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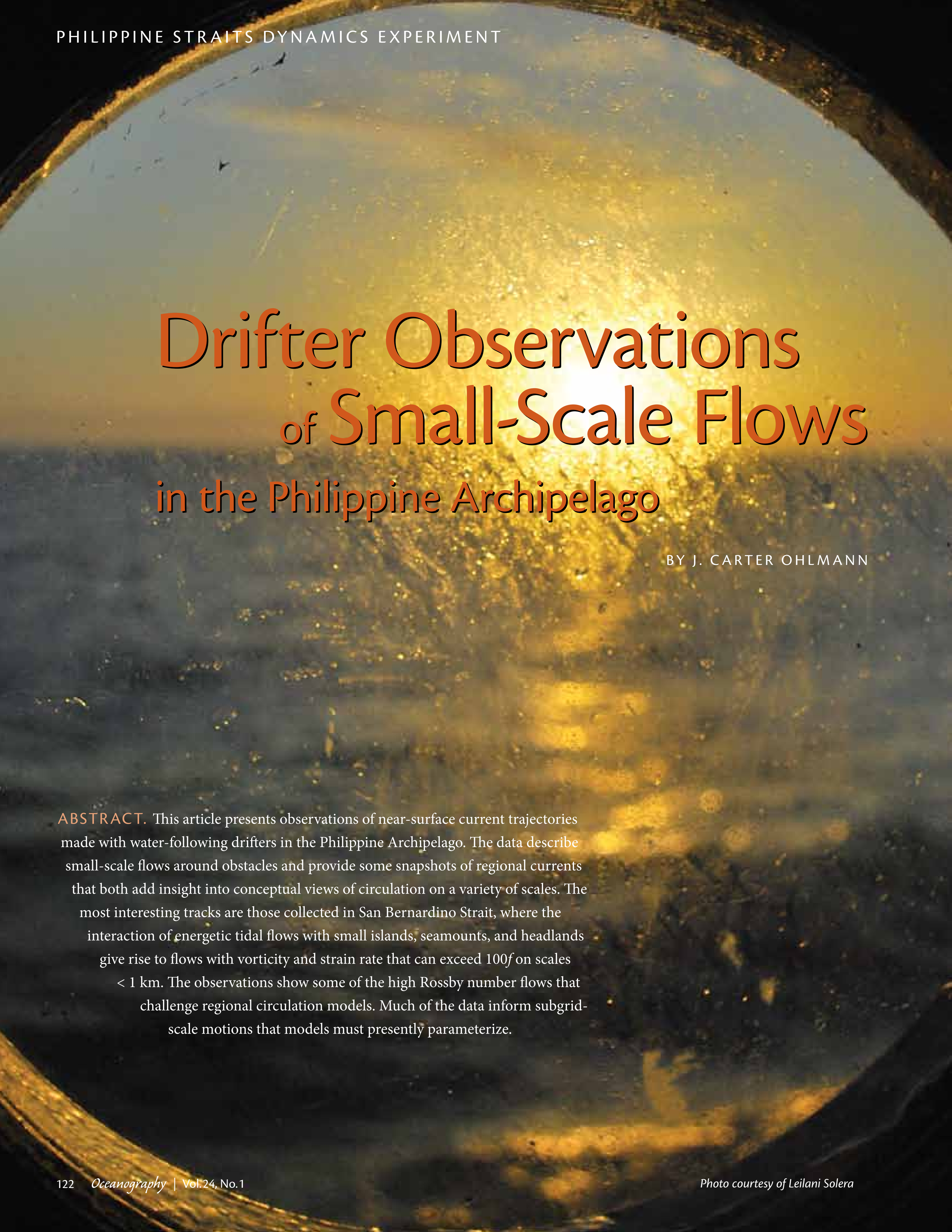
PHILIPPINE STRAITS DYNAMICS EXPERIMENT



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Drifter Observations of Small-Scale Flows in the Philippine Archipelago

BY J. CARTER OHLMANN

ABSTRACT. This article presents observations of near-surface current trajectories made with water-following drifters in the Philippine Archipelago. The data describe small-scale flows around obstacles and provide some snapshots of regional currents that both add insight into conceptual views of circulation on a variety of scales. The most interesting tracks are those collected in San Bernardino Strait, where the interaction of energetic tidal flows with small islands, seamounts, and headlands give rise to flows with vorticity and strain rate that can exceed $100f$ on scales < 1 km. The observations show some of the high Rossby number flows that challenge regional circulation models. Much of the data inform subgrid-scale motions that models must presently parameterize.

INTRODUCTION

Observations of surface currents from drifting buoys can be traced back to 1872 and the circumnavigation of the British research vessel HMS *Challenger*. Drifting buoys (drifters) were launched when the *Challenger* was on station performing bottom dredging (Thomson, 1878). Motion of the drifters relative to the fixed position of the *Challenger* provided surface current information. Today, drifters remain a valuable tool in the arsenal of ocean-observing instrumentation; however, a stationary ship is no longer necessary. Modern drifters obtain their absolute positions via satellite, and can provide near-real-time current information globally via satellite communications. Drag elements have greatly improved, and water-following performance is accurately quantified (e.g., Niiler et al., 1987, 1995; Ohlmann et al., 2005). The autonomous nature of water-following (Lagrangian) drifters offers great economy compared with continuous ship sampling throughout the global ocean.

The first published studies of modern-day drifter observations present position data from a single drifter to provide descriptive indications of surface current characteristics in the Agulhas (Stravropoulos and Duncan, 1974) and Gulf Stream (Kirwan et al., 1976) regions. As drifter technology evolved, surface currents were observed with numerous drifters deployed on numerous days. Flow visualization descriptions from 164 drifter tracks collected off the California coast provide some of the first direct measurements of eddies, jets, and squirts previously only inferred from remotely sensed sea surface temperature (SST) imagery (Davis, 1985).

At the time of this writing, nearly 15,000 drifter-years of data have been collected throughout the global ocean. More than 1000 unique drifters have sampled the large-scale circulation during each of the last 15 years, and more than 2000 have sampled during each of the last five years. These Surface Velocity Program (SVP) drifters typically record position, SST, and/or atmospheric pressure data every few hours, and have a half-life near 18 months. Statistics from observations collected over many years allow comprehensive studies of regional surface circulation (e.g., Centurioni et al., 2008) and contribute to understanding of global mean geostrophic flow (Niiler et al., 2003).

A thorough understanding of ocean circulation requires an extraordinarily large range of scales to be resolved (or parameterized). Recent advances in drifter technology relate to increases in both position accuracy and sampling frequency. Drifter position data from GPS, accurate to a few meters, can now be obtained every few minutes, giving current information and flow descriptions previously unresolved with Lagrangian measurements.

The overarching objective of the Philippine Straits Dynamics Experiment (PhilEx) is to obtain a regional view of water circulation within the Philippine seas. A more focused objective is improved understanding of how energetic (strait) throughflows interact with local bathymetry and give rise to complex current structures. The observational program is based on a series of regional cruises that measure current and temperature-salinity (T-S) profiles along ship tracks. Drifter observations contribute to the experiment by sampling regional circulation beyond ship tracks, and by sampling shallow regions inaccessible with a large research vessel. In addition, the Lagrangian observations provide time/space flow descriptions superior to those discerned from Eulerian shipboard transect data alone.

This article describes a subset of flows sampled with drifters during PhilEx. The observations span a variety of scales. The data show that small seamounts and headlands promote the most interesting flow structures, some with pronounced variations on spatial scales of < 100 m. The high spatial and temporal resolution of the observations, and the observed current variations on small scales, make them novel and worthy of description, similar to the first large-scale observations with modern drifters in the 1970s and 1980s. Presently, the resolved scales are smaller than those considered by most regional circulation models, typically with grid resolution ≥ 2 km (e.g., Pullen et al., 2008; Han et al., 2009). The observations thus show subgrid-scale motions that models must parameterize. However, with the advent of nested model grids and ever-increasing computer power, models will soon resolve the observed flows (e.g., Marchesiello et al., 2003).

INSTRUMENTATION AND LOGISTICS

Drifters used during PhilEx are of two different designs. SVP drifters are comprised of a holey sock drogue roughly 0.6 m in diameter and 6 m in length, centered at a depth of 15 m (Niiler, 2001). The drogue is attached to an acrylonitrile butadiene styrene (ABS) plastic surface float with a diameter of 0.4 m that houses electronics.

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SVP drifters obtain their position every hour with GPS (accurate to within a few meters), and by Doppler ranging with the Argos system (accurate to within 1 km) whenever an Argos satellite is in view (pass intervals variable between ~ 30 minutes and 4 hours). Data (position and SST) are transmitted via Service Argos and are available from a host computer roughly two to three hours after sampling.

SVP drifters are similar in style to the roughly 1400 units presently sampling the world ocean circulation as part of the Global Drifter Program (Lumpkin and Pazos, 2007), with the addition of hourly GPS position, necessary for velocity resolution on short time scales. SVP drifters that sample hourly have a half-life near six months, making them an adequate tool for observing regional Philippine circulation. A large and curious Philippine fishing fleet limited the expected sampling times of SVP drifters deployed during PhilEx.

Microstar drifters, manufactured by Pacific Gyre Inc. (Oceanside, CA), use a corner-radar-reflector-type drogue roughly 1 m in diameter centered at a depth 1 m below the sea surface (Ohlmann et al., 2005). Electronics are housed in an ABS plastic surface float roughly 20 cm in diameter. Microstar drifters obtain their positions (accurate to a few meters) every 10 minutes with GPS and transmit their position data through the Iridium satellite communications system. Near-real-time data are received in the field with a portable Iridium modem. The availability of near-real-time data every 10 minutes permits the drifters to be recovered and redeployed, thus allowing sampling regularity with a finite set of instruments (Ohlmann et al., 2007). The half life of Microstar drifters is roughly seven days, constrained by surface float size (i.e., batteries) and sampling frequency. The utility of the Microstar drifters is in repetitive sampling of flows with short time (hours to days) and/or small space (tens of meters to kilometers) scales.

SVP drifters are typically deployed from large ships in the open ocean and are considered expendable. Microstar drifters are typically deployed and retrieved from much smaller skiffs in the coastal ocean. Two novel deployment and recovery schemes were used during PhilEx. Sets of Microstar drifters were occasionally deployed and recovered directly from R/V *Melville*, a large oceanographic research ship. In other instances, *Melville's* workboat, a 6.4-m skiff was deployed with drifters and a crew of three at dawn. Drifter operations were performed from the skiff, and at the end of the day, the skiff (with recovered drifters) returned to *Melville*. This sampling plan was eminently successful during four days when *Melville* performed repeat surveys within San Bernardino Strait, a relatively small spatial domain (Figure 1).

RESULTS

A total of 168 drifter tracks were collected as part of the three-year PhilEx observational campaign (Figure 1). During the exploratory cruise (summer 2007), eight SVP and 36 Microstar tracks were recorded. Track length varied from a single day to nearly 90 days. All deployments and retrievals were from R/V *Melville*, primarily in Mindoro Strait. Deployments were performed to test the feasibility of recovering numerous drifters from a large research vessel, and to determine the response of the Filipino fishing fleet to freely floating instruments. During the (winter) 2008 Intensive Observational Period (IOP), 56 Microstar tracks (up to 10 days in length) were sampled using a Filipino *banca* in Pandan Bay. The 2008 deployments were planned to validate remotely sensed surface currents obtained with HF radars; however, the radars were not operational. During the (winter) 2009 IOP, 49 Microstar tracks (up to 10 days in length) were collected throughout the archipelago, primarily via a skiff deployed daily from *Melville*. A set of

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34 Microstar tracks were collected on two days in late May 2009, for validation of HF radar surface currents.

Regional Circulation

Prior to PhilEx, only six drifters had sampled within the Philippine Archipelago, an extremely small number compared with drifter sampling in the adjacent western Pacific (Figure 1). These SVP drifters followed the North Equatorial Current (e.g., Qiu and Lucas, 1996) westward from as far as 141°W (a location east of the Hawaiian Islands), moved into the western equatorial Pacific, and fortuitously passed through Surigao Strait. Four of the drifters made it into the Sulu Sea, two crossed the Sulu Sea, but none sampled within the archipelago for more than a few weeks. A relatively large portion of drifters that moved westward in the North Equatorial Current beached (or were recovered) along the Philippine Pacific coast. Drifters that entered the South China Sea through Luzon Strait mostly flowed southward along the Vietnamese coast (e.g., Centurioni et al., 2004).

SVP drifters deployed during summer 2007 as part of PhilEx sampled the Sulu Sea and moved northwestward through Mindoro Strait into the South China Sea (Figure 1). Drifters in the Sulu Sea moved mostly toward the west-southwest with velocities between 1 and 60 cm s^{-1} (average velocities near 20 cm s^{-1}), largely modulated by strong tidal variations. One track turned anticyclonically and moved northeastward. A drifter that entered the South China Sea through Mindoro Strait first sampled a large anticyclonic eddy, and then sampled a portion of a similar size cyclonic eddy. The drifter ultimately ended up very near its starting location after ~ 70 days. Both drifters that entered the South China Sea (through Mindoro Strait) eventually made their way northward along the west coast of Luzon.

Flow Around a Seamount in Mindoro Strait

Numerous seamounts and headlands throughout the Philippine Archipelago can generate significant local vorticity and, through flow separation, influence regional circulation. A set of six Microstar drifters were deployed from *Melville* on June 30, 2007, in the vicinity of Apo Reef, in an attempt to sample a presumed turbulent wake in the lee of the seamount. Apo Reef is a submerged series of atoll-like coral reefs that comprise an area of ~ 35 km^2 within Mindoro Strait (Figure 2). Three small islands extend above the sea surface, and water depths are mostly < 20 m. The reef is a marine protected area, making its boundary a popular fishing location. Four of the drifters were quickly recovered by Filipino boaters and returned to *Melville*. Two drifters sampled the

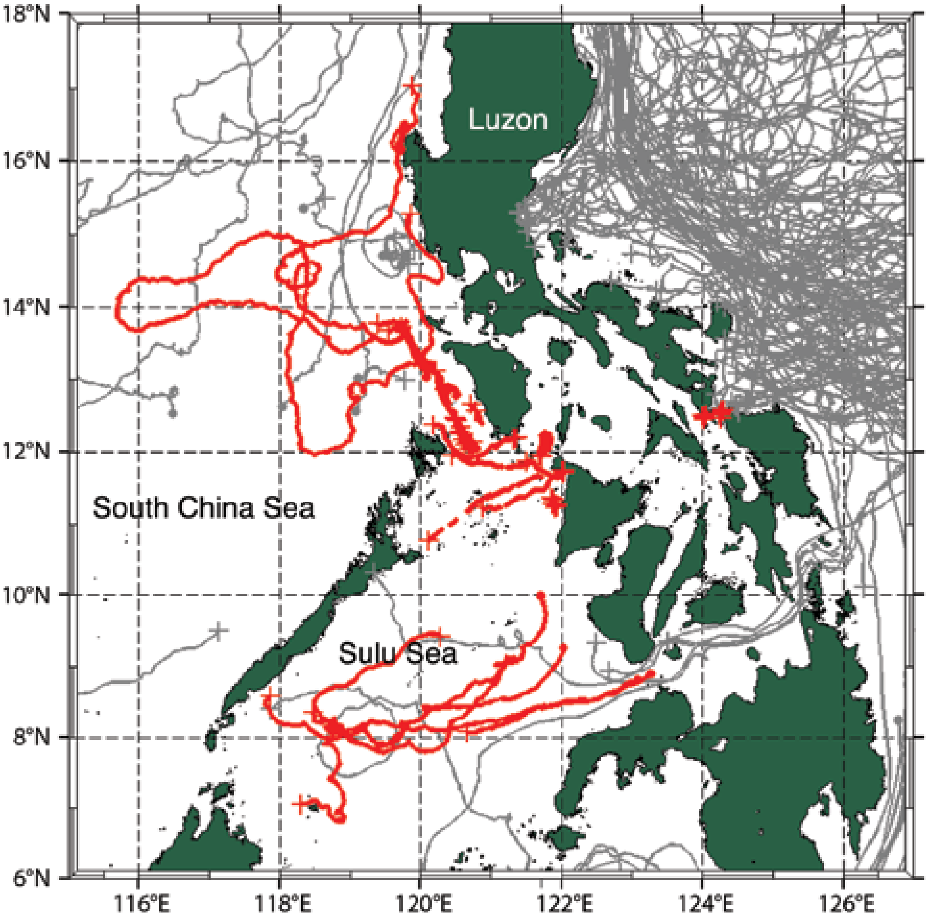

Figure 1. Regional view of the drifter trajectories collected during PhilEx (red lines). Dots indicate starting positions and plus signs show ending locations. Many shorter tracks collected in San Bernardino Strait (124°15'E, 12°30'N), Pandan Bay (122°E, 11°42'N), and Mindoro Strait (120°30'E, 12°15'E) are not resolved at this scale. Few historical trajectories (gray lines) have sampled within the Philippine Archipelago.

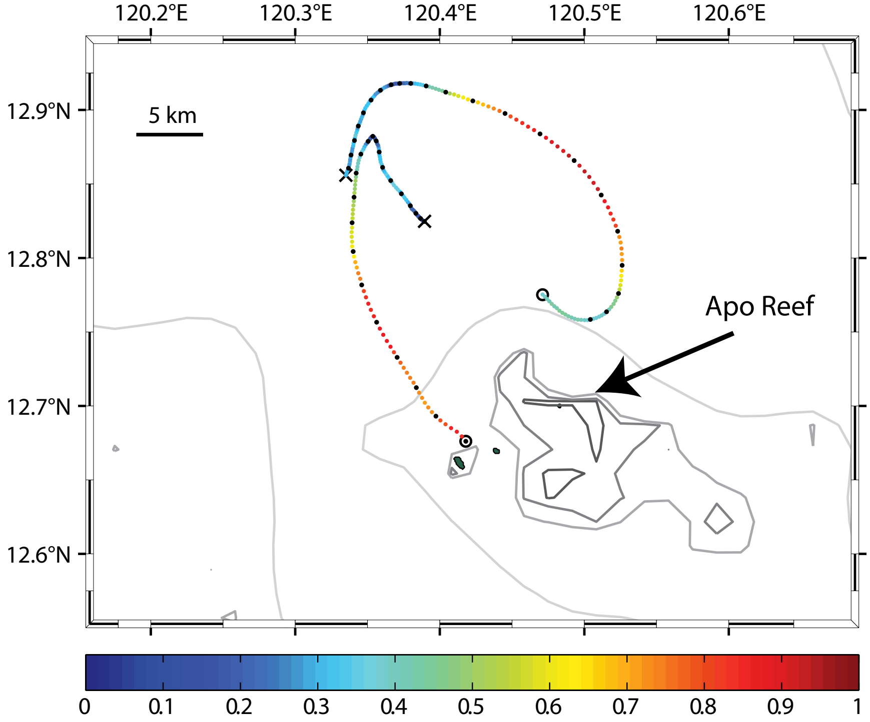

Figure 2. Flow past a seamount (Apo Reef) in Mindoro Strait. Dots represent position data recorded every 10 minutes. Color gives drifter velocity magnitude (m s^{-1}) computed as a first difference in position. Drifter starting locations are shown with large circles, and ending positions are indicated with plus signs. Black dots give drifter position every hour, with the first black dot on each track indicating a common time. Depth contours, drawn at 5, 20, 50, and 500 m, show Apo Reef, which presumably drives the recirculation.

circulation around the reef (Figure 2).

The drifter launched near 120.47°E, 12.78°N, began in the lee of Apo Reef and initially showed southeastward, presumed recirculation, flow. The drifter launched near 120.42°E, 12.67°N began alongside the reef (relative to the mean northwestward flow direction) and initially sampled northwestward flow. The Mindoro Strait channel flow reached nearly 1 m s^{-1} along the sides of the seamount. Once the drifters passed the seamount, they began to converge and their velocities decelerated to < 0.5 m s^{-1} (Figure 2). After continued deceleration and convergence, both drifters eventually reversed direction and moved southward. The flow patterns presumably arise from a local change in the pressure gradient caused by existence of the seamount within the flow field. Filipino boaters retrieved the drifters prior to the end of their desired sampling lives.

Although the tracks show flow recirculation, their premature termination prevents a complete view of the flow perturbation caused by Apo Reef. Reversing flow suggests existence of a stagnation point and thus flow separation although neither complete eddies nor eddy shedding are captured. The counterclockwise-turning drifter moved southward through the same location that the clockwise-turning drifter sampled 10 hours prior on its northward journey. This motion provides a glimpse into the time variability of the recirculation/eddy field. Limited observations prevent accurate quantification of relative vertical vorticity magnitude, $|\zeta^z| = \partial_x v - \partial_y u$, in the lee of the seamount. Rough estimates of $|\zeta^z|$, computed as 2ω, where ω is the average angular velocity during times of the most pronounced drifter turning, give values of $3f$ and $13f$, where f is the local Coriolis frequency, equivalent to a period of 57.5 hours. The large $|\zeta^z|$ values indicate the potential of the seamount to influence regional circulation. However, with only limited sampling in the Apo Reef region, data are insufficient for a thorough quantitative analysis.

Flow Through San Bernardino Strait Near Sidewalls

Some of the most interesting drifter observations come from sampling small-scale flow variations near the sidewall boundaries of a narrow strait with energetic tidal forcing. San Bernardino Strait is a roughly 18-km-wide waterway between Luzon and Samar islands that facilitates exchange of Pacific Ocean water (Jones et al., 2011). Drifters were deployed along the east side of the strait during flood tide to sample boundary-layer flow around headlands, and to observe tidal flow reversal (Figure 3). Drifters were deployed along the west side during flood tide to investigate flow in the lee of a small island just offshore of a bending coastline. Velocity measurements could not be made directly from R/V *Melville* in the shallow coastal regions sampled by drifters.

A set of six Microstar drifters were deployed on February 18, 2009, along the eastern side of San Bernardino Strait with ~ 100-m spacing in the cross-shore direction. The drifters were deployed in a location just upstream of a small headland during the initial phase of flood tide (Figure 4). The coastline is mostly jagged with occasional rock outcroppings. Drifters deployed furthest offshore (between ~ 500 and 700 m from the coast in a water depth near 20 m) moved with a constant velocity between 1.2 and 1.5 m s^{-1} (Figure 4a). In contrast, drifters within 500 m of the coast showed pronounced velocity changes over length scales as small as 100 m and time scales of 10 minutes (Figure 4b). The drifters closer to shore also moved considerably more slowly (velocities < 0.75 m s^{-1}) and generally followed bathymetry. Only the most inshore track, located within 50 m of the coastline, sampled boundary-layer recirculation in the lee of the small headland. Time and length scales of the recirculation are tens of minutes and 100 m, respectively.

The strong tidal flows near the coastline give $|\zeta^z|$ estimates (computed in a principal axis coordinate system from gridded velocity determined as the first difference in drifter position) ranging from $10f$, to $> 100f$ (Figure 4c). Accurate computation of ζ^z from clusters of three or more drifters (Molinari and Kirwan, 1975) gives slightly smaller values of similar magnitude, but with significantly reduced spatial coverage due to the cross-shore shear that aligns clusters; ζ^z is mostly positive, consistent with southward flow impeded by a boundary to the east. An expected characteristic of such large $|\zeta^z|$ boundary currents is flow separation. The single reversing trajectory indicates occurrence of a stagnation point and thus flow separation. However, the observations do not show vorticity advection toward the interior of the strait. Little can be said about flow separation, given the single Lagrangian

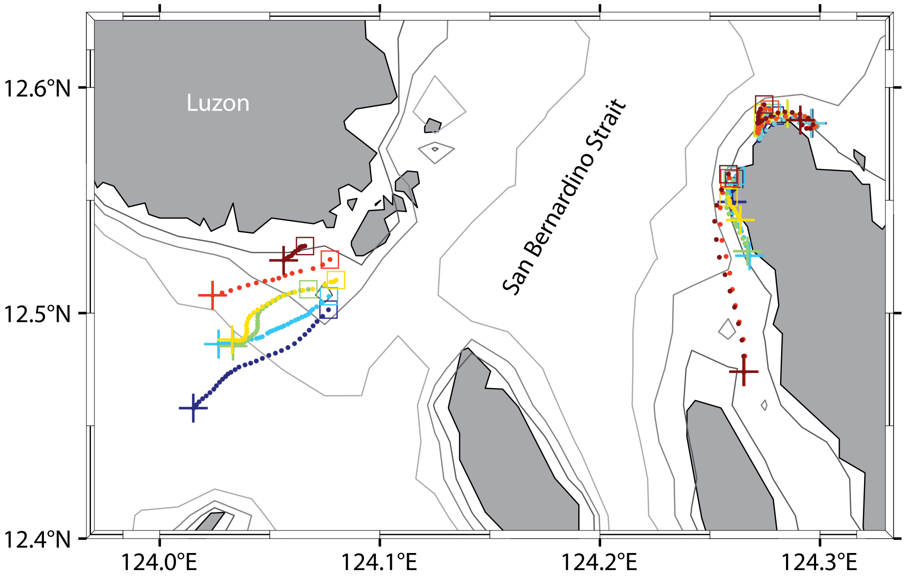

Figure 3. Drifter tracks collected in San Bernardino Strait during PhilEx. Dots represent drifter position data recorded every 10 minutes. Squares and plus signs indicate starting and ending drifter positions, respectively. Bathymetry contours are drawn at 20, 50, and 100 m. Flow characteristics of sets of tracks that sample inside the strait are given in subsequent figures.

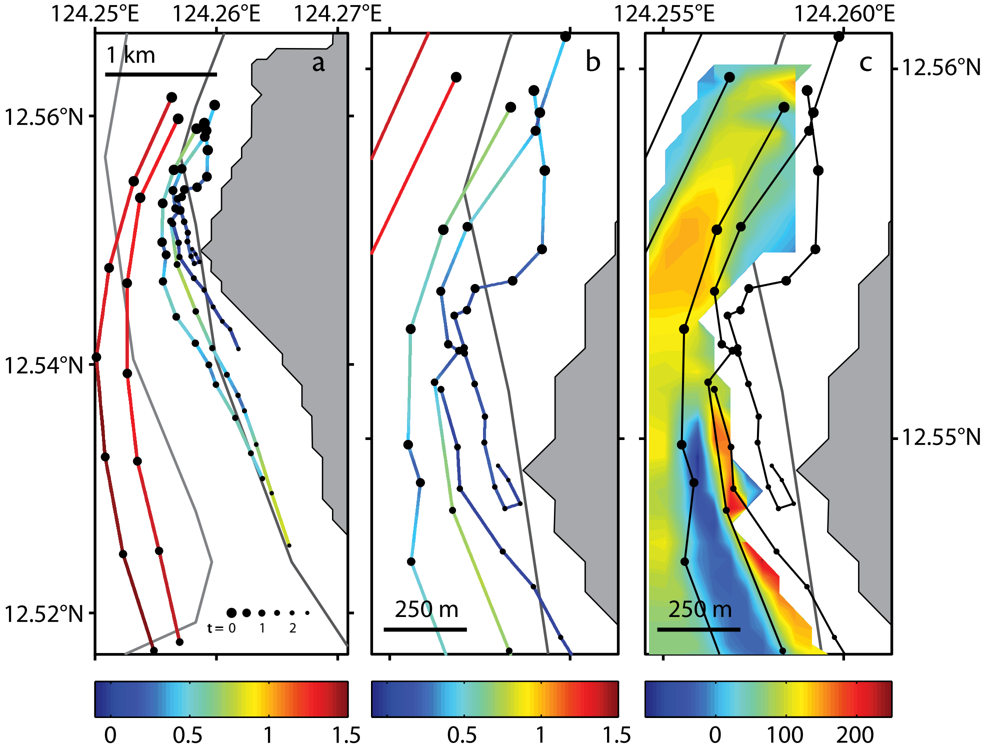

Figure 4. Flow past a small headland during flood tide in eastern San Bernardino Strait. Dots represent drifter position data recorded every 10 minutes. Dot size indicates time relative to a common starting time for all tracks. Integers given beneath the dot legend (in panel a) denote hours. Color indicates (a and b) velocity magnitude (m s^{-1}) and (c) $|\zeta^z|$ scaled by f. Grey lines show the 20- and 50-m depth contours. Only the most nearshore track, located within tens of meters from the shoreline, sampled recirculation.

snapshot within the much larger semidiurnal tidal cycle (e.g., Signell and Geyer, 1991). The limited observations give merit to high-resolution drifters as an observational tool that can be applied to more focused studies of small-scale boundary flows, and flows around small obstacles.

A set of six Microstar drifters were deployed on February 20, 2009, along the western side of San Bernardino Strait in a cross-shore line with roughly 1-km spacing. The deployment location is just downstream of a small island where the mainland coastline bends to become mostly south-facing (Figure 3). The drifter deployed nearest the shoreline (1 km from the coast) initially moved with a velocity near 0.1 m s^{-1} and its speed never exceeded 0.25 m s^{-1} (Figure 5a,b). The second drifter from the coast initially moved with a velocity between 0.8 and 1 m s^{-1}; its speed always exceeded 0.55 m s^{-1}. The strain rate, $\left[(\partial_x u - \partial_y v)^2 + (\partial_x v + \partial_y u)^2\right]^{0.5}$ (e.g., Molinari and Kirwan, 1975; Niiler et al., 1989; Capet et al., 2008), between the two drifters, estimated from velocity, is 25f (Figure 5c). The third and fourth drifters from shore began with velocities near 0.25 m s^{-1}, that quickly (within 40 minutes) accelerated to > 1 m s^{-1} and decelerated to 0.5 m s^{-1}. These drifters, separated by a few hundred meters at deployment, converged prior to their first GPS positions, and further converged with a third drifter later in their lives (Figure 5a,b). The three drifters were found along a horizontal line of floating debris, roughly 20–40 m in width, presumably associated with large vertical velocities (Jones et al., 2011). Strain rate at the point of convergence exceeded 40f (Figure 5c). Limited time in San Bernardino Strait did not allow for repeat sampling of the convergent feature during the same tidal phase on a subsequent day. The drifter deployed furthest from shore had a relatively constant velocity compared to shoreward drifters. Deceleration toward the end of tracks with the longest sampling times appeared to be associated with the semidiurnal tidal phase.

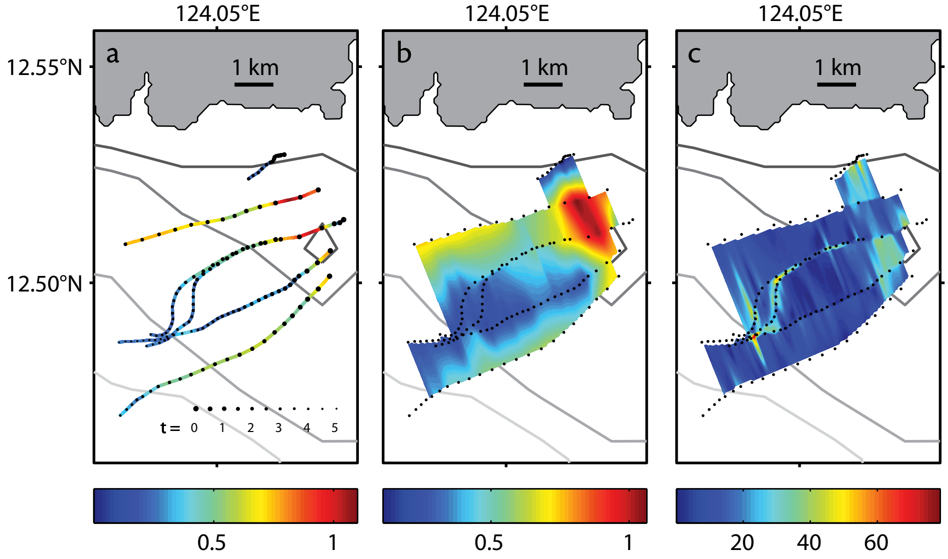

Figure 5. Flow around a bending coastline during flood tide in southwestern San Bernardino Strait. Dots represent drifter position data recorded every 10 minutes. Dot size (panel a) indicates time relative to a common starting time, with integer values denoting hours. Color indicates (a) observed and (b) interpolated velocity magnitude (m s^{-1}), and (c) strain rate scaled by f. Strain rate is estimated from gridded velocity and confirmed by computation from drifter clusters (Molinari and Kirwan, 1975) as described for $|\zeta^z|$ in the text. Gray lines show the 20-, 50-, 100-, and 150-m depth contours. The figures show significant variations in velocity and strain rate on scales of 10–30 minutes and a few kilometers.

SUMMARY AND CONCLUSIONS

The 20 trajectories, and their derived properties, described in detail here represent ~ 12% of the complete set of drifter tracks collected during PhilEx (Figure 1). The regional nature of the PhilEx observational plan resulted in a drifter data set mostly characterized by single snapshots of flows in a variety of locations throughout the archipelago. In addition, drifters sample temporal and spatial scales that range from hours to months and tens of meters to hundreds of kilometers, respectively. The disparate observations preclude the statistical and dynamical analyses necessary for improved quantitative understanding of the surface currents. Data are thus presented in a descriptive sense that adds insight into conceptual views of circulation. The observations are believed to provide some of the first Lagrangian indications of the sorts of high Rossby numbers that arise from channel flows past obstacles over a range of relatively small scales.

The most interesting tracks are those collected in San Bernardino Strait. The interaction of energetic tidal flows with small islands, seamounts, and headlands gives rise to flows with vorticity and strain rate that can exceed 100f on scales < 1 km. The observations make tidally rectified flows, which can influence net transport through the strait, easy to imagine. The observations also demonstrate the challenge faced by modeling efforts in the Philippine seas that must resolve flow perturbations caused by Apo Reef, and parameterize small-scale motions in San Bernardino Strait. The prospect of numerical models with increased grid resolution that will someday be tasked with resolving the observed small-scale flow structures is indeed exciting. More focused drifter studies of flows around obstacles can help root theory and improve both present and forthcoming modeling efforts. Combined HF radar and drifter sampling that provide time-space mean and instantaneous velocity information, respectively, can yield more comprehensive observational insight into the variable currents within small straits.

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