Regional Stratification and Shear of the Various Streams Feeding the Philippine Straits

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LONG-TERM GOALS

The Analysis of in situ and satellite data with model output to investigate the stratification and shear of the Philippine seas at sub-meso to meso-scales to regional scales, so as to understand their relationship to the larger scale ocean and monsoon forcing. This work contributes to the "Characterization and Modeling of Archipelago Strait Dynamics" DRI [PhilEx] goal: to enhance our understanding of the oceanographic processes and features arising in and around straits, and improve our capability to predict the inherent spatial and temporal variability of these regions using models and advanced data assimilation techniques.

OBJECTIVES

The overall objective of PhilEx was to resolve the circulation and mixing within the Philippine Archipelago and neighboring seas [South China Sea, Sulu Sea and boundary with the open Pacific Ocean], across a wide range of spatial and temporal scales. Features and processes of particular interest are those associated with the interaction of the mean and tidal currents with the strong seasonal forcing at regional and smaller scales, including the effects of the complex topography characteristic, passage constrictions and topographic sills of the Archipelago; the interaction of the interior seas of the Philippine Archipelago [Mindanao and Sibuyan Seas] with the larger scale dynamics; dense 'ventilating' overflow into isolated deep basins; the response of the circulation to highly textures wind stress curl patterns induced by the Archipelago configuration.

APPROACH

The stratification and circulation is revealed through an array of CTD/Lowered ADCP stations, as well as underway data [notably the hull mounted ADCP, SST/SSS and surface chlorophyll] collected during the field phase of PhilEx: Exploratory Cruise, June 2007; Regional IOP-08, January 2008; and Regional IOP-09, March 2009, as well as during the Joint Cruise of November/December 2007. These data are integrated with other observational data, including satellite sensing, moored instrumentation and model output, as needed to meet the DRI objectives.

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WORK COMPLETED

The dual ventilation of the deep Sulu Sea by Gordon, A.L., Z. Tessler, C. Villanoy was accepted for publication of GRL in August 2011.

Z Tessler, A. L. Gordon, C. R. Jackson 'Early stage soliton observations in the Sulu Sea' was *submitted* to JPO

J. Sprintall, A. Gordon, P.Flament, C. Villanoy 'Observations of Exchange between the South China Sea and the Sulu Sea' *to be submitted* by 30 September 2011 to JGR-ocean.

In March 2011 a special Issue on the Philippine Straits Dynamics Experiment was published in The Oceanography Society *Oceanography* entitled "The Oceanography of the Philippine Archipelago" (Volume 24, Number 1, March 2011). A.L.Gordon and C. Villanoy were the Guest Editors. See http://tos.org/oceanography/archive/24-1.html

The Table of contents:

1. The Oceanography of the Philippine Archipelago: Introduction to the Special Issue, A.L. Gordon and C.L. Villanoy. 2011. Oceanography 24(1):13, doi:10.5670/oceanog.2011.13.

2. Regional Oceanography of the Philippine Archipelago, A.L. Gordon, J. Sprintall, and A. Ffield. 2011. Oceanography 24(1):14–27, doi:10.5670/oceanog.2011.01.

3. Circulation in the Philippine Archipelago Simulated by 1/12° and 1/25° Global HYCOM and EAS NCOM, H.E. Hurlburt, E.J. Metzger, J. Sprintall, S.N. Riedlinger, R.A. Arnone, T. Shinoda, and X. Xu. 2011. Oceanography 24(1):28–47, doi:10.5670/oceanog.2011.02.

4. Two-Way Coupled Atmosphere-Ocean Modeling of the PhilEx Intensive Observational Periods, P.W. May, J.D. Doyle, J.D. Pullen, and L.T. David. 2011. Oceanography 24(1):48–57, doi:10.5670/oceanog.2011.03.

5. Development of a Hindcast/Forecast Model for the Philippine Archipelago, H.G. Arango, J.C. Levin, E.N. Curchitser, B. Zhang, A.M. Moore, W. Han, A.L. Gordon, C.M. Lee, and J.B. Girton. 2011. Oceanography 24(1):58–69, doi:10.5670/oceanog.2011.04.

6. Multiscale Physical and Biological Dynamics in the Philippine Archipelago: Predictions and Processes, P.F.J. Lermusiaux, P.J. Haley Jr., W.G. Leslie, A. Agarwal, O.G. Logutov, and L.J. Burton. 2011. Oceanography 24(1):70–89, doi:10.5670/oceanog.2011.05.

7. High-Frequency Nonlinear Internal Waves Around the Philippines, C.R. Jackson, Y. Arvelyna, and I. Asanuma. 2011. Oceanography 24(1):90–99, doi:10.5670/oceanog.2011.06.

8. Internal Wave Climates of the Philippine Seas, J.B. Girton, B.S. Chinn, and M.H. Alford. 2011. Oceanography 24(1):100–111, doi:10.5670/oceanog.2011.07.

9. Atmospheric and Oceanic Processes in the Vicinity of an Island Strait, J.D. Pullen, A.L. Gordon, J. Sprintall, C.M. Lee, M.H. Alford, J.D. Doyle, and P.W. May. 2011. Oceanography 24(1):112–121, doi:10.5670/oceanog.2011.08.

10. Drifter Observations of Small-Scale Flows in the Philippine Archipelago, J.C. Ohlmann. 2011. Oceanography 24(1):122–129, doi:10.5670/oceanog.2011.09.

11. Barrier Layer Control of Entrainment and Upwelling in the Bohol Sea, Philippines, O.C. Cabrera, C.L. Villanoy, L.T. David, and A.L. Gordon. 2011. Oceanography 24(1):130–141, doi:10.5670/oceanog.2011.10.

12. Tidally Driven Exchange in an Archipelago Strait: Biological and Optical Responses, B.H. Jones, C.M. Lee, G. Toro-Farmer, E.S. Boss, M.C. Gregg, and C.L. Villanoy. 2011. Oceanography 24(1):142–155, doi:10.5670/oceanog.2011.11.

13. Monsoon-Driven Coastal Upwelling Off Zamboanga Peninsula, Philippines, C.L. Villanoy, O.C. Cabrera, A. Yñiguez, M. Camoying, A. de Guzman, L.T. David, and P. Flament. 2011. Oceanography 24(1):156–165, doi:10.5670/oceanog.2011.12.

RESULTS

A.L.Gordon and C. Villanoy, Guest Editors, introduction to the PhilEx special issue: "The Oceanography of the Philippine Archipelago" published in *Oceanography* in March 2011.

Stretching some 2800 miles from Australia to Asia is a most impressive feature: an array of islands, straits and seas of varied sizes and depths, incorporating the Indonesian and Philippine domains. The regional mix of land and ocean, at the nexus of ENSO and Asian monsoon, where waters of the Pacific western boundary currents weave their way into the Indian Ocean, is exposed to a monsoon climate and strong tidal activity, making the "Mega"Archipelago of the southeast Asian Seas a challenge to observe and to model. To enhance our understanding of ocean dynamics within Archipelago configurations, as required to improve our capability to predict oceanic spatial and temporal variability, a program within the Philippine region, involving an integration of in situ and remote observational methods with global and regional model components, Philippines Experiment (PhilEx) Department Research Initiative (DRI) was sponsored by the Office of Naval Research. PhilEx involved US and Philippine research from numerous institutions.

PhilEx investigators posed a series of specific research questions: How does the archipelago stratification and circulation pattern respond to remote and local forcing? What are the dominant physical and dynamical balances that characterize the flow and mixing at different locations and scales within the Philippine Archipelago? How well do models simulate the observed characteristics? What are effective paradigms for representing Archipelagos dynamics? During cruise planning it became apparent that not only did the complexities of the flow within the network of straits and seas require high resolution observations, but also that a basic exploratory element was needed to better define the regional waters of the Philippine Seas.

There were 4 PhilEx expeditions (Figure 1) aboard the R/V Melville: the Exploratory Cruise in June/July 2007; the Joint Cruise in November/December 2007; the Intensive Observational Period cruise of January/February 2008, IOP08; and the IOP09 of February/March 2009. They provided regional synoptic views of the ocean stratification and circulation by CTD/LADCP, underway-surface data, including hull ADCP, towed vehicles. Observations obtained over a specific time interval are likely not to sample the environmental climatic condition. For example, 2008 winter was an anomalously wet, and as may be expected the observed regional surface layer was anomalously low in salinity. The model results help place specific observational periods in prospective of the longer-term conditions. Additionally, the cruise based observational periods are linked together with time series observations from moorings and sensors aboard untethered drifters, gliders and profilers. Land based high frequency radio provided a high spatial resolution of the surface currents within Panay Strait. Remote observations of sea surface temperature, ocean color, sea level from earth orbiting satellite complete the observational PhilEx menu, all of which are related to the output of varied models, as HYCOM, ROMS, COAMPS. Observations from ongoing programs provided information on the larger scale setting for the PhilEx program.

PhilEx uncovered many fascinating features of the horizontal and overturning circulation patterns across a broad range of spatial and temporal scales within the Philippine region that are presented in this Oceanography collection.

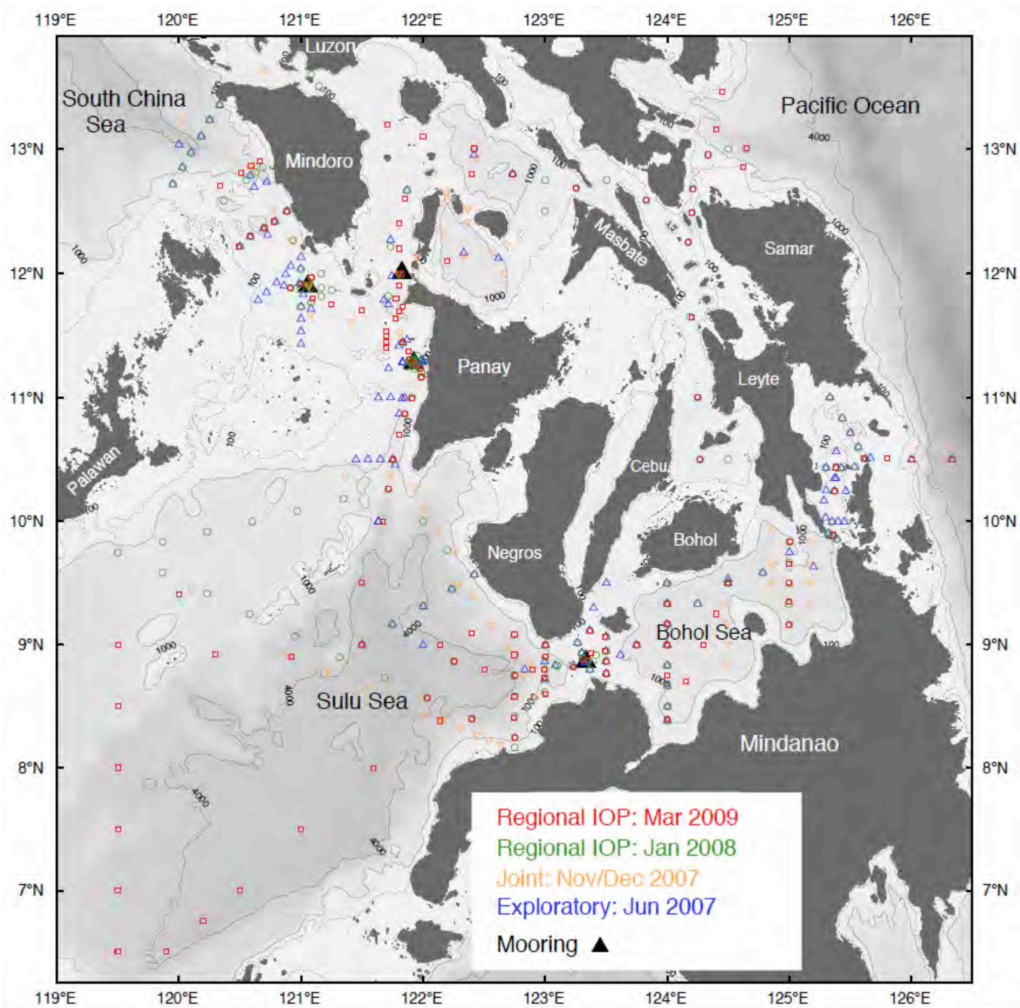

Figure 1. Conductivity, temperature, depth and dissolved oxygen and lowered Acoustical Doppler Current Profiler (CTD-O_2/LADCP) stations obtained by the four PhilEx cruises. The position of the PhilEx moorings are shown.

Gordon, Sprintall, Ffield, "Regional Oceanography of the Philippine Archipelago" *Oceanography*, provide an overview of the oceanography of the Philippine region. They report: Confined by the intricate configuration of the Philippine Archipelago, forced by the monsoonal climate and tides, responding to the remote forcing from the open Pacific and adjacent seas of Southeast Asia, the internal Philippine seas present a challenging environment to both observe and model. The Philippine Experiment (PhilEx) observations reported here, provide a view of the regional oceanography for specific periods. Interaction with the western Pacific occurs by way of the shallow San Bernardino and Surigao Straits. More significant interaction occurs via the Mindoro and Panay Straits with the South China Sea, which is connected to the open Pacific through the Luzon Strait. The Mindoro/Panay throughflow reaches into the Sulu Sea and adjacent Bohol and Sibuyan Seas, via the Verde Island Passage, Tablas and Dipolog Straits. The deep isolated basins are ventilated by flow over confining topographic sills that displace upward the older residence water made more buoyant by vertical mixing, which is then exported to surrounding seas to close the overturning circulation circuit.

The throughflow within Dipolog Strait, connecting the Sulu Sea to the Bohol Sea displays two inflow/outflow structures (Figure 2).

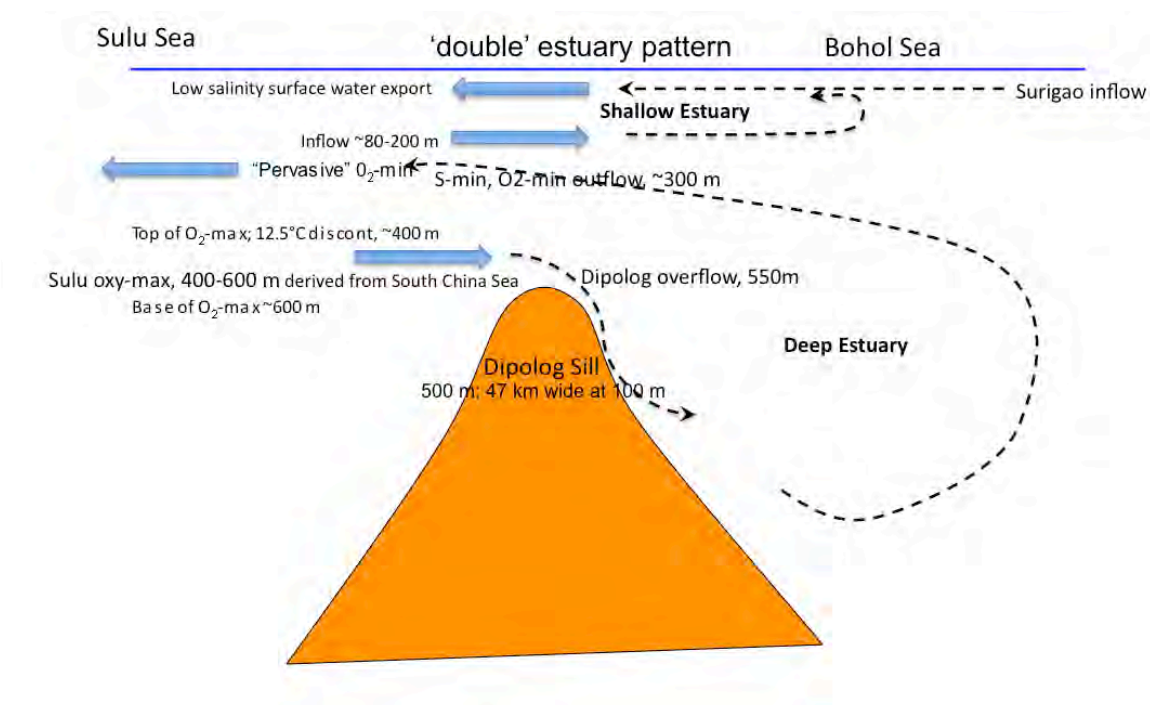

Figure 2 Schematic representation of the water exchange between the Bohol Sea and the Sulu Sea through Dipolog Strait. The depiction is based on the CTD-O_2/LADCP data from the PhilEx cruises.

The LADCP profiles reveal the highly layered circulation profile within the Dipolog Strait with two layers of inflow into the Bohol Sea and two outflow layers. The layers which exhibit export into the Sulu Sea are the surface water of the upper 50 m the other centered at 300 m. One can envision a double estuary overturning circulation within the Bohol Sea (Figure 5). The shallow estuary circulation is composed of surface water outflow to the Sulu Sea, compensated with upwelling by entrainment of thermocline inflow waters into the Bohol Sea, bolstered by the Surigao throughflow. The deeper estuary overturning circulation is controlled by dense water overflow to the depths of the Bohol Sea within the lower 50-100 m of the Dipolog Strait, with export in the 300-350 m interval towards the Sulu Sea derived from the upward displaced resident water. This water is low in oxygen (~1.3 ml/l) and is the likely source of a low oxygen core within the Sulu Sea within that depth interval. Estimates from the LADCP and mooring time series suggest that the deep overturning circulation amounts to ~0.2 Sv. The westward transport in the upper limb of the shallow cell, as estimated from the PhilEx cruises LADCP data across Dipolog Strait, may amount to ~0.5 Sv, part of which is drawn from the Surigao Strait. As the LADCP average for the lower limb is ~0.2 Sv, the Surigao Strait throughflow is probably around 0.3 Sv, assuming the Bohol Sea river inflow is negligible.

The Mindoro and Panay Straits connect the Sulu Sea with the South China Sea. These straits exhibit much variability in depth and width. A schematic of the Mindoro/Panay throughflow (Figure 3) provides a sense of the mean throughflow conditions. However, wind induced energetic eddies as observed in January-February 2008 induce much intraseasonal activity in this region that can obscure the mean, longer-term conditions. In the upper 150 m there is net flow towards the South China Sea. Eddies are generated as this flow encounters Apo Reef. At and below 150 m the flow is towards the Sulu Sea. Above ~500 m this water spreads at a similar depth into the Sulu Sea, marking a s-max near 300 m and an oxygen maximum near 500 m, traces of which enter into the Bohol Sea. Spill over topographic sills occurs into the Semirara Sea (the isolated 1300 m deep basin south of the Semirara Islands) and over the Panay sill to depths of 1200 m in the Sulu Sea.

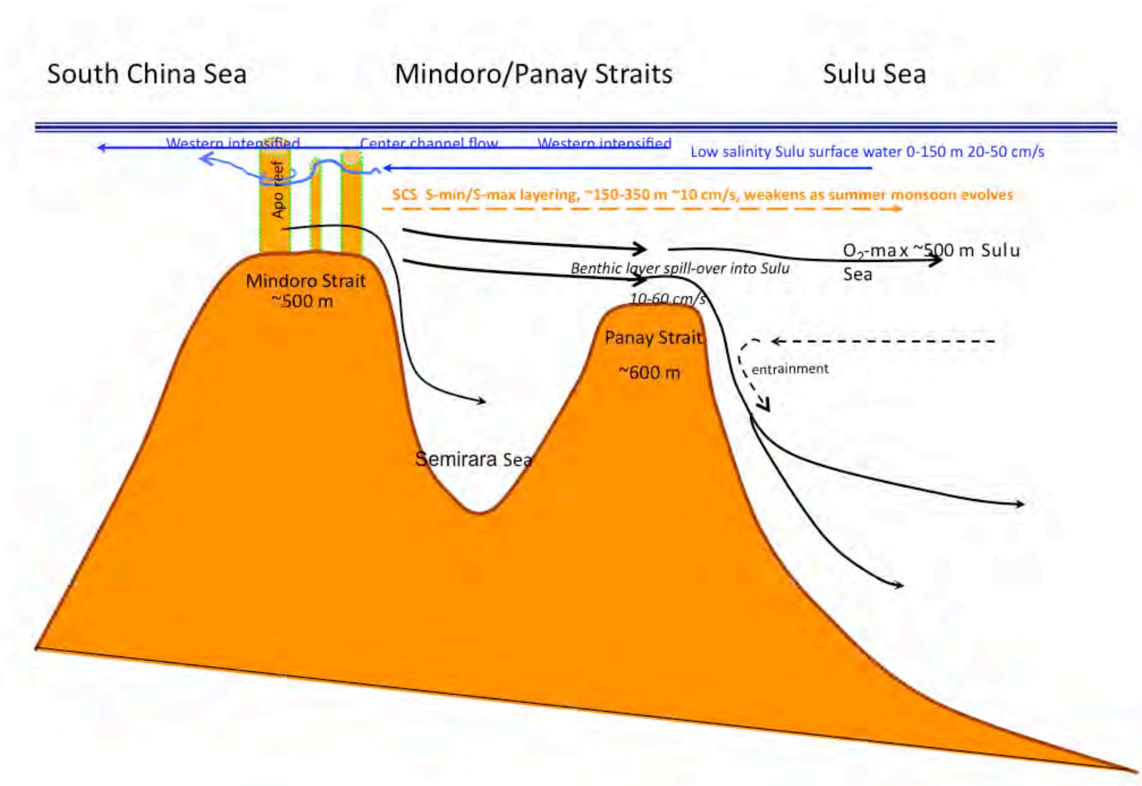

Figure 3 Schematic representation of the water exchange between the South China Sea and the Sulu Sea through Mindoro and Panay Straits. The depiction is based on the CTD-O_2/LADCP data from the PhilEx regional 2008 and 2009 cruises.

Gordon, Tessler, Villanoy, Dual Overflows into the Deep Sulu Sea. [in press GRL].

They find: The Sulu Sea, isolated from the neighboring ocean below 570 m, is nearly isothermal below 1250 m but with a marked salinity increase with depth. The source of the deep Sulu Sea water has been attributed to South China Sea water overflowing the 570 m topographic sill of Panay Strait. However, the Panay overflow (estimated as 0.32 x 10^6 m^3/sec) is an unlikely source for the saltier water Sulu Sea deep water. We propose that deep Sulu Sea ventilation is derived from the south, from the Sulawesi Sea through Sibutu Passage. Sulawesi Sea water between 245 to 527 m, is mixed water and heaved over the Sibutu Passage 234 m sill by the energetic tidal environment. Oxygen concentrations within the deep Sulu Sea suggest that the Sulawesi overflow is 0.15 x 10^6 m^3/sec, with a residence time of Sulu Sea deep water of 60 years. The deep tropical Sulu Sea has the unique distinction of being ventilated from two separate sources, whose ratio may fluctuate across a range of temporal scales, associated with regional thermocline depth changes (Figure 4).

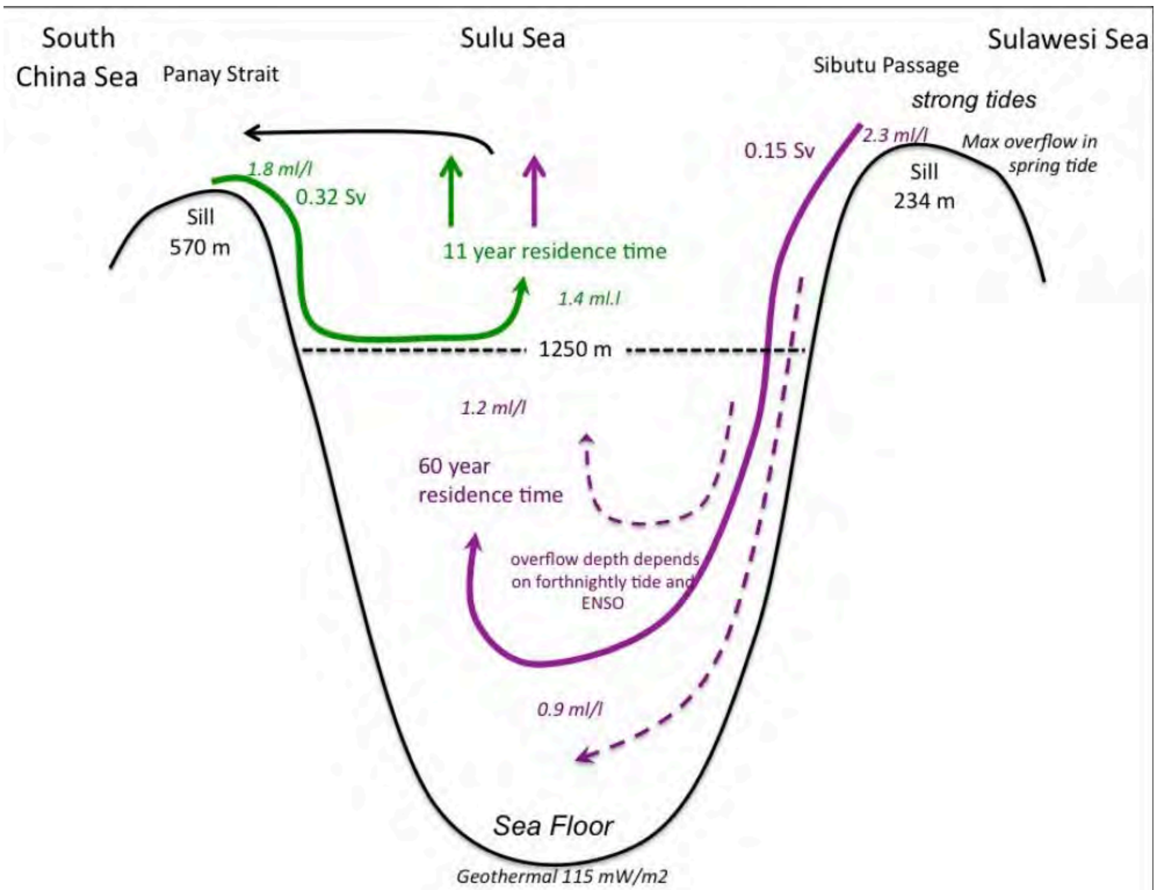

Figure 4. Schematic of the proposed Sulu dual ventilation environment, with the source of the deeper ventilation derived from the Sulawesi Sea via Sibutu Passage and the shallower ventilations drawn from the South China Sea via Panay Strait. The 11-year residence time for the 570-1250 m layer is based on Panay overflow of 0.32 Sv (Tessler et al. 2010). As the uncertainty is likely to be ~50%, with the overflow value likely to be an underestimate, the residence time may be less than 11-years. The Sibutu Passage is an extraordinary energetic Strait.

Z Tessler, A. L. Gordon, C. R. Jackson 'Early stage soliton observations in the Sulu Sea' submitted to JPO report: Observations of large-amplitude, non-linear internal waves in the Sulu Sea are presented. Water column displacement and velocity profile time series show the passage of two solitary-like waves close to their generation site. Additional observations of the same waves are made as they propagate through the Sulu Sea basin. These waves of depression have an estimated maximum amplitude of 43.5 m. Observed wave amplitude and background stratification is used to estimate parameters for both a Korteweg-de Vries (K-dV) and a Joseph wave solution. Model wave half-widths bracket the observed wave, with the Joseph model narrower than the K-dV model. Total potential energy in the modeled solitary waves are 1.6 x 10^8 J m^{-1} and 9.8 x 10^8 J m^{-1} for the K-dV and Joseph waves, respectively. Observed kinetic energy in the main wave crest contains 4.7 x 10^7 J m^{-1}; less than the estimated potential energy due to the early stage of development of individual wave crests.

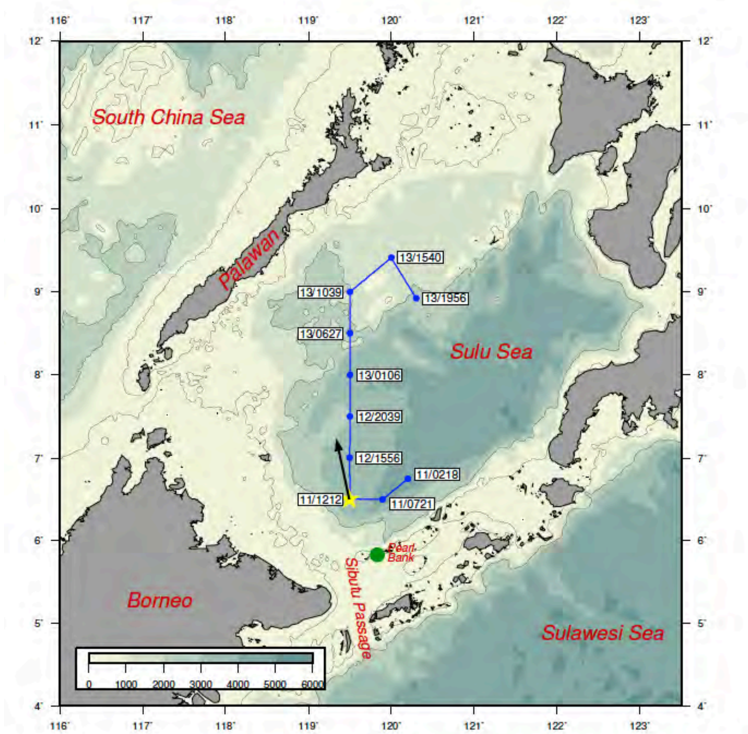

Figure 5. Study site. Yellow star marks time series location (shown in Figure 6), blue lines and dots mark ship track and CTD station locations. Arrow indicates dominant direction of wave motion, 348°. Green dot marks approximate soliton generation site. Contour lines are plotted at 100 and 2000 m depths. Timestamps mark March 2009 date and UTC time of arrival on station.

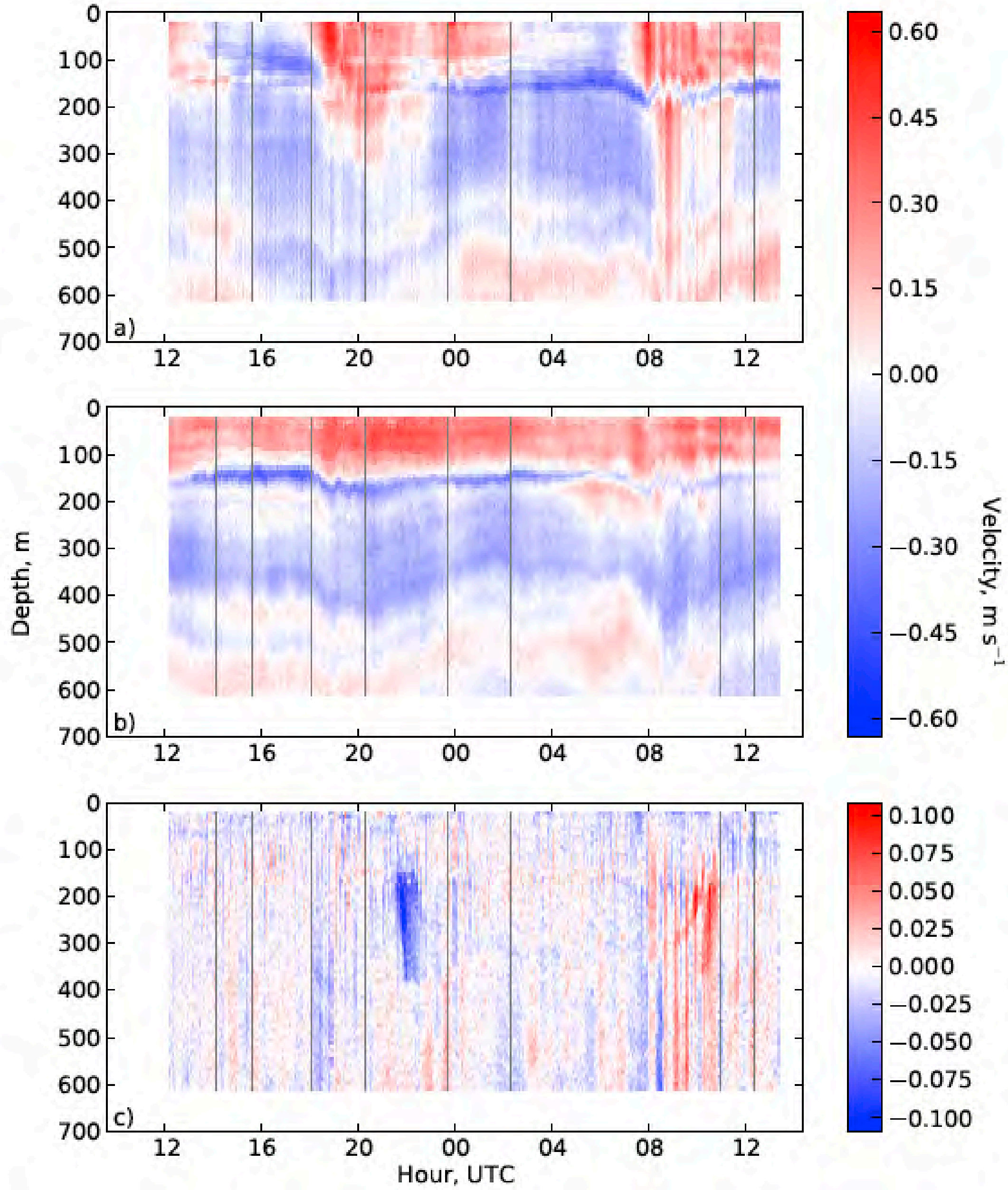

Figure 6. Velocity structure during time series, from the OS75 ADCP, on 11-12 March 2009. (a) Along-axis flow, (b) transverse flow, and (c) vertical flow. (a) and (b) share a common color scale. Strong vertical motions at 2200 UTC 11 March and 1000 UTC 12 March between 150 and 400 db are spurious signals related to diurnal migration of scatters in the water column. Wave-induced vertical motions have magnitudes between 0.01 an 0.05 m s^{-1}.

IMPACT/APPLICATIONS

The PhilEx cruises provide information for addressing the PhilEx objectives, by resolving the stratification and circulation patterns under varied forcing conditions, within the complex topography of the Philippine Seas. The resultant numerical model, honed by observations, and the enhanced understanding of the oceanography of the Philippine waters to be produced by the PhilEx program will have a multitude of applications in managing marine resources and the marine environment of the Philippines and other archipelagos, as well as for issues of marine safety and prediction of marine pollution dispersion.

TRANSITIONS

None

RELATED PROJECTS

None

PUBLICATIONS

Arango, H.G., Levin, J.C., Curchitser, E., Zhang, B., Moore, A.M., Han, W., Gordon, A.L., Lee, C., Girton, J.B. (2011) "Development of a Hindcast/Forecast Model for the Philippine Archipelago" Oceanography vol 24(1) 58 – 69. [published, refereed]

Cabrera, O., Villanoy, C., David, L., Gordon, A.L. (2011) "Barrier Layer Control of Entrainment and Upwelling in the Bohol Sea, Philippines" Oceanography 24(1) 130 – 141. [published, refereed]

Gordon, A.L., Sprintall, J., Ffield, A. (2011) "Regional Oceanography of the Philippine Archipelago" Oceanography vol 24(1) 14 – 27. [published, refereed]

Pullen, J., Gordon, A.L., Sprintall, J., Lee, C.M., Alford, M.H., Doyle, P., May, P. (2011) "Atmospheric and Oceanic Processes in the Vicinity of an Island Strait" Oceanography 24(1) 112 – 121. [published, refereed]

Tessler, Z., Gordon, A.L., Pratt, L., Sprintall, J. (2010) "Panay Sill Overflow Dynamics" Journal of Physical Oceanography vol 40(12): 2679 – 2695 [published, refereed]

Gordon, A.L., Z. Tessler, C. Villanoy (in press) Dual Overflows into the Deep Sulu Sea Geophysical Research Letters. [in press, refereed]

Tessler, Z, A. L. Gordon, C. R. Jackson 'Early stage soliton observations in the Sulu Sea' Jour Physical Oceanography [submitted]

PATENTS

None