinson* [1983] looked at these effect only in the frontal zone of the inner-shelf. Bulk estimates of F, the rate at which buoyancy is generated by river discharge, are available, but strong assumptions have been made in past studies to estimate the spatial extent of the river flux influence. Future work will try to constrain and estimate this flux in a spatially consistent way.

In the current study, based on equation 9, the only effects that we are going to estimate are the surface heat flux buoyancy effects, tidal mixing and wind mixing. This leaves important forcings out of the basic balance, but if appropriate parameter estimation is achieved, the general spatial features of the SAB shelf can be recovered.

3.3. Parameter estimation

The determination of efficiency of mixing parameters and, to a lesser degree, drag coefficients, remains an open question for the SAB. In future work, an estimation of these efficiencies needs to be determined. In the current work, only the values used in previous studies (1) are going to be discussed. **Table 1.**

A first study by *Simpson and Hunter* [1974] considered tidal efficiencies for the Irish Sea tidal fronts but they did not include the values used in their calculations. *Fearnhead* [1975] considered a similar mixing model for the shelf around the British Isles and obtained tidal efficiencies between $\varepsilon_b \sim 1 - 2 \times 10^{-2}$. *Simpson and Bowers* [1981] and *Simpson* [1981] presented a complete analysis of the efficiency models both for tidal and wind mixing for the shelf seas around the British Isles, including the feedback efficiency model. Their tidal efficiencies were substantially smaller then in *Fearnhead* [1975]. In the Georges Bank region, *Garrett et al.* [1978] and *Loder and Greenberg* [1986] presented tidal efficiencies on the same order of magnitude as *Simpson and Bowers* [1981] and used the same surface efficiency and drag coefficient values.

In the SAB, *Blanton and Atkinson* [1983] used tidal efficiencies from the Fearnhead study and bottom drag coefficients that ranged $C_{Db} \sim 2 - 6 \times 10^{-3}$. In *Atkinson and Blanton* [1986] they used similar bottom and surface drag coefficients, $C_{Ds} \sim 2 \times 10^{-3}$. The biggest limitation of their estimate is the fact that they did not include explicit efficiency models, assuming constant values that resulted in rather large efficiencies, at least in the tidal case, $\varepsilon_s \sim 3 - 5 \times 10^{-2}$ and $\varepsilon_b \sim 5 \times 10^{-2}$.

A possible approach to calculate the efficiencies for the SAB would be to follow the simple equation presented by *Garrett et al.* [1978]:

$$\varepsilon_b = \frac{\alpha g Q h}{2 C_p C_{Db} \rho \overline{|u_b|^3}} \tag{13}$$

This formulation assumes a balance between tidal mixing and heat flux, excluding wind mixing or any other effects. Using this equation for the SAB fronts, the resulting tidal efficiency is on the order of $\varepsilon_b \sim 0.015$. This result is between the two values proposed by *Fearnhead* [1975] and is significantly smaller than the assumed efficiency used by *Atkinson and Blanton* [1986].

4. Results

4.1. Range estimates

In this section the ranges of the different terms in equation 9 are estimated based on the ranges of the different parameters described above (Section 3.3). The objective is to estimate the dominating terms under certain assumptions and the conditions that would produce no change of potential energy with time, $dPE/dt = 0$. This is the basic condition established by *Simpson and Bowers* [1981] for prediction of frontal position, i.e., the onset of stratification.

The first term on the right-hand side of equation 9 is the heat flux effect. Using $\alpha \sim 2 \times 10^{-4}$ °C^{-1}, $g \sim 10\ ms^{-2}$, $C_p \sim 4 \times 10^3\ Jkg^{-1}$°C^{-1}, for a range of depths $h \sim [5, 50]\ m$ and considering that the heat flux varies from a minimum in winter to a maximum during summer, $Q \sim [-200, 200]\ Wm^{-2}$, the resulting range of buoyancy work done by heat flux is $[-2 \times 10^{-4}, 2 \times 10^{-4}]\ Wm^{-2}$ at 5 m and $[-2 \times 10^{-3}, 2 \times 10^{-3}]\ Wm^{-2}$

at 50 m. The heat flux is working towards breaking down stratification during winter by the action of convection, while during summer the heat flux is stabilizing the water column.

The second term of equation 9 is the work done by the tides. The range of efficiencies from previous work is $\varepsilon_b \sim [4 \times 10^{-3}, 2 \times 10^{-2}]$ and the bottom drag ranges are $C_{Db} \sim [2 \times 10^{-3}, 6 \times 10^{-3}]$. Using a value of density of $\rho \sim 10^3\ kg\ m^{-3}$ and for tidal stream velocity [*Blanton et al.*, 2003] varying significantly depending on the region of the shelf, $u_b \sim [10^{-2}, 2 \times 10^{-1}]\ ms^{-1}$, the resulting range of tidal work, $[8 \times 10^{-9}, 2.5 \times 10^{-3}]\ Wm^{-2}$, varies by several orders of magnitude between the regions with strong tidal currents, localized primarily along shallow banks and associated with the Estuaries and Tidal Inlet Complex (ETIC), and the rest of the shelf.

The third term of equation 9 corresponds to the work done by the wind. The range of surface efficiencies from previous work is $\varepsilon_s \sim [5 \times 10^{-3}, 5 \times 10^{-2}]$ and the surface drag ranges are $C_{Ds} \sim [1 \times 10^{-3}, 2 \times 10^{-3}]$, with $\gamma \sim 4 \times 10^{-2}$. Using a value of air density of $\rho_a \sim 1\ kg\ m^{-3}$ with a range of wind speeds varying significantly depending on the season, $W_{10} \sim [1, 10]\ ms^{-1}$, the resulting range of wind work, $[2 \times 10^{-7}, 4 \times 10^{-3}]\ Wm^{-2}$, varies accordingly by several orders of magnitude. Therefore a small increase in wind velocity might have a significant effect on the work done by wind.

The complete balance in equation 9 suggests a balance between tidal and wind work, and heat flux stabilization that varies seasonally and spatially. Strong pulses of wind forcing associated with the passing of storms could provide enough mixing to maintain frontal structures. Of course during the fall and winter, when the intensity of the wind increases, its relevance increases as well. However during that same period the net heat flux effect is negative and therefore contributes to the destruction of stratification as well.

4.2. Spatial distribution of terms

From the previous section (Section 4.1), it was obvious the large variability in the range of the different terms depending on the parameterization used to estimate them. In this section, the spatial distribution of the different terms in the work balance is presented. The basic feature that we are trying to identify is the position of the zero total work line. This line represents the change from stabilizing to mixing work conditions. While negative work corresponds to stabilization of the water column, positive work values represent work done towards breaking down the stratification. **Figure 4.**

Figure 4 presents the total work for May 2003 as well as the individual terms in the work balance equation (Eq. 9). The efficiencies used were the ones assumed by *Atkinson and Blanton* [1986], $\varepsilon_s = 0.05$ and $\varepsilon_b = 0.05$. The first term (Figure 4a) is the heat flux work. This field is negative in the entire shelf corresponding with positive net heat flux during May. The maximum is in the open ocean associated with the Gulf Stream. The second term (Figure 4b) corresponds to the work done by the wind and is always positive. The third term (Figure 4c) is the tidal work, which is positive everywhere and with maximum values associated with the tidal inlets and the central part of the shelf. The resulting work balance (Figure 4d) is dominated by the tidal work over the shelf and by the negative heat flux work in the open ocean. The zero work line is encountered along the shelf break associated with the position of the Gulf Stream front. In fact, this result is not appropriate because it implies that during May there are stabilizing conditions in the open ocean and mixed conditions over the entire shelf.

Both the climatological fields [*Blanton et al.*, 2003] and the 2003 fields [*Aretxabaleta et al.*, 2005], suggest that those were not the conditions during this period. This result suggest that this parameterization is not adequate for this period of time. **Figure 5.**

Figure 5 presents the total work for May 2003 using the efficiencies proposed by *Simpson and Bowers* [1981], $\varepsilon_s = 0.02$ and $\varepsilon_b = 0.004$. The spatial distribution of each term presents no variation with respect to the previous figure, but the magnitude of the fields are significantly smaller, especially the tidal term. The resulting work balance (Figure 5d) is completely different from the previous case. The zero work line is encountered along the 10-m isobath, with mixed conditions near-shore and stabilizing conditions over the rest of the shelf. This is consistent with the location of the tidal front in previous studies [*Blanton*, 1981; *Blanton and Atkinson*, 1983]. **Figure 6.**

A comparison of the resulting work balance for June 2003 using different parameterizations is presented in Figure 6. The first panel corresponds to the same parameterization as in Figure 4d but for the month of June. The same tidal dominance is observed. The second panel uses the parameterization by *Fearnhead* [1975] for the tidal efficiency ($\varepsilon_b = 0.02$) and the same value for the wind efficiency ($\varepsilon_s = 0.02$). The tidal work still dominates the work balance producing enough mixing to have well-mixed conditions over the entire shelf. The third panel presents the same parameterization as in Figure 5d. The suggested frontal position during June is along the 10-m isobath as well. The fourth panel corresponds to another parameterization presented by *Simpson and Bowers* [1981] that constituted a baseline for their feedback efficiency model ($\varepsilon_s = 0.005$, $\varepsilon_b = 0.001$). In this case the frontal position is closer to the shore, near the 5-m isobath and in the proximity of tidal inlets. Similar results for the four cases were obtained for the spring and summer months (not shown). During the fall and winter the combined effect of tidal mixing, stronger wind mixing and convection generated conditions favoring mixing over the entire shelf in all cases. From this comparison the most appropriate representation of the efficiencies seems to correspond with the *Simpson and Bowers* [1981] parameterization.

4.3. Seasonal cycle

Using the *Simpson and Bowers* [1981] parameterization the seasonal changes in the work balance are presented in Figure 7. During winter, represented by the January work balance (Figure 7a), the three different forcings considered in the balance combined to provide conditions favoring mixing over the entire shelf and even in the open ocean. However, this balance does not include the effects of advection and therefore predicts mixing favorable condition over the Gulf Stream, where the advection of stable water preserves the stratification year around. In spring, represented by the April work balance (Figure 7b), mixing favorable conditions remained near-shore, and the development of the near-shore front can occur. Conditions favoring stability are present over most of the shelf, while over the Gulf Stream, mixing-favorable conditions remained. The conditions during the summer are represented by the month of July (Figure 7c), even though more general conditions seem to be present during June (Figure 6c) and August (not shown). The conditions during summer resemble the ones during spring for most of the shelf, while the Gulf Stream conditions have change from mixing-favorable to stability-favorable due to the increased heat flux and the reduction of the wind work during the summer. The conditions during fall (October, Figure 7d) are similar to the ones during winter due to the combined effect of tidal mixing, stronger wind mixing and convection that produced mixing-favorable conditions over the entire shelf and open ocean regions. **Figure 7.**

5. Analysis

One of the main uses of this type of analysis is for the prediction of frontal positions. In the previous section, the possibility of approximating frontal location by the use of the work balance approach was described. The utility of that estimate depends on the availability of appropriate heat flux and wind information for an extended area. The location of the fronts can be approximated with a simpler approach. In previous studies [*Simpson and Hunter*, 1974; *Garrett et al.*, 1978], a simple factor was used to determine the location of tidal fronts using the work balance discussed in the previous section as an starting point. They assumed spatially and temporally constant heat flux and efficiencies and neglected the effect of wind forcing. The resulting parameterization presented appropriate skill in predicting the location of the tidal front when compared with remotely observed fronts. The location of the front was associated with a critical value of h/u^3, where h was the water column depth and u was the surface tidal velocity. This parameterization has been shown to be useful in several shelves with different tidal regimes [*Simpson and Bowers*, 1981; *Garrett and Loder*, 1981; *Elliott and Clarke*, 1991]. The basic argument is that tidally induced mixing from the bottom prevents the development of stratification swallower than a critical depth given by h/u^3.

To apply the same parameterization to the SAB, we have to consider the limitations presented in previous sections about the existing knowledge of mixing efficiencies. Assuming the work done by the wind is not significant, the critical value for which well-mixed areas are predicted is:

$$\frac{h}{u^3} \leq \frac{2C_p \varepsilon_b \rho C_{Db}}{g \alpha Q} \quad (14)$$

Figure 8.

The values of this parameter h/u^3 are basically constant in time, except for the tidal spring-neap cycle. Meanwhile, the values of the right term of equation 14 change seasonally and in shorter time scales, so this parameter is only an approximation for the location of the front. The resulting field is presented in Figure 8. The comparison of this field with observations is left for future work. We know from previous studies that the frontal zone has a tendendy to fluctuate around the 10-m isobath [*Blanton*, 1981; *Blanton and Atkinson*, 1983; *Blanton*, 1996]. The contour of h/u^3 that better approximates the 10-m isobath is $10^{3.05} = 1122\ s^3 m^{-2}$. The choice of the 10-m isobath seemingly arbitrary and the frontal zone extent varies substantially depending on wind strength and direction [*Blanton*, 1996], and river discharge [*Blanton and Atkinson*, 1983].

Using equation 14 we can now determine the value of tidal efficiency that corresponded with that contour of h/u^3. Assuming a constant value of heat flux, $Q \sim 100\ Wm^{-2}$, the resulting tidal efficiency is $\varepsilon_b \sim 6 \times 10^{-3}$. This value is similar to the efficiencies proposed by *Simpson and Bowers* [1981] ($\varepsilon_b = 4 \times 10^{-3}$) and one order of magnitude smaller than the assumed efficiency in *Atkinson and Blanton* [1986] ($\varepsilon_b = 5 \times 10^{-2}$). In fact, if we were to consider the effect of the work done by the wind, the resulting tidal efficiency would decrease to values approaching or smaller than those proposed by *Simpson and Bowers* [1981].

Figure 9.

The h/u^3 distribution of the SAB shelf present singular characteristics that distinguishes it from other shelf areas. The cross-shelf distribution of h/u^3 along a transect (offshore from Savannah, GA) is presented in Figure 9. h/u^3 increases sharply in the first 10 km from the coast. Then, the parameter decreases to a seemingly critical value of $log_{10}(h/u^3) = 3.05$ and remains at that value until 40 km offhore. Then the parameter slowly increases reaching the same values present in the inner-shelf at 150 km offhore in the outer-shelf. This remarkable characteristic implies that, assuming h/u^3 controls the stratification in the SAB, small changes in the level of mixing work done by the wind or stabilization provided by heat flux will displace the frontal zone significantly.

6. Discussion

In the previous sections the available data was presented and analyzed to determine the basic work balance between tidal- and wind-induced mixing and heat flux for the SAB. The analysis showed that the balance is sensitive to the mixing efficiencies used. Given historical estimates of the tidal front position [*Blanton and Atkinson*, 1983; *Blanton*, 1996], the best performance seems to be achieved with the use of the efficiency parameterization described in *Simpson and Bowers* [1981]. Even with this limitation the basic spatial and temporal characteristics of the work balance can be described. This work provides a simple description of the processes controlling the potential energy variability on the shelf. The main use of this approach is in the determination of approximate frontal position when observations are not available. The balance between tidal, wind and heat flux provides an estimate of the location of the areas where the conditions change from stabilization-favorable to mixing-favorable, which are associated with stable fronts. Another approach is the use of simple parameterizations, like h/u^3, to estimate frontal location. The results of that approach suggest that it could be appropriate but the assumptions of the approach reduce the applicability of the estimate for changing conditions (e.g., seasonal cycle, inter-annual comparisons).

The cross-shelf charater of the h/u^3 parameter suggest that small changes on the level of work on the shelf could significantly displace the location of the coastal frontal zone. This rapid displacement of the front has been observed in several previous studies [*Atkinson and Blanton*, 1986; *Blanton et al.*, 1989; *Blanton*, 1996]. The forcing mechanisms associated with this displacement is frequently not a direct effect of wind mixing, but the result of river discharge pulses and wind reinforcement of gravitational circulation [*Blanton*, 1996]. The advective processes in the frontal zone could reinforced the stratification (e.g., upwelling-favorable winds) or favor mixing (downwelling-favorable wind). Several studies [*Blanton et al.*, 1989; *Werner et al.*, 1993; *Blanton et al.*, 1994] have described the effect of advective processes in the SAB coastal frontal zone.

Therefore, the use of these estimates of frontal location is limited by the assumption of advection not being an important factor. Under rapidly changing conditions and to study the dynamics associated with the front, the use of model simulations is likely more appropriate. The benefits of the energetics approach are its simplicity and its adequate predictive skill in conditions for which there is limited observed information.

6.1. Limitations

The main limitation of this study is the lack of buoyant effects from river discharge. *Blanton and Atkinson* [1983] showed the difficulties of including river effects on the work balance in the SAB shelf. The fundamental difficulty is the determination of the extent of the fresh water influence. The distribution of these waters depend not only on the river discharge but on the wind conditions present as well [*Blanton*, 1981; *Blanton and Atkinson*, 1983; *Blanton*, 1996]. An additional limitation is the fact that the river discharge is usually sporadic, concentrated in pulses and the time integrated effect is difficult to determine. The inclusion of the buoyancy effects of river inputs is going to increase the stability of the water column, specially during spring.

Another limitation is associated with the approach taken to establish the balance and includes several aspects. First, the balance is depth integrated, therefore the inclusion of any effects except from surface and bottom fluxes, has to be approximated by a parameterization. Second, the balance does not consider the effects of advection. These effects are significant specially when the effects of the Gulf Stream and its instabilities are considered. In the inner-shelf, gravitational circulation reinforced by wind and river discharge, and wave-current interactions near-shore are not considered. Third, the current approach does not include the effects of stratification on the efficiencies of mixing and the dynamics of the shelf. Fourth, this approach lacks the effect of any internal mixing (e.g., internal wave effects, double diffusion). The described parameterization is therefore only an approximation to the balance of tidal and wind mixing versus thermal stratification in the SAB.

7. Conclusions

The variability in the processes controlling stratification in the SAB can be determined using a simple energy balance. The terms included in this balance are the wind and tidal mixing work as well as heat flux effects, both towards mixing (i.e., convection) and towards stabilization of the water column. In the current study the effects associated with river discharge are not included because of the lack of adequate representation of its spatial and temporal influence on the shelf. Even without this effect, the resulting work balance provides significant information about the scales of the processes dominating changes in stratification. The determination of appropriate wind and tidal mixing efficiencies remains a difficult task. Using several efficiency parameterizations, the resulting work balance fields showed significant differences. The parameterization that resulted in sensible results was based on work done by *Simpson and Bowers* [1981] for the Irish Sea.

During spring the method predicts a tidal mixing front around the 10-m isobath, with tidally-driven mixing in the near-shore region and stabilization-favorable conditions over most of the shelf. However, during this period is when the effect of the river discharge would be larger. Therefore the spatial distribution of the work balance will be significantly different when that term is included. During summer similar characteristics are predicted for the entire shelf, with the near-shore front present and stronger stabilization in the rest of the shelf and open ocean. During fall and winter the combined effect of tidal mixing, stronger wind mixing, caused by the passage of storms, and convection, due to the negative heat flux, generated conditions favoring mixing over the entire shelf.

This simple work balance parameterization, as well as h/u^3 type estimates, has been shown to be useful for frontal position determination. However, the character of the SAB shelf (small cross-shelf variation of h/u^3) produces large fluctuactions in the position of the front with small changes in forcing. This approach does not provide any understanding of the dynamics associated with the front, but still provides a simple and adequate tool when observed or model information is not available.

Acknowledgments.

This work was supported by SEACOOS (ONR) ...

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Received ________________________

This manuscript was prepared with AGU's LaTeX macros v5, with the extension package 'AGU^{++}' by P. W. Daly, version 1.6b from 1999/08/19.

Figure Captions

Figure 1. M_2 depth-averaged speed for the central SAB region from the latest ADCIRC's tidal database.

Figure 2. EDAS heat flux (red) compared with available heat flux observations at the R2 tower (blue) for January, April, May and June of 2003.

Figure 3. EDAS heat flux for 2003 at the R2 tower position. The blue line represents the monthly mean and the black lines correspond to the monthly standard deviation.

Figure 4. Work balance (Wm^{-2}) terms for May 2003 estimated using the parameterization by *Atkinson and Blanton* [1986]. The efficiencies used were $\varepsilon_b = 0.05$ and $\varepsilon_s = 0.05$. The first panel corresponds to the work done by the heat flux. The second panel is the work done by the wind and the third is the work done by the tides. The fourth panel is the addition of all the terms. Negative values represent stabilization of the water column and positive values correspond to work done towards breaking down the stratification. A white contour corresponds to the zero work value, which represents the change from stabilizing to mixing work conditions.

Figure 5. As in Figure 4 but using the parameterization by *Simpson and Bowers* [1981]. The efficiencies used were $\varepsilon_b = 0.004$ and $\varepsilon_s = 0.02$.

Figure 6. Total work balance (Wm^{-2}) for June 2003 estimated using several parameterizations. The first panel presents the resulting fields using the parameterization by *Atkinson and Blanton* [1986] ($\varepsilon_b = 0.05$, $\varepsilon_s = 0.05$). The second panel uses the parameterization by *Fearnhead* [1975] for the tidal efficiency ($\varepsilon_b = 0.05$) and the same value for the wind efficiency ($\varepsilon_s = 0.05$). The third panel corresponds to the *Simpson and Bowers* [1981] parameterization ($\varepsilon_b = 0.004$, $\varepsilon_s = 0.02$). The fourth panel presents an additional parameterization presented by *Simpson and Bowers* [1981] that was the baseline for their feedback efficiency model ($\varepsilon_b = 0.001$, $\varepsilon_s = 0.005$). The gray contour corresponds to the zero work value, which represents the change from stabilizing to mixing work conditions.

Figure 7. Total work balance (Wm^{-2}) estimated using the *Simpson and Bowers* [1981] parameterization ($\varepsilon_b = 0.004$, $\varepsilon_s = 0.02$) for several months during 2003 (January, April, July, October). The white contour corresponds to the zero work value, which represents the change from stabilizing to mixing work conditions.

Figure 8. Spatial estimate of the parameter $log_{10}(h/u^3)$ for the SAB based on the depth-averaged tidal velocity from ADCIRC's TDB. The contour of $log_{10}(h/u^3) = 3.05$ is presented in blue. Note the overlapping of the contour with the 10-m isobath.

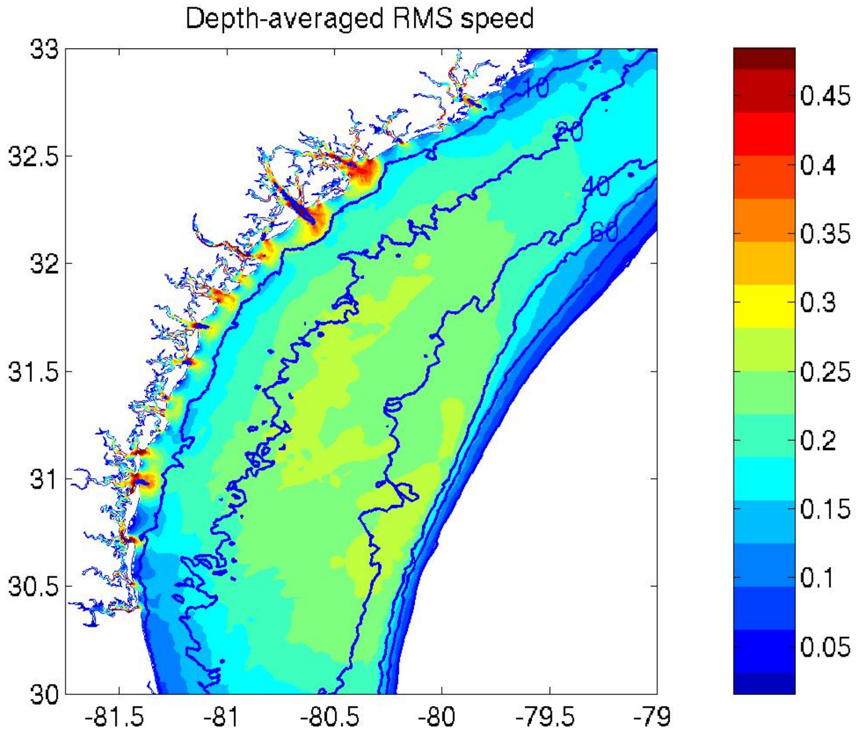
Figure 9. Cross-shelf transect (offshore from Savannah, GA to the shelfbreak) of the parameter $log_{10}(h/u^3)$ (blue line). The red line representes the bottom depth along the transect. The horizontal black line marks $log_{10}(h/u^3) = 3.05$.

Tables

Study	Region	Tidal efficiency ε_b	Bottom drag C_{Db}	Wind efficiency ε_s	Surface drag C_{Ds}
Fearnhead [1975]	British Isles	$1 - 2 \times 10^{-2}$	2×10^{-3}	–	–
Simpson and Bowers [1981]	Irish Sea	4×10^{-3}	2.5×10^{-3}	2×10^{-2}	1.5×10^{-3}
Garrett et al. [1978]	Georges Bank	2.6×10^{-3}	$2.1 - 2.4 \times 10^{-3}$	–	–
Loder and Greenberg [1986]	Georges Bank	2.6×10^{-3}	2.7×10^{-3}	2×10^{-2}	1.5×10^{-3}
Blanton and Atkinson [1983]	SAB	$1 - 2 \times 10^{-2}$	$2 - 6 \times 10^{-3}$	–	–
Atkinson and Blanton [1986]	SAB	5×10^{-2}	2×10^{-3}	$3 - 5 \times 10^{-2}$	2×10^{-3}

Table 1. Efficiency of tidal and wind mixing, and bottom and surface drag coefficients in previous studies.

Figures



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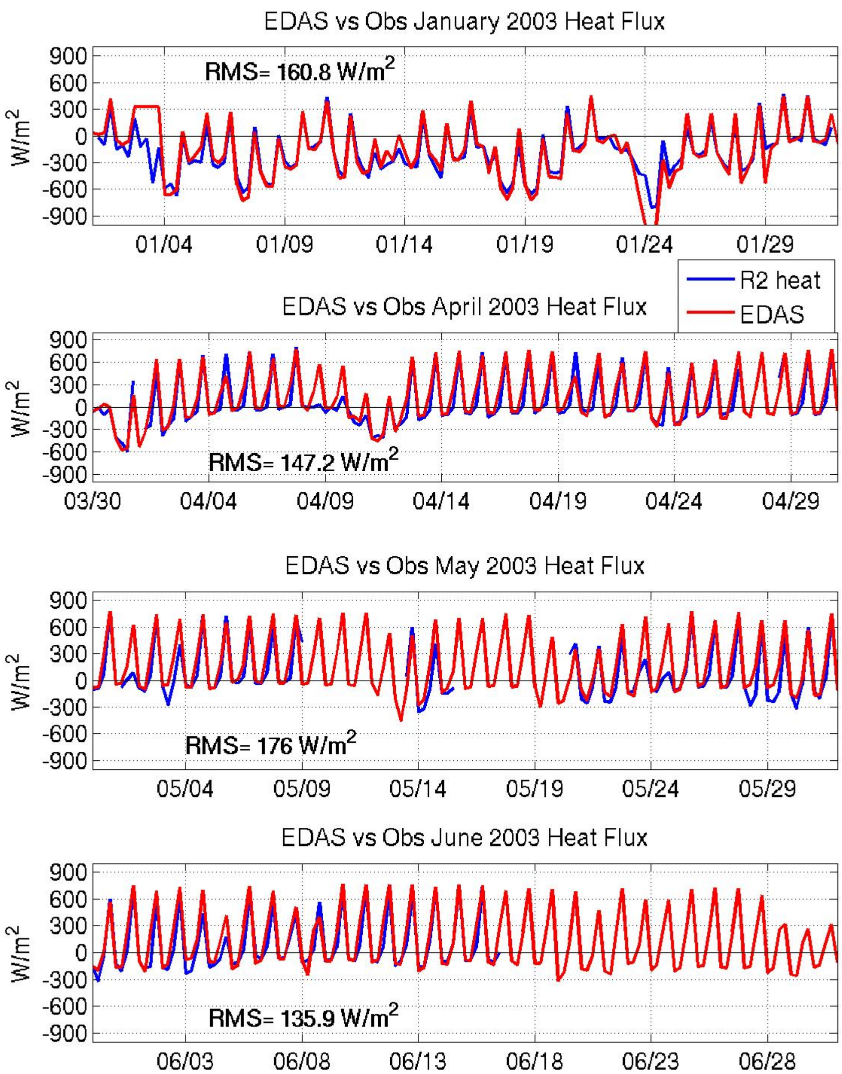

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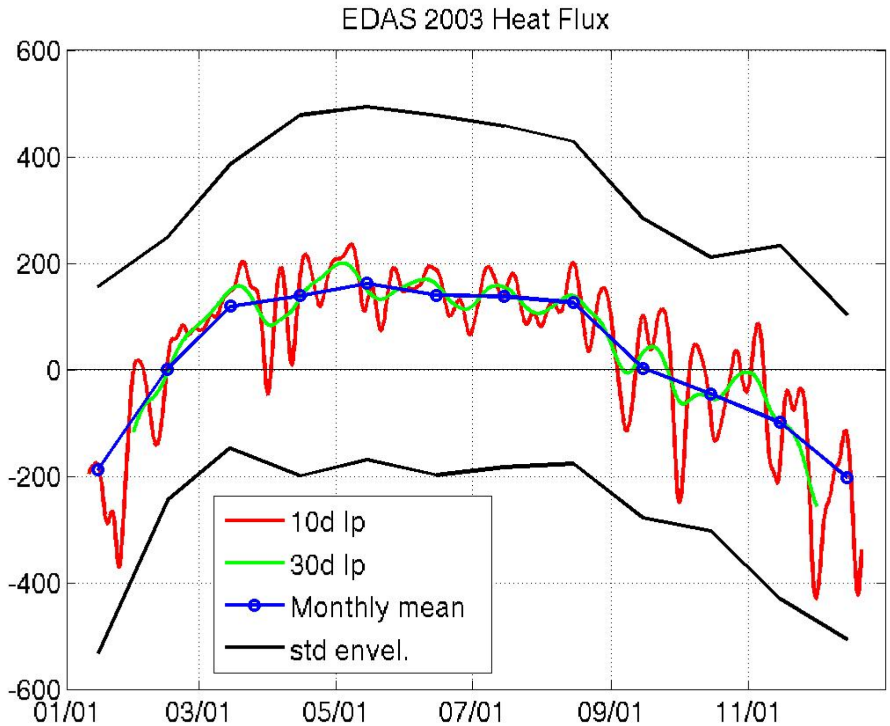

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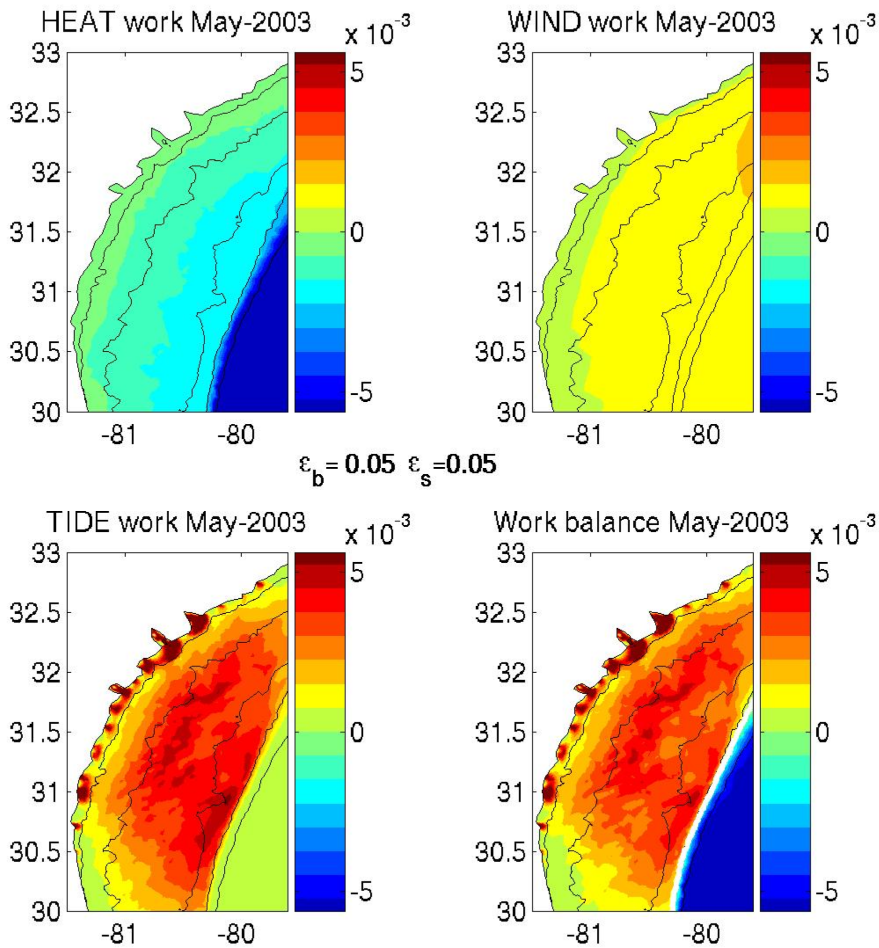

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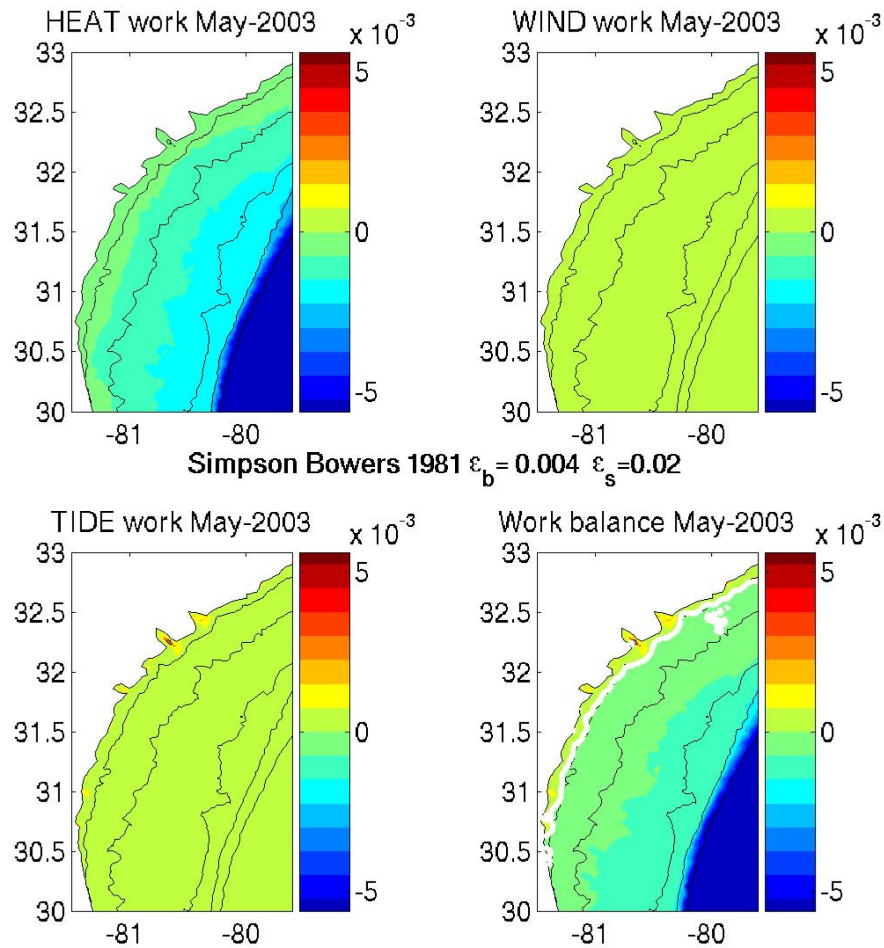

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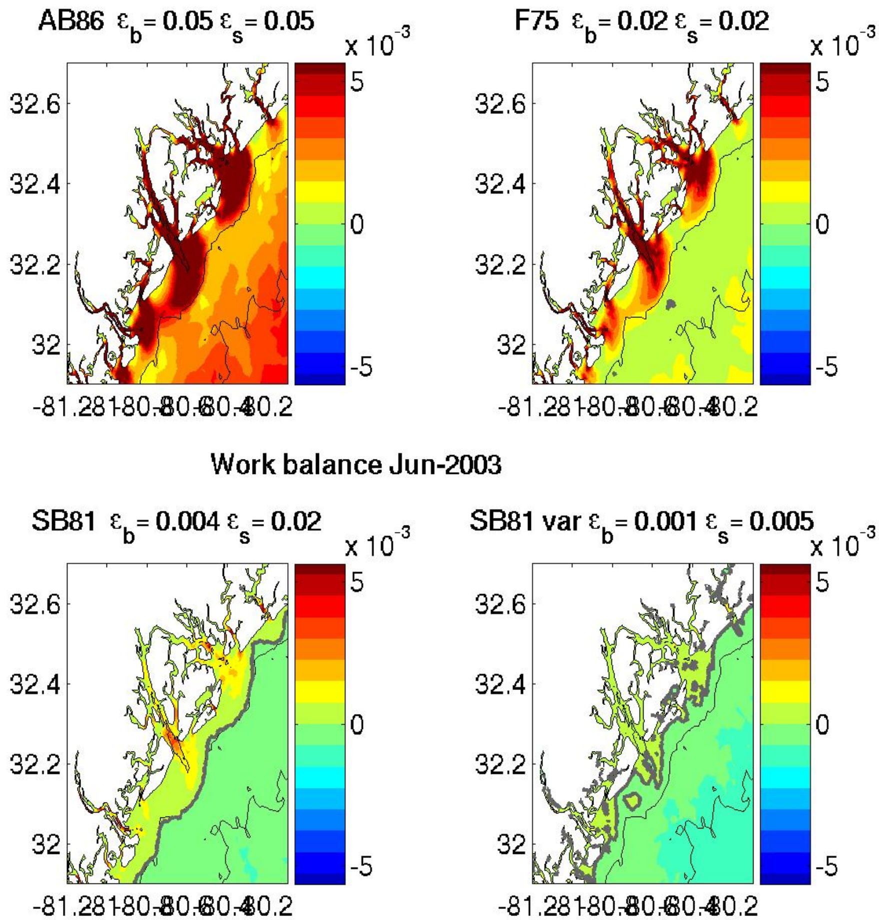

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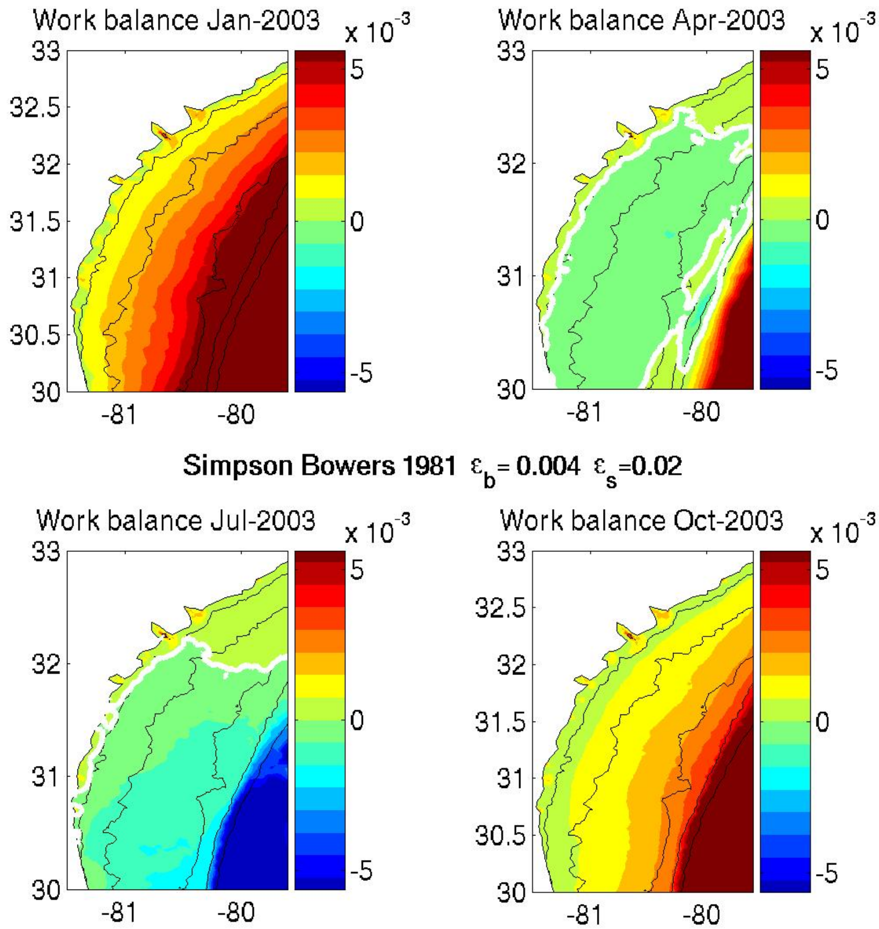

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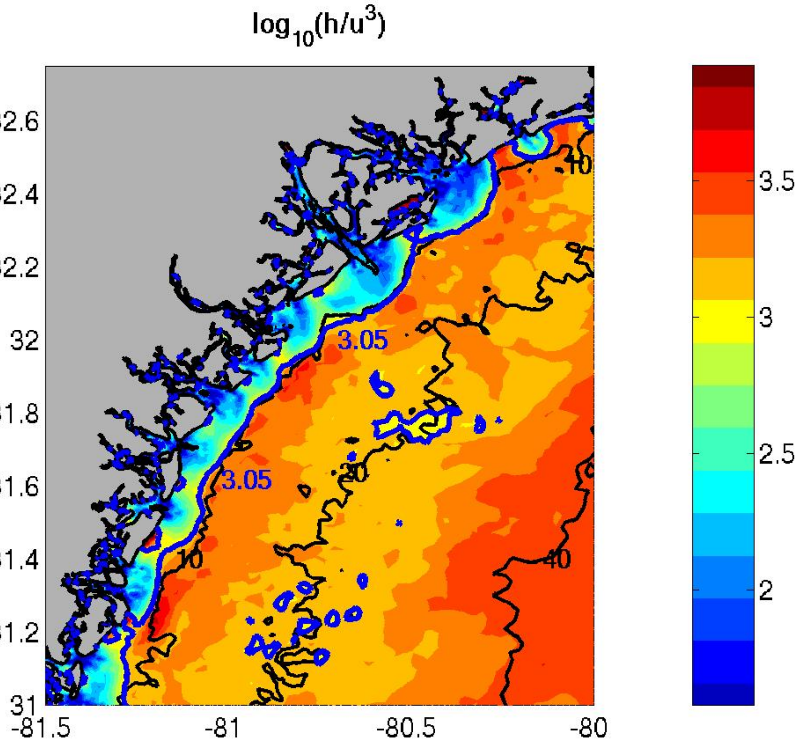

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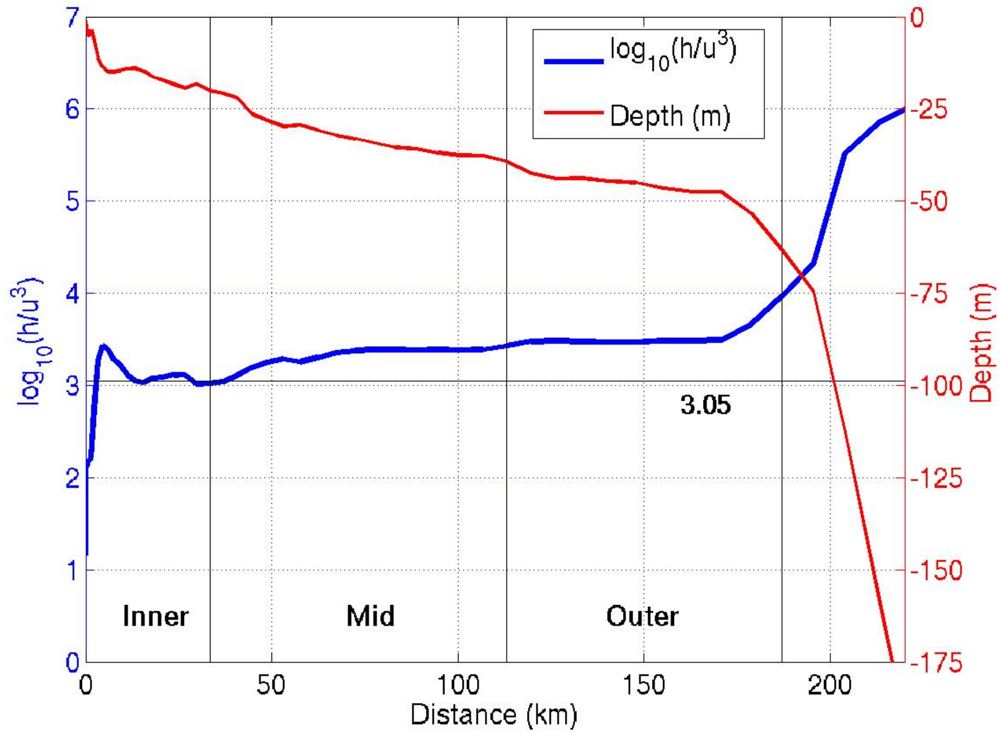

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