On the interannual variability of the Bonin high associated with the East Asian summer monsoon rain

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Abstract In order to assess how the Bonin high affects interannual variability of the East Asian summer monsoon (EASM) around the Korean Peninsula, the pulsation of the Bonin high and its association with teleconnection patterns was examined. The major factor for the interannual intensity of the EASM is the center position of the Bonin high rather than its center pressure. Up to 12 harmonics over time can be used to reconstruct the Bonin high, demonstrating its intraseasonal variation. The interannual variability of the Bonin high correlates with the Tibet high. This correlation is dominant for the EASM onset time, though not its retreat. The primary teleconnection pattern, reliant up on the interannual variability of the Bonin high, is the Western Pacific oscillation (WPO) in April. In relation to long-term variability, the correlation between the WPO and the Bonin high appears to contribute to the retreat stage of the EASM, which has itself increased since the mid-1970s. Furthermore, the WPO in May and the Tibet correlation has marked the onset rather than the retreat of the EASM since the 1970s. This highly correlated pattern since the mid-1970s may be the result of El Niño.

1 Introduction

In recent years, the Korean Peninsula has suffered from an extra-ordinarily heavy rainfall during the East Asian summer monsoon (EASM). Nevertheless the definition of rainfall intensity associated with the EASM and the mechanisms that affect its interannual variability are unclear. The East Asian summer monsoon rain over the Korean Peninsula, which is also called ‘Changma’, has been defined by approximately forty days of precipitation from late June to late July (Lu 2002; Ho et al. 2003; Ha et al. 2005). The most important aspect of the EASM is its large interannual variability. Therefore, predicting the interannual variability (IAV) of regional rainfalls over the East Asian monsoon region is an imperative task. Most studies on the IAV of the EASM have noted that summer rainfall in East Asian regions is statistically associated with the Eurasian snow cover (Yang and Xu 1994) and SST anomalies (Yang and Yuan 1996) in the equatorial Pacific and Indian Oceans.

Even though the relationship between snow cover/SST and EASM is statistically correlated, many scientists (Wang et al. 2004; Kang et al. 2002; Sumi et al. 2004) have suggested that simulations of the East Asian monsoon are less than conclusive. Instead of using the levels of precipitation as an indicator of the IAV of the EASM, the characteristic large-scale circulations have been investigated. Several circulation-based indices have been produced for predicting the monsoon. In addition, invaluable efforts have been made to create an index using circulation for the prediction of monsoons such as WYI (Webster and Yang 1992), East Asian/Pacific index (EAPI, Huang 2003), and the Changma index (Ha et al. 2005). They suggest
that circulation indices, as opposed to rainfall indices, would provide a better source of predictability of IAV of the EASM.

However, the large-scale circulations rely heavily on standing highs not necessarily available over the EASM region. Wu and Wang (2001) identified that three abrupt changes were identified in the atmospheric circulation for the onset of the climatological summer monsoon over the South China Sea and the western North Pacific (WNP) (110°–160°E, 10°–20°N). They emphasized that the WNP subtropical high displays a sudden eastward retreat or rapid northward displacement at the onset of each of the three stages. Enomoto et al. (2003) and Wakabayashi and Kawamura (2004) showed that the behavior of the standing high over the south of Japan (Bonin Island) differs from the behavior of the WNP high. Enomoto et al. (2003) reported that the localized descent over the east Mediterranean and Aral Seas coincide with the entrance region of the Asian jet and may act as stationary-wave forcing. As a result of the propagation of stationary Rossby waves along the Asian jet (“the Silk Road pattern”) and their accumulation in the jet-exit region near Japan, an equivalent-barotropic ridge is formed. Their hypothesis suggests that the Bonin high is formed as an indirect result of heating in the region of the Bay of Bengal.

In the present study, some evidence is presented regarding the influence that an index based on the Bonin high has on the IAV of the EASM. Observational data are used to demonstrate that the Bonin high forms over the Pacific Ocean south of Japan during the EASM. The interannual features of the Bonin high are described with an emphasis on its intraseasonal variation, namely the onset (late June) and retreat (late July). Teleconnection patterns over the Pacific were investigated in order to predict the circulation patterns associated with such highs. The IAV of the standing highs are discussed in relation to this association.

The rainfall data used in the present analysis are the pentad mean of the Climate Prediction Center merged and an analysis of precipitation (CMAP) data from 1979 to 2004. Data are given over a 2.5 × 2.5 grid (144 × 72). The National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) gridded (2.5 × 2.5 resolution) reanalysis data from 1948 to 2004 were also used.

2 A Changma index from Bonin high

2.1 Definition of Changma index using 500 hPa geopotential height

To determine the strong and weak EASM years over the Korean Peninsula, the Changma rainfall index (CRI) was defined based on a time average (from late June to late July, Changma period) and an areal average (123.75–131.25E, 31.25–41.25N) (Ha et al. 2005). From its interannual variability (Fig. 1), strong and weak EASM years were defined by more than and less than 0.5 deviation, respectively. It can be seen that the interannual variability is very large.

Figure 2 shows the mean precipitation from late June to late July for strong and weak EASM years, and their differences. The mean precipitations over the Korean Peninsula (CRI area) for strong and weak EASM years are 8.36 and 5.34 mm/day, respectively. In relation to the IAV of the EASM, the four standing highs of Bonin, Tibet, Okhotsk and the north Pacific were indexed to produce indices by Ha et al. (2005). These authors suggested that the model output stas-

Fig. 1 Interannual variability of the area (31.25–41.25°N, 123.75–131.25°E) and period (late June–late July) mean rainfall anomaly
Fig. 2  Mean precipitation (mm/day) from late June to late July for (a) strong EASM, (b) weak EASM years and (c) their differences. The rectangle in (c) represents the area of CRI (31.25–41.25°N, 123.75–131.25°E)
tics for the Changma indices are a more useful predictor than the rainfall itself. The circulation characteristics for the strong EASM years are allowed as follows: (1) a strong Bonin high and/or enhanced north Pacific high and an active migrating high over the northern part of China; (2) a strong low level convergence zone, which is formed by the merging of three streams, southwesterlies, southeasterlies, and northwesterlies over the Korean Peninsula; (3) an upper-level Asian jet developing in the downstream areas, which can create a strong diffluent flow; and (4) a Changma front located between the upper and lower-level jet, which is induced by the instability that results from a cold air flow in the upper level and warm and moist air in the lower-level.

As has already been mentioned, the Bonin and north Pacific highs are important for reinforcing the IAV of the EASM. To separate the Bonin and north Pacific highs, 54 years of data (1948–2001) on the geopotential height of 500 hPa from late June to late July was taken into account. Using the centers of the highs, we determined the Bonin high index area and the north Pacific high index area to be as shown in Fig. 3 (140–145°E, 25–30°N and 170–180°E, 27.5–30°N, respectively). In order to clarify the association between these highs and EASM, the time series from the averages of geopotential heights for the Bonin high area and the north Pacific high area were compared for strong and weak EASM years.

To identify the contributions of the Bonin high and the north Pacific high in the IAV of the EASM, temporal correlations between the two highs and CRI were investigated. While the Bonin high and CRI had a high correlation factor of 0.68 in the 23 years from 1979 to 2001, the correlation coefficient between the north Pacific high and CRI was as low as 0.20. The temporal correlation coefficient for the two highs is actually about 0.29 during the period of 1948–2001 which has decreased to 0.18 in recent years (1979–2001). The low coefficient between the two highs supports a scenario in which the IAV of the Bonin high does not mimic that of the north Pacific high.

From the temporal correlation analysis, we refer to the 500 hPa Changma index (hereafter CI500HB) as the Bonin high area average at a geopotential height of 500 hPa. Figure 4a shows the evolution of the three different CI500HBs with time in the strong and weak EASM years during the boreal summer times, and the climatological mean year. We found that the height amplitude in strong EASM years is larger than that for weak EASM years. The CI500HB increased rapidly during June with two peaks, one in late June (Changma onset) and one in late July (Changma retreat). The two peaks in the strong EASM years contrast with those in weak years during onset and retreat, showing a significant difference (thick black bar at the bottom of Fig. 4a) at onset (18 June–3 July) and retreat (21 July–1 August).

2.2 Harmonic amplitude and phase for the Changma index

Many natural phenomena occur in the form of sinusoidal wave, with the resulting wave as the sum of the component waves. A Fourier analysis in time is based on the concept that real signals can be approximated by the sum of the sinusoids, each at a different frequency. The intraseasonal oscillation of the Bonin high was investigated by applying this harmonic wave analysis to CI500HB.
The harmonic analysis can be given by

\[ X(t) = A_0 + A(n) \cos \left( \frac{2\pi n}{T} (t - \theta(n)) \right), \]  

(1)

where \( n \) is the wave number \([A(n)]\), is the amplitude for wave \((n)\), \([\theta(n)]\) is the phase day for wave \((n)\), and \( A_0 \) is the average amplitude over time. \( A(n) \) is obtained from the amplitudes for the sine and cosine functions of the Fourier harmonics, and the phase, \( \theta(n) \), is computed using the \text{arctan} function of the amplitudes of the sine and cosine waves.

The time series of reconstructed harmonics of up to 12 waves (approximately 30 days in the period) is an approximation representing the time series for CI500HB for strong and weak EASM years as shown in Fig. 4b. Although the value of the harmonic amplitude is slightly higher than the value in CI500HB, it is still very similar to the value in CI500HB because of the exclusion of high frequency waves. This supports the view that the low frequency oscillation of the Bonin high sufficiently represents the strength of the high and its association with the IAV of the EASM. The reconstructed harmonics of the 500 hPa index may be associated with the onset and retreat of the Changma. Figure 5 shows the spatial distribution of the 500 hPa geopotential heights with harmonics up to 12 waves at onset and retreat. In strong EASM years, the height is much higher than in the weak years. This confirms that significant differences exist between the Bonin high index area for the onset and retreat periods.
3 Characteristics of the Bonin high associated with the EASM

3.1 Convergence of moisture flux

There are many reasons for using the hydrologic cycle as a basis for determining the monsoon onset. Hydrologic fields, such as the convergence of moisture flux and vertical integrated moisture transport, are directly linked to the basic force of a monsoon rainfall. Therefore, it is useful to compare and contrast the differences in the composites of water vapor transport into the monsoonal front for strong and weak EASM years. Figure 6a and b show the latitudinal divergence in moisture flux during onset and retreat for strong and weak EASM years. At the onset time in strong EASM years, dominant convergences (negative $\partial qv / \partial y$) by a latitudinal gradient over the Korean Peninsula and a strong divergence over the southern ocean near 20°N are significant. The convergence around Korea is not strong in weak EASM years. Over the Korean Peninsula, the convergence of moisture flux is still prominent during the retreat for strong EASM years and the difference is also significant (Fig. 7). Convergence no longer exists for the retreat in weak EASM years. This result demonstrates a link between the intensity of the Bonin high and the intensity of transported moisture.
Fig. 6 The divergence (positive) of moisture flux (g/kg-day) in meridional direction ($\partial(qv)/\partial y$) at 850 hPa for onset in a strong EASM, b weak EASM and c their difference. Shaded areas in c represent significant areas (95% confidence level).
Fig. 7 Same as Fig. 6 except for the retreat
3.2 Interannual variability of the Bonin high

An empirical orthogonal function (EOF) analysis was performed for the 500 hPa geopotential height during the Changma period to describe the IAV of the Bonin and the north Pacific highs (Fig. 8). The analysis area was restricted to 110–200°E and 15–35°N, in order to acquire features of the two highs. In the first mode, the highs are coherently linked to each other. The two highs are separated in the second mode and the first two leading eigenvectors explain about 60% of the total variance. Despite separating the Bonin and the north Pacific highs for IAV in the discussion in Sect. 2.1, the Bonin high is coherently changing with the north Pacific high in some part of the variance. These two leading eigenvectors are closely associated with CRI (Table 1).

The interannual mean position and the intensity of the center heights of the Bonin and north Pacific highs were investigated during the Changma period and are shown in Fig. 9. The middle and bottom panels denote the onset and retreat. The position and intensity of the centers of the two highs indicate the location and magnitude of the highest heights around the Bonin and north Pacific highs. The sizes of the circle and rectangle in Fig. 9 are proportional to the magnitude of the centers. Overall, the northwestward extension, especially the north Pacific high, on the period of retreat is enhanced compared to onset. Strong EASM years have remarkable and intense Bonin high centers, while the Bonin high in weak EASM years becomes very weak or disappears. Unlike the Bonin high, the position and magnitude of the north Pacific high shows no correlation associated with the intensity of the EASM. The Bonin high centers at onset and retreat in strong

![Fig. 8](image_url)

**Fig. 8** First two leading eigenvectors and their associated time series obtained from the EOF analysis of the 500 hPa geopotential height during the Changma period from 1979 to 2004

<table>
<thead>
<tr>
<th>Corr.</th>
<th>EOF1</th>
<th>EOF2</th>
</tr>
</thead>
<tbody>
<tr>
<td>CRI</td>
<td>0.42</td>
<td>0.32</td>
</tr>
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EASM years are almost always located near 140–145°E and 25–30°N (black circle in Fig. 9), suggesting that the most important factor in generating a strong EASM is the position of the Bonin high at the times of onset and retreat.

3.3 Vertical structure

The above study examined the horizontal structure in interannual variation. Most teleconnection patterns tend to have equivalent-barotropic or barotropic characteristics in their vertical structures. To investigate the influence of a high pressure system on the summer climate of Japan, Enomoto et al. (2003) examined the equivalent-barotropic structure of the Bonin high with a simple GCM and reanalysis data. The equivalent-barotropic structure over the Bonin high area can be described by a longitude-height cross-section. Figure 10 shows the vertical structure of the Bonin high and the Tibet high during the periods of onset and retreat. The vertical-longitude section is along the 25–30°N latitude bands. The vertical-longitude sections of the geopotential height for strong EASM and weak EASM years are significantly different in the Bonin and Tibet high areas. An equivalent barotropic structure relies on vertical phase and amplitude with a vertical structure. From Fig. 10, it can be seen that the vertical structure in weak EASM years has nearly an opposite phase to that in strong
EASM years. This increase in vertical amplitude and phase with the height of the Bonin high in strong EASM years indicates that the structure is equivalently barotropic. At the onset phase, the vertically increased amplitude in the Bonin high is prominent. The Bonin and Tibet highs also have the same anomaly patterns at onset in strong and weak EASM years, as shown in Fig. 10. However, in the retreat phase in strong EASM years, the barotropic structure is weakened in the Bonin high area, and the Tibet high becomes baroclinic.

4 The linkage between the WP teleconnection pattern and highs

Teleconnection patterns may be the precursor of the high intensity associated with the EASM. Wakabayashi
Fig. 10 The vertical cross section of geopotential height anomaly (m) during the onset and retreat in strong and weak EASM years.
and Kawamura (2004) extracted major teleconnection patterns which might be associated with the anomalous summer climate in Japan. They concluded that the Europe–Japan patterns were linked with the variability of the Okhotsk high, and that the west Asia–Japan patterns were possibly connected to the strength of the anomalous convective heating caused by the Indian summer monsoon.

Various teleconnection patterns were first examined in terms of their temporal correlations with the intensity of the Bonin high in the western Pacific. The Climate Prediction Center (CPC) monitors primary teleconnection patterns and provides daily/monthly teleconnection indices. The teleconnection pattern indices used in this study were obtained from Climate Prediction Center website (http://www.cpc.ncep.noaa.gov/data/teledoc/telecontents.shtml). The daily and monthly Northern Hemisphere teleconnection indices have been changed as of June 1, 2005, but in this study, we used the old monthly teleconnection indices from 1950 to 2004 for the sake of consistency. Thirteen prominent teleconnection patterns are identified in the Northern Hemisphere throughout the year, and Barnston and Livezey (1987) showed all of these patterns.

The temporal correlation analysis indicated that the WP pattern is the primary mode of low-frequency variability over the North Pacific in all months (Barnston and Livezey 1987; Wallace and Gutzler 1981). The strong positive or negative phases in this pattern reflect pronounced zonal and meridional variations in the location and intensity of the entrance region of the Pacific (or East Asian) jet stream. The strong WP oscillation index has also been characterized by a weak Aleutian low and a weak East Asian jet stream. The WPO is strong in the winter and spring seasons, and the WPO becomes an especially significant mode for April and May (Barnston and Livezey 1987).

The correlation in April and May were examined as temporal correlation coefficients between the normalized monthly time series of the teleconnection indices and each of the Changma indices during the Changma period, at onset and retreat from 1979 to 2004. During the Changma period, it would appear that the WP index in April was correlated well with CRI for 1979–2004. The correlation coefficients differ in duration, onset, and retreat of the Changma. Although the correlation coefficients between CRI and CI500HB at onset are low, those at retreat are very high, 0.47. The WP in May is closely associated with the Tibet high index (index area: 90–95°E, 30–35°N) at onset. We analyzed the sliding correlation coefficients in the long-term time series in more detail.

Figure 11 shows the time series of the sliding temporal correlation coefficient between WPO and the highs. This sliding correlation is for 20 years, and was computed for each year during the period from 1950 to 2004. The sliding correlation coefficient analysis was done for onset and retreat anomalies. The results for the temporal variability of the sliding correlation coefficients show a significant difference for the onset and retreat phases of the highs. The correlation coefficients between the retreat of the Bonin high and the April WPO have increased remarkably since the mid-1970s, however it has been gradually decreasing over time. That is, the April WPO linkage with the Bonin high at retreat would probably correspond better in recent years than that for the Bonin high at onset. During the 1960s–1980s the temporal correlation coefficients are nearly 0.70. In contrast to this high correlation at retreat, the WP linkage with the Bonin high at onset has decreased since the mid-1970s, and a close correlation with the Bonin high no longer exists in recent years. Conversely the May WPO linkage with the Tibet high at onset has increased in recent years, compared to that for the onset of the Bonin high. Abrupt changes in correlation occurred in the 1970s.

A limitation of this study is the lack of an explanation for the WP–Bonin correlation that appears to contribute significantly to the retreat stage of the Changma and the WP–Tibet correlation that marks its onset. In addition, the temporal correlation coefficients, except for the El Niño or La Niña years, between WP and the two highs were examined to determine the effect of ENSO on the WP pattern and the Bonin high at onset and retreat. Figure 11c and d represent these correlation coefficients except for the El Niño years. Data for the El Niño and La Niña years were obtained from the Center for Ocean–Atmospheric Prediction Studies (COAPS) web site (http://www.coaps.fsu.edu/products/jma_index.php). When the El Niño years are omitted, the correlation coefficients between the April WP pattern and the Bonin high for retreat have decreased slightly since the mid-1970s to the present and its change is not great. The increasing correlation of this relationship since the mid-1970s may be due to the strong increase in SST since the mid-1970s (Emanuel 2005). Moreover, the relationship of the May WP and Tibet high for onset has changed significantly over time, so that the correlation coefficients have been low in recent years. From this result, it appears that the characteristics of ENSO have an impact on the onset and retreat of the EASM. However, the pattern changes only slightly when the
La Niña years are omitted. This suggests that the onset and retreat of the Changma are greatly affected by the behavior during the El Niño years.

Distributions of 500 hPa geopotential heights in April of strong (1979, 1980, 1981, 1987, 1991, 1995, 1998, 2003, 2004) and weak (1982, 1985, 1986, 1989, 1990, 1992, 2000) WP years and their difference are shown in Fig. 12. The heights in strong WP years are higher than those for weak WP years and the differences between the two periods are obvious. The dominant Bonin high during the Changma period is well organized in strong April WP pattern years and the difference in the low latitude region is still significant (Fig. 13). The high is separated into two centers at retreat and the difference becomes much clearer, which is seen in Fig. 14. This result demonstrates that the WP pattern is closely associated with the Bonin high at retreat. In other words, if the April WP pattern index is strong, the Bonin high will be strong at retreat.

5 Summary and conclusions

Ha et al. (2005) hinted in their study on the simulation in precipitation climatology that circulation indices provide a better source of predictability compared to the rainfall index of the EASM. In recent years the Korean Peninsula has experienced both strong and weak EASM. This study investigated the linkage between a large-scale circulation anomaly and the IAV of the EASM using a diagnostic analysis.

A composite analysis of the geopotential heights in strong and weak EASM years was conducted using NCEP–NCAR reanalysis data. The Bonin high Changma index (CI500HB) based on the Bonin high region shows a consistent anomaly during both onset and retreat in the composites of the strong and weak EASM years. The Bonin high is distinguished from the north Pacific high and can be represented with up to 12 harmonic waves over time. The interannual variability in intensity and the position of the...
center of the Bonin high is strong. The major difference between strong and weak years was the position of the Bonin high.

Onset and retreat of the EASM dominates the determination of the IAV of the EASM. When the Bonin high is positioned in the region over 140–145°E
and 25–30°N, a strong Changma occurs. Due to the vertically increased amplitude and in phase with height, the Bonin high at onset and retreat represents an equivalent-barotropic structure. The Bonin high with a deep vertical structure has a year-to-year variability and its IAV relates well towards the Tibet high.
We attempted to investigate the connection between teleconnected patterns with highs. The primary teleconnection was the WP pattern for interannual variability of the Bonin high, and the WP, which affected the April–Bonin correlation thus appeared to contribute substantially to the retreat stage of the Changma, especially
since the mid-1970s. This increasing correlation may be due to the remarkably strong El Niño that has occurred since the mid-1970s. The long-term change in temporal correlation is of obvious importance for climate change over the Pacific Ocean. The Tibet high correlated well with the Bonin high at onset and was correlated with the May WP pattern in recent years. There has been an increasing trend in correlation between the Tibet high at the onset of the Changma and the May WPO, and the relationship between the Bonin high at retreat and the April WPO has been dominate in recent years. More work will be needed to determine the reasons for the marked changes in their relationship since the mid-1970s.

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