Chapter 14

A Synoptic-Scale Cold-Reservoir Hypothesis on the Origin of the Mature-Stage Super Cloud Cluster: A Case Study with a Global Nonhydrostatic Model

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ABSTRACT

This chapter proposes a working assumption as a way of conceptual simplification of the origin of Madden–Julian oscillation (MJO)-associated convection, or super cloud cluster (SCC). To develop the simplification, the importance of the synoptic-scale cold reservoir underlying the convection and its interaction with the accompanying zonal–vertical circulation is highlighted. The position of the convection with respect to that of climatological warm pool is postulated to determine the effectiveness of this framework. The authors introduce a prototype hypothesis to illustrate the usefulness of the above assumption based on a numerical simulation experiment with a global nonhydrostatic model for the boreal summer season.

Premises for the hypothesis include 1) that the cloud cluster (CC) is a basic building block of tropical convection accompanying the precipitation-generated cold reservoir in its subcloud layer and 2) that a warm-pool-induced quasi-persistent zonal circulation is key for the upscale organization of CCs. The theory of squall-line structure by Rotunno, Klemp, and Weisman (hereafter RKW) is employed for the interpretation. No account is taken regarding the influences of equatorial waves as a first-order approximation. Given the premises, an SCC of $O(1000)\text{ km}$ scale is interpretable as a gigantic analog of a multicellular squall line embedded in the quasi-stationary westerly shear branch of the zonal circulation east of the warm water pool. A CC corresponds to the “cell,” and its successive formation to the east and westward movement represents an upshear-tilting core of intense updraft. The upshear-tilted SCC is favorably maintained with the precipitating area being separated from the gust front boundary between the cold reservoir and a low-level easterly, which is supported in the realm of the RKW theory where two horizontal vortices associated with the cold reservoir and vertical shear are opposite in sign but cold reservoir’s vorticity can be inferred to be larger, leading to upshear-tilted and multicellular behavior. As a counterexample, CCs to the west of the warm pool (Indian Ocean and Arabian Sea) are embedded in the easterly shear and organized into a less coherent cloud cluster complex (CCC) given the situation of RKW where two horizontal vortices associated with the cold reservoir and vertical shear are still opposite in sign, but the smaller vertical shear west of the warm pool causes even more suboptimal vorticity imbalance in the western flank of cold reservoir, leading to larger tilt with height and intermittent, less viable storm situations.

A cold pool or cold reservoir, having been prevalent in mesoscale convection research, is argued to be important for the MJO as pointed out by the emerging evidence in the international field campaign for the MJO called Cooperative Indian Ocean Experiment on Intraseasonal Variability (CINDY)/DYNAMO. The simplified and idealistic hypothesis proposed here does not cover all aspects of MJO and its validation awaits further modeling and observational studies, but it can offer a framework for characterizing a fundamental aspect of the origin of MJO-associated convection.

1. Introduction

The aim of this chapter is to provide a framework that we hope will be of value for understanding the origin of tropical large-scale organized convection over the
tropical warm water pool. A super cloud cluster (SCC; Hayashi and Sumi 1986; Nakazawa 1988), a typical example of this type of convection, is a loosely defined, albeit salient, ensemble of tropical convection of 3000–5000-km scale that propagates eastward over the high sea surface temperature waters in the equatorial open oceans. Its definition in this chapter is as described in italics. An SCC is frequently observed in the convectively active phase of the Madden–Julian oscillation (MJO), and it is hardly observed outside of the Pacific warm water pool (Madden and Julian 1971, 1972; Hayashi and Nakazawa 1989). It forms somewhere over or to the west of the Maritime Continent; develops into the active, well-identifiable form over the western Pacific; and decays as it approaches the central Pacific (e.g., Lau et al. 1991).

Over the Indian Ocean, on the other hand, there are relatively fewer observed cases of the purely eastward-propagating SCC sometimes associated with the propagation of the MJO (Julian and Madden 1981; Wang and Rui 1990; Mapes and Houze 1993; Chen and Houze 1997). The original schematic of Madden and Julian (1972) illustrating a prototype of the large-scale convection associated with the MJO perceptively indicates such a different nature—almost stationary or a slow-moving buildup—of convection over the Indian Ocean; the inference was supported by a cloudiness data analysis in almost the same target period (Julian and Madden 1981). The convection over the Indian Ocean illustrated in the schematic is decoupled from the underlying surface pressure anomaly, and the surface pressure and the low-level zonal flow are negatively correlated with each other. The negative correlation, being at odds with the eastward-propagating gravity wave dynamics, implies that some other mechanisms can be at work. Such a geographical preference (e.g., over the Pacific warm water pool) and the origin of the existence of SCC from a more general standpoint remain big unanswered mysteries; this chapter attempts to provide a simple hypothesis on this.

One of the long-standing interests in SCCs is that they involves features in common with the equatorial Kelvin wave (Hayashi and Sumi 1986). The previous modeling and theoretical studies have provided substantial progress in clarifying the association of SCCs with the equatorial (Kelvin) wave dynamics under the influence of tropical convection, and the importance of the Kelvin wave in SCC dynamics is well established by now. The major viewpoints include an instability of or interaction with the equatorial wave using a mechanistic model and a general circulation model with the parameterized effects of cumulus convection. There is extensive literature on this issue (e.g., Lau and Peng 1987; Takahashi 1987; Chang and Lim 1988; Numaguti and Hayashi 1991; Hendon and Salby 1994; Oouchi and Yamasaki 1997), and the viewpoints remain challenging research topics.

What makes the SCC even more unique is that its inner structure consists of a cloud cluster (CC) of \( O(100) \) km scale; the life cycle of the CC ultimately determines the pattern and behavior of the SCC. A typical picture indicates that a new CC develops successively to the east of the existing one, thereby creating an eastward-propagating SCC (Nakazawa 1988). Since the CC is ubiquitous in the tropical atmosphere, the mechanism of its upscale organization is at the heart of the investigation of the SCC (Chao and Lin 1994). From this standpoint, the resolution of the hierarchical convective feature consisting of the SCC and the CC is a prerequisite for successfully understanding the SCC; a cloud-resolving model (CRM) has come into wide use as a unique, fascinating tool for this purpose. Major CRM research on SCCs has used 2D zonal–vertical (Oouchi 1999; Grabowski and Moncrieff 2001; Tulich and Mapes 2008) and 3D global cloud-resolving frameworks (Nasuno et al. 2007). These studies have suggested that mesoscale processes play a critical role in the maintenance of SCCs by pointing out the importance of convectively induced gravity waves (Oouchi 1999; Mapes 2000), or gust-front waves (Tulich and Mapes 2008), and the precipitation-generated cold pool (Oouchi and Yamasaki 2001; Nasuno et al. 2007), as in the case of typical mesoscale tropical convection (Yamasaki 1988). A key finding is that such mesoscale processes are equally important for explaining the well-organized nature of the SCC, in addition to explaining the contributions of the equatorial waves and MJO (Oouchi 1999; Oouchi and Yamasaki 2001).

To look at the hierarchy of the SCC further down the scale, each CC consists of mesoscale convection of \( O(10) \) km (Chen and Houze 1997; Oouchi 1999). The class of convection is emphasized as an important ingredient for suitably representing any tropical disturbance in a coarser grid model (Yamasaki 1984), and there is no exception for the SCC (Oouchi 1999). Although a suitable examination of mesoscale convection in the SCC is very significant from a different viewpoint (Oouchi 1999), it is not directly relevant in the context of the present chapter, and therefore discussion is omitted.

Acknowledging the fact that all these hierarchical features are important for understanding the origin of the SCC, in this chapter, we take another simple view on the importance of the SCC–CC hierarchy. We focus on a two-way interaction of the SCC and the CC to understand the geographical preference of the SCC as a first-order approximation. The rationale behind this is the fact that the CC is the most fundamental building block of tropical convection on a synoptic scale in the tropics and that the SCC has a distinctive and quite
systematic characteristic involving the life cycle of a CC. The latter is, in a sense, reminiscent of a multicellular squall line. This type of squall line is a coherently organized ensemble of convective cells at the mesoscale (Houze 1977). It moves forward against the environmental flow, which is essentially a manifestation of the life cycle of the inner convective cell with mesogamma scale that occurs by a convergence at the leading edge of the system-scale cold pool; the flow feeds moisture into the inner cells and interacts with the cold pool to sustain the cells in the entire system and, as a result, the mature stage shifts from one cell to another, thereby yielding an entire squall-line system. Apparently, this feature is analogous to the SCC, although the scale of the SCC is one order larger.

In light of this analogy, we provide a bold, yet intuitively simple, assumption that the SCC can be viewed as a gigantic multicell squall line, being independent of, if not at the expense of, the widely held discussion of its association with equatorial waves. It is well known that the evolution of squall line is controlled significantly by the effect of the orientation of line-normal vertical wind shear (e.g., Yamasaki 1984; Rotunno et al. 1988, hereafter RKW), and the analogy is applicable to the SCC. On this assumption, we employ a working hypothesis that the SCC is maintained or suppressed under climatologically different vertical shear regimes of the warm water pool origin. Whether or not CCs are organized into SCCs depends on the location of the CCs with respect to the tropical warm water pool and the associated vertical shear regimes. The MJO can modulate the vertical shear and, therefore, indirectly control the organization of the SCC. We explore this hypothesis and derive a new interpretation of the origin of the SCC by focusing on some simulated cases of SCCs and other ensemble CCs. The results of this chapter are based solely on a simulation using the global cloud-resolving Nonhydrostatic Icosahedral Atmospheric Model (NICAM; Satoh et al. 2008), with less emphasis being placed on the comparison with observations. A reason for this is that the aim of this chapter is to propose a concept as a step before discussing the details of observational verification. This is an important step in pointing out the possible essential physics of the tropical convection even in an idealized framework. In the future, by pursuing its applicability through observational verifications, the interpretation is expected to help answer the question of why the SCC preferentially occurs in the western Pacific but not in the Indian Ocean and Arabian Sea, thereby providing new insight into the origin of the SCC.

Section 2 describes briefly the method of the experiments. Section 3 explains the background atmosphere condition and the convective regimes of interest for introducing the key factors for interpreting SCCs. Section 4 documents the typical cases of convective organization and flow fields for the proposed regimes with a comparison with observations. Sections 5 and 6 provide an interpretation and conceptual model for it, which is followed by discussion and summary in section 7.

2. Experimental design

This study used NICAM (Satoh et al. 2008; Tomita and Satoh 2004). The horizontal grid spacing was 14 km, which was fine enough to resolve CCs abundant in the tropics and the gross features of mesoscale convection (Yamasaki 1984). The horizontal domain covered Earth, and the vertical domain, consisting of 40 layers, extended up into the upper stratosphere with its top at 40 km. We used the cloud microphysics scheme of Grabowski (1998), which includes two classes of solid phases of ice and snow. To formulate turbulent boundary layer, an improved version (Noda et al. 2010) of the scheme of Nakanishi and Niino (2006) was employed.

The time integration was performed from 1 June to 10 November 2004, using the initial atmospheric conditions interpolated from the National Centers for Environmental Prediction (NCEP) Global Tropospheric Analyses at 0000 UTC 1 June 2004. The experiment included the sea surface temperature (SST) dataset from the weekly National Oceanic and Atmospheric Administration (NOAA) Optimum Interpolation SST. No nudging techniques were applied during the course of the time integration; therefore, the genesis of clouds and convection and their interactions with atmospheric disturbances were expressed as an internally driven spontaneous process in the global cloud-resolving model. The time integration period included the active period of the Asian monsoon season, which was long enough to discuss a couple of MJO cycles and the associated tropical cyclogenesis. For other details of the experimental design, refer to Oouchi et al. (2009).

A major aim of the experiment was to investigate the performance of NICAM in representing the boreal summer seasonal variation of tropical convective disturbances including the tropical cyclone and MJO, the SCC, and the associated seasonal change in Asian monsoons and relevant phenomena. It is regarded as a companion experiment of the boreal winter experiment that demonstrated a good performance of the MJO-related convection and the accompanying genesis of tropical cyclones (Miura et al. 2007). Boreal summer is a challenging season under the control of Asian summer monsoons. The insight obtained from the present experiment will help improve seasonal forecasts of the tropical phenomena in that season. Highlights of the
results and details of the performance of the NICAM revealed in the experiment are reported elsewhere, including a well-simulated relationship between the MJO and tropical cyclogenesis (Oouchi et al. 2009) and an improved representation of low-level/boundary layer clouds (Noda et al. 2010).

3. Convective regime and flow field diagnosis

Figure 14-1 plots snapshots of the outgoing longwave radiation as a proxy for convective activity in the Indian Ocean and western Pacific region. The three panels are selected to facilitate the following discussion about the three regimes—A, B, and C—of convective organization in the region. Each regime roughly corresponds to a different phase of an MJO event, as will be explained with Fig. 14-3. More systematic categorization with respect to various phases of MJO’s propagation or other atmospheric conditions is under development. The selection of the regimes here serves as our understanding of the typical patterns of organized convection in the region as seen in the global cloud-resolving model.

In all panels, we can see that the tropical atmosphere over the Indian Ocean and the western Pacific is characterized by an occurrence of active convection in a variety of forms. Typically, various types of convection are present in the tropical region. Some types are organized into a tropical cyclone with a clear eye near the Philippine Islands, as in Fig. 14-1a, and others are transient, creating ensembles in vague forms. What is immediately evident from these panels is the fact that the convection is identified as a patch of CCs of $O(100)$ km scale. Cloud clusters would be accompanied by a mesoscale circulation and interact with various disturbances in the tropics, including equatorial waves. Cloud clusters are known to be a basic, important building block of tropical convection (Nakajima and Matuno 1988; Satoh et al. 2008), and their own origins are an important research topic. Here, we regard CCs just as a basic element of tropical convection, and we focus on the issue of further upscale organization of CCs. A
well-known upscale organization of CCs is an SCC that is associated with the propagation or existence of the MJO. In Fig. 14-1a, an SCC is identified around 140°–180°E as an ensemble of CCs with more than a 4000-km scale flanked by a tropical cyclone. The coexistence of SCCs and tropical cyclones is a typically observed situation in the active phase of the MJO (Nakazawa 1986; Sui and Lau 1992; McBride et al. 1995).

In other periods and regions such as the Indian Ocean, we can see some transient, loosely detectable, upscale organization of CCs other than SCCs; we call this a cloud cluster complex (CCC). The behaviors of CCs in the real atmosphere and in the NICAM experiment are not so straightforward that one can objectively categorize them into a simple picture. The argument in this chapter is just one way of ad hoc categorization to highlight the background physics that might work behind the CCC and SCC.

The aim of this chapter is not to pursue the similarity between the observation and simulation, but to propose a conceptual model as a first step toward improving our understanding of SCCs. However, it is important to check whether the simulated convective fields deviate significantly from observations. Figure 14-2 plots the infrared radiation (IR) temperature compiled by NCEP, which serves as a proxy of convective activity—like outgoing longwave radiation. Note that the IR temperature is a variable that represents the physical quantity differently from the outgoing longwave radiation in Fig. 14-1, so the legends are different between the two figures. In Fig. 14-2a, we can see that an ensemble of convection is present near the equator, at 140°–160°E. The ensemble we called “SCC” is a focus of this chapter; it is reasonably simulated in the in regime A in Fig. 14-1. The SCC became less clear 6 days later (Fig. 14-2b), and

![Fig. 14-2. Snapshots of infrared radiation temperature (K) from NCEP-NCAR over the Indian Ocean and the Pacific region (30°S–50°N, 30°E–90°W) for (a) 13 June, (b) 19 June, and (c) 13 July.](image)
the weakening is also simulated to some degree in the model as regime B in Fig. 14-1. After approximately 20 days (Fig. 14-2c), the convective activity associated with the SCC looked further weakened, and a less intense cloud cluster occupied the western Pacific, a situation resembling simulated regime C in Fig. 14-1. Another important feature is that in Figs. 14-1 and 14-2, convection is less coherently organized in the Indian Ocean than in the western Pacific in all regimes. In this chapter, we call the less coherent convection "CCC." A mechanism for contrasting convective features of the western Pacific and Indian Oceans is the main subject of this chapter.

The association of the convective regimes in Fig. 14-1 with the simulated MJO event is illustrated based on the MJO index of Taniguchi et al. (2010) and Wheeler and Hendon (2004). The index was shown to serve as a good quantitative diagnosis of the MJO event simulated in the boreal winter experiment with NICAM (Taniguchi et al. 2010; Miura et al. 2007). It is derived from the leading two modes of empirical orthogonal function (EOF) analysis of the velocity potential at 200 hPa. Figure 14-3a plots the horizontal distributions of EOF 1 and EOF 2, and Fig. 14-3b plots principal component (PC) 1 and 2 on the phase space diagram. The MJO is identified by a combination of the leading two EOFs that represent, as a pair, a large-scale eastward propagation of the signals. EOF 1 represents a situation in which the MJO-associated convection is enhanced (suppressed) and yields divergence (convergence) in the upper troposphere (200 hPa) at the longitudes of the African continent, and convergence...
(divergence) in the mid-Pacific, while EOF 2 exhibits a pattern nearly in quadrature to that of EOF 1. A combination of Figs. 14-3a and 14-3b shows the behavior of the simulated MJO-associated large-scale circulation that propagates eastward over the central Pacific (regime A), while showing intensified divergence over the western Pacific (regime B) and reentering of the divergence signal into the Western Hemisphere and African continent (regime C). The regimes thus cover a cycle of the MJO that travels over the globe in the tropical regions; the regimes explain reasonably the enhanced (suppressed) activity of the MJO in the Eastern (Western) Hemisphere. The associated flow patterns are more clearly identified in the following arguments.

The key factor in this study is a vertical shear of the horizontal zonal velocity that changes systematically in association with the propagation of the MJO. This factor significantly controls the large-scale wind fields responsible not only for the favorable occurrence of tropical cyclogenesis (Gray 1968; Oouchi et al. 2009), but also for the manner of convective organization in the Indian Ocean and western Pacific as suggested in this chapter. To define the typical spatial patterns of the simulated vertical shear regimes, EOF analysis of the vertical shear of zonal winds (U200 minus U850) is performed for the region of interest covering the Indian Ocean and western Pacific (10°S–20°N, 40°E–140°W). Figure 14-4 shows the leading three EOFs and a set of corresponding principal components representing a normalized time series.

EOF 1 explains 27% of the total velocity variance and represents an elongated easterly shear (low-level westerly) in the subtropical regions and a westerly shear (low-level easterly) that is flanked on the southern side up to the equatorial region in and around the Maritime Continent (80°–150°E). The pattern in this region therefore represents a stronger meridional gradient of the horizontal shear and tends to generate an anticyclonic vortex in the lower troposphere. A comparison of the spatial pattern with PC 1 reveals that in the second half of June, the lower troposphere is favorable for cyclogenesis in view of the negative polarity of PC 1 (cyclone-generating sense). It is interesting that the polarity of EOF 1 becomes reversed on a time scale of more than
30 or 40 days, which is closely associated with the behavior of the MJO simulated in this period (Oouchi et al. 2009). Given its substantial amplitude in the off-equatorial region, the regime can also be controlled by monsoon-associated signals, which is beyond the scope of this study.

On the other hand, EOF 2, which explains 11% of the total variance, exhibits a temporal variation on the shorter time scale (approximately submonthly). Its spatial pattern shows a zonally aligned westerly–easterly shear region with its amplitude maximized around the equator. The strongest easterly shear is located in the Indian Ocean, that is, to the west of the Maritime Continent or the warm-pool region, while the westerly shear counterpart is in the equatorial western Pacific; its amplitude is smaller than the easterly shear in the Indian Ocean. As discussed in the following, this regime can be interpreted as resulting from a different manner of coupling between the vertical shear and CCC or SCC in different oceanic basins (the Indian Ocean and the western Pacific).

EOF 3 appears to reflect the regime with a time scale similar to that of EOF 2 and shows a reversed polarity, particularly during the period from mid-June to early July. However, the scattered nature of the spatial pattern in the maximum amplitude makes its interpretation difficult. The leading two EOF patterns serve as the key references of the environment by which the following interpretation of the organized convective regime becomes more easily adopted.

4. Overview of the regimes
   a. Simulation

The evolution of the convective ensemble in each regime in Fig. 14-1 is displayed in Fig. 14-5 (regime A), Fig. 14-6 (regime B), and Fig. 14-7 (regime C) as the daily snapshots of four consecutive days for precipitable water (shades), horizontal flow at 850 hPa (arrows) and precipitation (blue contours). In Fig. 14-5, it is evident that an envelope of convection in the tropical western Pacific (around 140°–150°E on 11 June) propagates eastward, which we define here as SCC. The SCC propagates in the low-level easterly duct that stretches across the western and central Pacific and is nearly collocated with the region with higher precipitable water. On 11 and 12 June, an off-equatorial precipitation...
pattern accompanied by a tropical cyclone is flanked by the SCC. As argued in Oouchi et al. (2009), SCCs and tropical cyclones are frequently observed in the convectively active period of the MJO in this experiment, and this is also the case here. As to the convection in the Indian Ocean, that is, to the west of the Maritime Continent or the western Pacific warm pool, it exhibited a pattern of organization different from the SCC in the western Pacific; it had a scale of about 2000 km (e.g., 60°–80°E on 12 and 14 June) and was therefore regarded as an ensemble of CCs (defined as CCC). However, the ensemble tended to stay in the low-level westerly region, and it decayed after 14 June.

Such a simultaneous occurrence of the low-level westerly and precipitation and the tendency for precipitation to stay within the Indian Ocean (or within the oceanic basin of the Arabian Sea or the Bay of Bengal) can be confirmed also in Figs. 14-6 and 14-7. Note that the convective pattern and the moisture and flow fields in the western Pacific in Figs. 14-6 and 14-7 are different from those in Fig. 14-5. We see neither conspicuous eastward movement corresponding to SCC nor extended easterly with little sign of meridional flow in the equatorial western and central Pacific; instead, the precipitation pattern takes the form of vortices, some of which can be identified as tropical cyclones.

On the other hand, the flow and precipitation patterns in the Indian Ocean and the Maritime Continent are different between Fig. 14-6 and Fig. 14-7. In Fig. 14-6, a persistent westerly stretches from off the eastern coast of Africa (as a Somali jet) to around the Maritime Continent (100°–120°E). The signature of the tendency of such an eastward extension of the westerly is obvious if one traces the snapshots from 11 June (Fig. 14-5) to 21 July (Fig. 14-6). The extension is obviously caused by the propagation of the MJO as suggested by Fig. 14-3b, which indicates the eastward propagation of the MJO from around the Indian Ocean to around the Maritime Continent, and the accompanying change in precipitation pattern, such as enhanced precipitation (another form of CCC) over 100°–120°E on 18–21 June in Fig. 14-7 (regime A to B). In Fig. 14-7, such widespread features of precipitation patterns and flow fields become weakened, and the coupling among the precipitation, flow, and moisture fields seems to be only locally activated in the Indian Ocean and the western Pacific. This is the regime, according to the MJO index in Fig. 14-3b, when the center of the MJO action propagates away from the

![Fig. 14-6](https://example.com/fig14_6.png)

Fig. 14-6. As in Fig. 14-5, but for the regime B period for 18–21 June.
Maritime Continent and the western Pacific region and approaches, or passes over, the Western Hemisphere. This is also suggested by the lower precipitable water in 80°–120°E on 12–15 July, which is likely to be caused by the subsidence associated with the MJO.

These results suggest that the SCC is seen favorably in the western Pacific, in association with the presence of low-level zonal (small meridional component) easterlies ahead and rotational flows behind, and that this is closely associated with the propagation of the MJO. This is consistent with Oouchi et al. (2009) and the widely held scenario (Hayashi and Sumi 1986; Hayashi and Nakazawa 1989, and many others). This is, therefore, just a confirmation of previous studies. However, we stress here that the different convective regimes (SCC and CCC) as shown in Figs. 14-5–14-7 can be controlled by the warm-pool-induced zonal circulation, which is explored in the following.

The specific question here is what is the difference between the SCC and other convective ensembles (CCC) regarding the relative location of the evaporatively driven cold pool, active cloud condensates, and environmental velocity fields, and how can one explain the favorable or unfavorable conditions for the occurrence of SCCs in light of this. To explore the problem, the vertical–zonal cross section along the active convection area in each regime in Fig. 14-1 is shown in Figs. 14-8–14-10, and for the SCC over the western Pacific in Fig. 14-8, CCC in the Indian Ocean in Figs. 14-9 and 14-10. In Fig. 14-8, the SCC is identified as an ensemble of the cloud cluster as is well known (Nakazawa 1988). We can see that the lower troposphere in the SCC region is occupied by a negative temperature anomaly (purple boxes) that might result from an evaporative cooling of rainwater, called “cold reservoir” here. The cold reservoir is defined as the entity of the negative temperature anomaly floating in the low- to midlevel air (up to about 700 hPa) of the troposphere plus the conventional cold pool, which refers to the negative temperature anomaly on Earth’s surface. The original cold pool is an important feature in mesoscale phenomena such as squall lines, and also in the SCC (Oouchi 1999; Nasuno et al. 2007). The bottom panel in Fig. 14-8 plots the temperature anomaly averaged in the vertical layer spanning 925–850 hPa (black line) and surface precipitation (blue line). We can see that with respect to the precipitation center (142°–155°E), the cold anomaly spreads to the west. As to the velocity fields shown in the middle panel of Fig. 14-8, a subsidence of

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**Fig. 14-7.** As in Fig. 14-5, but for the regime C period for 12–15 July.
the dry air in the mid- to upper troposphere is evident to the east of the SCC (east of 170°E). The low-level easterly over the central Pacific (160°E–150°W) flows into the cold pool beneath the active convection area (140°–160°E), and this should maintain the entire convective system of the SCC. As indicated by the flow field, in an averaged sense, over the active convection area of 140°–170°E, the axis of the updraft tilts westward with height. We propose that this is an important feature for maintaining SCCs; the precipitation from the active convective area of the SCC falls to the west of the area for interaction between the cold pool and the easterly inflow and therefore does not prevent the interaction from feeding moisture to the SCC. This situation highlighting the importance of the interaction between the cold pool and environmental flow resembles the maintenance of tropical mesoscale convection proposed by Yamasaki (1984) and is also in consistent with Oouchi (1999) and Nasuno et al. (2007) for SCCs. However, it is important to note that they argued the importance of the cold pool only for maintaining the inner convective element of the SCC, not for the SCC as a whole.

On the other hand, for the synoptic-scale CCC in the Indian Ocean (Figs. 14-9, 14-10), the location of the cold pool and the flow fields surrounding the CCC are not favorable for maintaining the CCC. For example, we can see in the bottom and middle panels of Figs. 14-9 and 14-10 that the cold pool and the low-level inflow take a pattern unfavorable for long-lived convective activity. Particularly in Fig. 14-10, we can see that the conspicuous low-level westerly enters into the system around 40°–60°E, and the location of the interaction between the low-level flow and the cold pool is to the west of the main convective region. In addition, the location is almost collocated with the area of the falling precipitation, and therefore the situation is unfavorable for maintaining the convective system. The situation is more clearly interpreted by using the theory of RKW; over the Indian Ocean, two horizontal vortices

FIG. 14-8. (top) Vertical cross section (average over 6°S–9°N) of the total hydrometeor (color shading), zonal and vertical velocity (vectors) that are colorized with relative humidity (see the color bar for values), and “negative” temperature anomaly (dotted contours) for 100°E–150°W. These are averaged over the consecutive 4-day periods during regime A for 11–14 June. (middle) Horizontal distribution of the temperature anomaly for the layers average (925–850 hPa, shading) and precipitation (contours) in the corresponding area and period. (bottom) Temperature anomaly for the layers (925–850 hPa) from the area average (black), and the area-averaged precipitation (blue) in the corresponding area and period. Note that y-axis labels are on the left for the temperature and the right for the precipitation.

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associated with the cold reservoir and vertical shear are still opposite in sign, but the smaller vertical shear west of the warm pool causes even more suboptimal vorticity imbalance in the western flank of cold reservoir, leading to larger tilt with height and intermittent, less viable storm situation. This is the situation frequently seen in the other CCC cases in the Indian Ocean. We can therefore infer that this might be responsible for the absence of well-organized SCC in the Indian Ocean (to the west of the warm water pool), if one views the SCC as a convective ensemble involving the intense, westward-tilting updraft core.

b. Comparison with the observations

The aim of this chapter is to propose and characterize the convective regimes associated with SCCs based on numerical simulations. At a next step, it should be instructive to verify their existence in the real atmosphere. As a first step, our aim is to investigate the morphological similarities between the simulated regimes (Figs. 14-8–14-10) and their observational counterparts. Figures 14-11, 14-12, and 14-13 indicate the plots of TRMM 3B42 (precipitation) and NCEP reanalysis (other variables) as the observational counterparts of each of the regimes—A, B, and C, respectively. Note that even though the period and region displayed happened to be the same as those in the numerical simulation, we cannot expect rigorous correspondence of the simulated regime-specific features with the observed counterparts because of the intrinsic nature of the initial value problem and the transience of cloud systems.

1) REGIME A

A comparison of the simulation (Fig. 14-8) and the observation (Fig. 14-11) indicates a common feature of regime A in terms of the active convective area—represented as total hydrometeors (top panel) and precipitation (middle panel)—that is mostly collocated with the negative temperature anomaly in the lower atmosphere, that is, the cold reservoir. This reinforces the key premise of the hypothesis. The relationship between the convection and the zonal–vertical flow fields (top panel) is also similar in that the updraft core tilts westward with height with respect to the active convection cell(s). To describe it another way, the low-level warm and moist air advances into the cold reservoir from the east, ascends to the middle troposphere, and constitutes a significant
easterly outflow core at the upper level to the west/rear of the entire convective system. This picture again reminds us of a typical feature of a squall line and suggests that the conceptual framework for regime A is plausible.

2) REGIME B

On the other hand, the vertical cross section (top panel) does not show close similarity between the simulation and the observation (Fig. 14-12) in terms of the structures of convection, but the low-level zonal wind is characterized by the common features of the predominant westerly. As a key feature of regime B, there is evidence of correspondence between the relatively less organized convection and the underlying positive temperature anomaly (i.e., a situation contrary to a cold reservoir), both in the simulation (Fig. 14-9, middle) and observation (Fig. 14-12, middle), which may be a result of inactive or decayed convective activity as compared to regime A.

3) REGIME C

Both in the simulation (Fig. 14-10) and the observation (Fig. 14-13), the flow fields (top panel) are characterized by a less-clear signature typical of serene conditions when convection is relatively inactive as compared with regimes A and B. The situation is consistent with this particular period when the MJO center propagates eastward away from the warm-pool region and reaches the Western Hemisphere (Fig. 14-3).

In summary, the comparison between the simulation and observation reveals a reasonable correspondence for regime A and, to a lesser degree, regimes B and C, in terms of the qualitative relationships among the key physical parameters constituting the proposed hypothesis. Given the nature of the systematic influences of the MJO on the intensification of synoptic-scale tropical convective activity for this particular period (Oouchi et al. 2009), the regime-dependent correspondences seem to be acceptable as the absence or the weaker phases of the MJO is likely to diminish the structured pattern of tropical convection and the related circulation.

5. Interpretation

a. Three-dimensional conceptual schematic

Figures 14-14 and 14-15 illustrate the schematics summarizing the results and associated inferences derived
from the above findings. First, we stand on the premise that contributions of wave-associated characteristics of the MJO and the equatorial waves including moist Kelvin waves are undoubtedly important in explaining some aspects of the SCC, including its organization and behavior (e.g., eastward movement). Details of the comprehensive analysis of the waves will be reported elsewhere. Independent of these factors, the discussion in this chapter focuses rather on the interaction between the ensemble of CCs and the warm-pool-induced climatological vertical circulation as well as on a possible background modulation of CCs by the MJO. This facilitates clarifying why SCCs are preferably organized in the western Pacific region and how the climatological vertical circulation contributes to maintaining the SCC.

Figure 14-14 depicts a large-scale overview of the boreal summer atmosphere of the Asian monsoon-susceptible region. As a basic environmental factor, the existence of the warm water pool in the western Pacific is very important, with the ascending motions staying over the warmest sea surface temperatures. Highlighted here are the MJO and the organized convection in the Indian Ocean (to the west of the warm water pool) and in the western-to-central Pacific (to the east of the warm water pool). Since a large part of the tropical convection is known to exist as a form of CC (Nakajima and Matuno 1988), we call the convection ensemble exceeding the scale of CC a cloud cluster complex (CCC). An SCC can be interpreted as a highly organized special form of CCC in the eastern branch of the quasi-stationary climatological circulation under some influence of the MJO. These atmospheric components are classified into three regimes depending on the possible background influence of the MJO (Fig. 14-3; Taniguchi et al. 2010; Oouchi et al. 2009).
The first regime (regime A) is the active MJO period, in which the center of the MJO propagates over the east of the Maritime Continent, and the quasi-stationary warm pool circulation and convective mode undergo significant modulation. The regime is characterized by a preponderance of SCCs in the western Pacific and the genesis of a tropical cyclone (TC). Both are important components of the MJO-related signal that appear in a combined form of Kelvin and Rossby waves (e.g., Matsuno 1966; Gill 1980; Lau and Peng 1987; Miyahara 1987; Oouchi et al. 2009). On the other hand, in the Indian Ocean, CCs stay transient, or the SCC is not coherently maintained as the region is under the influence of a strong low-level westerly jet associated with the Somali jet.

In the second regime (regime B) called the “decay of the MJO period,” the MJO (strictly a Kelvin wave signature) propagates away from the central Pacific, and low-level westerly anomalies overtake the western Pacific region. The low-level westerly jet also becomes enhanced and stretches up to the southwest of the Maritime Continent (see the change of polarity of PC 1 and PC 2 late in June in Fig. 14-4). The intensified jet is obviously influenced by the effect of the MJO-associated anomalous low-level westerly; we call this westerly anomaly of sizable extent the Somali–MJO westerly burst (SMWB). The SMWB is sometimes observed in the boreal summer monsoon season (Lestari and Iwasaki 2006). The Somali–MJO combined flow may originate essentially from a westerly jet in response to a heat source imposed somewhere north of the equator in the typical monsoon season. As the center of the action of the MJO shifts northward with respect to the equator in this season, the low-level anomalous westerly of the MJO can act to enhance and enlarge the original westerly jet. The realistic setup (topography and sea surface temperature) may modify this simple picture by strengthening the linkage between the SMWB and the land–ocean coupled system, and as a result, the region of the westerly jet stretches across a wide-spanning area from the Arabian Sea to the southeastern region of Asia. Under this regime, the SCC decays as the control by MJO’s control subsides, and some of the vortical disturbances in the wake of the MJO’s westerlies grow into a tropical cyclone (Miura et al. 2007; Oouchi et al. 2009).

The third regime (regime C), the inactive MJO period, is characterized by a revisit or reintensification of
the MJO-associated circulation in the Indian Ocean. It is a convectively quiescent period both in the Indian Ocean and the western Pacific, with some transient CCs developing and sometimes loosely organizing into CCCs (see the negative polarity of PC 2 after 10 July in Fig. 14-4).

The hypothesized control (propagation) of the MJO over the three regimes above is a possible enhancement of the moisture convergence to the east of the Maritime Continent, its interaction with CCs in that area, and the intensification of the SMWB, in combination with typical monsoon atmospheric conditions. Most of the features may have already been discussed in previous studies, and the schematic is just to reorganize the simulated situations in and around the warm water pool region. Investigation of these factors is beyond the scope of this study and will be an important future work.

b. Two-dimensional (vertical–zonal) conceptual schematic

To focus again on the organization of a CC into an SCC and the mechanism of its maintenance, the schematic of the SCC in association with the vertical circulation is shown in Fig. 14-15. The question here is what vertical shear regime is favorable for maintaining the SCC? Here, we propose a simple interpretation in terms of its analogy to a multicellular squall line. This should facilitate conceptual understanding. We assume that the convection under consideration is in the near-equatorial open ocean in the tropics and under a weaker rotational constraint. The schematic illustrates two types of convection, SCC and suboptimal SCC, as a counter example of SCC. The latter is suboptimal in the sense that there would be little chance such a type of organization would develop under the environmental factors in that region. The SCC, as was frequently observed in the western Pacific, is under the quasi-stationary climatological westerly shear regime as a result of the existence of the warm water pool. Given its eastward propagation and its inclusion of CCs exhibiting the successive formation of the new CC to the east while the matured one is accompanied by a trailing upper anvil to the west, the SCC generates a cold pool and heavier rainfall to its more western part (Fig. 14-8). From another viewpoint, the active core of the SCC, or the active CC inside the SCC, tilts westward with height as suggested by the westward tilt of the updraft core in SCC (Fig. 14-8). This is
consistent with an analysis of the convective momentum transport associated with SCCs that indicated an upward transport of easterly momentum (Moncrieff and Klinker 1997). Now that moist low-level flows move into the SCC from the east, the resultant interaction between the easterly and the cold pool is realized in such a way that heavier precipitation does not prevent the formation of a new CC on the eastern side of the SCC. The SCC is thus favorably maintained under the vertical shear regime.

On the other hand, if the suboptimal SCC in the Indian Ocean was in place, it would be under the easterly shear regime, as the region is to the west of the warm water pool. Compared to the western Pacific SCC, the reversed line of reasoning explains the less favorable condition for SCCs there. That is, moist low-level westerly flows move into the SCC from the west, and the resultant interaction between the westerly and the cold pool (Fig. 14-10) would occur in the region of heavier precipitation. This would be unfavorable for maintaining the ensemble of CCs, and therefore, the SCC would decay. Instead of an SCC, such a vertical shear regime might favor less organized, transient forms of convection (i.e., CCCs). The CCC involves no systematically aligned multicellular CCs. What is argued here is, in essence, analogous to that for a tropical squall line and the convection associated with an easterly wave (Yamasaki 1984), albeit in the larger (synoptic scale) context here.

The theory of squall line structure by RKW is helpful for interpreting and concisely defining the two situations. An SCC of $O(1000)$ km scale is interpretable as a gigantic analog of a multicellular squall line embedded in the quasi-stationary westerly shear branch of the zonal circulation east of the warm water pool. A CC corresponds to the “cell,” and its successive formation to the east and westward movement represents an upshear-tilting core of intense updraft. The upshear-tilted SCC is favorably maintained with the precipitating area being separated from the gust-front boundary between the cold reservoir and a low-level easterly (the situation of RKW, where two horizontal vortices associated with the cold reservoir and vertical shear are opposite in sign, but the cold reservoir’s vorticity can be inferred to be larger, leading to upshear-tilted and multicellular behavior). As a counterexample, a CC to the west of the warm pool (Indian Ocean and Arabian Sea) is embedded in the easterly shear and, from the reversed line of reasoning, organized into a less coherent CCC given the SCC’s geometry as defined above (the situation of RKW where two horizontal vortices associated with the cold reservoir and vertical shear are still opposite in sign, but the smaller vertical shear west of the warm pool causes even more suboptimal vorticity imbalance in the western flank of cold reservoir, leading to larger tilt with height and intermittent less viable storm situations). Note that the above interpretation in no way precludes the widely held viewpoint of interpreting the CC as the inner element of the SCC and in terms of most equatorial waves (e.g., Takayabu 1994; Wheeler and Kiladis 1999). Instead, we offer a simple, yet intuitively plausible, alternative interpretation of the origin of the SCC.

6. Some implications to test the hypothesis

To organize the new features and related inferences from this study, additional notes are presented in this...
These instructive notes can serve as a guide to motivate future studies on the origin of the SCC. This chapter highlights the role of the vertical shear and the cold reservoir inherent in the convective activity associated with SCCs, employing an analogy to multicellular squall lines (MCSLs).

Table 14-1 summarizes a comparison of some notable characteristics between SCCs and MCSLs. Each of the identified or inferred characteristics represents a possible pedagogic implication that will be further explored and validated in a future study. General comparisons can be made involving, horizontal size, possible origin, major building blocks of convection, and mechanisms of maintenance, as well as the entire system. Following are notes for some related points included or not covered in the table.

a. Horizontal scale

One might ask about the origin of the scales of the SCC (3000–5000 km) and the MCSL [(100) km] as a premise for comparison. An inference we could make is, as indicated in Table 14-1, SCCs may be related to the equatorial radius of deformation (Hayashi and Sumi 1986). This point will be investigated in a future study.

Table 14-1. Comparison of some features and related proposed mechanisms between SCC and MCSL in the tropical atmosphere. The items proposed in this chapter are in bold. Note that the list is not all inclusive.

<table>
<thead>
<tr>
<th></th>
<th>SCC</th>
<th>MCSL</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Horizontal scale</strong></td>
<td>3000–5000 km (Nakazawa 1988)</td>
<td>(100) km</td>
</tr>
<tr>
<td>and its origin</td>
<td>• Area affected by a combination of MJO circulation and warm-pool-induced easterly shear</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• The equatorial radius of deformation (Hayashi and Sumi 1986)</td>
<td>• Nearly homogeneous (quasi-equilibrium, Fovell and Ogura 1988) condition where convective motion is sustained</td>
</tr>
<tr>
<td>Major building block</td>
<td>• Cloud cluster (CC)</td>
<td>• Convective cell (thunder storm) or cumulus convection (Zipser 1977)</td>
</tr>
<tr>
<td></td>
<td>• Mesonconvection (MC) embedded in CC (Oouchi 1999)</td>
<td>• CISK (cumulus cloud) under conditionally unstable atmosphere</td>
</tr>
<tr>
<td>Mechanism for the</td>
<td>• Cold pool/mesoscale gravity wave (Oouchi 1999)</td>
<td>• Significant low- to midlevel vertical shear</td>
</tr>
<tr>
<td>building block</td>
<td>• 2-day inertia–gravity wave plus 1-day convective regime (Chen and Houze 1997)</td>
<td>• Cold pool</td>
</tr>
<tr>
<td>Mechanism for the</td>
<td>• Warm-pool-induced circulation/vertical shear and cold reservoir</td>
<td>• Conditionally unstable atmosphere</td>
</tr>
<tr>
<td>entire system</td>
<td>The other proposed mechanisms include</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• unstable Kelvin wave (Hayashi and Sumi 1986)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• diabatic heating of westward-propagating CC (Takayabu and Murakami 1991)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• MC-related mechanism (cold pool/mesoscale gravity wave) plus Kelvin-wave instability (Oouchi and Yamasaki 2001)</td>
<td></td>
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</tbody>
</table>

More generally, MC systems are preferred forms under latent instability condition, as argued in Matsuno et al. (2011).

b. Vertical shear and the organization of CCs (regimes A, B, and C)

Vertical shear is known to control large-scale organization of tropical convective systems (Yamasaki 1988), and one plausible manifestation of organized tropical convection in the tropics, although its internal dynamics had been left for future investigation.

On the other hand, a typical scale of MCSL measures (100) km, which is interpreted as a preferred scale with the specific form of organized convection under preferred atmospheric conditions, including vertical shear profile and strength.

The other important feature of the SCC and the MCSL that is associated with the scale consideration and suggested in this chapter includes the morphological similarity, in that successive generation and development of convective cells or CCs at different stages coexist in a leading-edge, normal-direction line under a specific vertical shear environment (i.e., easterly shear for SCC). This feature may also be important to determine the scale, because a typical configuration for organizing (enlarging) the entire system size consists of individual convective elements (Takeda 1971); in other words, the size is no smaller than the distance propagated by the mesoscale convection (CC) evolving in the single rearward direction, at a certain velocity range from the leading edge at a nearly periodic genesis rate [shorter than half a day (a few days)] for the MCSL (SCC). This point will be investigated in a future study.

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this chapter explores the further implications associated with SCCs, as mentioned above in the “horizontal size” issue. In MCSLs, vertical shear is necessary\(^1\) to cause successive generations of new convective cells, thereby creating longer-lived (longer than that of individual cumulus clouds), organized convective systems at \(O(100)\) km scale. Likewise, in SCCs, the vertical shear is helpful for successive generations of new cloud clusters, thereby creating and maintaining its ensemble at \(O(1000)\) km scale.

An underlying emphasis of this chapter is the role of the cold pool (or cold reservoir) that can act to cooperate with the vertical shear for the organization and longevity of the entire convective system. This chapter focuses on this aspect rather than on other possible effects (e.g., equatorial waves) for the organization of SCCs. The idea is simple enough. As long as convective activity persists, evaporation from the rain maintains downdrafts and cold air. The initial cooling creates a cold pool that spreads upstream at low levels, thus producing convergence with the ambient warmer air/flows. The location of the convergence and its effects on the longevity of the entire system are controlled by the tilt of the convection. It is likely to dissipate if a downshear updraft slope releases rain into the buoyant inflow air; the upshear slope of the updraft is therefore typical of tropical squall lines (Thorpe et al. 1982).

In terms of the SCC, similar reasoning should be applicable when cold pool is replaced with a cold reservoir and the ambient vertical shear is assumed to be affected by warm-pool-induced circulation. The preference of SCCs or other regimes of organization also can be determined by how long and how much the vertical shear works to sustain the CC’s organization. This is, in a sense, analogous to the longevity and maintenance of a given squall line in a nondestructive (homogeneous) environment, as suggested by Fovell and Ogura (1988). They indicated that a state of quasi-equilibrium can be attained and that squall lines do not decay as long as environmental conditions ahead of the storms are favorable and essentially unchanged during the course of the simulations. It can be postulated in this chapter that the environmental homogeneity in SCCs is controlled by the location of the SCC with respect to the tropical warm pool that creates the background shear for it.

c. Possible association of the Kelvin wave

One of the important questions related to the SCC is what mechanism sustains its eastward movement? If regarded as an analog of the MCSL, as assumed in this chapter, it is interesting to explore how the arguments here can or cannot be reconciled to the existing theoretical framework on equatorial Kelvin waves (Hayashi and Sumi 1986).

A key viewpoint is if the coexistence of the Kelvin wave and the MCSL-based mechanism above can be realized, and which contribution is more dominant in SCC. A hint as to the answer comes from Oouchi (1999), who noted coexistence of the synoptic-scale extension of the cold pool and an eastward-propagating gravity wave convective instability of the second kind (CISK) with a 2D cloud-resolving model for the realization of the SCC. As an unstable mode, the CISK worked to maintain a positive correlation between temperature anomaly and vertical motion (generating kinetic energy), in addition to a collocation of convective heating and synoptic-scale upward motion (generating available potential energy). One may find it interesting to relate the low- to midtropospheric negative temperature signal as a part of a cold reservoir behind the main convective region of the SCC (regime A, Fig. 14-8) to a part of the typical temperature signal associated with eastward-propagating gravity (Kelvin) waves. A close inspection of the temperature anomaly would confirm that the temperature is generally lower to the west of the active precipitation center than to the east. As the convection-associated low-level flow is westerly to the west, and easterly to the east of the precipitation center, this indicates that zonal velocity and temperature fields are negatively correlated with each other. Therefore, SCCs and CCCs can be somehow associated with eastward-propagating gravity waves, whatever the degree of coupling that might turn out to be significant. This is an important feature associated with the mechanism of generation of the eastward-propagating equatorial wave and its interaction with convections, which is a subject for investigation at the next step.

Note that the CISK defined in Oouchi (1999) is more comprehensive than what is generally thought in that it includes the effect of the cold pool. In the study, a cold pool (reservoir) spanning the synoptic SCC scale can create an ensemble of mesohighs and therefore horizontal pressure gradients and induced synoptic-scale circulation—a kind of rear-to-front/front-to-rear flow as seen in a squall line. The argument forms a basis for the proposed hypothesis of this chapter. We need further studies and observations of SCCs to assess the MCSL-related hypothesis and its relation to Kelvin-wave control on SCCs. It is hoped that the arguments above will solicit further discussion to better understand this aspect.

\(^1\) Given RKW, vertical shear that can at least partially oppose the cold pool circulation is needed for storms to be viable enough to be unsteady.
7. Discussion and remarks

This chapter provides a simplified interpretation of the origin of large-scale convection at its mature stage as associated with the MJO [or super cloud cluster (SCC)] by focusing on the existence of the warm water pool in the western Pacific and its accompanying climatological zonal circulation. The interpretation is proposed as a hypothesis that needs to be tested in future investigations using observational and various modeling datasets of MJO-related convection. A drastic simplification of the hypothesis is that the SCC is independent of the widely held viewpoint of its association with equatorial wave dynamics. Even though we do recognize that the equatorial waves play an important role in producing some aspects of the SCC, they alone cannot explain its origin and geographical preference (e.g., its dominance over the western Pacific as opposed to the global propagating feature of convection in the aquaplanet experiments). The hypothesis in this chapter proposes an interpretation in a broader working framework in which details of the existing MJO convection-associated theories could be based or complemented.

a. Vertical tilt of convection and convective regime selection

Focus is placed on the presence (absence) of SCCs in the western Pacific (Indian Ocean and Arabian Sea). We propose that the different situation in the oceanic basins is interpretable, by employing an analogy of a multicellular squall line, in terms of the preferred regimes of CCs (SCCs or CCCs) under different regimes of the warm-pool-induced climatological vertical circulation with some modification by the MJO. Given the well-known nature of SCCs in which CCs develop from the eastern portion of the entire system (as shallow convection) and move westward, growing and accompanied by anvils aloft, the center of the action in the entire ensemble of CCs tilts westward with height (upshear tilt) in the warm-pool-induced eastern branch of the climatological zonal circulation. This is a situation in which the interaction between the cold reservoir and low-level easterly inflow to the system stays intact, being separated from the heavier precipitation on the western portion of the system, and therefore SCC is maintained (the situation of RKW where two horizontal vortices associated with the cold reservoir and vertical shear are opposite in sign but cold reservoir’s vorticity can be inferred to be larger, leading to upshear-tilted and multicellular behavior). On the other hand, CCCs tend to be short lived or less systematically organized as compared to SCCs, making it harder to observe (the situation of RKW where two horizontal vortices associated with the cold reservoir and vertical shear are still opposite in sign, but the smaller vertical shear west of the warm pool causes even more suboptimal vorticity imbalance in the western flank of cold reservoir, leading to larger tilt with height and intermittent less viable storm situations). Favorable occurrences of SCC in the active phase of the MJO can be explained in terms of this interpretation.

The core concept described above is associated with Yamasaki (1984), who reported a significant relationship between a preferred regime of organized cumulus convection (ensemble of mesoscale convection) that is interactive with tropical large-scale disturbances and the environmental vertical shear and argued that the convection of the upshear-tilting type tends to be long lasting, while that of downshear-tilting type does not. It is surprising that the essence of this picture is also logically consistent with that proposed for a single long-lasting or short-lived cloud regarding the relationship between a cloud’s lifetime and a vertical shear regime (Takeda 1971). A recent modeling study has also indicated that the westward tilt is an important feature of MJO-associated convection in which convective momentum transport can support its coherent organization and slow phase speed (Miyakawa et al. 2012). It remains controversial if upshear-tilted or downshear-tilted convection is an optimal or suboptimal state for the storm’s strength even when applied to multicellular storms. At least we can note that convection under an upshear-tilted regime is likely to be more multicellular (Fovell and Ogura 1988), which is relevant to the types of convection both in the western Pacific and the Indian Ocean in this chapter.

An important factor for controlling the longevity of each convective regime is the cold reservoir. Its realization in NICAM as associated with the diurnal cycle of tropical precipitation was demonstrated by Sato et al. (2009). Although its importance in SCCs and the MJO was proposed by a cloud-resolving model (Oouchi 1999; Oouchi and Yamasaki 2001), the existence of those specific phenomena had not been observationally verified. Evidence is emerging as to the existence of the cold reservoir and its possible association with the development of the MJO over the Indian Ocean during the Cooperative Indian Ocean Experiment on Intraseasonal Variability (CINDY)/DYNAMO period (Yoneyama et al. 2013). Further analysis of the dataset and comparison with model results will serve to assess the importance of the cold reservoir and the hypothesis proposed in this chapter.

b. Eastward-propagating phase velocity of the SCC

The observed SCC propagates eastward against the low-level easterly at the ground-relative phase velocity
of less than 10 m s$^{-1}$. Likewise, a multicellular squall line propagates against the surrounding low- to midlevel airflow at a similar velocity. In both systems, system-relative flows contribute to feeding moisture into the inner elements and maintaining the systematic life cycle of inner convective structures. As a manifestation of this, whereas a squall line includes successive generations of new cells in the upstream side of the existing cells, the SCC follows a similar cycle for the CC. Determining the mechanism for creating the larger-scale moisture field by which the SCC’s eastward propagation is prompted is an important problem from a different perspective, and we may need to clarify the interaction between the SCC and equatorial waves as a possible control for this aspect.

To further pursue the characteristic of the eastward propagation of the SCC, it is tempting to note that there is a significant difference in the feature of propagation of SCCs between the aquaplanet setup and the realistic setup of topography and SST (existence of the warm water pool). The typical SCC in the aquaplanet setup propagates over the equatorial circumference at a phase velocity of 15–25 m s$^{-1}$, both in the conventional GCMs (Hayashi and Sumi 1986; Numaguti and Hayashi 1991) and global cloud-resolving models (GCRMs; Satoh et al. 2005; Tomita et al. 2005; Nasuno et al. 2007). This is faster than the observed velocity ranging typically from less than 5 m s$^{-1}$ (Nakazawa 1995) to $10^2$–$12^2$ day$^{-1}$ (less than 15 m s$^{-1}$; Takayabu and Murakami 1991). On the other hand, the typical SCC in the realistic setup propagates at a phase velocity similar to the observed one over the limited area of, in, and around the warm water pool, and specifically over the western Pacific. The reason the simulated phase velocity of the SCCs in the realistic setup is slower than that in the aquaplanet setup and is comparable to that of the observed SCC has to do with the existence of the warm water pool or the existence of zonal nonuniformity of the moisture field in the realistic setup, the latter being suggested by Miura et al. (2007) as a key controlling factor of the MJO’s propagation.

Here, we take the argument one step further and suggest that the existence of the quasi-stationary westerly shear (low-level easterly) to the east of the warm-pool center and its interaction with the CC of inherently nonpropagating nature are important factors that retard the eastward propagation of the SCC. From the interpretation discussed in this chapter, the westerly shear regime tends to favor the occurrence of SCCs, in which successive generation of new CCs to the east of the existing ones leads to the SCC’s propagation. In this situation, the new CC does not propagate so rapidly eastward as does the low-level easterly, and the vertical shear is capable of putting the center of the action of the CC more westward than otherwise. This speculation is supported when we consider the effects of the convective momentum transport associated with a simulated MJO case (Miyakawa et al. 2012). On the other hand, the opposite tendency—to drive the eastward propagation of the SCC as a whole—can be prompted by an equatorial (Kelvin) wave, although we excluded any discussion on the possible contribution of equatorial waves in this chapter. If the coupling between the SCC or, equivalently, the envelope of the CCs, and the wave is tight enough, eastward propagation would be more favorably prompted under the sufficiently conditionally unstable condition. The observed SCCs, however, suggest that this is not the case. The unrealistically clear propagation of SCCs in the aquaplanet setup is hypothesized to result from either or both of the factors: the absence of the warm-pool-induced vertical circulations and too strong a coupling between the CC and the low-level propagation being forced by a formulation of cumulus parameterization. The speculation needs to be checked against the observed SCCs and the climatology of flow fields.

c. Further remarks

The arguments in this chapter are limited to a highly simplified framework to focus on the basic aspects of SCCs. They excluded investigation into their relationship with environmental disturbances, including equatorial waves and the MJO. More satisfactory explanations as to the origin of SCCs should require considering these waves. The necessary factors still unclear include the Kelvin-wave instability viewpoint, teleconnection via mesoscale waves (Chao and Lin 1994; Oouchi 1999; Mapes 2000), and the buildup and advection of moisture associated with the topography around the Maritime Continent and westward-propagating disturbances (Miura et al. 2007). Additionally, a significant theme that has not been handled appropriately in the conventional GCMs is how the dynamics and thermodynamics of the mesoscale convections work in developing and maintaining the hierarchy of SCCs. Such an investigation was attempted by Oouchi (1999), Grabowski and Moncrieff (2001), and Oouchi and Yamasaki (2001), and more recently by Tulich and Mapes (2008). As suggested by these studies, the origin of mesoscale convection, or cloud clusters in broader meaning, is the key to understanding the mechanism of tropical convection. The classification of convective regimes presented in this chapter should be based on more rigorous criteria by taking into account more quantitative metrics of the organization regimes of mesoscale convection, as well as the activities of equatorial waves. The suggested
regimes here are classified solely by the phases of a single MJO and introduced for easier understanding of the hypothesis.

In terms of the multicellular feature of the SCC as an analogy to a squall line, it is interesting to note the view that the multicell feature of a squall line is a manifestation of vertically trapped gravity waves (Yang and Houze 1995). The multi-CC nature of the SCC is likely to be a result of its close linkage with 2-day inertia–gravity waves (Takayabu et al. 1996), or a result of the combined effect of the mesoscale gravity wave dynamics at the initial stage and the mesoscale cold reservoir at the mature stage (Oouchi 1999). A gravity wave control may also play a role in making the upper troposphere cloud last longer (Mapes et al. 2006). Investigating from this viewpoint will further our understanding of the origin of the SCC, and GCRM is a fascinating framework for this purpose.

The interpretation proposed in this chapter may be highly idealized and its elaboration is necessary, as is the test of its applicability to existing observational datasets. Moncrieff (2004) proposed a nonlinear dynamical model of the tropical organized convection associated with the MJO and discussed that the SCC-like organized structure is a self-maintaining system that contains westward-tilted structure with countergradient momentum transport in the equatorial vertical cross section. The present study supports this view and proposed that an additional factor—warm-pool-induced circulation—explains the observed preference or absence of SCCs. It is important to note that, in reality, there may be no clear-cut distinction between SCCs and CCCs and the underlying respective vertical-shear regime. The characteristic climatological environment of the SCC varies on more than a seasonal time scale (Wang and Rui 1990), and this should provide additional important modification to the climatological vertical shear and the manner of organizing the SCC. The influence of the boreal summer Asian monsoon should be enormous over the vertical shear and the MJO (Yasunari 1979) on a seasonal and longer time scale. Among the interactions that could work within the complex monsoon–MJO–SCC network, the simple interpretation proposed in this chapter highlights an aspect of the link between the warm-pool-induced circulation and SCCs; this is expected to offer a new insight into the mechanism of up-scale organization of CCs around the tropical warm water pool.

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REFERENCES


