

Interdisciplinary Modeling and Dynamics of Archipelago Straits

Dr. Pierre F.J. Lermusiaux

Department of Mechanical Engineering, Center for Ocean Science and Engineering,
Massachusetts Institute of Technology; Room 5-207B; 77 Massachusetts Avenue
Cambridge, MA 02139-4307

Phone: (617) 324-5172; Email: pierrel@mit.edu

Award #: N00014-07-1-0473

Web: <http://web.mit.edu/pierrel/www/>, <http://mseas.mit.edu/Research/Straits/index.html>

LONG-TERM GOALS

The general focus of this work is to explore, better understand, model and predict the interactive dynamics and variability of sub-mesoscale and mesoscale features and processes in the Philippine Straits region and their impacts on local ecosystems through

- i. physical-biogeochemical-acoustical data assimilation of novel multidisciplinary observations,
- ii. adaptive, multi-scale physical and biogeochemical modeling,
- iii. process, sensitivity studies based on a hierarchy of simplified simulations and focused modeling.

OBJECTIVES

The specific objectives are to:

- utilize and develop the Error Subspace Statistical Estimation (ESSE) system for interdisciplinary data assimilation and uncertainty estimation with the physical Primitive-Equation (PE) and generalized biogeochemical model of the Multidisciplinary Simulation, Estimation, and Assimilation Systems (MSEAS) group
- study, describe and model the variability and dynamics of flow separations and associated eddies and filaments, of water mass evolutions and pathways, and of locally trapped waves
- develop and implement schemes for parameter estimation and selection of model structures and parameterizations, and for high-resolution nested domains towards non-hydrostatic modeling

APPROACH

The technical approach is based on ocean dynamical modeling with free-surface primitive equation models with tidal forcing. It involves interdisciplinary data assimilation with ESSE, quantitative model evaluation and selection through adaptive modeling, and sensitivity and dynamical process studies.

The ongoing physical, acoustical and biogeochemical applications and scientific research focus on:

- Physical and interdisciplinary data assimilation (DA) of novel multidisciplinary data types
 - measurement models and interdisciplinary DA: investigate multi-grid DA/ESSE combination
 - high-resolution DA: assimilate sub-inertial processes and interactions without aliasing

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- Process and sensitivity studies
 - processes: variability and dynamics of flow; pathways and transformation of water masses; tidal – buoyancy flow interactions; biological responses; blooms; biological accumulations
 - model-based studies: sensitivity studies; term and flux balances and transports; energy diagnostics; estimation of dominant scales of variability; predictability
- Adaptive physical and biogeochemical modeling including: adaptive modeling, tidal modeling and multi-dynamics nested domains and non-hydrostatic modeling

WORK COMPLETED

Joint and post-IOP cruise data analysis: CTD casts from the December 2007 Joint cruise have been processed for our modeling, process and sensitivity studies. The data consists of 86 CTD casts from the R/V Melville from November 30, 2007 – January 3, 2008. Subsequent to the IOP cruise the UW-APL SeaGliders 122 and 126 collected data from 17 February – 21 May, 2008. 431 CTD casts were collected by SG122 and 431 were collected by SG126. Table 1 and Figures 1-2 describes these data.

Atmospheric forcing: Atmospheric variables necessary to force our ocean simulations were processed for all experimental time periods to date. These variables were acquired from FNMOC via the Metcast system. Currently utilized products are COAMPS at 0.2° resolution and NOGAPS at 1.0° resolution.

Transport Estimates of PHILEX region: A schematic and table of transports for the straits and other waterways of the Philippine archipelago were created from published literature. The schematic (Figure 3) and a summary table (Table 2) are included below. These values are used as a component of the initialization of the dynamical modeling in MSEAS-HOPS.

Initial data and idealized Simulations of Coupled Physics-Biology: World Ocean Atlas 2005 data have been processed to initialize a model for coupled regional physics and biology. Data and their standard errors were plotted for nitrate, silicate, phosphate, and oxygen. Data were plotted for temperature and salinity. All fields were studied for the months and seasons of the exploratory and joint cruises. A 2D idealized simulation of coupled physics and biology was set-up on a structured Arakawa C-grid. A Nutrient-Phytoplankton-Zooplankton (NPZ) model represents the biology advected by the flow through a strait over a simplified bathymetry. This model is the first step in identifying which physical processes in the Mindoro Strait are most important to biology.

Objective Analysis for complex geometries: The two-staged objective analysis (OA) approach which utilizes the Kalman update steps of the Kalman filter has been updated to map data sets in the Philex Archipelago domain. The structure of the correlation function is first specified. Correlation parameters are then obtained using the separation distance estimated from two numerical techniques: a) Level Set Method (LSM) and b) Fast Marching Method (FMM). Knowledge of spatial-time scales provide a measure for the parameters of the analytical correlation function and thus improve field estimates obtained using OA. A third mapping method was also implemented and used: it uses a numerical diffusion equation to extrapolate the sensor data. Adaptive methods have been implemented to learn the largest and most energetic scales directly from ocean data (prior to mapping these data). A method is based on obtaining the structure function (Denman and Freeland, 1985) from the available data and utilizing non-linear least square fit to a specified analytical form to estimate the scales in the data.

Improved Model Grids: Six modeling domains were used to create 2 sets of telescoping nested domains with resolutions of 27km, 9km, 3km, and 1km. The largest domain includes coarse resolution influence from the eastern Pacific and the South China Sea (Figure 4). The next largest provides 9km resolution around the Philippine archipelago. The remaining four domains are arranged in 2 separate pairs to support 1km resolution in the Mindoro and Surigao Straits. The vertical structures of these domains were revised in three key areas. (1) A new topography was constructed by joining the 1 minute NCOR bathymetry obtained from Dr. Sen Jan (NCU of Taiwan) with the Smith and Sandwell (v10.1) 1 minute topography. (2) The topography in each domain was conditioned to restrict the reduced slope ($\text{grad}(h)/h$) and the absolute slope. This was done in stages to minimize the changes to 4 isobaths (25, 144, 275 & 500m), chosen to preserve important sill depths. (3) The number of vertical levels was increased to 70 and their distribution was revised to improve the representation of vertical TS structure. To do so, 3D T/S fields mapped on constant depths were interpolated onto the terrain-following coordinates of the modeling domains and re-interpolated back to the original constant depths. Differences between the original fields and the doubly-interpolated fields were then examined.

Revised Initialization Procedures: Our original procedures integrated the density in the vertical to produce dynamic height fields, which were then horizontally differentiated to obtain velocity. To avoid contamination from extrapolated values beneath topography, the order of operation was swapped such that the horizontal gradient of density is computed first then integrated in the vertical. When computing horizontal gradients on the B-grid, if any of the 4 density points falls under topography, the horizontal gradients are set to zero. Another modification was made to handle the large number of islands. Initial barotropic velocities (constructed to have a divergence free transport) are constructed in a multistep process. First an island-free transport streamfunction, Ψ_0 , is constructed. Then constant values for Ψ along each island are constructed and a final “island aware” Ψ is found. The new step is to determine the island constant values by evaluating Ψ_0 along each island coast, determining an estimated minimum transport between each island from differences of these values and finally constructing a weighted least-square functional to find the constant island values which best fit these estimates. The weights were the squares of the reciprocals of the shortest inter-island distances. The functional was augmented with similar terms for the difference between each island and each external (known) coast and between each island and the nearest open boundary point.

Inverse Multi grid Tidal Modeling: A new inverse methodology designed to account for errors of representativeness by employing a multi-grid data-assimilative framework has been developed for the Philex domains and regional seas (Logutov and Lermusiaux, 2008; Logutov, 2008). The observational network utilized consisted of the Topex/Poseidon altimetry (harmonically analyzed Topex-Poseidon data for Philex domains provided to us by Dr. Richard Ray, Goddard Space Flight Center) and data from two ADCP moorings, provided to us by Dr. Janet Sprintall, Scripps Institution of Oceanography.

Steady-state Wind-driven Circulation: Ocean response to steady wind forcing was computed using our new linear steady-state 2-D and 3-D shallow water model, with wind-forcing at the surface specified from Hellerman/Rosenstein wind stress 2-by-2 deg climatology. Wind-driven transports and the SSH anomaly were obtained and decomposed into total, Ekman layer and Ekman pumping driven transports and velocities. The 3-D shallow water model utilizes the total transports and the SSH anomaly obtained from the 2-D solution and employs the continuity and the momentum equations to solve for the vertical velocity shear between layers. The bottom boundary condition on the vertical velocity shear is specified such as to match the total transport in the 3-D solution with the 2-D solution.

Steady-state Density-driven Circulation: Ocean steady-state response to baroclinic forcing was computed using the above linear shallow water models. A solution of the depth-integrated problem, forced by the baroclinic density-driven pressure gradient integrated through the water column, is first carried out. This gives density-driven transports and surface pressure gradients assuming geostrophy (with friction) and continuity, given realistic coastlines and bathymetry. Secondly, a 3-D steady-state problem is solved, with the surface pressure gradients obtained from the previous step and the 3-D continuity enforced to provide velocity shear between layers given local baroclinic forcing. No large scale forcing through OBCs was applied: only the interior driven flows were considered.

Ocean Dynamics. Circulation features were described and researched using our data-driven simulations. These included the: source of the deep Sulu Sea water, variability of the inflow/outflow in the Mindoro Strait and the deepening of mixed layer as the Summer Monsoon establishes.

RESULTS

Joint and post-IOP cruise data analysis: We found good agreement among the different data sets and sensors. Evidence of multiple water masses is apparent in the CTD data. There is a deep thermocline to 200m with a separation into various local water masses below that. Surface salinity is considerably fresher in December as compared to the Exploratory Cruise data. Isohaline water extends to 60-70m in December. The SeaGlider data is more geographically constrained and exemplifies local water masses. Work is ongoing to resolve issues with salinity spikes in the SeaGlider data.

Atmospheric forcing: During June 2007 (Exploratory Cruise) winds are light and generally from the south-southeast (start of summer monsoon) but the direction is variable. June winds are typically well under 10 knots while significant events can reach 20 knots. During December 2007 and January 2008 (the winter monsoon), winds are much stronger and consistently from the northeast. Typical winds are 15-20 knots while events can easily exceed 30 knots (Figure 5). COAMPS and NOGAPS products have been found to be in good general agreement in both magnitude and direction of events.

Transport Estimates of PHILEX region: Mean estimates of transport have been utilized to specify transports in dynamical simulations. As transport values vary dramatically with seasons, a number of simulations are ongoing to verify these estimates and understand the effects of the transport variations.

Initial data and idealized Simulations of Coupled Physics-Biology: Standard error plots show that nitrate, silicate and phosphate have very poor coverage in the PHILEX domains. Oxygen has better coverage, especially in summer. Due to the limited in situ data, the merging of climatology and in situ data is necessary but challenging. The 2D idealized simulations of coupled physics and biology was compared to a code using Discontinuous Galerkin Finite Element Method on an unstructured grid.

Objective Analysis for complex geometries: The coastline constraints have been appropriately implemented, i.e. the optimal spatial separation distances have been accurately computed such that there is no direct relationship across landforms (islands, peninsulas) in the OA approaches using LSM or FMM. The results obtained using these numerical techniques (Figure 6) are equivalent, but FMM is computationally much less expensive (operation count: $O(N^2 \log N)$) when compared to iteratively obtaining the steady state solution of the Level Set equation with finite difference discretization (operation count: $O(N^3)$). These OA maps were compared to OA maps obtained with the numerical diffusion approach. Initial transport estimation is underway. Finally, the scales estimates that are obtained using the adaptive learning algorithm are used to guide the scales to be used for OA maps.

Revised Initialization Procedures: Restructuring the geostrophic initialization procedure significantly improved the initial velocity estimates in the presence of topography. A spuriously strong circulation around the Sulu Sea basin (over the bounding steep slopes) was eliminated. The introduction of the minimization procedure for the inter-island transports controlled the creation of erroneously large barotropic velocities between the islands. The choice of vertical levels (in tandem with topographic conditioning) has been shown to control the appearance and growth of numerical modes. The double-interpolation comparison, described in the work completed section, is an important tool in aiding that choice. In Figure 7, the reduction of error when going from 36 to 70 levels is shown in the left and center panels. However, over the Philippine trench, the levels are spread and the error in the upper ocean increases. This was also a region where spurious waves were being generated. By shifting levels to the upper sigma system and allowing the upper system to cover the upper 400m, the errors over the trench were reduced (right panel) and the spurious waves were suppressed.

Inverse Multi-grid Tidal Modeling: Observed depth-averaged ADCP velocities, with mean removed, versus inverse-model velocities at ADCP locations show that the inverse coarse-resolution solution (5-min resolution) in a stand-alone large-scale domain can't fit interior data well. With the coarse-resolution setup, the Sulu, Bohol, Visayan, and Sibuyan seas had model values consistently higher than the observed SSH by an average of 10 cm, with even larger misfits at several locations (see Figure 8). This discrepancy is related to misrepresentation of tidal transports through the Surigao and the San Bernardino straits, as well as across the straits of the Sulu Archipelago. Our new nested approach, with 1-min resolution domains, allows for the resolution of these transports and prevents corruption of larger scales in tidal estimates due to errors of representativeness. The OBC schemes, baro-2-baroclinic conversions and bottom friction need to be further investigated.

Steady-state Wind-driven Circulation: Wind-driven circulation around the Philippines Archipelago is strongly affected by the coastline geometry and is horizontally inhomogeneous even under homogeneous wind forcing. Wind forcing can cause non-local effects through flow continuity given complex coastline and bottom topography in the region. Figure 9 exemplifies the wind-driven ocean response to the northeast monsoon (January) at different depth levels. In the Mindoro straits, the winds drive northward flows caused by the non-local wind forcing. The wind-driven component to upper-layer inflows at San Bernardino and Surigao is around 20 cm/s. Future work should include tuning of vertical mixing parameters and use of synoptic winds, as well as comparisons to HOPS solutions.

Steady-state Density-driven Circulation: Steady-state computations show a strong southward overflow current in the Mindoro and Tablas straits, with complex spatial pattern and eddies, with velocities ~5-20 cm/s at 100m. Figure 10 shows density-driven transports in the upper 1000m based on the Exploratory Cruise data (June 2007), with the hydrographic OA computed using our diffusion-equation scheme. Results indicate coastal density-driven currents along the west coasts of Panay and Mindoro islands and Zamboanga peninsula. Density-driven "gyres" and coastal jets result from coastal and topographic effects. The inflow to Mindanao through the Surigao Strait is found to be driven by NEC and winds while the internal density flow can be opposite. The Panay coastal current and the inflow from the South China Sea to the Sulu Sea through the Mindoro strait appear density-driven.

Ocean Dynamics. Features found in data analyses (A. Gordon) were confirmed in our simulations. A new result is that the source of the deep Sulu Sea water seems to be the Sulawesi Sea and that this overflow is driven by strong episodic wind and tidal forcing. As the summer Monsoon establishes, the inflow/outflow in the Mindoro Strait is also found to increase and the mixed layer to deepen.

IMPACT/APPLICATIONS

This research will contribute to coastal physical and biogeochemical oceanography in general and dynamics of Straits in particular. This will increase capabilities of navy operations in these regions, especially the surveillance of transit routes, safety of man-based activities, management of autonomous vehicles, and overall tactical and strategic decision making under uncertainties in sensitive areas.

TRANSITIONS

Interactions and coordination are ongoing with several investigators and teams involved with this DRI, specifically with observational efforts, and numerical and theoretical modeling investigations.

RELATED PROJECTS

Collaborations occur under the ONR grant “Physical and Interdisciplinary Regional Ocean Dynamics and Modeling Systems” (MIT follow-up to N00014-05-1-0335).

PUBLICATIONS

Logutov, O.G. and P.F.J. Lermusiaux, 2008. Inverse Barotropic Tidal Estimation for Regional Ocean Applications. *Ocean Modelling*, 25, 17-34. doi:10.1016/j.ocemod.2008.06.004 [in press, refereed].

Logutov, O.G., 2008. A Multi-Grid Methodology For Assimilation of Measurements into Regional Tidal Models. *Ocean Dynamics*. [accepted, refereed].

The main PHILEX presentation was given at NRL at the end of August 2008 and is available from <http://mseas.mit.edu/Research/Straits/index.html> or from the PHILEX site. Several other presentations and publications are available from the MSEAS web-site. Specific figures are available upon request.

FIGURES

Table 1: Data collected during PHILEX Experiment, 6 June, 2007 – 21 May, 2008.
Exploratory and Joint Cruise data sets have been used and assimilated.

Cruise Name	Designation	Dates	CTDs	SeaGliders
PhilEx01	Exploratory	6 June – 3 July 2007	142	Sg122 – 110 casts Sg126 – 191 casts
PhilEx02 (1)	Joint	27 – 29 Nov. 2007	None	None
PhilEx02 (2)		30 Nov. – 18 Dec. 2007	52	None
PhilEx02 (3)		19 – 26 Dec. 2007	13	None
PhilEx02 (4)		26 Dec. 2007 – 1 Jan. 2008	27	None
PhilEx03 (1)	IOP	9 – 22 January 2008	101	None
PhilEx03 (2)		22 Jan. – 1 Feb. 2008	52	None
		17 Feb. – 21 May 2008	None	Sg122 – 431 casts Sg126 – 421 casts

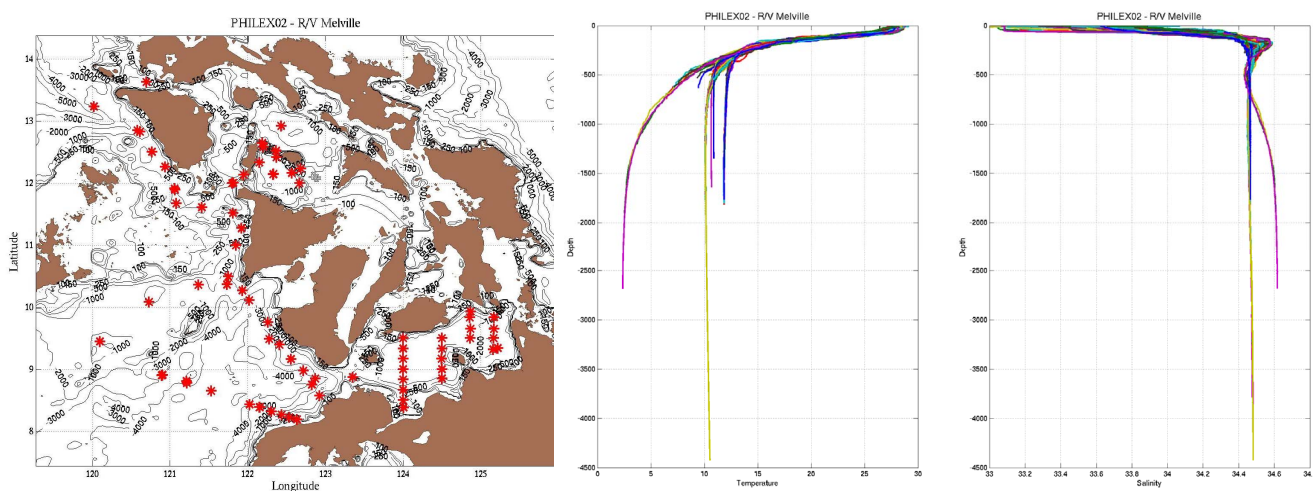


Figure 1: 86 CTD casts from PHILEX Joint Cruise, November 30, 2007 – January 3, 2008;
(left) location, (center) temperature versus depth, 0-4500m, (right) salinity versus depth, 0-4500m.

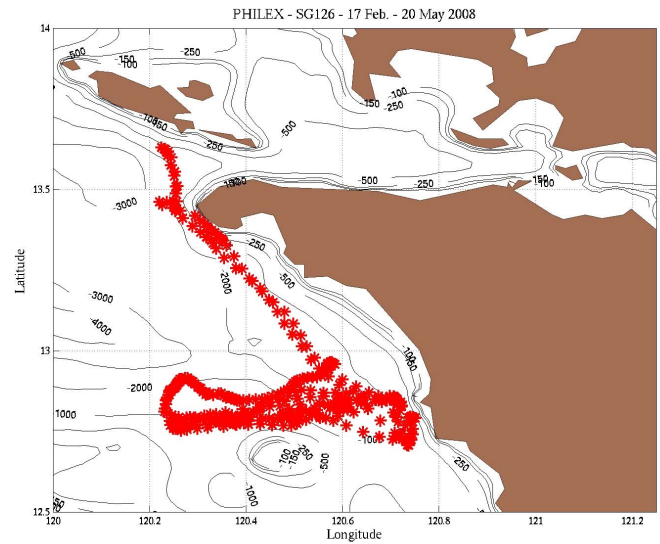
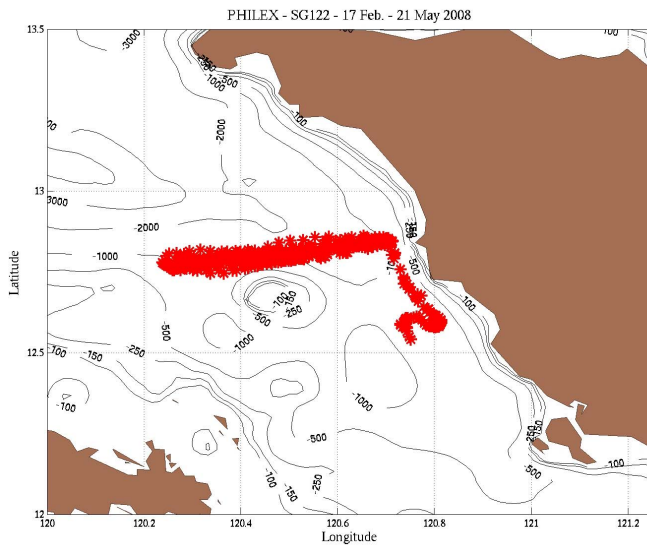
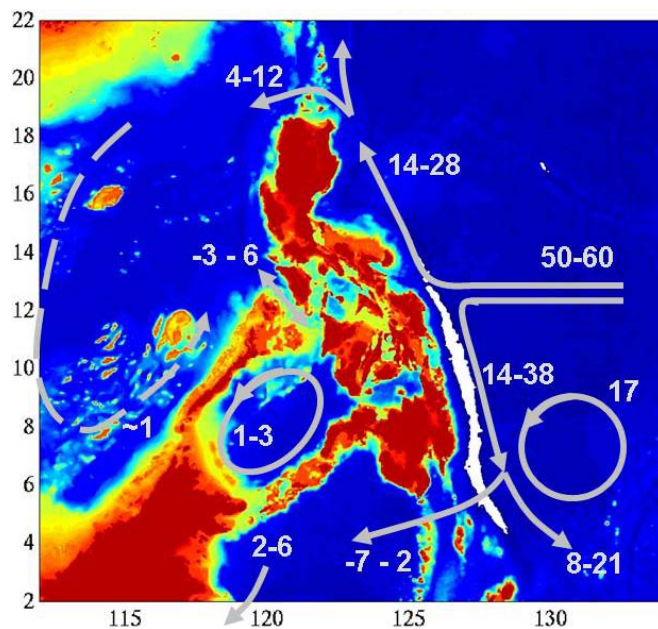


Figure 2: Location of SeaGlider casts from PHILEX Experiment, 17 February – 21 May, 2008; (left) SG122, (right) SG126



Mean transport estimates (in Sv)

East of Luzon:	18.83
East of Mindanao – 1:	-25.23
East of Mindanao – 2:	-26.33
Luzon Strait:	-3.1
Sibutu Passage:	-3.3
East of Vietnam:	-8.65
Sulawesi-Mindanao:	-3.6
Makassar Strait:	-6.8
PACIO throughflow:	-8.9
Leyte Gulf:	-0.1
San Bernadino Strait:	-0.8

Figure 3: Transport schematic (left); Table 2: Estimates of transports for various straits (right).

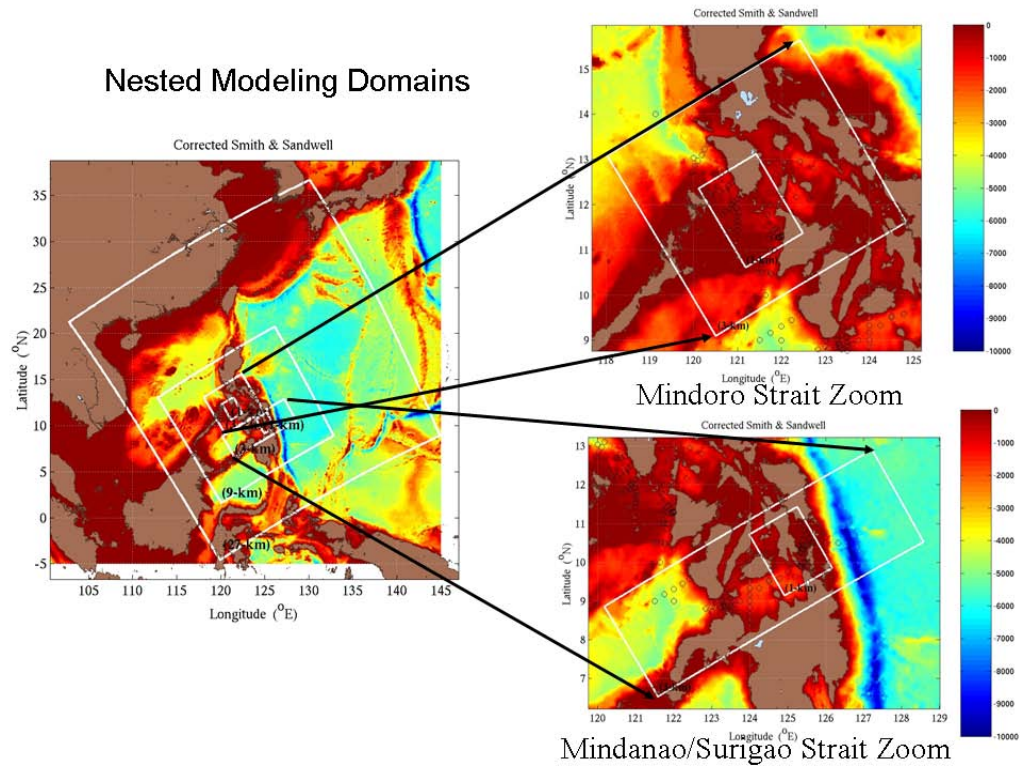


Figure 4: Complete set of nested modeling domains (left) and nested domain pairs (right).

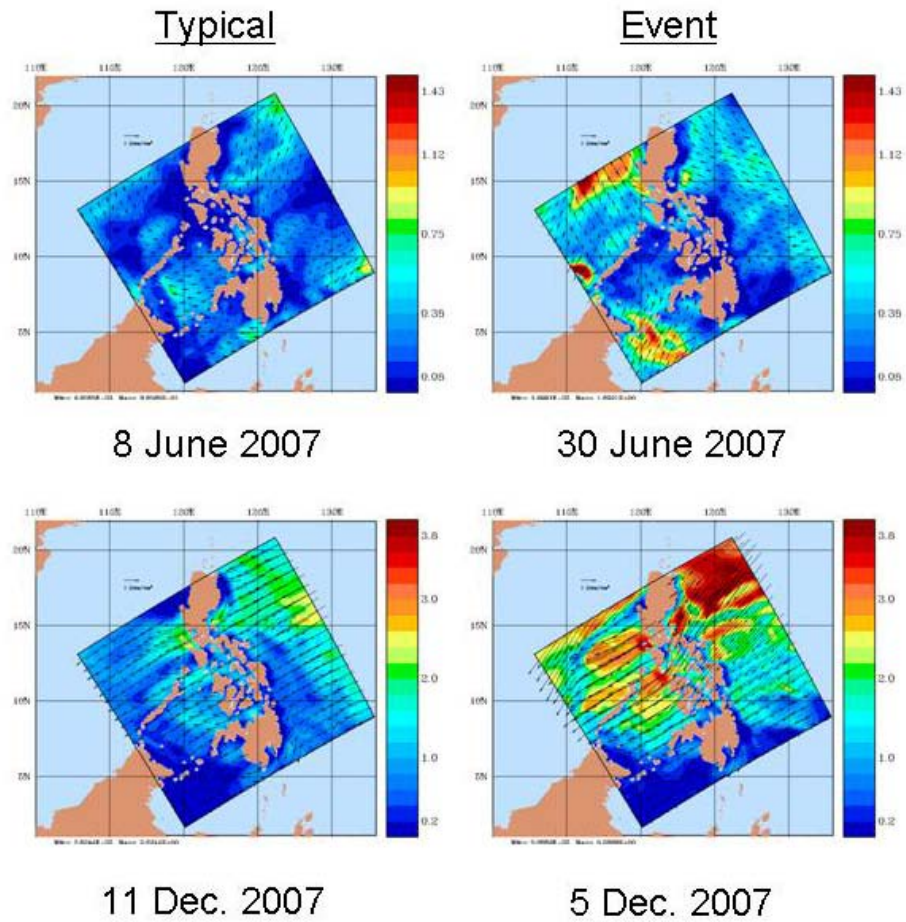


Figure 5: Wind stress from COAMPS; (left) typical scale events; (right) extreme events.

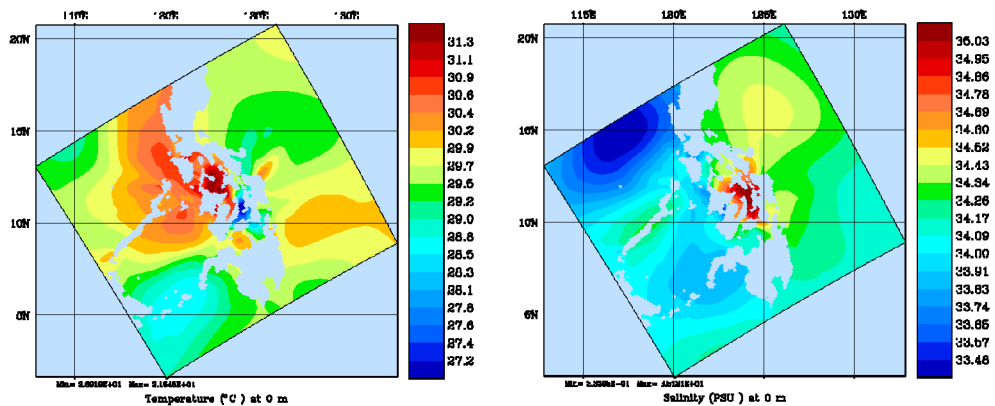
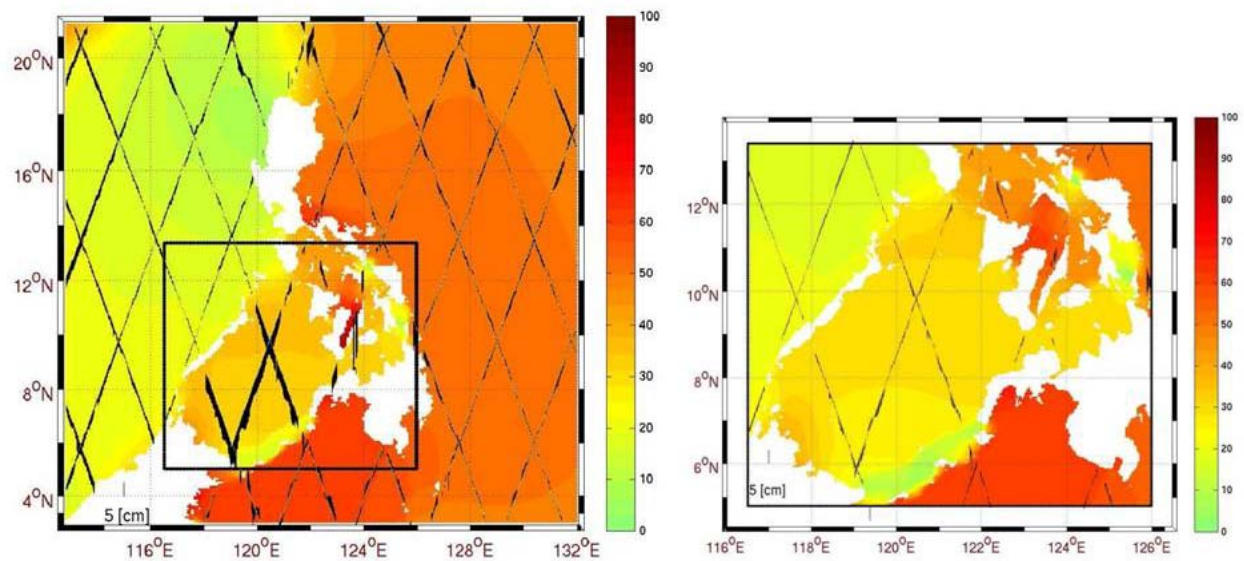
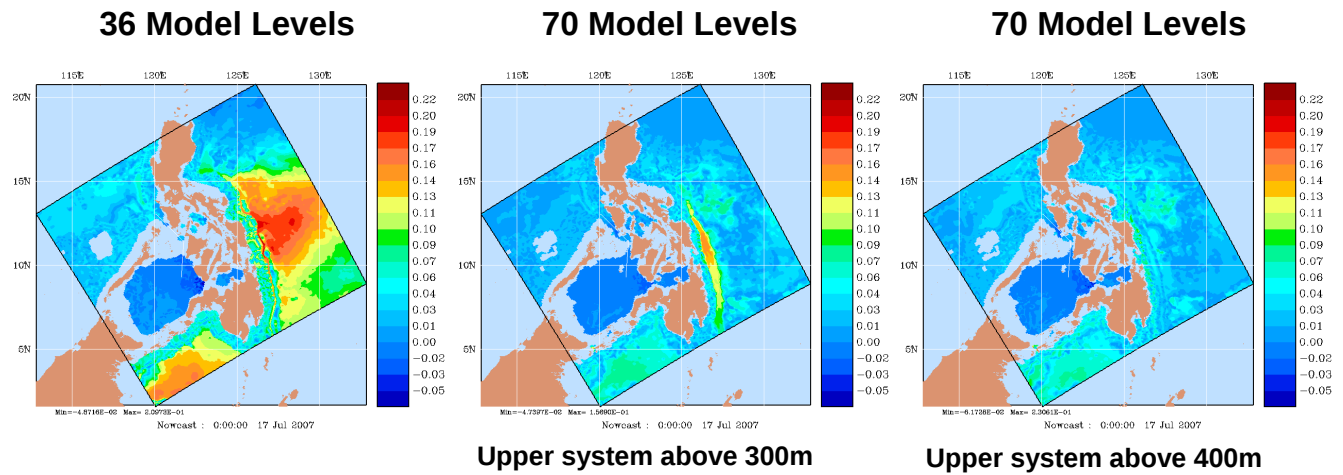


Figure 6: Field estimates (Temperature and Salinity) for Philippines Archipelago. Data Source: Exploratory Cruise + June 2007 GTSP + Hydrobase2 Climatology



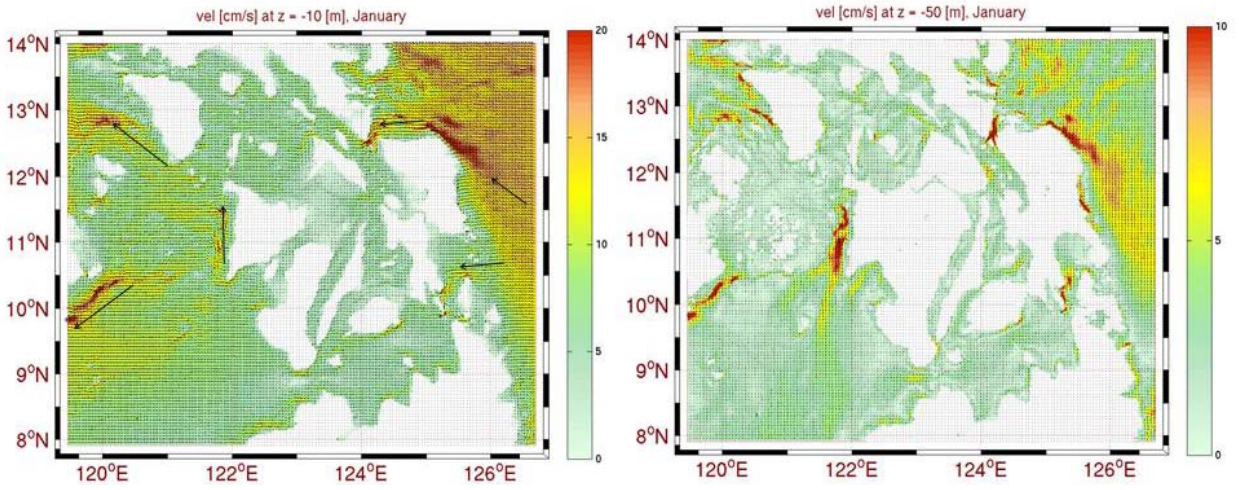


Figure 9: wind-driven ocean response to the northeast monsoon (January); (left) 10m, (right) 50m.

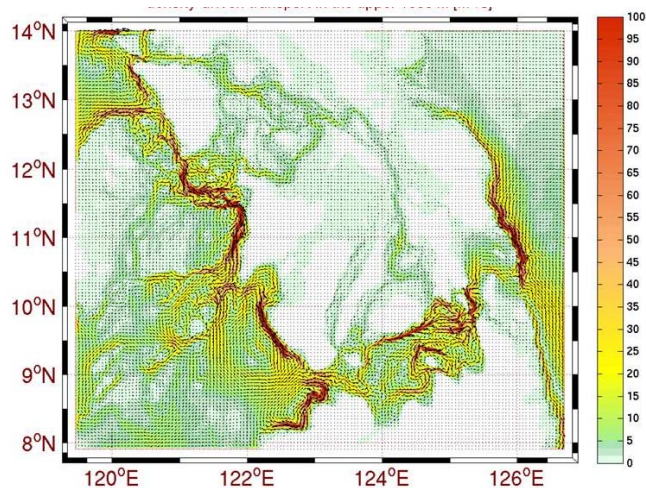


Figure 10: Density-driven transports in the upper 1000m.