

## **Analysis of the PhilEx Moored Velocity and Pressure Gauge Measurements**

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### **LONG-TERM GOALS**

The long-term goal is to understand the processes that control the generation, evolution and distribution of small-scale, time-dependent features within straits, and how these features interact with the large-scale sub-tidal throughflow within which they are embedded. The effort will focus on a multi-year time series from an ocean sensor array of moored ADCP and temperature-conductivity sensors, and pressure gauge observations in the internal straits of the Philippine archipelago. The aim is to characterize the spatial and temporal variability of the small-scale features and large-scale flows, and how they may vary seasonally to interannually as the remote and local (monsoonal) forcing changes. Ultimately, this will enable a better representation and prediction in numerical and theoretical models of the structure and evolution of the small-scale features common to sea straits, including their time-dependent variability.

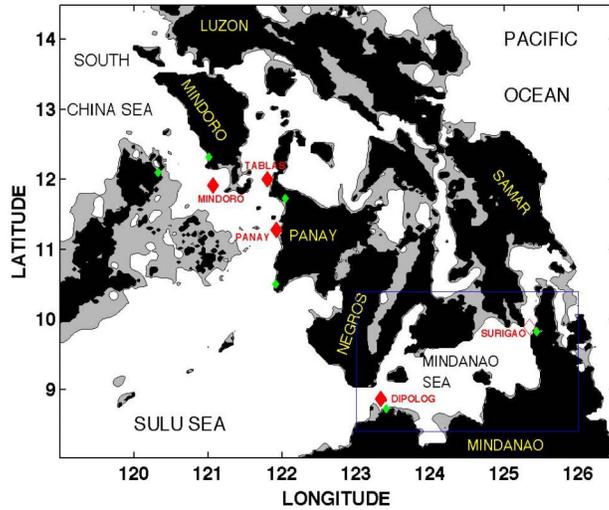
### **OBJECTIVES**

The primary objective is to improve our understanding of the oceanographic processes that lead to small-scale variability in the flow structure of straits. Specifically, the main objectives are:-

1. To examine the relative roles of the tidal and longer timescale flows in the generation and evolution of the small-scale dynamical flow features in straits,
2. To determine how small-scale features evolve with across- and along-strait variation in sea-level and the corresponding strength and direction of the mean flow,
3. To identify how the small-scale flow structures and sea-level variability may be modulated by both the remote and the local forcing, particularly in response to the seasonal reversal in the monsoon winds.

### **APPROACH**

As part of the "Characterization and Modeling of Archipelago Strait Dynamics" DRI, an ocean sensor array of moorings and pressure gauges were deployed within the straits of the Philippine archipelago (Figure 1). The array resolves both the along-strait and the cross-strait variation in flow and properties, and enables us to observe any response in the circulation patterns related to the mesoscale and submesoscale processes. The straits connect the internal Philippine seas to the large-scale flow from the Western Pacific and the South China Sea.



**Figure 1: a) Regional map showing the location of PhilEx deployed moorings (red diamonds) and pressure gauges (green diamonds).**

The moorings consisted of ADCPs to measure water-column currents, and discrete Temperature-Salinity sensors, thus providing direct measurements of the velocity, temperature and salinity at sampling rates of  $\sim 0.5$  hours. The pressure gauge array helps to resolve the sea level signal associated with the tidal forcing (to assist with the validation of the barotropic tidal models) and the leakage of long planetary waves from the boundaries of the Philippines seas. SBE37 CTDs co-located with the shallow pressure gauges add some information on surface temperature and salinity variability. The Paroscientific quartz pressure sensors return high precision (0.3 mbar) data with sampling periods of 10 seconds to accurately resolve the tidal flow and changes in sea level (pressure) along and across the strait.

The ocean sensor array was constructed and assembled by engineers and marine technicians at the Scripps Institution of Oceanography (SIO) Hydraulics Laboratory, under the guidance of Senior Development Engineer Mr. Paul Harvey.

The shallow pressure gauge array was deployed at 6 locations within the Philippines with the assistance of Dr. Cesar Villanoy and his team at the University of the Philippines.

## **WORK COMPLETED**

The first PhilEx mooring in Panay Strait (sill depth  $\sim 580$  m) was deployed as part of the Exploratory Cruise on the *R/V Melville* in June 2007. This mooring was recovered and redeployed after 3 weeks to provide contextual data for the hydrographic measurements made as part of this cruise. During the June 2007 Exploratory cruise, moorings were also deployed in Dipolog Strait ( $\sim 480$  m) and Surigao Strait ( $\sim 160$  m). These three moorings were recovered, refurbished and the data downloaded, then redeployed during the Joint USA-Philippine cruise in December 2007. Additional moorings were deployed in Mindoro Strait ( $\sim 450$  m) and in Tablas Strait (565 m) during the December 2007 cruise. All moorings (except Surigao, see below) were recovered in March 2009.

The majority of the ADCP and property instrumentation successfully returned 100% of the 15-18 month velocity time series data. Unfortunately the Surigao mooring ADCP failed during the first deployment period, and the acoustic releases failed during the second deployment period. In Tablas Strait, the ADCP designed to capture the bottom flows flooded at some stage during the deployment period, and efforts by a commercial data recovery service were also unable to extract any information from the ADCP data card. All velocity, temperature and salinity data have been quality controlled. Pressure time series from the ADCPs and available discrete CTD sensors was used to account for mooring blowover through tidal and low frequency forcing. The velocity data were then vertically linearly interpolated onto a 10-m depth grid and a common time base of 1 hour.

During this report period, the focus has been on analyzing the velocity variability from the moorings (Tessler et al., 2010; Gordon et al., submitted), and using the moored time series as a metric for PhilEx models (Hurlburt et al., submitted; Pullen et al., submitted). The PI is also presently preparing a more comprehensive manuscript that discusses the transport variability and how it is partitioned through the major straits in relationship to the monsoonal forcing. Major results from these manuscripts are discussed further below.

In February 2010, the PI presented a talk on the velocity variability from the mooring time series at the AGU Ocean Sciences Meeting, Portland, Oregon. The PI and University of the Philippine (UP) colleague Dr. Cesar Villanoy organized and co-chaired the session “Marginal Seas of the Western Pacific” at the Western Pacific Geophysics Meeting in Taiwan, June 2010. The PI presented a talk in this session discussing the transport variability from the mooring time series.

Six shallow pressure gauges (see Figure 1) were deployed with the help of UP colleagues Drs. Cesar Villanoy and Laura David. Deployment sites and available data (absolute pressure, temperature and salinity) periods are San Jose, Mindoro Island (deployed 11 December 2007); Coron, Calamian Island (15 September 2007 – 15 December 2007; redeploy 2 February 2008); Pandan, Panay Island, collocated with HF radar (21 October 2007 – 24 April 2008; redeploy 24 April 2008); Tobias Fornier, Panay Island, collocated with HF radar (12 August 2007 – 3 May 2008; redeploy 3 May 2008); Dapitan, Apo Island, Bohol Sea (6 October 2007 – 1 July 2008; redeploy 1 July 2008); Surigao, Mindanao Island, Pacific boundary (lost; redeploy 1 June 2008). All pressure gauges were recovered in June-July 2009, and data were quality controlled.

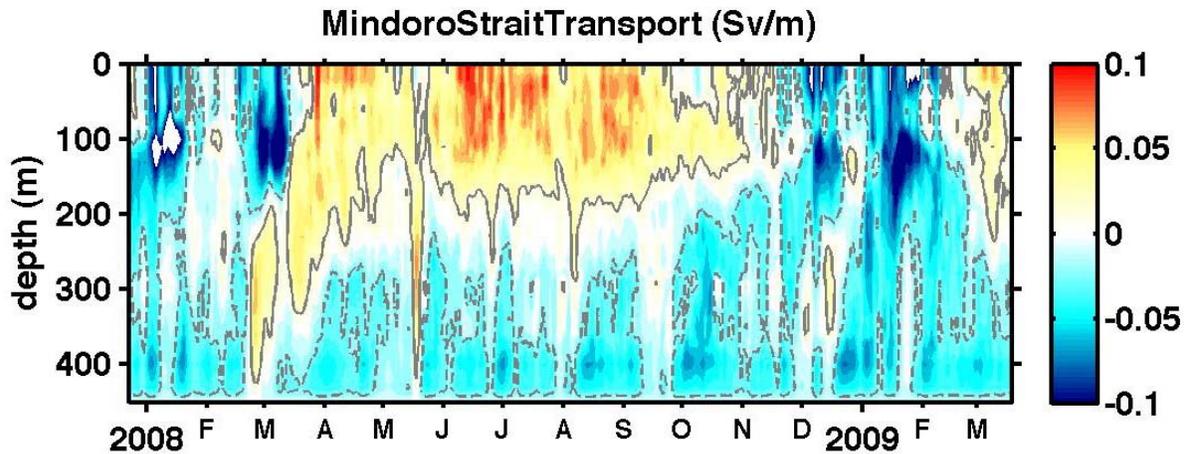
The shallow pressure gauge data will form the basis of UP student Leilani Solera’s thesis work, supervised by Villanoy. During this report period Sprintall was formally added to Solera’s PhD Committee, and will continue to work closely with her on her analysis of the tidal signals derived from the pressure gauge and HF Radar data. Solera presented a poster on her tidal analysis at the Western Pacific Geophysics Meeting, Taiwan, June 2010.

## **RESULTS**

The mooring deployments provide the first time series that measure the flow and properties in these Philippine straits. In this section, I will highlight the transport estimates from the ADCP measurements in Mindoro Strait (Figure 2) to illustrate some of the distinctive characteristics in common with much of the observed variability in the other Philippine straits.

The mooring deployment in Mindoro Strait shows a vigorous benthic layer (Figure 2). The flow in the lower 100 m is consistently directed toward the south, the along channel direction, and downstream

results in a strong spill-over into the Sulu Sea through Panay Strait. Analysis of Froude number variation across the Panay sill shows the flow is hydraulically controlled (Tessler et al., 2009). Similar strong bottom flow is also found in Dipolog Strait, and acts to ventilate the deep Bohol Sea basin (Gordon et al., submitted).



**Figure 2: Time series of the vertical distribution of the along-strait transport (Sv/m) estimated from the ADCP measurements in Mindoro Strait. Positive transport is northward, away from the Sulu Sea. Grey contours are indicated at  $\pm 0.05$  Sv/m. Note vigorous benthic flows that act to ventilate the deep Sulu Sea, the surface reversals during the monsoons, and the subsurface southward pulses during the northeast monsoon.**

The surface layer transport in Mindoro Strait is dominated by the annual cycle, with northward transport from the surface to  $\sim 170$  m during the south-west monsoon, and strong southward transport appearing in two distinct pulses of  $\sim 3$  weeks duration during each of the two surveyed north-east monsoons (Figure 2). The surface pulses are separated in time by periods of weak or reversed transports during the north-east monsoon. Pullen et al. (submitted) examined the surface flow reversal in early February 2008 using the moored observations and the high-resolution COAMPS model, and attributed it to a strong northerly wind surge that directly facilitated northward Ekman drift in the upper layer. During the north-east monsoon there is a clear separation of the surface intensified southward surface pulses from equally strong southward pulses at depths centered  $\sim 120$  m depth. These subsurface pulses are also evident in the longer time series available in Panay Strait that fully sampled two north-east monsoon seasons, suggesting a relationship to the regional wind forcing.

Local and remote winds force equatorial and coastally-trapped waves that can wend their way around the Philippine internal seas. Northward reversals are evident at mid-depth in late February 2008 and again in May 2008. These reversals are also found in the mooring time series in Panay Strait. We are examining the possibility that they are related to Kelvin waves. These waves are also manifested as pressure (sea level) changes in the coastal waveguides along the islands and are evident in the pressure gauge data collected as part of PhilEx. Wind and sea surface height data will be used to determine the likely generation region of these waves.

Finally, the transport estimates presented here rely on various assumptions about the flow structure across the passage. In this case, we have assumed that the velocity measured at each mooring (generally located on the sill near the center of each passage) represents the flow structure over half the passage width and tapers to zero at the passage side-walls. However, some cross-passage ADCP surveys (Gordon et al., submitted) and the high resolution Hycom model (Hurlburt et al., submitted) suggest that there may be stronger flows that may not have been captured by the mooring. This is particularly the case in the surface to sub-thermocline depth range where the passage geometry is wider. Our goal is to use these shipboard data and model output to fine-tune our cross-passage velocity structures, and to help establish realistic error bars on the transport time series.

## **IMPACT/APPLICATIONS**

The high-resolution time series data has been used to test the veracity of numerical models in the Philippine region (Logutov, 2008; Pullen et al., submitted; Hurlburt et al., submitted), with obvious application to other archipelago straits characterized by small-scale processes. To date, most of our knowledge of the generation, evolution and fate of these dynamical mesoscale structures within the Philippine seas has come principally from the models, which have generally been poorly constrained because of the lack of observational data in the region. The high-frequency time series observations will provide a test for evaluation and refinement of all models and their predictions that are not possible from shipborne observations alone. Ultimately, this will enable better representation and prediction of the structure and evolution of the small-scale features, including their time-dependent variability.

## **RELATED PROJECTS**

The ocean sensor array provides temporal context for the “synoptic” shipborne flow and property measurements taken as part of PhilEx (PI Gordon), as well as ground-truthing of high frequency radar (PI Flament) and SAR images (PIs Asunumu; Jackson; Arnone). The PI is also working closely with numerical modelers (PIs Pullen; Metzger; Hurlburt; Han; Arango) to explore the dynamics of the Philippine seas, as well as using the data to validate the models.

## **PUBLICATIONS**

- Gordon, A.L., J. Sprintall and A. Field, 2010. Regional Oceanography of the Philippine Archipelago, *Oceanography*, 24(1), [submitted].
- Hurlburt, H., J. Metzger, J. Sprintall, S. N. Riedlinger, R. A. Arnone, T. Shinoda, and X. Xu, 2010. Circulation in the Philippine Archipelago simulated by 1/12° and 1/25° global HYCOM and EAS NCOM, *Oceanography* 24(1) [submitted].
- Logutov, O.G., 2008. A multi-grid methodology for assimilation of measurements into regional tidal models. *Ocean Dynamics*, 58:441-460. DOI 10.1007/s10236-008-0163-4 [published, refereed]
- Pullen, J., A.L. Gordon, J. Sprintall, C. Lee, M. Alford, J. Doyle, P. May, 2010. Winds, Eddies and Flow through Straits. *Oceanography*, 24(1), [submitted].
- Tessler, A., A.L. Gordon, L. Pratt, J. Sprintall, 2010. Transport and dynamics of Panay Sill overflow in the Philippine seas. *Journal of Physical Oceanography*. [in press]