The Cloud and Convection Evolution in the Subtropical Western North Pacific during Summer Monsoon Onset

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Abstract

The monsoon onset in July over the subtropical western North Pacific (SWNP, 15-25°N; 130-150°E) is investigated by focusing on the relationship between the rapid deepening of the monsoon trough and the westward movement of cloudy region east of the SWNP. At the monsoon onset, which corresponds to the arrival of the westward moving disturbances, there are a deepening of the monsoon trough and a rapid northeastward extension of strong convections from the tropical western North Pacific to the SWNP. Before the monsoon onset, the sea surface temperature (SST) over the SWNP increases due to strong surface heating associated with weak winds and clear skies. Right after the SWNP monsoon onset, winds increase and convections enhance, leading to a rapid decrease of surface heating and SST. It is concluded that the SWNP monsoon is triggered by the westward-moving upper-level disturbances in July when low-level atmospheric conditions favor development of deep convections.

(Key word: Summer monsoon onset)

1. Introduction

Climatologically, the monsoon onset in the SWNP occurs in mid-summer, which is much later than the monsoons in India and the South China Sea [LinHo and Wang, 2002]. The onset is generally characterized by the rapid deepening of the monsoon trough (MT) and the sharp extension of strong convective region from the tropical western North Pacific to the SWNP [Ueda and Yasunari, 1996]. Wu and Wang [2001] indicated that the precipitation of summer monsoon over the western North Pacific was associated with the stepwise monsoonal transition in South and Southeast Asia. On the other hand, there are 30- to 60-day intra-seasonal oscillations (ISO) [Hsu and Weng, 2001] propagating northward and northwestward in the South China Sea and the Philippine Sea. It is likely that the rapid monsoonal transition is a result of the interaction between the smooth seasonal evolution of solar heating and the phase-locked ISO [Wu and Wang, 2001].

The warming of the Philippine Sea in early July was considered to play a leading factor for the onset [Ueda and Yasunari, 1996; Wu, 2002]. Recently, Ueda et al. [2009] used general circulation model (GCM) simulations to evaluate the impact of SST on rapid monsoon transitions. The GCM simulations showed that the impact of SST on the SWNP monsoon onset is weak when compared to solar radiation, land memory, and atmospheric transient effects. On the other hand, Sato et al. [2005] studied the Marcus Convergence Zone (MCZ) formation, which followed the formation of the upper cold-low (UCL) in the subtropical North Pacific (~20-25°N and 150-170°E), and might have implications on the monsoon onset in the SWNP. The weakening and cut-off processes of the UCL were studied by Sakamoto and Takahashi [2005]. More recently, Lu et al. [2007] investigated the relationship between the intraseasonal circulation in the mid-latitude upper tropospheric and convections in the SWNP. They suggested that the latter might be affected by the former.

In this study, we further studied the relationship between the mid-ocean upper tropospheric circulation and the rapid shift of convection in the SWNP using satellite-inferred SST, outgoing longwave radiation (OLR), high-level thick clouds (HTC), and surface heat fluxes, as well as the model analysis of winds. The emphasis of this study is the thermal and dynamical conditions prior and during the monsoon onset in the SWNP.

2. Data and monsoon onset definition

Data used in this study cover a period of 22 years from 1985 to 2006. Those data include: (a) OLR at the top of the atmosphere from National Oceanic and Atmospheric Administration (NOAA) [Liebmann and

Smith 1996]; (b) Upper- and lower-tropospheric winds from Version 2 of the National Centers for Environmental Prediction reanalysis (NCEP-R2) [Kanamitsu et al. 2002]; (c) Cloud amount from the International Satellite Cloud Climatology Project (ISCCP) D1 data set [Rossow and Schiffer, 1999]; (d) SST from the NOAA Optimum Interpolation (OI) analysis [Reynolds et al., 2007]; (e) The 10-m wind speed and surface latent and sensible heat fluxes from the Objectively Analyzed Air-Sea Heat Fluxes (OAFlux) [Yu et al., 2007]; (f) Surface net shortwave and longwave fluxes from the NASA World Climate Research Programme/Global Energy and Water-Cycle Experiment (WCRP/GEWEX) Surface Radiation Budget (SRB) project. We calculated the surface net heat flux using the OAFlux and SRB data.

All the data have a temporal resolution of 1 day. The spatial resolution is: (a) 2.5° latitude-longitude for the NOAA OLR, the NCEP-R2 winds, and the ISCCP D1 clouds; (b) 0.25° latitude-longitude for the NOAA OI SST; (c) 1° latitude-longitude for the OAFlux and SRB data.

Due to a large variation of tropical convections, the date identified as monsoon onset will vary with methods used. Most previous studies identified the monsoon onset using information either from the satellite-measured brightness temperature [Ueda and Yasunari, 1996] or from OLR [Lu et al., 2007]. In this study, twelve years of the 22 years were analyzed that the OLR in the SNWP have a clear shift in July (Figure 1). In the onset definition, the 15-day mean OLR over the SWNP after the onset date is less than that before the onset date by 30 Wm^{-2}, and the onset date occurs in middle to late July. We also used the empirical orthogonal function (EOF) analysis of OLR to define the SWNP monsoon onset [Wu et al. 2009]. Analyses of the monsoon onset using the EOF method yielded similar conclusions as using the OLR variation in this study.

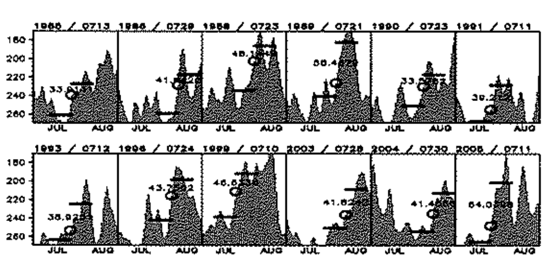

Figure 1. The 12-year OLR over the SWNP region (15-25°N; 130-150°E) that have a clear shift in middle to late July. The black lines indicate the 15-day mean OLR. The onset dates when the maximum differences (values near the circles; unit: Wm^{-2}) between two 15-day mean OLR are given in the figure (circles).

3. Results

Figure 2 shows the weekly composites of the 850-hPa streamlines and the high-level clouds with a large optical thickness before and after the onset. Data from the twelve years that were identified as having a clear monsoon onset were used for constructing the composites. Two weeks prior to the onset (Figure 2a), the ridge of the high-pressure system (thick line) extends southwestward to ~20°N near Taiwan. At the northern flank of the subtropical high is a band of HTC stretching from southeastern China to Japan, and further to the south of Bering Sea. To the southwest of the subtropical high, there is also a band of HTC associated with the MT. The convection over the SWNP is weak with a small amount of HTC. In the mid-ocean, there are nearly no HTC, except in the region around 25°N and the dateline. This patch of high clouds is associated with the mid-ocean trough and the UCL as elaborated, respectively, by Chen et al. [2001] and Sato et al. [2005]. In the week prior to the onset (Figure 2b), The small patch of high clouds in the mid-ocean at dateline is now expands westward to ~160°E. Right after the monsoon onset (Figure 2c), the MT located at ~10°N deepens and penetrates eastward to ~150°E. Convection strengthens not only along the Intertropical Convergence Zone (ITCZ) south of ~10°N but also expands northward to the entire SWNP. Corresponding to the deepening of the MT, the west section of the anti-cyclonic ridge shifted northward by ~10° latitude to the south of Japan.

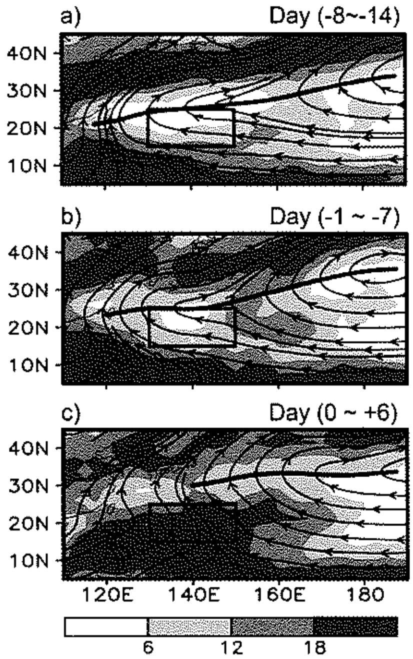

Figure 2. Spatial distributions of weekly mean high-thick clouds (HTC, shaded, unit: %) and 850-hPa streamlines. (a) Two weeks prior to the onset, (b) the week prior to the onset, and (c) the week after the onset. Clouds were classified as HTC for cloud top higher than the 440-hPa level and the optical thickness greater than 3.6. The box indicates the SWNP region.

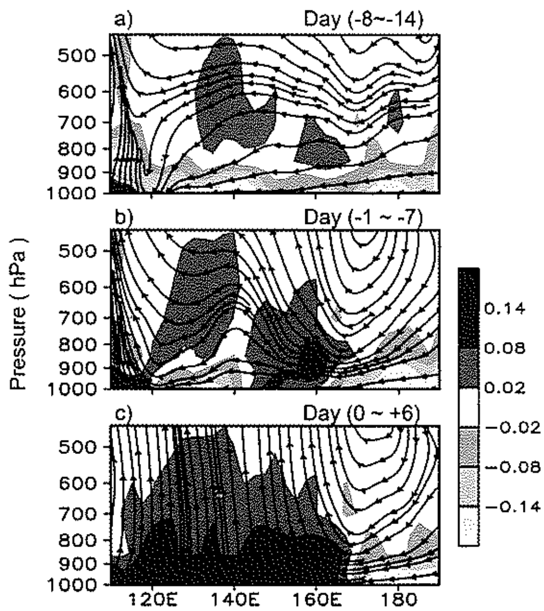

Figure 3. Vertical spatial distributions in cross-section (15-25°N) of weekly mean moisture convergence (shaded, unit: 10^{-6} s^{-1}) and streamlines (multiply by 100 for the vertical velocity). (a) Two weeks prior to the onset, (b) the week prior to the onset, and (c) the week after the onset.

To illustrate the association between the convection and the upper tropospheric circulation in the mid-ocean, the 200-hPa streamline and vorticity were also studied (not shown in the figure). The high-level vorticity changes significantly around the moving cloudy region corresponding to the westward moving high clouds (Figure 2). Patches of high clouds are located on the northwest side of the mid-ocean trough, which is consistent with the results shown in Sato et al. [2005]. After the onset, the stretch of the high-level trough west of 170°E bends significantly southward and the mid-latitude jet weakens (not shown), indicating a large change in circulation not only in the lower troposphere but also in the upper troposphere.

The results shown in Figure 2 seem to suggest that the rapid enhancement of convection in the SWNP is related to the westward expansion of high-level clouds from the mid-ocean. To support this view, we investigated the evolutions of circulation and moisture convergence during the monsoon onset. Figure 3 shows the weekly composites of vertical distribution in cross-section (15-25°N). Along the 15-25°N zone, the mid- to low-level moisture convergence increases two weeks prior to the onset at 160°E (Figure 3a).

Corresponding to the region of enhanced HTC, moisture convergence at middle to low levels moves westward to 150°E in the following 7-day period, which is associated with an increase in low-level cyclonic circulation (not shown). After the onset, the region of enhanced HTC further moves westward to the SWNP with a strong enhancement in moisture convergence (Figure 3c). At this stage, the cloud amount in the convective bands previously located at the northern flank (~25°-50°N) and southern flank (south of 10°N) of the high-pressure ridge decreases greatly, signifying the onset of a new phase of the summer monsoon circulation.

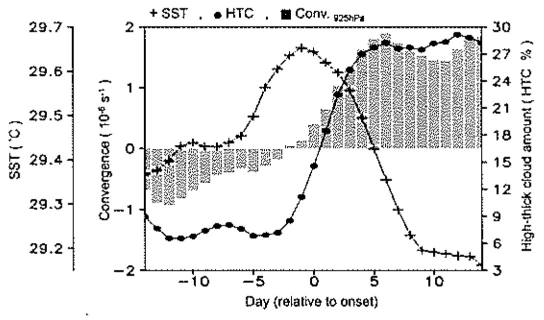

Figure 4. The SWNP (15-25°N; 130-150°E) domain-mean 925-hPa air convergence (bars), HTC amount (dots), and SST (pluses) before and after monsoon onset.

Figure 4 summarizes the thermal and dynamical conditions surrounding the SWNP onset. Within two weeks prior to the onset, the atmosphere in the SWNP is clear and stable. The surface wind is weak (not shown), and the surface air is diverging (bars). The stable condition leads to a small amount of HTC (dots). Corresponding to the weak winds and clear skies is a weak evaporative cooling and a strong solar heating of the ocean. The consequence is a large total heating of the ocean during the two-week period prior to the onset (not shown). The SST increases toward the onset date by 0.3°C in the two-week period (pluses). Regardless of the increasing SST, the surface wind remains divergent. It indicates that, prior to the onset, the SWNP is under the strong influence of the subtropical high-pressure system and that the increase in SST does not destabilize the atmosphere.

A few days prior to the onset, the surface wind and HTC begin to increase, and the surface heating begins to decrease. However, the SST continues to increase and reaches a maximum at the onset date. So, the change of SST lags the change of the surface heating by a few days. After the onset, the HTC, surface wind, and convergence continue to increase. Simultaneously, the surface heating and SST continue to decrease. Cloud systems move westward to the SWNP and trigger a new phase of summer monsoon.

4. Conclusions

The monsoon onset in the SWNP is investigated through twelve years identified as having a strong monsoon onset in the SWNP in middle to late July. Prior to the onset, sky is generally clear in the subtropical mid-ocean, except in the region around the dateline. This cloudy region around the dateline propagates westward and is associated with the upper-troposphere mid-ocean trough. When this mid-ocean cloud system propagates to the SWNP, the region of high-thick cloud with low OLR expands from the tropical western North Pacific (south of ~10°N) northward and northeastward to the SWNP. It essentially enters a new phase of the summer monsoon in East Asia and the western North Pacific.

Prior to the monsoon onset, the surface wind of SWNP is weak and divergent, and the cloud amount is small, resulting in the strong heating of the ocean. The diverging wind and the high SST is an indication that the latter is due to a strong surface heating associated with a calm, stable atmosphere under the influence of the subtropical high-pressure system. After the monsoon onset, the surface wind increases and becomes convergent. Convections strengthen and clouds increase. It leads to rapid decreases of surface heating and SST. All these thermal and dynamical conditions surrounding the monsoon onset in the SWNP suggest that the monsoon onset is triggered by the westward propagation of the mid-ocean disturbances in July when both the upper and lower tropospheric conditions favor the strengthening and penetration of the MT from the tropical western North Pacific to the SWNP.

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