about 400 m. At depths greater than 1000 m, the horizontal variations of climatological monthly mean salinity are relatively small.

Model Results

We integrate the nested-grid system for eleven years from the beginning of 1990 to the end of 2000 and discuss the model results of the last ten years in this paper. Figures 6 and 7 show the instantaneous near-surface (1 m) and sub-surface (450 m) currents and temperature at day 450 (March 26, 1992) produced by the nested-grid system. The near-surface circulation produced by the outer model at this time is characterized by a persistent through flow known as the Caribbean Current, which is relatively broad and roughly westward in the central and eastern Colombian Basin (Figure 6a). The Caribbean Current bifurcates before reaching the Nicaragua Rise, with a weak branch veering southwestward to form the cyclonic, highly variable Panama-Colombia Gyre in the southwestern Caribbean Sea. The main branch of the Caribbean Current turns northwestward and flows along the outer flank of Nicaragua Rise to form a narrow offshore flow running westward and then northward to the Gulf of Mexico. The sub-surface circulation in the WCS at day 450 (Figure 7a) has several large-scale cyclonic gyres in the Colombian Basin, an intense westward flow entering the Cayman Basin from Windward Passage, and strong northwestward flow entering the MBRS from the Colombian Basin through the deep channel between Nicaragua Rise and Jamaica.

The near-surface circulation produced by the intermediate-resolution middle model at day 450 has strong and broad westward currents over the MBRS (Figure 6b). The westward currents bifurcate before reaching the Belize Barrier Reef, with the main branch flowing northward along the eastern coast of Belize, and a small branch flowing southward to the Gulf of Honduras. The sub-surface currents produced by the middle model have a large-scale cyclonic recirculation over the southern MBRS (Figure 7b). A comparison of Figures 6 and 7 demonstrates that the middle model results have similar large-scale circulation features as the outer model results, with more small-scale features resolved by the middle model.

The fine-resolution inner model produces much more small-scale circulation features affected by the local topography over the BS (Figures 6c and 7c), in comparison with the outer and middle model results. The currents produced by the inner model at day 450 are roughly southwestward at 1 m and northward at 450 m on the shelf region and deep waters around Turneffe Islands. The near-surface temperature produced by the inner model is relatively uniform and about 24°C over the deep water, and slightly warmer over the coastal shallow region of the BS.

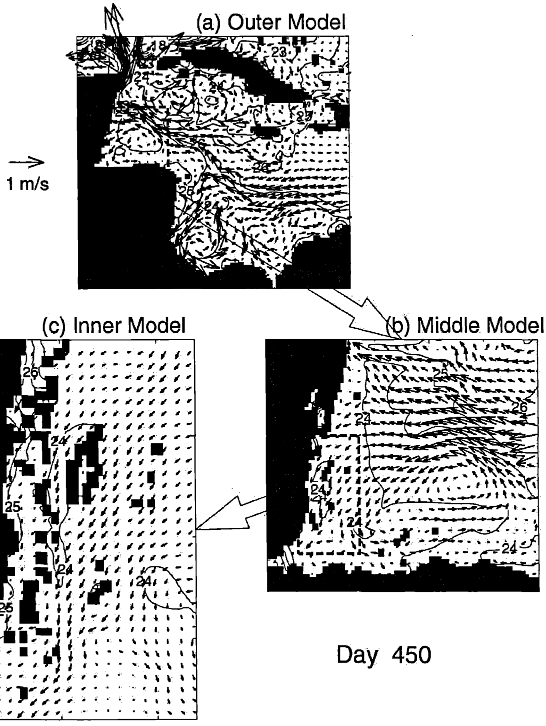

Figure 6. Near-surface (1 m) currents and temperature at day 450 (March 26, 1992) produced by the (a) outer model; (b) middle model, and (c) inner model. Velocity vectors are plotted at every third model grid point.

Figures 8 and 9 present the near-surface (1 m) and sub-surface (450 m) monthly mean currents in February, May, August, and November, calculated from 10-year (1991-2000) results produced by the outer model. The monthly mean currents in the four months are characterized by the persistent Caribbean Current flowing from the eastern Colombian Basin to the western side of the Yucatan Channel and the Panama-Colombia Gyre over the southwestern CS. The Caribbean Current is relatively narrower and stronger in August than in the other three months. The Panama-Colombia Gyre is highly variable, which qualitatively agrees with the previous findings based on the satellite altimetry data (Nystuen and Andrade 1993; Andrade and Barton 2000) and near-surface drifter data (Fratantoni 2001).

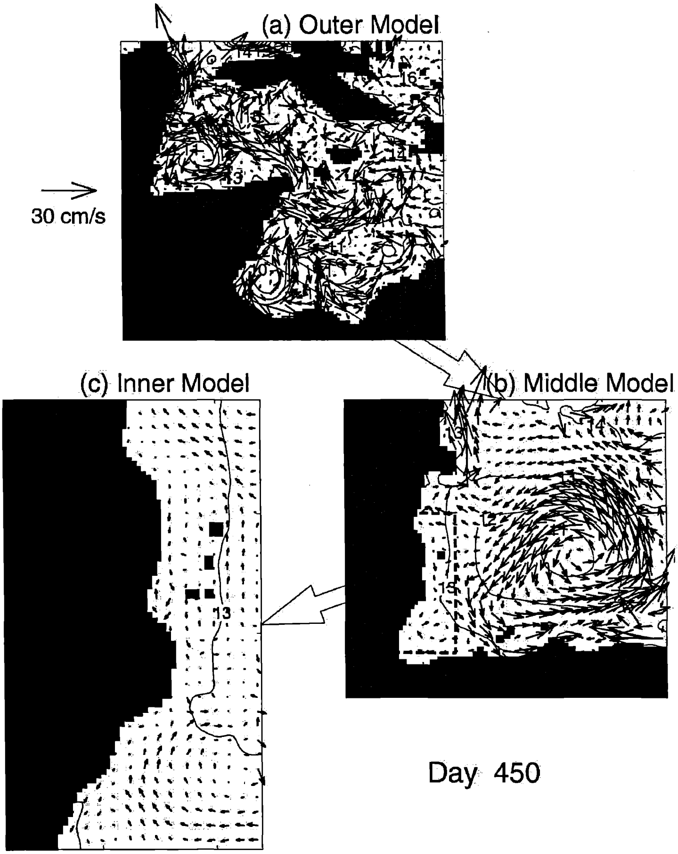

Figure 7. Sub-surface (450 m) currents and temperature at day 450 produced by the (a) outer model; (b) middle model, and (c) inner model. Velocity vectors are plotted at every third model grid point.

The main features of the monthly mean circulation produced by the outer model are in good agreement with those produced by Sheng and Tang (2003) using a single-domain model for the same region and climatological monthly mean wind forcing, and are also in good agreement with the current knowledge of the general circulation in the WCS (Maul, 1993; Mooers and Maul, 1998; Johns et al., 2002; Ezer et al., 2003; Ezer et al., 2005).

The monthly mean near-surface (1 m) temperatures produced by the outer model in the four months (now shown) are horizontally uniform in the central CS and about 25°C in February, 27°C in May and November, and 28°C in August. There is a pool of cold waters in the surface layer over the Campeche Bank off northern Yucatan Peninsula. This pool of cold waters is produced by the intense coastal upwelling occurring in the area. The monthly mean near-surface salinity in the four months is horizontally uniform in the central WCS, with relatively salty waters in the eastern Cayman and Yucatan Basins and fresh waters in the southern Yucatan Basin.

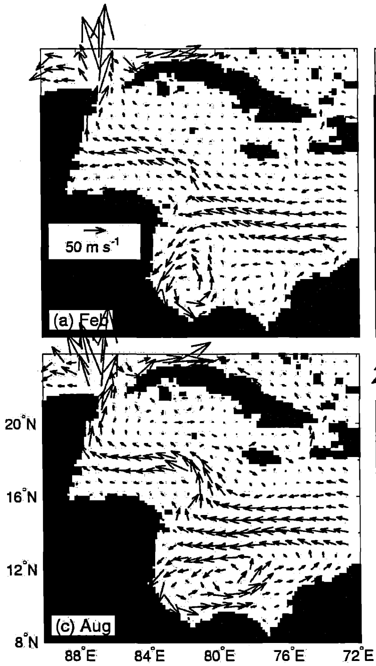

Figure 8. Monthly mean near-surface (1 m) currents calculated from 10-year results from 1991 to 2000 produced by the outer model in (a) February; (b) May; (c) August; and (d) November. Velocity vectors are plotted at every four model grid point.

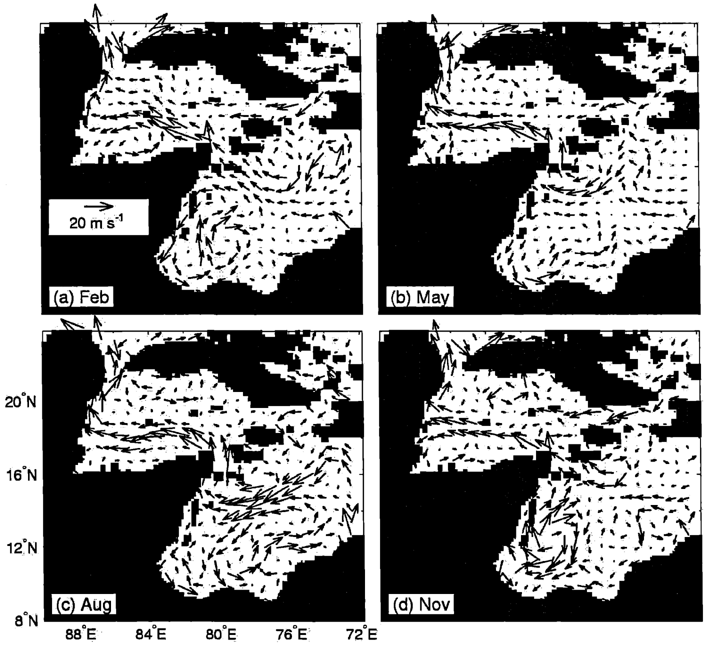

Figure 9. Monthly mean sub-surface (450 m) currents calculated from 10-year results from 1991 to 2000 produced by the outer model in (a) February; (b) May; (c) August; and (d) November. Velocity vectors are plotted at every four model grid point.

The sub-surface temperatures at 450 m have large seasonal variability, with relatively stronger cross-shelf gradients over the western sides of Cayman and Yucatan Basins in August than in February (Figures 10). In comparison with the temperature climatology, the model results maintain reasonably well the horizontal gradients of the sub-surface temperature in the region, particularly over the western Cayman and Yucatan Basins.

The 3D temperature and salinity produced by the outer model are used to calculate the domain-averaged temperature and salinity and associated standard deviations with respect to the domain means at each depth in the four months (Figure 11). In comparison with the climatological hydrographic data in Figure 5, the outer model reproduces reasonably well the vertical structure of the domain-averaged temperature and associated horizontal variations in the WCS. The outer model also reproduces reasonably well the vertical structure of the domain-averaged salinity and associated horizontal variations at depths greater than 1000 m, but less well in the top 1000 m. Plausible explanations for the model deficiency in simulating the domain-averaged salinity in the top 1000 m include the application of the restoring boundary conditions for the surface salinity and simple vertical mixing parameterizations used in the model.

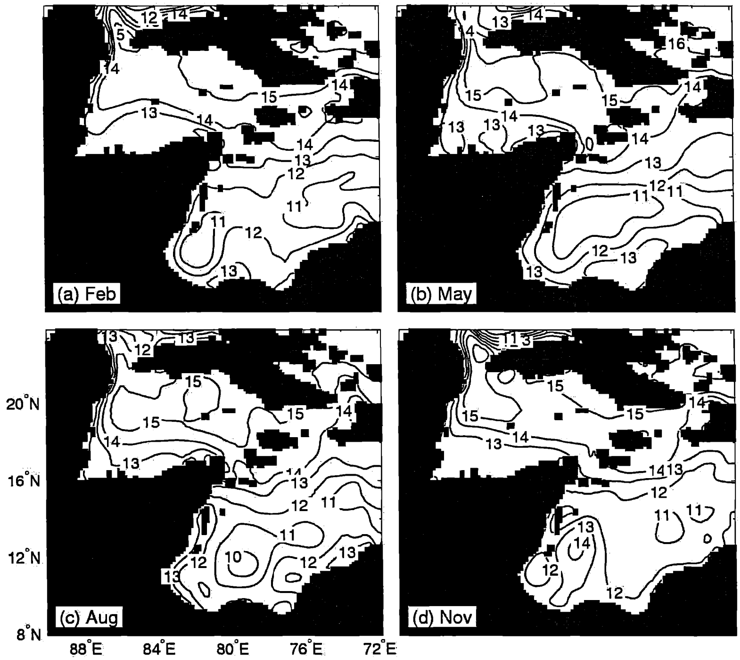

Figure10. Monthly mean sub-surface (450 m) temperature calculated from 10-year results from 1991 to 2000 produced by the outer model.

To quantify the temporal variability of the circulation in the WCS, I follow Sheng and Tang (2003) and calculate the root-mean-square (rms) values of $\sigma_{|u|}$ (= $(\sigma_u^2 + \sigma_v^2)^{1/2}$) at each grid point from the 10-year model results. Here σ_u and σ_v are respectively the rms values of the eastward and northward components of the currents with respect to the decadal means. Figure 12a demonstrates that the temporal variabilities of the near-surface currents produced by the outer model are large in the WCS, particularly over the southwestern Colombian Basin, with a maximum value of $\sigma_{|u|}$ of about 18 cm s^{-1}. The large rms values over the southern Colombian Basin are associated mainly with the highly variable Panama-Colombian Gyre. The rms values of the near-surface currents are also large over the MBRS, with a maximum value of $\sigma_{|u|}$ of about 12 cm s^{-1}, indicating that the Caribbean Current has significant temporal variability over the region. In comparison with the near-surface results, the rms values of sub-surface currents at 140 m (Figure 12b) are relatively smaller, but still significant particularly over the southwestern Colombian Basin and MBRS region. The typical rms values of the sub-surface currents are about 6 cm s^{-1} over the MBRS and about 10 cm s^{-1} over the southwestern Colombian Basin.

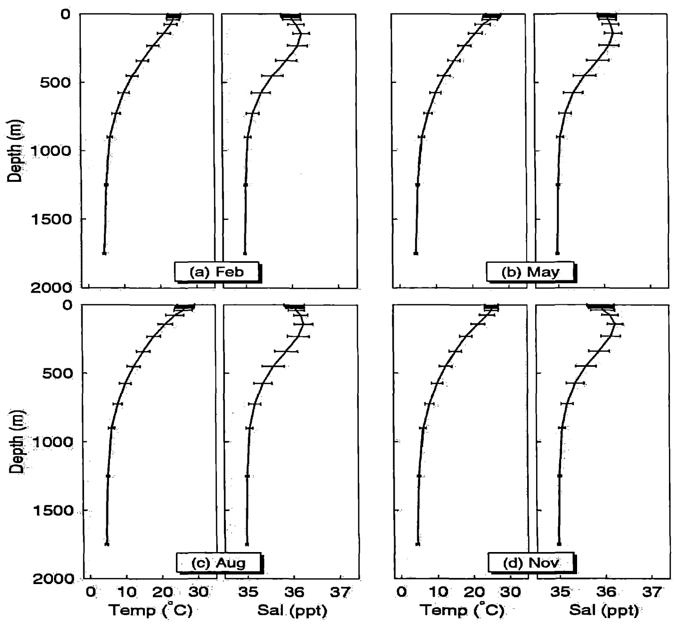

Figure 11. Vertical profiles of domain-averaged monthly mean temperature and salinity produced by the outer model in (a) February; (b) May; (c) August; and (d) November. The error bar represents 2 standard deviations with respect to the domain mean at each depth.

To assess the performance of the nested-grid system, the decadal mean currents at 16 m produced by the outer and middle models are compared with the decadal-mean currents inferred by Fratantoni (2001) from trajectories of the satellite-tracked 15-m drogued drifters made during the 1990s (Figure 13). The nested-grid outer model reproduces reasonably well the large-scale features of the observed currents in the WCS, including the persistent Caribbean Current and the intense Panama-Colombia Gyre (Figure 13a). The middle model results also reproduce reasonably well the observed currents in the southern MBRS.

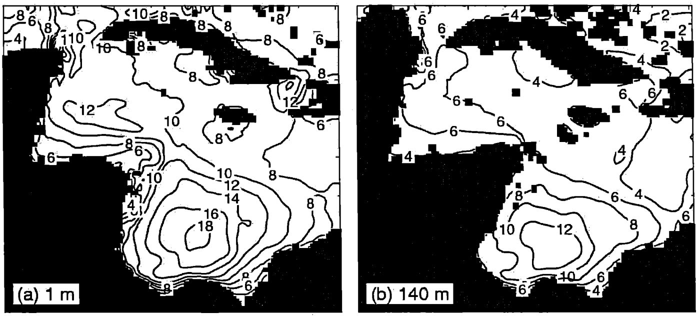

Figure 12. The root-mean-square values of $\sigma_{|u|}$ (in units of cm s^{-1}) of model currents at (a) 1 m; and (b) 140 m calculated from 10-year results produced by the outer model.

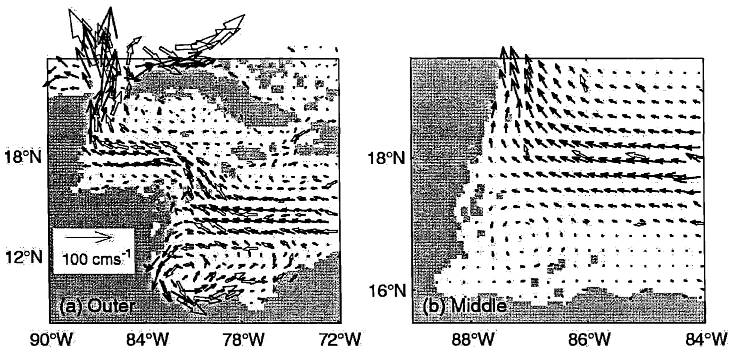

Figure 13. Comparison of modeled (solid arrows) and observed (open arrows) currents (a) in the WCS and (b) in the MBRS. The modeled currents are the decadal mean currents at 16 m produced by the nested-grid outer and middle models respectively. The observed currents are the gridded decadal mean currents during the 1990s inferred from trajectories by Fratantoni (2001).

Summary and conclusion

A triply nested-grid ocean modeling system was used to study the three-dimensional ocean circulation and water mass distributions on the Meso-American Barrier Reef System (MBRS) of the northwestern Caribbean Sea. The two-way nesting technique based on the smoothed semi-prognostic method (Sheng et al., 2005) was used to exchange information between sub-components of the system. The main advantage of this nesting technique is that it prevents unrealistic drift of the middle and inner models by adjusting large-scale circulations produced by the two models using the outer and middle model results, respectively, while the model temperature and salinity of the nested-grid model are fully prognostic.

The nested-grid system was forced by the 6-hourly NCEP wind forcing and monthly mean sea surface heat and freshwater fluxes. The system simulates reasonably well the general circulation in the WCS during the 10-year period from 1991 to 2000. The monthly mean near-surface circulation in the MBRS produced by the system is characterized by a strong and persistent northwestward flow over the MBRS, as a direct result of the interaction between the strong, directional Caribbean Current, and weak, spatially variable currents in the southern and inner Belize shelf. The upper-ocean circulation produced by the system also has significant spatial and temporal variability over the MBRS.

Acknowledgments

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