Monitoring and Predicting the Intraseasonal Variability of the East Asian–Western North Pacific Summer Monsoon

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ABSTRACT

In this study, a new index is defined to capture the prominent northward propagation of the intraseasonal oscillation (ISO) in boreal summer in the East Asian and western North Pacific (EAWNP) region. It is based on the first two modes of empirical orthogonal function (EOF) analysis of the combined fields of daily anomalies of zonally averaged outgoing longwave radiation (OLR) and 850-hPa zonal wind (U850) in the EAWNP region. These two EOFs are well separated from the rest of the modes, and their principal components (PCs) capture the intraseasonal variability. They are nearly in quadrature in both space and time and their combination reasonably well represents the northward propagation of the ISO. As no future information beyond the current date is required as in conventional time filtering, this ISO index can be used in real-time applications. This index is applied to the output of the 24-yr historical hindcast experiment using the Global Environmental Multiscale (GEM) model of Environment Canada to evaluate the forecast skill of the ISO of the EAWNP summer monsoon.

1. Introduction

Tropical intraseasonal variability is dominated by the Madden–Julian oscillation (MJO), which has been under intensive study since its discovery in early 1970s (e.g., Madden and Julian 1971, 1994; Salby and Hendon 1994; Zhang 2005). The MJO represents a large-scale zonal overturning circulation that propagates eastward along the equator, associated with anomalous convective activity. Its amplitude and propagation have a strong seasonal dependence. During the boreal winter the MJO is strong and propagates predominantly eastward. In the boreal summer, however, the intraseasonal oscillation (ISO) propagates not only eastward, but also has a significant northward component in the Asian summer monsoon region (e.g., Yasunari 1979; Krishnamurti and Subrahmanyam 1982; Wang and Rui 1990). The northward movement is also observed in the East Asia–western North Pacific (EAWNP) and South China Sea regions (e.g., Lau and Chan 1986; Chen and Murakami 1988; Hsu and Weng 2001).

The EAWNP summer monsoon with strong variabilities in convection over the South China Sea–Philippine Sea regions is a relatively independent monsoon system from the Indian summer monsoon (e.g., Wang and Fan 1999; Wang et al. 2001). Lin (2009) demonstrated that the precipitation anomalies of the two monsoon systems are not correlated and their associated global circulation patterns are different. The northward propagation of the ISO has an important impact on the weather in the East Asian summer monsoon in a highly populated region. The ISO northward propagation accompanied with anomalous precipitation was found to be often associated with active and break periods of the East Asian summer monsoon (e.g., Lau et al. 1988; Chen et al. 2000; Wu and Wang 2001). The ISO influences precipitation associated with the mei-yu in central China and the baiu in Japan (e.g., Chen and Chen 1995; Ding et al. 2004; Hsu et al. 2004). In addition, the ISO in the western North Pacific region can modulate the subtropical high and typhoon (e.g., Liu and Lin 1990). It is clear that a close monitoring and a skillful forecast of the ISO in the EAWNP region is of great societal and economical importance. Besides its local impact, the western North Pacific summer monsoon, through its variability in diabatic thermal forcing, has a far-reaching influence on the global atmospheric circulation (e.g., Lin 2009).
To facilitate monitoring and prediction of the local ISO in the EAWNP region, an ISO index is designed in this study. There have been many ISO (or MJO) indices proposed in previous studies. Most of them use the first two leading modes of an empirical orthogonal function (EOF) analysis of a tropical field related to convection. For example, some studies use upper-tropospheric velocity potential (e.g., von Storch and Xu 1990) or outgoing longwave radiation (OLR; e.g., Lau and Chan 1985; Ferranti et al. 1990). In most cases, a time filtering was used before extracting the ISO signal. Wheeler and Hendon (2004, hereafter WH04) developed an MJO index based on the first two combined EOFs of the meridionally averaged OLR and zonal winds at 850 and 200 hPa. An advantage of this index is that the low-frequency signal and structure of the MJO can be isolated from the observational and forecast data without the use of a typical (e.g., Lanczos) bandpass filter as in many previous MJO-related studies, and is thus feasible for real-time MJO monitoring and forecast verification. Like most of the MJO indices, the WH04 index was designed to capture the eastward propagation feature of the tropical intraseasonal variability. Although the WH04 index was calculated using annual data and was designed for use in all seasons, the northward propagation of the ISO in the Asian summer monsoon region is not well represented (Kikuchi et al. 2012).

Kikuchi et al. (2012) developed a bimodal ISO index that consists of MJO mode with predominant eastward propagation along the equator and boreal summer ISO (BSISO) mode with prominent northward propagation in the Asian summer monsoon region. An extended EOF (EEOF) analysis with −10- and −5-day lags was conducted using the intraseasonal time-filtered OLR data in the entire tropics between 30°S and 30°N. The MJO mode was derived using the data from December to February, whereas the BSISO mode was calculated using data from June to August. The principal components of the first two EEOFs are used to define the index for each mode. It was found that from December to April the MJO mode dominates while from June to October the BSISO mode dominates. Although the BSISO captures the main feature of the northward propagation in the Asian summer monsoon region, the distinct behaviors of the ISO in Indian and EAWNP regions are not addressed. Also, using the Lanczos bandpass filter in preprocessing the OLR data makes the index difficult for real-time application.

In this study, a new ISO index is defined specifically to capture the prominent northward propagation of the ISO in the EAWNP summer monsoon region. It is compared with the WH04 index. Then this index is applied to evaluate the forecast skill of the summer EAWNP ISO in a 24-yr historical hindcast experiment using a global dynamical model.

Section 2 describes the data and ISO hindcast experiment. In section 3 a combined EOF analysis is performed to isolate the ISO signal in the EAWNP summer monsoon region. The temporal characteristics of the leading EOFs are analyzed. In section 4, a bivariate boreal summer EAWNP ISO index is defined using the combination of the principal components of EOF1 and EOF2. Section 5 presents composites of atmospheric variables in different phases of the EAWNP ISO. In section 6 the EAWNP ISO index is compared with the WH04 index, and their relationship is discussed. The skill of the summer EAWNP ISO forecast by a dynamical model is assessed in section 7. A summary and discussion follow in section 8.

2. Data and ISO hindcast experiment

Daily-averaged values of zonal and meridional winds at 850 and 200 hPa from the National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) global reanalysis (Kalnay et al. 1996) are used. To represent a proxy for the tropical convection, we use the daily-averaged satellite-observed OLR from the National Oceanic and Atmospheric Administration (NOAA) polar-orbiting series of satellites (Liebmann and Smith 1996). The pentad data of the Climate Prediction Center (CPC) Merged Analysis of Precipitation (CMAP; Xie and Arkin 1997) are also used. [These data are provided by the National Oceanic and Atmospheric Administration/Office of Oceanic and Atmospheric Research/Earth System Research Laboratory/Physical Sciences Division (NOAA/OAR/ESRL PSD), Boulder, Colorado, from their website at http://www.esrl.noaa.gov/psd/]

All the datasets have a 2.5° longitude × 2.5° latitude horizontal resolution. They cover a time period from 1 January 1979 to 31 December 2008. In this study we focus our discussions on the boreal summer season which covers 153 days from 1 May to 30 September each year. Data outside this period are used only for the purpose of removing the annual cycle and interannual variability, as will be explained in the next section.

Also used is the daily Real-Time Multivariate MJO (RMM) index of WH04 that is from the Australian Bureau of Meteorology website (http://cawcr.gov.au/staff/mwheeler/maproom/RMM/). The RMM1 and RMM2 were calculated by projecting the combined fields of 15°S–15°N meridionally averaged OLR and zonal winds at 850 (U850) and 200 hPa (U200) onto the two leading EOF structures as derived using the same meridionally averaged variables. The time series of RMM1 and RMM2

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vary mostly on the intraseasonal time scale, and the associated three-dimensional flow structure captures the MJO variability.

To evaluate the forecast skill of the boreal summer EAWNP ISO, we make use of the output of the intraseasonal hindcast experiment using the Global Environmental Multiscale (GEM) model (Lin et al. 2010; Lin and Brunet 2011). GEM is an operational model at the Canadian Meteorological Centre (Côté et al. 1998a,b). In the hindcast experiment, the GEM model is run at a horizontal resolution of $2^\circ \times 2^\circ$ and 50 vertical levels. A total of 10 parallel integrations of 45 days are conducted for the 24-yr period of 1985–2008 using GEM starting from the 1st, 11th, and 21st of each month. We analyze the forecast skill up to a lead time of 30 days. The initial atmospheric conditions are taken from the NCEP–NCAR reanalysis. To get the initial conditions for different ensemble members, perturbations that are randomly generated but balanced among variables are added to the reanalysis data. As GEM is an atmospheric-only model, global sea surface temperatures (SST) are predicted using the persistence of the anomaly of the preceding 30 days (i.e., the SST anomaly from the previous 30 days is added to the climate of the forecast period). Sea ice extents and snow cover are initialized with the analysis and relaxed to climatology over the first 15 days of integration. Forecasts that are initialized in the boreal summer season (May–August) are analyzed. Note that the last two forecasts of each summer extend well into September, consistent with the ISO analysis period of May to September. The total number of forecasts that are used is $24 \times 3 \times 3 = 288$.

3. Combined EOF analysis

To isolate the ISO signal in the EAWNP summer monsoon region, a combined EOF analysis is performed for the daily anomalies of zonally averaged OLR and zonal wind at 850 hPa (U850). Several steps are taken to process the daily data before the EOF calculation in order to focus on the intraseasonal variability. Starting from the unfiltered daily averaged data of the NCEP–NCAR reanalysis of U850, and the satellite-observed OLR for the whole year from 1979 to 2008, the seasonal cycle, which is the time mean and first three harmonics of the daily climatology, is first removed for each grid point. Then the time average of the 120 days immediately preceding each day is subtracted, and the daily anomaly data are obtained. By subtracting the previous 120-day average most of the interannual variability, including those related to the El Niño–Southern Oscillation (ENSO) and variability with even longer time scales, is removed. Next we select the daily anomaly data of the boreal summer period (1 May to 30 September). To capture the ISO signal in the EAWNP summer monsoon region, a longitudinal average from $90^\circ$ to $150^\circ$E is performed for the daily anomalies of OLR and U850, while retaining the latitudinal variation of the two fields from $10^\circ$S to $40^\circ$N. The selection of the longitudinal range is based on the variance of convection of the EAWNP summer monsoon (Ding 2007; Lin 2009). From Kikuchi et al. (2012, see their Fig. 2b), it can also be seen that within this longitudinal range the ISO is zonally elongated, which is different from that in the Indian summer monsoon region that is northwest–southeast oriented. With the longitudinal average, the data are reduced to a single dimension in latitude, with 21 points on a $2.5^\circ$ interval. After that, each variable is normalized by its own meridional average of temporal standard deviation, and the two fields are then combined to perform the EOF analysis. This normalization is necessary to ensure that each field contributes equally to the variance of the combined vector. The above procedure to remove the annual cycle and interannual variability is similar to WH04. No future information beyond the current date is used as in conventional temporal filtering; therefore, this approach can be applied to real-time applications.

Figure 1 shows the percentage of variance explained by each EOF mode. As can be seen, the first two leading modes dominate, jointly explaining about 45% of the total variance. These two EOFs are well separated from the rest of the modes according to the criterion of North et al. (1982). Shown in Fig. 2 are the latitudinal distribution of the leading two EOFs of the combined fields of OLR and U850. EOF1 is characterized by a negative OLR anomaly with enhanced convection centered near $15^\circ$N, whereas EOF2, almost in quadrature to EOF1, has a dipole OLR structure with an above-normal convection near $22^\circ$N and a below-normal convection around $8^\circ$N. For both EOF1 and EOF2, above (below) normal convections \{i.e., negative (positive) OLR\} are mostly
embedded in a westerly (easterly) zonal wind anomaly, with the maximum (minimum) convection about $5^\circ$ to the north of the maximum of westerly (easterly) wind.

To discuss the temporal characteristics of the leading EOFs, power spectra of the principal components of EOF1 and EOF2 (PC1 and PC2) are displayed in Fig. 3 and are compared with that of PC3. Similar to WH04, the spectra are illustrated with an area-conserving format in which variance is proportional to area. PC1 and PC2 have a large part of variance at intraseasonal periods (20–70 days) that are typically associated with the ISO of the EAWNP summer monsoon (e.g., Lau et al. 1988; Chen et al. 2000) and the MJO (e.g., Yasunari 1979; Lau and Chan 1986). PC1 and PC2 account for 63% and 56% of their respective total variance in this band, significantly more than a red noise does (29% and 36%). For PC3, though its power spectrum shows a peak at a shorter time scale around 10–15 days, the variability between 20–70 days is not different from a red noise. It was found in previous studies (e.g., Hsu 2005) that two frequency bands equivalent to the 30–60- and 10–30-day periods dominate the EAWNP ISO. The shorter variations of 10–30 days propagate mainly westward between $5^\circ$ and $15^\circ$N. When doing a zonal average, only the ISO with a longer period of 30–60 days remains, which propagates northward.

We have seen that both PC1 and PC2 have statistically significant peaks in the intraseasonal time scale. The cross spectrum is also calculated to see if these periodicities in PC1 and PC2 are related to each other. As is shown in Fig. 4, the coherence squared between PC1 and PC2 also peaks in the intraseasonal time scale around 40 days. The phase relationship near this frequency shows that PC1 leads PC2 by about $90^\circ$ (a quarter cycle). Comparing the meridional structure of EOF1 and EOF2 (Fig. 2), this phase relationship implies a northward propagation of the boreal summer ISO in the EAWNP region.

The autocorrelation of PC1 and the lag correlation between PC1 and PC2 are illustrated in Fig. 5. The autocorrelation of PC1 reaches its minimum value at a lag of about 25 days, reflecting a cycle of about 50 days, consistent with the spectrum analysis (top panel of Fig. 3). The lag correlation between PC1 and PC2 peaks when PC1 leads PC2 by 10 days, and reaches the minimum value when PC1 lags PC2 by 10 days, indicating that EOF1 and EOF2 represent a northward-propagating...
signal with a period of about 40 days, in agreement with the above cross-spectrum analysis.

We did several other EOF analyses either with each individual variable (of OLR, U850, and U200) alone, or with different combinations of them, with the objective of finding the optimal way of isolating the ISO in the EAWNP region. We hope to use the first two EOFs to capture the main features of the ISO including its frequency and the northward propagation. Several requirements should be satisfied: 1) EOF1 and EOF2 jointly explain the variance of variability as much as possible, 2) EOF1 and EOF2 are well separated from the remaining modes, 3) both PC1 and PC2 have significant power spectrum peaks on the intraseasonal time scale of 20–70 days, and 4) EOF1 and EOF2 have a nearly quadrature relationship in both space and time. For the combined EOF analysis using all the three variables, the two leading modes jointly explain less than 40% of the total variance (the least among all the tested combinations), and EOF2 is not separated from EOF3 according to the criterion of North et al. (1982). A comparison of the EOF analyses with each individual variable alone indicates that the EOF with U200 has a very different characteristic. For the case with U200 alone, PC1 and PC2 have a much weaker power spectrum in the intraseasonal time scale than those with the other two variables, and EOF1 and EOF2 are not coherent in space and time. Therefore, we decide not to include U200 in the EOF calculation. For the three EOF analyses using either OLR or U850 alone, and the combination of these two variables, a detail comparison indicates that the combined EOF has a clear advantage. Both PC1 and PC2 have the largest percentage of variance explained by the intraseasonal variability of 20–70 days. Also EOF1 and EOF2 are more coherent in space and time. The mean spectra of PC1 and PC2 of the EOF analysis for different combinations of variables are presented in Fig. 6a, and the lag correlations between PC1 and PC2 are shown in Fig. 6b. As is evident, the combination of OLR and U850 is our best choice.

4. A bivariate summer EAWNP ISO index

From the analysis in the last section, we can conclude that the leading two modes of the combined EOF analysis of OLR and U850 jointly represent a significantly large part of intraseasonal variability and its northward propagation in the EAWNP summer monsoon region. Therefore, a bivariate boreal summer EAWNP ISO index is defined using the combination of PC1 and PC2.

There are many similarities between our EAWNP ISO index and the RMM index of WH04; for example, both come from a combined EOF of variables with spatial averages but without time filtering, and both use the leading pair of EOFs, except that the RMM index was designed to represent the eastward propagation of the MJO along the equator, whereas the EAWNP ISO index captures the northward propagation of the ISO in the EAWNP summer monsoon region. Similar to WH04 but for northward propagation, we adopt a two-dimensional phase space of PC1 and PC2 to represent the state of
EAWNP ISO at a particular time. The distance of a point from the origin can be considered as the ISO amplitude, and a northward propagation of the ISO is reflected by an anticlockwise movement in the phase space plot. Plotted in Fig. 7 are the trajectories of the observed EAWNP ISO in the phase space for all summer days from 1979 to 2008. In addition to the weak ISO region where the amplitude is less than one, eight phases are defined and marked in Fig. 7 together with an indication of where the ISO convection is roughly located.

To see how well the EAWNP ISO indices can represent the original anomalies of the two input fields for the EOF analysis, we compare the reconstructed fields with the original anomalies. The reconstructed anomalies of OLR and U850 are obtained by summing up the two EOFs multiplied by their respective PC values at a given date. Figure 8 shows an example of the reconstructed anomalies compared to the original anomalies for the summer of 1996. The summer of 1996 had an active 30–60-day variability in the EAWNP monsoon region (Kajikawa and Yasunari 2005). The two-EOF reconstructed anomalies capture quite well the main features of the intraseasonal variability in the EAWNP region, and at the same time most of the high-frequency components are filtered out.

Two-dimensional anomaly fields can also be reconstructed using the EAWNP ISO indices. The 2D ISO signal is reconstructed based on a two-variable linear regression between the observations and the two PCs. Taking U850 as an example, we first use the linear regression equation between the observed daily U850 anomaly and the two PCs over the 30 summers to obtain two regression coefficients at each grid point. Then, with these regression coefficients and PC1 and PC2 at all dates, a series of 2D U850 anomaly fields can be obtained. We then can calculate the variance of such a reconstructed anomaly, and compare to that the original field to assess the fraction of variance explained by the two-EOF reconstructed ISO component. Figures 9a,b depict such a percentage of variance explained for U850 and OLR, respectively. The two-EOF reconstructed U850 explains a large part of the total variance in the EAWNP region. Over the South China Sea, more than 50% of the total U850 variance can be accounted for by the ISO indices. For OLR, the percentage of variance explained is smaller, with a maximum of about 30% in about the same region as U850.

5. Composites

Starting from the daily PC1 and PC2 values for the summer season from 1979 to 2008, the days that belong
FIG. 8. (a) Time–latitude plot of the observed anomalous OLR (shading) and U850 (contour) in summer 1996 that are zonally averaged from 90° to 150°E. (b) As in (a), but for the OLR and U850 anomalies reconstructed from the leading two EOF modes. The contour interval is 0.2 m s⁻¹. Contours with negative values are dashed.
to each of the eight phases of the ISO with an amplitude greater than 1 (the weak ISO area in Fig. 7 is excluded) are identified. Listed in Table 1 are the number of days and the averaged ISO amplitude for each phase. It can be seen that phases 2–3 and 7–8 have a relatively high frequency of appearance. The maximum amplitude of the ISO tends to occur in phases 5–6, which correspond to an enhanced convection over the South China Sea as will be seen in the following OLR and precipitation composites.

Composites of the observed OLR and 850-hPa wind anomaly for different ISO phases are shown in Fig. 10. Starting from phases 8 and 1, enhanced convection develops over the equatorial eastern Indian Ocean and Maritime Continent. In phase 2, the negative OLR anomaly moves northward into the sector of South China Sea and the western North Pacific. In the subsequent phases, the negative OLR anomaly propagates farther northward and by phase 7 it reaches southeastern China. In the northward propagation process, the enhanced convection is preceded by easterlies and closely followed by westerly anomalies. A band of enhanced convection occurs in the southern part of a zonally elongated anomalous cyclonic circulation, and suppressed convection happens in the southern part of an anticyclonic flow anomaly.

The above association between the convection and circulation anomalies is in general consistent with previous studies. For example, Kemball-Cook and Wang (2001) observed that the 850-mb easterlies of the boreal summer intraseasonal oscillation in the Asian summer monsoon region move northward ahead of the convection and the westerlies appear within and behind the convection. Hsu and Weng (2001) found that negative (positive) vorticity anomalies of the western North Pacific intraseasonal oscillation are located to the northwest of the positive (negative) OLR anomaly.

Using the CMAP pentad precipitation data, Fig. 11 illustrates composites of the observed precipitation rate for different ISO phases. Here PC1 and PC2 are grouped into pentads in the same way as in the CMAP precipitation dataset, and composites are calculated using the pentad data. Consistent with the OLR anomaly, enhanced precipitation starts in the eastern Indian Ocean in phases 8 and 1, and propagates northward to influence southeastern China and subtropical western North Pacific by phase 7. This enhanced precipitation band can be seen to continue moving northward in phases 8, 1, and 2, with a noticeable increase of precipitation in eastern China and Japan before it dissipated.

### 6. Comparison and relation with the WH04 index

In this section we compare the regional representation of ISO by the EAWNP ISO index and the RMM index in the same summer months. With the same procedure as that used to calculate Fig. 9, two-dimensional anomalies U850 and OLR can also be reconstructed using the RMM index and their variances are computed. Shown in Fig. 12 are fractions of variance of the reconstructed field relative to the total variance for U850 and OLR.

<table>
<thead>
<tr>
<th>Phase</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. of days</td>
<td>321</td>
<td>378</td>
<td>376</td>
<td>349</td>
<td>349</td>
<td>329</td>
<td>373</td>
<td>377</td>
</tr>
<tr>
<td>Mean amplitude</td>
<td>1.58</td>
<td>1.56</td>
<td>1.59</td>
<td>1.66</td>
<td>1.79</td>
<td>1.79</td>
<td>1.63</td>
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</tr>
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</table>
respectively. Compared to Fig. 9, the U850 and OLR reconstructed by the RMM index have a variance that is limited to the equatorial region south of 15°N. In the EAWNP summer monsoon region, the fields reconstructed by the EAWNP ISO index explain a much higher percentage of variance than those reconstructed by the RMM index.

The regional EAWNP ISO index is not independent of the global RMM index. Previous studies have shown that the tropical MJO propagates eastward along the equator, and after it reaches the Asian summer monsoon region some of the ISO disturbances propagate northward (e.g., Wang and Rui 1990; Hsu and Weng 2001). To see the relationship between the EAWNP ISO index and the RMM index, correlation coefficients are calculated between the two PCs and two RMMs during the boreal summer season from 1979 to 2008. Significant positive correlation (0.56) is found between

![Simultaneous composites of OLR (color; W m⁻²) and 850-hPa wind anomalies (vectors) in the EAWNP region for different ISO phases. The scale of wind vector (in m s⁻¹) is marked at the right bottom of each panel.](image-url)
PC1 and RMM2, and negative correlation ($-0.47$) exists between PC2 and RMM1. In the phase space of Fig. 7, RMM2 would be in the same direction as PC1 and RMM1 would go along the opposite direction of PC2. Therefore, the axes of RMM1 and RMM2 would turn into PC1 and PC2 by a 90° counterclockwise rotation. Therefore, there is a two-phase lag between the PC1 and PC2 phase space comparing to the RMM1 and RMM2 space. To confirm this, composites of the observed OLR and 850-hPa wind anomaly are calculated for different RMM phases and are shown in Fig. 13, that can be compared to Fig. 10 of the PC phases. As mentioned in the above discussion, PC phases lag RMM phases by a quarter cycle, thus PC phase 1 would correspond to RMM Phase 3. As can be seen, the two sets of index have a similar representation of ISO in the tropics south of 15°N with convection centers at similar locations. Both have a northward-propagating signal in the tropics.
EAWNP region, although the RMM composites show a clearer eastward propagation. The PC composites have a much stronger amplitude in both winds and OLR, especially in the region north of 15°N. The RMM composites completely lack the north–south OLR “dipole” anomaly in RMM phases 4–5 (or PC phases 2–3; no suppression to the north) and RMM phases 8–1 (or PC phases 6–7; no enhancement to the north).

7. Forecast

In this section, we evaluate the forecast skill of the boreal summer EAWNP ISO. In the verification for the ISO forecasts, the observational data are the daily average of the NCEP–NCAR reanalysis, which match the output time of the model. The same steps as described in section 3 are applied to both the observed and the forecast data to calculate the observed and forecast PC1 and PC2. In the forecast, when we remove the interannual variability part, we do not have 120 days of forecast data, so we use the observations before the start of integration to replace those days missing (i.e., when removing the 120-day mean for the forecast at day \( n \), the average of the \( 120 - n + 1 \) days of observational data preceding the forecast and the forecast data from day 1 to day \( n - 1 \) is used). Both the observed and forecast PC1 and PC2 are normalized by the standard deviations of the observed PC1 and PC2.

To measure the forecast quality of the bivariate boreal summer EAWNP ISO index, two metrics are used: the correlation skill \( \text{COR} \), and the root-mean-squared error (RMSE). They are similar to those defined in Lin et al. (2008) where the skill is for the RMM index. The correlation skill \( \text{COR} \) is defined as

\[
\text{COR}(\tau) = \frac{\sum_{i=1}^{N} [a_{1i}(t)b_{1i}(t) + a_{2i}(t)b_{2i}(t)]}{\sqrt{\sum_{i=1}^{N} [a_{1i}^2(t) + a_{2i}^2(t)] \sum_{i=1}^{N} [b_{1i}^2(t) + b_{2i}^2(t)]}}
\]

(1)

where \( a_{1i}(t) \) and \( a_{2i}(t) \) are the observed PC1 and PC2 at day \( t \), and \( b_{1i}(t) \) and \( b_{2i}(t) \) are their respective forecasts for the \( i \)th forecast with a \( \tau \) day lead. Here \( N \) is the number of forecasts.

The root-mean-square error \( \text{RMSE} \) can be written as

\[
\text{RMSE}(\tau) = \sqrt{\frac{1}{N} \sum_{i=1}^{N} [(a_{1i}(t) - b_{1i}(t))^2 + (a_{2i}(t) - b_{2i}(t))^2]}
\]

(2)

Shown in Fig. 14 is the COR and RMSE skill for all the 288 summer forecasts, compared with that of the persistence forecasts where the forecasts are simply the initial condition. If we take a correlation of 0.5 as the minimum for useful skill, GEM produces skillful forecasts up to 9 days (Fig. 14a). In contrast, the persistence forecast maintains a useful forecast only until day 5. Similar conclusions can be made for the RMSE skill.

The amplitude of the ISO is defined as \( \text{amp} = \sqrt{\text{PC1}^2 + \text{PC2}^2} \). Here we look at the dependence of forecast skill on the ISO amplitude in the initial condition. Cases of strong and weak ISO forecasts are determined based on the observed ISO amplitude in the initial conditions. For a strong ISO, the initial ISO amplitude is greater than 1, whereas for a weak ISO the amplitude is smaller than 1. In all the 288 forecasts during the boreal summer, we have 186 strong ISO cases and 102 weak ISO forecasts. Figure 15a shows the correlation skill for the ISO index of forecast cases with strong and weak ISO signals at the initial state. It is seen that up to a forecast lead time of about 10 days the forecast skill is significantly higher when the initial condition has a strong ISO signal. For the RMSE skill little difference can be found. As the correlation skill measures the skill in forecasting the phase of the ISO and is insensitive to amplitude errors, the above results indicate that the
phase of the ISO is predicted better when there is a strong ISO in the initial condition. On the other hand the amplitude error as measured by RMSE is not sensitive to the initial ISO amplitude.

8. Summary and discussion

In this study, a combined EOF analysis is performed for the daily anomalies of zonally averaged OLR and U850 in the EAWNP region to isolate the ISO signal. A new regional summer bivariate ISO index is defined based on the PCs of the first two leading EOFs, which are nearly in quadrature in space. These two EOFs are well separated from the rest of the modes, and jointly explain about 45% of the total variance. Power spectrum analysis reveals that PC1 and PC2 both have a large part of variance at intraseasonal periods (20–70 days) that are typically associated with the ISO of
the EAWNP summer monsoon and the MJO. The cross spectrum indicates that the coherence squared between PC1 and PC2 also peaks in the intraseasonal time scale around 40 days. The lag correlation between PC1 and PC2 peaks when PC1 leads PC2 by 10 days, and reaches the minimum value when PC1 lags PC2 by 10 days, indicating that EOF1 and EOF2 represent a northward-propagating signal with a period of about 40 days.

This EAWNP ISO index is applied to the 24-yr subseasonal historical hindcast output of the GEM model to evaluate the forecast skill of the summer ISO in the EAWNP region. There is a clear advantage in forecast skill for the dynamical model comparing to a persistence forecast. The skill is dependent on the strength of ISO signal in the initial condition. A strong ISO initial condition leads to a more skillful forecast than a weak ISO initial condition based on correlation skill.

There are several possible aspects that can be considered in the GEM model subseasonal forecast in order to have an improved summer ISO prediction. Besides the model resolution and initial condition, anomalies in SST may lead to changes in air–sea heat flux and convection, which affect atmospheric circulation (e.g., Woolnough et al. 2007). The lack of air–sea interaction in the hindcast experiment may also affect

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**Fig. 14.** (left) Correlation skill and (right) RMSE skill for the bivariate ISO index. The solid curve is for GEM forecast and the dashed curve is for the persistence forecast.

**Fig. 15.** (left) Correlation skill and (right) RMSE skill of the bivariate ISO index for strong ISOs (dashed) and weak ISOs (solid).
the forecast skill of the summer ISO in the EAWNP region.

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