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Role of coastal convection to moisture buildup during the South China Sea summer monsoon onset

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Abstract

In this study, the climatological characteristics of object-based precipitation systems (OPSs) and moisture development are analyzed over the South China Sea (SCS) during the sharp transition of summer monsoon onset. The satellite observed statistics of the OPSs showed that over the 20-day pre-onset period, OPSs of small (<100 km) to medium size (100-300 km) are active over the lands surrounding the SCS. The pre-onset composite mean shows a basin-scale (~1000 km) local circulation with anomalous subsidence over the ocean, and ocean convection is mostly suppressed. Over the 20-day post-onset period, large (>300 km) OPSs develop over the coastal ocean and contribute to over 60% of the total precipitation. The number of observed large OPSs significantly increases along with the sharp moisture buildup within 10 days after onset. The moisture budget suggests that local contribution from convective vertical mixing is the major moisture source during the first pentad after onset. The relationship between moisture buildup and convection organization is then examined using a set of idealized cloud-resolving model (CRM) experiments, with a land-ocean configuration approximating the SCS basin. The CRM appropriately represents the observed development of coastal convection. In the no-shear environment, a strong basin-scale circulation is formed, which suppresses the ocean moisture development. When large-scale vertical wind shear is imposed to represent the changes of large-scale circulation
during the onset pentad, organized convection systems are increased over the coastal ocean and propagate toward the open ocean, accompanied by fast ocean moistening within 5-10 days.

Keywords: Coastal Convection, Moisture, TRMM, CloudSat, Cloud-Resolving Model
1. Introduction:

The South China Sea (SCS) and Maritime Continent (MC) region is a challenging and important area to study convection multi-scale interactions of the tropical atmosphere. This region is at the heart of the rising branch of both the Hadley circulation and Walker circulation. Surrounded by islands and continents with complex topography, the atmospheric convection systems in the SCS-MC region exhibit prominent diurnal variability, organization, and propagation. The occurrence and organization of convection systems can be highly modulated by the large-scale environment associated with seasonal variabilities, such as monsoon onset, and associated with intraseasonal variabilities, such as the Madden-Julian Oscillation (MJO) and the boreal summer intraseasonal oscillation (BSISO).

The SCS-MC coastal regions are the occurrence hotspots of highly organized meso-scale convection systems (MCSs), as reported by several intensive observation campaigns (e.g., Houze et al. 1981; Johnson and Priegnitz 1981; Ciesielski and Johnson 2006; Aves and Johnson 2008; Kanamori et al. 2013) and from multi-year statistics of satellite observation (e.g., Williams and Houze 1987; Yang and Slingo 2001; Mori et al. 2004; Nesbitt and Zipser 2003; Ichikawa and Yasunari 2006; Yuan and Houze 2010; Yanase et al. 2017). The large and intensive MCSs associated with monsoon environment are the major contributors to the regional extreme precipitation (Hamada...
et al. 2014). From the perspectives of both climate and extreme weather, it is imperative to understand how the coastal convection systems over the SCS-MC respond to large-scale conditions, especially the controlling physical mechanism, and how the current atmospheric model can represent these convection multi-scale interactions. These topics are also the key scientific themes of several intensive international field campaigns over the SCS-MC region, namely, the Years of Maritime Continent (YMC, 2017-2019, see websites: http://www.bmkg.go.id/ymc/ and http://www.jamstec.go.jp/ymc/), the South China Sea Two-Island Monsoon eXperiment (SCSTIMX, 2016-2019, see websites: https://scstimx.as.ntu.edu.tw/) (Lin et al. 2016), and the Propagation of Intra-Seasonal Tropical OscillatioNs (PISTON, 2018-2019, see website: https://onrpiston.colostate.edu/).

Environmental water vapor content is important to the development of deep convection. Observational studies indicate that enhancement of moisture in the low to mid-troposphere favors the development of deep convection, while the drier atmosphere might inhibit its growth (Bretherton et al. 2004; Neelin et al. 2008; Holloway and Neelin 2009; Kuo et al. 2017). The moisture development is considered part of the dynamical systems in which the interactions between convection, environmental water vapor, and atmospheric motions is important in understanding the multi-scale variabilities in the tropics (Yu and Neelin 1994; Raymond and Torres 1998;
Sobel and Bretherton 2003; Raymond and Fuchs 2007, 2009; Sugiyama 2009). Using idealized cloud-resolving model simulations, Tsai and Wu (2017) further identified the environment for increasing probability of the development of large aggregated convection when the environmental column relative humidity (CRH) is greater than 80% (67%) without (with) environmental wind shear. Their results also suggested that, after the critical CRH is met, the degree of aggregation is enhanced with the increase of CRH.

In this study, the moisture buildup and the development of organized convection during the South China Sea summer monsoon (SCSSM) are carefully examined using object-based analysis of satellite observations and cloud-resolving simulations. The SCSSM onset is a period when a sharp rainfall burst over the coastal ocean occurs, associated with an abrupt reversal of large-scale low-level winds within 5-10 days (Wang and LinHo 2002; Wang et al. 2009). Chen et al. (2019) identified the precipitation bias associated with the interactions among fast physical processes in a general circulation model (GCM) during the SCSSM onset using the multi-year hindcast approach. Their results showed that during the pre-onset period the land-ocean precipitation contrast is underestimated, whereas during the post-onset period the organized coastal convection was not captured. These biases are associated with the underrepresentation of convection diurnal cycle and the issue of precipitation...
sensitivity to environmental moisture in the physics parameterizations. Therefore, the
objective of the current study is to provide a detailed description of the evolution of
coastal convection and moisture development during the onset period, emphasizing the
importance of the land-sea configuration over the SCS in modulating the response of
the coastal convective systems. Section 2 describes the observational data sets and the
methodology for identifying objected-based precipitating systems (OPSs), as well as
the cloud-resolving vector vorticity model (VVM). The observed occurrence of OPSs
of different size categories and the accompanied moisture buildup during the SCSSM
onset period is presented in Section 3. Section 4 shows the VVM simulation results that
examine the response of coastal convection to large-scale vertical wind shear, with an
idealized land-ocean configuration approximating the SCS basin. Summary and
discussion are presented in Section 5.

2. Data and Methodology

2.1 Data sets

The observed precipitation data from the Tropical Rainfall Measuring Mission
(TRMM) 3B42 version 7 dataset (Kummerow et al. 2000; Huffman et al. 2010) is
analyzed in the present study (1998-2015), which is the microwave, precipitation radar,
and infrared level-3 rainfall product with 0.25 degree horizontal spatial resolution and
3-hourly temporal resolution. The vertical distribution of cloud is obtained from the CloudSat R04 2B-GEOPROF cloud mask (Marchand et al. 2008), in our analyses (2007-2015), which is detected by the 94 GHz nadir-pointing Cloud Profiling Radar at a nominal horizontal footprint of 1.4 km across by 1.8 km along the track, with 125 vertical bins spanning from surface to 30 km altitude and a vertical resolution of 240 m. We note that after 2010 the 2B-GEOPROF is available only for daytime overpass owing to the spacecraft battery issues.

Atmospheric temperature, water vapor, and the wind fields are based on the 6-hourly European Centre for Medium-Range Weather Forecasts Reanalysis-Interim (Dee et al. 2011) with 0.75 degree horizontal resolution (ERA-Int). Daily outgoing longwave radiation (OLR) is taken from the 2.5 degree interpolated data obtained from National Oceanic and Atmospheric Administration (NOAA) polar-orbiting satellite (Liebmann and Smith 1996). The NOAA Optimum Interpolation Sea Surface Temperature 0.25 degree data (NOAA OISST v2.; Reynolds et al. 2002) is used as well.

2.2 Object-based analysis

The OPSs are identified over the SCS region with TRMM 3B42. Individual OPS is determined by connecting the spatially contiguous grids with estimated precipitation intensity > 1 mm hr$^{-1}$. The horizontal scale (size) of the OPSs is then defined as the
square root of its total areal coverage (Su et al. 2019). This allows us to investigate the occurrence location and frequency of the OPSs with different sizes.

A similar approach is applied to the CloudSat GEOPROF cloud mask to obtain the vertical cloud object. The cloudy pixels are defined with cloud mask confidence level \( \geq 20 \) (Marchand et al. 2008; Hagihara et al. 2010). Contiguous cloudy pixels are connected to obtain cloud objects along the orbit (x-z direction). As we are focusing on convective clouds in this study, it should be noted that CloudSat may miss the lower part of heavily precipitating clouds due to attenuation of cloud profiling radar and high thin cirrus due to the detection limit. With this consideration, we subjectively define “convective” cloud objects as the cloud objects satisfying both base height < 3 km and top height > 6 km. The size of each convective cloud objects is defined by the total x-z area of the connected cloudy pixels.

2.3 SCS summer monsoon onset index

A rapid transition of wind direction over the SCS is observed during the onset period. Following Wang et al. (2004), the \( U_{\text{scs}} \) index is defined as the zonal wind at 850 hPa averaged over 5-15°N, 110-120°E, illustrating the transition of wind direction during the monsoon onset. The onset date of SCSSM in individual year is determined when the following criteria are met: (1) The first pentad after April 25\(^{\text{th}}\) when \( U_{\text{scs}} \) is positive;
(2) $U_{\text{scs}}$ in subsequent four pentads (including the onset pentad) must be positive in at least three pentads; (3) The accumulative four pentads mean of $U_{\text{scs}}$ is larger than 1 m s$^{-1}$. The climatological mean onset pentad is 27.5 (~mid-May) over these 1998-2015, with interannual standard deviation of 1.7 pentads. In the following analysis the first day in the onset pentad is considered as day 0 for each year.

To examine the relationships between convection and its large-scale environment during SCSSM onset, we analyze 20 days before/after the onset date in each year, called pre-onset (day -20 to day -1) and post-onset (day 0 to day 19) respectively. The domain of SCS is defined as 12.5°N to 17.5°N, 110°E to 120°E, which has the most sensitive precipitation response during the transition of monsoon. We note that the latitude of the selected domain is different from that of $U_{\text{scs}}$. The $U_{\text{scs}}$ index provides the state of synoptic circulation, and its region is defined by the dominant empirical mode of low-level wind that signifies not only the onset over the SCS but also the entire broadscale East Asia summer monsoon (Wang et al., 2004). As our purpose here to identify the response of the convective scale phenomenon to the large (synoptic)-scale circulation, we use the region that best represents the signal in either scale (i.e. the selected SCS domain for convective scale, and the $U_{\text{scs}}$ region for synoptic scale) to carry out the composite analysis.
2.4 Vector vorticity equation cloud-resolving model (VVM)

The vector vorticity equation cloud-resolving model (VVM) used in this study was developed by Jung and Arakawa (2008) based on the three-dimensional anelastic vorticity equations. A unique aspect of this model is that the model predicts horizontal components of vorticity and diagnoses the velocity by a three-dimensional elliptic equation. A bulk three-phase cloud microphysics parameterization including cloud droplets, ice crystals, rain, snow, and graupel is applied in this model (Krueger et al. 1995). The topography is implemented through the immersed boundary method in height coordinate (Wu and Arakawa 2011; Chien and Wu 2016). The NOAH land surface model (Chen et al. 1996; Chen and Dudhia 2001) is implemented as the bottom boundary for surface fluxes (Wu et al. 2019) coupled with the radiation parameterization using rapid radiative transfer Model for GCMs (Iacono et al. 2008).

The model has also been used to study the convective aggregation under different vertical wind shear and column moisture conditions (Tsai and Wu 2017), convection organization with heterogeneous land surface fluxes (Wu et al. 2015), the transition of stratocumulus clouds (Tsai and Wu 2016), the precipitation hotspots caused by the afternoon thunderstorm in Taipei basin (Kuo and Wu 2019) and the design of the unified parameterization for deep convection (Arakawa and Wu 2013; Wu and Arakawa 2014).
The detail of the land-ocean configuration of the simulated domain in this study will be introduced in Section 4. The object-based analysis is also applied to the simulated cloud field, following the method in Tsai and Wu (2017). The grids with the sum of cloud water and cloud ice mixing ratio greater than \(10^{-5}\) kg kg\(^{-1}\) are defined as “cloudy”, and the spatially contiguous cloudy grids are connected to identify the 3D cloud objects in the simulations. The size of each 3D cloud object is represented by the total volume occupied by the connected cloudy grids.

3. Results

3.1 Object-based statistics during Pre- and Post-onset of SCSSM

Figure 1 illustrates the composite mean precipitation and 850 hPa horizontal circulation over the SCS for the pre- and post-onset periods from years 1998 to 2015. During pre-onset periods, low-level easterly dominates over this region and precipitation is significantly suppressed over the ocean. During the post-onset period, the low-level circulation changes to strong southwesterly and heavy precipitation occurs over the ocean. The most significant precipitation enhancement is found near the coastal regions west of the Philippines.

To understand how convective systems of various sizes contributes to the pre- and post-onset precipitation, OPSs are identified using the TRMM 3B42 data and classified
by the horizontal scale into small (<100 km, S), medium (100-300 km, M), and large
(>300 km, L) categories. Figure 2 shows the spatial distribution of the occurrence count
for these three categories during pre- and post-onset periods of 1998-2015. For each
OPS identified, all the 3B42 grids (0.25°) that are covered (connected) within the object
would be counted once. Therefore in Figure 2, the occurrence count represents how
many times each 3B42 grid had been covered by OPSs of the particular size category.
The fractional contribution by each OPS size category to the composite mean total
precipitation is shown in Fig. 3. In the pre-onset period, nearly all small OPSs locate
over land with 20% to 40% contribution of precipitation; medium OPSs dominate over
land and coastal regions with 60% to 80% and 40% to 60% contribution respectively;
large OPSs, however, are not likely to develop over this region. It should be noticed
that over the ocean, it is difficult for the convective system to develop during pre-onset
periods. During the post-onset period, precipitation contributions among the OPSs
change dramatically. Large OPSs dominate over the ocean and contribute 60% to 80%
amount of precipitation, even above 80% in some areas. The results suggest that these
large OPSs could have an important role during the transition of SCSSM.
The vertical cloud frequency profiles (Fig. 4a) and the size distribution of vertical
convective cloud objects (Fig. 4b) identified from CloudSat GEOPROF cloud mask are
also analyzed for the pre- and post-onset period from year 2007 to 2015. Cloud
frequency profile during post-onset periods is higher by 10% in all altitudes, and the enhancement of the “top-heavy” structure indicates the occurrences of organized convection with extensive anvil clouds (Houze 2004). According to the areas of along-track-vertical cross section, the convective cloud objects are also classified into three size groups: <100 km$^2$, 100-1000 km$^2$, and > 1000 km$^2$. Owing to the differences between TRMM 3B42 and CloudSat in resolution and retrieved target (rainfall versus vertical cloud), the size of cloud object cannot be directly compared to the size of the TRMM OPSs. As we require the convective cloud object to have a minimum vertical extent of 3 km, the three size bins would roughly correspond to <33 km, 30-330 km, and >330 km, respectively, in the horizontal spans of cloud cover. The convective cloud objects in the largest size bin are mostly associated with large OPSs. The numbers of cloud objects are higher during post-onset than pre-onset for all size categories, but the number of the largest size category increases most significantly, which is qualitatively consistent with the statistics of the TRMM 3B42 OPSs. Note that the number of diagnosed cloud objects is considerably low due to the sampling frequency of CloudSat and the selected domain size.

3.2 Evolution of large OPS number and moisture buildup during onset period
Evolution for individual years of the domain-averaged precipitation and large OPS number during the -/+20 days of onset based on the $U_{scs}$ are presented in Fig. 5. Twelve years with typical activation pattern of SCSSM onset evolution are subjectively selected for the subsequent analyses if an obvious transition of precipitation and moisture occurs near the onset date, namely, 1998, 2000, 2001, 2002, 2003, 2004, 2006, 2008, 2009, 2010, 2011, and 2014. Years with active precipitation or high moisture (ERA-Int column water vapor over 50 mm) during the pre-onset period (e.g., 1999, 2007, 2013), or years without major precipitation activity throughout the whole onset period (e.g., 2005, 2012, 2015) are excluded. For years 2003, 2008, and 2009, the pre-onset precipitation was contributed by tropical disturbances passing through the SCS, and the column-integrated water vapor remained suppressed (<50 mm) after the event, so these years are still included in the analysis.

Figure 6 indicates the evolutions of precipitation over land and ocean during the onset period for these selected years. Terrestrial precipitation dominates over the SCS region from 15 days before to the monsoon onset pentad (day -15 to day +3), while the ocean precipitation starts to rise around 5 days before onset, sharply increases after day +3, and becomes comparable to the land precipitation after the onset pentad. The obvious land-ocean precipitation contrast during the pre-onset period is worthy of a more detailed examination. During the pre-onset period, the climatological mean sea
The land-ocean contrast of precipitation, however, indicates the existence of an additional regional mechanism during the pre-onset period that prevents precipitation over the ocean center, which may be associated with the active convection over the lands surrounding the SCS. Figure 7 demonstrated the regional zonal-vertical anomalous circulation over the SCS from ERA-int. During the pre-onset periods of the 12 selected years (Fig. 7a), anomalous upward motion locates in continents and coastal areas (118-123°E and east of 108°E), while downward motion favors the open ocean in middle and lower layers. The anomalous circulation further indicates regional subsidence induced by ascending motion over the continents, where convective activities are frequently observed with a diurnal pattern during the pre-onset periods. During the post-onset periods (Fig. 7b), the organized coastal convection over the west coast of Philippines produces strong anomalous updraft (downdraft) in the eastern (western) half of the ocean basin and strong subsidence over the western half through the troposphere.

Figure 8 illustrates Hovmöller diagrams of precipitation over the SCS region in 2014, a year nearly free from possible perturbations associated with typhoons, northern frontal systems and intruding convective systems. During the pre-onset period (day -20
to day 0), active diurnal cycle is visible over both coastal regions, while only very weak precipitation occurs over the open ocean. Precipitating systems on the western coast of Philippines can propagate but retreat to near 118°E. However, within 5 days after the monsoon onset, precipitation quickly evolves to highly intensity there, and these precipitating systems are able to march further with more extensive coverage with intensity above 20 mm day$^{-1}$, and heavy precipitation eventually occurs over the entire open ocean during the post onset period. As presented in Section 3.1, these systems reaching the open ocean are well-organized and dominate the contribution of rainfall there.

Evolution of daily large OPS number, NOAA OLR and ERA-Int column water vapor (CWV) over the ocean is shown in Fig. 9 for the selected years and their composite mean. A sharp increase of large OPSs and a decrease in OLR after the onset date is observed and continues for 5-10 days. The moisture buildup is evident near the onset date where CWV is around 45 mm in the pre-onset period and then arises sharply to 60 mm within 10 days after the onset.

The increasing occurrence of large OPSs is accompanied by strong moisture build up. A budget analysis of vertically-integrated moisture averaged over the onset pentad (day 0 to +4) and over the SCS ocean (same domain as in Fig. 9) is carried out, which can be written as (Chou and Neelin 2004; Chou et al. 2009; Lo and Famiglietti 2011)
\[
\langle \frac{\partial q}{\partial t} \rangle = (E - P) - \langle V \cdot \nabla q \rangle - \langle \omega \frac{\partial q}{\partial p} \rangle
\]

Eqn. (1)

where \( q \) is specific humidity, \( E \) is evapotranspiration, \( P \) is precipitation, \( V \) is horizontal winds, \( \omega \) is pressure velocity, \( p \) is pressure, and \( \langle \; \rangle \) represent a mass integration throughout the troposphere. All the parameters in the budget analysis are taken from ERA-Int, including precipitation. The left-hand side of Eqn. 1 is thus the tendency of CWV. The budget shows that during this strong moistening pentad the major column moisture source is the vertical transport within the analyzed domain of SCS ocean \((-\langle \omega \frac{\partial q}{\partial p} \rangle = +6.37 \text{ mm d}^{-1})\). On the other hand, the large-scale horizontal moisture convergence at the same period is weak \((-\langle V \cdot \nabla q \rangle = -0.07 \text{ mm d}^{-1})\). The moistening is mainly balanced by the sink of \( E-P \) \((-4.57 \text{ mm d}^{-1})\).

We note that the SCSSM onset each year is highly influenced by synoptic weather. Therefore in this section we rely on the composite analysis to average out the synoptic "noise" in the observations so that the climatological features during onset period can be identified, including:

- The diurnal terrestrial convection is active during the pre-onset stage; the updraft associated with the land convection and the subsidence suppressing the ocean precipitation suggests the existence of a basin-scale local circulation. (Here the basin-scale refers to the width of the SCS plus the surrounding land/islands, which is \(~1000 \text{ km})\).
With the quick transition of low-level winds to westerlies, the number of large convective systems increases over the coastal region of the Philippines. These coastal systems are triggered diurnally but their propagation into the open ocean becomes more extensive day by day.

The increase of large coastal OPSs during the onset pentad is accompanied with fast column moistening over ocean. Vertical transport by local convection is the dominant process to the strong moisture buildup.

Based on the above observational evidences, we hypothesize that

1. The coastal organized convection plays an essential role in the moisture buildup over the SCS. Without the organized convection, the land convection will dominate and build up a basin-scale local circulation thus suppressing the ocean convection.

2. The increasing occurrence of the organized coastal convection can modulate the basin-scale circulation and build up the moisture over the SCS.

To examine the above hypothesis, we design a set of idealized cloud-resolving simulations in the next section.

4. **Idealized VVM simulations**

We perform idealized VVM simulations with the land-ocean configuration to further investigate the development of coastal convection and its relationship with the
moisture buildup. The idealization focuses on the basin-scale circulation over the SCS as shown in Fig. 10. A triangle-shaped mountain (128-km wide, 1-km high, parallel to the coastline) is imposed over the 256 km flat land area so that the coastal convection is geographically locked over the ocean. With the periodic boundary conditions, the ocean (768-km wide) is bounded in east and west by the same land areas, a proxy of SCS bounded by Philippine and Indochina. Sensitivity experiments show that without the mountains, the convection propagates from land to sea easily, interfering the development of coastal convection. The rest of the model settings are listed below: the domain size is 1024 km (x, east-west) \( \times \) 512 km (y, north-south) with a horizontal resolution of 2 km. This idealized setup over the SCS provides a useful framework in studying the development of coastal convection. By turning on/off the large-scale vertical wind shear, the causal relationships between moisture buildup and the organized convection can be evaluated.

Two experiments are performed in this study, in the “shear” experiment, a low-level wind shear with \(-2.5 \text{ ms}^{-1} \text{ km}^{-1}\) is imposed below 2 km with 5 ms\(^{-1}\) westerly at the surface to represent the large-scale vertical wind shear during the onset pentad. Above 2 km, the wind gradually decreases to \(-1 \text{ ms}^{-1}\) at around 4 km and is kept constant toward the model top. On the other hand, in the “no-shear” experiment, a uniform 3 ms\(^{-1}\) southerly wind at all levels is imposed representing no change of large-scale circulation.
The southerly wind is added so that the surface fluxes over the ocean remain close to reality. With no background wind, the ocean becomes too dry (subsidence plus no latent heat from the ocean). By comparing the two experiments, the role of coastal convection to the moisture buildup over the SCS can be evaluated. Both experiments were integrated for 10 days after spin-up. The SST is fixed at 302.5 K which is the climatological mean of the 12 typical onset years selected above based on NOAA OISST. The land surface type is represented by evergreen broadleaf forest using the NOAH land model. A stretching grid is used in the vertical with the grid size of 100 m near the surface and 1000 m near the model top around 30 km. The model is initialized with the horizontally uniform thermodynamics profiles from the ERA-Int data averaged over the pre-onset period. The model is first spun up for three days before the two experiments are performed. Figure 11a shows the zonal-vertical distribution of moisture (contour), vertical motion (vectors), and cloud fraction (shading) in the no-shear experiment, averaged along the y-direction of the domain during the last five days of the simulation. With the periodic boundary condition, the western land in Fig. 11 is a duplicate of the eastern one. We plotted the domain this way to approximate the land-ocean distribution of the SCS basin. The deep clouds and the associated updrafts develop mainly over the mountain areas, and the anvil areas extend to the flat land. Over the coastal ocean on
the east and west side of the basin, deep clouds also occur but are limited near the coastlines. Further into the ocean center, the cloud fraction is low (~10%) and shallow (below 4 km), and strong subsidence occurs from the upper atmosphere all the way to the lower levels. Corresponding to the convection distribution, a strong land-ocean moisture gradient is formed, with enhanced moisture over land and suppressed moisture over ocean center. The averaged profile of subsidence velocity over ocean (Fig. 11b) shows subsiding motion through most levels. The basin-scale circulation and strong land-ocean contrast in convection and moisture in the no-shear simulation are consistent with the pre-onset observations presented in Section 3.

Figures 11c and 11d show the results in the shear simulation. Imposing a low-level westerly shear leads to the development of strong, deep convection with strong updraft over the windward coast (eastern side of ocean), with anvil extends to the ocean center. The deep convection over land is now more confined to the mountain areas. The vertical motion and moisture distribution characterizes an east-west gradient over the ocean, with enhancement in the eastern half. The averaged oceanic vertical motion is weak, with updraft in the mid-levels and subsidence in low- and high-levels.

Figure 12 presents the size (volume) distributions of the 3D cloud objects collected over the eastern half of the ocean in the two experiments. The shear simulation contains more large-size (volume > $10^3 \text{ km}^3$) clouds, indicating the enhancement of convection
organization under the shear environment, which is consistent with the increasing
presence of large OPSs over the Philippine coast during post-onset of the SCSSM.

The Hovmöller diagrams of oceanic precipitation for these two simulations from
day 1 to day 5 are shown in Fig. 13. For the no-shear case (Fig. 13a), a clear diurnal
cycle over both coastal regions is simulated, a similar pattern to the observed pre-onset
composite in the year 2014 shown in Fig. 13c. Strong suppression of precipitation can
be found over the open ocean. Even though precipitating systems are generated near
the coastlines, they cannot propagate to the open ocean, and strong precipitation is
therefore confined within 150 km offshore. Note that as the observed coastal diurnal
cycle exhibits day-to-day variation (Fig. 8), the 20-day pre-onset period is averaged
into 5-day long composites to provide more relevant comparison with the idealized
simulation (see caption for details). For the shear case (Fig. 13b), the magnitude of
precipitation over the western side of ocean reduces, while precipitating systems on the
eastern side of the ocean are still triggered diurnally, and propagate further and further
into the open ocean each day; by day 5 heavy precipitation can occur over the eastern
half of the ocean basin. The response of the simulated coastal convection to the imposed
low-level wind shear resembles the observed evolution during the onset pentad in the
year 2014 (Fig. 13d).
Given the differences in local circulation and convection population and propagation, the moisture buildup over the ocean shows drastic contrast between the two experiments (Fig.14). The average CWV over open ocean in the no-shear experiments maintains around 43-47 mm in the 10-day integration, while in the shear experiment, the CWV increases sharply from 43 to 52 mm in the first 5 days and remains around 53 mm steadily after day 6. The quick moistening from day 1 to day 5 in the shear experiment is consistent with the continuous intrusion of coastal propagating systems to the open ocean, and our simulation indicates that it takes around 5 to 10 days for the ocean to transition from a convectively suppressed state to an active state. This time scale is similar to the composite evolution of CWV in Fig. 9c that the significant moistening occurs within 10 days after the large-scale low-level winds switch to westerly.

5. Summary and discussion

This study investigates the detailed evolution of convective activities and moisture buildup during the SCSSM onset by applying object-based composite analyses on satellite precipitation and vertical cloud mask observations over the SCS, as well as carrying out idealized CRM simulations with land-ocean configuration. The overall results highlight the essential role of propagating coastal organized systems to the ocean
moistening during the onset pentad, and the impact of land convection on the basin-scale circulation. The patterns of the diurnal cycle, precipitation distribution, and ocean moistening in the VVM simulations capture the key features in the observed climatology in the absence of the disturbance from the synoptic scale weather. The results suggest the potential need of improving the representation of organized coastal systems in GCMs for capturing a more realistic pattern of monsoon onset, as suggested in Chen et al. (2019). The organization and propagation of the coastal systems can be sensitive to the strength and vertical distribution of vertical wind, as observed during the SCSMEX field campaign (Johnson et al. 2005). The convection development can also depend upon the initial (pre-onset) moisture level and hence the SST. In the future, systematic sensitivity experiments on these large-scale conditions will be carried out with the same land-ocean configuration to investigate their effects on the ocean moistening time scale. Previous studies have shown that the boundary layer (BL) gravity waves from diurnal cycle over land (e.g., Mapes, 2003ab; Warner et al., 2003; Hassim et al. 2016; Yokoi et al., 2017) and the land-sea breeze circulation (e.g., Houze et al., 1981; Mori et al., 2004; Wapler and Lane, 2012) may play an important role in triggering the offshore propagating systems (or their precursor convection) over the coastal ocean. In our simulations, the propagation speed of the weak precipitation (<5 mm hr\(^{-1}\)) into the open ocean in Fig. 13 is close to phase speed of the BL gravity waves.
(~ 14 m s\(^{-1}\)) in the current model configuration. After examining the BL temperature
perturbation, we found that these weak convections are triggered by the BL gravity
waves from the land convection (peaks in the afternoon) and coastal convection (peaks
in early morning) on both sides of coastline. Therefore the weak precipitation exhibits
semi-diurnal variation, particularly in the no-shear simulation, which coincides with the
semi-diurnal variation of the CWV (Fig. 14). In the shear simulation, the propagation
of the coastal organized convection is slower than the weak precipitation. If estimated
using the envelope of heavy rainfall (>10 mm hr\(^{-1}\)) in Fig. 13, the propagation speed is
~ 4 m s\(^{-1}\), generally within the range of the near-shore propagating convection observed
by Mori et al. (2004) and Yokoi et al., (2016) over the west coast of Sumatra. The
difference in the propagation speeds between the faster front of weak precipitation and
the slower near-shore heavy precipitation is also consistent with the observations. In
the future, by changing the land surface type to modulate the intensity and timing of the
diurnal peak over land, the response of the propagating coastal convection can be tested
and analyzed from the VVM output. Considering the sensitivity of the current results
to the horizontal resolution of CRM, a test simulation has been carried out by increasing
the horizontal resolution to 500 m. The preliminary results suggest that qualitatively the
dependence on the environment shear still holds but the moistening time scale varies.
We speculate that this is related to the variability of cold pool captured in the high-
resolution (500 m) simulations, and the cold pools effects will be analyzed and discussed with more details in the paper following the present work.

The present study identifies the close relationship between coastal convection and ocean moisture buildup over the SCS. Similar processes may also occur around other coastal areas exhibiting of strong monsoon transition or intraseasonal variabilities, such as the Bay of Bengal, the west coast of Indian Continent, major islands over MC, and the Timor Sea and the Arafura Sea over northern Australia. These coastal regions are the hotspots where the favorable environment for aggregated convection frequently occurs, as identified in Fig. 13 of Tsai and Wu (2017) using CWV >45 mm and critical vertical wind shear > 2 m s\(^{-1}\)/100 hPa within low-level layers (1000-850 hPa). In the observational analysis of Hamada et al. (2014), extreme rainfall over these regions is contributed mainly by convection systems that are both large in size and strong in intensity. In the future, the framework of idealized CRM simulations with the land-ocean configuration in the current study can be utilized, with appropriate adjustments to the scale of topography and large-scale conditions, to study the relationship between organized coastal convection and moisture transition in these coastal areas.

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The observation and reanalysis data sets were downloaded from the following sources:

  (Accessed Mar 21, 2019)

The VVM simulations are available for online sharing upon request, due to the large volume of data sets and limited disk space.
Reference


Neelin J. D., Peters Ole, Lin Johnny W.-B, Hales Katrina, and Holloway Christopher E, 2008: Rethinking convective quasi-equilibrium: observational constraints


**Figure Caption**

Figure 1. Climatology of composite mean TRMM 3B42 precipitation (shading) and ERA-Int 850 hPa circulation (vectors) during the 20 days (a) before and (b) after the onset date of SCS summer monsoon from 1998 to 2015.

Figure 2. Spatial distribution of the occurrence frequency of the three size categories of the OPSs in pre-onset (upper) and post-onset (bottom) periods: (left) Small (< 100 km), (middle) Medium (100-300 km), and (right) Large (>300 km). The size of the OPSs refers to the horizontal scale, which is defined as square root of the connected precipitating areas. The numbers are the total counts from TRMM 3B42 over 1998-2015 during the 20 days before and 20 days after the onset date defined by the $U_{SCS}$ index every year.

Figure 3. Similar to Fig. 2 but showing the fractional contribution to total precipitation by the three size categories of the OPSs. Note that the definition of the OPSs excludes pixels with precipitation rate < 1 mm hr$^{-1}$, while the total precipitation includes precipitation of all intensity, therefore in some areas the fraction of all three categories does not add up to 1.

Figure 4. CloudSat-identified (a) mean cloud frequency profiles and (b) size distribution of convective cloud object over the SCS ocean (110°-120°E, 12.5°-17.5°N) in pre-onset (blue) and post-onset (red) periods. The vertical cloud frequency is the ratio of cloudy pixels to the total sampled pixels in each vertical bin. Convective cloud objects are the cloud objects with base height < 3 km and top height > 6 km. The size bins correspond to the areas of along track-vertical cross section of <100 km$^2$, 100-1000 km$^2$, and >1000 km$^2$, respectively.

Figure 5. Evolution of average precipitation (red line) and count number of the organized convection system (grey bars) over the SCS ocean (110°-120°E, 12.5°-17.5°N) during the onset period in each year based on the TRMM 3B42 estimates. The organized convection systems are defined as the OPSs larger than 300 km in horizontal scale. The day 0 in the x-axis represents the first onset date defined by the $U_{SCS}$ index. Twelve years with typical evolution of precipitation activation are subjectively identified: 1998, 2000, 2001, 2002, 2003, 2004, 2006, 2008, 2009, 2010, 2011, 2014

Figure 6. Evolution of averaged precipitation in TRMM 3B42 estimates during the onset period over land (dashed line) and ocean (solid line) regions of the SCS (108°-
122°E, 12.5°-17.5°N). The lines show the composite means of the 12 typical activation years.

Figure 7. (a) Pre-onset composite anomalous zonal-vertical circulation over the SCS for the 12 typical activation years from ERA-Int. Vectors show the anomalous u and -omega*50, and color shading shows anomalous –omega (in Pa s\(^{-1}\)). Only the days when ocean areas exhibit low-level subsidence are conditionally selected (daily mean ERA-Int omega over 110°-118°E, 12.5°-17.5°N < 0.005 Pa s\(^{-1}\) for all levels between 1000 hPa and 500 hPa; 140 out of the total 240 days (58%) during the pre-onset period satisfy such criteria). (b) Similar to (a) but for the post-onset composite without conditional sampling by subsidence (total 240 days). The zonal mean anomaly of u and omega are computed as follows: first, the vertical profiles are averaged meridionally over 12.5°-17.5°N at each longitude; then the domain mean vertical profile over 106°-123°E, 12.5°-17.5°N is subtracted to get the anomalous profile at each longitude.

Figure 8. Hovmöller diagrams of zonal precipitation distribution over the SCS from TRMM 3B42 during the ±20-day onset period in the year 2014. Day 0 (onset date) corresponds to June 5, 2014.

Figure 9. Evolution of (a) large OPS number in TRMM 3B42, (b) NOAA OLR, and (c) ERA-Int CWV averaged over the SCS ocean (110°-120°E, 12.5°-17.5°N) during the onset period of the typical activation years listed in Table 2. Black lines show the composite mean of the 12 typical activation years (see caption of Fig. 5), while the grey lines show the evolution for individual years.

Figure 10. Land-ocean configuration of the idealized VVM simulations. Length (y-direction) = 512 km; Ocean width = 768 km, SST=302.5K; Land width = 256 km, surface type = evergreen broadleaf; Mountain range height = 1km and width = 128 km. Periodic boundary is applied in both x- and y-direction. A snapshot of simulated cloud field is shown by the red (q\(c\) > 10\(^{-5}\) kg kg\(^{-1}\)) and white (q\(i\) >10\(^{-5}\) kg kg\(^{-1}\)) iso-surfaces for liquid and ice cloud, respectively.

Figure 11. (a) Zonal-vertical distribution of cloud fraction (shading, interval of 10%), vertical velocity (vectors; in m s\(^{-1}\)), and water vapor mixing ratio (contour; in g kg\(^{-1}\)), meridionally averaged over y=0-512 km. Only the vertical velocity with a magnitude greater than 0.005 m s\(^{-1}\) is plotted, and the downdraft is multiplied by 5 for clearer visualization. (b) Averaged profile of subsidence velocity over ocean (averaged over
x=256-1024 km, y=0-512 km; positive values correspond to subsidence. Results are daily averaged over the last 5 days of the no-shear simulation. (c) and (d) are similar to (a) and (b) but for the shear simulation.

Figure 12. Probability distribution of convective cloud size in no-shear (black) and shear (red) experiments over the eastern half of the ocean (x=640-1024 km, y=0-512 km in Fig. 11a) during the last five days of simulations. Note both x-axis and y-axis are in logarithmic scale.

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Figure 14. Time evolution of CWV over open ocean areas (x=448-832 km in Fig. 11a) in the VVM simulation without vertical wind shear (blue line) and with vertical shear (red line).
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