Winds, Eddies and Flow through Straits

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14. ABSTRACT

A reversal of the mean flow through the Philippines? Mindoro Strait occurred in early February 2008. The flow was southward through the strait during late January and northward during most of February. The flow reversal coincided with the period between two intensive observing cruises (IOP08-1 and IOP08-2) sponsored by Office of Naval Research (ONR) as part of the Philippine Straits Experiment (PhilEx). Employing highresolution models of the ocean and atmosphere along with in situ ocean and air measurements, we detail the regional and local features that influenced this flow reversal. High-resolution air/sea modeling simulations captured the flow reversal and agreed with measured currents from two moorings in the vicinity of Mindoro Strait. A short (24-27 January) easterly monsoon surge and a longer (9-16 February) northerly surge were represented in the model as well as in QuikSCAT and underway wind data taken during IOP08-2. Mesoscale oceanic dipole eddies off Mindoro and Luzon (Pullen et al., 2008) were formed/enhanced and subsequently detached by these wind events. The cyclonic eddy associated with the easterly surge was opportunistically sampled during the IOP08- 1 cruise and the modeled eddy characteristics were verified using in situ shipboard data. The presence of the cyclonic eddy near Mindoro Strait favored a geostrophic flow southward through the strait. This dominant flow was interrupted by a strong and sustained wind-driven (by the northerly surge) flow reversal in early February when the cyclonic eddy was absent. Enhanced upper ocean stratification in winter 2008 due to anomalously high precipitation served to isolate the near-surface circulation in the observations.

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Abstract

A reversal of the mean flow through the Philippines' Mindoro Strait occurred in early February 2008. The flow was southward through the strait during late January and northward during most of February. The flow reversal coincided with the period between two intensive observing cruises (IOP08-1 and IOP08-2) sponsored by Office of Naval Research (ONR) as part of the Philippine Straits Experiment (PhilEx). Employing high-resolution models of the ocean and atmosphere along with *in situ* ocean and air measurements, we detail the regional and local features that influenced this flow reversal. High-resolution air/sea modeling simulations captured the flow reversal and agreed with measured currents from two moorings in the vicinity of Mindoro Strait. A short (24-27 January) easterly monsoon surge and a longer (9-16 February) northerly surge were represented in the model as well as in QuikSCAT and underway wind data taken during IOP08-2. Mesoscale oceanic dipole eddies off Mindoro and Luzon (Pullen et al., 2008) were formed/enhanced and subsequently detached by these wind events. The cyclonic eddy associated with the easterly surge was opportunistically sampled during the IOP08-1 cruise and the modeled eddy characteristics were verified using *in situ* shipboard data. The presence of the cyclonic eddy near Mindoro Strait favored a geostrophic flow southward through the strait. This dominant flow was interrupted by a strong and sustained wind-driven (by the northerly surge) flow reversal in early February when the cyclonic eddy was absent. Enhanced upper ocean stratification in winter 2008 due to anomalously high precipitation served to isolate the near-surface circulation in the observations.

1. Introduction

The circulation through the Philippine Archipelago is the result of the influences of local, regional and remote forcing of both oceanic and atmospheric origin. Here we survey the contributions of these processes, acting on different scales, to the dynamics of a strait. Mindoro Strait, separating the South China Sea from the Philippine internal Sulu Sea via Panay Strait (Figure 1b), is an important conduit of exchange between the interior and exterior of the archipelago. We aim to elucidate the various contributing factors to the flow through Mindoro Strait, so as to create an integrated picture of the mechanisms involved in a reversal of the mean current through a major pathway.

Two ONR-sponsored PhilEx research cruises (designated IOP08-1 and IOP08-2) plied the waters of the Philippine archipelago during boreal winter 2008. In the period between the two cruises the flow in Mindoro Strait reversed from southward to northward. Our work synthesizes observations and modeling to probe the role of various forcing factors in the evolution of the flow reversal. These factors include winds, eddies, and stratification effects.

2. Wind Jets and Mesoscale Dipole Eddies

As previously described in Pullen et al. (2008) monsoon surges (intensifications in the near-surface winds) lead to the formation and detachment of a pair of mesoscale oceanic dipole eddies in the coastal waters adjacent to Mindoro and Luzon islands. The eddies move away from the coast and travel westward across the South China Sea, interacting with the complex offshore eddy field along the way. Pullen et al. (2008) utilized high-resolution ocean and atmosphere modeling to document the generation and migration of these eddies in response to the atmospheric surge events. Satellite observations of sea surface temperature, winds, and chlorophyll were used to verify the wind and eddy characteristics produced by the ocean and atmosphere models. In that research, it was hypothesized that the detachment of the oceanic eddies is a robust response to episodic wind surges arising from atmospheric pressure cell displacements over Asia whose synoptic meteorology is detailed in Chang et al. (2006) and Wu and Chan (1995, 1997).

Rypina et al. (2010) further characterized the Philippine dipole eddies of Pullen et al. (2008) from the perspective of chaotic advection – revealing the stable and unstable manifolds of the flow structures, their pathways of transport, and the implications for biology. They found that Manila Bay and surrounding coastline regions were source waters for the eddies. Flow from the Verde Island Passage that separates the islands of

Mindoro and Luzon was not a significant factor in feeding the eddies. This represents further evidence of the uniquely wind-driven origin of the Philippine dipole eddies.

By contrast, in other volcanic island regions of the world (including the Hawaiian, Cabo Verde, and Canary Islands) instabilities and fluctuations associated with ocean currents channeled through island straits are largely responsible for inducing oceanic eddy shedding (Lumpkin, 1998; Barton et al., 2000; Flament et al., 2001). In these locales wind-driven dynamics do not directly control the eddy detachment but instead contribute to the initial dipole spin-up via Ekman pumping (Chavanne et al., 2002; Sangra et al., 2007).

During the first of the winter 2008 research cruises we utilized Coupled Ocean-Atmosphere Mesoscale Prediction System (COAMPS) real-time forecasts to guide our sampling strategy. The model used 9 km resolution for the atmosphere and 3 km resolution for the ocean. In the simulations presented here the basic configuration is the same as described in Pullen et al. (2008), but now include tides specified at the boundaries from the Oregon State University tide model (Egbert and Erofeeva, 2002).

The boreal winter IOP08 cruises occurred during the north-easterly monsoon period in the Philippines. An easterly monsoon surge was predicted near the end of the IOP08-1 cruise by our real-time atmospheric forecasts. The model-predicted wind is compared with QuikSCAT ~25 km resolution winds (Figure 1a & 1b). The atmospheric wind jets possessed an easterly orientation as best evidenced by the downwind portion of the jet originating between Mindoro and Panay (the Panay jet, cross in Figure 1b) extending westward across the northern tip of Palawan. The satellite and model maps both display this wind orientation in common. In the Panay jet, easterly surge mean winds of 12.7 m s^{-1} and standard deviation of 1.3 m s^{-1} were produced in the model, with maximum winds of 14.5 m s^{-1}. This particular wind surge lasted ~3 days, as determined by model winds exceeding the model wintertime mean (~11 m s^{-1}) by one standard deviation (~3 m s^{-1}), with diminished intensity intervals lasting less than 24 hours.

The real-time COAMPS ocean forecast that we were consulting while on the ship at sea revealed a dipole eddy pair spinning up off the coast of Mindoro and Luzon following the easterly wind surge. In response, we designed and commenced a ship track to sample the ocean cyclone (the southern eddy in the dipole pair). The 25-m Acoustic Doppler Current Profiling (ADCP) shipboard measurements and model currents show a strong correspondence during 27-31 January of IOP08-1 (Figures 2a & b). Notably, the approximately 100-km diameter cyclonic eddy between 13˚N and 14˚N at 119˚E is present in both maps, and is apparent down to ~150 m in the ADCP and model fields (not shown). The southward flow (~25-50 cm s^{-1}) through Mindoro Strait is also evident in the observations and model.

The winds had calmed by the time the winter research cruise IOP08-1 ended on 31 January. About 12 days later the winds again intensified as part of a cold surge originating from the Asian mainland, with the winds this time displaying a more northerly orientation. The prolonged northerly surge was longer in duration and stronger in intensity than the earlier easterly surge. The downwind extent of the Panay wind jet ran parallel to the island of Palawan in both the model and satellite fields – thereby illustrating the northerly orientation of this particular event (Figure 1c & d). The northerly surge lasted ~7 days with maximum wind strength in the Panay jet of 17.1m s^{-1}.

The mean wind speed in that location (marked by a cross in Figure 1d) over the ~7-day event was 12.9 m s^{-1}, with standard deviation of 1.8 m s^{-1}. Except for its prolonged duration, the statistical characteristics of this event are similar to the northerly surge identified and analyzed in Pullen et al. (2008).

The shipboard anemometer data from the second research cruise of the north-east monsoon season (IOP08-2) is compared with the model-derived winds (Figure 2 c & d). (Unfortunately the anemometer was not functioning properly during the first research cruise.) Winds were enhanced in the gaps between islands and were muted and more directionally variable in the wake in the lee of the island of Mindoro. The ground-truthing of the predicted winds during IOP08-2 (Figure 2c & d) and the near-surface currents during IOP08-1 (Figure 2a & b) increases confidence in the performance of the model.

As in winter 2005 (Pullen et al., 2008), the northerly surge was somewhat stronger in the mean and had greater maximum intensity (by >15%) than the easterly surge. The two atmospheric surge events occurring in winter 2005 were ~10% (1.3 m s^{-1}) stronger in the mean than those documented here in 2008. Both easterly and northerly surge events in 2005 lasted 2-3 days as did the 2008 easterly surge (24-27 January 2008), while the 2008 northerly surge lasted ~ 7 days (9-16 February 2008) and tapered off slowly with significant wind peaks still evident out to 21 February. Fluctuation levels during the surges were similar among the events over the two years (2005 and 2008), and were quite muted (1-2 m s^{-1}) compared to the winter seasonal standard deviation of ~ 3 m s^{-1}. The separation of the wind events was 17 days in 2005 and 12 days in 2008. In 2008 the easterly surge preceded the northerly surge, whereas in 2005 the sequence was reversed.

The 85-m deep temperature derived from the model on 24 January 2008 clearly shows the northern anticyclonic (warm) eddy centered at 119.5˚E, 15˚N and the southern cyclonic (cold) eddy centered at 119˚E, 13˚N that are associated with the easterly surge (Figure 3a). A Hovmőller diagram constructed at latitude 12.7˚N reveals the propagation of the resultant cyclonic eddies detached in response to the easterly surge (ES) and northerly surge (NS) (Figure 3b). A cyclone was present in the area before the easterly surge and was briefly perturbed by a tropical storm that passed through the region on 23 January 2008. The cyclone was strengthened and released into the South China Sea in response to the easterly monsoon pulse that began the following day. Frequently pre-existing eddies are intensified and repositioned or detached by wind events, as was also the case in the simulations of winter 2005.

2. Mindoro Strait Flow Reversal

As part of the PhilEx program, several moorings were instrumented in the vicinity of Mindoro Strait. The Moored Profiler (MP1) (Morrison et al., 2001) and Mindoro mooring velocity measurements captured the flow reversal in Mindoro Strait and give more details as to how the reversal evolved over time. At the end of the easterly surge the 25 m currents were directed to the south over a several week period at the MP1 site in both the model and observations (Figure 4a). The model produced a stronger current than was observed. The mean observed current in the interval between surges is -7 cm s^{-1}, while the model produced a mean current of -27 cm s^{-1}. The southward flow did not occupy the full width of the Strait in the model results in the 30 January map (Figure 4b). Indeed a local anticyclonic eddy was situated within the Strait in the velocity maps from 30 January 2008 (Figure 4b) and 1 February (Figure 4c). The intensity and shape of the small anticyclonic eddy appeared to vary over time and this variability may be a factor in the model-to-observation along-strait mean current discrepancy.

Several days after the northerly surge commenced, the current at MP1 reversed to northward and increased dramatically. The mean velocity measured at the MP1 site was 50 cm s^{-1} during 10-22 February, while the modeled current was quite a bit weaker at 9 cm s^{-1}. MP1 was located on the periphery of a strong northward jet in the model (Figure 4d) and positional variations may influence the model-to-observation agreement. The standard deviation of the 25 m current at MP1 for the time period 10-22 February was 16 cm s^{-1} in the observations and 11 cm s^{-1} in the model, so the fluctuation structure was reproduced reasonably well in the model. To verify that modeled ocean jet speeds attained the levels seen in the observation, a model location ~20 km west of the actual MP1 site was chosen (Fig. 4a, blue line). The close correspondence between the model at this displaced site (mean of 49 cm s^{-1} during 10-22 February) and the observation (mean of 50 cm s^{-1} during 10-22 February) reinforces the conclusion that the core of the modeled jet was slightly offset from the observed jet during this time.

At the Mindoro mooring, intensified cross-strait flow occurred following the northerly monsoon surge. This flow was -32 (-51) cm s^{-1} on average during 10-22 February in the observation (model). As depicted in the model-derived surface current map for 15 February (Figure 4d), this flow was part of a continuous westward current emerging from Tablas Strait separating the islands of Panay and Mindoro.

In our prior simulations of winter 2005, the Mindoro Strait flow was southward in the period surrounding the surge events (Pullen et al., 2008) - consistent with seasonal model-derived maps of Mindoro Strait that show flow is typically southward during wintertime (Han et al., 2009). This suggests a dominant geostrophic balance that was disrupted during the northerly surge of February 2008 as the Mindoro Strait flow reversed to northward. An explanation for this reversal lies in the off-shore migration of the cyclone detached by the easterly surge (see Figure 4c) which served to weaken the geostrophic flow that previously prevailed (see Figure 4b). The near-surface Ekman flow (directed to the right of the applied wind stress) presumably intensified with the onset of the northerly surge and dominated the dynamics in the vicinity of Mindoro Strait, leading to a strong northward flow through the strait. The transient local anticyclonic eddy in Mindoro Strait was most likely a feature of the flow relaxation during this transition between regimes (Figure 4c).

How unique were the conditions that led to the flow reversal? Following the detachment of the lee eddy pair generated by the easterly surge, the cyclonic eddy was absent for a period of time lasting the first several weeks of February 2008 (Figure 3b). This temporal gap seems to have supplied an opening for the Ekman drift to control the local flow dynamics and enact a flow reversal, particularly under the impetus of a sustained northerly surge. There were no Mindoro Strait flow reversals associated with the wind surges in the model results of winter 2005 presumably because the lee eddies were a more persistent feature in winter 2005, albeit with periodic detachment by the monsoon surges (Pullen et al., 2008).

The subsurface flow measured at the MP1 site in 2008 revealed that the flow reversal extended to approximately 100 m, and was strongly surface-intensified in the upper 25-50 m (not shown). The model did not replicate as well the pronounced near-surface intensification that was observed. We explore the source of this model-to-observation discrepancy by examining stratification.

4. Regional Stratification Effects

In order to examine the vertical ocean structure and assess the model-to-observation correspondence, we calculate Brunt-Vaisala frequency (N^2) and vertical velocity shear $(dU/dz)^2$, the components of gradient Richardson number ($N^2/(dU/dz)^2$). The constituent *in situ* values come from the IOP08-1 CTD profiles at 2-m vertical spacing, and lowered ADCP horizontal velocity at coincident sites with vertical spacing of 10 m. The model fields were produced on a vertically stretched grid with vertical spacing ranging from 2-5 m in the upper 25 m. Differenced (observed-model) quantities at two depths (25 m and 200 m) are displayed (Figure 5). Generally in the vicinity of Mindoro Strait the model was too well-mixed as evidenced by the too weak N^2 values (Figure 5a). However the model-observation correspondence increased with depth (Figure 5b). Likewise, in Mindoro Strait the square of the vertical shear $(dU/dz)^2$ difference is greatest near the surface, with the observations displaying enhanced shear relative to the model (Figure 5c). However, by 200 m the model showed characteristics more aligned with the observations (Figure 5d).

The preponderance of stations at near-surface depths where the model is not sufficiently stratified is suggestive of missing buoyancy effects. Indeed, the upper ocean possessed enhanced stratification in winter 2008 due to anomalously high precipitation probably related to the La Niña event that peaked in February 2008. Interestingly, winter 2008 was the rainiest on record in 40 years (Gordon, Sprintall, Ffield, this issue). Precipitation effects were under-represented in the model due to the absence of river run-off in the simulations coupled with the difficulty numerical weather models have in accurately simulating local area rainfall. The impact of river run-off is evident in the spatial pattern of near-surface N^2 differences (Figure 5a). The observed N^2 is higher for coastal locations (Mindoro, Verde Island Passage, Panay) and also Tablas Strait, while model N^2 is higher for outer (off-shore) Mindoro sites and the 2nd occupation of Panay stations. This suggests that buoyant discharge not captured by the model is most prevalent right near the coast, leading to larger observed N^2 values in those locations. The buoyancy input due to the freshwater created a more layered near-surface flow in the observations.

5. Conclusions

The Philippines straits contain a myriad of local flow regimes with forcing mechanisms operating on multiple scales. We have brought together model results and observational data of both the ocean and atmosphere in order to examine the evolution of a flow reversal in Mindoro Strait. The flow reversal took place between two intensive sampling research cruises: southward flow was measured during IOP08-1 while northward flow was encountered during IOP08-2 cruise. *In situ* measurements including moorings and CTDs complement the underway and satellite data to form a picture of the timing of the flow transition. High-resolution ocean and atmosphere modeling completes the integrated picture by providing insight into the circulation characteristics that exist away from measurement sites.

The wind jets play a primary role in shaping the flow by spinning up dipole eddies in the lee of Mindoro and Luzon via Ekman pumping. We were fortunate to sample within a cyclonic eddy using shipboard measurements following an easterly surge in January 2008. Basic features of the eddy including size (~100 km), current magnitude (25-50 cm s^{-1}, and depth (~150 m) in the model accorded with underway ADCP observations. The prevalence of mesoscale dipole eddies in wintertime creates a geostrophic flow pattern that is predominantly southward through Mindoro Strait, as a portion of the onshore flow in the southern limb of the cyclonic gyre is commonly deflected southward through the strait. During strong wind events the eddies are prone to detach and subsequently migrate across the South China Sea. In the particular flow reversal studied here, the absence of a cyclonic eddy near Mindoro Strait facilitated a directly wind-forced northward Ekman drift.

A contributing factor in the strong ocean response to the wind stress was the anomalously fresh near-surface waters that were sampled by the research cruises in winter 2008. The Philippines experienced the rainiest winter in 40 years in 2008, and this fresh lens of water created more stratified flow in many parts of the archipelago. Although the modeled wind and current fields were in reasonable agreement with many observed quantities, the model produced an upper ocean structure that was not sufficiently stratified. The model configuration did not account for river run-off nor accurately predict local rainfall. Future simulations will include river discharge and improved microphysical parameterizations.

The dominance of wind-driven processes in the evolution of the eddies is a hallmark of the Philippine region and makes it unique among the volcanic island regions of the world. By contrast in the Hawaiian, Cabo Verde and Canary Islands, the driving mechanism in the eddy dynamics is instabilities and fluctuations of the impinging ocean current as it is channeled through the island passages. The compounding ways that winds can act on ocean structures to both move them about and induce local flows, as demonstrated here, is beginning to receive more attention in process studies (Morel and Thomas, 2009). The complex Philippines Straits is a fascinating realistic example where the island geometry renders the channel and gap flow highly dynamic in the ocean and atmosphere.

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Figure Captions

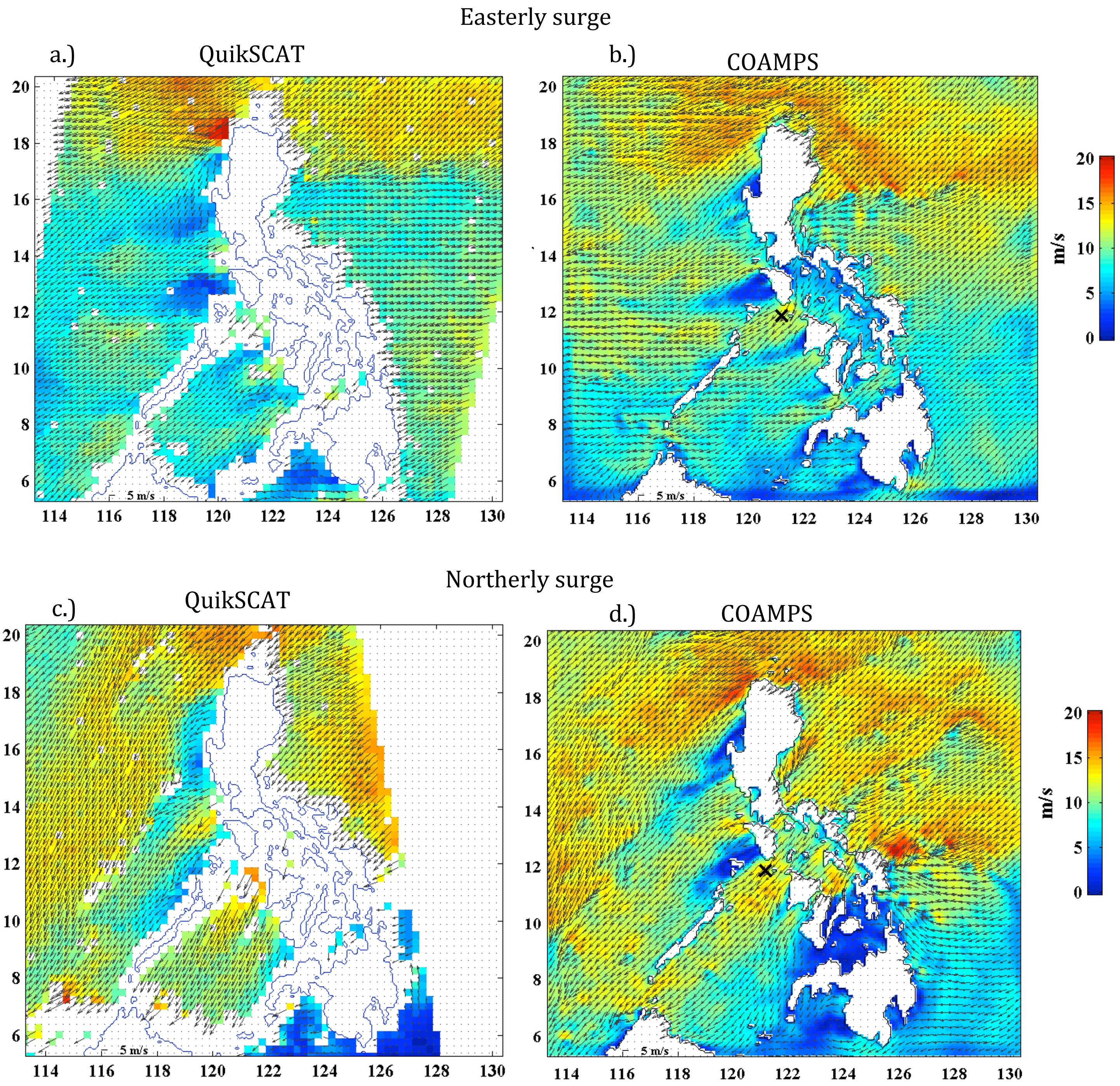
Figure 1: Near-surface winds (m s^{-1}) from (left) QuikSCAT satellite (approximately 25 km resolution) and (right) COAMPS (9 km resolution) during two different monsoon surges in winter 2008. The top shows winds from an easterly surge on 9 UTC 25 January 2008, while the bottom shows winds during a northerly surge that occurred on 21 UTC 15 February 2008. The cross is located in the Panay jet, for which statistics are reported in the text.

Figure 2: (a.) Underway Acoustic Doppler Current Profiler (ADCP) 25 m currents from the IOP08-1 research cruise 27-31 January 2008, and (b) model-predicted 25 m currents extracted for the same time as they were measured. (c) Underway winds as measured by the shipboard anemometer (10 m height) during the IOP08-2 research cruise 10-23 February, and (d) model-predicted 10-m winds extracted for the corresponding times.

Figure 3: (a.) 85 m deep model temperature (˚C) showing the dipole cold eddy (~13˚N) and warm eddy (~15˚N) on 24 January 2008 during the easterly monsoon surge. (b.) A Hovmőller diagram of 85 m temperature at the location of the section shown in the left panel. The cyclones associated with the easterly (ES) and northerly (NS) surges are labeled and the surge durations are denoted with the dashed white lines. The disturbance on 23 January was a tropical storm that passed through the region.

Figure 4: (a.) Measured and modeled 25 m currents at two moorings: MP1 and the Mindoro mooring, whose locations are shown with crosses. Other panels show snapshots of the model-produced 25 m current field on (b.) 30 January, (c.) 1 February, and (d.) 15 February 2008. Currents are rotated -45 degrees to create along and across-strait velocities. The “O” in panel c.) denotes the core of the small anticyclonic eddy within Mindoro Strait.

Figure 5: Observed-model difference plots of 25 m and 200 m N^2 (top panels) and shear^2 (bottom panels). The observed values are calculated from lowered ADCP and CTD data at 48 stations occupied 23-29 January 2008, during the IOP08-1 research cruise.



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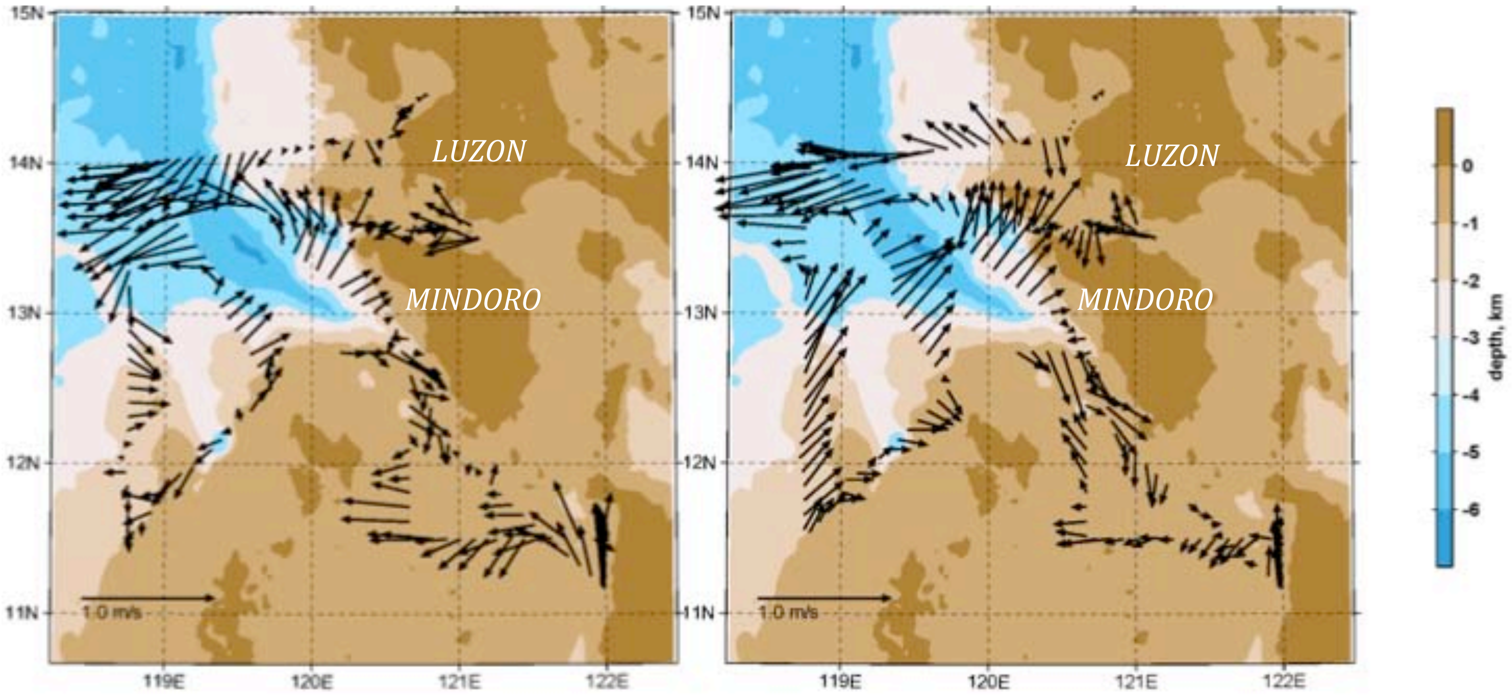
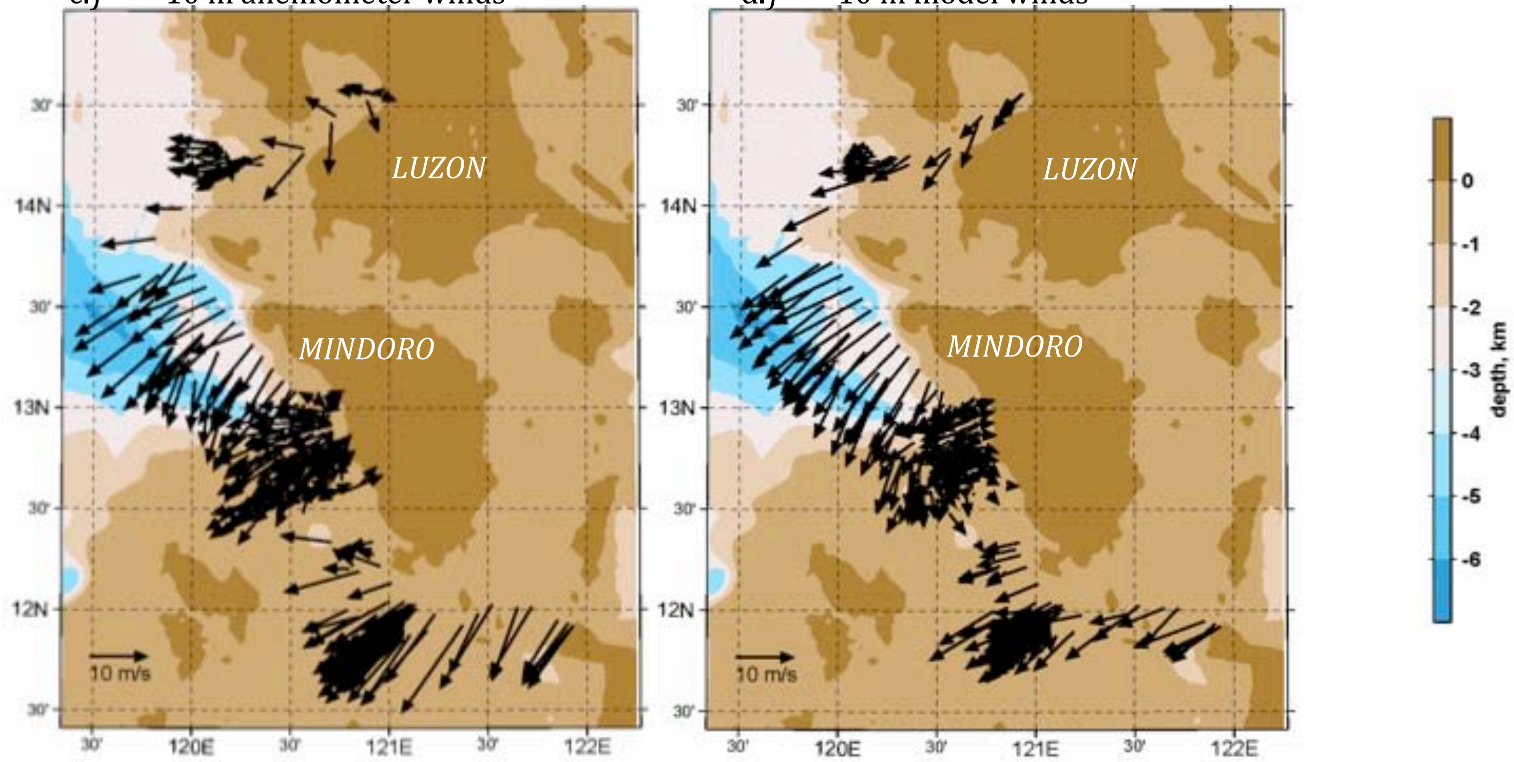
b.) 25 m model currents



c.) 10 m anemometer winds

d.) 10 m model winds



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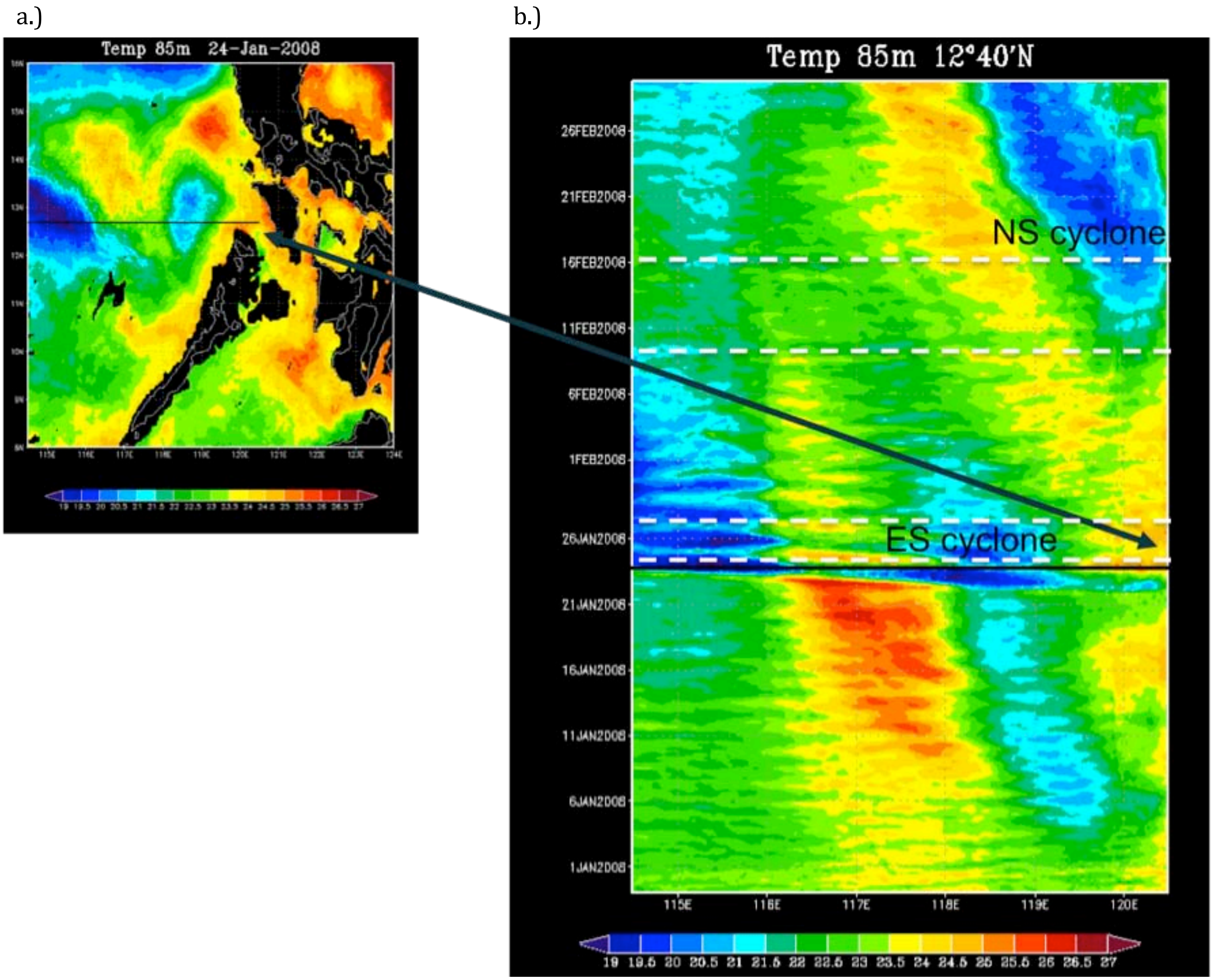

Figure 3: (a.) 85 m deep model temperature (˚C) showing the dipole cold eddy (~13˚N) and warm eddy (~15˚N) on 24 January 2008 during the easterly monsoon surge. (b.) A Hovmőller diagram of 85 m temperature at the location of the section shown in the left panel. The cyclones associated with the easterly (ES) and northerly (NS) surges are labeled and the surge durations are denoted with the dashed white lines. The disturbance on 23 January was a tropical storm that passed through the region.

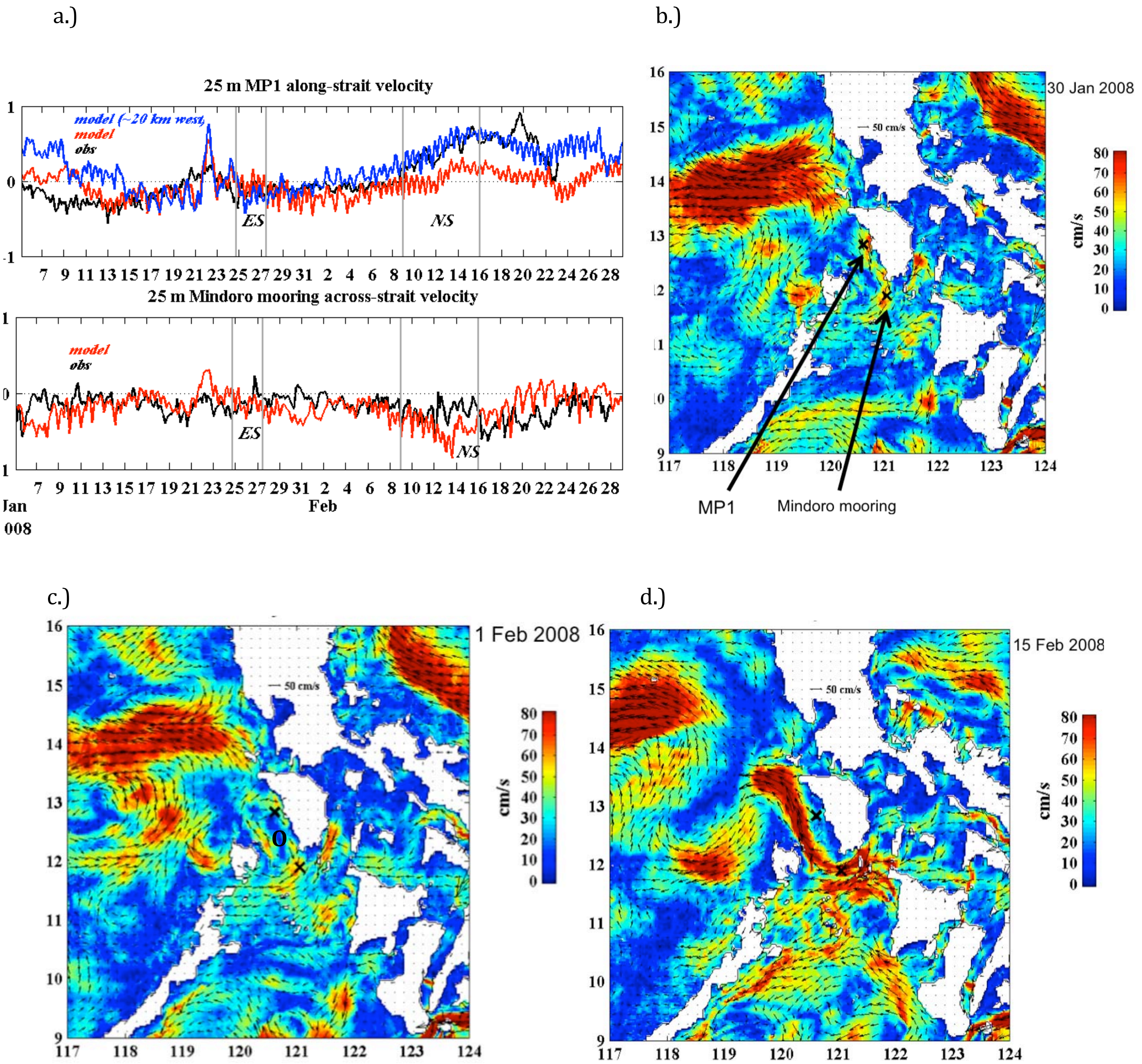

Figure 4: (a.) Measured and modeled 25 m currents at two moorings: MP1 and the Mindoro mooring, whose locations are shown with crosses. Other panels show snapshots of the model-produced 25 m current field on (b.) 30 January, (c.) 1 February, and (d.) 15 February 2008. Currents are rotated -45 degrees to create along and across-strait velocities. The "O" in panel c.) denotes the core of the small anticyclonic eddy within Mindoro Strait.

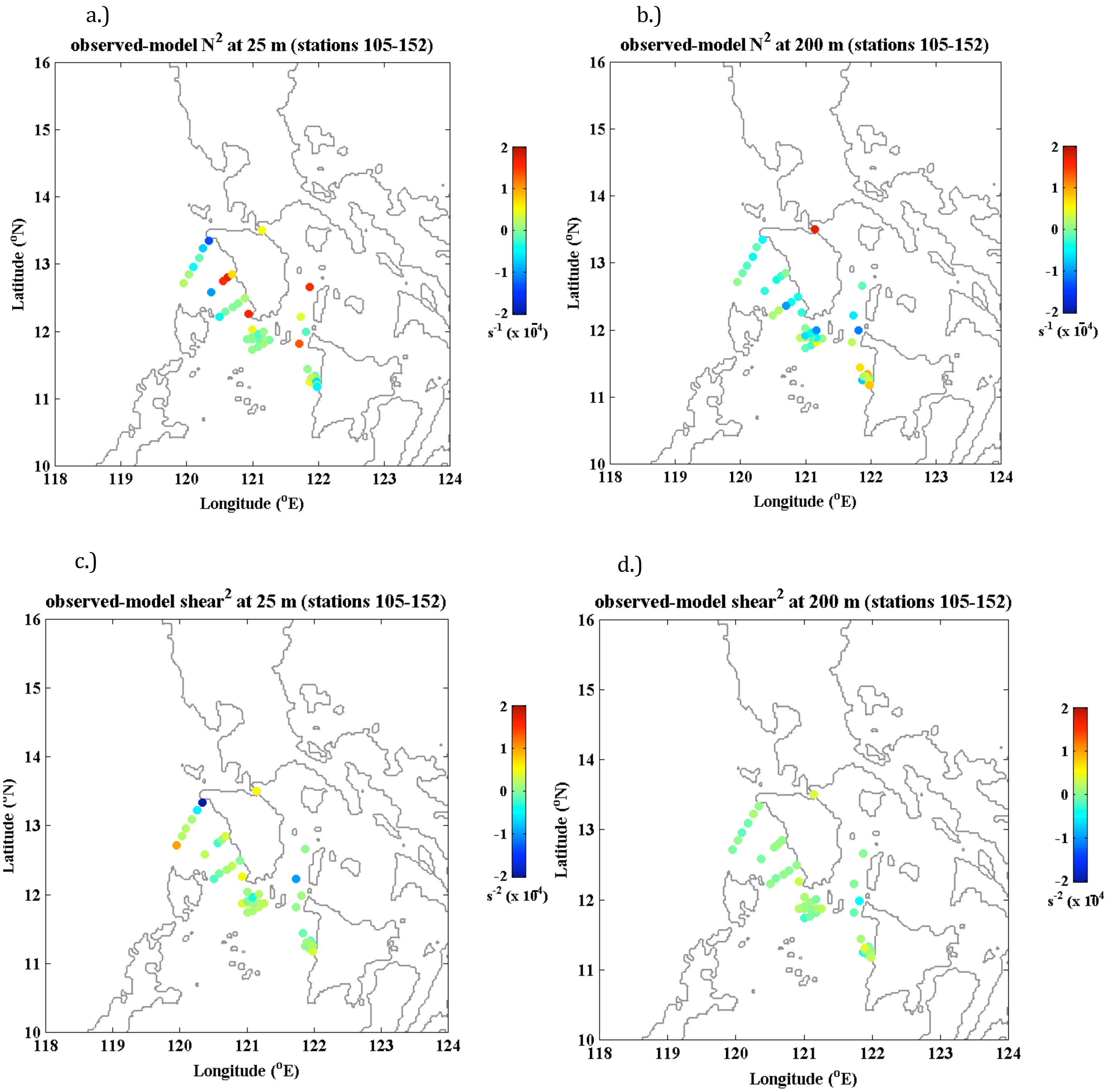

Figure 5: Observed-model difference plots of 25 m and 200 m N^2 (top panels) and shear^2 (bottom panels). The observed values are calculated from lowered ADCP and CTD data at 48 stations occupied 23-29 January 2008, during the IOP08-1 research cruise.