Ocean Modeling and the Representation of Unresolved Scales

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Ocean circulation is a prototypical "Strongly Coupled Multiscale Phenomenon" wherein a vast range of spatial and temporal scales interact to produce intricate and complex behavior that drives low-frequency climate variability. The computational challenge of modeling ocean circulation is to accurately represent this vast range of spatial and temporal scales and their interactions.

State-of-the-art climate studies use realistic ocean models but at coarse resolutions. Comparisons of modeled circulation at these resolutions with satellite observations and in-situ measurements show that the modeled circulation and its variability are both pathologically sluggish.

The separation of the Gulf Stream from the East coast of the United States in models highlights the issue. In Fig. 1 [1], while at the higher resolution on the left, the Gulf Stream separates correctly at Cape Hatteras and the simulation correctly captures dynamics of the separated jet further downstream; most of these features are incorrect in the simulation on the right. The latter simulation uses reduced resolution, which is still higher than resolutions used in climate studies. The importance of the unresolved small-scales is highlighted by the fact that the reduced-resolution simulation is configured identically to the higher-resolution simulation.

A new approach to modeling unresolved subgrid-scales [2] in simulations such as these is based on the idea of regularizing small resolved scales. This is done by modifying the nonlinear cascade processes so that the importance of small scales is de-emphasized [3,4,5]. An attendant feature of this regularization is a modification of the dispersion relation for short waves in the system [5,6] that ameliorates time step constraints [6]. This approach is in contrast to the traditional approach of modeling the effects of unresolved scales on resolved scales as a dissipative downgradient closure. The chief advantage of the new approach over the traditional downgradient closure lies in the ability of the new approach to represent backscatter [7]—a nondissipative influence of the small unresolved scales on the resolved scales—besides the usual damping effect of the small unresolved scales.

Figure 2 shows a simplified setup that highlights the applicability of this approach to the problem of Gulf Stream separation. Again, the higher resolution simulation on the left shows proper separation at Cape Hatteras, but the reduced-resolution run (center) displays the characteristic stationary anticyclonic meander that prevents proper separation. On the other hand, at the reduced resolution, with the new regularization-based subgrid model on the right, the stationary anticyclonic meander is absent and the overall representation of the dynamics of the Gulf Stream separation is improved.

This improvement is due to an enhancement of the inverse-cascade of energy, a characteristic feature of large-scale flows. The enhanced inverse-cascade makes the large-scale flow more inviscid, as shown in an idealized setting in Fig. 3. In that figure, the distribution of energy with scale is shown on a log-log plot for different values of the regularization parameter alpha. All the flows are fully resolved. The solid line corresponds to the original (un-regularized) system. Dotted, dashed, and dot-dashed lines correspond to increasing values of alpha. Note the de-emphasizing of small scales with increasing alpha. Inverse energy cascade results when energy flows from the forcing scale (k=10) to larger scales. That regularization of small

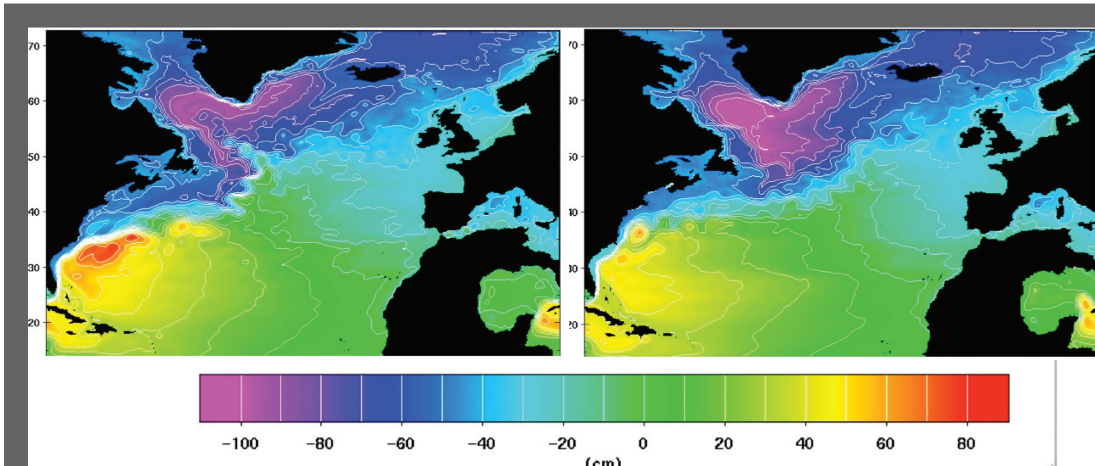

Fig. 1. Mean sea surface height. Left: 0.1 deg.; Right: 0.2 deg; From Bryan et al. (http://www.cgd.ucar.edu/oce/bryan/woce-poster.html) with modifications.

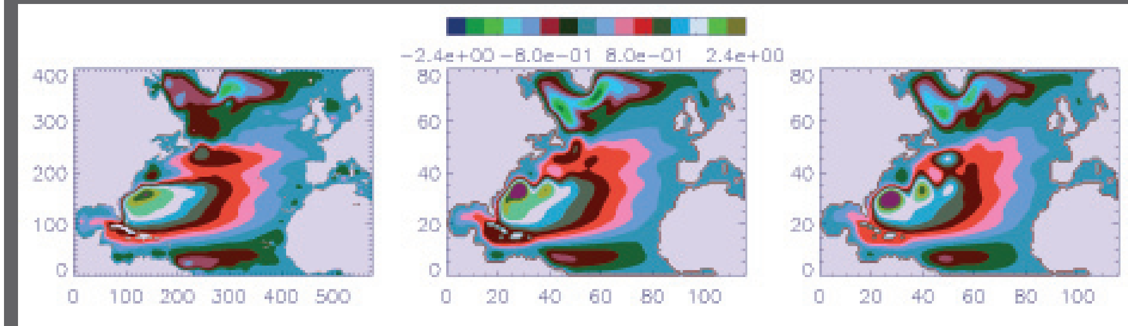

Fig. 2. Regularization-based subgrid model improves the representation of separation dynamics at low resolutions. Left: high resolution. Center: 5x reduced resolution, no model. No separation at Cape Hatteras; Right: Low resolution with regularization-based subgrid model.

scales results in an enhancement of the inverse-cascade of energy to large-scales also demonstrates the important interplay between numerics and physics in the simulation of these systems.

Work is underway to a) further understand and improve the subgrid model, and b) to implement such subgrid models in ocean models used in IPCC-class climate simulations [8].

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Funding Acknowledgments

- Department of Energy, Office of Biological and Environmental Research, Climate Change Prediction Program
- Los Alamos National Laboratory Directed Research and Development Program

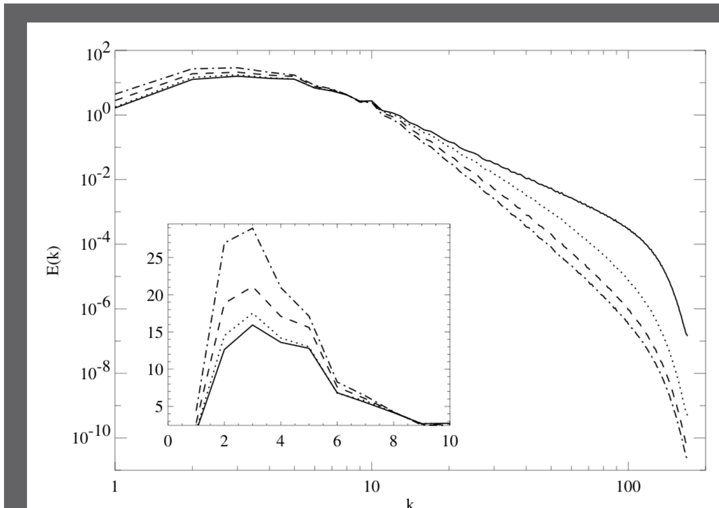

Fig. 3. Spectrum of energy as a function of wavenumber (log-log scale). In the inset in linear scale. Regularizing small scales results in enhancing inverse cascade of energy to large scales. Solid line: no regularization. Dotted, dashed, and dot-dashed lines: increasing scale of regularization.