NOTES and CORRESPONDENCE

NICAM Predictability of the Monsoon Gyre over the Western North Pacific during August 2016

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Abstract

In August 2016, a monsoon gyre persisted over the western North Pacific and was associated with the genesis of multiple devastating tropical cyclones (TCs). A series of hindcast simulations were performed using the non-hydrostatic icosahedral atmospheric model (NICAM) to reproduce the temporal evolution of this monsoon gyre. The simulations that were initiated at dates during the mature stage of the monsoon gyre successfully reproduced its termination and the subsequent intensification of the Bonin high, whereas the simulations initiated before the formation and during the developing stage of the gyre failed to reproduce subsequent gyre evolution even at a short lead time. These experiments further suggest a possibility that the development of the Bonin high is related to the termination of the monsoon gyre. The high predictability of the termination is likely due to the predictable midlatitudinal signals that intensify the Bonin high.

Keywords monsoon gyre; Bonin high; monsoon circulation; tropical cyclogenesis

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1. Introduction

In boreal summers, a large-scale lower-tropospheric cyclonic circulation, called the monsoon gyre, occasionally forms and persists over the western North Pacific, affecting the circulation in this area and in East Asia (Chen et al. 2004; Wu et al. 2013). Monsoon gyres are characterized by a large, low-level cyclonic vortex that has an outermost closed isobar with a

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diameter on the order of 2,500 km and a cloud band bordering the southern through eastern periphery of the vortex (Wu et al. 2013; Lander 1994; Molinari and Vollaro 2012). Monsoon gyres generally last for about two weeks and interact with disturbances of the midlatitude westerly jet stream and with convection in the equatorial Pacific (American Meteorological Society 2012). Monsoon gyres have larger spatial and temporal scales than those of tropical cyclones (TCs), and they support the formation of TCs. For example, a monsoon gyre in August 1991 accompanied Typhoon Ellie (TY9110) and Typhoon Gladys (TY9112), whereas another gyre in October 2004 accompanied Typhoon Tokage (TY0423) and Typhoon Nock-Ten (TY0424). The near-surface circulation of the monsoon gyre is narrower and stronger than a typical monsoon trough. Lander (1994) and Yoshida and Ishikawa (2013) described the monsoon gyre as a synoptic-scale gyre embedded within a larger-scale monsoon trough. Several studies have provided different definitions of monsoon gyres, but the occurrence frequencies largely disagree between the definitions. Lander (1994) estimated one gyre every two years, whereas Wu et al. (2013) identified 3.7 gyres per year. Molinari and Vollaro (2017) set a partly objective definition and identified 53 gyres during the six-month period between June and November from 1983 to 2013, giving an average of 1.7 per year.

Previous studies have tried to clarify the connection between surrounding weather systems and monsoon gyres: Lander (1994) and Chen et al. (2004) discussed the interaction of monsoon gyres with tropical cyclogenesis, and Molinari and Vollaro (2012) investigated a midlatitude tropospheric trough that influenced the formation of a monsoon gyre. Molinari and Vollaro (2017) argued that Madden–Julian oscillations (MJOs) and El Niño Southern Oscillations (ENSOs) influence the position of monsoon gyres, but no previous works have addressed the predictability of monsoon gyres using numerical models. Bi et al. (2015) and Yan et al. (2017) investigated the interaction between TCs and monsoon gyres with numerical experiments, but they did not intend to reproduce the monsoon gyre itself.

The purpose of the current work is to examine the reproducibility of the course of life of the August 2016 monsoon gyre event and to examine the roles of related phenomena. A persistent low pressure spread across the region encompassing 130–160°E and 10–25°N in the western North Pacific in August 2016. Several TCs formed and developed within the low. The cyclonic circulation showed a typical structure of a monsoon gyre on 18 August (Fig. 1). The lower-tropospheric

Fig. 1. The mature phase of the August 2016 monsoon gyre, based on observational data. SLP (contour), 850 hPa horizontal wind (vector) based on NCEP FNL Operational Global Analysis data, and OLR (shading) data based on the NCEP/NCAR Reanalysis 1 project at 00:00 UTC on 18 August 2016. The three boxes denote domains A, B, and C. The contour interval is 2 hPa, and the unit vector of 30 m s^{-1} is shown at the bottom right.

condition and outgoing longwave radiation (OLR) at that time displayed the characteristics of a monsoon gyre described previously: The low-level cyclonic vortex had a closed isobar with a diameter of 2,500 km, the horizontal wind in the lower troposphere was the strongest at the southern periphery of the gyre, and a deep convective cloud band located on the gyre's equatorward and eastern sides.

In this study, we use a global nonhydrostatic icosahedral atmospheric model (NICAM) along with explicitly calculating convective processes to reproduce the monsoon gyre. Using hindcast experiments, we investigate the predictability of the monsoon gyre and related processes. We first analyze the observed three-dimensional structure of the monsoon gyre and then examine whether the simulations reproduced the formation and the termination in the lifetime of the monsoon gyre. In the termination phase, we also focus on the related phenomena in the western North Pacific.

2. Data and methods

We investigated the large-scale circular low in August 2016 using National Centers for Environmental Prediction (NCEP) final (FNL) Operational Global Analysis data and OLR data from the NCEP/National Center for Atmospheric Research (NCAR) Reanalysis 1 project. We used three variables to characterize the monsoon gyre and surrounding condition:

- Sea-level pressure (SLP) averaged over domain A (130–160°E, 15–25°N) to represent the strength of the center of the low.
- 850 hPa zonal wind averaged over domain B (130–160°E, 10–20°N) to represent the wind band at the southern periphery of the gyre.
- 200 hPa geopotential height averaged over domain C (120–140°E, 30–40°N) to represent the modulation of the upper-tropospheric ridge related to the Bonin high.

Domains A, B, and C are shown in Fig. 1. Note that we defined domain C to evaluate the activity of mid-latitude disturbances, whereas we used SLP averaged over domain A and 850 hPa zonal wind averaged over domain B as indices of development of the monsoon gyre.

We used NICAM (Tomita and Satoh 2004; Satoh et al. 2008, 2014) version 14.2 with a horizontal grid interval of approximately 14 km. There were 38 vertical layers ranging from 80 m to about 36.7 km above surface level. Cumulus parameterization was switched off and cloud processes were explicitly calculated using the NICAM Single-moment Water 6 (NSW6) cloud microphysics method (Tomita 2008). Although the 14 km mesh size is relatively coarser than that of typical cloud-resolving models without a cumulus parameterization scheme, our model effectively captures large-scale convective organization in the tropics, including MJOs, as described by Miyakawa et al. (2014, 2017), Miura et al. (2007), Kodama et al. (2015), and Satoh et al. (2017). We used the mstrnX-AR5 radiation transfer scheme (Sekiguchi and Nakajima 2008). The land surface condition was calculated using Minimal Advanced Treatments of Surface Interaction and Runoff (MATSIRO) (Tanaka et al. 2003). We used a slab ocean model to calculate the sea surface temperature (SST), and we nudged it to the SST of the NCEP FNL data with a relaxation time of seven days and an ocean depth of 15 m. We conducted 25 simulations beginning at 00:00 Coordinated Universal Time (UTC) each day from 30 July to 23 August 2016. Time integration was performed for seven days. The initial atmospheric conditions were based on

Japan Meteorological Agency grid point value data.

3. Results

3.1 Observation of the monsoon gyre evolution

a. Formation

The observed SLP in domain A started to decrease from 1 August, building a large-scale low (Figs. 2a, b). Typhoon Omais (TY1605) formed in the southwest of the gyre in this phase. During the same period, 850 hPa zonal wind in domain B stayed in the high value, indicating a westerly wind band at the southern periphery of the gyre. The large-scale low persisted until late August, with some fluctuation of strength. During the lifespan of the gyre, five TCs—Typhoon Omais (TY1605), Typhoon Chanthu (TY1607), Typhoon Mindulle (TY1609), Typhoon Lionrock (TY1610), and Typhoon Kompasu (TY1611)—developed over the gyre area. As Molinari and Vollaro (2017) pointed out, some TCs rotated cyclonically with time around the gyre.

b. Termination

After the mature phase in middle August, the gyre started to decay, and the near-circular structure broke down on 22 August. The termination of the monsoon gyre is shown in Figs. 2c and 2d, accompanied with 200 hPa geopotential height shading, which shows that a ridge developed in the upper troposphere over Japan. The area of low SLP over the western North Pacific (Fig. 2c; 130–160°E, 10–25°N) weakened, and a deep anticyclone predominated (Fig. 2d; centered around 170°E, 40°N). This process is similar to that of the development of the Bonin high, which has been described as a subtropical anticyclone in the western North Pacific that has a deep vertical structure throughout the troposphere (Enomoto et al. 2003).

The overlap of the upper-tropospheric and sea-level anticyclones near Japan was characteristic of a typical Bonin high. This feature is more clearly noticeable in the longitude–height cross section of geopotential height anomaly (Fig. 3). The upper-level ridge over Japan had the center (160°E, 200 hPa in Fig. 3a; 145°E, 200 hPa in Fig. 3b) that was distinct from the Tibetan high and the north Pacific high at 35°N. In the lower troposphere, the upper-level ridge merged into the broad anticyclone region in the Pacific. Since the lower-level anticyclone in the Pacific had a large horizontal scale, its southern periphery appeared from 160°E to the west at 20°N (Fig. 2d). As the monsoon gyre weakened, the barotropic anticyclone expanded to the southwestward and the lowest levels of the ridge superposed with the area of the monsoon gyre

Fig. 2. Evolution of the monsoon gyre in August 2016, based on observational data. SLP (contour) and 200 hPa geopotential height (shading) based on NCEP FNL data (a) at 00:00 UTC on 1 August, (b) at 00:00 UTC on 5 August, (c) at 00:00 UTC on 18 August, and (d) at 00:00 UTC on 22 August. The contour interval is 2 hPa.

in the near-surface atmospheric layer of the western North Pacific (the red boxes in Figs. 3c, d). As for the case in August 2016, the monsoon gyre pattern and the Bonin high pattern were mutually exclusive in the western North Pacific.

3.2 NICAM simulations of the monsoon gyre evolution

We conducted a series of numerical experiments to investigate the model reproducibility of the August 2016 monsoon gyre and related phenomena that contributed to its evolution. Figure 4 displays the time series of monsoon gyre indices in observations and NICAM simulations.

a. Formation

The formation of the monsoon gyre was not reproduced well; a large circulation did not develop in the simulations that started prior to the formation of the observed monsoon gyre (on 4 August). Figures 4a and 4c show that, in the simulations that started before 4 August, SLP averaged over domain A increased to a level far above the observed SLP. In those simulations, the westerly wind band did not develop enough (Figs. 4b, d). Figures 5a and 5b display snapshots of the same variables as Fig. 2, produced by the NICAM simulation that was initiated at 00:00 UTC on 31 July. The large-scale low that appears in Fig. 2b (a TC is merged with the gyre at that time) was not reproduced.

Fig. 3. Upper-tropospheric and sea-level anticyclones related to the monsoon gyre, based on observational data. (a, b) Longitude–height cross section of geopotential height deviation from the zonal mean (m) at 35°N (a) on 18 August and (b) on 22 August, based on NCEP FNL data. (c, d) Same as (a, b) but for the cross section at 20°N. The red boxes show the position of the monsoon gyre on 18 August. The contour interval is (a, b) 40 m and (c, d) 20 m with negative contours dashed.

Fig. 4. Observations and NICAM simulations of the August 2016 monsoon gyre. Time series of (a) SLP averaged over domain A and (b) 850 hPa zonal wind averaged over domain B for each hindcast simulation using NICAM (black) and observations (red). Time-integrated time diagram of (c) SLP averaged over domain A and (d) 850 hPa zonal wind averaged over domain B for the simulations from 30 July to 29 August in the horizontal axis with a different lead time shown on the vertical axis. The bottom line (obs.) denotes the observation.

Fig. 5. Evolution of the August 2016 monsoon gyre, based on simulations with NICAM initialized (a, b) at 00:00 UTC on 31 July and (c, d) at 00:00 UTC on 17 August.

In the simulations with initial dates of 4–11 August, the large-scale low decayed too early compared to the observation, although they reproduce the cyclonic structure of wind circulation to some extent.

b. Termination

Figures 5c and 5d display snapshots produced by the NICAM simulation that was initiated at 00:00 UTC on 17 August. The cyclonic structure of the SLP field was comparable to the observed level (Fig. 2c). The simulations that started during the lifespan of the monsoon gyre (from 4 to 18 August) predicted the

upcoming development of the monsoon gyre and realistically reproduced its termination after 18 August, even with the long lead time of six days; the SLP averaged over domain A increased (Figs. 4a, c) and the westerly wind averaged over domain B decreased (Figs. 4b, d). Our simulations also captured the deep barotropic structure of the Bonin high during the decay phase of the monsoon gyre. Figure 6 shows the time series of 200 hPa geopotential height averaged over domain C in observations and simulations. The simulations predicted the observed elevation of 200 hPa geopotential height, indicating the development

Fig. 6. Observations and NICAM simulations of the upper-tropospheric ridge. (a) Time series of 200 hPa geopotential height averaged over domain C for each NICAM hindcast simulation (black) and observations (red). (b) Time-integrated time diagram of 200 hPa geopotential height averaged over domain C for the simulations from 30 July to 29 August in the horizontal axis with a different lead time shown on the vertical axis. The bottom line (obs.) denotes the observation.

of the upper-level ridge of the Bonin high.

It has been reported that the modulation of the Bonin high is driven by the propagation of midlatitude upper-tropospheric Rossby wave packets (Enomoto et al. 2003). It is possible that the high predictability of the gyre termination is due to the predictable mid-latitude signals that intensify the Bonin high.

4. Summary and discussion

A series of hindcast simulations using NICAM successfully reproduced the termination of the monsoon gyre in August 2016 based on the initial conditions one week before the termination. Observational data showed that the Bonin high developed over the western North Pacific as the monsoon gyre decayed in late August 2016. This process was also reproduced well in our numerical experiments. The monsoon gyre pattern and the Bonin high pattern were mutually exclusive in the western North Pacific in August 2016. Our results suggest a possibility that the evolution of the Bonin high led to the gyre termination. Further investigations are required to examine whether the termination of a monsoon gyre is generally related to development of the Bonin high.

By contrast, the formation of the monsoon gyre was not reproduced well, even at a short lead time of four days. This suggests that the formation is affected by processes that are relatively difficult to predict, such as responses to convective activity in the open ocean of the western North Pacific. The model configuration that we used with a 14 km horizontal resolution might not have been sufficient to capture key processes of the monsoon gyre formation. This suggests that the

deep convection band concomitant with monsoon gyres is a different type of convective organization than those associated with intraseasonal oscillations, which are relatively well reproduced using the same model configuration (MJOs: Miyakawa et al. 2014; Boreal Summer Intraseasonal Oscillation: Nakano et al. 2015).

Inside and around the August 2016 monsoon gyre, five typhoons were generated, and the large-scale circulation influenced their frequency and trajectories. However, how these TCs interacted with the monsoon gyre is not well understood. Understanding the dynamics of monsoon gyres will therefore contribute to the prediction of TC activities in the western North Pacific.

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