

Coastal ocean wind fields gauged against the performance of an ocean circulation model

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[1] Atmosphere model-derived flux fields are used to force coastal ocean models. Coarse resolution and incomplete boundary layer dynamics limit the accuracy of these forcing fields and hence the performance of the ocean models. We address this limitation for the west Florida shelf using optimal interpolation to blend winds measured in situ with winds produced by model analyses. By improving the coastal wind field we improve the fidelity between currents modeled and currents observed. Comparisons between momentum analyses performed independently from the model and the data demonstrate the fidelity to be of a correct dynamical basis. We conclude that the primary limitation to coastal ocean model performance lies with the boundary conditions. *INDEX TERMS*: 4219 Oceanography: General: Continental shelf processes; 4255 Oceanography: General: Numerical modeling; 4263 Oceanography: General: Ocean prediction; 4546 Oceanography: Physical: Nearshore processes. **Citation**: He, R., Y. Liu, and R. H. Weisberg (2004), Coastal ocean wind fields gauged against the performance of an ocean circulation model, *Geophys. Res. Lett.*, 31, L14303, doi:10.1029/2003GL019261.

1. Introduction

[2] Ocean models are generally forced with surface fluxes simulated by atmosphere models. Atmosphere models are often unable to generate accurate coastal ocean flux fields because of coarse resolution and incomplete boundary layer dynamics, particularly near-shore where flux variability induced by topography and interacting ocean/atmosphere and land/atmosphere boundary layers are unresolved. Such deficiencies impair the use of ocean models for diagnosing a wide range of coastal ocean state variables.

[3] We address this problem for the West Florida Shelf (WFS), focusing on the circulation modeled over a two-month interval, March and April 2001. Two wind fields are used. The first derives from an atmosphere model alone. The ocean model performance is good, but deficiencies are evident. The second uses Optimal Interpolation (OI) to blend observed winds with the atmosphere model winds. Significant improvements are achieved when quantitatively gauged against in situ ocean data.

[4] Section 2 describes the atmosphere model winds, the in situ winds, the OI blending of these, and coastal ocean

model experiments. Section 3 compares results of the ocean model simulations driven by the atmosphere model winds and the blended winds. These comparisons are followed in section 4 by inner-shelf dynamics analyses performed independently on the model output and on the data. Section 5 provides conclusions.

2. Data and Model

2.1. Atmosphere Model Fields

[5] The National Centers for Environmental Prediction (NCEP) provides operational model forecasts. Their Eta Data Assimilation System (EDAS) merges 3 hr Eta model forecasts with wind profiler, ship, and aircraft observations using three-dimensional variational (3DVAR) data assimilation. EDAS does not reproduce observations exactly because of the errors of the model background field and the errors of the data (G. Dimego, personal communication, 2003). The EDAS successive 3 hr analyses are archived by the Air Resources Lab (ARL). To mediate storage demand ARL extracts every other grid point of the EDAS 3 hr, 40 km output to produce a 3 hr, 80 km dataset. Although coarse, this resolution is improved over the NCEP $2.5^\circ \times 2.5^\circ$ reanalysis fields that the coastal oceanography community often uses. Available EDAS archived winds are therefore a reasonable starting point for the coastal ocean model analyses of this study. Figure 1 shows the WFS analysis footprint sub-sampled from the archived EDAS analysis grid.

2.2. In Situ Wind Observations

[6] WFS locations for winds measured by buoys [of the National Data Buoy Center (NDBC) and the University of South Florida (USF) Coastal Ocean Monitoring and Prediction System (COMPS)] and by coastal stations [of the NOAA National Water Level Observing Network (NWLON) and the USF COMPS] are also shown in Figure 1. After standard measurement height scaling these in situ wind data are sub-sampled every 3 hrs to be concurrent with the EDAS winds. Comparisons between the in situ and EDAS winds show significant differences from time to time, suggesting that the EDAS fields are often insufficient to account for the WFS wind variability, particularly near-shore where data are available.

2.3. OI Wind Fields

[7] Our goal is to construct an improved surface wind field by blending the EDAS winds with in situ measurements. The underlying assumption is that the coastal and near-shore wind measurements contain important information that is either absent or inadequately parameterized in the atmosphere model. By improving the wind field we seek to improve the performance of a WFS ocean model.

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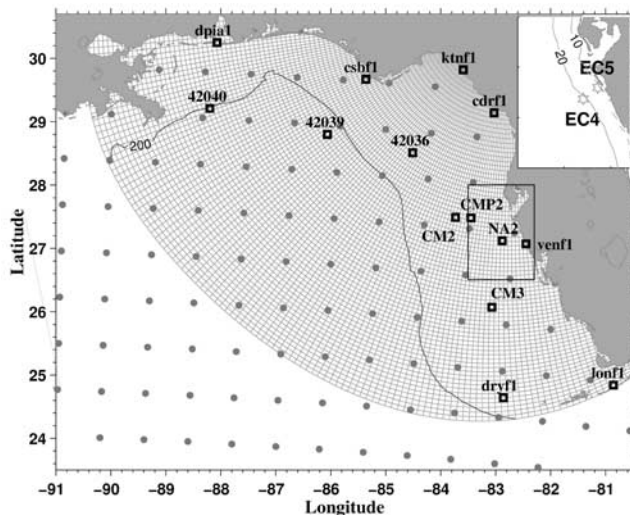


Figure 1. NCEP EDAS analyses footprint (black dots) on the WFS and the locations of coastal winds measured (black squares) by a combination of buoys and coastal stations, overlain on the WFS circulation model grid. The upper right panel shows the locations of moorings EC4 and EC5 on the 20 m and 10 m isobaths, respectively.

[8] Given the data distribution we use the 200 m isobath as a demarcation line between the EDAS and observed winds. EDAS winds sampled over deeper water are merged with observed winds sampled over the shallower shelf and along the coast using an OI scheme similar to that of *He et al.* [2003], the only differences being that here we interpolate in space only, using a 300 km decorrelation scale based on the *Cragg et al.* [1983] findings for WFS coastal wind stations. The resultant OI winds are validated by direct comparison with observed winds over the entire shelf. Relative to the EDAS fields, the OI fields, by including coastal wind measurements, better represent the near-shore flux spatial and temporal variability, thereby reducing the magnitude and direction errors of EDAS fields near the coast. Such improvement is demonstrated by the significant reduction of the root mean square (*rms*) deviations between the analysis and the measurements for both the east and north components of wind velocity. The overall reductions of *rms* deviations are more than 50%. Interested readers may view the time series comparisons, along with quantitative statistic metrics, online at <http://ruoyingh.who.edu/OIwind/>.

2.4. The Coastal Ocean Model

[9] The coastal ocean model is an adaptation of the primitive equation, Princeton Ocean Model (POM) of *Blumberg and Mellor* [1987], the details of which are given by *He and Weisberg* [2002]. The model domain (Figure 1) extends from the Mississippi River to the Florida Keys, with an open boundary in between. Given that the inner-shelf generally responds primarily to local winds and heat fluxes [e.g., *He and Weisberg*, 2002; *Weisberg and He*, 2003], and our focus on how improving local wind fields may improve coastal ocean model performance, we can neglect the offshore Gulf of Mexico Loop Current by

imposing a radiation condition [*Orlanski*, 1976] at the open boundary.

[10] Two model simulation runs are performed for the period, March and April 2001: Case I driven by EDAS winds alone and Case II driven by the OI blend of the EDAS and observed winds. For either case, the two-month POM run is initialized with a horizontally uniform, but vertically stratified temperature and salinity constructed from a ship survey in early March 2001. Following *He and Weisberg* [2002; see also *Ezer and Mellor*, 1992] the surface heat flux fields in both runs are corrected with the daily, cloud-free SST analysis of *He et al.* [2003]. Rapid baroclinic adjustment occurs through the combined effects of winds and surface heat flux when the net heat flux is initially out of the ocean so that convective overturning adjusts the density field to be in balance with the surface forcing [*He and Weisberg*, 2002].

3. Comparisons With Observations

[11] We use in situ measurements from acoustic Doppler current profilers (ADCP) and bottom pressure sensors moored at the 10 m, 20 m, and 25 m isobaths (Figure 1). Figures 2 and 3 compare modeled and observed current

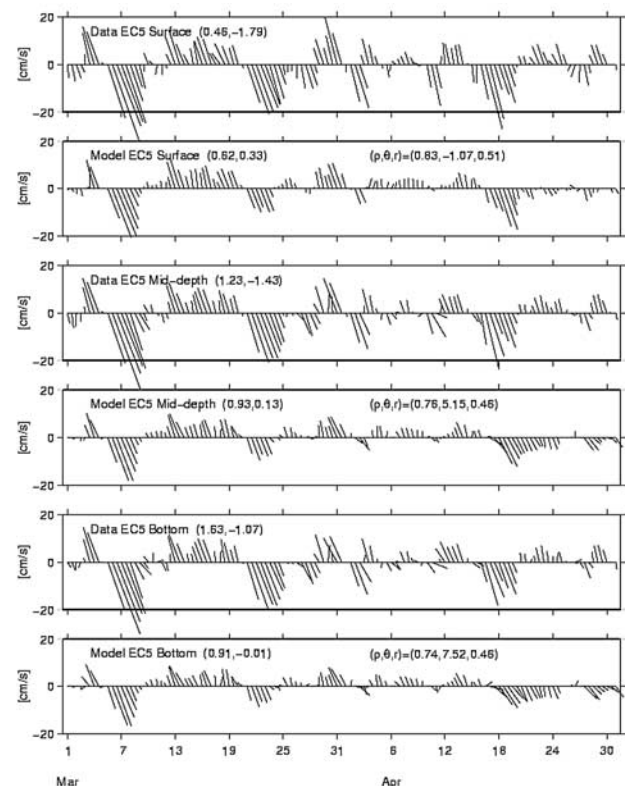


Figure 2. Observed and Case I modeled currents at the 10 m isobath (mooring EC5) sampled near-surface, at mid-water column, and near-bottom. Quantitative comparison metrics are: the two-month mean east and north velocity components (left hand couplet) for each time series, and the vector correlation coefficient, angular deviation (in degrees measured counterclockwise), and vector regression coefficient (right hand triplet) for each pair of modeled and observed time series.

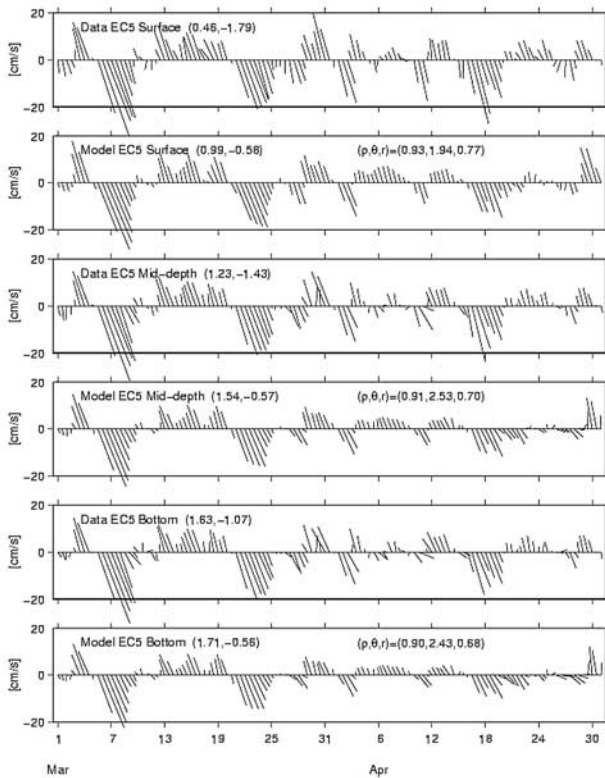


Figure 3. Same as Figure 2, except for Case II.

time series at the 10 m isobath for Cases I and II, respectively. Performances are quantified at three positions in the water column: near-surface, mid-depth, and near-bottom, using a complex correlation analysis [Kundu, 1976] that provides a vector correlation coefficient, a vector orientation difference, and a vector regression coefficient. Also provided for each vector time series are the two-month mean values for the east and north components of velocity.

[12] Consider first the Case I results for EDAS winds. The correlation coefficients between modeled and observed currents range between 0.74 and 0.83 and the orientations differ by -1° to $+8^\circ$. This is good, but the model performance degrades toward the end of April. Moreover, throughout the record, the modeled currents underestimate the amplitude of the observed currents by $\sim 50\%$. The resultant two-month east and north component means also show some contrary behaviors.

[13] Model performance is significantly improved when forced by the Case II merged winds. The correlation coefficients now range between 0.90 and 0.93 at all three depths, and the orientation differences are only about $+2^\circ$. The amplitudes are also improved, with regression coefficients now ranging from 0.68 to 0.77. Moreover, the amplitudes for the modeled and observed currents are nearly the same over the first half of the record. Disparities occur over the latter half, but the degradation for Case II is much less than for Case I, with the model now tending to get the reversals of the currents correct. Significant improvements are also seen in the mean value comparisons. For Case II the modeled and observed mean velocity components all have the same sign and their magnitudes agree better. These improvements are a manifestation of the blended winds over

the EDAS winds since all other aspects of the Cases I and II model runs are identical.

4. Momentum Analyses

[14] Given a quantifiable fidelity between modeled and observed coastal ocean currents can it be said that the model performance is correct dynamically? We address this by diagnosing the vertically integrated momentum balance using in situ data and model results independently. Neglecting the advective acceleration terms, the depth-averaged, along-shelf and across-shelf momentum equations are:

$$\begin{aligned} \frac{\partial u}{\partial t} - fv &= -\frac{1}{\rho_0 H} \int_{-H}^{\eta} \frac{\partial P}{\partial x} dz + \frac{\tau_s^x}{\rho_0 H} - \frac{\tau_b^x}{\rho_0 H} \\ \frac{\partial v}{\partial t} + fu &= -\frac{1}{\rho_0 H} \int_{-H}^{\eta} \frac{\partial P}{\partial y} dz + \frac{\tau_s^y}{\rho_0 H} - \frac{\tau_b^y}{\rho_0 H} \end{aligned} \quad (1)$$

(A) (B) (C) (D) (E)

where u , v are the depth-averaged across-shelf and along-shelf velocity components. (A) and (B) are the local and Coriolis acceleration terms, respectively. (C), (D), and (E) are the pressure gradient, the surface (wind) stress, and the bottom stress terms, respectively. Time series of all of these may be obtained directly from the Case II model simulation. We also have sufficient data to diagnose these terms as an average between the 10 m and 20 m isobaths, where we have bottom pressure records (and also making use of along-shelf pressure records from the 25 m isobath). The details of the data derived analyses will be reported elsewhere (Liu, in preparation). Here we sample the model at the nearest grid point and overlay the observed and modeled results in Figures 4 and 5 for the across-shelf and the along-shelf balances, respectively.

[15] For either the across-shelf or along-shelf momentum balances, the terms are ordered from top to bottom accordingly by their relative amplitudes. Thus, the primary balance in the across-shelf direction is geostrophic, complimented by wind stress and to a much lesser degree by bottom stress. The primary balance in the along-shelf direction is between the wind stress and bottom stress, complimented by the pressure gradient, local acceleration, and Coriolis terms. In addition to supporting the classical theoretical characterization of the inner shelf dynamics [e.g., Brink, 1998; Csanady, 1998], the agreements between independent data and model derived momentum analyses indicate that the present computation and parameterization schemes for the ocean model, while in need of continued improvements, are not the limiting factor to model performance. Given improved forcing fields, coastal ocean models (POM in this application) are capable of producing inner-shelf currents quantifiably well and for correct dynamical reasons.

5. Summary and Conclusion

[16] We begin with the premise that operational atmosphere models and analyses suffer from coarse resolution and incomplete boundary layer dynamics. While providing essential information on the large-scale atmosphere circulation, they may fail to produce forcing fields accurate enough for the coastal ocean. We address this problem for the WFS

using a coastal ocean model and two renditions of NCEP EDAS model winds, one for the EDAS winds alone, and the other for the EDAS winds blended (using OI) with near-shore buoy and coastal station winds. Analyses are provided for the two-month period, March and April 2001 for which we have sufficient in situ data to quantitatively gauge the ocean model performance. We find that the ocean model, when forced by the OI blended winds, performs significantly better than when forced by the EDAS winds alone. We also find, through across-shelf and along-shelf momentum balances diagnosed independently from the model results and the data, that when the model and data agree they do so for correct dynamical reasons.

[17] Two conclusions are adduced. First, accurate surface forcing is required for coastal ocean model simulations. Notwithstanding the need for continued improvements to computation and parameterization schemes, the primary limitation to coastal ocean model and data fidelity appears to be with the boundary conditions, which is true even for a perfect model. In our case, over the inner-shelf, the primary boundary condition limitation is with the surface fluxes. When forced with an improved wind field, the POM (with Mellor and Yamada [1982] turbulence closure) can reproduce current observations very well. For broader scale applications the boundary conditions must also include the deep-ocean/shelf interactions via the regional model open boundaries. Second, the importance of emergent coastal ocean observing systems (COOSs) cannot be overempha-

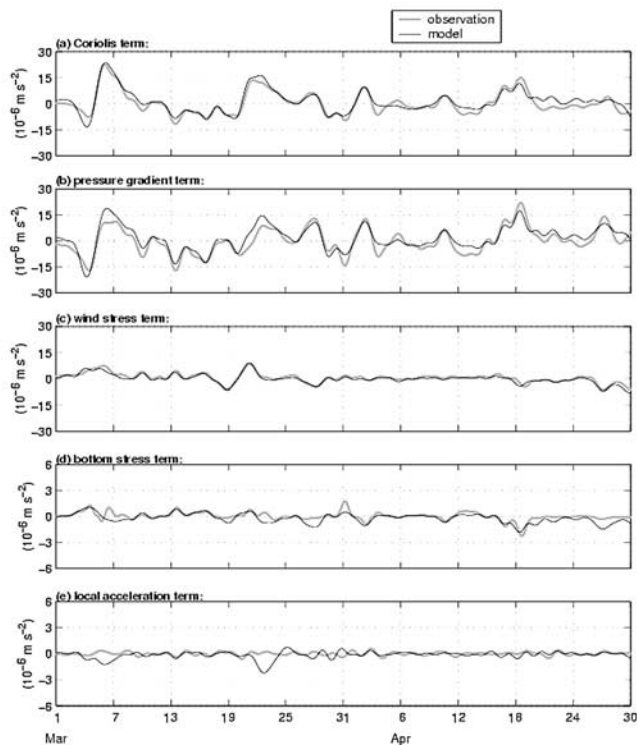


Figure 4. Case II modeled (thin, black lines) and observed (thick, gray lines) across-shelf momentum analysis. From top to bottom are (a) Coriolis, (b) pressure gradient, (c) surface wind stress, (d) bottom stress, and (e) local acceleration terms (Units: 10^{-6} ms^{-2}). Note the scales changes for (d) and (e).

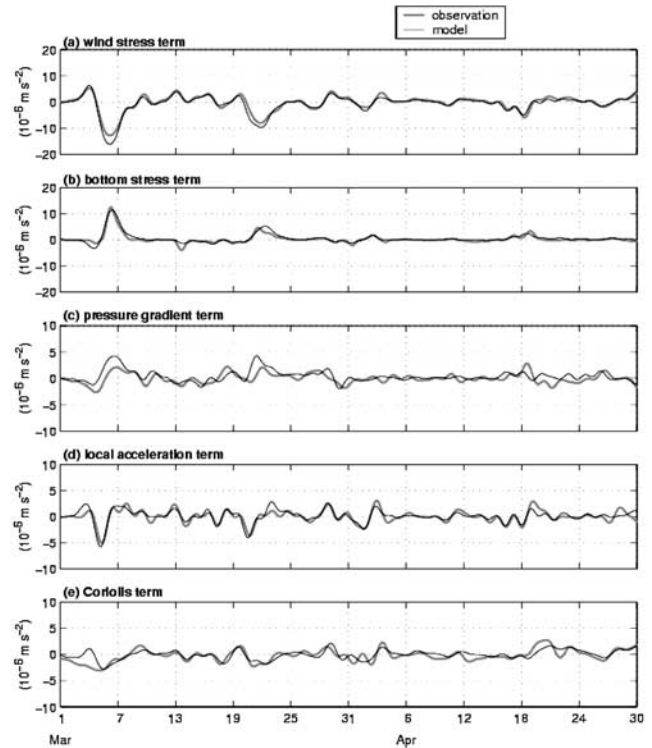


Figure 5. Case II modeled (thin, black lines) and observed (thick, gray lines) along-shelf momentum analysis. From the top to the bottom are (a) surface wind stress, (b) bottom stress, (c) pressure gradient, (d) local acceleration, and (e) Coriolis terms (Units: 10^{-6} ms^{-2}). Note the scales changes for (c), (d), and (e).

sized. Along with oceanographic variables these observing systems must have coverage sufficient to promote improvements in the coastal ocean surface flux fields. Either by simple OI analyses, or by more sophisticated data assimilation schemes, COOSs will lead to improved marine weather specification/prediction, upon which hinges improved ocean state variable specification/prediction.

[18] **Acknowledgments.** Support was provided by the Office of Naval Research, Grant #s N00014-98-1-0158 and N00014-02-1-0972. RH is presently a Woods Hole Oceanographic Institution CICOR Postdoctoral Scholar. EDAS archives are available from NOAA ARL, and we thank Dr. G. DiMego of NCEP/EMC for helpful discussions on the EDAS analysis.

References

- Blumberg, A. F., and G. L. Mellor (1987), A description of a three-dimensional coastal ocean circulation model, in *Three-Dimensional Coastal Ocean Models, Coastal Estuarine Ser.*, vol. 4, edited by N. Heaps, pp. 208–233, AGU, Washington, D. C.
- Brink, K. H. (1998), Wind-driven currents over the continental shelf, in *The Sea*, vol. 10, *The Global Coastal Ocean: Processes and Methods*, edited by K. H. Brink and A. R. Robinson, pp. 3–20, John Wiley, Hoboken, N. J.
- Cragg, J., G. Mitchum, and W. Sturges (1983), Wind-induced sea-surface slopes on the west Florida shelf, *J. Phys. Oceanogr.*, *13*, 2201–2212.
- Csanady, G. T. (1998), The non-wavelike response of a continental shelf to wind, *J. Mar. Res.*, *56*, 773–788.
- Ezer, T., and G. Mellor (1992), A numerical study of the variability and separation of the Gulf Stream, induced by surface atmospheric forcing and lateral boundary flows, *J. Phys. Oceanogr.*, *22*, 660–682.
- He, R., and R. H. Weisberg (2002), West Florida Shelf circulation and temperature budget for the 1999 spring transition, *Cont. Shelf Res.*, *22*, 719–748.

- He, R., R. H. Weisberg, H. Zhang, F. Muller-Karger, and R. W. Helber (2003), A cloud free satellite derive sea surface temperature analysis for the west Florida shelf, *Geophys. Res. Lett.*, *30*(15), 1811, doi:10.1029/2003GL017673.
- Kundu, P. K. (1976), An analysis of inertial oscillations observed near the Oregon coast, *J. Phys. Oceanogr.*, *6*, 879–893.
- Mellor, G. L., and T. Yamada (1982), Development of a turbulence closure model for geophysical fluid problems, *Rev. Geophys.*, *20*, 851–875.
- Orlanski, I. (1976), A simple boundary condition for unbounded hyperbolic flows, *J. Comput. Phys.*, *21*, 251–269.
- Weisberg, R. H., and R. He (2003), Local and deep-ocean contributions to anomalous water properties on the west Florida Continental shelf, *J. Geophys. Res.*, *108*(C6), 3184, doi:10.1029/2002JC001407.
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