Impacts of Vertical Resolution on a Numerical Model of the Gulf of Mexico

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Abstract - **Numerical high-resolution numerical simulations of the Gulf of Mexico using the Navy Coastal Ocean Model are used to examine the life cycle of Loop Current system including its shed eddies. In particular, the interaction of the anticyclonic Loop Current Eddies with bottom topography is investigated. These energetic baroclinic anticyclonic eddies have depth scales of several hundred meters and are not significantly affected by the ocean bottom during their westward propagation. When they reach the western continental margin, however, the ocean bottom over the continental slope rises to intersect the active upper ocean and the eddies begin to "feel" the bottom. The impacts of bottom topography and resolving the vertical structure of the water column on the decay of the Loop Current Eddies are explored using a series of numerical experiments to examine the decay of an eddy in the western Gulf of Mexico. The effects of vertical resolution on the Loop Current Eddy behavior are also explored using identical twin numerical experiments with differing vertical grid spacing[1].**

I. INTRODUCTION

The circulation in the Gulf of Mexico (GoM) is dominated by the energetic Loop Current (LC) and its associated Loop Current Eddies (LCEs). Large anticyclonic LCEs pinch off from the LC at irregular intervals and drift generally westward where they decay against the continental margin. These features have vertical scales of several hundred to 1000 m and thus remain offshore of the continental shelf break.

The dynamics of the LC have been studied using a variety of numerical models and treatments of the vertical coordinate. Vertically averaged barotropic models and multi-layer isopycnal coordinate baroclinic models were used to successfully model and study the LC and eddy shedding dynamics [1,2]. These models were useful to explore the dynamics governing the eddy shedding process, and to distinguish between the roles of barotropic and baroclinic instabilities. These models may or may not incorporate bottom topography, as they may be run as reduced gravity simulations. Higher vertical resolution models with level-type coordinate systems have been used to investigate the problem as well [3]. These models are useful to examine the vertical structure of the LC and LCEs, and the role of bottom topography. However, typically the vertical dimension is resolved by perhaps 20 to 40 grid points in these types of models. Historically, more attention has been paid to resolving the large vertical gradients in the upper ocean due to the interest in upper ocean simulation and prediction. However, it is uncertain whether models with these vertical grids can adequately resolve the vertical gradients and shear zones that exist deeper in the water column associated with jets and eddies.

Other studies have focused on the later stages of LCEs in the GoM, in particular, their decay and interaction with the western continental margin. Realistic numerical ocean model results have suggested that bottom friction plays an important role in the decay of LCEs [3]. Some previous numerical studies of the interaction of the eddies with the continental shelves have not included bottom friction, and have not attempted to resolve the vertical structure of the eddies. These works have focused mainly on eddy migrations along the boundary [4,5].

This study seeks to examine the role of ocean model vertical resolution in simulating the LCE formation, propagation, and interaction with topography. It is quite possible that even the highest vertical resolution models published to date are not adequately resolving the large vertical gradients associated with the LC and LCEs, nor are adequately resolving near-bottom processes that may affect the upper ocean circulation. The impacts of vertical resolution are studied with the Navy Coastal Ocean Model (NCOM) configured to simulate the GoM in realistic simulations, and configured to examine the decay of eddies in the western GoM. Experiments are run with differing vertical resolutions and the eddy behavior in the solutions is examined.

Results suggest that higher vertical resolution simulations produce a more variable eddy field, and stronger LCEs. The propagation pathways appear more realistic compared to Topex/Poseidon satellite altimeter observations. In the lower vertical resolution simulation, LCEs tend to decay more preferentially in the northwestern corner of the GoM resulting in an unrealistically permanent anticyclone. This anticylonic feature is much weaker in the higher vertical resolution simulation.

Unforced simulations of an anticyclone in the western GoM are run to examine the eddy decay processes with differing vertical resolutions. The anticyclone tends to

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decay faster in the lower vertical resolution experiment. This may be due to a diffusive layer near the ocean bottom extending farther from the boundary due to poor vertical resolution than in the high vertical resolution simulation, where this diffusive layer is more closely trapped to the topography.

II. THE MODEL

The NCOM is a three-dimensional primitive equation hydrostatic ocean model developed at the Navy Research Laboratory [6]. The model's hybrid sigma (terrain following) and z (geopotential) level vertical coordinate is useful for simulating upper ocean processes in domains encompassing both deep ocean basins and very shallow shelves. The NCOM is set up to simulate the entire GoM and Caribbean north of Honduras (15.55°N) to 80.6°W with 1/20° between like variables on the C-grid, 20 sigma levels above 100 m and either 20 or 40 z-levels below 100 m to a maximum depth of 4000 m [7]. The model is forced by discharge from 30 rivers, transport through the open boundary (with monthly climatology temperature and salinity) yielding a mean transport through the Yucatan Strait of approximately 27 Sv ($10^6 m^3 s^{-1}$), and monthly climatology surface heat and momentum flux. A surface salinity flux has the effect of uniformly evaporating an amount of water at a rate equal to the sum of the annual average discharge rates of the 30 rivers. The model is run for 10 years for each experiment, with the last seven years used for analysis.

A second set of experiments consists of configuring the NCOM as above, but with a closed eastern boundary at 91°W. The model is initialised with fields from the 60 layer/level GoM experiment. The model is run with the 20 and 40 z-level (both with 20 sigma layers in the upper 100m) grids as in the GoM simulations. The model runs unforced for 200 days to examine the eddy spin down in the western GoM.

III. RESULTS

The variance of the model sea surface height (SSH) shows highest values in the region of the LC retroflection and LCE separation (Fig. 1). A region of high SSH values stretch westward from the LC across the GoM near the latitude band of 23°N to 28°N, showing the preferred westward propagation pathways of the shed LCEs. The 60 level experiment shows much larger values of the SSH variance, with a more pronounced maximum near the LC retrofleciton, and a less pronounced secondary maximum in the northwestern corner of the GoM than the 40 level experiment.

The mean SSH (surface deviation from a resting level) maps from the two GoM experiments both show a high in the northwestern corner of the GoM, indicating a preferred location for the anticyclonic LCEs to reside. The 40 level experiment has relative maxima here of over 30 cm, compared to less than 20 cm for the higher vertical resolution 60 layer experiment. The mean SSH scaled by the standard deviation is less than 1.0 in the 60 level experiment, indicating that the anticyclone is not a permanent feature at this location. However, in the 40 level experiment, the SSH mean scaled by the standard deviation is greater than 3.0 in the northwestern GoM suggesting a nearly permanent anticylonic feature exists here. Although an anticyclone is evident in the mean dynamic topography from historical data, observations do not support that this is a permanent feature. Thus, the higher vertical resolution experiment seems to simulate a more realistic eddy field in the western GoM.

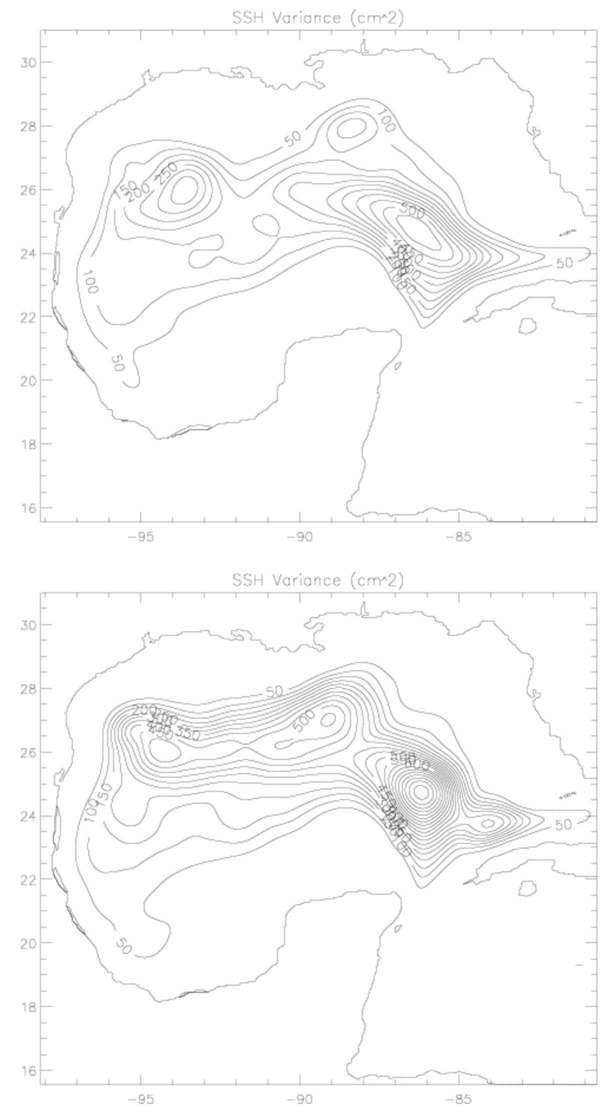


Fig. 1. Variance (cm^2) of the model SSH from the 40 level experiment (top) and the 60 level experiment (bottom). The contour interval is 50 cm^2.

The sea level variability across a line coincident with a Topex/Poseidon satellite altimeter (T/P) ground track is compared between NCOM GoM simulations and T/P data (Fig. 3). LCEs cross this track as they propagate westward from the Loop Current. The sea surface height variance versus latitude plot gives some indication of the eddy strength and preferred propagation path. The results show weaker than expected sea level variability across this track in the 40 level experiment, and much better agreement in the near-twin experiment with 60 vertical levels.

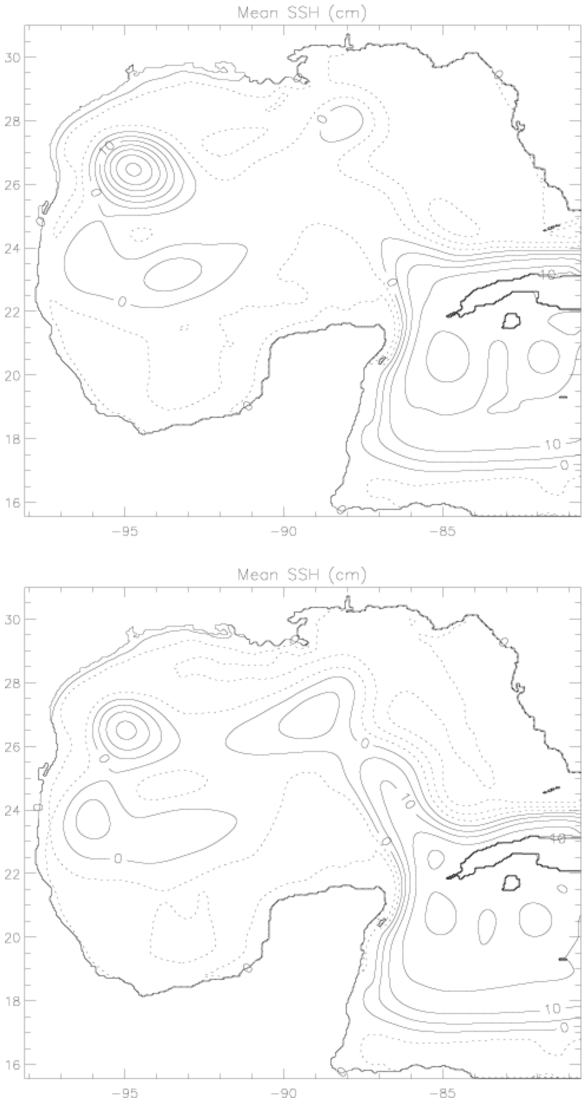


Fig. 2. Model mean SSH (cm) from the 40 level experiment (top) and the 60 level experiment (bottom). The contour interval is 5 cm and negative values are indicated by dotted contour lines.

The eddy decay process is further studied by running a simulation of the western GoM, initialized with a nearly isolated anticyclone from an output record of the 60 level GoM simulation, and run unforced with both 40 vertical levels and 60 vertical levels. The time series of the area enclosed by the 18°C isotherm at 300m depth gives an indication of the decay rate of the anticyclone (Fig. 4). The coarse vertical resolution (40 level) model shows a faster decay rate of the anticyclone than the higher vertical resolution model.

A plot of the time averaged vertical diffusion term from the model momentum equations:

$$\partial/\partial z\left(k_m \, \partial\vec{v}/\partial z\right), \text{ where } k_m \, \partial\vec{v}/\partial z\,\big|_{z=-h} = c_b|\vec{v}|\vec{v}, \qquad (1)$$

across the mean position of the center of the anticyclone shows a high diffusive layer near the ocean bottom (Fig. 5). This layer is better resolved by the high vertical resolution model, and so is more closely trapped to the bottom. In the coarse vertical resolution model, this layer extends much higher off the bottom and may result in a faster spin down of the anticyclone as it interacts with the continental shelf slope.

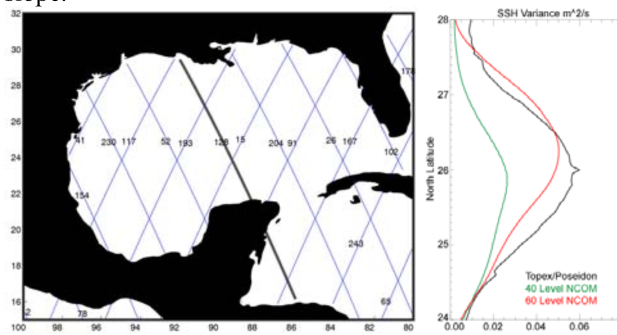


Fig. 3. Right: Variance of the sea surface height versus latitude for seven years of data across T/P ground track 128 shown highlighted at left. Black curve: Topex/Poseidon altimeter. Green curve: 40 level simulation. Red curve: 60 level simulation.

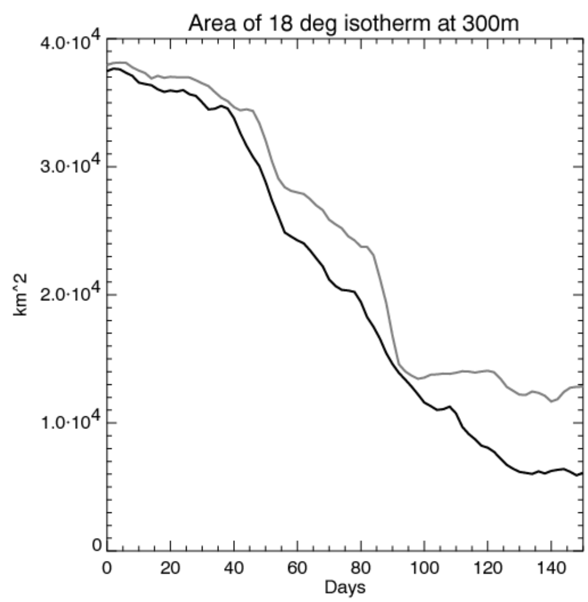
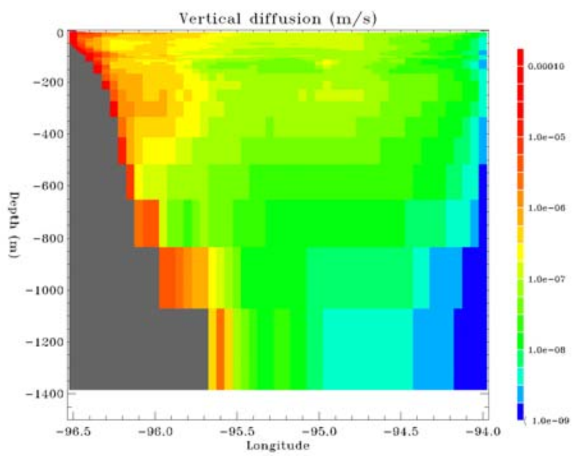


Fig. 4. Area of the 18°C isotherm at 300m from the western GoM eddy decay experiments. Shown are the time series from the 40 level experiment (black) and the 60 level experiment (gray).

IV. SUMMARY

Experiments using high-resolution numerical simulations of the GoM and western GoM have been used to investigate the impacts of vertical resolution on the LCE formation, propagation, and decay. Identical twin experiments were run with vertical resolution being the only experimental variable. Experiments were run with 20 z levels and 40 z levels (each with 20 sigma layers in the upper 100 m). The experiments show dependence of the LCE behavior on the vertical resolution. The reasons for this dependence are likely linked to improper resolution of vertical gradients in the middle and deep water column, and near bottom topography.

The high vertical resolution GoM simulation produces more realistic LCEs, both in strength and variability of propagation pathways. Although the western GoM experiments suggest faster eddy spin-down in the coarse vertical resolution experiment due to a poorly resolve bottom trapped diffusive layer, the 40 level GoM model still shows an unrealistically permanent anticylonic feature in the northwestern Gulf. A more highly variable westward eddy propagation and decay location in the higher vertical resolution model may be responsible for reducing the magnitude of this anticyclonic feature.



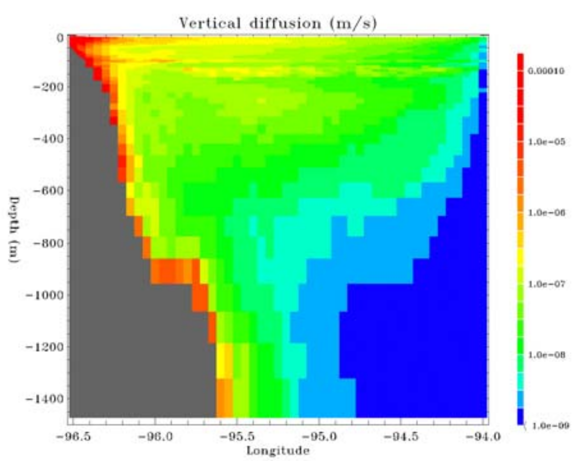


Fig. 4. Time averaged vertical diffusivity term (1) from the NCOM momentum equations for the western GoM eddy decay experiments. Top: 40 level experiment. Bottom: 60 level experiment.

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