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The Importance of High Horizontal Resolution and Accurate Coastline Geometry in Modeling South China Sea Inflow

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Abstract. As resolution is increased from 1/2° to 1/32° in Pacific Ocean simulations using the NRL Layered Ocean Model, marked changes are found in the Kuroshio's mean pathway as it intrudes into the South China Sea (SCS) via the Luzon Strait. With increased horizontal resolution comes a more accurate representation of the coastline geometry associated with the Batan/Babuyan Islands within the strait, and a reduction in the modeled westward intrusion of the Kuroshio into the SCS. The 1/16° model is extremely sensitive to two very small scale shoals (Calayan Bank and a shoal north of Calayan Island) that are resolvable at this grid spacing. The exclusion of these three model gridpoints significantly alters the mean Kuroshio pathway to resemble the pathway from the 1/8° model. In addition, excluding all islands within the Luzon Strait in the 1/16° model gives a deep intrusion mean pathway as found in the 1/2° model.

Introduction

An accurate representation of numerical ocean model coastlines can have a significant impact on the mean pathways of ocean currents. Two issues at the core of proper model boundary definition are horizontal grid spacing and the accuracy of digital topographic databases. A finer horizontal grid allows for smaller scale features to be resolved, but many digital databases have serious deficiencies in defining small islands and shoals. Therefore, it is prudent to rely on other topographic sources, including the use of navigational charts.

Experience with the Naval Research Laboratory (NRL) Layered Ocean Model (NLOM) has shown that even relatively small changes in the model boundaries can have a significant impact on mean current pathways. These include a study on the effect of Halmahera Island on the Indonesia throughflow [*Morey et al.*, 1999], modifications to the coastlines in the Intra-Americas Seas affecting the Florida Strait transport [*Hurlburt and Townsend,* 1994; *Hurlburt and Hogan,* 2000] and minor model boundary changes affecting the direction of the Sea of Japan outflow through the Tsugaru Strait [*Hurlburt et al.,* 1996].

Metzger and Hurlburt [1996; 2001] noted the modeled westward intrusion of the Kuroshio into the South China Sea (SCS) via the Luzon Strait was less pronounced with higher horizontal resolution. This was attributed in part to a better representation of the Luzon Strait island chain. This study focuses on the importance of high horizontal resolution and accurate coastline representation in modeling this region, but the implications extend beyond it.

Model Description

The NRL Layered Ocean Model is a primitive equation layered formulation where the equations have been vertically integrated through each layer. The 6-layer, thermodynamic, finite depth model of the Pacific Ocean used in this study is a descendant of the model by *Hurlburt and Thompson* [1980] and *Wallcraft* [1991]. Specific details and the model equations can be found in *Metzger and Hurlburt* [2001].

The model domain covers the Pacific Ocean from 20°S to 62°N and 109.125°E to 77.21°W. but the focus here is on the Luzon Strait that connects the northern SCS with the Pacific Ocean. Experiments with two different horizontal resolutions are used: 1/8° (1/8° in latitude by 45/256° in longitude for each prognostic model variable) and 1/16° (1/16° in latitude by 45/512° in longitude). All experiments are forced by a monthly climatology formed from European Centre for Medium-Range Weather Forecasts (ECMWF) Reanalysis 10 m winds that span 1979-93 [*Gibson et al.,* 1997]. The winds were converted to stresses using a stability dependent drag coefficient and temperature dependent air density [*Kara et al.,* 2000]. No heat flux forcing is used in these experiments.

A modified version of the 1/12° ETOP05 bottom topography [*NOAA,* 1986] was used in the model. The 200 m isobath generally defines the model land/sea boundary but there are some exceptions, e.g. the Taiwan Strait, and the inflow/outflow straits to the Sea of Japan. A systematic problem of accurate representation of small islands exists in ETOP05, including the Batan and Babuyan Islands that run north-south within the Luzon Strait. Thus, navigational charts from the Defense Mapping Agency were also used to determine the model land/sea boundary in this and other

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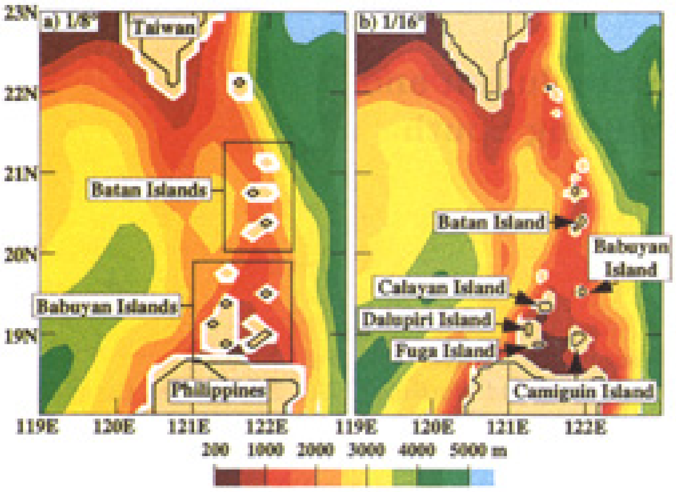

Plate 1. The bottom topography (in meters) and model coastline of the Luzon Strait in the a) 1/8° and b) 1/16° NLOM. The contour interval is 500 m.

regions [*Defense Mapping Agency,* 1980; *Defense Mapping Agency,* 1995]. Plate 1 depicts the bottom topography and model coastlines for the 1/8° and 1/16° models. Both contain the same islands and shoals within the Luzon Strait, although more crudely on the 1/8° grid.

Results/Discussion

Metzger and Hurlburt [1996; 2001] noted decreased westward intrusion of the modeled Kuroshio into the SCS with increasing horizontal resolution. In particular, the Batan and Babuyan Islands within the Luzon Strait were better represented as the resolution increased and no Luzon Strait islands were present in the 1/2° NLOM grid. Decreased westward intrusion is supported by a finding in *Hurlburt and Thompson* [1982] who used a constant absolute vorticity trajectory analysis to determine a length scale $L_I = (v_c/\beta)^{1/2}$ for westward bending of the Loop Current in the Gulf of Mexico after it passes through the Yucatan Channel and is no longer supported by a western boundary. This westward bending is due to planetary vorticity (β) advection, where v_c is the velocity at the core of the current. *Leonardi et al.* [2001] additionally accounted for the inflow angle of the current as it separated from the coast and define the westward bending space scale $b_I = L_I(1 + cos\theta_I)$, where θ_I is the inflow angle measured from the positive x-axis. This means that higher velocity in higher resolution models tends to increase the length scale for westward bending and to reduce the westward bending on a given length scale $< b_I$. The westward bending is further reduced by a narrower strait at higher resolution, a result consistent with the modeling work of *Li et al.,* [1996].

While the northeast-southwest monsoon cycle causes large seasonal variability in the SCS, the focus here is on mean current pathways. Figure 1 shows six-year mean sea surface height (SSH) from 1/8° and 1/16° NLOM simulations. The simulations are identical in all respects except for the eddy viscosity (100 m^2/s for 1/8° and 30 m^2/s for 1/16°) and the horizontal resolution and hence the coastline configuration (Plate 1). The Kuroshio intrusion in the 1/8° model is much more pronounced than in the 1/16° model. Annual mean dynamic height at 100 m presented by *Qu* [2000] indicates a flow field more consistent with the 1/16° model simulation. The core of the Kuroshio parallels the Luzon Strait and doesn't exhibit significant westward intrusion in this 1/2° analysis. The observed flow [*Qu,* 2000] that enters the SCS emanates from the lee of the Babuyan Islands in the southern half of the Luzon Strait, again a feature consistent with the 1/16° model.

This difference between the two model simulations is attributed to the coastline representation within the

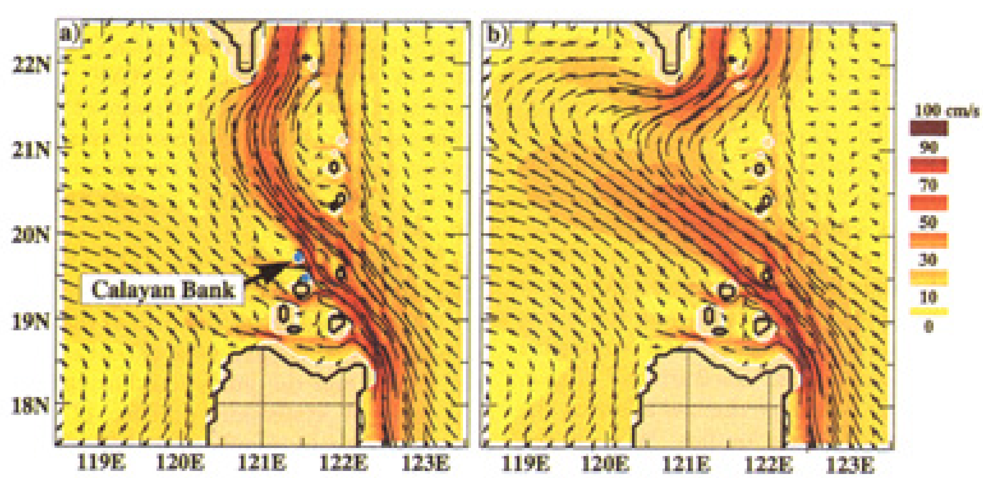

Plate 2. The 6-yr mean upper layer speed and currents from 1/16° NLOM simulations that a) include Calayan Bank and the shoal just north of Calayan Island and b) that exclude these three model gridpoints. The specified model gridpoints are highlighted in blue in panel a).

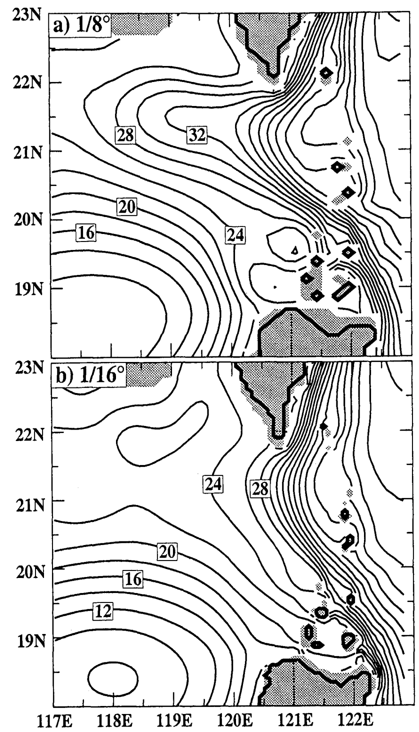

Figure 1. The 6-yr mean sea surface height from a) 1/8° and b) 1/16° NLOM simulations forced with climatological ECMWF 10 m winds. The contour interval is 2 cm. The net westward Luzon Strait transport is 2.2 Sv and 3.0 Sv for the 1/8° and 1/16° simulations, respectively. *Qu* [2000] estimates the Luzon Strait transport at 3.0 Sv.

Luzon Strait and the higher eddy viscosity at 1/8°. The coarser resolution 1/8° simulation cannot resolve the small scale islands and shoals as well as the 1/16° model. This is especially true in the southern half of the strait with regard to Calayan, Dalupiri and Fuga Islands and the passageways between them. This has a significant impact on the mean pathway of the Kuroshio's westward intrusion into the SCS (Figure 1). At 1/8° resolution, these shoals and islands are a contiguous group of land points. This effectively forces the core of the Kuroshio northward with the main branch entering the strait between Batan and Babuyan Islands, rather than between Babuyan and Camiguin Islands. At 1/16°, the resolution allows for an open passageway between Calayan and Dalupiri Islands and a lower eddy viscosity allows more flow through the passages south of Babuyan Island and the shoal north of Calayan Island. In this simulation the main branch of the Kuroshio takes a more southern route between Babuyan and Camiguin Islands.

To further isolate the cause of reduced Kuroshio intrusion into the SCS in the 1/16° model, note that two small scale shoals are having a substantial "blocking" effect. These are highlighted in blue on Plate 2a and are Calayan Bank (121.4°E, 19.7°N) and the shoal north of Calayan Island (121.5°E, 19.5°N). These shoals produce two effects: 1) they narrow the Luzon Strait and thus reduce the westward bending compared to the case where they are absent, and 2) more importantly they deflect the flow so that the inflow angle is more northward, the latter corroborated by a 1/32° NLOM Pacific simulation (not shown). The significance of these three model gridpoints is illustrated in a simulation where the shoals were removed (Plate 2b). While the main branch of the Kuroshio still enters the strait between Babuyan and Camiguin Islands, the removal of the shoals at 1/16° changes the mean pathway to resemble that of the 1/8° model (Figure 1a). When Calayan Bank is removed in a 1/8° simulation, the mean pathway of the Kuroshio is almost unaffected (not shown) because the main branch of the Kuroshio continues to take the more northern route between Batan and Babuyan Islands and the inflow angle is essentially the same in both simulations.

What effect does the entire island chain have on Kuroshio intrusion? Figure 2 shows mean SSH from a 1/16° simulation with all Luzon Strait islands and shoals removed. Ocean depths at the surrounding gridpoints were averaged to convert the former model land points to ocean points. With a much wider Luzon Strait, the entire Kuroshio unrealistically loops into the northern SCS, a result similar to the 1/2° global model simulations of *Metzger and Hurlburt* [1996] that also excluded islands within the strait, and consistent with the idealized strait simulations by *Li et al.,* [1996].

Summary and Conclusions

Past and present simulations using the NRL Layered Ocean Model at 1/2°, 1/8°, 1/16° and 1/32° resolution have shown the importance of accurate representation of the north-south island chain within the Luzon Strait that connects the northern SCS and the Pacific Ocean. At 1/16° and 1/32° resolution, the mean pathway of the Kuroshio changes such that it bypasses the SCS rather than intruding deeply into it, a result consistent with the observations of *Qu* [2000]. The accuracy of

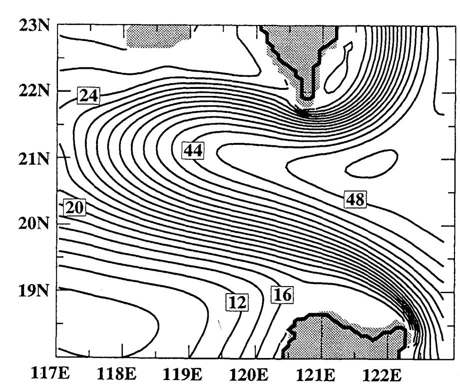

Figure 2. Same as Figure 1 except for a 1/16° NLOM simulation that excluded all Luzon Strait islands and shoals. The net westward Luzon Strait transport is 2.9 Sv.

model coastlines is obviously a function of horizontal resolution, but grid spacing as fine as 1/8° cannot adequately resolve the Babuyan Islands in the southern latitudes of the Luzon Strait. At this resolution, the Calayan/Dalupiri/Fuga Island complex is a contiguous land mass and the higher eddy viscosity restricts the flow through open passages south of Babuyan Island. This forces the main branch of the Kuroshio to enter the SCS by a more northern route between Batan and Babuyan Islands and to enter with a substantial westward inflow component. In the 1/16° model, a passageway exists between Calayan and Dalupiri Island. This and the lower eddy viscosity allow the main branch of the Kuroshio to take a more southern route between Babuyan and Camiguin Islands. However, Calayan Bank has a "blocking effect" on this southern branch that turns the flow to a more northward inflow angle, thus reducing the westward bending into the SCS.

This has important consequences for modelers of this region. The results suggest that horizontal resolution of at least 1/16° is needed to adequately represent the islands and shoals in the Luzon Strait and thus simulate a Kuroshio more consistent with observations. Furthermore, the mean pathway is extremely sensitive to three seemingly inauspicious model gridpoints. Removal of these increases the westward intrusion to resemble 1/8° model results.

The need for accurate coastline representation goes beyond this region and resolution as demonstrated in earlier work cited in the introduction. Past experience with the NRL Layered Ocean Model has shown that interpolation of a standard digital topography like ETOP05 is insufficient since existing digital topographic databases are often not accurate at scales representable on grids at least as coarse as 1/4°. Thus, extra effort has been required when defining the land/sea grid, including the use of navigational charts and other topographic sources.

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