Appendix E Circulation in Lingayen Gulf inferred from temperature and salinity

Cesar Villanoy
Marine Science Institute, University of the Philippines
Diliman, Quezon City 1101, Philippines

Introduction

The exchange of water masses between the coastal and open oceans plays a direct role in the flux of materials either within the water column or indirectly through the sediments. The characterization of the transport processes that govern material transport is an important element in the understanding of complex interactions in the coastal zone. This includes interactions between material inputs (e.g. pollutants, nutrients, sediments), the various forms of chemical constituents and their associated chemical reactions, and the complex biological processes which can transform and exchange materials between the water column and the underlying sediments (Blumberg et al., 1993).

Hydrographic Characteristics.

Temperature and salinity distributions in Lingayen Gulf were obtained from conductivity-temperature-depth (CTD) surveys conducted in February 1997, April 1997, April 1998 and July 1999. Data from previous surveys (April 1993 and January 1994) were also included in the analysis. The CTD data were objectively interpolated into a 2.5km x 2.5km grid using a 20 km covariance scale based on the method by Carter and Robinson (1987). This procedure was done for each 5 m interval and interpolated data with less than 10% standard error were included in the objectively analyzed data set. The vertical density profiles were calculated to ensure that no spurious density inversions were produced in the interpolation procedure.

Perhaps the most interesting feature of the hydrographic characteristics of Lingayen Gulf is the fact that most of the isotherms and isohalines in horizontal distributions show a high degree of orientation parallel to the gulf axis (e.g. Figures 2 – 5, main report). The general trend of the isotherms do not differ significantly between January and July which suggests that other processes other than the local wind forcing are important. The salinity distributions (Figures 4 and 5) indicate that the eastern side of the Gulf is slightly fresher than the western side. This may indicate that freshwater input into the Gulf is mixed and advected out of the Gulf through the eastern side.

Freshwater from both surface and groundwater runoff in Lingayen Gulf is significant enough to influence the density distribution up to depths of 100-140m. This may not be apparent, initially, because of the absence of strong horizontal salinity gradients. However, the relatively large salinity difference in the upper 100m between South China Sea and Lingayen Gulf waters indicates otherwise. It is likely that strong mixing within the gulf quickly erodes horizontal salinity gradients but may still be fresher that open ocean values at the same depths. During the dry season, when the influence of surface water runoff on gulf salinity is reduced, subsurface groundwater discharge from the western and eastern sides of the gulf is evident.

Tidal Circulation:

The circulation in Lingayen Gulf is influenced by three main driving forces; the tidal component, local wind-driven forcing and the interaction with remotely forced alongshore currents along the western Luzon Shelf. Characterization of the tidal circulation patterns was inferred from the results of a tidal model based on the two-dimensional, vertically-integrated version of the Princeton Ocean Model (Blumberg and Mellor, 1986). The model makes use of a curvi-linear grid extending from Zambales to the northern part of La Union (Figure E1). This type of grid was used to conveniently allow the incorporation of alongshore shelf currents off the western coast of Luzon. The western open boundary roughly coincides with the 1000m isobath.

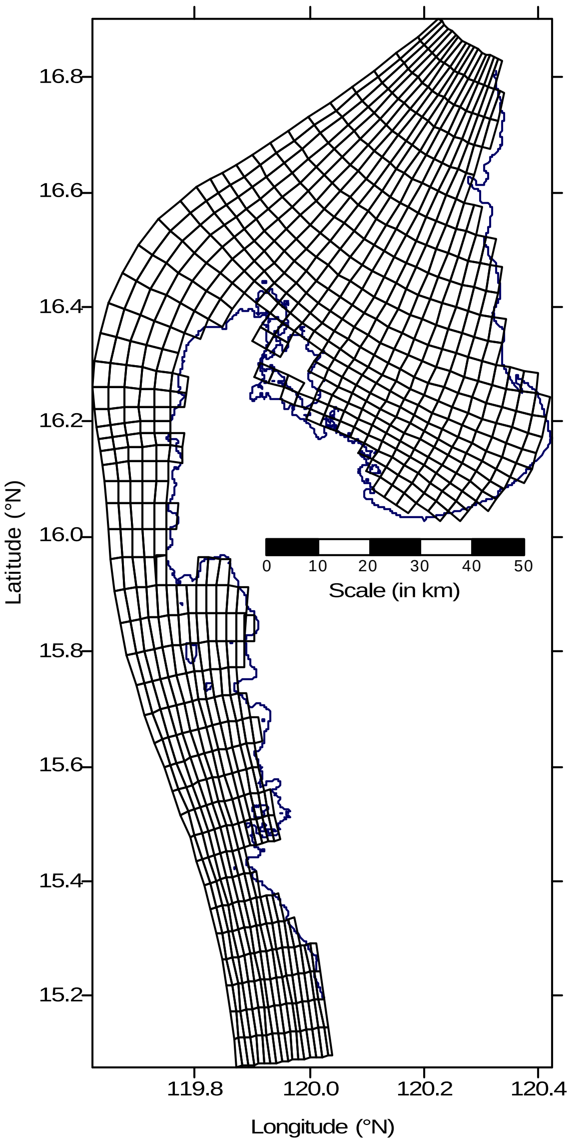

Figure E1. Curvi-linear grid used in the Lingayen Gulf model.

Tidal forcing was prescribed by allowing the sea level at the open boundaries to oscillate at tidal frequencies. The offshore tidal characteristics were obtained from the global tide model of Matsumoto et al. (1996) for two diurnal (O_1 and K_1) and two semidiurnal (M_2 and S_2) tidal components. The amplitudes of the tidal elevations all increase towards the south but the propagation direction is perpendicular to the coast for the diurnal components and parallel to the coast for the semidiurnal components.

The model, initially run in 2-dimensional mode with purely tidal forcing, was integrated for a period of 16 days, including a one-day spin-up time. Hourly vertically integrated velocities were stored and the amplitudes and phases of the tidal current velocities were extracted using harmonic analysis and were used to produce the tidal ellipses shown in Figure E2. The oscillation of the tidal currents occur mainly in the alongshore direction except inside the Gulf where tidal flow is simply in and out of the Gulf. Near the head of the Gulf, the main axis of the ellipses is oriented perpendicular to the coast. In the northern half of the bay, the orientation of the ellipses show that flow across the Gulf mouth occurs at the eastern part (La Union side) for the O_1, K_1 and M_2 components. The S_2 component is the weakest of the four components considered in the simulations. An interesting feature of the tidal circulation is where the alongshore flow outside the gulf meets the flow from the interior of the Gulf. This occurs northeast of Cabarruyan Island and is also where the tidal currents exhibit a higher degree of rotation, particularly for the M_2 component.

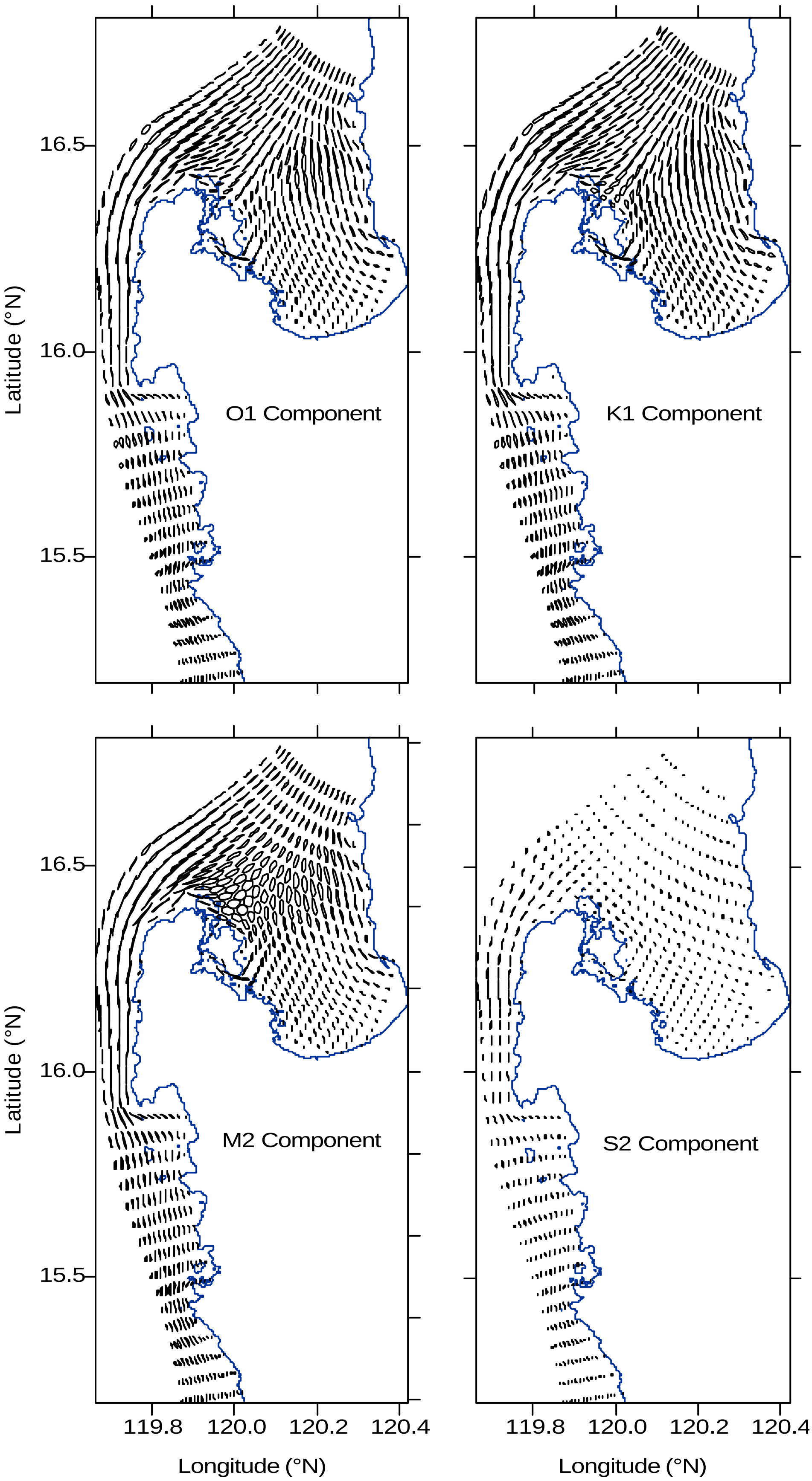

Figure E2. Tidal ellipses for the dominant diurnal and semi-diurnal components.

The interaction of the tidal currents with topography and coastline shape can lead to a net transport of water over a spring-neap cycle (Figure 6, main report). In the northern half of the Gulf, the residual flows are towards the south in the eastern part, turning west and out towards the northeast off Bolinao. Together with the northeastward residual flow off the mouth, this forms a clockwise gyre pattern centered at the mouth of the gulf. The southward residual flow in the eastern part of the Gulf persists along the eastern boundary up to the head of the Gulf. On the western side, the residual flow is towards the north off Cabarruyan Island but is southward south of the Hundred Islands.

Influence of alongshore shelf currents:

The tidal model results show some degree of interaction between the tidal flow outside and inside the gulf. Off the western coast of Luzon, a northward coastal current appears to exist which persists throughout the year. Although no direct measurements are available, surface current derived from ship's drift (Richardson's Ship's Drift Database), dynamic calculations (Liu et al., 1992), and modeling studies of the South China Sea (Shaw and Chao, 1994) all show northward flow east of Luzon. This current is considered to be the return flow of the dominant cyclonic gyre in the South China Sea.

Dispersal of volcanic lahar discharged from rivers in Zambales during the eruption of Mount Pinatubo shows a net northward transport off the coast of Zambales.

Previous circulation models of the Lingayen Gulf circulation extended only to the mouth and processes outside the mouth were not considered (e.g. Balotro, 1992). The distribution of temperature and salinity across the mouth, however, suggests that interaction with shelf processes cannot be neglected. Numerical experiments were conducted using the curvi-linear grid described above and applying the full 3-dimensional version of the Princeton Ocean Model (POM). The model was initialized with a horizontally uniform temperature and salinity profile of the adjacent area of the South China Sea. At the northern and southern cross-shelf open boundaries of the model, transport northward of about $0.8x10^6$ m^3s^{-1} was prescribed.

The result for the coastal current forced model is shown in Figure 7 (main report). The velocity component normal to the eastern boundary was set to zero to constrain the prescribed current to flow in the alongshore direction. Since the outer boundary generally coincides with the 1000m isobath, this assumption can be argued using the conservation of potential vorticity. The transport through the southern boundary was assumed to be equal to the transport in the northern boundary but the difference in velocities is accounted for by the difference in their cross-sectional area. The narrower shelf west of Zambales results in stronger currents compared to the broader shelf area to the north. Upon reaching the northern tip of Cape Bolinao, part of the flow turns southward into Lingayen Gulf forming an eddy on the leeward side of Cape Bolinao. The southern part of this eddy which flows westward extends up to about a third into the Gulf after back north off the eastern coast of Bolinao. The sea surface temperatures show a ridge of warm water extending from Bolinao to San Fernando, La Union which may be due to geostrophic adjustment by the northeastward alongshore current and the return flow inside Lingayen Gulf. The interior of the Gulf is characterized by a counterclockwise gyre.

Wind Driven Circulation

In the presence of the wind, the vertically-averaged currents outside Lingayen Gulf did not show a distinct variation from the purely coastal current forced model. The effect of local wind forcing was more evident in the interior of the Gulf. Both the vertically-averaged currents and the surface currents for both northeast and southwest monsoon forcing are shown in Figure 8 and 9 (main report) respectively. The vertically-averaged currents still show the leeward eddy off the eastern coast of Bolinao for both monsoon seasons albeit with slightly different magnitudes and location.

In the southern half of the Gulf, the circulation exhibits a higher degree of variability with local wind forcing. During southerly wind forcing, a counterclockwise circulation in the southern half of the Gulf is formed but this pattern disappears at the surface where there is a net eastward flow off the Gulf head which turns north at the eastern side of the Gulf. The northerly wind-forced simulations, however, do not show such a distinct feature. Instead, the flow is dominated by a net southwestward flow at the surface and Gulf wide counterclockwise flow for the net transport.

Summary

The circulation in Lingayen Gulf is influenced by conditions outside the gulf mouth. Outside the gulf, particularly along the narrow western shelf extending from Zambales to La Union, the prevailing current is a northward coastal current which is forced remotely by the basin-wide gyre circulation of the South China Sea. As it flows past the Cape of Bolinao, the current loops southward and enters the northern half of the gulf before turning back to exit on the other side of the gulf mouth. The significantly steep slope of isotherms across the gulf mouth manifests this feature. Penetration into the gulf is limited to the northern half, based on the decrease in isothermal slopes towards the gulf head. Local wind forcing is not strong enough to reverse the coastal current outside the gulf, thus the net transport along the western Luzon shelf is northward throughout the year. However, wind forcing can produce seasonally reversing recirculating gyres in the southern half of the gulf.

The tidal component of the flow influences the gulf circulation in a similar manner because the main axis of the tidal currents over the shelf is alongshore. Residual currents show a similar loop feature. This feature has implications on the flushing of the bay as it forms a barrier that can reduce mixing and transport from the southern part of the bay. Consequently, most of the flow in and out of the gulf occurs on the eastern and western edges of the bay mouth.

Freshwater from both surface and groundwater runoff in Lingayen Gulf is significant enough to influence the density distribution up to depths of 100-140m. This may not be apparent, initially, because of the absence of strong horizontal salinity gradients. However, the relatively large salinity difference in the upper 100m between South China Sea and Lingayen Gulf waters indicate otherwise. It is likely that strong mixing within the gulf quickly erodes horizontal salinity gradients but may still be fresher than open ocean values at the same depths. During the dry season, when the influence of surface water runoff on the gulf salinity is reduced, subsurface groundwater discharge from the western and eastern sides of the gulf is evident.

References

Balotro, R.S. 1992 A barotropic wind and tide-induced circulation model for the Gulf of Lingayen. *MSc Thesis.* Dept of Meteorology and Oceanography, University of the Philippines.

Blumberg, A.F., Signell, R.P. and Jenter, H.L. 1993 Modelling transport processes in the coastal ocean. *Journal of Marine Environmental Engineering* **1**:31-52.

Blumberg, A.F. and Mellor G.L. 1987. A description of a three-dimensional coastal ocean circulation model. Pages1-16 in Heaps N.S. (ed). *Three-dimensional coastal ocean models.* American Geophysical Union, Washington D.C.

Liu C.T., Pai, S.C., Jacinto, G.S. and Bentillo, I. 1992. The circulation near Luzon. *Proceedings of the PORSEC Conference*. Taiwan, February 1992. P1-5.

Matsumoto, K, Ooe, M., Sato, T. and Segawa, J. 1995 Ocean tide model obtained from TOPEX/POSEIDON altimetry data. *Journal of geophysical Research* **100** (C12):25319-25330.

Shaw, P. and Chao 1994 Surface circulation in the South China Sea. *Deep-Sea Research* **41**(11/12): 1663-1683.