NOTES AND CORRESPONDENCE

On the Effects of Horizontal Resolution in a Limited-Area Model of the Gulf Stream System

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ABSTRACT

An adiabatic, primitive equation, eddy-resolving circulation model has been applied to the Gulf Stream System from Cape Hatteras to east of the Grand Banks (30°–48°N, 78°–45°W). A two-layer version of the model was driven both by direct wind forcing and by transport prescribed at inflow ports south of Cape Hatteras for the Gulf Stream and near the Grand Banks of Newfoundland for the deep western boundary current. The mean upper-layer thickness was sufficiently large for interface outcropping not to occur. Numerical experiments previously run at 0.2° horizontal resolution ($\sim$20 km) had some realistic features, but a key unresolved deficiency was that the highest eddy kinetic energies obtained near the Gulf Stream were too low relative to data by a factor of about 2, with inadequate eastward penetration.

A unique set of new numerical experiments has extended previous results to higher horizontal resolution, all other conditions being held fixed. At 0.1° horizontal resolution, eddy kinetic energies in the vicinity of the Gulf Stream realistically increase by a factor of roughly 2 relative to 0.2°. The increase in eddy activity is a result of enhanced energy conversion from mean flow to fluctuations due to barotropic and baroclinic instabilities, with the nature of the instability mixture as well as eddy energy changing with increased resolution. One experiment at 0.05° horizontal resolution ($\sim$5 km) yielded kinetic energies and key energy transfer terms that are within 10% of the equivalent 0.1° case, suggesting that convergence of the numerical solutions has nearly been reached.

1. Introduction

Detailed comparisons between ocean model results and observations have increased dramatically in the past decade. This is due in part to the availability of new datasets and more realistic ocean models (Schmitz et al. 1983; Treguier 1992). For the North Atlantic and North Pacific, results from idealized domain, quasigeostrophic models have been compared with observations in a series of studies (e.g., Schmitz and Holland 1982; Holland and Schmitz 1985; Schmitz and Holland 1986). Such investigations were extended to more realistic geometry by Thompson and Schmitz (1989, hereafter TS89) for a limited-area, two-layer, primitive equation model of the Gulf Stream System (see also Hallock et al. 1989).

Here, we extend TS89 to include a new sequence of numerical experiments, with emphasis on the effect of horizontal resolution while leaving *all* other model properties unchanged. To resolve better the Gulf Stream, which has a width scale of 100 km and a first baroclinic radius of deformation of 35 km, we decided to examine numerical experiments at a resolution of 10 and 5 km to compare with previous numerical experiments (TS89) at 20 km. We begin in the next section by describing the basic numerical experiments, followed by a section on special runs and a section on energetics. Then we summarize the new results and outline conclusions. As noted by TS89, our Gulf Stream model was adapted from an earlier formulation by Hurlbut and Thompson (1980).

2. The basic numerical experiments

The most realistic numerical experiment completed by TS89, at 0.2° horizontal resolution, was called 5.5 (parameters are listed in Table 1). Two versions of this model configuration were discussed [here labeled 8.8

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TABLE 1. Model 5.5 (0.2° horizontal resolution) parameters.

A	10^6 cm^2 s^{-1}
g	980 cm s^{-2}
g'	2 cm s^{-2}
H_1	1000 m
H_2	4000 m
Δx, Δy	0.2°
Δt	20–80 min
C_b	0 and 2×10^{-3}
DWBC	20 Sv

(5.5a) with no bottom friction and 9.3 (5.5b) with quadratic bottom friction coefficient $C_b = 2.0 \times 10^{-3}$ (see TS89)]. For the sake of brevity and clarity, we will focus the discussion on the case with nonzero, but small ($C_b = 2 \times 10^{-3}$) bottom friction.

Upper- and lower-layer eddy kinetic energies (hereafter EKE1 and EKE2, respectively; always per unit mass in units: cm^2 s^{-2}) for numerical experiment 9.3 (Table 1) are contained in Fig. 1. These time averages are typically calculated over a 3-year period after the model run is spun up to statistical equilibrium, the latter normally taking 10–15 years. EKE1 patterns are too weak west of the New England Seamounts. EKE2 values (Fig. 1b) are weaker than observed at 55°W by a factor of about 2 (see also TS89).

The paths of the Gulf Stream (defined as in TS89) for 8.8 and 9.3 are variably displaced latitudinally relative to observation, to the north more often than south. There is "overshoot" of the model axis just to the east of Cape Hatteras, and the model 9.3 Gulf Stream rides somewhat north over the abyssal plain east of the New England Seamounts, with corresponding errors in EKE (and other) fields. That is, specification of a deep western boundary current (DWBC) of 20 Sv (Sv ≡ 10^6 m^3 s^{-1}) helped but did not "solve" the axis location problem in the experiments considered by TS89. Similar path discrepancies (W. R. Holland, personal communication) have also been experienced with another model (Bryan and Holland 1989); the separation problem has recently been discussed in detail by Cessi (1990), Cessi et al. (1990), and Chassignet and Gent (1991) (see also Ezer and Mellor 1992; Pickart and Watts 1990; Watts 1991).

We decided to examine the effect of horizontal grid spacing on these discrepancies by exactly doubling the resolution for 9.3 to 0.1°, all other parameters held

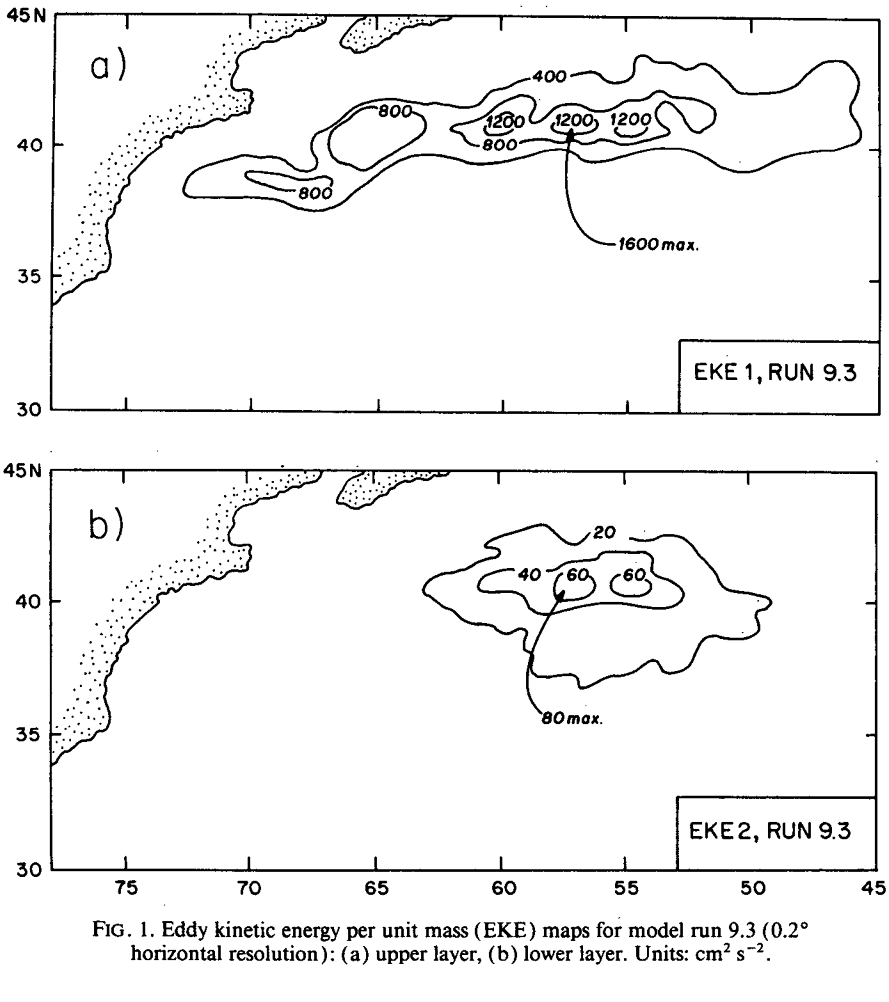

FIG. 1. Eddy kinetic energy per unit mass (EKE) maps for model run 9.3 (0.2° horizontal resolution): (a) upper layer, (b) lower layer. Units: cm^2 s^{-2}.

constant. In so doing, forcing functions, topography, and coastlines previously digitized on a 0.2° grid were linearly interpolated to a 0.1° (double-resolution) grid. With these choices, we isolate the effect of horizontal resolution on the solutions. The new experiment, labeled 9.4, is identical in parameters to Table 1 except that shorter integration time steps were needed for 0.1° resolution to satisfy numerical stability requirements.

The EKE1 values in Fig. 2a for 0.1° horizontal resolution (numerical experiment 9.4) are more energetic than the equivalent cases at 0.2° resolution (numerical experiment 9.3) in Fig. 1a by about a factor of 2. The EKE2 values in Fig. 2b are also more energetic than those in Fig. 1b by a factor of roughly 2. Generally speaking, all EKE fields, especially for the lower layer, show increased (too much perhaps) eastward penetration or displacement for 0.1° relative to 0.2° horizontal resolution. The divergences of the model axes from the observed Gulf Stream axis are still present, somewhat more so than was the case for 0.2° resolution.

3. Special numerical experiments

To find out if convergence of these solutions was at hand, we also carried out a numerical experiment at 0.05° resolution. We were limited to one computer run by the amount of machine time involved, and by sensitivity at this resolution to the outflow boundary condition during extreme eastward penetration of the jet. All input fields were linearly interpolated from the equivalent 0.1° case. EKE1 results for 0.05° resolution in Fig. 3a are within about 10% of the equivalent fields in Fig. 2a, the analogous 0.1° case, and with a continued tendency toward increased eastward penetration of the EKE1 field. A similar summary statement applies to EKE2 (Fig. 3b vs Fig. 2b). The small-scale maximum in abyssal K_E between 65° and 70°W in Fig. 2b is absent at 0.05° (Fig. 3b). This feature has observational support (Luyten 1977; Bane et al. 1990; Shay and Bane 1990). Path problems were not ameliorated in moving from 0.1° to 0.05° resolution.

We also reran a case at 0.1° resolution and $C_b = 2 \times 10^{-3}$ with the transport of the DWBC = 0 instead of DWBC = 20 Sv. The results were similar to those described by TS89 in that a DWBC shifted the Gulf Stream separation latitude southward, as cyclonic potential vorticity was advected southward; however, the effect was not as strong as in the 0.2° experiments. We have not experimented with moving the DWBC core up and down the slope to test separation sensitivity to

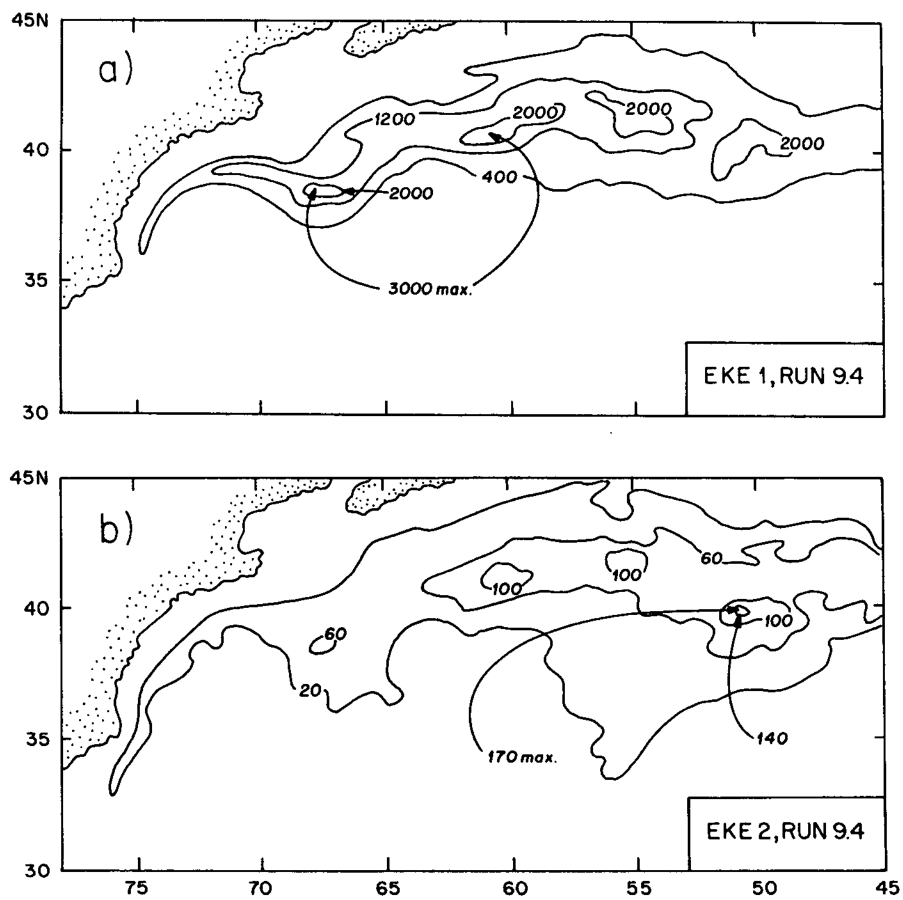

FIG. 2. As in Fig. 1 but for model run 9.4 (0.1° horizontal resolution).

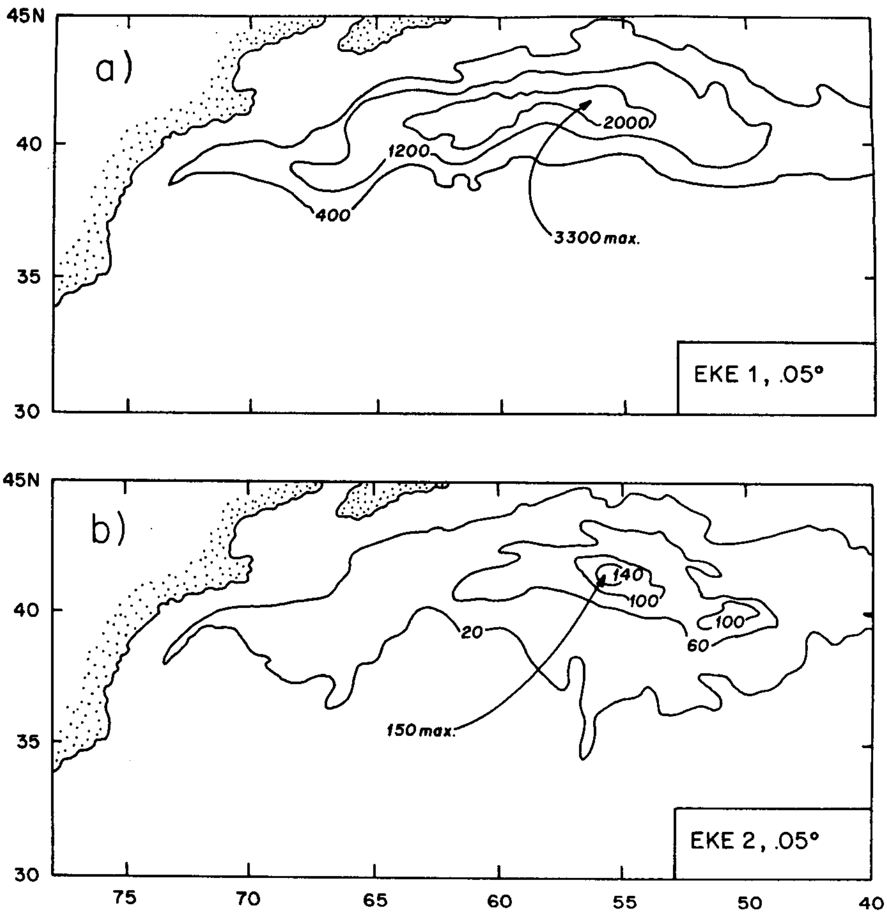

FIG. 3. As in Fig. 1 but for model run 2.0 (0.05° horizontal resolution).

DWBC location. We conclude that increased horizontal resolution only does not significantly alter path overshoot.

4. Energetics analysis

The model Gulf Stream energy levels in Figs. 1–3 change significantly from the 0.2°- to 0.1°-resolution experiments, and not much in moving from 0.1° to 0.05° horizontal resolution. To examine these changes further, we have constructed an energy budget reservoir and flow diagram (Fig. 4) for experiments 9.3 (0.2°), 9.4 (0.1°), and for the 0.05° experiment (2.0). Energy reservoirs are shown in the boxes on Fig. 4 and energy transfer rates are shown with the arrows connecting the boxes. In each experiment the model data is sampled every four days for four years after reaching approximate statistical equilibrium. The domain used in calculating the energetics extended from 33° to 45°N and 76° to 50°W. Terms and notation are standard (Hurlburt and Thompson 1982) with one exception. In formulating the model in terms of transport, the Laplacian of transport was used to parameterize diffusion. For small variations in layer thickness this is equivalent to using the Laplacian of velocity in the momentum equations. Because the eddy-mean energetics equations are formulated in velocity rather than transport form, there is a slight inconsistency between model output data and energetics calculations [see Hurlburt and Thompson (1982) for details]. We have verified that this difference in the magnitude of the diffusion is always less than 10% of the absolute magnitude of the sum of all the transfer terms in or out of a given box. We have therefore calculated the diffusion term in each KE box as a residual to insure balance. Our conclusions do not depend on the small difference this procedure makes in the energy transfer magnitudes.

Energy budget results are summarized in Table 2. Note that the transfer rate from mean to eddy kinetic energy in the upper layer increases by a factor of 2 from 9.3 (0.2° horizontal resolution) to 9.4 (0.1° horizontal resolution), as does the energy level itself (Fig. 4; Table 2). The mixture of barotropic and baroclinic instability influences, as measured by MKE1 → EKE1 and MPE → EPE → EKE1, respectively, becomes more barotropic for the upper layer with increasing horizontal resolution. That is, MKE1 → EKE1 increases by a factor of 2. The dominant process for the

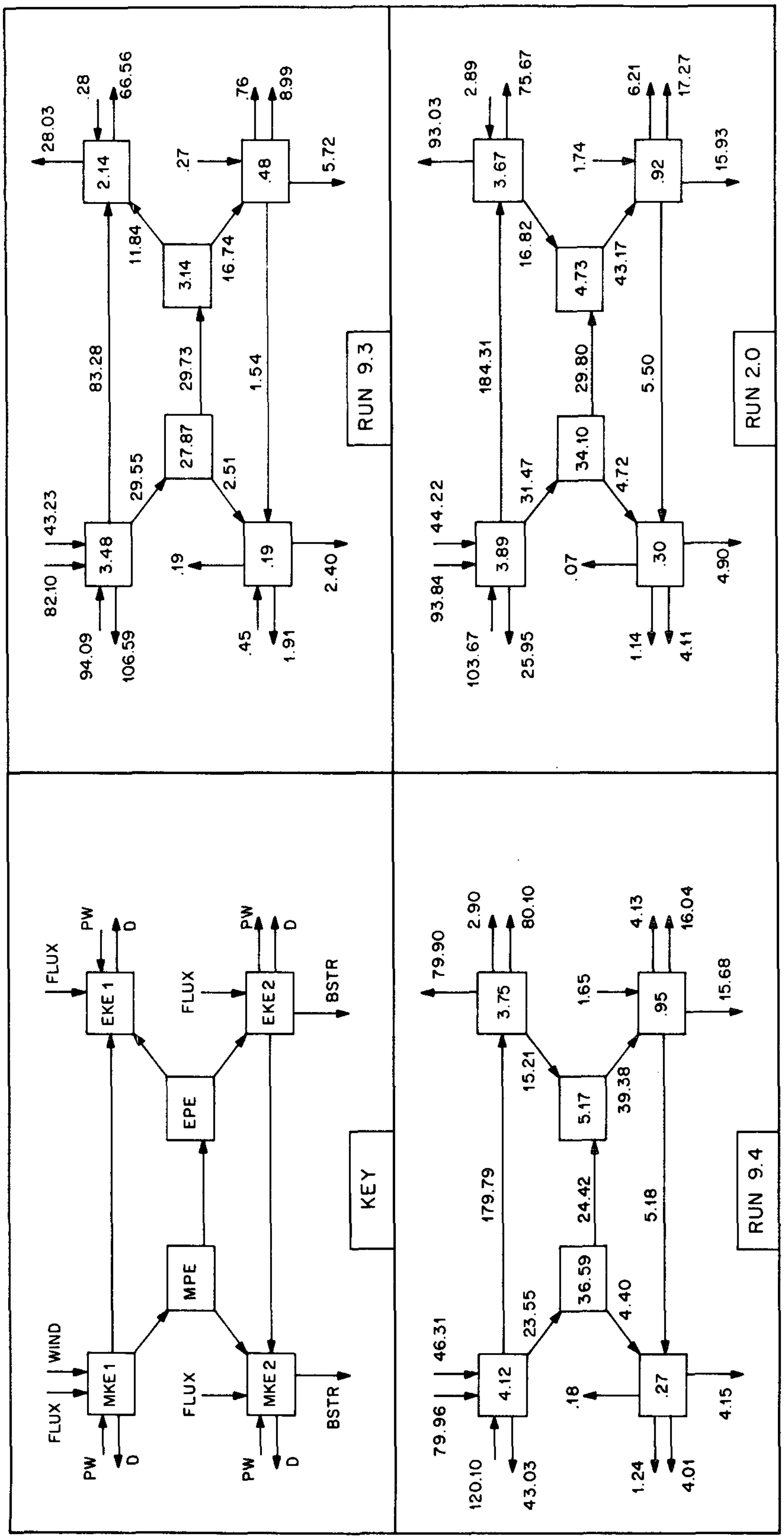

FIG. 4. Energetics box diagrams. The key for the transfer and reservoir terms is contained in the upper left-hand box. See Hurlburt and Thompson (1982) for a detailed formulation. PW refers to pressure-work, D is dissipation via Laplacian friction, and BSTR is bottom stress (quadratic). Reservoir units: 10^4 J m^{-2}; transfer units: 10^{-4} J m^{-2} s^{-1}.

TABLE 2. Selected energetics results.

Run (horizontal resolution)	Total K_E				
	Upper layer	Lower layer	MKE1 → EKE1	MPE → EPE	EPE → EKE2
9.3 (0.2°)	2.14	0.48	83.3	16.7	16.7
9.4 (0.1°)	3.75	0.95	179.8	39.9	39.4
2.0 (0.05°)	3.67	0.92	184.3	43.2	43.2

lower layer is still MPE → EPE → EKE2, which also doubles approximately in moving from 0.2° to 0.1° horizontal resolution (Fig. 4; Table 2). These diagrams also demonstrate that the model solutions have nearly converged at 0.05° resolution, with both reservoir and transfer terms changing from 9.4 to 2.0 by 10% or less. As resolution increases, total potential energy and kinetic energy levels also increase, but their ratio (roughly 5.5) changes little from experiment to experiment. Pressure work terms are relatively more important compared to dissipation in the higher-resolution experiments.

As noted by a reviewer, parameter choice, layer depths, and model type can have tremendous influences on the nature of the instability. In the context of this investigation, however, we have shown that if we change only model resolution from the TS89 experiments (which we compared extensively with observations), the barotropic instability increases in relative importance to baroclinic instability and the deep EKE is more realistic at 55°W. There is currently no convincing observational evidence supporting the dominance of baroclinic or barotropic instability in the Gulf Stream System from Cape Hatteras to the Grand Banks. We do see that the velocity structure downstream of the New England Seamount Chain has a larger barotropic component than is the case upstream (Hogg 1992). Our view is that we are dealing with a mixed instability with baroclinic dominating in the formation region of the Gulf Stream and barotropic dominating in the decay region, along with relatively different influences on upper- and lower-layer fields. Holland and Schmitz (1985) examined midlatitude jet penetration in quasigeostrophic models of the Gulf Stream having up to eight layers. Barotropic instability dominated baroclinic instability in all experiments by factors of 2 to 100. Thinner layers increased the relative importance of barotropic instability as did larger lateral friction. Finally, unlike the jet stream in the troposphere, where baroclinic instability dominates the energy transfers, the Gulf Stream from Cape Hatteras to the Grand Banks is not a free zonal jet. It is distinctly nonzonal, influenced greatly by lateral boundaries and topography, and has a very different vertical distribution of velocity.

Barnier et al. (1991) and Böning and Budich (1992) found that increased resolution tends to increase baroclinic instability relative to barotropic instability. We find that as the solutions converge in our experiments, the increasingly dominant process is barotropic instability. This may be a result of our two-layer system or differences in the friction parameters chosen. While our results are limited, they do suggest that conclusions about relative roles of baroclinic and barotropic instability may change as solutions converge.

5. Summary and conclusions

We have applied a primitive equation numerical model as a two-layer analogue of the Gulf Stream System to a limited area from Cape Hatteras to east of the Grand Banks (30°–48°N, 78°–45°W). The new results reported here are associated with calculations made at 0.1° and 0.05° horizontal resolution, as compared to previous studies at 0.2° (TS89). At 0.2° resolution the model had eddy kinetic energies that were too low relative to observation by a factor of about 2. Also, the EKE patterns in both layers at 0.2° resolution had a distribution that was too westward intensified. At 0.1° horizontal grid spacing, eddy kinetic energies are of notably higher amplitude than at 0.2°, roughly double, and definitely a realistic tendency. These results are due to stronger instabilities whose relative importance changes with resolution. There is also much more eastward penetration at 0.1° resolution, perhaps too much. This result is consistent with investigations using other models (Barnier et al. 1991; Böning and Budich 1992). The one run at 0.05° resolution suggests that convergence of the numerical solutions has been achieved to within roughly 10%. We believe that this explicit demonstration of numerical convergence is unique.

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