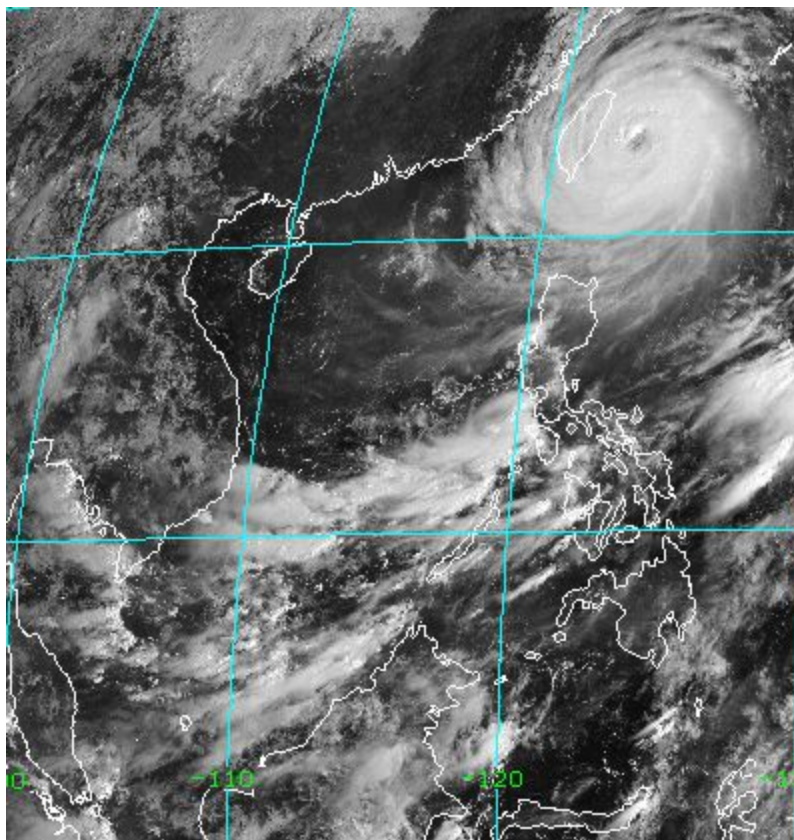


Propagation of Intra-Seasonal Tropical Oscillations (PISTON)

Office of Naval Research Departmental Research Initiative (DRI)

SCIENCE PLAN



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EXECUTIVE SUMMARY

The boreal summer intraseasonal oscillation (BSISO) is characterized by eastward and northward propagation of convection and associated large-scale circulation anomalies across the north Indian Ocean and South China Sea (SCS). In addition to producing profound variability in winds and precipitation in the Philippines Archipelago and other parts of the Maritime Continent (MC), the BSISO is associated with active and break cycles of the south and east Asia monsoons, has been implicated in the modulation of tropical cyclones across the tropics, and is associated with prominent teleconnections to the extratropics. Unfortunately, weather forecasting and climate models have traditionally had difficulty in simulating the BSISO, which limits the ability to forecast the local and global impacts of the BSISO. The propagation mechanisms for the BSISO are poorly understood. The factors that impact propagation of the BSISO may include interactions with the ocean, surface flux over land and ocean, higher frequency variability including the diurnal cycle and tropical depressions, and the mean wind and humidity distribution. The inability of models to properly simulate many of these processes limits their ability to properly simulate the propagation of the BSISO and hence predict its future evolution.

The goal of PISTON is to forge a better understanding of the multiscale, air-sea, and land-atmosphere interaction processes that regulate BSISO propagation and intensity, develop an observational dataset to benchmark model simulations of the BSISO, and use these models and observations to address the overarching PISTON hypotheses defined below. PISTON will identify processes (e.g. convective and surface) in the MC to which model simulations of the BSISO are particularly sensitive, with the goal of improving their representation to enable improved prediction of propagating intraseasonal disturbances that transect the Philippines Archipelago and MC. PISTON field observations and high-resolution models will foster process understanding that leads to improved model and predictions.

PISTON is guided by these four overarching hypotheses:

- *Large scale atmospheric circulation variability over the South China Sea related to the monsoon, intraseasonal oscillations, and convectively coupled waves modifies the local diurnal cycle and air sea interaction in the coastal regions and nearby open seas.*
- *Convection over the Maritime Continent is inherently multi-scale, with large scale flow and environment (e.g., shear, thermodynamic state, etc) setting the context for embedded convective systems that range in scale from individual cumulus clouds to convectively coupled waves. Small scale convective processes (e.g., interaction with complex terrain and coastlines, cloud microphysical processes, and the details of convective cold pools), in turn, influence the propagation of larger convective systems across the region.*
- *3-dimensional oceanic processes are important to BSISO propagation in the SCS.*
- *Local and mesoscale processes related to the presence of land and topography, atmosphere-ocean interactions, and atmosphere-land and river-ocean interactions influence the development and propagation of the BSISO. These processes include land-sea breezes, the diurnal cycle, surface fluxes, gravity waves, convective variability, and upper-ocean dynamics, and river runoff.*

These objectives and hypotheses will be addressed in an observational campaign during the late summer of 2018 in the SCS. The observational program will be tightly coupled to a ocean and atmosphere modeling program. The observational campaign will consist of about two months of shipborne measurements from the *R/V Thomas G. Thompson* near the West Coast of Luzon that will sample the northward-propagating BSISO and interactions with offshore-propagating convective disturbances and the upper ocean. Shipborne C-band polarimetric Doppler radar and radiosonde observations form the central atmospheric observational component for PISTON. Near-surface boundary layer meteorology and surface flux observations collected at high-resolution from the ship will sample the turbulent to mesoscale coherent structures related to shallow and deep convection, stratiform precipitation, and land-sea circulations. Shipborne ocean observations include microstructure profiles to estimate heat fluxes in the upper 200-300 m and particularly across the diurnal warm layer and seasonal mixed layer. Measurements include concurrent profiles of velocity, temperature, and salinity, two subsurface moorings consisting of Acoustic Doppler Current Profilers (ADCPs), conductivity, temperature, and depth devices (CTDs) and Oregon State University chi-pods every 20-30 m in the upper several hundred meters, and broader spatial surveys to characterize the regional oceanography and large-scale gradients.

A hierarchy of modeling tools will be employed in PISTON including large-eddy models, cloud-system-resolving models (CSRMs) that span local to regional domains, and climate simulations, forecasts, and reforecasts of global models. Models will be used in the pre-field phase, field phase, and post-field phase to inform field campaign deployment, develop and/or test science hypotheses, and provide real-time campaign forecasting support at both short range (1-3 days) and extended range (3 days to multi weeks). The model hierarchy of models will also be subject to scrutiny from PISTON observations to assess their process-level fidelity that will provide a path toward model improvement.

PISTON will include coordination with the NASA Cloud and Aerosol Monsoonal Processes-Philippines Experiment (CAMP²Ex) that will operate in the Philippines from mid-August to the end of September 2018, the NOAA Climate Variability and Predictability (CVP) Program initiative entitled Observing and Understanding Processes Affecting the Propagation of Intraseasonal Oscillations in the Maritime Continent Region, and the Years of the Maritime Continent international project (and the Philippines component, SALICA, Taiwan's South China Sea Two-Island Monsoon Experiment, described below), among other international linkages.

1. Introduction

1.1 Introduction to the boreal summer intraseasonal oscillation (BSISO)

Interest in modes of tropical intraseasonal variability has increased substantially during the last decade due to the recognition of their importance for subseasonal prediction of the large-scale atmospheric state and associated weather extremes, including in the extratropics (e.g., Robertson et al. 2015). The intraseasonal timescale is a bridge between weather and climate, and tropical intraseasonal modes have important interactions with both longer and shorter timescale phenomena. The most prominent mode of tropical intraseasonal variability is the Madden-Julian Oscillation (MJO, Madden and Julian 1971), a phenomena characterized by coherent fluctuations in winds, moisture, and precipitation at 40-50 day timescales that propagates eastward across the Indo-Pacific warm pool at about 5 m s^{-1} . A form of the MJO also exists during boreal summer that we will refer to as the boreal summer intraseasonal oscillation (BSISO), which is characterized by both eastward and northward propagation (e.g., Fu and Wang 2004; Lee et al. 2013). Overall intraseasonal precipitation variance in the tropics shifts from a distribution that is more equatorial and Southern Hemisphere-biased during the 6-month period centered on boreal winter (the strong variability to the east of the Philippines is an interesting exception), to one that is weighted toward the Northern Hemisphere with maxima in the South China Sea (SCS), Bay of Bengal, and to the east of the Philippines during boreal summer (**Figure 1** from Sobel et al. 2010). Notable during both seasons is the relative minimum in intraseasonal precipitation variance over the larger islands of the Maritime Continent (MC), although this behavior is not as strongly apparent over the Philippines during boreal summer.

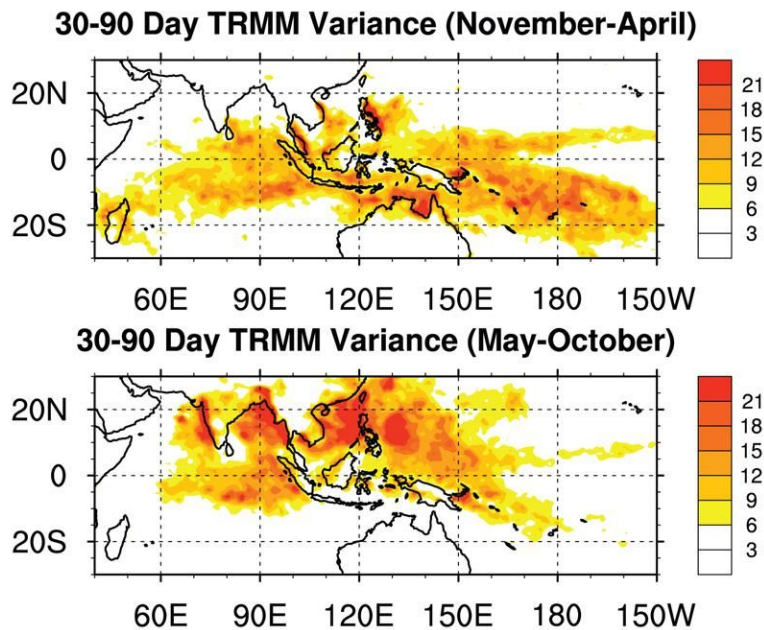


Figure 1. From Sobel et al. (2010). Intraseasonal variations in rainfall for a) November-April and b) May-October ($\text{mm}^2 \text{d}^{-2}$). Daily-averaged TRMM 3B42 precipitation data during 1998-2005 averaged to a $1^\circ \times 1^\circ$ grid are used.

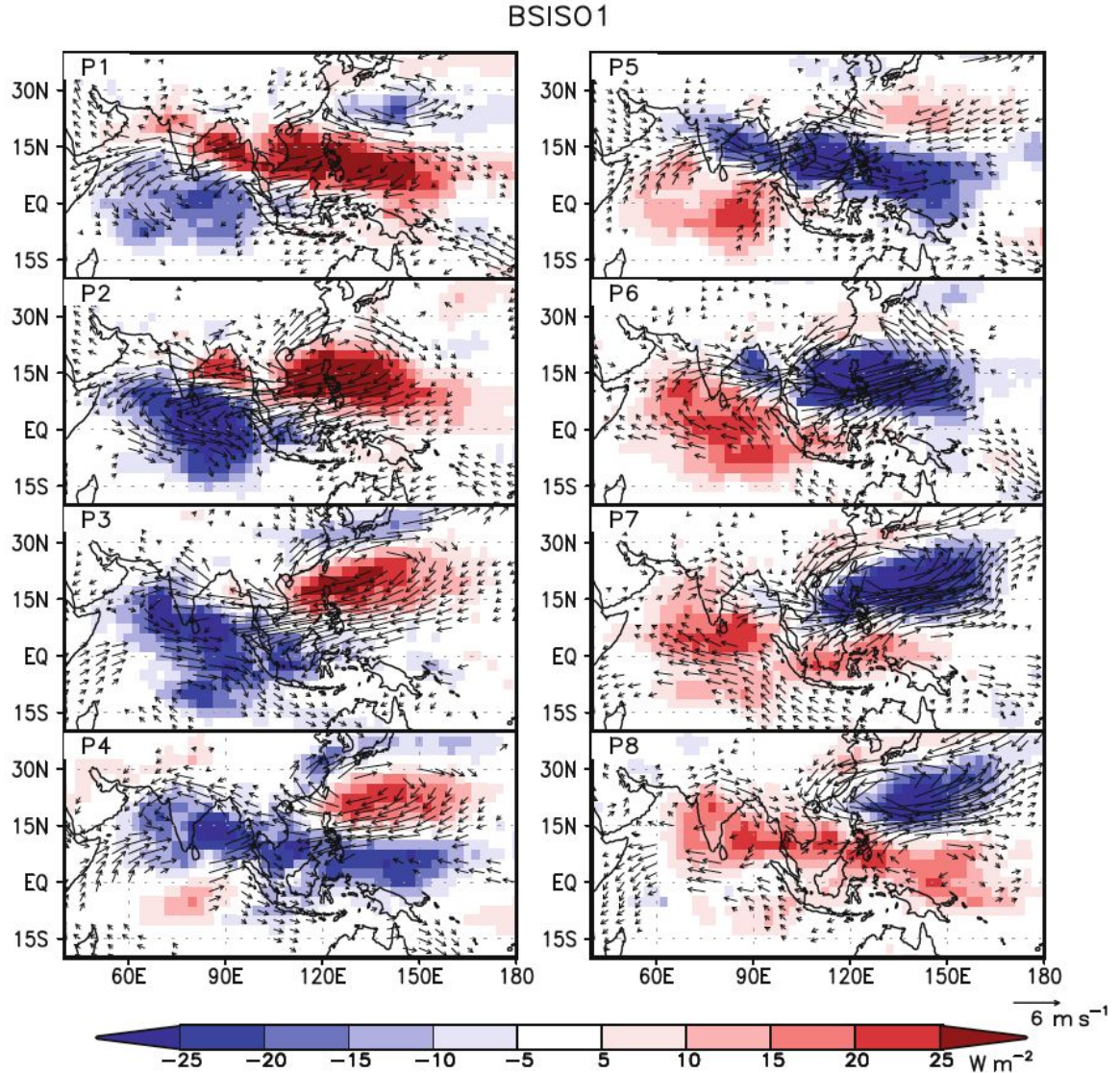


Figure 2. From Lee et al. (2013). Composite 850 hPa wind and OLR anomalies as a function of BSISO phase (indicated by P# in each panel).

Figure 2 from Lee et al. (2013) shows a composite lifecycle of the BSISO derived from the leading multivariate EOFs of boreal summer 850 hPa zonal wind and outgoing longwave radiation (OLR). OLR and 850-hPa winds are composited in this figure. While this figure shows evidence of eastward propagation of BSISO convection anomalies across the MC after convection initiates in the central Indian Ocean during phase 1, the propagation characteristics of the BSISO are more complex than that of the boreal winter MJO (e.g., Wheeler and Hendon 2004). Significant northward propagation of precipitation and wind anomalies is a well-defined characteristic of the BSISO in both the Indian Ocean and SCS. Convection anomalies are characterized by a northwest-southeast “tilted rainband structure” during certain phases (e.g. Wang and Xie 1997), such as phase 5 when positive convection anomalies extend from the Bay of Bengal southeast into the SCS. Northward propagating positive convection anomalies are accompanied by westerly wind anomalies near and to the

south of the convective center, with easterly anomalies to the north. Given the westerly mean low-level flow across the Bay of Bengal and SCS during boreal summer, low-level westerly anomalies add constructively to the westerly mean flow to foster positive surface latent heat flux anomalies.

As will be discussed below in Section 1.6 in the introduction to ocean processes and air-sea interaction, the combination of surface flux, surface shortwave radiation (produced by variations in BSISO cloudiness), and surface momentum flux anomalies engender SST anomalies that move northward coherently with the BSISO convective envelope. As shown in **Figure 3** from Roxy and Tanimoto (2012), which displays composite SST and surface wind anomalies relative to maximum intraseasonal SST events in the SCS, cold SST anomalies follow periods of westerly wind anomalies, and warm SST follows easterlies. These SST anomalies may modulate northward propagation of the BSISO in the SCS, which will be discussed in more detail below.

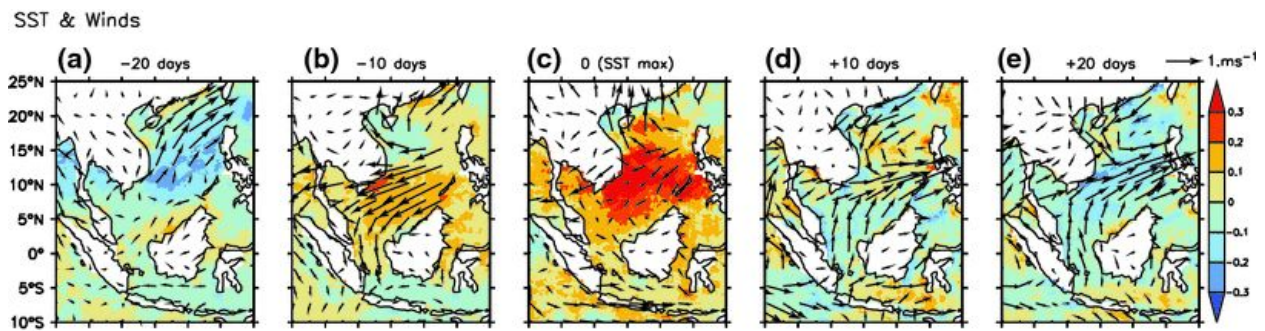


Figure 3. From Roxy and Tanimoto (2012). Composite surface wind vector and SST anomalies relative to positive SCS intraseasonal events in region bounded by 109–114°E, 9–12°N.

While the 30-60 day BSISO has received the majority of attention in the scientific literature, the boreal summer focus of PISTON will also leverage the fact that the SCS and surrounding regions support a rich spectrum of boreal summer intraseasonal variability on other timescales (e.g., Nakazawa 1986; Tanaka 1992; Hartmann et al. 1992; Chen and Chen 1993; Chen et al. 2000; Fukutomi and Yasunari 2002). For example, Fukutomi and Yasunari (1999; 2002) document the behavior of a prominent 10-25 day mode of boreal summer intraseasonal variability that is particularly prominent over the SCS. Lee and Wang (2016) in their study of the regional BSISO indices note that while in the Indian Ocean the variability is concentrated in the 30-45 day band, while the Western Pacific has a broad spectral peak in 10 through 60 days. In the SCS, barotropic conversions between the mean monsoon flow and the 10-25 day eddies help maintain these disturbances, although baroclinic conversions become important at higher latitudes. Regardless of the cause, the rich diversity of intraseasonal variability in the SCS will enhance the likelihood of capturing different intraseasonal basic states during the PISTON field phase that will allow state-dependent interactions with synoptic variability, the diurnal cycle, and other high frequency disturbances to be examined.

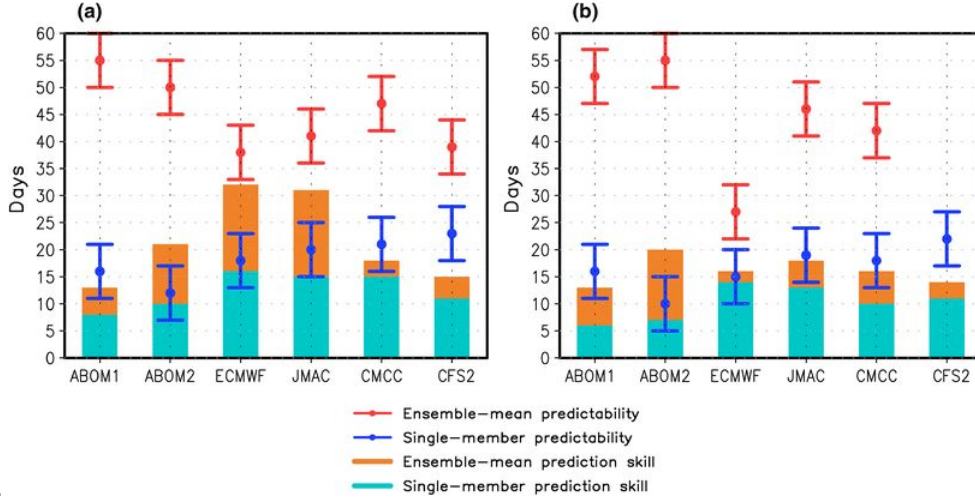
1.2 BSISO impacts

The BSISO has profound impacts both locally and globally that may be predictable at medium range given the slowly-evolving nature of this mode (e.g., Waliser et al., 2003; Slade and Maloney 2013), providing urgency to better understanding and simulating this phenomenon. The BSISO is associated with active and break periods of the South Asian and east Asian

monsoon. The South Asian seasonal mean flow and precipitation are intensified during BSISO active phases, with the opposite conditions typically present during BSISO suppressed phases (e.g., Goswami and Ajaya Mohan 2001; Goswami 2012). Similarly, monsoon active and break periods in the SCS and across east Asia are induced by the BSISO, with the possibility for out-of-phase relationships between monsoon conditions between these two regions given their geographical separation and the large-scale structure of the northward-propagating BSISO (e.g., Chen et al. 2000; Hsu 2005). The BSISO has been implicated in monsoon onset in east and south Asia, and a climatological component exists associated with the onset of monsoon conditions moving progressively further north from the SCS to North China from mid-May through early August (Wang and Xue 1997; Hsu 2005).

The BSISO has been implicated in the modulation of tropical cyclones across the tropics, including the Indian Ocean, the northwest Pacific, the northeast Pacific, and the Atlantic (Liebmann et al. 1994; Maloney and Hartmann 2000a,b; Higgins and Shi 2001; Klotzbach 2014). Coincident modulation of tropical depression-type disturbances in these basins also occur as a function of BSISO phase. For example, tropical depression-type disturbances in the Philippine Sea and SCS are substantially more active during low-level westerly phases of the BSISO versus easterly phases (e.g., Maloney and Dickinson 2003; Hsu et al. 2011). Tropical cyclone (TC) genesis is enhanced during periods of enhanced tropical depression (TD) activity in the northwest Pacific (Hsu et al. 2011). Goswami et al. (2003) similarly document a substantial increase in the number of monsoon depressions and lows in the Bay of Bengal during the convectively enhanced phase of the BSISO there. Bay of Bengal depressions have been implicated in extreme precipitation events in South Asia (e.g., July-August 2010 Pakistan floods, Houze et al. 2011). A bit farther afield, the BSISO produces significant variability in west African rainfall (e.g., Matthews 2004), with easterly wave activity that seeds Atlantic and east Pacific tropical cyclone formation being enhanced during periods of enhanced rainfall (Alaka and Maloney 2012). The strong influence of the BSISO on tropical cyclogenesis suggests that improved prediction of intraseasonal oscillations can improve genesis forecasts at longer lead time (Nakano et al. 2015). However, the links between BSISO modulation of the synoptic-scale environment and mesoscale organization of the TC are not well understood. Detailed observations of the convective character in pre-depression disturbances are lacking, especially in the western North Pacific. Further research is required to distinguish cloud clusters that continue to organize or fail to develop, and to better understand the physical mechanisms involved in convective organization leading to genesis.

Teleconnections to the extratropics that modulate temperature and precipitation also occur in association with the BSISO, but for the sake of brevity these impacts will not be discussed here (e.g., Moon et al. 2013). The ability to predict the large-scale pattern associated with the BSISO, let alone the various impacts discussed above, is currently limited. **Figure 4** from Lee et al. (2015) shows the current capability of several forecast models to predict the large-scale patterns associated with two leading combined EOFs used to generate the composites in **Figure 2**. Symbols in **Figure 4** represent predictability (ensemble mean and single member) using a perfect model assumption, and shadings represent the actual prediction skill relative to the observed state. Prediction skill is severely limited for the BSISO relative to predictability, with prediction skill over 3 weeks lower than predictability using the multimodel mean predictability estimate. This highlights room for substantial improvement in forecast model simulations of the BSISO. Model biases in simulating the BSISO will be discussed in more detail in the next



section.

Figure 4. From Lee et al. (2015). Predictability and prediction skill for the Lee et al. (2013) BSISO indices when a) strong and b) weak BSISOs exist in the initial conditions.

1.3 Modeling of the BSISO

Weather forecasting and climate models have traditionally had difficulty in simulating the BSISO. **Figure 4** showed the unrealized prediction capability associated with hindcasts of the BSISO from weather forecasting models that might be improved through parameterization development. Neena et al. (2016) provides a comprehensive analysis of the ability of a suite of 27 general circulation models to simulate the BSISO. **Figure 5** shows a lag regression of Indian Ocean precipitation anomalies onto itself as a function of latitude and time, indicating the substantial difficulties that many models have in simulating the northward propagation of the BSISO. Neena et al. (2016) also showed that success at simulating northward propagation of the BSISO is correlated with eastward propagation skill ($r \sim 0.6$), although some models produced divergent skill between eastward and northward propagation.

Model propagating patterns are assessed using an index derived by projection of model precipitation onto the leading extended EOFs of TRMM 3B42 precipitation anomalies, averaged over longitudes characteristic of the Indian Ocean. **Figure 6** shows that the ability to realistically represent northward propagation of the BSISO is in part related to the ability of models to simulate the tilted NW-SE rainband structure captured in **Figure 2** (e.g., most evident in Phases 1 and 5). Simulations with a better propagation skill, as represented by a pattern correlation of the model plots in **Figure 5** with the observations (upper left corner plot), tend to produce a better composite tilt to the rainband structure. However, simulating this tilted structure remains a challenge for models (e.g., Sperber and Annamalai 2008), with Figure 6 indicating that all models underestimate the tilt.

While simulating the propagation characteristics and amplitude of the BSISO remains a challenge, previous studies have hypothesized various factors that can lead to improved simulations of the BSISO. Some studies have demonstrated that coupling atmospheric models to an interactive ocean substantially improves the amplitude and propagation characteristics of the BSISO (e.g., DeMott et al 2014; Fu and Wang 2004; Fu et al. 2007); however, this does not appear to be the case of all models (e.g., Neena et al. 2016). Coupling a model often affects the mean state, which can make it difficult to isolate the direct effects of coupling on BSISO simulations from those of mean state changes (e.g., Klingaman and Woolnough 2014).

Assessing the importance of ocean coupling to BSISO propagation and destabilization is

a research priority of PISTON.

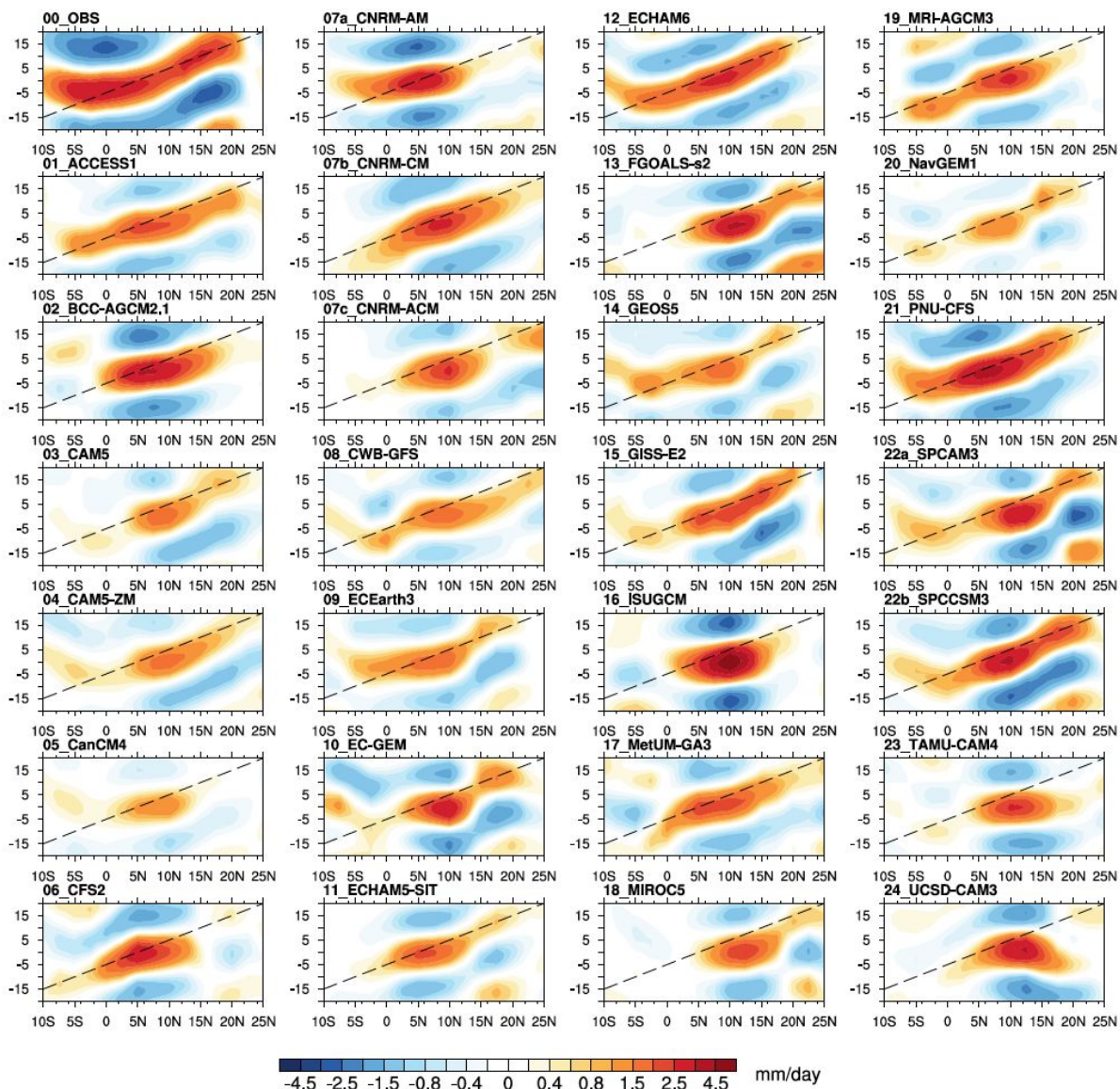


Figure 5. From Neena et al. (2016) Latitude-time diagram of 20-90 day Indian Ocean rainfall anomalies regressed against a near-equatorial reference point. The dashed line represents 1 m s^{-1} propagation speed.

As implied above, simulating realistic mean wind, wind shear, precipitation, humidity, and other aspects of the mean state may be important for simulating BSISO propagation and amplitude, consistent with some of the theorized propagation mechanisms for the BSISO described in the next section (see the discussion in Sperber and Annamalai 2008). However, aspects of the basic state that have been hypothesized to be important for northward BSISO propagation (e.g., vertical shear) do not always show a strong correlation with BSISO propagation skill in models (Neena et al. 2016). Previous studies have cited the importance of simulating realistic convection-free tropospheric humidity feedbacks for producing realistic

intraseasonal variability, including during boreal summer (e.g., Kim et al. 2014; Maloney et al. 2014). While there may be a strong link between the strength of moisture-convection coupling and ISO amplitude, the impact on BSISO propagation is unclear (Neena et al. 2016). Finally, observations and regional models suggest potentially important interactions between intraseasonal modes of variability and the diurnal cycle of convection over the MC (e.g., Wang et al. 2011; Rauniyar and Walsh 2011; Peatman et al. 2014, Birch et al. 2016), although the nature of these interactions is poorly understood.

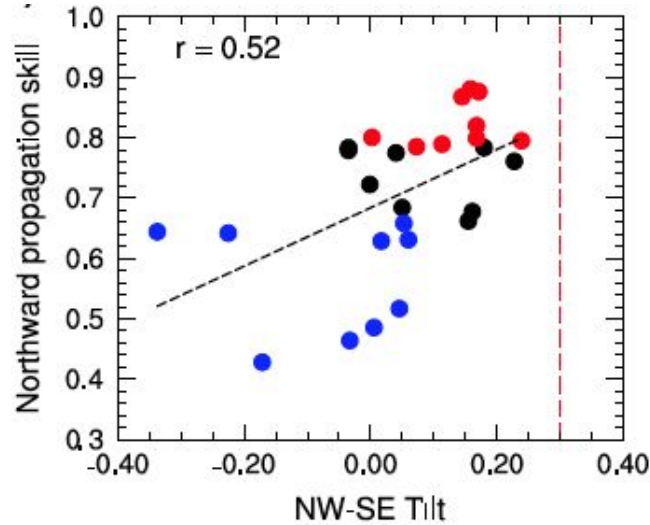


Figure 6. From Neena et al. (2016). Northward propagation skill versus an index of NW-SE tilt of the model BSISO composite rainband. The observed value of 0.3 is shown as the vertical dashed line.

The failure of most GCMs to accurately simulate the amplitude and timing of the diurnal cycle in the MC (e.g., Neale and Slingo 2003; Birch et al. 2015) may limit the ability to simulate realistic BSISO-diurnal cycle interactions and any salient impacts on eastward and/or northward propagation. More generally, Takasuka et al. (2015) used an aquaplanet GCM with idealized MC islands to demonstrate that propagating MJO disturbances in the model have complex interactions with the land surface and associated topography. Although topography enhances MJO convection on the upwind side in their model, the presence of land surfaces generally weaken the MJO, leading to faster propagation due to a reduction in positive surface flux anomalies that trail enhanced MJO oceanic convection to the east due to the presence of a land surface. Intraseasonal prediction skill for many models is limited during ISO phases where convection is located in the Indian Ocean and about to transit the MC (e.g., Vitart and Molteni 2010), indicating that models do not correctly simulate interactions between land surface processes and intraseasonal modes. Predictability during these same phases is similar to other intraseasonal phases, indicating that the MC is not a prediction barrier, but rather that model parameterization improvement is necessary to make MJO/BSISO interactions with the land surface more realistic (e.g., Kim et al. 2016). ***How local processes related to topography and diurnal variability influence the development and propagation of the BSISO is an important focus of PISTON.***

1.4 Propagation mechanism for BSISO: Current Hypotheses

The dominant northward propagation mechanism for the BSISO is not well understood;

therefore, advancing our understanding in this area is a key goal for the PISTON program. Hypotheses on northward BSISO propagation will be briefly reviewed here, although a more extensive review can be found elsewhere (e.g., DeMott et al. 2013). It should be noted that similar uncertainties exist regarding the propagation mechanism for the boreal winter MJO, although recent literature suggests important roles for horizontal moisture advection, surface flux feedbacks, and possibly vertical moisture advection in regulating eastward propagation (e.g., Adames and Kim 2016; Chikira 2014; Klingaman et al. 2015). Given that at least one of the hypotheses for northward propagation of the BSISO is tightly coupled to its eastward propagation, the possible lack of independence of a general eastward MJO propagation mechanisms should be kept in mind here.

A subset of propagation mechanisms invokes large-scale atmospheric dynamics and involves interactions between the perturbation BSISO flow and the mean monsoon flow, with frictional boundary layer convergence often an important agent. One hypothesis suggests that interaction of BSISO heating and vertical velocity with the basic state vertical shear is important for BSISO northward propagation (Jiang et al. 2004; Drbohlav and Wang 2005). In this mechanism, vertical velocity in the BSISO convective region in the presence of easterly basic state vertical shear leads to positive barotropic vorticity generation to the north of the convective region. Frictional convergence is induced in this region of positive vorticity that leads to moistening and northward propagation of the BSISO convective center. Wang and Xie (1996; 1997) also hypothesize the importance of easterly mean shear for BSISO structure and propagation dynamics. In this hypothesis, easterly mean shear causes preferential generation of northwestward translating equatorial Rossby waves in the northern Hemisphere to the west of convection as the BSISO convective center propagates eastward in the west Pacific. Enhanced convection is produced through frictional convergence in these Rossby wave centers to the north of the equator, and results in a tilted “NW-SE rainband structure” when combined with near-equatorial convection. Northward propagation results as the BSISO equatorial convective center moves east when viewed from the reference frame at a fixed longitude. Bellon and Sobel (2008) cite the importance of positive barotropic vorticity generation to the north of the BSISO convective center through advection of anomalous vorticity by the mean meridional flow. Consistent with the hypotheses above, frictional moisture convergence is induced into the resulting positive vorticity center, resulting in the formation of positive convective anomalies to the north and hence northward propagation.

Boos and Kuang (2010) propose a mechanism for northward BSISO propagation that involves beta-drift of embedded cyclones that exist within the larger BSISO envelope of deep ascent. When using a zonally symmetric nonhydrostatic model with 1000-km zonal width, these drifting cyclones induce moistening through Ekman convergence, shifting convection and the envelope of deeper ascent towards the north. Radiative feedbacks and surface flux feedbacks contribute to destabilization of the BSISO in this study.

As suggested in the mechanisms above, frictional convergence (that causes upward motion at the boundary layer top and positive vertical moisture advection) has been cited as a potentially important mechanism in northward BSISO propagation. However, other processes that regulate the tropospheric moisture budget have also been cited as important for BSISO propagation. Horizontal moisture advection is one mechanism that may contribute to northward propagation (e.g., Prasanna and Annamalai 2012). **Figure 7** from Sooraj and Seo (2013) shows a breakdown of the vertically integrated moist static energy budget regressed against a near-equatorial intraseasonal time series as a function of latitude and time lag in days. This analysis was conducted on a version of the National Centers for Environmental Prediction Climate Forecast System (NCEP CFS), although results are broadly consistent with results from

reanalysis datasets (e.g., Prasanna and Annamalai 2012). Horizontal advection (dominated by moisture) is in phase with the total tendency and dominates the other terms, although vertical advection also contributes to the tendency (consistent with the dynamical processes discussed above). Sooraj and Seo (2013) cite the mean southerly meridional summer flow as being important for moisture advection and propagation. Prasanna and Annamalai (2012) cite the anomalous flow acting on the mean humidity gradient as being the major mechanism for regulating horizontal advection. A recent analysis by DeMott et al. (2011) using European Centre for Medium-Range Weather Forecasts Interim Reanalysis (ERA-I) fields suggests that both horizontal moisture advection by the mean and perturbation meridional flow and barotropic vorticity generation to the north of the existing BSISO convective center support northward propagation in the SCS, although SST feedbacks as discussed below also contribute.

As mentioned above, TD-type disturbances are also strongly modulated by the BSISO. Previous studies have suggested that these disturbances provide an important agent for horizontal advection associated with the MJO (e.g., Maloney 2009; Andersen and Kuang 2011). During BSISO phases characterized by anomalous westerly flow and enhanced precipitation when these eddies are more active, they facilitate greater mixing of higher latitude air into the tropics across the mean meridional moisture gradient. Likewise, suppression of eddies stifles this mixing process. Given the geographical emphasis, PISTON may be well suited to assess the impact of such higher-frequency transients and their state dependence on the moisture budget of the BSISO and their possible role in propagation and destabilization. A sounding network would be extremely helpful for this analysis.

Finally, positive surface flux anomalies lag the BSISO convective center to the south, and negative surface flux anomalies lead to the north (e.g. see the turbulent flux panel in **Figure 7**). This phase relationship would tend to slow BSISO propagation by delaying moistening to the north (e.g., Boos and Kuang 2010). As mentioned below, SST feedbacks can modulate the strength of fluxes and potentially diminish their role in slowing northward propagation (e.g., Bellon et al. 2008).

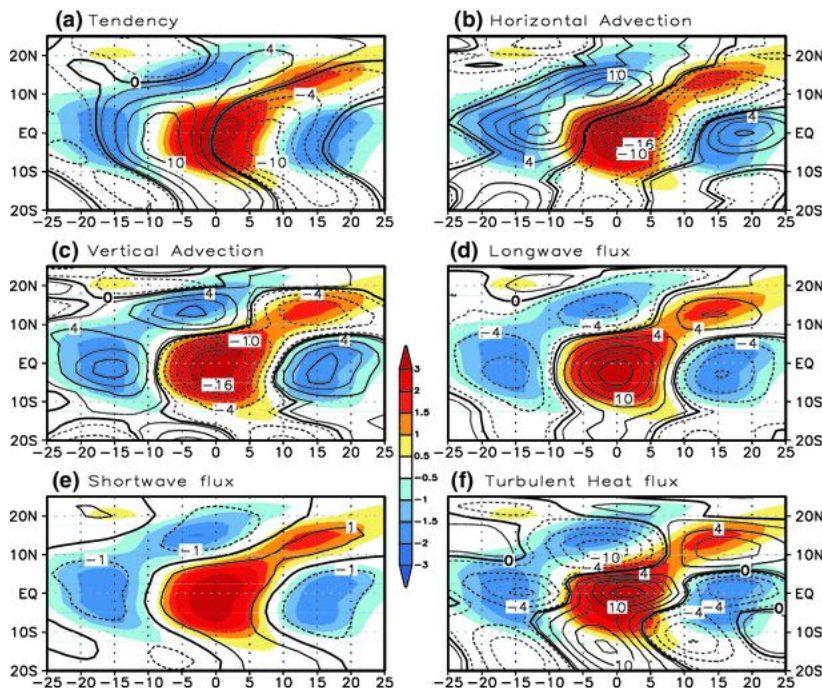


Figure 7. Adapted from Sooraj and Seo (2013). Vertically-integrated MSE budget terms regressed onto equatorial Indian Ocean intraseasonal precipitation anomalies in the NCEP CFS model. Color shading in each panel shows identical precipitation anomalies, and the contours represent the budget terms in $W m^{-2}$.

Lastly, ocean coupling has been cited to play an important role in BSISO propagation. One mechanism through which this can occur is through SST gradient-induced boundary layer convergence (e.g., Lindzen and Nigam 1987; Back and Bretherton 2009). Positive SST anomalies to the north of the BSISO convective center (e.g., **Figure 3**) can imprint temperature anomalies on the atmospheric boundary layer. Through hydrostatic balance, positive SST anomalies produce negative surface pressure anomalies that in the atmospheric boundary layer can induce frictional moisture convergence. Negative SST anomalies to the south of BSISO convection have the opposite impact. Such convergence anomalies have been hypothesized to play a significant role in fostering propagation of intraseasonal disturbances (e.g., Hsu and Li 2012). Previous studies have also cited decreased convective stability associated with the warmer, moister boundary layer to the north of existing BSISO convection as contributing to the northward propagation (e.g. Fu and Wang 2004; Klingaman et al. 2008).

Another means by which coupling can impact propagation is through direct modification of intraseasonal surface fluxes. It has been demonstrated in multiple studies that the SST response to intraseasonal convective disturbances acts to oppose the wind-induced component of the surface flux anomalies (e.g., Shinoda et al. 1998; Bellon et al. 2008; Riley Dellaripa and Maloney 2015). This results in diminished positive surface flux anomalies near and south of BSISO convection and diminished negative surface flux anomalies north of BSISO convection. In extreme cases, idealized modeling studies coupled to very shallow mixed layer slab oceans indicate that such thermodynamic feedbacks can completely negate surface flux anomalies and cause atmospheric intraseasonal variability to collapse (e.g., Maloney and Sobel 2004).

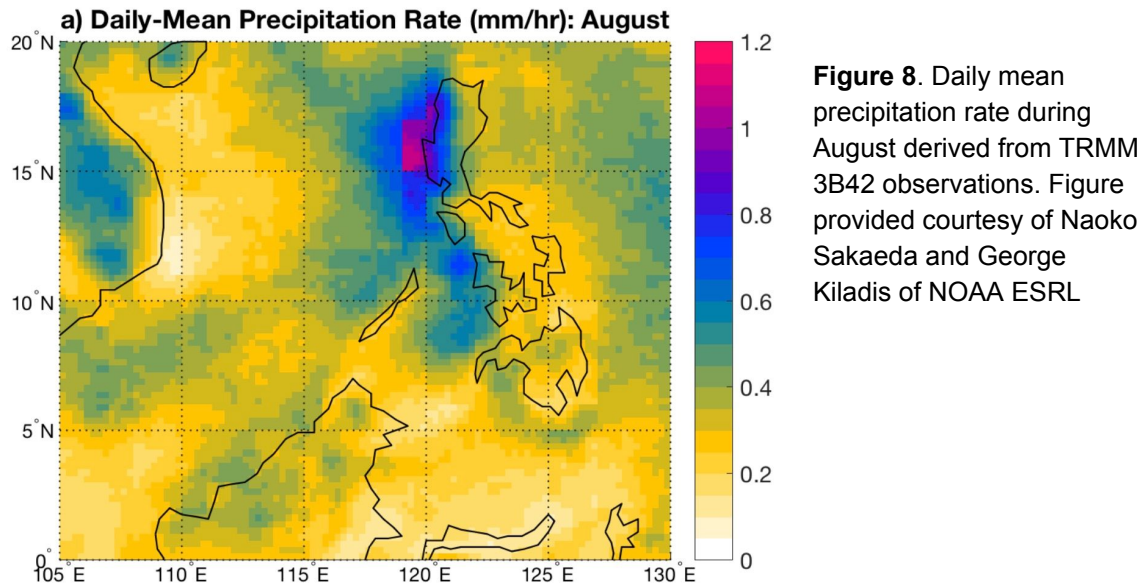
Both of the SST feedbacks described above would act to speed the northward propagation of the BSISO, given the role of surface fluxes in slowing BSISO propagation discussed in the context of **Figure 7**. Indeed, modeling studies have demonstrated an increase in northward propagation speed of the BSISO with the inclusion of ocean coupling (e.g., Fu and Wang 2004; Bellon et al. 2008), although these findings are not universal.

1.5 The land surface, diurnal cycle, and interactions with intraseasonal variability

The tropical land surface has strong influences on tropical convection across a range of timescales. **Figure 8** shows the daily mean TRMM 3B42 climatological August precipitation rate over the SCS and surrounding regions, indicating generally enhanced precipitation on the windward side of the islands of the Philippines archipelago in the presence of southwesterly monsoon flow and suppressed precipitation in the lee (figure provided courtesy of Naoko Sakaeda and George Kiladis of NOAA ESRL). The east-west mean precipitation gradient across the SCS is associated with greater orographic influence and warmer sea surface temperatures on the eastern side of the basin (e.g., Xie et al. 2006). Bergemann et al. (2015) found that up to 40-60% of the mean precipitation in the MC region could be associated with coastline effects.

Using a simple sinusoidal daily harmonic and fitting to the diurnal cycle allows an assessment of the diurnal amplitude and phase variations across the SCS. **Figure 9** shows the August diurnal amplitude and phase as derived from TRMM 3B42 (courtesy of Naoko Sakaeda and George Kiladis). Precipitation over the Philippines generally peaks during the evening, and

then the timing of the diurnal maximum gets progressively later offshore, with mid-to-late morning peaks in the interior of the SCS. For a state of strong westerly flow associated with enhanced westerly BSISO periods, Park et al. (2011) documented a late morning peak to the west of the Philippines, consistent with the results shown here. They attribute this peak to the interaction of large-scale diurnal circulations generated over SE Asia and mesoscale processes near the Philippines including cold pools produced by convection over land and



land-breezes supported by land-sea temperature differences that propagate offshore. Inertia-gravity wave propagation has also been cited as an additional offshore propagation mechanism in the MC region in other studies (e.g., Yang and Slingo 2001; Love et al. 2011; Vincent and Lane 2016). The diurnal cycle of convection and its offshore propagation tends to be maximized in regions of strong coastal topography (Yamanaka 2016). Mori et al. (2004) summarizes some of the dominant mechanisms regulating the propagation of diurnal convective systems generated near islands. Global models typically have trouble simulating the offshore propagation of diurnal convective disturbance. This has implications for the model's simulation of mean precipitation near coastlines, although increasing resolution can help mitigate some of these biases (Ploshay and Lau 2010).

Previous studies have detailed complex interactions between intraseasonal oscillations and land surfaces of the MC and Philippines archipelago, including interactions with the amplitude and phase of the diurnal cycle. For example, Ichikawa and Yasunari (2006) demonstrate that the direction of the anomalous MJO flow from east to west changes the direction of leeward propagation of diurnal disturbances from Borneo's topography, moving precipitation from one side of the island to the other. Rauniyar and Walsh (2011) separated the MJO into broadly defined active and inactive oceanic phases over the MC, and demonstrated that rainfall over land and the diurnal cycle are generally enhanced during inactive MJO phases versus active phases, generally supporting earlier findings of Sui and Lau (1992). The phase of the diurnal cycle is also delayed during MJO active periods, with propagation of diurnal convective disturbances extending further offshore during active phases than inactive phases. Peatman et al. (2014) separated the MJO lifecycle into eight phases defined based on the index

of Wheeler and Hendon (2004) and showed that the diurnal cycle and daily mean precipitation over MC land regions peaks about 6 days before the eastward propagation of the broader MJO oceanic convective envelope into the region.

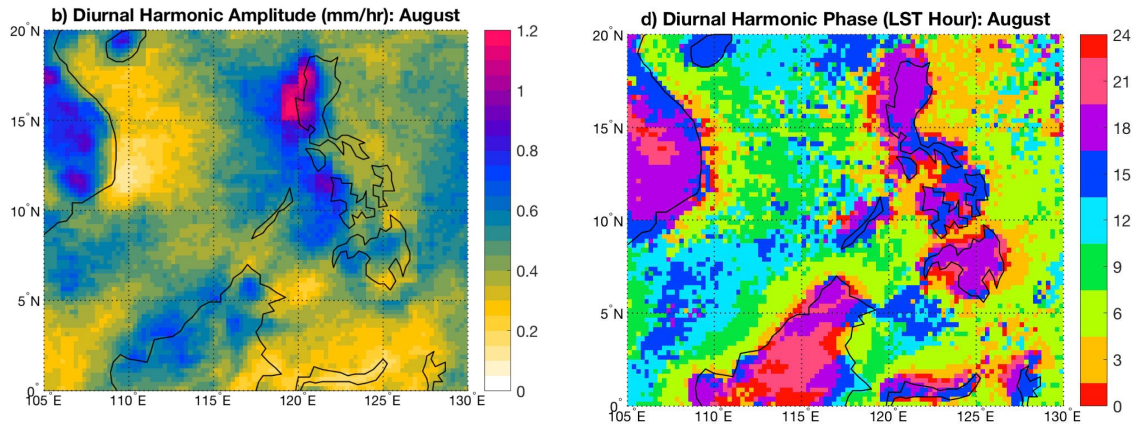


Figure 9. Amplitude and phase of the daily harmonic of precipitation during August derived from TRMM 3B42 observations. Figure provided courtesy of Naoko Sakaeda and George Kiladis of NOAA ESRL.

Interestingly, Peatman et al. (2014) also showed that outgoing longwave radiation (OLR) no longer becomes a good proxy for precipitation variability over MC islands, suggesting that using OLR as a proxy for MC precipitation variability should be done with caution. This study argues that suppressed cloudiness and frictional and topographic convergence in advance of the oceanic convective envelope leads to an enhanced diurnal cycle and daily mean precipitation over the MC islands before the oceanic convective envelope with enhanced regional cloudiness arrives. These results are supported by Birch et al. (2016) and Vincent and Lane (2016), who argue that suppressed cloudiness and high surface insolation (that generates strong land-sea breeze circulations), light winds, and an increasingly moist troposphere support enhanced diurnal precipitation variability over the MC islands in advance of the large-scale MJO convective envelope. Birch et al. (2016) and Vincent and Lane (2016) also highlight the limited ability of regional models to realistically simulate multiscale interactions between the MJO and islands of the MC. All of the studies above indicate that the nature of feedbacks of land-induced processes onto the larger MJO convective envelope is unclear.

Another aspect of land processes is the role of precipitation in the mountains delivered to the coastal ocean as river discharge. There is recent evidence of the MJO wet phase signal measured at the watershed scale (water level and precipitation) in the complex terrain of the MC (Matthews et al., 2013). Though not represented in many models, the hydrology component can have a large impact on the coastal ocean of the Philippines (Pullen et al., 2015), and feedback to the atmosphere through oceanic barrier layer formation (DeMott et al., 2015). Work to document the interactions of the BSISO with islands of the MC and the Philippines archipelago has been more limited. Chen and Takahashi (1995) used brightness temperature measurements to show that the diurnal cycle is suppressed over land regions surrounding the SCS during the BSISO active (westerly) phase and enhanced during the BSISO inactive (easterly) phase, although this study did not find a significant change in the phase of the diurnal cycle from one BSISO phase to the next. Ho et al. (2008) used TRMM precipitation radar fields to argue that the phase of the diurnal cycle in the SCS changes as a function of phase of the BSISO, with a late morning peak to the west of the Philippines during the BSISO westerly phase

and an evening peak during BSISO easterly periods. Park et al. (2011) found phasing generally consistent with this during the westerly phase of the BSISO. The interaction between the BSISO and diurnal cycle may also be an important component of tropical cyclone genesis in the SCS. Park et al. (2015) suggest that the positive phasing between afternoon convection over the Philippine islands and the late morning oceanic convective maximum during an active BSISO phase was critical to the development of tropical storm Mekkhala (2008). Examining the timing of diurnal precipitation in **Figure 9** for different phases of the BSISO does not indicate a significant change in diurnal phasing (not shown), and discrepancies still exist from study to study in how the BSISO affects the phase of the diurnal cycle in the SCS. These interactions may depend on the type of the BSISO or how the BSISO is defined.

As suggested by **Figure 1**, intraseasonal precipitation variability tends to be minimized over MC islands, and MJO propagation is frequently disrupted in the MC region (Matthews 2008; Kim et al. 2014). Models have particular problems in propagating intraseasonal oscillations across the MC region (e.g., Vitart and Molteni 2010) and tend to overdo the suppression of the intraseasonal signal in that region. However, the means by which the presence of extensive land surfaces suppresses propagation of intraseasonal oscillations through the MC and SCS is not well understood, although several ideas have been proposed. The topography of the MC can block the propagating atmospheric dynamical signal of the ISO, a process that might be too effective in some models (Inness and Slingo 2006). The vertical heating structure may be affected over the islands of the MC, changing the nature of the interactions between convection and the large-scale dynamics (e.g., Miyahara 1987). The strong diurnal cycle associated with the low heat capacity of the land surface can compete with the intraseasonal timescale for instability (e.g. Wang and Li 1994; Zhang and Hendon 1997; Neale and Slingo 2003). The low thermal inertia of the land surface can also suppress intraseasonal surface fluxes that help to destabilize intraseasonal oscillations (e.g., Maloney and Sobel 2004; Sobel et al 2010). Finally, Chikira (2014) suggests that reduction in intraseasonal variability over the MC islands is due to the mean humidity and temperature vertical profiles being substantially different over land versus ocean, which impacts the ability for intraseasonal moisture anomalies to be supported by vertical advection. ***Forging a better understanding of interactions of MC and Philippine archipelago land surfaces with the BSISO and the resulting impact on BSISO propagation and destabilization is an important focus of PISTON.***

1.6 Oceanography and air-sea interaction

Because of its greater heat capacity and density, the ocean acts as a slowly-responding regulator for atmospheric disturbances. The degree to which the ocean influences the atmosphere is in proportion to the ratio of net surface heat flux (J_q^o) to the turbulent heat flux through the ocean's mixed-layer base (J_q^t). When $J_q^o/J_q^t \gg 1$, the ocean heats and cools in phase with the atmospheric disturbance. This is the case for nighttime convection, for example (Shay and Gregg 1986; Anis and Moum 1994). At the other extreme, when $J_q^o/J_q^t \ll 1$, the atmosphere extracts heat from the ocean in sufficient quantities to fuel tropical cyclones (D'Asaro 2003; Pasquero and Emanuel 2008). In equatorial intraseasonal oscillations (the MJO), $J_q^o/J_q^t \sim 1$, and the ocean responds by feeding back to the atmosphere on the time scale of the oscillation (at least < 5 days). Strong intraseasonal pulses can strongly reduce upper ocean heat content that attenuates subsequent intraseasonal events, with weak pulses having the opposite impact (Moum et al. 2016).

The intent of the oceanographic portion of PISTON is to quantify J_q^o/J_q^t and identify the processes responsible for J_q^t . Such advances are a primary goal of PISTON and

should help to substantially improve ocean-only models. For example, models that include parameterizations of the mixing in the Indonesian seas decrease SST by $\sim 0.5^{\circ}\text{C}$, increase ocean heat uptake by $\sim 20 \text{ W/m}^2$ and reduce the overlying deep convection by as much as 20%, all changes that align the model output in better agreement with the observations (Koch-Larrouy et al. 2008, 2010, 2015; Sprintall et al. 2014).

We first describe the four primary processes (labeled below in bold text) anticipated to give rise to turbulence (**Figure 10**) - the importance of each of which on J_q^o/J_q^t depends on the mixed-layer depth, which is in turn modulated by lower-frequency processes that are described below.

While direct bottom-boundary-layer mixing by tides is important in the region's shallow seas, **internal tides** are much more important in the deep basins. The world's strongest internal tides (Alford et al. 2015; **Figure 10**, lower left) are generated in the Luzon Strait, some of which propagate southward into the Philippines Archipelago (Alford 2008; Chinn et al. 2012). They can break via shear and/or convective instability, leading to extremely strong, tidally modulated turbulence (Alford et al. 2011, 2015; **Figure 10**, lower right). The constrictions and sills of the Indonesian throughflow (ITF) are also very strong generators of internal tides (Katsumata and Wijffels 2006; Katsumata et al. 2010), though they are very poorly observed; these give rise to fortnightly cycles in SST (Field and Gordon 1992, Ray and Susanto 2016).

Near-inertial internal gravity waves generally dominate kinetic energy in the surface mixed layer; their shear at its base is the dominant mechanism for its deepening. Turbulence both there (Johnston and Rudnick 2009; Dohan and Davis 2011) and below in the ocean interior (**Figure 10**, lower left) can give rise to inertially modulated turbulence; their inclusion in a climate model significantly impacted tropical SST and precipitation (Jochum et al. 2012). Near-inertial power input for the PISTON region should show a very sensitive wind-speed dependence, giving rise to the likelihood of strong monsoonal cycles of the associated mixing (Alford and Gregg 2001).

Diurnal cycling. The surface waters of the low-latitude ocean are heated by the sun at rates that can exceed 1000 W m^{-2} . In moderate conditions, a warm layer ($2\text{-}4^{\circ}\text{C}$) forms in the top few meters of the sea over the course of a sunny afternoon. Turbulence due to nighttime convection caused by heat loss to the atmosphere (and possibly turbulence related to diurnal internal tides) then destroys this temperature gradient. Known as the Diurnal Surface Layer (DSL, **Figure 10**), this feature of low-latitude oceans has a lifecycle that both depends on and affects larger-scale, air-sea interaction processes. Specifically, DSL formation in the proposed study region to first order depends on active and suppressed phases of the MJO (Anderson et al. 1996). This process and its intra-seasonal variability are thought to have a profound effect on tropical precipitation and wind patterns. For example, inclusion of diurnal cycling in coupled ocean-atmosphere general circulation models (CGCM) leads to an increase in tropical SST, particularly in the equatorial Pacific, a redistribution of precipitation in the ITCZ, enhanced equatorial upwelling, and a stronger and more coherent MJO cycle in precipitation, all improving model comparisons to climatology (Bernie et al. 2008).

Small-scale and turbulent mixing processes that set SST

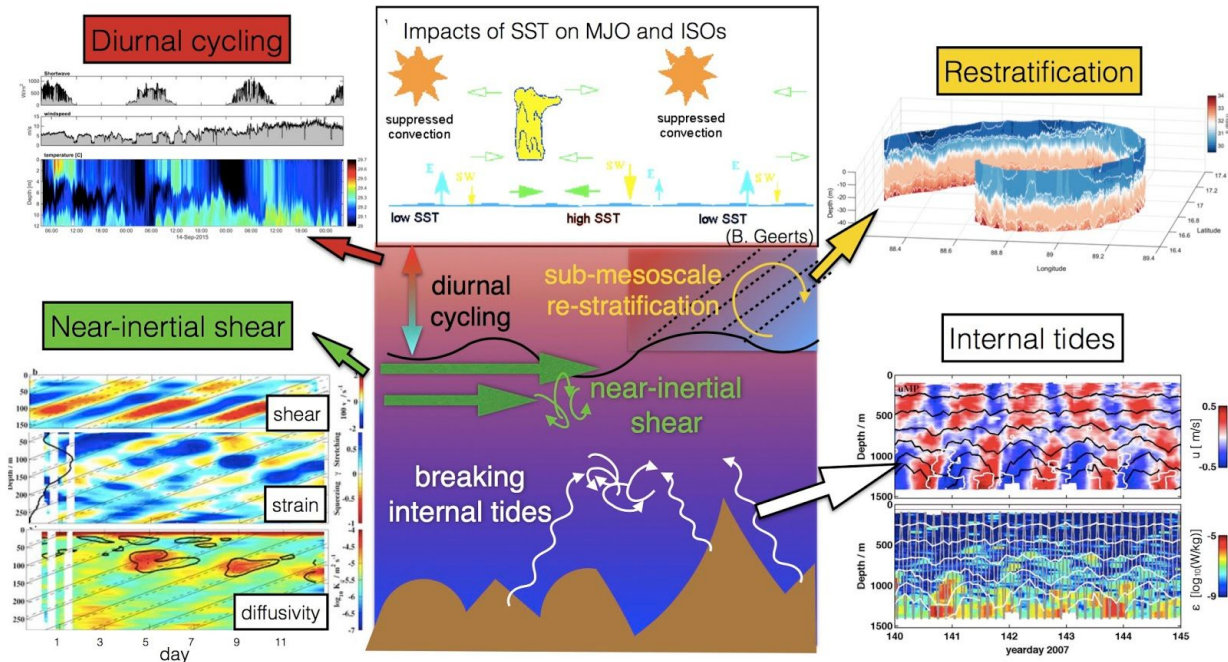


Figure 10. Cartoon of target small-scale oceanic processes that contribute to SST, which in turn modulates the MJO and other intraseasonal Oscillations (ISOs). They include: diurnal cycling (upper left figure of bow-chain measurements); turbulence from wind-forced, downward radiating breaking near-inertial internal waves; Banda Sea observations of near-inertial shear, strain, and microstructure estimates of turbulent diffusivity with clear inertial pulses (lower left figure, Alford and Gregg 2001); sub-mesoscale instabilities and associated re-stratification (upper right figure of wire-walker salinity observations); and turbulence from breaking internal tides (lower right figure shows strong baroclinic velocity and isopycnal heave every tidal period and resultant tidally modulated turbulent dissipation rates; Alford et al [2011]).

In the presence of large near-surface lateral buoyancy gradients (such as from river inputs, rain, or local heating) **submesoscale instabilities** frequently act to re-stratify the upper ocean by 'slumping' horizontal gradients into vertical stratification. The process renders 1-dimensional vertical mixing models inadequate, frequently leading to modeled mixed layers that are too deep, and resultant persistent SST cold biases. Globally, the inclusion of an initial estimate of parameterization of submesoscale processes has led to dramatic reduction of some long-standing model biases in both mixed-layer depths and SST (Fox-Kemper et al., 2011). However, further parameterization efforts have been thwarted by a lack of in situ observations on the relevant scales.

All of these processes are modulated by **lower-frequency processes** such as the monsoon cycle and the regional circulation and the seasonal cycles of stratification, necessitating a good understanding of the regional oceanography of the extremely geographically and oceanographically complex MC. The western Pacific warm pool is pressed against a leaky western boundary feeding into the marginal seas of the MC. Weaving through the network of pathways is the ITF that facilitates the exchange of water between the Indian and Pacific Oceans. The characteristics of the ITF, with its transport and vertical profile, represents an integrated, coupled response to the regional and larger-scale ocean and climate systems (Gordon 2005; Gordon et al. 2011; Sprintall et al. 2014; Hu et al. 2015). The ITF, at a rate of

approximately $15 \text{ million m}^3 \text{ s}^{-1}$, is greater during the boreal summer monsoon (June-September) as well as during La Niña (Gordon et al. 2010; Sprintall et al. 2014).

Air-sea exchange and convective activity within the atmosphere are closely coupled to sea surface temperature (SST), representing the surface expression of the ocean mixed layer. The SST reflects the monsoonal forced radiation balance and wind field. In the boreal winter (December to March), warm SSTs greater than 29°C are shifted southward relative to the boreal summer pattern (June-August; **Figure 11**). As argued above, SST varies across a wide range of spatial and temporal scales in response to a balance between atmospheric forcing, the turbulence-producing processes above, and lower-frequency ocean processes.

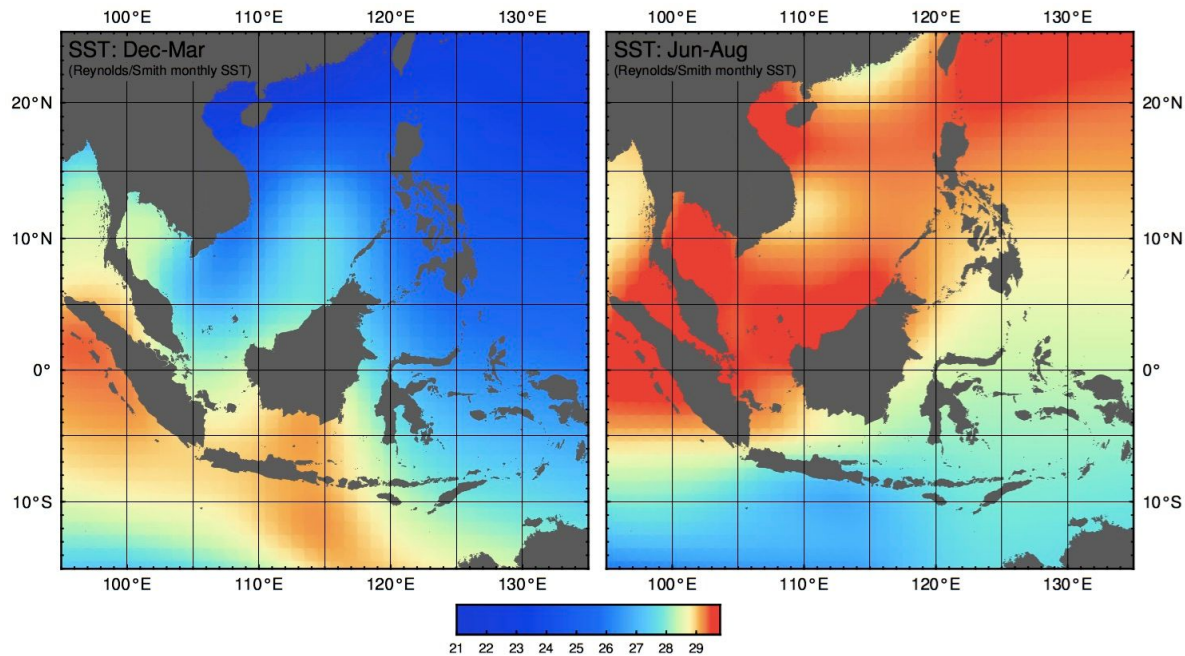


Figure 11. Climatological SST for the Boreal winter (December-March) and Boreal summer (June-August).

For example, imprinted on the seasonal patterns of SST are the intraseasonal signals imposed by ocean Kelvin waves (Drushka et al. 2010; Pujiana et al. 2013) as well as from the atmosphere by the MJO (Zhang, 2005; 2013). MJO activity over the Indian Ocean and MC is enhanced during neutral and negative Indian Ocean Dipole (IOD) events (high low-level humidity) relative to +IOD events (Wilson et al. 2013). Intraseasonal variation accounts for about 40% of SST variability within the MC, with the strongest signature observed in the Banda Sea (Napitu et al. 2015).

Mixed-layer depth is a major factor in dictating the relative roles of the atmosphere and the ocean in setting SST. A deeper thermocline with a thicker warm surface layer occurs during the northeast monsoon (December-February) and during La Niña periods than during the southwest monsoon (June-September) and El Niño periods. Within the Banda Sea, Ekman wind-induced upwelling during boreal summer lifts the thermocline by $\sim 40 \text{ m}$ and leads to cooler SST by $\sim 3^\circ \text{C}$ (Gordon and Susanto 2001) than during the downwelling winter season.

The MJO signature in SST is strongest during the boreal winter when the mixed layer tends to be deeper. This acts to diminish the role of ocean processes driving vertical heat transfer between subsurface and surface layers. A slab model (the ocean is represented only by the homogeneous mixed layer) accurately reproduces the observed intraseasonal variations of

SST during the boreal winter months but underestimates those during the summer months because of cooler subsurface water closer to the sea surface; i.e., ocean processes play a larger role than air-sea fluxes (Napitu et al. 2015). During the active MJO phase, SST should be affected more by upper-ocean dynamics when the colder subsurface water is closer to the sea surface - e.g., boreal summer and during El Niño - as entrainment of the cooler subsurface water into the mixed layer is more likely. During winter and La Niña the SST should respond more to the direct air-sea MJO forcing, as the cold water is more remote from the sea surface, reducing the direct effect of ocean processes on SST.

Developing a quantitative description of the combined atmospheric and oceanic processes governing SST is required to understand the atmospheric convection over the MC across a broad range of scales, including the evolving characteristics of the BSISO and MJO as they propagate across the MC. The keys to this understanding are sustained measurements of the ocean circulation, air-sea fluxes, and the small-scale ocean mixing processes that affect SST. We need to determine the spatial and temporal patterns of mixing, and the associated vertical heat exchange between the surface and thermocline layer from daily to tidal frequencies (including biweekly).

2. Science Objectives and Hypotheses

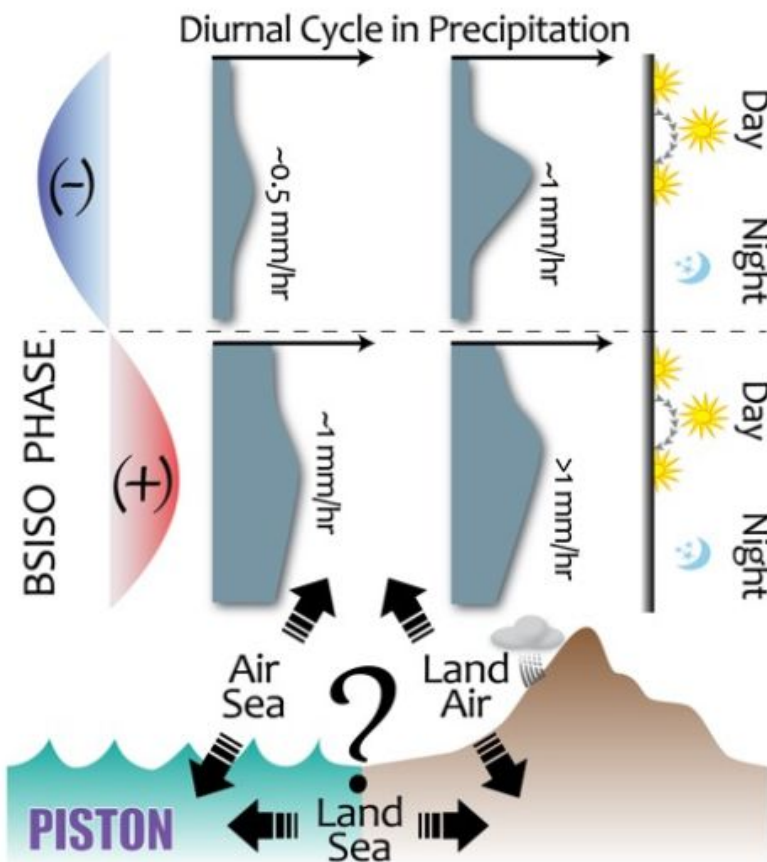


Figure 12. The multiscale, air-sea, and land-atmosphere interaction processes that regulate BSISO propagation and intensity

The goals of PISTON are to forge a better understanding of the multiscale, air-sea, and land-atmosphere interaction processes that regulate BSISO propagation and intensity (**Figure 12**), develop an observational dataset to benchmark model simulations of the BSISO, and use these models and observations to address the overarching PISTON hypotheses defined below. PISTON will identify processes (e.g. convective and surface) in the MC to which model simulations of the BSISO are particularly sensitive, with the goal of improving their representation to enable improved prediction of propagating intraseasonal disturbances that transect the Philippines Archipelago and MC. PISTON field observations and high-resolution models will foster process understanding that leads to improved model and predictions.

The introductory science discussion motivates a coordinated observational and modeling program that is guided by the following overarching hypotheses (**a, b, c, d**):

a. Large scale atmospheric circulation variability over the South China Sea related to the monsoon, intraseasonal oscillations, and convectively coupled waves modifies the local diurnal cycle and air sea interaction in the coastal regions and nearby open seas.

Work on characterizing the amplitude and phase of the diurnal cycle of convection in the SCS and adjacent land areas during boreal summer as a function of large-scale atmospheric regime has been limited. Different satellite-derived rainfall estimates provide different depictions of the mean diurnal cycle in the SCS and adjacent land areas (e.g. TRMM 3B42 and PR, Steve Rutledge, personal communication), and limited comparisons of the amplitude and phase of the diurnal cycle as a function of BSISO regime produce conflicting results (e.g. Chen and Takahashi 1985; Naoko Sakaeda and Steve Rutledge, personal communications). Previous studies for the broader MC region have argued that suppressed cloudiness and high surface insolation (that generates strong land-sea breeze circulations), light winds, and an increasingly moist troposphere support enhanced diurnal precipitation variability over land regions in advance of the large-scale intraseasonal convective envelope (e.g. Birch et al. 2016; Vincent and Lane 2016), though other studies have shown stronger diurnal cycles during the active phase (Peatman et al. 2014). It is anticipated that the strength of the land/sea breeze circulation will maximize with weak mean flow; as the mean flow increases, the land/sea breeze circulation will also weaken; with further increases of mean flow (larger Froude number), the mesoscale circulation around the island may transition from a boundary trapped vortical flow associated with the land/sea breeze to linear gravity waves with alternating ascent/descent throughout the troposphere (Wang and Sobel 2017). It is of great interest to understand how those circulation changes can potentially modify convective triggering, organization and evolution. However, an enhanced diurnal cycle of SST during high insolation, light wind conditions in coastal waters may moderate land-sea breeze circulations and weaken the diurnal cycle and propagation of strong convective systems near land.

These ideas are testable by both models and observations in the pre- and post-field phase. Large-scale intraseasonal conditions can be identified by using existing intraseasonal indices such as the Indian ocean and Western Pacific BSISO, MJO, MISO indices (Kikuchi et al 2012, Lee et al 2013, Suhas et al 2013, Lee and Wang, 2016). Observed local conditions will be compared to canonical BSISO projections. The diurnal variability under these different mean conditions will be examined for selected cases in coordinated multi-model experiments. The field phase observations will validate the models' diurnal variability under these different large-scale states. Models may have different local diurnal response to the large-scale forcing

which may provide insight into important physical processes prior to the field phase that can refine the observation strategy. Further, sensitivity tests that modify the treatment of the ocean and land surface can test the salience of various factors to regulation of the diurnal cycle and its propagation.

Key questions include: How does the phase and amplitude of the diurnal cycle vary over ocean and land as a function of BSISO phase? How do variations in wind speed and ventilation as well as the diurnal cycle of surface insolation as a function of BSISO phase affect the diurnal cycle over land and ocean? How does the presence of ocean diurnal warm layers that form in light wind, high insolation conditions affect the strength of the land-sea breeze circulation near the Philippines? How does the direction and strength of the large-scale BSISO flow impinging on the topography of islands such as Luzon affect the strength and propagation of diurnal disturbances?

1) We hypothesize that the diurnal cycle of convection over land is enhanced during the convectively suppressed phase of the BSISO due to a general decrease in large-scale cloudiness, associated increase in the diurnal cycle of surface incident shortwave radiation, and light winds.

2) We hypothesize that a stronger diurnal cycle of SST during the suppressed phase of the BSISO associated with increased surface insolation and light winds that peaks in the late afternoon moderates the strength of the land-sea breeze system and hence weakens offshore propagation of diurnal convective disturbances initiated over land.

3) We hypothesize that the precipitation diurnal cycle over the islands is significantly modulated by the large-scale flow across the islands, which controls the strength of thermally direct land/sea breeze circulation.

b. Small scale convective processes (e.g., interaction with complex terrain and coastlines, cloud microphysical processes, and the details of convective cold pools) influence the propagation of larger convective systems across the region. This happens because convection over the Maritime Continent is inherently multi-scale, with the large scale flow and environment (e.g., shear, thermodynamic state, etc) setting the context for embedded convective systems that range from individual cumulus clouds to convectively coupled waves.

Processes on the scale of isolated individual convective elements, such as cold pools, gust fronts, and latent heating/cooling in convective cores and downdrafts, can influence organization of convection on the mesoscale ($O(100-1000 \text{ km})$), specifically the formation and evolution of MCSs. The development and propagation of individual convective elements and MCSs over and around tropical islands are hypothesized to be influenced by the spatial and temporal variability of the flow and thermodynamic profile, the limited heat capacity of land and its resulting sensitivity to the diurnal cycle of insolation, island orography and other factors. Processes that influence MCS development also drive and interact with land-sea breezes in complicated ways that are not fully understood. MCSs constitute the building blocks of tropical convectively coupled waves (CCWs) and the BSISO and MJO (Mapes et al. 2006), and are comparatively modulated more than other cloud types by the phase of the CCWs, BSISO, and MJO (e.g., Jiang et al. 2011; Riley et al. 2011).

Key questions include: How do changes in the large scale flow and environment, consistent with the propagation of CCWs and the phase of the BSISO, modulate the upscale development of convection and the properties of MCSs? How do environmental factors interact with the limited heat capacity of the land surface versus ocean to influence the development of MCSs and their resulting propagation? How do gravity waves and cold pools generated by convective disturbances over land regulate offshore convective system propagation? How do the specifics of convective element and MCS development feed back on large scale CCW characteristics and propagation?

1) We hypothesize that the production and properties of cold pools and gravity waves , along with the organizing influence of shear, influence the propagation of CCWs across the MC.

2) We hypothesize that gravity waves generated by convection generated over MC land regions are an important factor in the off-shore propagation of diurnal convective systems.

3) We hypothesize that ubiquitous MCS generation over land regions of the MC is dependent on the low heat capacity of the land surface rather than topographic forcing.

c. 3-dimensional oceanic processes are important to BSISO propagation in the SCS.

The SST during BSISO events is likely modulated by a variety of 3-dimensional ocean processes, including a) breaking internal waves of near-inertial and tidal frequency, b) shear instability of low-frequency flows, and c) lateral mixed layer instabilities such as slumping. The formation of diurnal warm layers can significantly modulate surface heat fluxes. Klingaman et al. (2011) suggest that accurate simulation of these sub-daily variations in a coupled model, using very high (~1m) vertical resolution in the ocean near the surface, is essential to accurate simulation of the BSISO in the Indian Ocean region. It has also been suggested that diurnal variations are important in the South China Sea (SCS) and elsewhere (Clayson and Bogdanoff 2012). Thus, high vertical resolution near the ocean surface may be important for the simulation of both the diurnal cycle and the BSISO in the SCS. This can be tested by sensitivity experiments in which vertical resolution near the ocean surface is increased or decreased. The upper-ocean diurnal warm layer is affected by variations of the wind stress, surface buoyancy flux, and stratification through nonlinear processes among the mixed layer depth, barrier layer depth, heat flux, and land-sea breezes. Observations of the ocean stratification and current profiles, along with fluxes of buoyancy and momentum can be used to validate the model-simulated relationships between these processes.

Ocean coupling has more potential to amplify the BSISO by generating SST anomalies that reinforce its propagation (e.g., Wang et al. 2006; Bellon et al. 2008) in the northern vs. southern SCS. For instance, intraseasonal variance in precipitation is larger in the northern part of the SCS where the ocean is relatively deep and wind-induced mixing has the potential to bring up cold water. In contrast, further south where the continental shelf is shallow and bottom water is relatively warm, mixing will have less impact on sea surface temperature (A. Gordon, personal communication). The deeper ocean in the northern SCS may allow stronger coupled feedbacks due to greater potential for mixing-induced surface cooling. This can be tested in coupled models by artificially reducing the depth of the bathymetry in the northern SCS, with the prediction that BSISO propagation into that region will be inhibited by the smaller SST

anomalies generated.

Key questions include: How do breaking internal waves of near-inertial and tidal frequency, shear instability of low-frequency flows, and lateral mixed layer instabilities such as slumping regulate SST during BSISO events? How do diurnal warm layers in the ocean contribute to northward BSISO propagation? How does the diurnal cycle of the upper ocean regulate the propagation of convective disturbances that initiate over land and propagate offshore? How does the modulation of ocean heat content by one BSISO event influence subsequent events? Do ocean bathymetry changes across the SCS cause ocean feedbacks to the atmosphere to be different in some parts of the basin than others?

1) We hypothesize that diurnal warm layers generated preferentially during the BSISO suppressed phase are important to BSISO propagation, and modeling them requires high vertical resolution near the ocean surface.

2) We hypothesize that modulation of SST by ocean processes both influences the propagation of individual BSISO events, and also provides ‘oceanic memory’ from one event to the next, so that a strong BSISO event can weaken the next one.

3) We hypothesize that ocean coupling plays a stronger role in BSISO propagation and maintenance in the north SCS than south SCS, due to deeper bathymetry in the north.

d. Local and mesoscale processes related to the presence of land and topography, atmosphere-ocean interactions, and atmosphere-land and river-ocean interactions influence the development and propagation of the BSISO. These processes include land-sea breezes, the diurnal cycle, surface fluxes, gravity waves, convective variability, and upper-ocean dynamics, and river runoff.

As the BSISO propagates northward and eastward, its amplitude is reduced during the passage over the Philippine islands. We suggest that this disruption is caused by the presence of land itself, through the reduction in effective surface heat capacity compared to ocean (Sobel et al. 2010), rather than through topography, albedo, vegetation, or some other impact. The implication is that modeling experiments in which the islands are made flat will still show the disruption, as will experiments in which albedo or vegetation are altered, as long as the surface is still land. On the other hand, experiments in which the islands are eliminated altogether, and replaced by ocean with characteristics broadly similar to those of the surrounding seas, will not show the disruption, but will allow the BSISO to pass uninhibited.

Very high-resolution large eddy simulation (LES) of land-atmosphere-ocean interactions will explain how the Philippine islands alter the phase relationships between wind, SST, and surface fluxes, compared to open ocean. The diurnal pulsing of convection, due to the low heat capacity of the land, may relieve the atmosphere of moist static energy – thereby reducing variability at intraseasonal time scales in the neighborhood of islands. Diurnal land-sea breezes and convection also affect the diurnal cycle of upper ocean stratification, and atmosphere-ocean heat and momentum exchange. These effects may rectify on the mean upper ocean heat budget, air-sea fluxes, and atmospheric profiles.

The influence of island topography on the atmosphere will be investigated in parallel model experiments. The ability of organized convection into the MCS to traverse the island barrier will be influenced by the environmental moist Froude number relative to the height of the topography. The intensity of MCS convective activity and the distribution of associated eastward/westward propagating precipitation across Luzon can be analyzed in relation to the cold pool structure and flow regime. Numerical experiments to quantify the sensitivity of the MCS updraft strength and cold pool depth due to the influence of terrain height will determine the contribution of orographic ascent/descent to overall storm strength, as well as the responsiveness of the land- and sea-breeze circulations to topography. Also of interest is how those circulation changes modify convective organization and evolution. To understand how topography is important to BSISO maintenance and propagation through the Philippines region, a comparison between model-simulated BSISO events that successfully propagate or fail to propagate through the Philippines region can be made.

River discharge, with maximum values in the Philippines in later summer to early fall, is a source of significant freshwater to the coastal ocean. The significance of these factors was suggested by prior modeling and observations in the region (Pullen et al., 2015). In particular, Luzon has substantial river run-off with the largest river discharge by volume and 3rd largest by area in the Agno River basin draining into Lingayen Gulf. The occurrence of barrier layers associated with these low salinity waters can impact the fluxes and feedback to the atmosphere (DeMott et al., 2015). The episodic nature of the discharges with a maximum in the fall, and the intense spatial gradients of these features is likely important to the dynamics. The impacts on models can be tested both with cloud resolving model (CRM) (sensitivity studies with lower boundary condition modifications) and coupled model runs. In particular, simulations that compare climatological river discharge values with gauged discharge values can assess the impact of run-off in this region. Another aspect of this effort is the testing of the linkage of a hydrology model, WRF-Hydro, within the COAMPS framework.

Land use patterns may also modulate the BSISO propagation by modifying the diurnal cycle of temperature and precipitation at local and regional scales. Urban environments have been known to modify convective events (Bornstein 1968). The comparison of simulations with and without urban parameterization will reveal the role of urban areas, if any, on the diurnal cycle of temperature and precipitation.

An important physical process over the land surface that is not included in most models, including the WRF-ARW, is the surface cooling due to precipitation (QP). Since raindrops are cooler than the land (or ocean) surface, precipitation cools the land (or ocean) surface temperature. During intense rainfall events over ocean, QP may be as high as 200 Wm^{-2} and may exceed the cooling due to latent heat flux from the surface (Gosnell et al. 1995). The role of QP on the diurnal cycle of surface temperature and its role on the BSISO will be quantified.

It is likely that the thermodynamic adjustment of deep convection is different for convection triggered by high surface temperature over land, compared to marine convection. The latter maintains radiative convective equilibrium under weak surface temperature gradients and temporal variability. An expected result of this hypothesized difference is stronger convective cold pools due to enhanced precipitation evaporation through drier air masses originating over land. Colder, drier, and deeper cold pools are expected to enhance gusts and surface fluxes near land.

Key questions include:

Is it the presence of land itself through low heat capacity, or other factors such as topography or vegetation, that causes the weakening of the BSISO over land? How does the diurnal cycle deprive the BSISO of its vital energy sources near and over land? How does the diurnal cycle and MCS strength depend on the height of topography? How does episodic river discharge affect ocean barrier layer strength and feedback onto the atmosphere? How do the different characteristics of convective cold pools over land versus ocean impact surface heat exchange, and what are the implications for BSISO dynamics? How does the spatial and temporal evolution of river discharge modify coastal gradients of temperature and salinity and potentially feedback to the atmosphere on diurnal to intra-seasonal timescales?

1) We hypothesize that the low heat capacity of the land surface, rather than topography, albedo, or vegetation, is responsible for disrupting the BSISO over the Philippine islands.

2) We hypothesize the diurnal pulsing of convection, due to the low heat capacity of the land, relieves the surface and atmosphere of moist static energy – thereby reducing variability at intraseasonal time scales in the neighborhood of islands by preventing a true suppressed phase from occurring over islands to the extent it can over the open ocean.

3) We hypothesize that barrier layers formed by river discharge to the coastal ocean enhance the diurnal cycle amplitude during offshore propagation.

A discussion of the observational and modeling strategy to address these hypotheses is contained in the following sections.

3. Observational Strategy

3.1 Justification for location and timing of PISTON field observations.

According to Lee et al. (2013), the leading mode of convective and wind variability that explains the BSISO has substantial variance in May-October, with a maximum in August. A variance maximum associated with this mode occurs in the SCS to the west of Luzon (see their Figures 1 and 2, and also **Figure 1** of this document), with prominent northward propagation through this region. A local minimum in intraseasonal OLR variance occurs over the Philippine islands, consistent with the general minimum in intraseasonal convective variance observed over other MC islands. As suggested by **Figures 8** and **9**, the seas near the west coast of Luzon are also characterized by a maximum in daily mean precipitation and diurnal cycle amplitude. These maxima are strongest during July and August, with the magnitude of both features being reduced by at least 20% during June and September (not shown).

The western Pacific has the highest concentration of tropical cyclone activity in the world, and although TCs can develop all year the frequency and geographic location of genesis varies by season. **Figure 13** shows the location of genesis events for the months of July-October, indicating the maximum probability for a genesis event in the SCS west of Luzon would occur in August and September. A high probability of genesis is also present in July, but the activity decreases and shifts southward in October. It is noted that the majority of genesis events in the SCS do not reach major typhoon intensity (100 kts), and frequently peak below typhoon

intensity (65 kts). The climatology suggests that most major typhoons originate east of the Philippine islands and daily forecasts would provide ample warning time to reposition the ship to avoid high swell and wind conditions. Weak TD formation in the SCS would be a target for science operations, and would be probable in August and September.

The high-amplitude intraseasonal variability, strong diurnal cycle, greater likelihood of tropical depression activity, and rich interactions among these processes suggest that a field program centered during August-September 2018 would be well-suited to answer the scientific hypotheses discussed above.

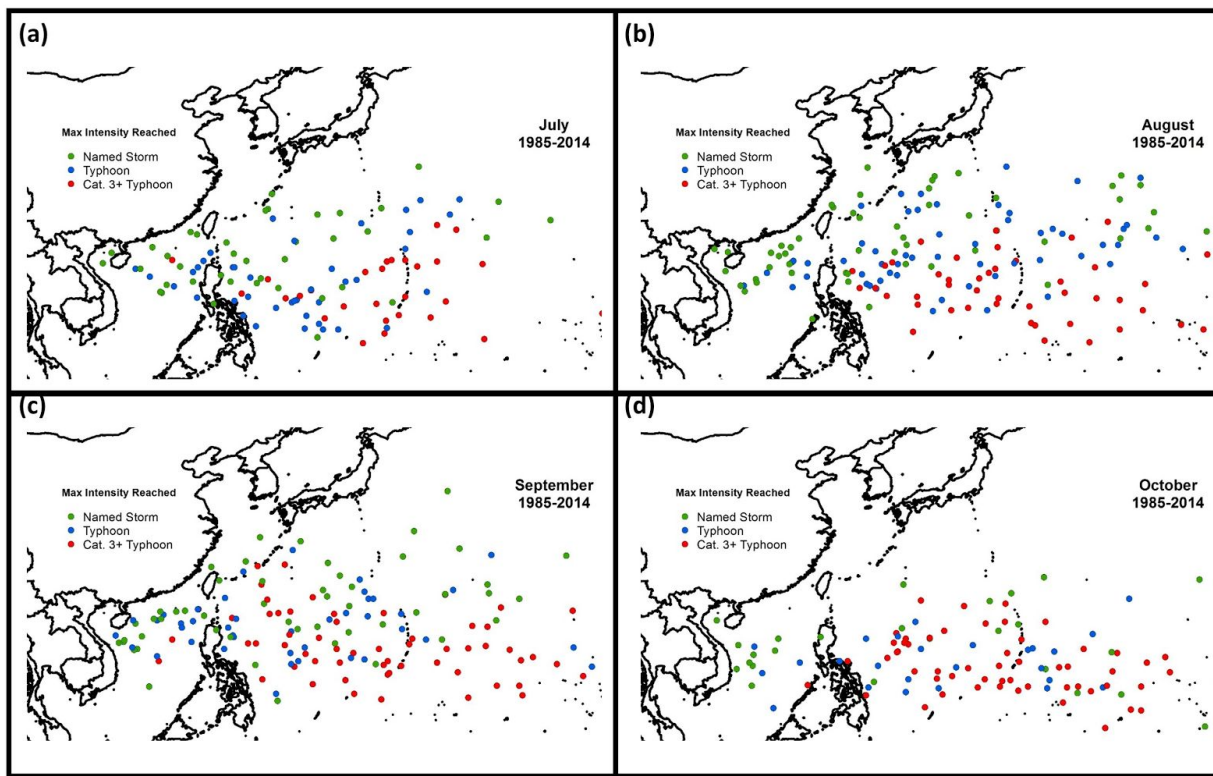


Figure 13. Tropical cyclone genesis locations from 1985 - 2014 in (a) July, (b) August, (c) September, and (d) October. Green circles denote cyclones with lifetime maximum intensity less than 65 kts, blue circles denote maximum intensity between 65 - 100 kts, and red circles denote maximum intensity greater than 100 kts.

3.2 Atmospheric observations

The detailed observational strategy will be developed in an experimental design document to be published in 2017, and hence the details provided below are purely suggestive and subject to substantial revision. One possible strategy is presented here, shown schematically in **Figure 14**. In this strategy, the research ship (*R/V Thomas G. Thompson*) would be located along 18°N, 50 km offshore from Luzon for cruise 1 and along 16°N, 200 km offshore for cruise 2. Cruise 1 will provide observations of over-land convection and sea/land-breeze circulations. Cruise 2 will

provide similar observations for open-ocean convection. These two locations will also provide important time series observations for air-sea fluxes and upper-ocean turbulence/mixing.

A primary atmospheric observational component for PISTON is designed to understand the diurnal cycle of convection both onshore and offshore of the west coast of the Philippines and how this convection interacts with the BSISO. Shipborne weather radar and radiosonde observations are central atmospheric observations for PISTON. Radar observations are needed for both convection over the high terrain of Luzon as well as immediately offshore, where locally heavy precipitation occurs. Radar observations of Doppler velocity, reflectivity and a full suite of polarimetric variables will be obtained 24/7 and will provide information on storm structure, kinematics, cloud microphysical processes and rainfall amounts. Radar observations will be provided by SEA-POL, a state-of-the-art C-band polarimetric, Doppler radar currently being developed at Colorado State University. The radar observations will provide a wealth of information regarding sea-breeze forced convection over land. Radar observations will determine convective and stratiform rain fractions, as well as mesoscale organization. To document the thermodynamical environment for convection, radiosondes will be launched from the ship (e.g *R/V Thomas G. Thompson* or equivalent) at a frequency of eight per day. Taken together, these observations will document the roles of land breezes and gravity-wave mechanisms as possible forcing agents for the nocturnal offshore convection.

The ship radar and radiosonde observations will be complemented by planned C-band polarimetric radar observations and radiosonde observations at Taiping Island (Spratly Island chain) by Taiwan. The distance between the nominal SEA-POL location and Taiping Island is approximately 800 km, similar to the distance between the Reville and S-Pol radars deployed in DYNAMO. During that experiment, the S-Pol radar on Gan Island provided upstream observations of the MJO convective envelope prior to its arrival at the R/V Reville to the east. We envision similar coordination here between SEA-POL and the Taiping Island radar. As discussed below in the linkages section, PISTON will benefit from flight-level data on board the NASA P-3 involved in Cloud and Aerosol Monsoonal Processes-Philippines Experiment (CAMP²Ex) for characterizing the environment for convection, along with a means to validate SEA-POL radar-based hydrometeor identification algorithms with in situ microphysical observations.

Near-surface boundary layer meteorology and surface flux observations collected at high-resolution from the ship will sample the turbulent to mesoscale coherent structures related to shallow and deep convection, and land-sea circulations. Combined with observations of the atmosphere above from soundings and radar, and observations of the upper ocean below, the atmospheric boundary layer observations measure the interactions, notably the exchange of moist static energy, that couple the ocean and atmosphere on turbulent, diurnal, synoptic, and intraseasonal time scales.

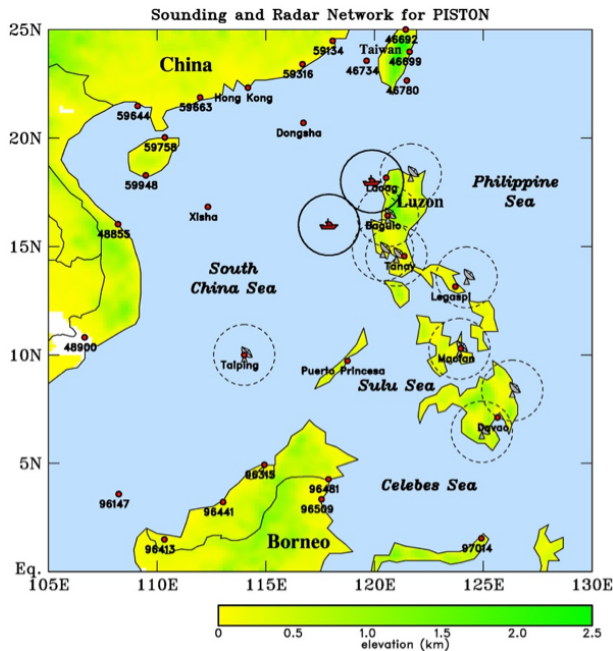


Figure 14. PISTON experimental domain. Operational and research sounding sites are indicated by red dots. Radar sites with 150 km range circles are marked. Topography is indicated by shading with scale at bottom.

3.3 Ocean observations

The goals of the ocean observations are to 1) obtain many-month time series of upper-ocean (subsurface) heat fluxes, 2) identify the processes responsible, and 3) obtain sufficient spatial measurements to contextualize them in terms of the larger-scale oceanic background. To these ends, we envision a two month shipboard program nested within moored time series that are as long as possible. Though the details are not yet firm, we anticipate the following components of the observational program:

- 1) Shipboard time series of microstructure profiles to estimate heat fluxes in the upper 200-300 m and particularly across the diurnal warm layer and seasonal mixed layer. Additional concurrent profiles of velocity, temperature, and salinity will enable calculation of key parameters such as mixed-layer depth, heat content, and lateral contributions to temperature budgets. These measurements will also provide crucial information on the processes responsible.
- 2) Two subsurface moorings consisting of Acoustic Doppler Current Profilers (ADCPs), conductivity, temperature, and depth devices (CTDs) and Oregon State University chi-pods every 20-30 m in the upper several hundred meters, giving long time series (at least 3 months; longer if additional ships of opportunity including Filipino vessels and/or the *R/V Ron Brown* can be used for deployments and recoveries) of turbulence, shear, and stratification in the upper few hundred meters. We view these moored time series as critical to the success of the experiment, providing measures of not only the near-inertial wave response to ISO wind bursts, but also the incoming internal tide that might contribute to mixing under some conditions. These two subsurface moorings will be augmented by an additional two similar moorings deployed by scientists at Tongji University (Dr. Yanwei Zhang, China),

- 3) Spatial surveys to characterize the regional oceanography and large-scale gradients. These might entail 100-km crosses or boxes centered on the moored and shipboard time series. With underway CTD or towed vehicles such as Scripps Institute of Oceanography Shallow Water Integrated Mapping System (SWIMS) profiler, these surveys could be done very quickly (~1 day) at the beginning and end of each cruise.

4. Modeling Strategy

4.1 Introduction

Models play a key role in the motivation and implementation of PISTON. On one hand, to the degree we can rely on aspects of models to reasonably represent the variability and processes in the PISTON domain, they are a necessary part of the research activities and implementation plan to address the PISTON hypotheses. On the other hand, we also know that models exhibit shortcomings in their representations of diurnal, synoptic, subseasonal, and seasonal variability in the PISTON domain, and a big part of the motivation for carrying out PISTON is the expected improvement in our simulation/forecast models that will come from incorporating the knowledge that we gain from the PISTON observations. With these two considerations in mind, we see models playing the following roles in the motivation, planning, implementation, and analysis activities of PISTON:

- 1) In advance of the PISTON field phase, simulated observations and observing strategies will be tested with high resolution model output to help guide the deployment of field resources. Idealized model experiments before the field phase will identify model processes on which convection and the BSISO sensitively depend. Some of these processes may be constrained by the field measurements. Forecast sensitivity experiments (e.g., varying resolution, domain size) will also be performed to determine the configuration of the real-time forecast system that will support the field-phase.
- 2) During the field phase, forecast models will be used to identify phenomena of interest and guide the deployment of mobile platforms (e.g., ship, aircraft).
- 3) During the analysis phase, models will be combined with observations via data assimilation to yield more complete and continuous state estimates of the ocean, atmosphere, and land systems, thereby providing a more comprehensive data set for addressing the PISTON hypotheses.
- 4) Models that compare favorably to observations on a process level can be used in sensitivity tests to address PISTON hypotheses.
- 5) Where PISTON observations and analyses result in advances in process knowledge and identification of specific model shortcomings, this information will enable and facilitate model improvements.

Models that are determined through detailed comparison to PISTON and other observations to contain a realistic representation of the mean monsoonal state, BSISO, convectively coupled waves, the diurnal cycle, and their underlying processes can provide invaluable tools for furthering understanding beyond that directly provided by field measurements. Such models, including those used for data assimilation, can provide high temporal and spatial resolution process information and the ability to conduct sensitivity experiments that is not possible given

limited observational resources and the inability to conduct mechanism-denial experiments on the real Earth. For example, the atmospheric and oceanic diurnal cycle can be minimized in modeling experiments, and the resulting impacts on BSISO propagation assessed. Similarly, studies can evaluate the influence of river discharge on atmospheric propagating features.

This section will summarize the modeling resources that are contributed by the PISTON science team, provide a preview of how these models are expected to be used to address PISTON hypotheses, and discuss synergies between models and observations that foster PISTON goals including data assimilation, OSSEs, and the ability of PISTON observations to foster modeling improvement.

4.2 Modeling tools

PISTON science team members contribute directly, or indirectly via their involvement in community science activities, to a hierarchy of modeling tools including large-eddy models, cloud-system-resolving models (CSRMs) that span local to regional domains, and climate simulations, forecasts, and reforecasts of global models. Model experiments are proposed that employ uncoupled atmospheric versions of these models, coupling to fully dynamical oceans, and coupling to 1-dimensional mixed-layer models. These modeling tools will be briefly summarized here, along with how they will be used to address PISTON hypotheses.

- The Coupled Ocean/Atmosphere Mesoscale Prediction System (COAMPS®), coupled to the Naval Research Lab (NRL) Coastal Ocean Model (NCOM), and two inter-changeable wave models Simulating Wave Nearshore (SWAN) Wave Watch III (WW3, Tolman 1991). COAMPS will be two-way coupled to NCOM and one-way coupled to WW3 for the PISTON realtime forecast support. During the analysis phase, COAMPS will be coupled with SWAN to examine the ocean-current and air-sea interactions. COAMPS is a hydrostatic primitive equation model that is fully compressible (Hodur et al. 2002; Chen et al. 2010). While the standard microphysics scheme is single-moment, the version to be used for the analysis phase may contain generalized microphysics advancement that may be important to improve COAMPS microphysics and precipitation prediction for MC region. NCOM is a hydrostatic primitive equation ocean model that uses a hybrid sigma-height vertical coordinate (Martin 2000). A new generalized vertical coordinate in NCOM can reduce the computational cost of running the ocean component. An embedded NOAA land-surface model will be included for COAMPS realtime forecast. This modeling framework will be run with resolutions as high as 1-3 km for the ocean and atmosphere for a nested region that covers Luzon and the proposed RV Thompson location, and 1/9 of the resolution for the coarse domain that covers the entire MC region. In advance of the PISTON field phase, additional COAMPS runs using idealized initial and boundary conditions will be used in conjunction with the real data simulations.
- The NRL coupled NAVGEM/HYCOM (Hogan et al. 2014; Metzger et al. 2010) global prediction system will be used in hindcast mode. In the pre- and post-PISTON campaign phases, a 80 or 90-day NAVGEM/HYCOM hindcast will provide COAMPS the initial and boundary conditions for COAMPS intraseasonal sensitivity experiments.
- The Skillingstad and Edson (2009) large eddy simulation (LES) model will be used to simulate land-atmosphere-ocean interactions. The model solves momentum equations

in flux form using a formulation based on Deardorff (1980), and employs a subgrid closure derived from Ducros et al. (1996). A seven-component microphysics scheme and parameterization of solar and infrared radiation are included. The LES will be coupled to a one-dimensional ocean model based on the *K*-profile parameterization mixing scheme (KPP, Large et al. 1994). The LES is coupled to the ocean using the COARE bulk flux algorithm of Fairall et al. (1996). Skillingstad and de Szoeke (2015) used a version of this model with 300 m grid spacing in a 500 km x 500 km domain to study convective variability and interaction with surface fluxes during DYNAMO MJO events.

- Multiple science team members plan to use the Advanced Research Weather Research and Forecasting Model (WRF-ARW) run using cloud-system-resolving horizontal grid spacing (e.g., Skamarock et al. 2008). WRF is maintained as a community resource for both research and operational applications. Numerous physics options are available for WRF-ARW contributed by both WRF model developers and the user community. The PISTON science team will use various configurations for WRF including local (e.g., order hundreds of kilometers), regional (order thousands of kilometers), and tropical channel (entire tropics) domains. Coupled simulations will also be conducted to examine the impact of ocean coupling on BSISO propagation.
- The Regional Atmospheric Modeling System (RAMS, Pielke et al. 1992; Cotton et al. 2003) will be used at convection-permitting grid spacings of 1 to 8 km. RAMS is fully compressible and non-hydrostatic with multiple microphysics, interactive radiation, surface, and turbulence schemes available (e.g., Cotton et al. 2003). RAMS uses the Land Ecosystem-Atmosphere Feedback 3 (LEAF-3) sub-model to represent atmosphere-terrestrial heat and moisture feedbacks (Walko et al. 2000). As for the Skillingstad and Edson (2009) model described above, RAMS will be coupled to the 1-dimensional vertical mixing ocean model KPP (Klingaman et al. 2011; Large et al. 1994) to evaluate the role of air- and land-sea feedbacks in maintaining the diurnal cycle of convection and contributing to BSISO propagation. RAMS will be used both in local and regional domains.
- The “Vertical structure and physical processes of the Madden-Julian Oscillation” model diagnostics project features a database from 28 global models of 20-year climate simulations, and 20-day and 2-day hindcasts during MJO events in the winter of 2009-2010, with the temporal frequency of output ranging from 6-hourly for the climate simulations down to time step level for the 2-day hindcasts (e.g., Klingaman et al. 2015). Moreover, the model outputs include momentum, moisture and temperature tendency terms, and full vertical profiles. The project was conducted under the auspices of the Year of Tropical Convection Program (Moncrieff and Waliser 2015) in collaboration with the Working Group on Numerical Experimentation (WGNE) MJO Task Force and the Global Atmospheric System Studies (GASS) panel of the Global Energy and Water Cycle Experiment (GEWEX). As stated in Klingaman et al. (2015), “the overall aim of the project is to characterize, compare, and evaluate the heating and moistening processes associated with the MJO in GCMs, with a particular focus on the vertical structures of those processes.” The database features both coupled and uncoupled simulations, and is an excellent tool to study the ability of models to propagate the BSISO through the MC region (e.g., **Figures 5 and 6**), the implications for prediction, and process-level understanding of possible deficiencies.
- The WWRP-WCRP S2S Prediction Project (Vitart et al. 2016) is a database that includes ensemble predictions from eleven operational S2S forecast systems around the world

(ECMWF, NCEP, JMA, CMA, HMCRC, Meteo-France, CAWCR, EC, KMA, UKMO, CNR), along with their multi-decade reforecast datasets, in order to do bias correction, quantify hindcast fidelity, and provide uncertainty quantification for present-day forecasts. Each forecast center provides ensemble forecasts and reforecasts, with lead times ranging between 4-8 weeks – albeit with a 3-week time delay, ensemble sizes ranging between 4 and 51 members, forecast frequency ranging between daily to every 2 weeks, and reforecasts ranging from 15 to over 30 years, depending on the center. Forecast model output includes all basic meteorological quantities (e.g., wind, temperature, and specific humidity at a few levels, plus sea level pressure) as well as a number of application/process quantities (e.g., soil moisture, snow quantities, surface radiation, convective available potential energy, etc.) with daily temporal resolution, except for precipitation which is provided every 6 hours. (For additional details, see <http://s2sprediction.net>.)

4.3 Addressing hypotheses with models

As mentioned above, models that exhibit some fidelity at representing PISTON-targeted processes/variability provide an essential tool for addressing PISTON hypotheses. Model evaluation will include assessing the realism of the diurnal cycle, the BSISO, convectively coupled equatorial waves, the mean state, and their interactions relative to PISTON observations and complementary datasets. This validation will include a careful analysis of local convective processes in models, such as diurnally generated convective systems compared to PISTON observations from radar and other sensors. The ability of models to properly simulate the mean state and variability of the upper ocean and its interaction with atmospheric convection that is locally generated and/or propagating from land is also a key focus. Detailed analysis of the ability of models to simulate the thermodynamic (diurnal temperature and partitioning of sensible and latent heat flux), roughness, and terrain effects of islands and their connection to biases in convective variability on diurnal, intraseasonal, and seasonal timescales will be an important focus. This exercise will not only provide a benchmark of model performance and highlight areas where models might be improved through parameterization development, but will also assess whether models simulate salient processes with enough fidelity to use in addressing PISTON hypotheses.

Models will be used to address the hypotheses above using both process-oriented diagnosis of high time and space resolution model output fields, and active experimentation with model process formulation to assess the sensitivity to various processes. In the context of model diagnosis, different environmental conditions associated with large-scale tropical disturbances such as the BSISO (SST, wind direction, shear, CAPE, aerosols) will be prescribed to simulations for events during the PISTON period, and how interactions of convective disturbances with complex archipelago terrain change as a function of large-scale conditions will be identified. The regulatory processes of SST and upper ocean structure for different BSISO phases will be diagnosed in coupled simulations, including the mechanisms causing vertical mixing in the Indonesian Seas and the South China Sea: wind mixing, role of air-sea interaction and surface heat and freshwater fluxes, surface waves, and shear-induced mixing at the base of the mixed-layer depth. The coupling between boundary-layer winds and SST variations, including impact on wind stress and wind stress curl in vicinity of strong SST gradients, will also be a key focus. Detailed diagnosis of model atmospheric budgets of moist-static energy, moisture, and momentum will be used to assess feedbacks of the ocean, large-scale wind and

radiation anomalies, and storm-scale convective elements onto large-scale convective organization and propagation.

Model sensitivity tests will be used extensively by the PISTON science team for hypothesis testing. Tests will be conducted that reduce or eliminate terrain and individual or multiple islands in the Philippines and other regions of the MC to assess changes to the diurnal cycle, and how these diurnal cycle changes and other changes from modified topography feedback onto BSISO propagation. Conversely, the land surface of the MC can be expanded in models to assess its impact. The diurnal cycle over ocean and land will also be modified through other means such as fixing insolation or changing the ocean-atmosphere coupling frequency to daily to assess the diurnal cycle importance for BSISO propagation. The vertical resolution of upper-ocean layers will be varied to assess the importance of shallow diurnal warm-layer generation for BSISO propagation. Also impacting the upper ocean near the coast is river run-off that peaks in the time period of PISTON observations. It is expected that climatological river discharge values do not capture the extent and magnitude of the coastal ocean changes induced by river discharge. Hence sensitivity studies with climatological and measured river discharge will be pursued. The impact of urban areas such as Manila on the diurnal cycle and BSISO propagation will also be tested by turning on/off urban canopy parameterizations.

The impact of ocean processes on BSISO propagation will be tested more broadly using various methods. While not a direct assessment of the role of ocean coupling, the impact of specification of the SST boundary condition on BSISO propagation will be tested. Various modeling groups within the PISTON science team will employ coupled versus uncoupled versions of atmospheric models to assess the importance of ocean-sea interaction to BSISO propagation, including effects mediated by the diurnal cycle. Still more active intervention is proposed to assess the influence of particular ocean processes, including reducing the depth of bathymetry in the northern SCS to test the hypothesis that deeper bathymetry allows stronger air-sea interaction through greater mixing-induced surface cooling.

Wind-induced surface and radiative flux feedbacks and their impact on BSISO propagation and destabilization will also be tested through direct modification of parameterizations. For example, air-sea interactions can be disabled in simulations by prescribing surface fluxes, wind speed, and/or atmospheric radiative heating rates to be the mean of a control simulation. Microphysical parameters can also be changed to make cloud ice and cloud water less radiatively active in the longwave and/or shortwave portions of the infrared spectrum.

Ensemble approaches will be used to provide insight into BSISO dynamics and prediction. Analysis of S2S hindcast ensembles will be used to determine common conditions for members that propagate the BSISO across MC and those that do not, providing possible insight into limitations in prediction skill. An ensemble of mesoscale simulations at cloud-resolving grid spacing on a mesoscale domain will be used to determine how variability on small scales affects mesoscale convective organization during different BSISO regimes, and will quantify the resulting feedbacks onto the BSISO. A series of high-resolution ensemble simulations to examine stochastic impacts on tropical cyclone genesis will be run for cases of interest, likely during enhanced convection phases of the BSISO.

Although the suite of modeling tools presented above is large, coordinated experiments among modeling groups within PISTON will be developed that maximize chances of project success.

This coordination will allow the model-dependence of results to be tested to address robustness, will create efficiencies by allowing sharing of codes and techniques, and will foster a rich intellectual exchange of ideas that enable greater insight into BSISO dynamics and its interactions with the islands of the Philippines and MC to be reached. An experiment design document for the modeling component of PISTON will be generated much like that for the observing strategy.

4.4 Synergy between modeling and observations.

PISTON observations will directly and indirectly provide a valuable validation dataset to aid model development and improvement. The observations can be used to directly assess the fidelity of a given model on a process level. They can also be used indirectly to aid parameterization development in coarse-resolution models in a hierarchical approach in which cloud-system-resolving models are validated with observations, and the rich, high-resolution dataset provided by these models can be used as a resource for parameterization development in coarser-resolution models. While such goals are achievable, it is important to keep in mind that parameterization development using field observations is often a long-time-scale endeavor that does not bear fruit immediately.

Modeling and observations during PISTON will also be integrated in other ways that improve process understanding and aid design of the PISTON field phase. Very high-resolution COAMPS real-time forecasts through COAMPS-OS® will be conducted to support the PISTON field campaign (<https://cavu.nrlmry.navy.mil/COAMPSOS/>). Forecasts during summer 2017 in advance of the fields phase can be used in a “dry run” framework to test how the use of these forecasts will be used for deployment of field resources, including radar observations, aircraft, radiosondes, surface meteorology measurements, and oceanic measurements such as autonomous gliders, wave gliders, and floats. This model can also provide high-quality data assimilation in the vicinity of the SCS that can be used for subsequent process studies. After the campaign, a variational analysis technique called Spline Analysis at Mesoscale Utilizing Radar and Aircraft Instrumentation (SAMURAI; Bell et al. 2012) that combines radar, soundings, and numerical model output will be used to integrate the various observational datasets into high quality mesoscale analyses that can be used for process studies, including examination of TDs and TC genesis.

5. Synergy with other efforts

5.1 YMC

Years of the Maritime Continent (YMC, <http://www.jamstec.go.jp/ymc/>) is a two-year international project during July 2017-July 2019 designed to increase understanding and prediction of the multiscale interactions that form the basis of the weather and climate system of the Maritime Continent (MC). YMC is designed to provide socioeconomic benefit both in the MC and globally given the strong teleconnections of tropical heating in this region to other parts of the globe. YMC is organized around five science themes that include atmospheric convection, upper-ocean processes and air-sea interaction, stratosphere-troposphere exchange, aerosols, and prediction improvement. To address these science themes, activities to be conducted include data sharing, field campaigns, modeling, prediction and applications, and outreach and capacity building. YMC has the support of various World Meteorological Organization bodies

including the Working Group on Tropical Meteorology Research (WGTMR), the Subseasonal to Seasonal Prediction Project (S2S), the Working Group on Numerical Experimentation (WGNE), including the MJO Task Force, the World Climate Research Programme (WCRP), and the Commission for Atmospheric Sciences (CAS). Several members of the PISTON science team contributed to the YMC science plan, which can be accessed at the following site: http://www.jamstec.go.jp/ymc/docs/YMC_SciencePlan_v2.pdf. The YMC science plan had input from researchers at the Manila Observatory at the Ateneo de Manila University in Quezon City, Philippines. YMC has an expanded focus that includes understanding multiscale interactions and intraseasonal variability during boreal winter in regions of the MC closer to the Equator, and hence coordination with YMC field campaigns will allow a broader area and time period to be covered, to the mutual benefit of both YMC and PISTON.

5.2 CAMP²Ex

Overlapping with PISTON will be the planned NASA CAMP²Ex program, Cloud and Aerosol Monsoonal Processes-Philippines Experiment, intended to operate from late-July through early September 2018. The central goal of CAMP²Ex is to characterize the role of anthropogenic and natural aerosols in modulating the frequency and amount of warm- and mixed-phase precipitation associated with the Southwest Monsoon in the near vicinity of the Philippines. This is a prime question motivated by the growing economy of southeast Asia, where industrial processes and expanding urbanization produce pollution that results in extensive aerosol plumes moving over the SCS and surrounding waters. The primary research platform for this experiment will be the NASA P-3B, operating out of Subic Bay on the western side of Luzon. This NASA aircraft will be equipped with a full suite of in situ and remote-sensing equipment for characterizing clouds and quantifying the impact of aerosols on their precipitation processes. Approximately 150 flight hours are anticipated, allowing roughly two 8-11 hours missions per week. Given the close proximity of Subic Bay to the planned locations of the *R/V Tommy Thompson* for PISTON, there will be ample opportunities for interactions between PISTON and CAMP²Ex. PISTON will benefit from flight-level data on board the P-3 in characterizing the environment for convection, along with a means to validate SEA-POL radar-based precipitation and hydrometeor identification algorithms with in-situ microphysical observations. CAMP²Ex will utilize the ship radar data in determining suitable cloud targets for remote and in-situ sampling.

5.3 WGNE MJO Task Force-S2S subproject

A joint research effort between the S2S Prediction Project mentioned above and the Working Group on Numerical Experimentation (WGNE) MJO Task Force (MJOTF) has recently been developed to address interactions between the MJO and the MC with the goal of improving weather forecasts and climate model simulations of the MJO and related phenomena. The overall goal of the MJOTF (http://www.wmo.int/pages/prog/arep/wwrp/new/MJO_Task_Force_index.html) is to facilitate MJO improvements in weather and climate models to increase the predictive skill of the MJO and related weather and climate phenomena. Research priorities of S2S (<http://s2sprediction.net>) include 1) evaluating potential predictability of subseasonal events, including identifying windows of opportunity for increased forecast skill; 2) understanding systematic errors and biases in the subseasonal to seasonal forecast range; and 3) comparing, verifying, and testing multi-model combinations from these forecasts and quantifying their uncertainty. The joint research activity between S2S and the MJOTF involves understanding

interactions of the MJO in the MC region with the diurnal cycle, synoptic variability, the monsoons, ENSO, the land surface, and the ocean. Further, the collaboration will address NWP and climate model simulations of subseasonal variability in the MC region, focusing on model bias and other errors in subseasonal prediction. Hence, this S2S-MJOTF collaboration shares many common goals with PISTON, particularly given the recent MJOTF emphasis on boreal summer prediction that resulted in the Lee et al. (2013) paper discussed above, which featured development of a BSISO real-time monitoring index.

5.4 ONR Oceanic Control of Monsoon Intra-seasonal Oscillations in the Tropical Indian Ocean and the Bay of Bengal (MISO-BOB)

ONR _DRI with the goal of understanding atmosphere-ocean interaction in the Bay of Bengal and its role in intensity and propagation of the MISO signal in this region

<http://www.onr.navy.mil/en/Science-Technology/Departments/Code-32/All-Programs/Atmosphere-Research-322/Physical-Oceanography/MISO-BOB%20DRI.aspx>

The ship observations, modelling and data assimilation will be included in this effort. The ship observations are planned for the Summer of 2018 providing the synergy with PISTON. Some of the PISTON PIs are involved in this project

5.5 NOAA Climate Variability and Predictability (CVP) Program.

The NOAA CVP program recently produced an FY17 call entitled Observing and Understanding Processes Affecting the Propagation of Intraseasonal Oscillations in the Maritime Continent Region. This call seeks to fund projects that “improve understanding of processes that affect the propagation (speed, intensity, disruption, geographic placement) of intraseasonal oscillations in the Maritime Continent and broader region by using a combination of in situ and remote observations, data analysis, modeling, and/or theoretical understanding of local and remote processes.” Funded projects are expected to leverage activities associated with PISTON, YMC, and CAMP²Ex and contribute to process-oriented diagnosis of the BSISO and MJO using shipborne observations and models.

5.6 SALICA (Sea-Air-Land Interactions in the Context of Archipelagos)

The overall objective of this University of the Philippines project is the improvement of rainfall predictions. The achievement of this objective encompasses the understanding and representation of multiple processes operating across many scales. In particular, resolving diurnal scales and invoking high-resolution observations and models are essential. Other key research questions include:

1. Can understanding the diurnal cycle and land-sea-air interaction in coastal areas improve forecasts of extreme rainfall events? How does the diurnal cycle influence seasonal and intraseasonal rainfall in the Philippines?
2. How important is the feedback of freshwater runoff from rivers to the coastal seas on the air-sea interaction and convective processes? How important are regional differences – i.e. areas with strong tidal interaction, strong advection? Or big and flat vs. steep and small watersheds

5.7 SCSTIMX (The South China Sea Two-Island Monsoon Experiment)

SCSTIMX is Taiwan's contribution to the YMC led by the National Taiwan University. The objectives of SCSTIMX are to study the interaction of convective processes with the large-scale flow. These include the Siberian High and tropical interaction, summer/winter ISO and monsoon onset, and TCs and severe rainfall in Taiwan and neighboring areas. SCSTIMX will conduct observations with a suite of atmospheric and ocean instruments at Donsha and Taipin islands from 2016-2019 during May-June and Dec-Jan. Additional observations will also be collected from the ship during its transects between Taiwan, Donsha, and Taipin.

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