Intraseasonal Meridional Surges and Equatorial Convections during the Southern Hemisphere Summer

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Abstract

Relationships between midlatitude cold surges and tropical convections are investigated utilizing 30–60 day filtered 850 mb meridional winds and outgoing longwave radiation (OLR) data during the three Northern Hemisphere winters of 1980–83. The 30–60 day southerly surges over the eastern Indian Ocean off the west Australian coast act as the trigger and intensifier of low-frequency convective systems which systematically propagate eastward across the equatorial Indian Ocean and the western Pacific. In comparison, the northerly surges from the subtropical western Pacific (east of Philippines) tend to enhance equatorial convection between about 150°E and the date line, which is about 20 to 50 degrees of longitude downstream of the northerly blowing longitudes (120°–130°E).

1. Introduction

The summer monsoon over the Indonesia-northern Australia region is one of the most important components of the global atmospheric circulation during the Northern Hemisphere winter*. It is characterized by a low-level monsoonal trough extending from southern Africa eastward through Australia to the date line with accompanying surface westerly winds equatorward of the trough. Within the SH monsoon region, the low-frequency (approximate 30–60 day period) oscillations of equatorial convection are well-defined and act as a major regulator of the monsoonal activities (Murakami and Sumi, 1981; McBride, 1983; and many others). By examining 28–72 day filtered outgoing longwave radiation (OLR) and global 250 mb streamfunctions for ten winters, Weickmann *et al.* (1985) found a strong response in the 250 mb streamfunction fields over the subtropical and middle latitudes, implying a tropical-midlatitude inter-

action on this time scale.

Krishnamurti and Gadgil (1985) detected a strong signal of low-frequency oscillations in high-latitude regions. These oscillations are nearly in-phase in the vertical, implying that they are essentially barotropic. This is contrasted with the vertical structure of equatorial low-frequency modes which are basically out of phase between the upper and lower troposphere (baroclinic nature), as first pointed out by Madden and Julian (1971 and 1972). Recently, Lau and Phillips (1986) found significant extratropical-tropical teleconnections through certain preferable conjunctions in association with low-frequency oscillations during the NH winter.

Another important aspect of the Australian monsoonal circulation is that outbreaks of midlatitude cold air over specific geographic regions penetrate to the equator and strongly affect tropical convective activity. Several investigators have documented the short term and regional-scale aspects of cold surges originating from Siberia and blowing through the north-western Pacific and the South China Sea; and from the midlatitude Indian Ocean and extending over the west Australian coast. The most important fea-

*For brevity, the term "Southern Hemisphere (SH)" "Northern Hemisphere (NH)" will rarely be used when identifying the season. Thus, the term "winter" refers either to the NH winter or to the SH summer.

ture of cold surge outbreaks over extratropics is the response of the tropical circulation and the resulting heavy equatorial convections. However, as mentioned earlier, the variations of tropical convective activity over the monsoon area are dominated by 30–60 day low-frequency oscillations. Therefore, the effect of cold surge also needs to be investigated on this time scale. The observational studies have confirmed that the low-frequency modes exist in midlatitudes, although the short-period synoptic-scale perturbations are more prevalent. It is then reasonable to expect that the low-frequency component of cold surge, called “low-frequency cold surge” or “low-frequency surge” in this paper, are essentially responsible for the interaction of the equatorial and midlatitudinal low-frequency oscillations. The investigation of this conjunctural effect of low-frequency surge is the main objective of the present study.

2. Data and computational procedures

This study utilized daily 850 mb grid-point meridional wind (v) data at a 2.5° longitude-latitude resolution during the three winters (1 Nov.–31 Mar.) of 1980–83. The data were extracted from the objectively analyzed data set prepared by the European Center for Medium Range Weather Forecasts. Daily outgoing long-wave radiation (OLR) data, supplied by NOAA with same resolution over a tropical belt between 45°N and 45°S , were also used.

Applying harmonic analysis, harmonics 1–3 were calculated for all variables in each year (1 July–30 June). Here, the first harmonic corresponds to the yearly cycle, and the second harmonic represents the half-yearly cycle. The sum of the first three harmonics mainly corresponds to the seasonal trend. Braces are then introduced to represent the seasonal trend and a prime to define the departure from it. OLR , for example, can be expressed as:

$$OLR = \langle OLR \rangle + OLR'. \quad (1)$$

OLR' represents the intraseasonal component of OLR .

To confirm the presence of low-frequency oscillations, the seasonal trend removed OLR' data were subjected to a spectral analysis using

the maximum entropy method for every winter. Figure 1 depicts frequency-longitude dependency of spectra for OLR' averaged between the equator and 10°S from 60°E to 120°W . There exist two pronounced spectral peaks with a period range of about 30 to 60 days during each winter over the Indian Ocean and the central and western Pacific, respectively. This reflects the dipole characteristic of low-frequency equatorial convections, although year-to-year varia-

FIG. 1. Longitudinal dependency of power spectral amplitude ($\text{W}^2\text{m}^{-4}\text{day}^{-1}$) for equatorial OLR' averaged between the equator and 10°S from 60°E to 120°W . Intervals are 100, 200, 500, 1000, 2000, 5000 and 10000 units with spectra exceeding 1000 shaded.

bilities in the intensity and location of the major heating anomalies are quite substantial. The dipole pattern is associated with the eastward propagating E–W oriented Walker circulation (anomaly) across the Indian Ocean and the western Pacific (Lau and Chan, 1985). This propagating feature apparently stalls and intensifies as it reaches these oceanic regions.

Having established the existence of tropical low-frequency oscillations, we then applied prefiltering to OLR' variables by utilizing the procedure formulated by M. Murakami (1979). The band-pass filter employed in this study covers a wide period range from 30 to 60 days with the center at day 45. These filtered data are hereafter signified by the notation $(\sim)$. We therefore separate OLR' into two parts as follows:

$$OLR' = \tilde{OLR} + OLR^*, \quad (2)$$

where OLR^* is associated with short-period transient variations with periods shorter than 30 days.

As shown in Fig. 1, the intraseasonal variability of tropical convection is dominated by a dipole heating anomaly with centers over the Indian Ocean and the equatorial western and central Pacific. The standard deviation of the seasonal trend removed OLR' data (Fig. 2a) and the 30–60 day filtered OLR data (Fig. 2b) show very similar distribution, and high values appear in an equatorial belt stretching from the western Indian Ocean to the central Pacific between the equator and 15°S , with the maxima over the two centers of the dipole. The standard deviation is also substantial in northern Australia, reflecting a strong monsoonal variability over this vicinity. The percentage explained by low-frequency oscillations is about 35% of the non-seasonal standard deviation.

As noted by Murakami *et al.* (1986), the activity of low-frequency oscillations differs significantly from one year to another. For example, during the 1982/83 El Niño–Southern Oscillation event which started sometime around the 1982 early summer and ended before the 1983 fall, the activity of low-frequency oscillations was depressed well below normal and their phase propagation became irregular with many occasions of stagnant or even westward propagation.

Fig. 2. Standard deviations of (a) seasonal trend removed OLR' and (b) 30–60 day filtered $\tilde{OLR}$ averaged for three winters. Intervals are 10 (5) Wm^{-2} for OLR' ($\tilde{OLR}$). Shading indicates regions larger than 30 (10) Wm^{-2} for OLR' ($\tilde{OLR}$).

Thus, it is important to further investigate the interannual variability of low-frequency perturbations. However, this topic is beyond the scope of the present study.

3. Determination of low-frequency surges

Davidson *et al.* (1983) and Davidson (1984) proposed, from a limited amount of observational evidence, that the tropical convective activities associated with the onset and the earlier part of the 1978–1979 Australian monsoon could be a response to surges of low-level southerly flow off the west Australian coast. As pointed out by Ramage (1984), the southeastern Indian Ocean is most preferable region for the equatorward penetration of SH midlatitude cold fronts during the SH summer. The maximum entropy spectral analysis was then applied to areal averaged 850 mb meridional winds over the southeastern Indian Ocean ($27.5^\circ\text{--}30^\circ\text{S}$, $95^\circ\text{--}105^\circ\text{E}$). For brevity, these areal averaged meridional winds are hereafter signified as “ $V(S)$ ”. The results of power spectral analysis of $V(S)$ are presented in Fig. 3a. One notes the presence of dominant

Fig. 3. Spectral analysis of meridional wind at three reference areas: (a) $V(S)$, (b) $V(N)$, and (c) $V(NP)$, respectively. Dashed line is for the 95% significant level of power amplitudes (unit: $\text{m}^2 \text{s}^{-2} \text{day}^{-1}$). Refer to the text for further information.

spectral peaks with a period range of 30–60 days. The $V(S)$ signals of low-frequency surges for two winters (1981–82 and 1982–83) surpass the 95% significance level, while the signal for the 1980–81 winter is close to the same criterion. In the next section, an attempt will be made to investigate the response of equatorial convection to 30–60 day filtered $\tilde{V}(S)$ surges* off the west coast of Australia.

Lau (1982) and Lau *et al.* (1983) investigated individual cold surges that originate in Siberia and move southward through East Asia, reaching as far equatorward as the South China Sea. On the other hand, Murakami and Sumi (1982) and Murakami *et al.* (1984) emphasized the role of individual cold surges across the western Pacific-Philippines region for the enhancement of equatorial convection. Figure 3b shows the spectral power for areal averaged 850 mb meridional

wind $V(N)$ over the South China Sea (17.5° – 20°N , 110° – 120°E), while Fig. 3c is for areal averaged meridional wind $V(NP)$ over the region east of the Philippines region (15° – 17.5°N , 120° – 130°E). Both figures clearly indicate the dominance of low-frequency oscillations. In the next section, the 30–60 day filtered meridional winds $\tilde{V}(N)$ and $\tilde{V}(NP)$ are used as indexes to determine the timing of equatorial convection responses.

4. Relationship between low-frequency surges and tropical convection

Since large-scale convection on the intraseasonal time scale does not vary independently within the tropics (Lau and Phillips, 1986), there exists the possibility that midlatitude forcing, which is characterized by polar cold air outbreaks (active surge phase) and then penetrating equatorward to the tropics, can act as either a trigger and initiator and/or intensifier of tropical convection. The relationship between surge activities and tropical convection may differ dependent on the geographical location and temporal phase of cold surges. This point will

*This study only deals with cold surge in the 30–60 day time scale. Hereafter, the terms “low-frequency cold surge” and “cold surge” or “surge” will be used interchangeably. For distinction, the word “individual” will be used to specify a surge on a day-to-day time scale, e.g., “individual cold surge” or “individual surge”.

be investigated by computing lag correlations between $\tilde{V}$ and $\tilde{OLR}$. Here, caution must be exercised when interpreting these computed correlations. The time series being correlated have been subjected to a 30–60 day band pass filter. Thus, time series are forced to have the same periodicity of about 45 days. There is a possibility of obtaining high correlation values due to errors by the analysis method used. In the present study, our judgement on the reality of the computed correlation patterns is based not only on the statistical test but also on their continuity in space and time (lag), as well as on agreement with previous observations. To test the significance of correlation coefficients, the effective number of degrees of freedom is determined according to Davis (1976). Based on this degree of freedom (~ 30), the correlation coefficients greater (less) than 0.3 (-0.3) are significant at the 95% confidence level. Recall that the total number of days for three winters is 453 days.

The lag-correlation pattern between $\tilde{V}(S)$ and equatorial $\tilde{OLR}$, which is averaged between the equator and $10^\circ S$ from $60^\circ E$ to $120^\circ W$, is shown in Fig. 4a. Regions of significant correlation coefficient in excess of the 95% confidence level are either shaded (negative) or stippled (positive). At lag 0 day (active surge phase; $\tilde{V}(S) > 0$), the maximum tropical convective activity (negative correlations) is found over the eastern Indian Ocean (100° – $120^\circ E$) region which is just downstream of the low-frequency southerly surge blowing longitudes (95° – $105^\circ E$). Simultaneously, a dipole pattern or an E–W oriented cell is well defined with the western leg wet over the eastern Indian Ocean and the eastern leg dry over the western Pacific between $160^\circ E$ and the date line. Between lag about 0 and 20 days, regions of negative correlation (convection) systematically propagate eastward. At day 20, a reverse dipole pattern is established with dry weather over the eastern Indian Ocean and wet weather over the western Pacific. Further east of the $160^\circ W$, the correlation drops dramatically, indicating a decoupling of the extratropical circulation and tropical convection over these regions. This is as expected because deep convection very seldom occurs over the equatorial eastern Pacific. The phase speed of eastward propagation for the

Fig. 4. Lag correlation pattern between equatorial $\tilde{OLR}$, averaged between the equator and $10^\circ S$ from $60^\circ E$ to $120^\circ W$, and three selected low-frequency surge indexes: (a) $\tilde{V}(S)$, (b) $\tilde{V}(N)$, and (c) $\tilde{V}(NP)$. Intervals are 0.1. Regions of greater (less) than 0.3 (-0.3) are stippled (hatched). Abscissa is for longitude, while ordinate is for lag days, e.g., -20 means equatorial $\tilde{OLR}$ leading $\tilde{V}$ by 20 days.

lag-correlation pattern is approximately 5 ms^{-1} . Between days -20 and -5 , $\tilde{V}(S)$ is northerly (anomaly) and no significant tropical convection occurs either downstream or upstream. This strongly implies that tropical convections are initiated and regulated by the low-frequency southerly surge originating in the eastern Indian Ocean.

The lag-correlation is also computed for the surge case $\tilde{V}(N)$ with unexpected features appearing in Fig. 4b. Although the correlation patterns are similar to those in Fig. 4a, the statistically significant correlation coefficient either larger than 0.3 or less than -0.3 exists only west of $90^\circ E$ and east of $170^\circ W$. No significant correlation occurs between about $100^\circ E$ and the date

line. Here, an examination of the FGGE IIb data, as an independent data set, exhibits the vertical decoupling of winds above and below the planetary boundary layer over the South China Sea (not shown). The 850 mb pressure level appears to behave as a critical layer. Therefore, the meridional winds at 850 mb over the South China Sea may not be appropriate for the study on intraseasonal time scale cold surge.

Figure 4c shows the correlation pattern between northerly surges $\tilde{V}(NP)$ near the Philippines and tropical OLR . When northerly surge $\tilde{V}(NP)$ is the strongest at day 0, the maximum tropical convection (positive correlations) is centered at 150°E . At day -13 (leading to active surge), the maximum correlation is over the eastern Indian Ocean. A well-defined zone of convection then propagates eastward to the central Pacific with the same phase speed as in the $\tilde{V}(S)$ case (Fig. 4a).

Lag-correlation between $\tilde{V}(S)$ and $\tilde{V}(NP)$ reaches its negative peak (-0.53) at lag 13 days

(not shown). Therefore, an active convection center (maxima correlation of $+0.7$) in Fig. 4c over the eastern Indonesia ($100^\circ\text{--}110^\circ\text{E}$) on -13 day is probably regulated by the southerly surge $\tilde{V}(S)$. The most important indication in Figs. 4a, b, and c is the existence of high correlations over an extensive domain covering the Indian Ocean and the western Pacific, and including a continuous time span from day -20 to $+20$. Furthermore, all correlation patterns indicate a systematic eastward phase propagation of equatorial OLR perturbations across the Indian Ocean and the western Pacific, in agreement with previous observations (e.g., Murakami *et al.*, 1986). This agreement lends creditability to the correlation maps. This then leads us to conclude that $\tilde{V}$ surges are one of the major regulators of equatorial OLR perturbations.

To facilitate further discussion, the SH surge index $\tilde{V}(S)$ is used as a reference parameter. First, the simultaneous and lag-correlations for OLR perturbations with reference to $\tilde{V}(S)$ are

Fig. 5. Lag correlation map between surge index $\tilde{V}(S)$ and $\tilde{OLR}$ from 45°S to 45°N with lag days (a) -20 , (b) -10 , (c) 0 , and (d) 10 . Intervals are 0.15 when correlation is larger (less) than 0.3 (-0.3); no zero contour lines. Stippled (hatched) areas indicate values greater (smaller) than 0.3 (-0.3). Areal percentage that surpasses the 95% local significant level (LS), is shown on the top of each correlation map. Global significance criterion at the 95% confidence level (GS) is 21%, as shown at the top-right corner of this diagram.

computed to address the surge influence on convections. In Fig. 5, only synoptic features which are locally significant at the 95% confidence level (>0.3 , or <-0.3) will be highlighted. The areal percentage that surpasses the local 95% confidence level is signified as “*LS*”. *LS* is shown at the top of each correlation map. The global significance of each of the correlation maps is also tested by using Monte Carlo techniques (Livezey and Chen, 1983), which takes spatial independence into account. In order for a given correlation map to be globally significant at the 95% significance level, *LS* must be equal to or exceed a certain critical value. This globally significant criterion is denoted as “*GS*”, which is shown at the top-right corner of Fig. 5. Since *LS* is greater than *GS* in Figs. 5a to 5d, all correlation maps are considered to be globally significant at the 95% confidence level (Shrestha and Murakami, 1987).

Prior to $\tilde{V}(S)$ surges, the activity of equatorial convection is depressed below normal. For example, Fig. 5b depicts the predominance of positive correlation ($\tilde{O}LR > 0$) over the maritime continent. Once surge becomes active off the west Australian coast, convection over the west-

ern Indian Ocean and the maritime continent strongly increases (refer to Figs. 5c and 5d). By day 20 to 25 (approximately recurring at day -20 with a quasi 45 days periodicity), the major convection center moves to the date line. From this location, it appears to spread away from the equator into the extratropics of both hemispheres.

The NH northerly $\tilde{V}(NP)$ surge becomes strongest about 13 days after the SH southerly $\tilde{V}(S)$ surge. The lag 15 day correlation map (not shown) indicates that regions of major convection are centered around $150^{\circ}E$; thereby, reconfirming previous finding in Fig. 4c. In general, regions of strong equatorial convection are found downstream of the active cold surge regions. It is then tempting to speculate that a forcing, in terms of a phase-locking due to low-frequency surges, coming either from the Indian Ocean or from the Philippines-western Pacific region to the Australian monsoon region is very important for the excitation of tropical convective activities.

The correlation map does not reflect the intensity of $\tilde{O}LR$ perturbations. In order to further examine this aspect, a composite technique is introduced whereby $\tilde{V}(S)$ is utilized as a

Fig. 6. Composite $\tilde{O}LR$ fields (unit: Wm^{-2}) for categories 1 to 4 with reference to $\tilde{V}(S)$. Heavy (thin) full lines represent negative (positive) contours smaller (greater) than -2.5 ($+2.5$) units. Intervals are for 5 units (no zero line). Dark (light) mesh denotes regions where negative (positive) composite anomalies satisfy the 95% local significance test. *LS* value shown at the top of each category map is to be compared with *GS* values at the top-right corner of this diagram.

reference. Category 1 (5) is assigned to dates of maximum positive (negative) $\tilde{V}(S)$ surges, while category 3 (7) is defined for dates of $\tilde{V}(S)=0$. The total number of composite dates is seven. One cycle with an approximate 45 day period is expressed by categories 1 to 8. Composite maps for categories 5 to 8 are nearly identical, except for a change of sign, to those for categories 1 to 4. The statistical significance of the difference between the mean composite values for categories i and $i+4$ ($i=1, 4$) was tested using the method described by Lau and Chang (1985), and Murakami (1987). The areal percentage that surpasses the local 95% significant level of each $\tilde{OLR}$ composite map, denoted as LS , is shown at top of the diagram. The corresponding 95% global significance (GS), as shown on the top-right corner of the composite $\tilde{OLR}$ map (Fig. 6), was evaluated by Monte Carlo simulation.

In Fig. 6 are shown the composite $\tilde{OLR}$ fields for categories 1 to 4. By definition, the category 1 pattern corresponds to the active $\tilde{V}(S)$ surge phase with negative $\tilde{OLR}$ anomaly (above normal convection) over the equatorial eastern Indian Ocean, and some weaker convection over eastern Africa and western Australia. By category 2, convection is substantially strengthened over the eastern Indian Ocean and stretches to the maritime continent and Australia. The convective activity intensifies further in the Australian monsoon region and propagates eastward as well as southward between category 2 and 3. From category 5 to 7 (same pattern as categories 1–3 except with an opposite sign), negative $\tilde{OLR}$ perturbations appear to propagate more quickly eastward, while weakening considerably, across the western Pacific. When negative $\tilde{OLR}$ anomalies pass the date line into the eastern Pacific, they appear to move from the equatorial region into the extratropics and their eastward propagation becomes relatively ill-defined with a much larger phase speed. By category 8, three weak negative $\tilde{OLR}$ anomaly areas are all away from the equator, *i.e.*, southeastern Africa, the south Indian Ocean, and the North Africa-western Arabian Sea, respectively. One cycle later at the succeeding category 1, these negative $\tilde{OLR}$ anomalies converge into the equatorial eastern Indian Ocean, and they are drastically reintensified.

An east-west dipole pattern is well defined at category 2. Associated with this is the initiation of an active monsoon period over Indonesia and northwestern Australia, *i.e.*, one category after the active surge phase off the west Australian coast. Conversely, the establishment of a reverse dipole pattern at category 6 is followed by a commencement of break monsoons over these regions. At this time, the South Pacific Convergence Zone (SPCZ) over the western South Pacific seems to be most active.

The zonal mean $\tilde{OLR}$ profiles, as shown in Fig. 6, reveal an interesting phenomenon associated with surge events in the SH . At category 1 when southerly $\tilde{V}(S)$ becomes strongest, the major atmospheric zonal mean energy source (negative zonal mean $\tilde{OLR}$) is located within the 20° – $40^{\circ}S$ latitudinal belt. This may be related to strong synoptic-wave train activities in the SH midlatitudes. Between $20^{\circ}S$ and $5^{\circ}N$ is the sink region. By category 2, the source region tends to shift equatorward with the maximum just south of the equator. A significant intensification of the energy source over the equatorial belt ($10^{\circ}N$ – $15^{\circ}S$) occurs at category 3 with a sink region north of $15^{\circ}N$. A drastic decrease in the energy source over the equatorial band from category 4 to 5 is followed by a break monsoon phase over Indonesia and northwestern Australia during categories 6 and 8. These results may suggest a strong teleconnection between the SH midlatitudes and the equatorial region in terms of low-frequency surge activities.

5. Concluding remarks

Based upon 850 mb wind and outgoing long-wave radiation data during three winters of 1980–81, 1981–82, and 1982–83, the relationship between 30–60 day equatorial $\tilde{OLR}$ perturbations and low-frequency southerly (northerly) surges bursting out of the $S(N)H$ extratropics is investigated. The most important results of this study may be summarized as follows:

1. There is a strong indication that low-frequency surges unique to the central-southeastern Indian Ocean act as an initiator and/or an amplifier of equatorial convection (anomaly) over the SH summer monsoon region. The NH low-frequency surge bursting through the Philippines-

western Pacific region tends to intensify equatorial convection over the western Pacific east of New Guinea and west of the date line.

2. Surges from both the SH extratropics, $\tilde{V}(S)$, and the NH extratropics, $\tilde{V}(NP)$, appear to act as bridges for the interaction between the two hemispheres in the low-frequency domain. The variations of equatorial convection from the eastern Indian Ocean to the central Pacific appear to be linked to intrinsic low-frequency fluctuations over both hemispheric midlatitudinal circulations, regulated through the surge activities over specific geographical locations.

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南半球の夏における季節内変動的な南北方向 の吹き出しと赤道域での積雲対流

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1980年から1983年にかけての3シーズンの北半球の冬の期間における中緯度での寒気吹き出しと熱帯域積雲対流との関係を、30～60日周期でフィルターされた850 mb面の南北風と外向長波放射(OLR)を用いて調べた。オーストラリア西岸沖の東インド洋における30～60日周期の南風による吹き出しは、東インド洋および西太平洋にかけて組織的に東進する長周期変動的な積雲対流系にとっての誘発作用および強化作用を及ぼす。これと比較して、西太平洋亜熱帯域(フィリピン諸島東方)における北風による吹き出しは、東経150度から日付変更線にかけての赤道域の積雲対流を強化する傾向をもち、その強化域は北風の吹く経度(東経120～130度)に対して経度にして約20度から50度風下に位置している。