Salt-plug estuarine circulation in Malampaya Sound, Palawan, Philippines

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Malampaya Sound is an enclosed bay in Palawan, Philippines. A salinity maximum or salt plug was discovered in the middle of the Sound by a field survey in May 2005 and successfully simulated using a Delft3D numerical model of the sound, forced with tide and freshwater discharge at the lateral boundaries, and evaporation at the surface. Different conditions to simulate the major monsoonal regimes of 2005 (dry inter-monsoon, southwest-wet, and northeast-dry) indicate that the salt plug persists, although its relative position changes with the magnitude of freshwater discharge. The salt plug effectively limits the exchange of water between the Inner and the Outer Sound, which may account for differences in nutrient levels and the phytoplankton assemblage during the same survey. Such a thermohaline circulation has important consequences for sediment transport, phytoplankton bloom formation, and accumulation of pollutants in the Sound.

KEYWORDS

Salt-plug estuary, thermohaline circulation, numerical model, Malampaya Sound

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INTRODUCTION

Salt-plug estuaries, relatively uncommon among the world's estuaries, include the Gulf of Fonseca in Honduras (Valle-Levinson and Bosley 2003) and the Bay of Guaymas in Mexico (Valle-Levinson et al. 2001). Characteristically, they each have two vertical thermohaline cells: an inner typical freshwater-estuarine circulation and a seaward reverse estuary. High evaporation rates coupled with long residence times produce a salt plug, or surface salinity maximum in the estuary. Formation of a reverse estuary in the seaward portion of an estuary modifies its transport pattern, reducing flushing of its inner portion and modifying the transport of nutrients and other substances within it.

Malampaya Sound is a shallow embayment in northwestern Palawan, Philippines that opens northwestward to the South China Sea (Figure 1). The bay narrows in its middle portion, which also contains a group of small islands that demarcates the shallow Inner Sound from the deeper outer portion. Draining into the Sound's southeast portion is the Abongan River, estimated to discharge about 200 x 10^6 m^3 annually or at a rate of 6.3 m^3 s^{-1} (Alejandrino et al. 1976). November to April is the dry season of the northeast monsoon, and the wet southwest monsoon lasts from June to October.

Malampaya Sound is a unique estuary in the Philippines. Specimens of the rare Irrawaddy dolphin have been reported in it (Dolar et al. 2002). In July 2000, it was proclaimed a protected area for its rich waters and potential for shellfish production and

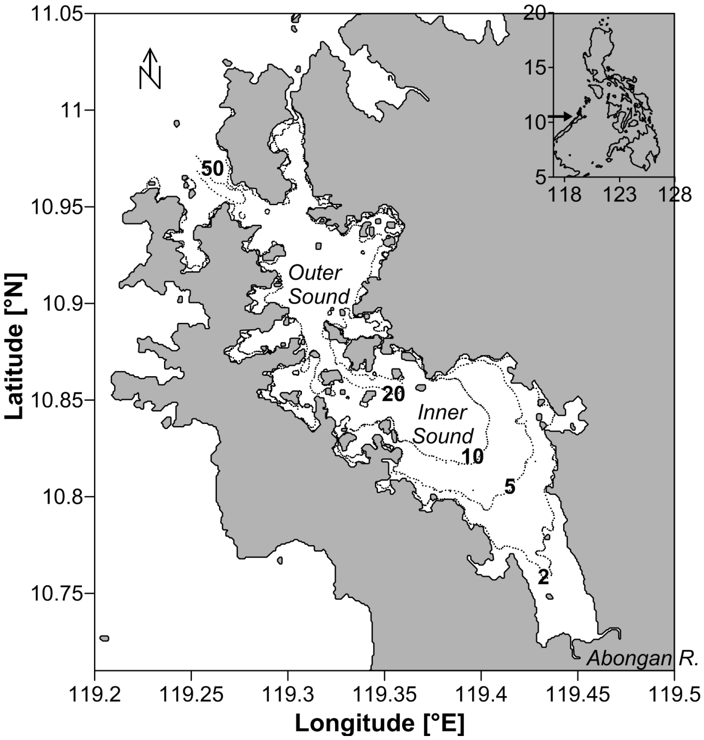

Figure 1. Location and bathymetry of Malampaya Sound, Palawan, Philippines.

tourism. Shellfish farms, particularly of green mussels (*Perna viridis*), abound, especially in the Inner Sound; however, harmful algal blooms have been reported there as early as 1998 (Bajarias et al. 2006). Most research in Malampaya Sound has been concerned with plankton (Estudillo 1987, Borja et al. 2000), nutrient distributions (David et al. 2008), and sedimentation rates (Sombrito et al. 2004). The observed nutrient and plankton distributions appear consistent with the salt-plug estuary characteristics of the Sound, even for only certain periods of the year.

This paper describes the salt-plug hydrodynamics of Malampaya Sound from field data and a numerical model, and examines the implications of the circulation for the nutrient distribution and phytoplankton composition.

MATERIALS AND METHODS

Field Survey

During field work on 23-24 May 2005, temperature, salinity, chlorophyll, and surface currents were measured at 21 stations. A SEACAT SBE19 Conductivity-Temperature-Depth profiler with a Turner SCUFA fluorometer gathered data for constructing vertical profiles of salinity, temperature, and chlorophyll. The CTD is equipped with a thermistor probe (with 0.01 °C accuracy), a conductivity cell (with 0.001 Siemens m^{-1} accuracy), and strain gauge pressure sensor (with 12.5 psi accuracy), all factory-calibrated to derive temperature, salinity in practical salinity units or psu (based on ratio of conductivity of sample and conductivity of known standard), and depth in meters. Readers are referred to the Seabird website (http://www.seabird.com/sbe19plusv2-seacat-ctd) for visualization and further information on CTDs. The attached fluorometer on the other hand has an ultra Bright Blue LED light source and a photodiode detector for measuring *in vivo* fluorescence of chlorophyll a of phytoplankton, also factory-calibrated to convert fluorescence to concentrations of chlorophyll a in ug L^{-1}. Surface currents were measured using a holey-sock drogue with an attached handheld GPS that logs coordinates every 5 seconds, with current speed and direction derived from start and end point locations after 1 minute. After each drogue release, wind speeds and directions were also measured by a handheld anemometer and compass. At 10 of these stations, water samples were also collected with a Niskin sampler and stored frozen for nutrient analysis, and filtered onto GF/F filters with the filters frozen for chlorophyll analysis in the laboratory. Phytoplankton samples were collected using a plankton net (30 cm diameter with 25 µm mesh size) and preserved with Lugol's solution.

Laboratory Analyses

In the laboratory, the water samples were analyzed for nutrients using a San Plus Skalar Autoanalyzer, following the method of Strickland and Parsons (1972), while chlorophyll a was extracted from the filtrate and measured following JGOFS protocol (Knap et al. 1996) to calibrate the conversion factor of fluorescence to chlorophyll a concentrations. Phytoplankton were identified and counted under a microscope. After appropriate dilutions, 1-ml aliquots containing at least 100 cells were transferred to a Sedgewick Rafter counting chamber. Cells were identified mostly to genus, or to species level whenever possible, based on the phytoplankton guide of Tomas (1997). Two-way Indicator Species Analysis or TWINSPAN was used for the phytoplankton data to characterize the spatial distributions, TWINSPAN being a simple statistical method for identifying spatial patterns based on presence or absence of species.

Model Setup

To simulate the estuarine circulation in Malampaya, a numerical model was developed using the open-source, modular Delft3D Software. The Delft3D Flow module calculates two- or three-dimensional flow by finding solutions to the basic equations of fluid motion that follows the laws of conservation of mass (continuity equation), momentum (Navier-Stokes equation), heat, and salt. The software is especially well-suited for coastal, river, and estuarine areas because it can take into account tidal forcing at the lateral boundaries, atmospheric exchange of heat, freshwater and momentum at the surface, pressure and density gradients, and the Coriolis effect due to the Earth's rotation (Delft Hydraulics 2013). It can account for time-variant sources and sinks such as river discharge and evaporation, and it can model transport of salt, heat, and other conservative constituents. It has been shown to simulate realistic hydrodynamics in various seas and estuaries, with one study that yielded model results in reasonable agreement with data of the seasonal thermal cycle in the South China Sea (Twigt et al. 2007).

The model domain is a 300 x 300m rectangular grid with 6 vertical layers that vary in thickness depending on the depth, otherwise known as the σ-coordinate system. The forcing prescribed at the open boundaries was based on sea level fluctuations with 8 tidal harmonics: O_1, K_1, P_1, Q_1 with diurnal frequency, and M_2, S_2, N_2, K_2 with semidiurnal frequency. The am-

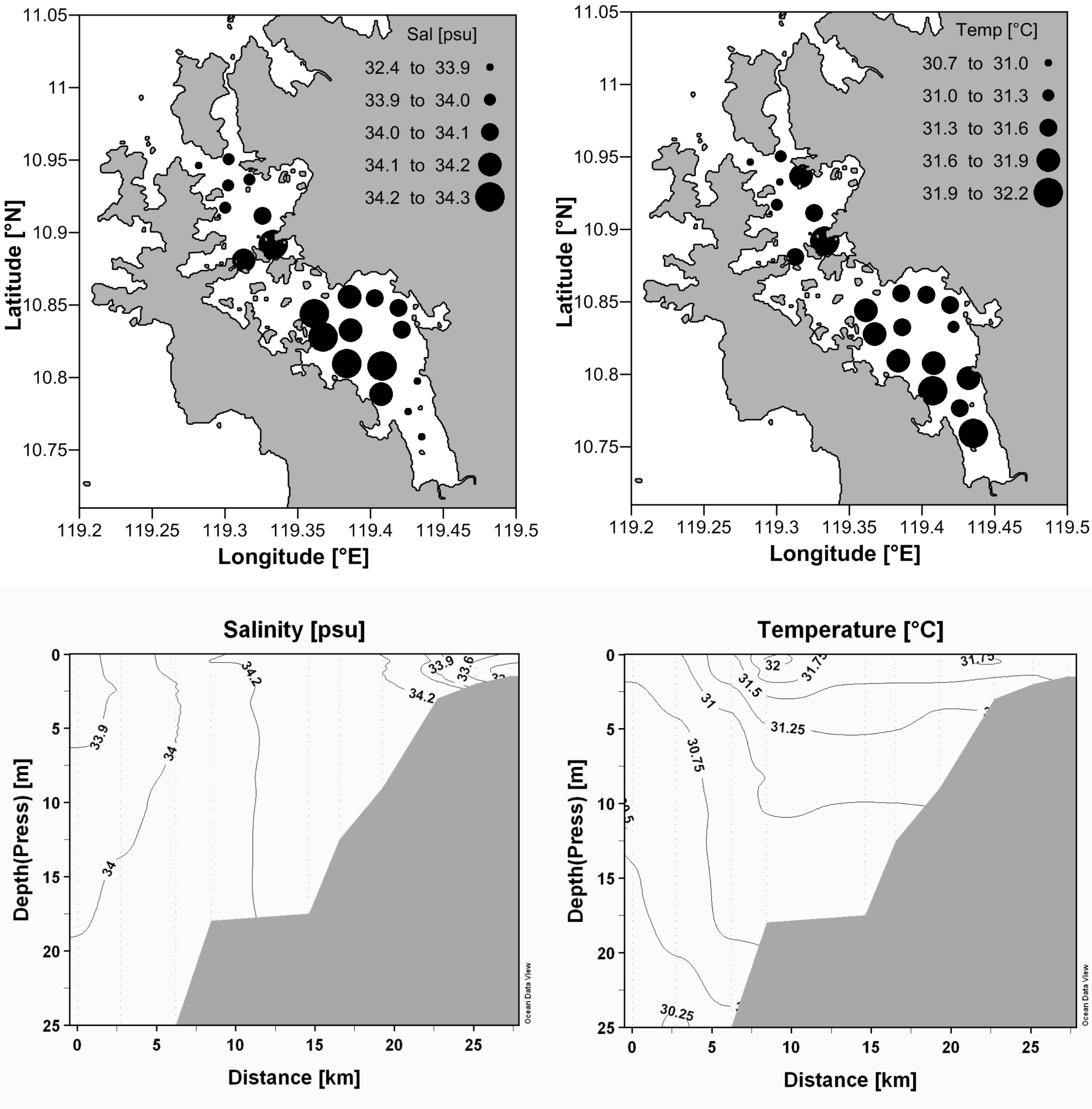

Figure 2. Salinity and temperature distribution at the surface and across the Malampaya Sound (from outermost sampling station to station nearest Abongan River).

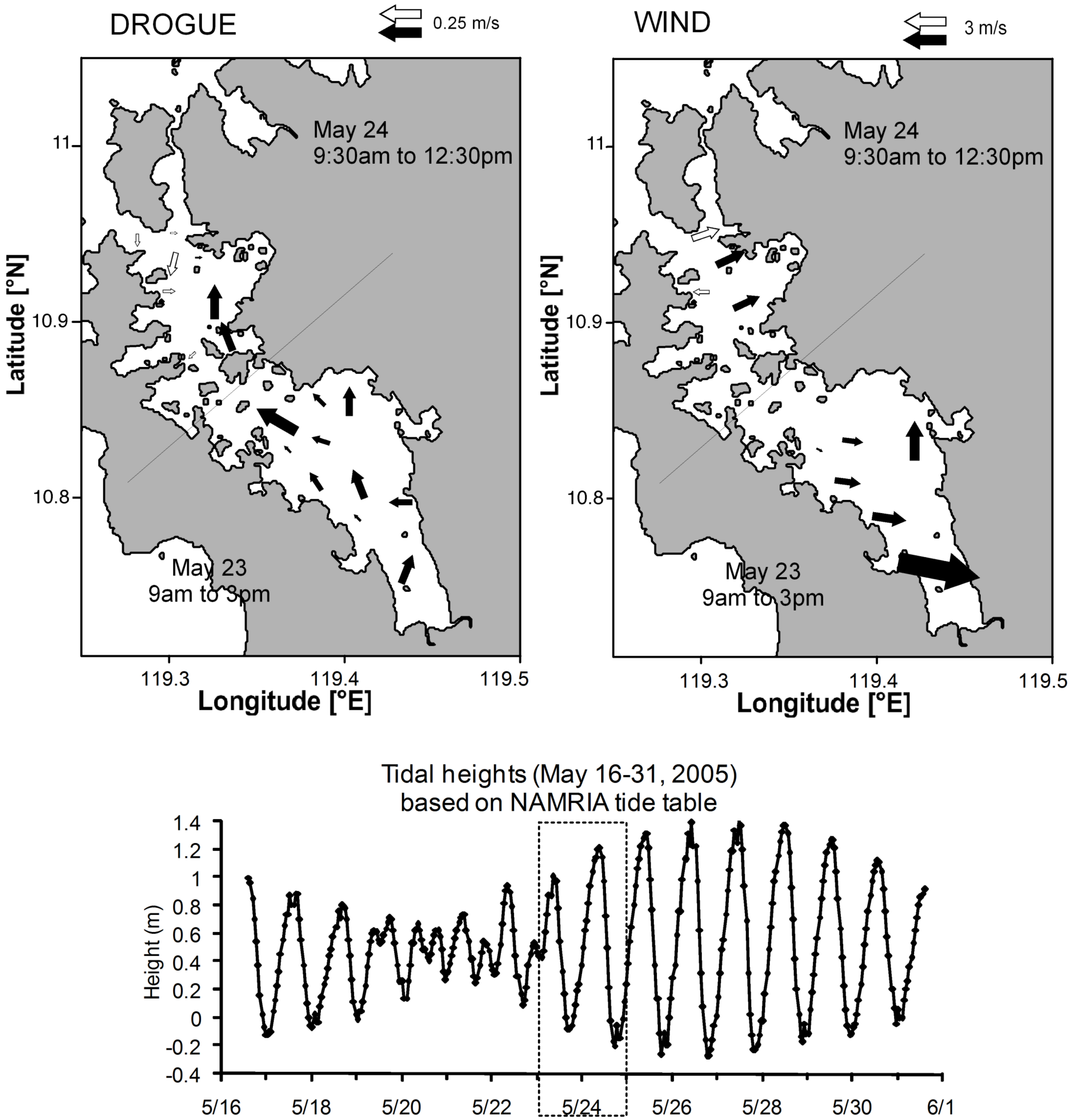

Figure 3. Surface currents and winds measured during the May 2005 field survey with predicted tidal heights based on the tide table published by the National Mapping Resources and Information Agency of the Philippines. Solid and open arrows depict measured currents that coincided with the tidal ebb and flood, respectively.

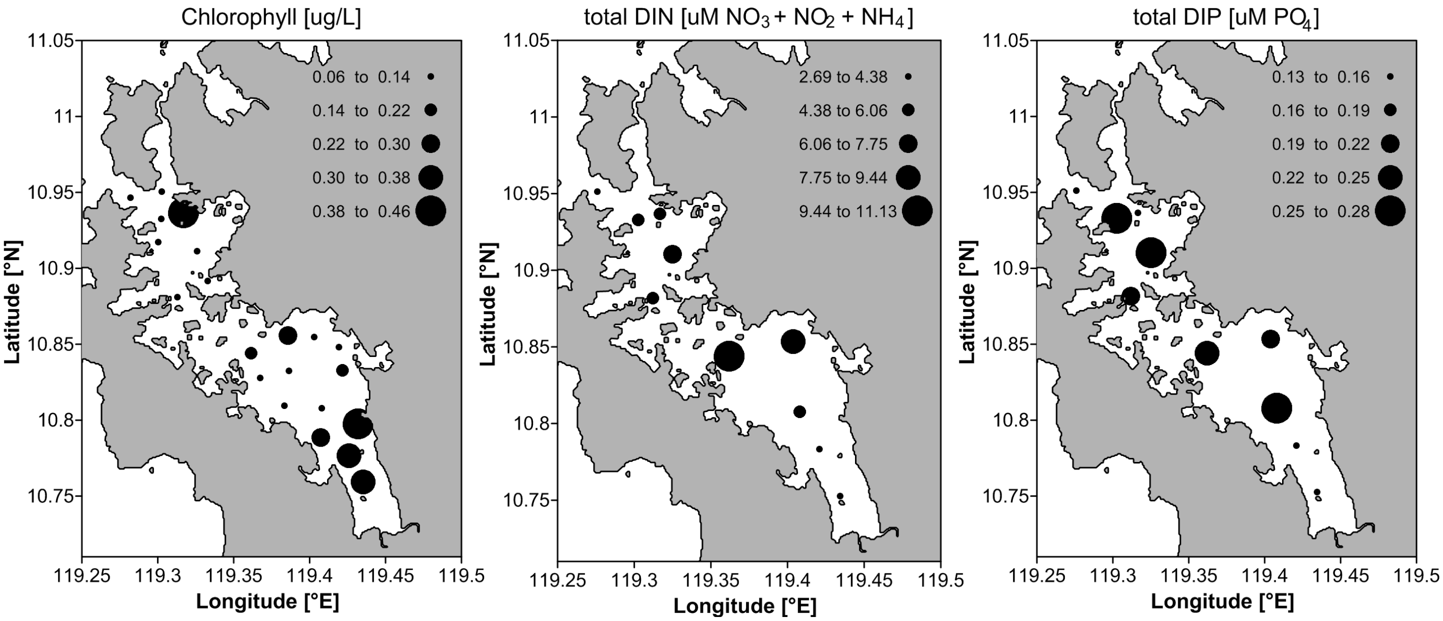

Figure 4. Surface distribution of chlorophyll, total dissolved inorganic nitrogen (in the forms of NO_3, NO_2 and NH_4), and dissolved inorganic phosphorus (in the form of PO_4) in Malampaya Sound.

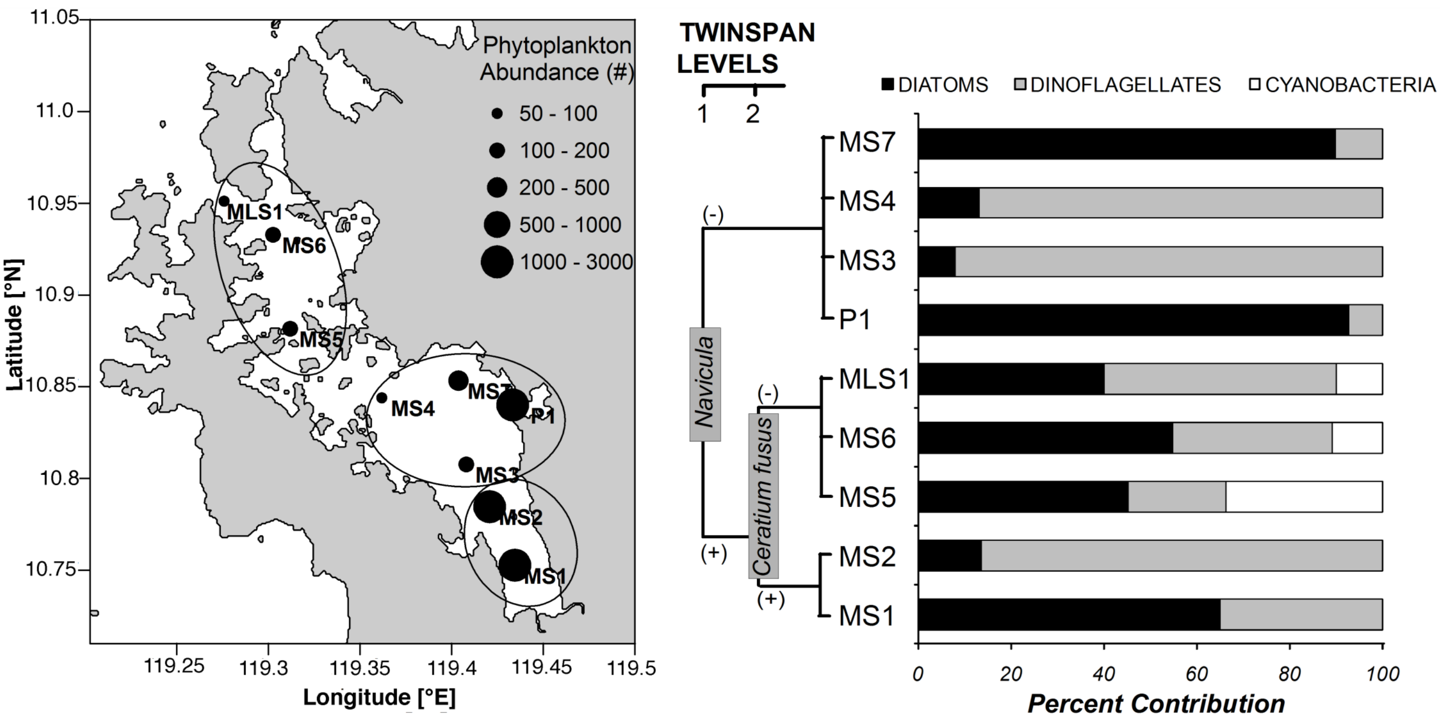

Figure 5. Phytoplankton abundance and percent group composition in Malampaya Sound, with station grouping according to Two-way Indicator Species Analysis (TWINSPAN).

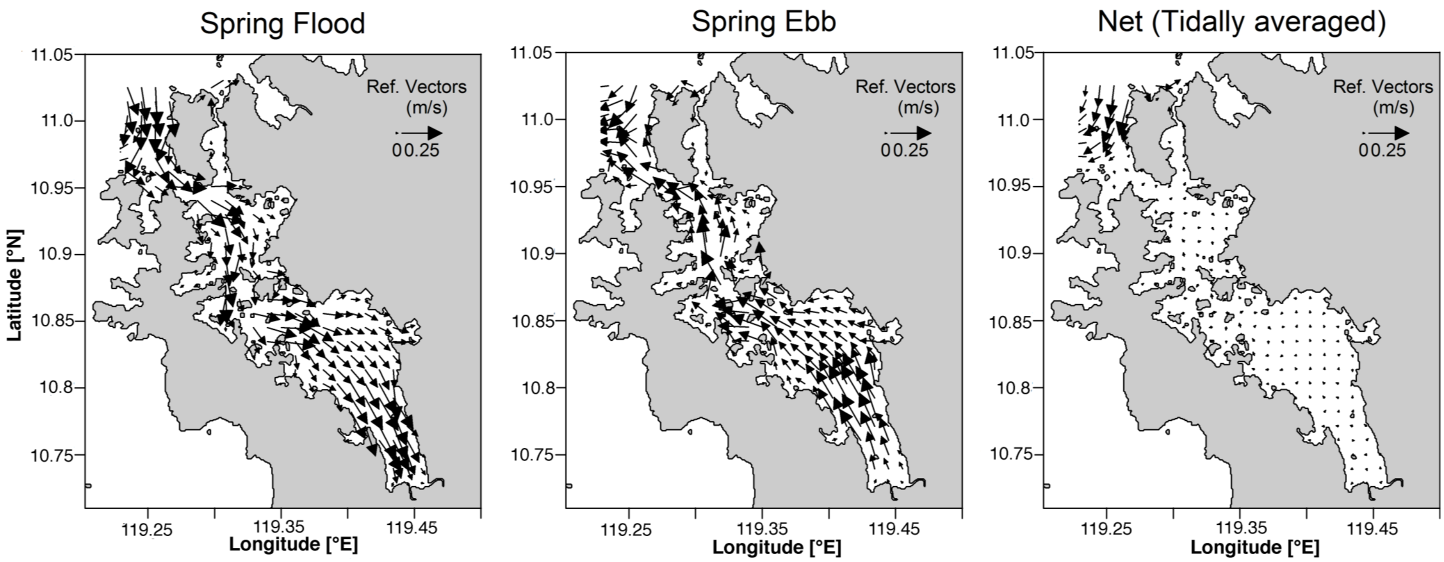

Figure 6. Simulated current patterns in Malampaya Sound using tide only as forcing.

plitude and phase values at the open boundaries were obtained from Magno's (2005) regional tide model by using the Oregon State University Tidal Inversion Software (OTIS). Different simulations were made to account for the effects of tide only, tide with river discharge, and tide with river discharge and surface heat flux.

Actual freshwater discharge data were lacking; thus, mean discharge for Abongan River of 6 m^3 s^{-1} normalized with monthly precipitation data from the TRMM satellite was used to simulate dry and wet seasons. For the heat flux model, the heat exchange at the free surface was modeled taking into account the separate effects of both short- and long-wave radiation, back-radiation heat loss, evaporation, and convection. Actual nearby meteorological data were also unavailable, and so prescribed solar radiation, air temperature, relative humidity, and wind data were obtained from the National Centers for Environmental Prediction (NCEP) and the National Center for Atmospheric Research (NCAR) reanalysis model (Kalnay et al. 1996). At the open boundaries, the salinity of seawater is assumed to be uniform, and temperature is assumed to show a 10-m step change from surface to bottom values. Table 1 summarizes the physical parameters used in the model runs. Run time was 45 days to allow for spin-up and to span spring- and neap tide-variations.

RESULTS AND DISCUSSION

During the May 2005 sampling, salinity was highest (34.3) at the middle portion of the sound and lower at both the mouth and head of the sound (Figure 2). At the outermost station, salinity was 33.9, typical for South China Sea surface waters, while it was 32.3 at the innermost station, most likely diluted by the Abongan River. Temperatures were more than 1 °C cooler at the outermost stations. The along-estuary section shows weak vertical temperature and horizontal salinity gradients all throughout the Sound.

Surface currents mostly oscillated with the tides despite persistent eastward winds (Figure 3). Surface current measurements were too limited to resolve the tidal variations, although all ebb and flood measurements respectively showed downstream and upstream flow. Tidal dominance is expected in long and narrow embayments such as Malampaya Sound.

Chlorophyll values were generally higher (>0.36 μg L^{-1}) in the vicinity of the river, and both nitrogen and phosphorus were generally higher in the middle of the sound (Figure 4). Phytoplankton were more abundant in the Inner Sound. TWINSPAN analysis of phytoplankton composition showed three groupings: Outer Sound stations; stations in the middle part of the Sound; and Inner Sound stations near the Abongan River (Figure 5).

Numerical Modeling

The surface velocity fields for flood and ebb tides as well as the net flow over a spring neap cycle are shown in Figure 6. If forced only by tides at the mouth, ebb and flood currents were nearly symmetrical, and tidally averaged flow inside the sound is

Table 1. Computational parameters of the hydrodynamic model.

Physical Parameter	Value
Grid size ($\Delta x = \Delta y$)	300 m
Vertical coordinate	σ, 6 layers with thickness 10%, 20%,
Time step	0.5 s
Horizontal eddy viscosity and diffusivity	10 m^2 s^{-1} 5 m^2 s^{-1}
Vertical eddy viscosity and diffusivity	κ-ε model
River discharge	6 m^3 s^{-1}; (2 m^3 s^{-1} for dry and 10 m^3 s^{-1} for wet season)
Open boundary Condition	Sea level, 8 tidal constituents (O_1, K_1, P_1, Q_1, M_2, S_2, N_2, K_2)

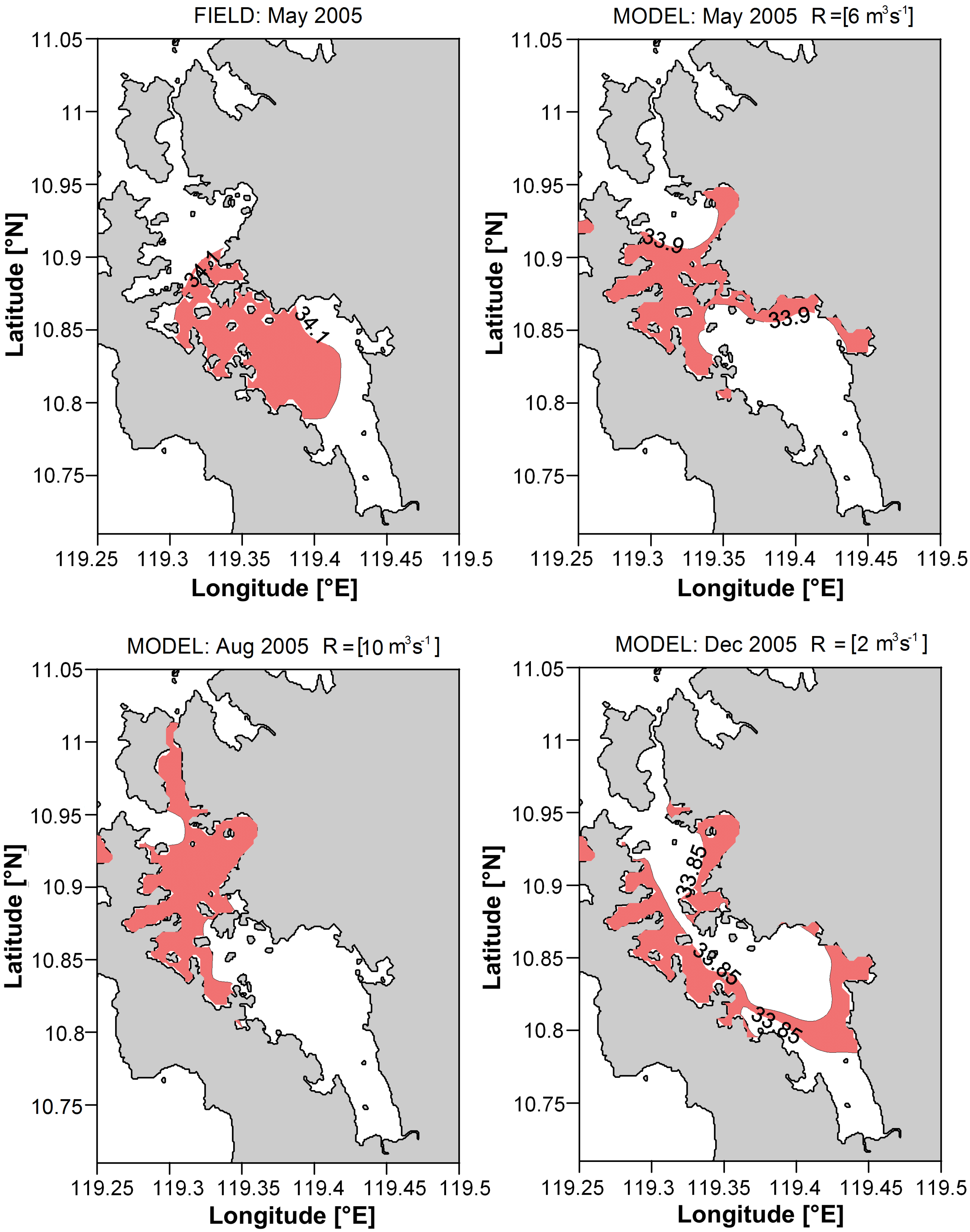

Figure 7. Salt plug in Malampaya Sound as shown by field sampling and simulations.

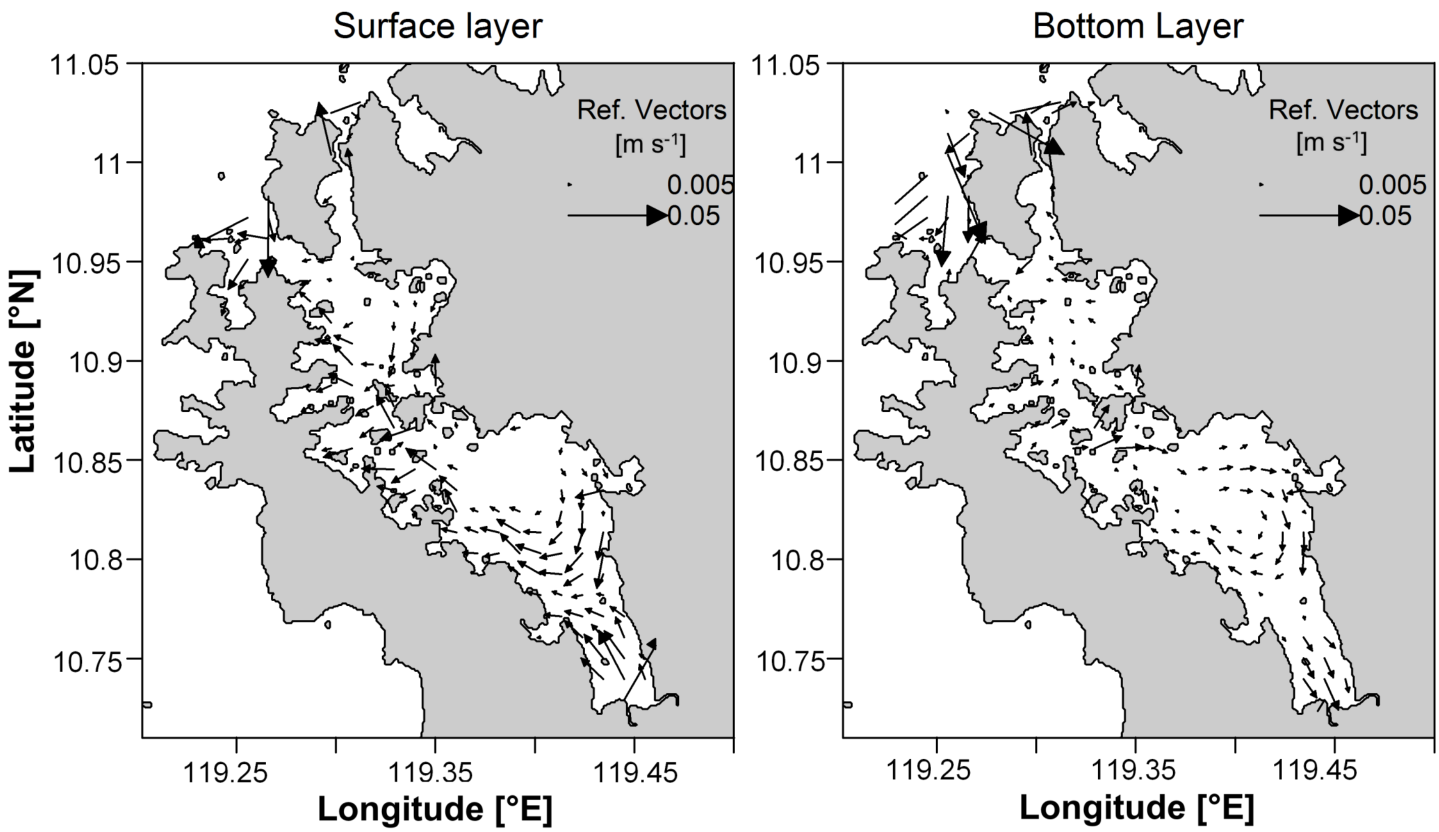

Figure 8. Simulated net flow in Malampaya Sound with tides, discharge, and heat flux forcings. Note the near zero flow at the vicinity of the salt plug in the middle of the Sound and the outward surface flow and inward bottom flow near the Abongan River.

almost nil, especially because Cagbalalu Island impedes tidal currents at the mouth (Figure 6). Simulation with tides and freshwater discharge set at 6 m^3 s^{-1} shows a salinity gradient that increases from the Inner to the Outer Sound, and a net outward flow of the surface layer but almost no net flow for the bottom layer. No salinity maximum is observed in the middle of the sound.

When simulation includes the effect of evaporation through the heat flux model, a salt-plug forms at the middle of the Sound. It moves outward when freshwater discharge is high, such as in August, and moves inward when discharge is low, like in December (Figure 7). Net tidal flow inside the Malampaya Sound is still very low but, interestingly, there is almost no horizontal flow in the vicinity of the salt-plug, whereas the Inner Sound exhibits a net outward surface flow and an inward bottom flow (Figure 8). The salt plug limits water from entering and leaving the Inner Sound. This, coupled with the breadth of the Inner Sound, maintains a recirculating gyre within it.

First reported by Wolanski (1986), salinity-maximum zones or salt-plugs occur in Australian estuaries due to high evaporation rates. In the Philippines, Malampaya Sound is the first known instance of a bay or estuary with a similar salinity distribution. We hypothesize that the narrow and elongated shape of the Sound, combined with the high evaporation rate during the dry season (April-May), induces salt-plug formation. It is unfortunate that pan-evaporation rates are not available in the area to test this idea.

Circulation in estuaries is strongly influenced by tides, but the presence of a salt-plug implies the presence of two thermohaline cells, with flow on one side of the salt plug driven by freshwater input and the other driven by exchange with the open sea (Wolanski 1986). This salt-plug circulation was simulated through the DELFT3D model when accounting for the effect of the tides, freshwater discharge, and heat flux. Our model, however, shows only the riverine gyre, but clearly reproduces the near-zero flow in the vicinity of the salt plug. The salinity-maximum zone thus effectively limits the exchange of water between the Inner and the Outer sound, and may cause long-term trapping of dissolved and particulate matters in the estuary. Our nutrient analysis supports this, because the waters in the mid-section of Malampaya Sound tend to contain and accumulate nutrients. Furthermore, David et al. (2008) have shown that nutrients are more abundant in a sediment core taken from the middle of the Sound than in cores taken either in the Inner, or the Outer, Sound. Sediment trapping was also reported by Sombrito et al. (2004), indicated by sedimentation rates of 2 and 4 cm yr^{-1} in the middle of the Sound compared to only 0.8 cm yr^{-1} in the Inner Sound and only 0.2 cm yr^{-1} in the Outer Sound.

The salt plug and its tendency to trap sediment and nutrients may have ecological impacts, especially on phytoplankton distribution. In essence, the salt plug allows only very limited entrance of oceanic water into the inner reaches of the sound and very little discharge of river water into the sea. This effect was alluded to by Wolanski (1986), but he presented no data to expound on the ecological impacts.

Phytoplankton in the Sound are distributed into three distinct assemblages: in the area of the salt plug, the Inner Sound, and the Outer Sound. A bloom of *Noctiluca scintillans* was found in the middle of the Sound, but not *Navicula* spp. A two-gyre circulation implies that a downwelling current prevails in the area of the salt-plug and the dinoflagellate *Noctiluca*, but not the pennate diatom *Navicula*, may prefer this.

Limited transport of oceanic and riverine waters through the salt plug may also have negative environmental consequences because it can cause pollutants as well as nutrients and sediments introduced by the Abongan River to accumulate in the Inner Sound. One positive consequence, however, is that incoming oceanic materials can only reach the Outer Sound and are easily flushed out. This may be one reason why Malampaya Sound was not affected by the Palawan-wide bloom of *Cochlodinium* in March 2005 (Azanza et al. 2008). In our study, one example of phytoplankton that occurred only in the Outer Sound was the nitrogen-fixing cyanobacteria *Trichodesmium.*

CONCLUSIONS

The geochemical characteristics of an estuary are strongly influenced by hydrodynamics. In Malampaya Sound, a salt plug forms during the dry periods when evaporation rates are relatively higher and river discharge rates are minimal. So far, this situation is unique to Philippine estuaries. The salt plug limits water exchange between the Inner and Outer sound, and most likely accounts for the difference in their nutrients and sediments, as well as the distinct grouping of phytoplankton in the Inner and Outer Sound. It may also be responsible for the prevention of the spread of the 2005 bloom of *Cochlodinium* into the Sound. There is also a negative environmental consequence because the salt plug traps pollutants from the Abongan River in the Inner Sound.

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CONFLICT OF INTEREST

None

CONTRIBUTION OF INDIVIDUAL AUTHORS

Cabrera, OC: Data Collection, Model set-up, Physical data analysis, TWINSPAN, Write-up. Villanoy, CL: Project Conceptualization, Data Collection, Model set-up, data analysis, Write-up. Jacinto GS: Data Collection, Chemical data analysis. Bernardo, PL: Model set-up. Ferrera CM: Data collection, phytoplankton identification and counting. Velasquez I: Data collection, Chemical data analysis. Azanza RV: Data collection, phytoplankton analysis.

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