Supplemental Material

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Interannual Variation of the Summer Rainfall Center in the South China Sea
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Supplement 1 Calibration of Rainfall Datasets

Table 1 provides several rainfall datasets (including measurements of WMO stations, APHRODITE, TRMM, PERSIANN, and GPCP) used to cover the period 1979–2016. Since these rainfall datasets are prepared by different procedures and algorithm, we applied a simplified regression technique to merge these rainfall datasets into a more uniform one. The calibration procedure for rainfall used in the present study and a companion study (Chen et al. 2016) basically follows the essence of the multimodel, superensemble forecast with a multiple regression technique introduced by Krishnamurti et al. (1999). The model forecasts are regressed against an analysis (observed) field and the least-squares minimization of the difference between the model and analysis field is used to determine the weight. To prepare this hybrid rainfall dataset, the following procedure for rainfall calibration is adopted:

1) Validation of APHRODITE gridded rainfall against the gridded rainfall of the WMO station measurements over Japan south of 40°N

Using the 16-point Bessel interpolation scheme introduced by Jenne (1970), the daily rainfall measurements for the WMO stations (red dots) in Japan south of 40°N are projected onto a 0.5°×0.5° grid in Fig. S2-1a to match the NCEP GFS and ERA-Interim 0.5°×0.5° reanalysis. The scatter diagram for the APHRODITE 0.5°×0.5° daily rainfall south of 40°N vs. the gridded daily rainfall of WMO stations over the cold season (Oct-Feb) for 1998–2016 is shown in Fig. S1-1b. As revealed from this scatter diagram, the least-squares fit line (red) coincides with the diagonal (black) for P(station) and P(APHRODITE). The daily 0.5°×0.5° gridded rainfalls generated by these two approaches are close to each other over the available period of TRMM rainfall.

2) Calibration of the TRMM precipitation against the APHRODITE daily rainfall with the spatial resolution of 0.5°×0.5°

Figure S1-1c shows the scatter diagram of P(TRMM) vs. P(APHRODITE) over Japan south of 40°N, the cold-season (Oct-Feb) for 1998–2016. The diagonal line for this scatter diagram is black. The least-squares fit line (red) for scatter (black dots) reveals the TRMM precipitation is underestimated and should be corrected by a factor 1.2 (regressive weight).

3) Calibration of the PERSIANN precipitation against the calibrated TRMM precipitation

Because the APHRODITE rainfall data cover land, the calibrated TRMM rainfall data are used to calibrate the PERSIANN over both land and ocean. The daily PERSIANN rainfall is calibrated against the measured TRMM daily precipitation over the 0.5°×0.5° grid over the SCS summer rainfall center (Fig. S1-2a) west of the Philippines to illustrate its use. Over this rainfall center with a threshold value of rainfall ≥10 mm·day^{-1} at each grid point for the corresponding rainfall seasons, the scatter diagrams for $\hat{P}$(PERSIANN) vs. calibrated $P$(TRMM) are shown in Figs. S1-2a. Clearly, $P$(PERSIANN) is underestimated compared to calibrated $P$(TRMM) by a regressive weight $\approx 1.2$.

4) Calibration of the GPCP precipitation against the TRMM precipitation

The PERSIANN precipitation data are only available for 1983–present. Prior to 1983, the GPCP precipitation data cover the 1979–1982 period. The temporal-spatial resolution for the GPCP precipitation is only 2.5°×2.5° daily. The scatter diagram for $P$(GPCP) vs. calibrated $P$(TRMM) is shown in Fig. S1-2d at each grid point over the SCS summer rainfall center with a threshold rainfall ≥ 10 mm·day^{-1} at each grid point. $P$(GPCP) shows an underestimation in
constraint with the calibrated $P(\text{TRMM})$ by a regressive weight $\sim 1.2$.

The merger for calibrated $P(\text{TRMM})$, $P(\text{PERSIANN})$, and $P(\text{GPCP})$ rainfall with available WMO station rainfall measurements is also performed with the 16-point Bessel interpolation scheme (Jenne 1970) of NCAR. The variances of daily rainfall difference between the calibrated $P(\text{TRMM})$, $P(\text{PERSIANN})$, and $P(\text{GPCP})$ daily rainfall are shown in Fig. S1-3. This merger does not exhibit a significant difference over the SCS summer rainfall center.

**References:**
Fig. S1-1 (a) Climatology for the rainfall distribution over mid-May–August 1998–2007 superimposed with surface stations (red dot) and the 0.5°×0.5° grid points over Japan. (b) The scatter diagram for the daily rainfall measured by the WMO surface stations projected on the 0.5°×0.5° grid over Japan vs. the APHRODITE daily 0.5°×0.5° grid rainfall. (c) The scatter diagram for the daily 0.5°×0.5° TRMM rainfall vs. the APHRODITE daily 0.5°×0.5° grid rainfall. The red solid line is a linear regression line.
Fig. S1-2 (a) Climatology for the rainfall distribution over mid-May–August 1998–2016 superimposed with surface stations (red dot) and the 0.5°x0.5° grid point over the SCS summer rainfall center. (b) The scatter diagram for the daily 0.5°x0.5° calibrated $P$(PERSIANN) vs. the daily 0.5°x0.5° calibrated $P$(TRMM) over the SCS summer rainfall center. (c) and (d) are the same as (a) and (b), respectively, except for daily 2.5°x2.5° $P$(GPCP).
Fig. S1-3 Variance for the differences of daily precipitation with and without merging with the WMO surface station data of the Philippines.
Supplement 2 Classification of the Rain-Producing Weather Systems Propagating Across the South China Sea Summer Rainfall Center

The classification of the rain-producing weather systems propagating across the SCS summer rainfall center is outlined below:

1) **SCS monsoon trough (TR): Developments of four types of rain-producing weather systems related to the SCS TR**

   - Regular TR (without interaction with other weather systems): Across the southern part of Indochina, the tropical-subtropical monsoon westerlies may develop a NW-SE-oriented monsoon trough. This trough may cyclonically rotate its orientation closer to the WNW-ESE direction within the SCS, but does not interact with other weather systems (Fig. S2-1).
   - Cutoff cyclone developed from TR: Intensifications of the tropical monsoon westerlies across Indochina and the SCS, and the southeasterlies of the western subtropical Pacific anticyclone may lead the SCS TR to form a cutoff cyclone over Indochina and the SCS (Fig. S2-2).
   - Merger of a named TY/TS with the SCS TR, but this TY/TS is still identified by JTWC as a named TY/TS in the SCS (Fig. S2-3).
   - Merger of a TD or closed tropical vortex with the SCS TR. We classify it as EI (interaction of the SCS monsoon trough with a westward-propagating weather system) (Fig. S2-4). This type of rain-producing weather system is classified as part of the EI group.

(ii) **Easterly Wave (EW): Two types of rain-producing weather systems are developed from EW**

   - Pure EW with null interaction with the SCS TR. This EW may be amplified when it propagates across the Philippines (Fig. S2-5).
   - The westward-propagating EW may sometime develop into a closed vortex east of the Philippines. This EW vortex may catch the southeast end of a SCS TR line and develop a link with this SCS trough, but not merge with it. This link leads to form a southeastward extension of the SCS trough across the Philippines (Fig. S2-6).

Interactions of a TD/closed vortex and EW with the SCS TR are classified into two types of EI rain-producing weather systems:

   - Interaction of the SCS TR with a TD/closed vortex, but still maintains as a TR (Fig. S2-4)
   - Interaction of the SCS TR with an EW extends this SCS TR southeastward across the Philippines (Fig. S2-6).

Note, TY/TS are identified not only by JTWC, but also are verified by the JMA surface maps and NCEP SRRS (Tropical strip analysis and observation). We also prepare the 850 streamline charts (with the reanalysis data of NECP GFS and ERA-Interim) superimposed with the Tbb image and calibrated rainfall from several sources listed in Table 1. These charts are used to identify the rain-producing weather systems, and are verified with the JMA and NCEP SRRS charts.
Fig. S2-1 A regular South China Sea (SCS) trough (TR) over its life cycle depicted by the 850hPa streamline charts superimposed with rainfall. The synoptic time and date of every streamline chart and the color scale of rainfall are shown on the top of every panel.

Fig. S2-2 A SCS cutoff cyclone developed from the SCS trough. It is depicted by the same method as Fig. S2-1.
Fig. S2-3  Merger of a named TY (Molave; reaches Category 1 at 0600UTC 18/7/2009) with the SCS TR; this TY is still identified by JTWC as it merges with the SCS TR.

Fig. S2-4  Same as Fig S2-3, except the merger of a TD or closed tropical vortex with the SCS TR.
The westward-propagating easterly wave developed into a closed vortex east of the Philippines, and eventually catches the southeast end of a SCS TR. This link leads to form a southeastward extension of the SCS trough across the Philippines.
A westward-propagating easterly wave enters the SCS across the Philippines, but is amplified by the Philippines.

Fig. S2-6
Supplement 3 Interannual Variations of Occurrence Day, Occurrence Frequency, and Occurrence Duration for Four Groups of Rain-Producing Synoptic Systems

The occurrence day, occurrence frequency (i.e. case), and occurrence duration for the four groups of rain-producing weather systems (SCS TR, TY/TS, EI, and EW), which contribute to the formation of the SCS summer rainfall center are shown in Figs. R3-7, R3-8, and R3-9, respectively. The information provided from these figures is well reflected by the rainfall contrast produced by these four groups of rain-producing weather systems between strong and weak monsoon summers over the SCS summer rainfall center shown in Figs. 11m and 11n.
Fig. S3-1  Summer occurrence day of the SCS rain-producing weather systems in the SCS presented in terms of histogram: (a) SCS TR, (b) EI, (c) EW, and (d) TY/TS. The dry (weak), wet (strong), and normal monsoon summer are marked by red, blue, and white colors, respectively. The mean value and standard deviation of occurrence day are added to each histogram figure.
Fig. S3-2 Same as Fig S3-1, except the occurrence frequency (i.e. cases) for each group of every rain-producing weather system to move across the SCS summer rainfall center.
Occurrence duration

(a) TR

(b) TY

(c) EI

(d) EW

Fig. S3-3 Same as Fig R3-1, except the duration for every group of rain-producing weather system to move across the SCS summer rainfall center.
Supplement 4  The summer (mid-May – August) mean charts for $(\psi_Q, P)_T$ and the composite $(\chi_Q, Q_D, P)_T$ around the SCS for four synoptic systems (TR, TY, EI, EW) during the strong and weak Southeast-Asian summer monsoons

Four sets of figures are shown in this supplement:

1. The summer (mid-May–August) mean charts for $(\psi_Q, P)_T$ for the 1979-2016 period are shown in Fig. S4-1.

2. The composite charts $(\chi_Q, Q_D, P)_{TR}$, $(\chi_Q, Q_D, P)_{TY}$, $(\chi_Q, Q_D, P)_{EI}$, and $(\chi_Q, Q_D, P)_{EW}$ are shown in Fig. S4-2.

3. Same as Fig. S4-2, except for $(\chi_Q, P)_{TR}$, $(\chi_Q, P)_{TY}$, $(\chi_Q, P)_{EI}$, and $(\chi_Q, P)_{EW}$.

4. The variances for difference between the following variables:
   (a) $[\text{Composite } \Delta(\psi_Q, P)_T - \text{Composite } \Delta(\psi_Q, P)_C]$(strong),
   (b) $[\text{Composite } \Delta(\psi_Q, P)_T - \text{Composite } \Delta(\psi_Q, P)_C]$(weak),
   (c) $[\text{Composite } \Delta(\chi_Q, P)_T - \text{Composite } \Delta(\chi_Q, P)_C]$(strong), and
   (d) $[\text{Composite } \Delta(\chi_Q, P)_T - \text{Composite } \Delta(\chi_Q, P)_C]$(weak).

The variance ratio for differences between $[\text{Composite } \Delta(\psi_Q, P)_T - \text{Composite } \Delta(\psi_Q, P)_C]$(strong) and $[\text{Composite } \Delta(\chi_Q, P)_T - \text{Composite } \Delta(\chi_Q, P)_C]$(strong) and $[\text{Composite } \Delta(\psi_Q, P)_T - \text{Composite } \Delta(\psi_Q, P)_C]$(weak) and $[\text{Composite } \Delta(\chi_Q, P)_T - \text{Composite } \Delta(\chi_Q, P)_C]$(weak) and composite $\Delta(\psi_Q)_T$(strong), $[\text{Composite } \Delta(\chi_Q, P)_T - \text{Composite } \Delta(\chi_Q, P)_C]$(weak) and composite $\Delta(\chi_Q)_T$(weak), $[\text{Composite } \Delta(\psi_Q, P)_T - \text{Composite } \Delta(\psi_Q, P)_C]$(weak) and composite $\Delta P_T$(weak), and composite $\Delta P_T$(strong) and composite $\Delta P_T$, and $[\text{Composite } \Delta P_T - \Delta P_C]$(weak) and composite $\Delta P_T$(weak). These variance ratios are shown in Table S4-1.

<table>
<thead>
<tr>
<th>monsoon</th>
<th>variable 1</th>
<th>variable 2</th>
<th>variable 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Strong monsoon</td>
<td>$[\text{Composite } \Delta(\psi_Q, P)_T - \text{Composite } \Delta(\psi_Q, P)_C]$/Composite $\Delta(\psi_Q)_T$</td>
<td>$[\text{Composite } \Delta(\chi_Q)_T - \text{Composite } \Delta(\chi_Q)_C]/\text{Composite } \Delta(\chi_Q)_T$</td>
<td>$[\text{Composite } \Delta P_T - \Delta P_C]/\text{Composite } \Delta P_T$</td>
</tr>
<tr>
<td>Weak monsoon</td>
<td>8.2%</td>
<td>9.0%</td>
<td>9.1%</td>
</tr>
<tr>
<td></td>
<td>8.4%</td>
<td>8.3%</td>
<td>9.3%</td>
</tr>
</tbody>
</table>
Fig. S4-1  Summer (mid-May – August) mean charts for \((\psi_Q, P)_T\) for 1979-2016. The contour interval of \((\psi_Q)_T\) and the color scale of \(P_T\) are shown on the top of the figure.
Fig. S4-2 Composite charts for $(\psi Q, P)_\text{TR}$, $(\psi Q, P)_\text{TY}$, $(\psi Q, P)_\text{TY}$, $(\psi Q, P)_\text{EI}$, and $(\psi Q, P)_\text{EW}$. Contour interval for $(\psi Q, P)_\text{()}$ is shown in the upper left corner of every panel of the left column, while the color scale for $P_\text{()}$ is displayed in the lower right corner of every panel in the right column.
Fig. S4-3
Fig. S4-3 Same as Fig S4-2, except for ($\chi_Q$, $Q_D$, $P$)$_{TR}$, ($\chi_Q$, $Q_D$, $P$)$_{TY}$, ($\chi_Q$, $Q_D$, $P$)$_{EI}$, and ($\chi_Q$, $Q_D$, $P$)$_{EW}$. Contour interval for ($\chi_Q$)() is shown in the upper corner of every panel in the left column, while the color scale for $P()$ is displayed in the lower corner of every panel in the right column.
Fig. S4-4
Fig. S4-4 Variance for differences between the following variables:
(a) [Composite $\Delta(\psi_Q, P_T)$ - Composite $\Delta(\psi_Q, P_C)$](strong),
(b) [Composite $\Delta(\psi_Q, P_T)$ - Composite $\Delta(\psi_Q, P_C)$](weak),
(c) [Composite $\Delta(\chi_Q, P_T)$ - Composite $\Delta(\chi_Q, P_C)$](strong), and
(d) [Composite $\Delta(\chi_Q, P_T)$ - Composite $\Delta(\chi_Q, P_C)$](weak).
Contour intervals of $(\psi_Q)_T$ and $(\chi_Q)_T$, and color scale for $\Delta P_T$ and $\Delta P_C$ are shown on the top of panel (a) and (c), respectively.