The Sub-mesoscale Cascade of the South China Sea (SCSCS)

Executive Summary

The S. China Sea is understood to be one of the most energetic regional seas in the global ocean. The combination of the Kuroshio Current, the monsoon, strong tides, and the dramatic topography of the Luzon Straits lead to a rich physical forcing environment. In addition to the enhanced internal wave environment that has been the focus of much work (ASIAEX, NLIWI and IWISE), the region southwest of Taiwan has been documented as a maximum in eddy kinetic energy. However, outside of the realm of internal wave processes, the physics of the sub-mesoscale cascade of energy has been poorly studied.

Here, we describe the case for a new examination of sub-mesoscale processes in the S. China Sea. The focus will be the class of oceanographic variability that is poorly constrained in models including eddies, rings, vortices and filaments, and their interactions with smaller-scale phenomena. The work will focus on in-situ sampling with a heavy emphasis on autonomous instrument platforms, which have the ability to follow features of interest over weeks to months. The region of interest is just southwest of Taiwan, and is accessible to both Taiwan and UNOLS vessels. This topic has outstanding potential to produce new understanding of small-scale and rapidly evolving variability in the S. China Sea. With the momentum from recent Taiwan/US partnerships (QPE, ITOP, OKMC, and IWISE) still strong, and the new Taiwan global-class vessel ready for work, the time is right for this program. It will continue an outstanding legacy of international partnership between Taiwan and the US.

Introduction

The mesoscale is the scale of ocean variability, most notably that of ocean eddies, typically on the order of 50-km. The mesoscale sits at the limit of the “large-scale” physics of the ocean, and is generally the scale to which global-scale numerical models begin to break down in predictive skill. Energy from the mesoscale, in turn, passes to smaller scales, often referred to as the “sub-mesoscale cascade.” These scales, on the order of 1 to10 km, are typically beyond the range of numerical prediction of large scale models, and at the limit of prediction of regional-scale models. Features at the sub-mesoscale include the smaller cousins of eddies, such as wakes, and vortices, and coherent structures which can include frontal features and filaments. These phenomena evolve rapidly (days) and chaotically, eventually leaking energy to the fine-structure (10 to 100 m) and microstructure (< 1 m) scales where energy is dissipated.

We distinguish processes of the sub-mesoscale cascade from the more general class of “sub-gridscale” physics in that the cascade reflects to passing of energy from the mesoscale on down. Processes such as Langmuir circulations, frontogenesis, and upwelling, are generally triggered by direct forcing of the atmosphere (albeit, in conjunction with background currents), rather than by the breakdown of mesoscale flow.

Numerical codes attempt to represent the physics of all sub-gridscale phenomena using parameterizations. This can be effective if the only goal is to gain predictive skill on how the sub-gridcale processes feedback onto the larger-scale circulation. Good examples include

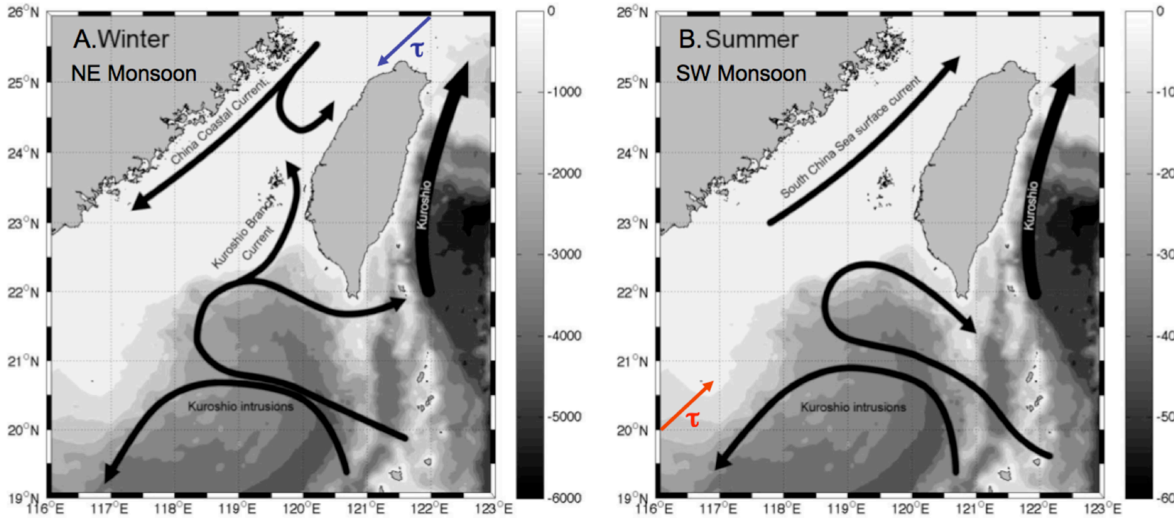

Figure 1. Schematic diagram of flow regimes of the S, China Sea. A. The winter monsoon is characterized by northeasterly winds. B. The summer monsoon is characterized by southwesterly winds. Both periods feature intrusion of the Kuroshio Current, During the winter monsoon, the Kuroshio may branch in the S. China Sea, or enter the S. China Sea completely. During the summer monsoon, the intrusion is likely in the form of a loop that exists back into the Pacific. During both seasons, the Kuroshio is the source of much eddy activity in the S. China Sea. Figure courtesy of G. Gawarkiewicz (WHOI).

modeling efforts of large-scale variability such El Nino/La Nina cycles. This type of modeling in now the province of the national labs (NCAR, GFDL, etc). Far more difficult is the problem of predicting the physics at the sub-mesoscale. For example, predicting the evolution of a front over a 3-day period. No large-scale, predictive model can yet do this, and no parameterization will suffice to achieve this. Regional models, such as ROMS, have been developed to fill this need, and the community effort on this is nearly exclusively supported by ONR. Programs such as ASAP, AESOP and LATMIX, in particular, have been themed on this issue in recent years.

The S. China Sea is understood to be one of the most energetic regional seas in the global ocean. The combination of the Kuroshio Current, the monsoon, strong tides, and the dramatic topography of the Luzon Straits lead to a rich physical forcing environment. The forcing of the tides, in particular, and the associated internal wave environment, has been the focus of much work, including that during ASIA-EX, NLIWI and IWISE. However, outside of the realm of internal wave processes, the physics that describe the flow of energy from the mesoscale to the sub-mesoscale has been poorly studied in the S. China Sea.

In addition to the strong tidal forcing in the Luzon Passage, the upper ocean of the SCS is forced by the monsoon, coupled with the presence of the Kuroshio Current (Figure 1). The combination of these elements leads to a regional sea that is one of the most active sub-mesoscale cascades in the global ocean. In addition to eddies (Hwang and Chen, 2000; Wang et al. 2000, Yuan et al. 2007), phenomena such as rings (Li et al., 1998), vortices (Zheng et al. 2008), thermal fronts (Wang et al. 2001), and jets and filaments (Xie et al., 2003; Xie et al., 2007) have been documented in the literature.

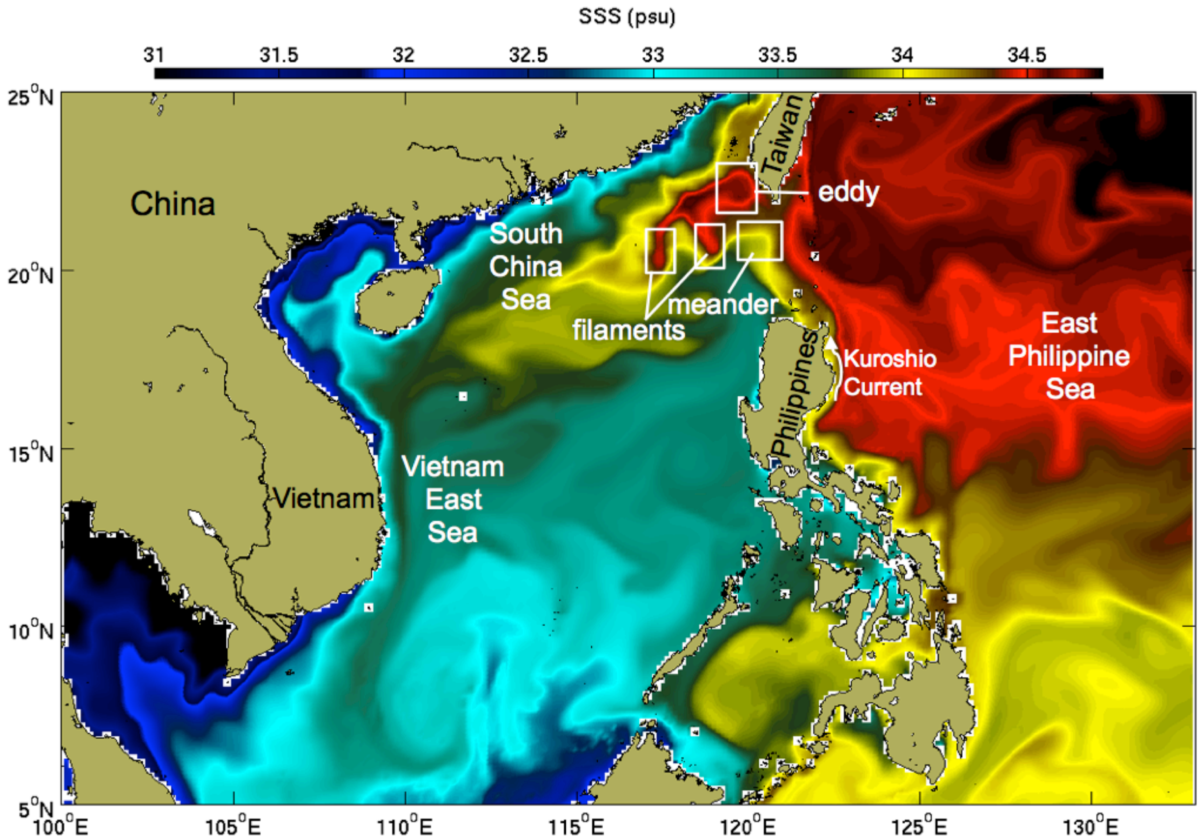

Figure 2. Example of SSS imagery from the UAF-GOLD model showing December conditions in the S. China Sea. During this realization, the Kuroshio Current has completely entered into the S. China Sea through the Luzon Strait in the region southwest of Taiwan. There, the current meanders, breaking into eddies, and submesoscale features such as filaments. Figure Courtesy of H. Simmons (UAF).

Despite a legacy of previous studies, at the same time this class of phenomena has received little focused effort. The topic has drawn most attention from the Chinese academic establishment. This is in contrast to the internal wave topic, which gained momentum from the US establishment. Nearly all papers on the subject are based on data from altimeters, or from eddy-resolving numerical simulations. Actual in-situ studies that have intentionally sampled spatial and temporal scales of non-internal wave, sub-mesoscale phenomena, are apparently quite rare.

Eddy resolving model simulations of the S. China Sea have long shown the rich mesoscale phenomena of the region. Simulations done with the Global Ocean Layered Dynamics Model (GOLD), as implemented by H. Simmons at U. Alaska – Fairbanks, resolves both mesoscale and internal wave modes. With a resolution of 12 km, these simulations show many of the dramatic features of the cascade from the mesoscale to sub-mesoscale.

Some examples of Sea Surface Salinity (SSS) of these simulations are shown in Figures 2, 3, and 4. These were taken from years 2-3 of a 6-year model evolution, well after initial spin-up effects have ended. The model utilizes hourly tidal forcing and 6-hourly winds taken from the period

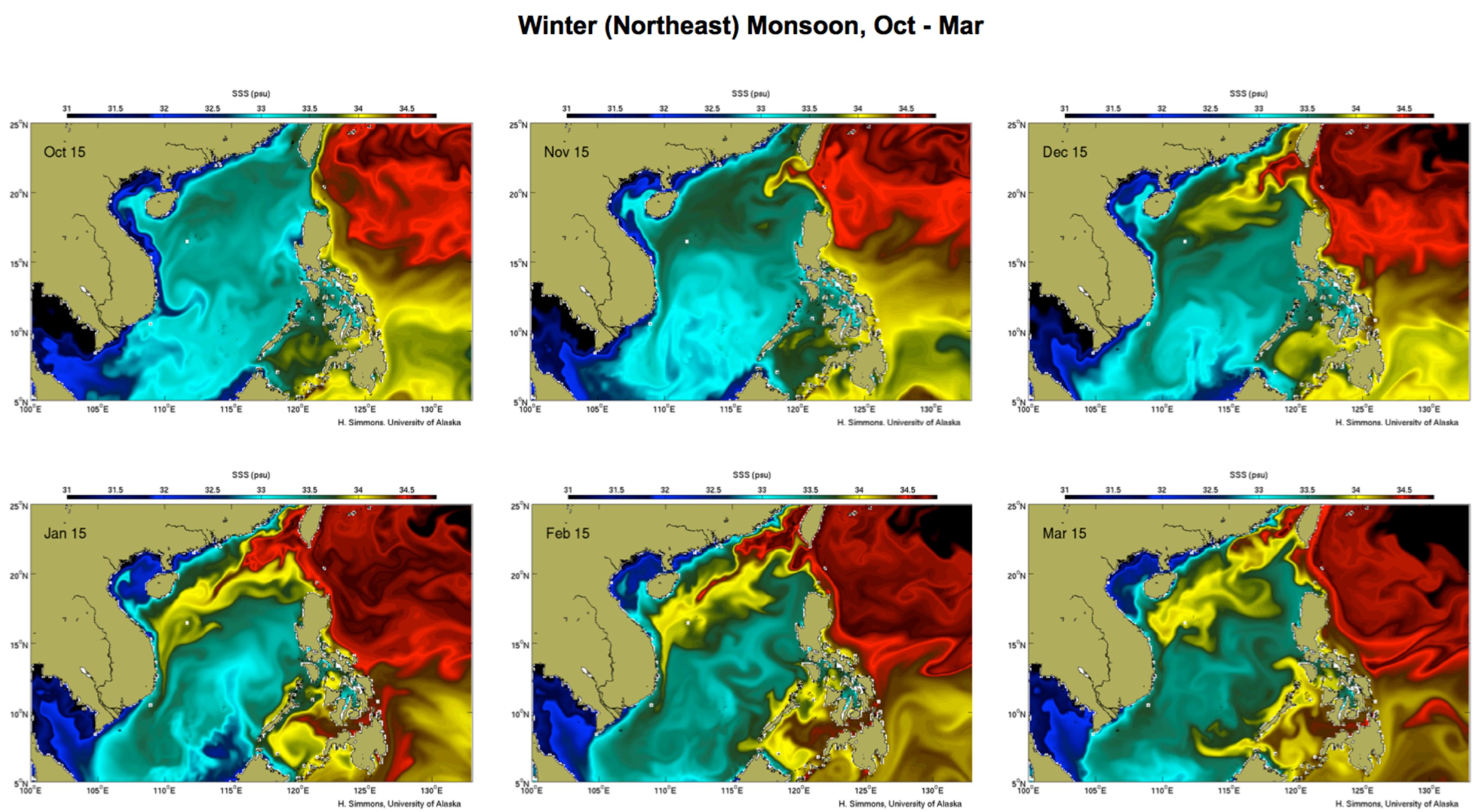

Figure 3. Snapshots from the U. Alaska – Fairbanks GOLD model simulations showing SSS realizations from each month of the winter monsoon season in the western Pacific region. The S. China Sea (central portion of each panel) shows the ubiquitous nature of variability that includes eddies, meanders, and filament-like structures. The region just southwest of Taiwan is of central interest. Figures courtesy of H. Simmons (UAF).

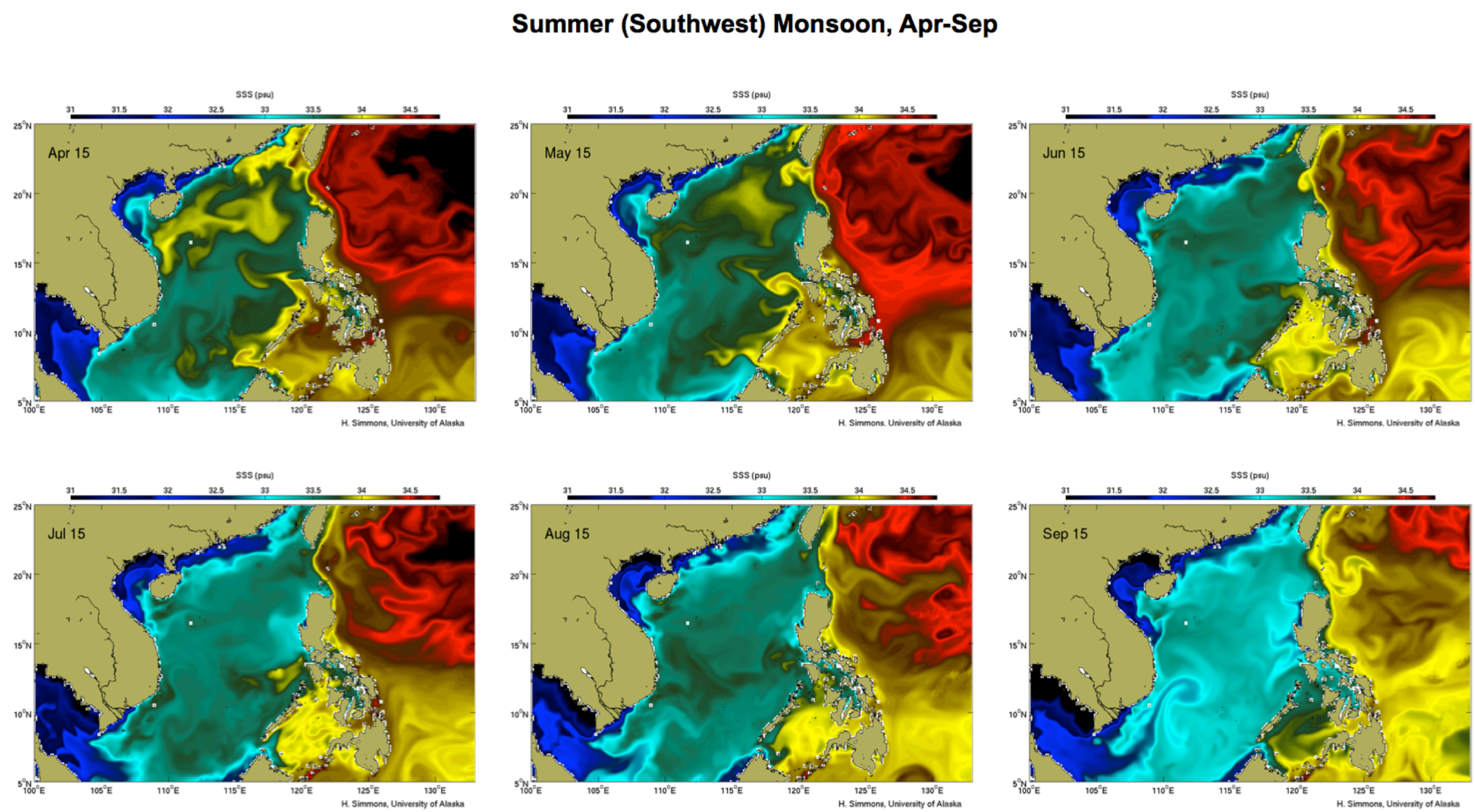

Figure 4. As described in Figure 2, but for the case of the summer monsoon season. Figures courtesy of H. Simmons (UAF).

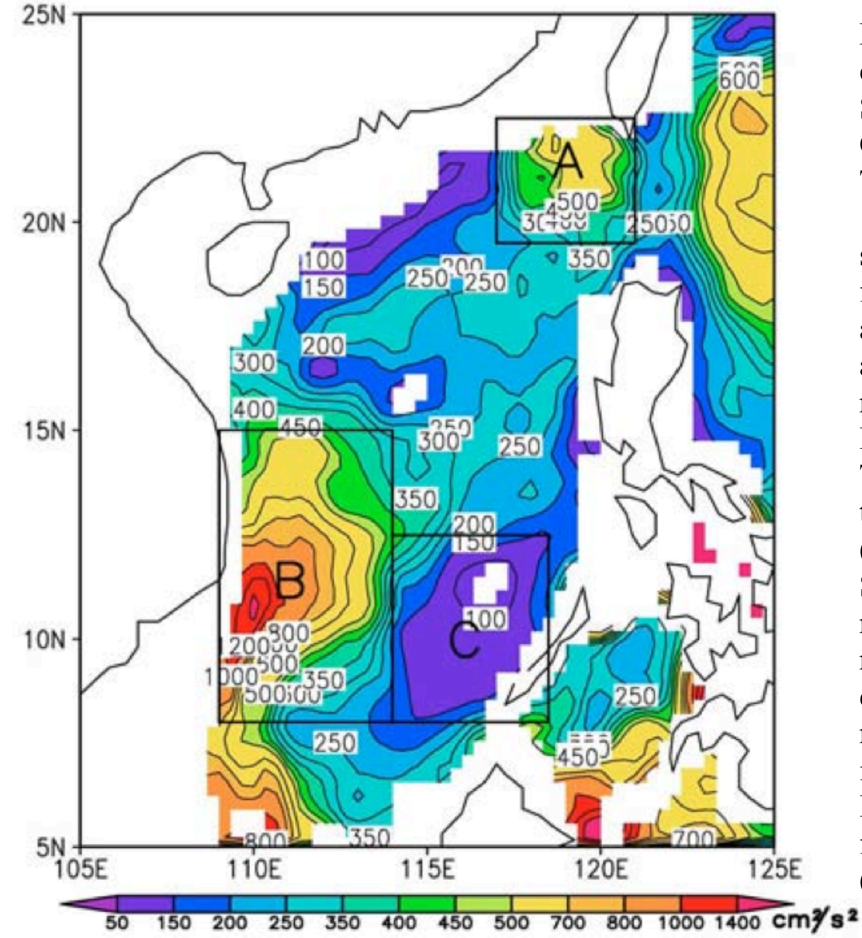

Figure 5. Eddy kinetic energy of the S. China Sea as estimated by Cheng and Qi (2010). This is the mean from a 15-yr record of sea-surface height, using data from two independent altimetry platforms. The analysis reveals two regions of heightened EKE: southwest of Taiwan (region A), and the Vietnam East Sea (region B). The Southwest-northeast region between these regions defines an active eddy pathway. The minimum region of EKE is that of the Spratly Islands (region C). Figure from Cheng and Qi (2010)

2002-2008. As such, the simulations are a case study in the type of mesoscale to sub-mesoscale variability typically observed in the S. China Sea.

Figure 2 shows a snapshot of the model simulation from December. During this period, the Kuroshio Current has completely entered the S. China Sea though the Luzon Straits. There, the current meanders and produces features rich in sub-mesoscale characteristics, including a very tight (small-scale) eddy and filaments. The area just southwest of Taiwan is extremely active as a site for all classes of sub-mesoscale activity.

We have separated snapshots from an annual cycle of the monsoon by Winter (Figure 3, Oct – Mar) and Summer (Figure 4. Apr – Sep) monsoon periods. The S. China Sea is shown in the central portion of each panel. There, SST imagery shows heighted mesoscale to sub-mesoscale activity in the core months of each monsoon; Jul-Sep in summer, and Dec-Feb in winter. Eddies, meanders, filaments and frontal structures are visible. An obvious area of activity in the region directly south and west of Taiwan is clearly associated with the presence of the Kuroshio and its interaction with the basin scale circulation, which is cyclonic in winter and anti-cyclonic in summer.

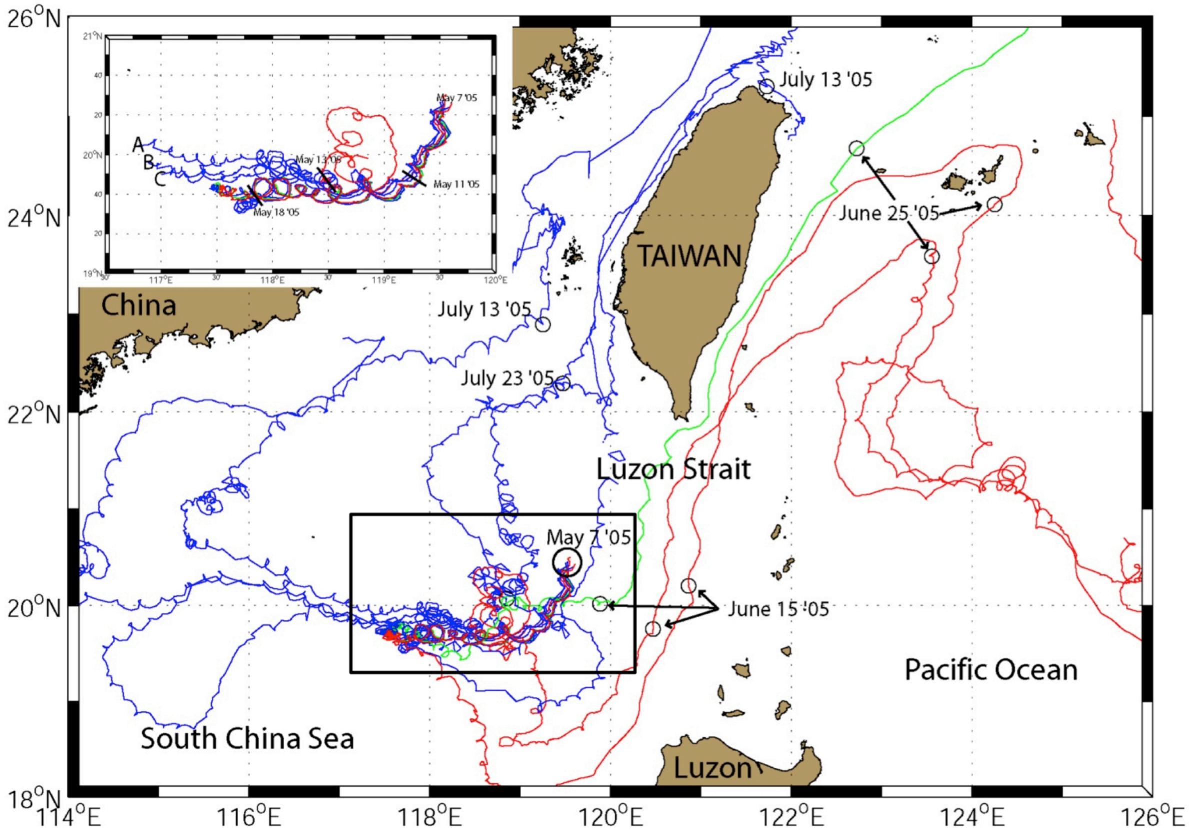

Figure 6. Trajectories from drifters released in the high-EKE region southwest of Taiwan during May 2005. All six drifters experienced strong sub-mesoscale variability in the initial two weeks after deployment (inset panel). Three of the drifters stayed in S. China Sea (blue), while two entered the E. Phipippine Sea (red), and one entered the core of the Kuroshio Current (green). From Centurioni et al. (2007).

The most basic measure of mesoscale activity is that of eddy kinetic energy (EKE). On the basin scale, this analysis is generally done from altimetry data, using geostrophic estimates of eddy velocity. Estimates by Cheng and Qi (2010), based on data from the TOPEX and ERS altimeters, are shown in Figure 5. EKE values range from 50 to 1400 cm^2/s^2, with a basin mean value of around 360 cm^2/s^2. EKE is largest southwest of the Taiwan (Fig. 4, region A) and in the Vietnam East Sea (Fig. 5, region B), where the EKE can reach 1400 cm^2/s^2. Minimum values (<200 cm^2/s^2) are observed near Spratly Islands (Fig. 5, region C) and along Chinese shelf south of Dongsha. A band of moderate EKE occurs along a path that crosses the basin, starting at Taiwan in the northeast and extending to the Vietnam East Sea in the southwest. Eddies have been documented to be very active in this zone (Wang et al*.,* 2003; Cheng et al*.,* 2005).

Altimetry, while providing basin coverage, yields rather poor spatial resolution and cannot sample the fast evolving flows in the Kuroshio intrusion region. The only way to resolve the finer sub-mesoscale features of the circulation is to use in-situ methods, such as drifters. Drifters released as part of the global program have been sparse in the S. China Sea. However, those released for a dedicated study during 2005 (as part of NLIWI/VANS) clearly show aspects of the sub-mesoscale physics (Figure 6). More recently, drifters released in the Luzon Strait region

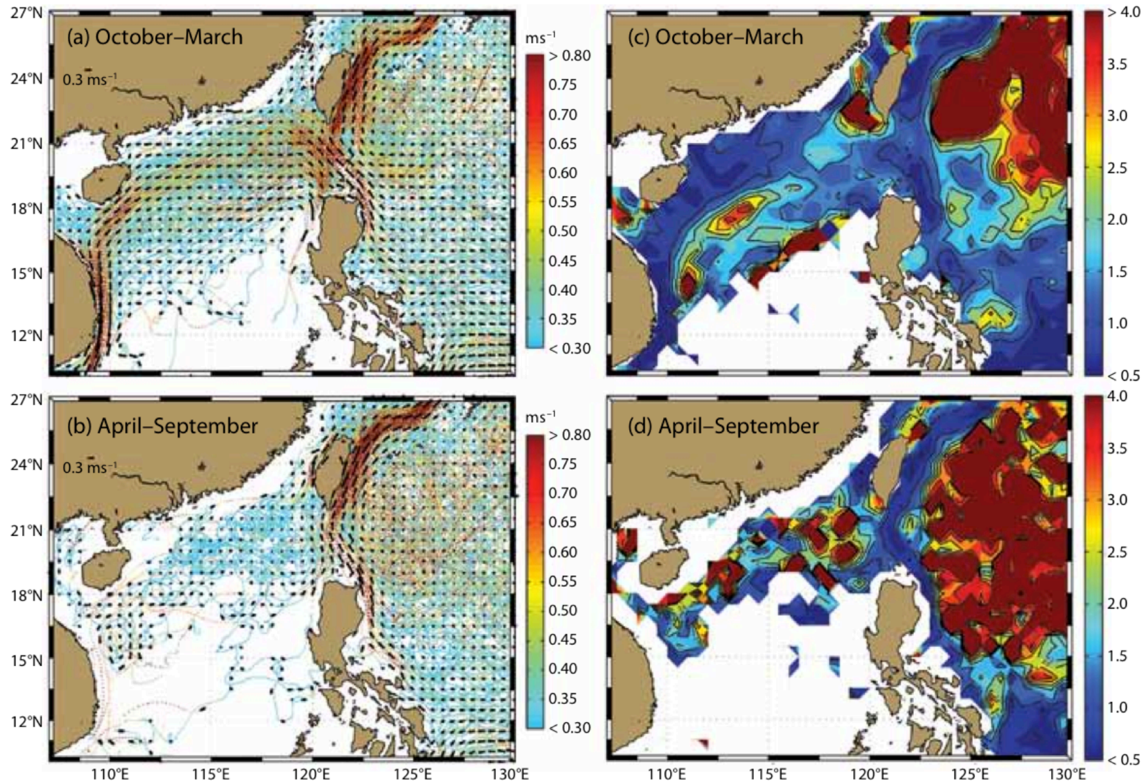

Figure 7. Drifter trajectories and binned velocity records from the S. China Sea during the winter (a) and summer (b) monsoon seasons. The ratio of root-mean-square eddy to mean velocity is shown for the same data (c and d). Elevated ratios above unity indicate that eddies dominate over the mean flow. From Rudnick et al. (2011).

(2003-2006 ONR core program) and the E. Philippine Sea as part of OKMC have provided a substantial dataset of finescale velocity (Figure 7), although summer observations are still sparse. Rudnick et al. (2011) have examined velocity data from the winter and summer monsoon seasons, and they find EKE levels are above mean flow energy during both periods. They find the same regions of enhanced EKE as the Cheng and Qi (2010) study. In particular, the high-EKE region southwest of Taiwan is among the most active eddy regions.

Pathways for the sub-mesoscale cascade

The region southwest of Taiwan is known to be a hotspot of mesoscale activity and EKE. It is clear that this enhanced mesoscale environment fuels a sub-mesoscale cascade in which energy flows to smaller scales. Here, we list several physical interactions that are likely pathways between the mesoscale and sub-mesoscale.

Meander breakup. Meanders in the region of the Kuroshio as it intrudes into the S. China Sea are ubiquitous, as depicted in numerical simulations (Figs. 2, 3 and 4). These meanders eventually break up, leading to eddies. The eddy identified in the numerical simulation shown in Figure 2 appears to be such a case, although the process of meander break-up has never been directly observed (Steve Ramp, personal communication). In rare cases, this process may result in anti-cyclonic rings (Li et al. 1998), though this in believed to be rare. More generally, eddies are likely formed by barotropic or baroclinic instability processes associated with the flow. Some mesoscale eddies are also observed to leak through the Luzon Strait (Centurioni et al. 2004). These features continue to interact, eventually leaving the region, or dissipating locally. Eddies that leave the area generally drift to the west and south, subject to Rossby wave physics (Nan et al. 2011). They either migrate to the Dongsha Plateau region, where they shoal along the reef-laden shelf, or they migrate in deep water to the Vietnam East Sea. In shallow water, boundary layer processes surely act to break up these eddies.

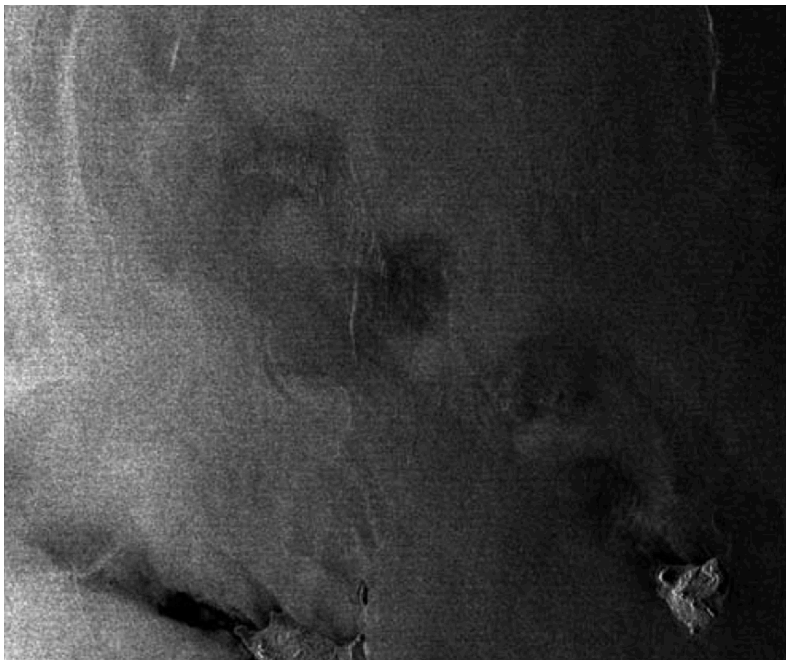

Figure 8. Sub-mesoscale vorticies in the wake of an island in the Luzon Strait. These vorticies are triggered by the interaction of the Kuroshio with the island. Unlike eddies, these smaller vorticies are not subject to geostrophic balance. From Zheng et al. (2008).

Sub-mesoscale vortices. Sub-mesoscale vortices differ from larger-scale mesoscale eddies in that they do not conform to geostrophic balance. As such, they do not have a clear dynamical link to sea-surface height, and are not resolvable by altimetry data. These fine-scale features are sometimes visible using SAR imagery. Zheng et al. (2008) describe a vortex train emanating in the wake of an island in the Luzon Strait (Figure 8). This example was found in satellite tracked drifter data and coincident SAR imagery. Such vortices are common in areas like Luzon, where strong flows interact with islands. Vortex trains must also occur close to Taiwan, from the Batan Islands, where the Kuroshio intrudes into the S. China Sea. Vortices generated in the Batan Island region would populate into the high EKE region southwest of Taiwan.

Filament production. The interaction of eddies and meanders can produce instabilities that lead to the production of filamentary structure. These are thin, elongated features that stretch and advect in the background eddy flow. They often are associated with temperature, salinity, and vorticity anomalies. Examples of filament production in the S. China Sea are described by Xie et al (2007). In addition to eddy interaction, Xie et al. (2007) find that interseasonal wind pulses, occurring over several week periods. These features persist only for several weeks, and their fate is not precisely known. Such features have never been directly sampled using in-situ measurements.

Interactions with internal waves. Pervious ONR studies in the S. China Sea have primarily focused on internal wave physics (ASIA-EX, NLIWI, and IWISE). This is reasonable, as the SCS is one of the most active internal wave environments in the global ocean. However, little work has been done on the interaction between the internal waves and the mesoscale. Recent observations by Ramp and Yang (IWISE) in the sector southwest of Taiwan clearly show an eddy interaction slowing internal waves. Furthermore, the 1-year record of internal wave activity collected by Ramp et al. (2010) clearly shows a significant decrease in internal wave occurrence during the winter monsoon. To the extent that these seasonal variations in internal wave activity are caused by mesoscale and sub-mesoscale interactions has yet to be determined.

Sampling the mesoscale to sub-mesoscale field of the S. China Sea

Satellite remote sensing imagery is of limited utility for resolving the sub-mesoscale processes of the S. China Sea. Altimetry provides a year-round means of estimating the large-scale EKE, but it is too coarse in space and time to resolve sub-mesoscale features. Furthermore, at the sub-mesoscale, the geostrophic balance assumptions of the large-scale eddy field breakdown, making sea-surface height less than ideal as a proxy of energy. Sea-surface temperature can provide imagery of fine-scale phenomena occurring in the upper ocean, but cloud cover, common in the S. China Sea during the monsoons, is a significant barrier. By virtue of their timescale, sub-mesoscale events persist for days to weeks, making them difficult to study from stand-alone ship surveys. Moorings provide time series, but no mooring array is able to resolve the spatial scales of variability that capture the breakdown of mesoscale energy. Thus, remote sensing and conventional hydrographic observing methods are both inadequate for observing the sub-mesoscale cascade. It is understandable that little previous work exists on this important energy pathway.

With the advent of autonomous oceanographic sampling technologies, and their widespread application in ONR programs during the past 10 years, the community is now in a position to sample the sub-mesoscale cascade directly, on the spatial and temporal scales of the actual physical processes of interest. A combination of drifters, floats, gliders and other autonomous assets could execute a yearlong measurement program at manageable cost, supported by research vessel expeditions at 3 to 6-mo intervals.

The high-EKE region southwest of Taiwan is an ideal setting for a new joint Taiwan/US field study of the sub-mesoscale cascade. The region is easily accessible to research vessels, being only 1-day's sail from Kaohsiung, and within easy reach of other potential Taiwan ports. The region is also east of 117.5 E, and therefore within the zone accessible by UNOLS vessels.

There are a rich host of science questions available for a focused DRI. These include:

- What is the magnitude of the sub-mesoscale (sub-grid) kinetic energy?
- Are sub-mesoscale variations originating in the Taiwan high-EKE region significantly different during the winter and summer monsoon seasons?
- Which classes of sub-mesoscale events (e.g. meanders, rings, vortices, filaments, etc) are most typical, and which are the most significant in terms of energetics of the cascade?
- How often do meanders of the Kuroshio Current break up to form eddies?

- Over what time-scale do sub-mesoscale features persist?
- To what extent are sub-mesoscale events near-surface phenomena, and to what depth are they important?
- Do sub-mesoscale events dissipate locally, or do they propagate out of the high-EKE region?
- Do sub-mesoscale events significantly interact with the internal wave field? By what mechanisms?
- Do numerical models have a correct parameterization for sub-mesoscale energy?

Experimental Design

In-situ observations. Given the class of motions that characterize the sub-mesoscale cascade, the emphasis on a DRI program should be on measurements. We propose an observational program in the high EKE region southwest of Taiwan (Figure 9) with two intensive observation periods: each associated with the peak of the monsoon season. Numerical simulations suggest that each monsoon reaches peak EKE levels about 2-3 months into the season: December-January for the winter, June-July for the summer. The intensive observations will be timed for these peak EKE periods. Prior to these peak EKE periods, an initial ship-based survey, and the release of drifters and gliders, will provide a reconnaissance stage of the program.

Drifters have previously provided the richest dataset of sub-mesoscale motions in the S. China Sea. They are a central means of monitoring and tracking sub-mesoscale features in near real time. As such, of GPS drifter clusters in the high-EKE zone southwest of Taiwan would serve to initiate an observational effort that would aim to track sub-mesoscale feature evolution. The initial deployment of drifters would serve to provide reconnaissance on developing sub-mesoscale phenomena. After roughly 4-6 weeks of accumulated drifter data, several features of interest could be targeted by surveys utilizing research vessels and the deployment of floats, gliders, and potentially other autonomous platforms.

The combination of Taiwan's research vessel fleet (including their new global class vessel) and a UNOLS global class vessel would provide an impressive resource base for supporting the survey and autonomous asset work for the 1 year program. The vessels would provide the only means of collecting full-depth data, such as Lowered Acoustic Doppler Profiling, needed to examine the role of deep currents. In the case of the Taiwan vessels, measurement surveys could perhaps be summoned to action on an opportunistic basis, to sample evolving sub-mesoscale events indicated by AUVs and remote sensing.

Remote sensing. Remote sensing can fill the gap left between observations and modeling. In the reconnaissance phase of each sample period, remote sensing can be used to assess signals of interest identified by the initial ship survey, the drifters, and the model simulations. Given the scales of interest, SST (MODIS, or other platforms) and SAR imagery both have significant potential to contribute in the identification of rings, vortices, filaments, and other potential features the intensive field program may wish to target.

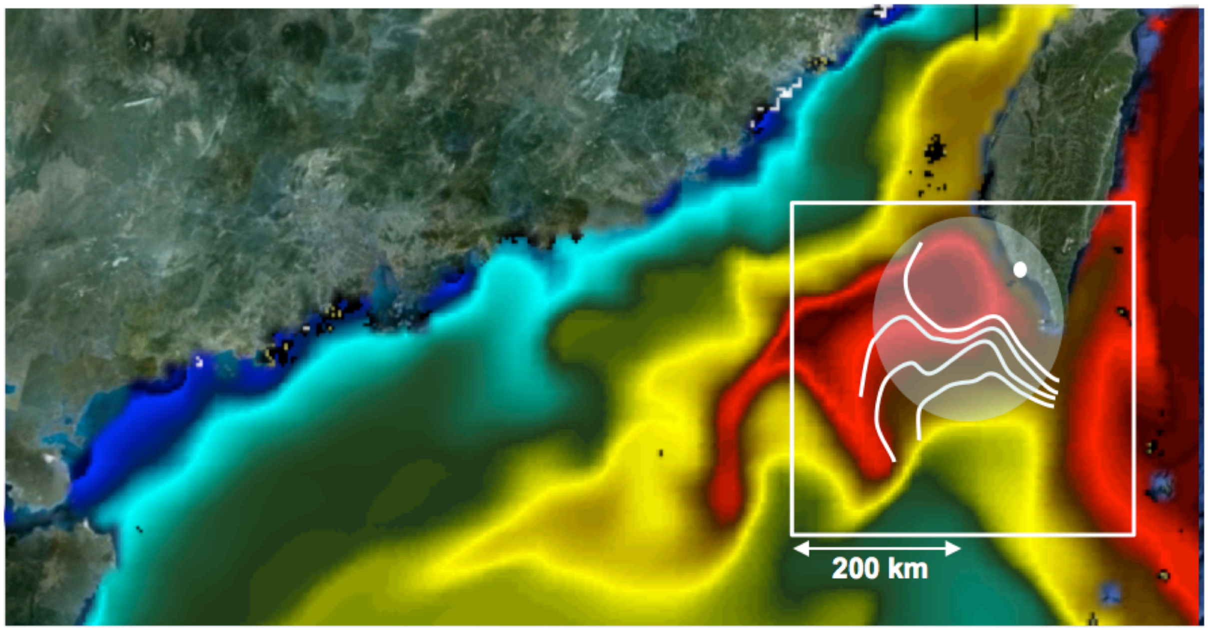

Figure 9. Map showing the proposed worksite. The boxed region shows the high-EKE area southwest of Tawain, where an active sub-mesoscale cascade is predicted by numerical simulations. The western edge of the box is at 118 E longitude, the US State Department boundary for UNOLS vessel operations. Taiwan vessels may work in any area of the S. China Sea. Hypothetical drifter tracks are shown. The shaded circle shows the hypothetical range of CODAR pair in southern Taiwan. The port of Kaohsiung is indicated by the dot.

Surface high-frequency radar, such as CODAR, can be used to great affect to image the surface currents in the sector southwest of Taiwan (Figure 9). Dr. Yiing Jang Yang already has the CODAR equipment necessary to provide such coverage.

Modeling. Numerical simulations, in the form of high-resolution global and regional models, should be an integrated part of the DRI. Global models such as GOLD and HYCOM can be pushed to resolutions <10 km, which resolve some parts of the sub-mesoscale cascade. These models should be utilized as planning tools to gauge the intensity of the mesoscale forcing that will pre-condition the sub-mesoscale cascade. Regional models, such as SUNTANS and ROMS can easily resolve the scales of interest, and could be used as semi-predictive tools for the field program. These models could be fed data from the staging phase of the program, with the drifter data and the initial ship survey providing the basis for model initiation conditions. This type of assimilative model use is an ONR tradition (ASAP, AESOP, LATMIX, QPE). This will be the first time such an approach will be tested in the S. China Sea.

Taiwan PIs involved in regional modeling efforts of the S. China Sea include Dr. Jan Sen and Dr. Shih-Nan Chen of National Taiwan University.

Synergies with other programs

This program would serve as an intellectual successor to several recent programs jointly run with Taiwan, most notably OKMC and IWISE. Both previous programs were focused on the detailed physics of the Luzon region. The momentum of both of these programs, as well as momentum from QPE and ITOP, is still strong, as meetings and paper writing activities for these programs are reaching their peak now. Thus, the time is right to plan a new ONR program in the S. China Sea. The technical capabilities of both Taiwan and US are well oiled to take on this effort. Taiwan has a new global-class vessel, the *Ocean Research V* (OR5), and our Taiwan colleagues are hungry to use this ship in a major collaborative program with the US ONR PIs.

Our Taiwan collaborators are enthusiastic about this research project. In the time since ASIA-EX, ONR has fostered collaborations that have now transcended a generation of students: the Taiwan and US graduate students who worked on ASIA-EX are now the PIs, with graduate students of their own. In many cases, the current students are already working with US PIs on the various projects of QPE, ITOP, OKMC, and IWISE.

Timeline and Scientific Outcomes

This program would initiate with a community workshop held jointly between Taiwan and US PIs in Spring 2013. This meeting could be held in conjunction with the end-of-program meetings for IWISE and OKMC, both of which will touch on issues relevant to the sub-mesoscale cascade program. Given the interest in the monsoon cycle, the fiscal year calendar actually works well for this proposed program, having a start date in October 2013. The program could then be conducted over the 3-year period between FY14-FY16. FY14 will be for planning and modeling studies. The observational effort will be planned for FY15: Oct 2014-Mar 2015 for the winter monsoon observational period, and Apr 2015 – Sep 2015 for the summer monsoon period. FY16 will be for analysis and synthesis. Outcomes are expected on fundamental principles:

- Improve our physical understanding of sub-mesoscale variations in the S. China Sea.
- Testing hypothesis related to our questions of spatial, temporal, and evolution scales of the sub-mesoscale cascade.
- Production of a dataset suitable for model validations, leading to improvement of the forecast skills of high-resolution coupled models of the S. China Sea.

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