A Statistical Study of Winter Monsoon Cold Surges over the South China Sea and the Large-Scale Equatorial Divergence

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(Manuscript received 9 July 1991, in revised form 25 October 1991)*

Abstract

A 14-winter (1974/75–1987/88, November–March) tropical global band data set is used to study the relationship between the occurrence of cold surges over the South China Sea and the variation of the 200 mb and surface tropical divergence from the western Pacific to the eastern Indian Ocean. The data are truncated by 12 empirical orthogonal function modes. A canonical correlation analysis (CCA) between the surface meridional winds over the South China sea between the surge onset and 48 h later is used to define a basic cold surge mode. This mode represents the spatial- and time-coherent variations of cold surge events and is constructed from 8 CCA modes which contain approximately half of the total variance of the surface northerly winds. Lag correlations between this mode and the surface meridional velocity, 200 mb velocity potential and surface velocity potential, respectively, are computed to examine the effect of the surges.

The results show that, within 72 h of the surge onset, the anomalous surface northerlies reach 5 m/s centered in the northern South China Sea, and the anomalous southerlies reach 2 m/s over Burma. They represent about 70 % and 30 % of the total variance of the local surface meridional winds in the two areas, respectively. The cold surge-related 200 mb tropical divergence variations have two centers. The primary one is located in the equatorial South China Sea between the Malay Peninsula, Sumatra and Borneo, which is about 50° to the west of the long-term winter mean divergence center in the equatorial western Pacific around 155°E. The secondary center is over the Bay of Bengal. Divergence around both centers increases after the surge onset, with the primary one accounting for >25 % of the local variance after 5 days, and increasing to 40–50 % if the surge lasts 7–8 days. The magnitude of the increased divergence in the equatorial South China Sea is positively correlated with the surge intensity only during the first three days, while that in the Bay of Bengal is correlated with the surge intensity throughout the surge period. At the surface, anomalous tropical convergence increases during a surge event and develops into two centers. The first one is over northwestern Borneo near the 200 mb anomalous divergence center. It probably reflects the importance of the diurnal Borneo convection system. The other surface center is in the eastern Indian Ocean south of the Bay of Bengal. At both centers the surge-related fractional variances are approximately 40 % two days after the onset, and become >50 % five days after the onset. There is no indication of cold surge influences on the long-term mean divergence center in the equatorial western Pacific.

1. Introduction

During the northern winter monsoon, strong baroclinic regions can develop over the subtropics due to the outbreak of polar air masses off the coast of East and Southeast Asia. This often leads to synoptic events of cold surges, which means a rapid drop in surface temperature over southern China and a freshening of the surface northeasterlies (Ramage, 1975). The strengthening of the northeasterlies may encompass a wide longitudinal span from the western Pacific to the Indian Ocean, but it is the strongest over the South China Sea as the strong northeasterly winds penetrate deeply into the equatorial

latitudes. Here during a surge event the surface northeasterlies often accelerate by >10 m/s over one or two days, and the strong wind is sustained for several days thereafter. In southern China a steep temperature drop (>5°C in Hong Kong) and significant pressure rise (>5 mb) at the surface accompany the freshening of the winds. In the South China Sea the temperature and pressure changes are much less noticeable (Chang *et al.*, 1983), but the freshening of the northeasterlies remains strong. This event is often used as a major indicator for weather prediction in the equatorial latitudes during northern winter (Cheang, 1987). Several investigators have noticed that the cold surge is often followed by increased tropical convection over the maritime

continent (*e.g.*, Ramage, 1975; Murakami, 1979a, b; Chang and Lau, 1980, 1982; Lau and Chang, 1987; Chen *et al.*, 1988). There are also suggestions that the cold surge over the South China Sea may have cross-equatorial influences in the Southern Hemisphere (Lim and Chang, 1981; McBride, 1987).

Since the tropical convection over the maritime continent is one of the most energetic heat sources of the atmosphere and may play a substantial role in the atmospheric circulation during the northern winter (Lau and Chang, 1987), the possible relationship between the northeasterly cold surges and the tropical convection deserves a systematic investigation. However, previous studies of this relationship were all based on either case studies or a very limited number of the cases, mostly within one season. For example, Ramage (1975) and Chang and Lau (1980) observed an increase of tropical rainfall or upper-level divergence over the maritime continent for a few individual cases. Murakami (1979a, b) performed statistical studies over the entire Asian winter monsoon region for the 1970–71 season, and showed that the synoptic-scale surges over the South China Sea coincide with rising motion throughout the troposphere. Lau and Chang (1987) counted that seven out of the 11 cold surges during the 1978–1979 Winter MONEX show enhanced tropical convection downstream from the surge 3–5 days later. Chang and Lau (1982) were only able to identify eight strong surge cases over four winters in their composite study in order to show clearly that the time series of the area-mean 200 mb divergence over the maritime continent increases following the surge. Furthermore, in all of these studies the surge event is defined by a surface parameter at a fixed local point (usually the area-averaged wind in a pre-selected small area in the northern South China Sea), and the upper-level divergence that is used to represent the tropical convection is often artificially selected to be the value averaged over the location of the seasonal-mean divergence center. This kind of approach does not give the complete spatial structure of the cold surges at the surface or the related tropical divergence at the upper levels. It risks the possibility that the pre-selected local points are not representative of the structure and behavior of the motion system.

The main reason that only very small samples were used in these case studies is due to upper-air data availability problems over the tropics. The poor coverage of tropical upper air data makes divergence estimates especially difficult. The small number of surge cases each season means that an extensive statistical study needs to analyze the divergence data of many years. Operationally produced objective analyses, while providing an extensive data base, also have problems in tropical divergence, especially if the study is to span over

multi-years. Most of these analyses are produced by four-dimensional data assimilation in numerical weather prediction (NWP) systems. The NWP divergence field can be overwhelmed by model forecast divergence, as a result the divergence is often significantly underestimated (Lambert, 1989; Uden, 1989) and it is sensitive to the model cumulus parameterization. Since the operational NWP systems are changed frequently, its analyses may have different characteristics from one year to another. This is especially true in the tropical region, with the most serious inhomogeneous problem occurs in the tropical divergence field (Trenberth and Olson, 1988).

In this study, we will conduct a statistical study of 103 surge cases during 14 winter seasons (1974/75–1987/88) to examine the possible relationship between the surface northeasterly surges over the South China Sea and the 200 mb equatorial divergence. The data used are the U.S. Navy's operational numerical variation analysis over the tropical global band (40°S–60°N). This analysis uses 6-hour persistence at the first guess, therefore its divergence field is completely free from model forecast influences. Any synoptic-scale variation is due to actual observation data. It is also a relatively long-term homogeneous data set as the analysis scheme remained unchanged for the entire 15 years.

It may be noted that an alternative of the divergence field is the satellite Outgoing Longwave Radiation (OLR) data. However, while large-scale OLR and divergence over the tropics are positively correlated, significant differences exist between the two. For example, Weickmann and Khalsa (1990) showed that for the 30–60 day period band the equatorial 150 mb velocity potential and the OLR patterns propagate at a speed that differs by a factor of 2 to 3. Since the time scale of cold surges is much shorter, the difference might be even larger. We plan to use OLR in a subsequent study of the cold surges.

We will first compute the empirical orthogonal functions (EOF) to represent the surface wind fields, and then use canonical correlation analysis (CCA) between two different times of a surge event to identify the surface structure of a composite “cold surge mode” representative of these times. Even though the starting data of each surge case needs to be defined by a criterion that is based on the surface wind fluctuations over a pre-selected local area in the northern South China Sea, the EOF-CCA computations allow the two dimensional structure of the composite cold surge mode that is coherent in space and time to be revealed. The time variations of this mode, which is a projection of the surface wind field over the entire South China Sea, can then be studied. Lag correlations and regressions are carried out between this cold surge mode and a velocity potential field that represents the smoothed divergence fields at 200 mb and the surface. The results give

the time variation and structure of the portion of the upper level divergence that is correlated with the cold surge mode.

In Section 2 the data and the analysis methods will be briefly described. In Section 3 the results of the EOF and CCA of the surface meridional winds, which lead to the objective determination of the cold surge mode, will be presented. In Section 4 the lag-correlation and regression between the cold surge mode and three fields: the surface meridional velocity, the velocity potential at 200 mb and at surface, will be discussed. It will be shown that the structure of the part of the tropical upper level divergence variations that may be attributed to the cold surge mode is different from that of the seasonal mean tropical divergence center in the western Pacific. A summary and the conclusions are given in Section 5.

2. Data and analysis methods

a. Tropical global band analysis data

The wind data used are the operational Global Band Analyses (GBA) of the Fleet Numerical Oceanographic Center, Monterey, California, during 1974–1988. These data were produced four times daily by objective procedures on a Mercator grid which extends from 60°N to 40°S. The use of the Mercator secant projection resulted in a change in the distance between grid points from 140 km at 60°N to a maximum value of 280 km at the equator. The objective analysis scheme was designed to take advantage of all the reports in the operational data base: surface synoptic, aircraft, pilot balloons, rawinsonde and satellite data.

The analysis was performed every six hours for the surface, 700, 400, 250 and 200 mb levels, using a successive corrections method, with the six-hour persistence used as the first guess. Both wind and temperature were analyzed and then adjusted by a set of numerical variational analysis equations which incorporated the dynamical constraints of the momentum equations with friction included in the surface layer (Lewis and Grayson, 1972). Temperature and wind fields were adjusted subject to mutual constraints on the fields. However, the 200 mb wind data used here served only as a boundary condition for the analysis and were not subject to the adjustment.

The use of persistence as the first guess, rather than using short-term NWP predictions, may cause a concern for data-sparse tropical area. However, comparison between the monthly-mean 200 mb divergence from GBA and the OLR data (Boyle and Chang, 1984, and Lau and Boyle, 1987) shows that the agreement is at least as good as that between the four-dimensional assimilated NWP analysis and OLR. In addition, daily GBA divergence data in the tropical Pacific have been used successfully in study-

ing synoptic time scale variations (*e.g.*, Chang and Lum, 1985; Lau and Chang, 1987). Furthermore, the Australian Bureau of Meteorology also uses persistence as the first guess in its tropical regional analysis over the western Pacific since September 1983. Their domain covers the area of interest in this study. By comparing with the ECMWF gridded data, Hendon (1988) concluded that the large-scale tropical circulation is depicted quite well in the NWP-free Australian analysis.

In this study only the surface and 200 mb winds are used. At surface the GBA is a particularly data-rich set compared to other operational surface analyses. It incorporates all the commercial and Navy ship data in addition to the land-based data, and the analysis is drawn closely to the observation as there is no model constraint. The 200 mb is a level enhanced by frequent AIREP (commercial aircraft) data over the tropical western Pacific. Since 1979 it also benefited from the Japanese Geostationary Meteorology Satellite-derived cloud top winds. The surface northerly winds will be the basic parameter to define the cold surge events, and the 200 mb divergence will be considered as the indicator of the outflow of deep tropical convection.

Two domains are selected for this study, with the smaller domain of the South China Sea and its vicinity imbedded in the larger domain of the East Asia, western Pacific, and eastern Indian Ocean. The smaller domain covers 10°S–25°N, 90°E–130°E. The larger domain covers 20°S–50°N, 70°E–150°E (Fig. 1). The basic structure of the cold surge is determined from the surface meridional winds in the small domain. The effect of the surge is computed for the large domain. The time periods for this study are the 14 winters of the entire data period, with each winter defined as a five-month period, from 1 November to 31 March of the following year.

b. Computation of velocity potential

To represent the large-scale divergent motion, the velocity potential (χ) was computed from the following equation:

$$\nabla^2 \chi = -D, \quad (1)$$

where the divergence is

$$D = \partial u / \partial x + \partial v / \partial y,$$

and was computed using centered difference on the GBA Mercator grid.

Equation (1) was solved using the boundary condition that $\chi=0$ at the north and south boundaries, which are at 60°N and 40°S, respectively. Extensive comparisons between χ and divergence fields confirms that while the former is the inverse Laplacian of the latter, it represents very well the smoothed pattern of divergence, both for time means and anomalies (Chang *et al.*, 1991).

Fig. 1. The domains of study. The small (South China sea) domain is indicated by a rectangle inside the large domain. The area for averaging the northerly surface wind, denoted by v_N , is used for selection of cold surge period. (See text for details.)

Since the values of χ at maximum and minimum centers will be used to represent divergence and convergence, there is a possibility that the time variations of χ outside our domain of interest may give false signals of divergence variations inside the domain. This possibility is minimized by subtracting the area-averaged χ field over the (large) domain of interest from the χ data at each time point. The gradient of χ , which represents the strength of the divergent wind, is preserved.

c. Empirical orthogonal function and canonical correlation analysis

We will use the empirical orthogonal function (EOF) analysis to decompose and recombine the surface wind fields, so that the time varying values at 255 grid point in the small (South China Sea and vicinity) domain may be represented by a truncated EOF composite for further analysis. In order to find correlated variations of two fields, the canonical correlation analysis (CCA) [Glahn, 1968] will be used. (In general, EOF analysis can be applied to only one variable field. Two or more different fields have been included in one field for an EOF analysis, and was referred to as “extended EOF”, or EEOF [e.g. Weare and Nasstrom, 1982]. However, partial structures of this EEOF are generally not uncorrelated with their counterparts in other EEOF’s, nor with other partial structures. There is also no guarantee that significant correlations exist between the partial structures of two fields associated with same EEOF. Therefore the relationship between two vari-

able fields cannot be directly assessed through the EEOF approach.)

The CCA method is basically a search for optimal correlations between two variable fields by linearly combining the elements of each field. These combinations are called canonical components. The method also gives a pair of patterns (one for each field) that solely correspond to each optimized correlation, and their respective variance contributions. Conventional CCA can be used for investigating the correlation between two fields, but often it can only reveal maximum correlations without regard to the variance significance. Modified CCA (e.g., Chen, 1989) that combines EOF analysis and conventional CCA will be used for investigating correlations between two different fields in this study. By computing the EOF first, the data are truncated to retain only EOF’s with significant variance contributions. Small variance modes with very high correlations are therefore filtered out.

The EOF computations are based on the complete 14-winter data set, so each EOF mode is an anomaly from the 14-winter mean (average over 2118 days, or 4236 twice-daily data points). In order to be consistent with this definition, all the CCA computations are done with respect to a reference of the same 14-winter mean. So the CCA modes, even though computed from data during only the 103 surge cases (1403 twice-daily data points), are departures from the 14-winter mean rather than from the mean of the 103 surge periods. This also means that, unless specifically stated otherwise, the correlation coefficient computed between two fields includes both the correlation due to inter-case variations and that due to the variations of the anomalies from the 14-winter mean.

3. Surface meridional velocity

a. Selection of cold surge cases

The first step of the study is to select cold surge cases during the 14 winters. Here we follow the criteria of Chang and Lau (1982), who used the area-averaged surface northerly wind over the area of 18°N–20°N, 110°E–120°E, which is just off the southern China coast, as an index to determine the timing of the cold surge and break. This area is marked in Fig. 1. A cold surge case is defined when the area-averaged northerly surface wind over this area, v_N , satisfies the following two conditions: 1) an acceleration of >5 m/s over 12–24 h, and 2) a period of three or more days over which the increased northerly wind speed attained in 1) is ≥ 7 m/s.

Out of the 14 winters, a total of 103 cases of cold surges are selected. beginning from the onset of the surge, which is defined at the time the acceleration stipulated in criterion 1) starts ($\tau=0$), the duration of each case lasts from 3.5 days ($\tau=84$ h) to 8 days ($\tau=192$ h) or longer. Data are included in the anal-

Fig. 2. A sequence of the 12-EOF truncated composite of surface meridional velocity, v_{sfc} , over the small (South China Sea) domain. The time (h) after the surge onset, τ , is indicated in the upper left corner of each map. The contour interval is 1 m/s. Solid lines indicate negative values (northerly winds) and dashed lines indicate positive values (southerly winds).

ysis only if they are within the duration of a cold surge case, up to 5.5 days ($\tau=132$ h) or longer after the onset of the surge. At 5.5 days the number of cases is reduced to 57. Including the data up to the same duration of 5.5 days for all 103 cases would be problematic, because many of the shorter-duration cases are followed closely or even immediately by another cold surge. [Hereafter the notation τxx is used to denote $\tau=xx$ h, *e.g.*, $\tau 00$ means $\tau=0$ h, $\tau 48$ means $\tau=48$ h, and $\tau 132$ means $\tau=132$ h, *etc.*]

b. Determination of the basic structure of the cold surge mode

An objective of this study is to determine the structure of the surface wind field that may be associated with the cold surges in a spatial- and temporal-coherent sense. This will be done by correlating the surface meridional velocity (v_{sfc}) fields at different stages (τ 's) of a surge. Taking into consideration the methodology of the cold surge criteria of Chang and Lau (1982) as defined above, we decided to use the $\tau=0$ and $\tau=48$ h as the base stages for this correlation. At $\tau=0$ the surface northeasterly winds in the South China Sea are actually weaker than the winter mean and do not resemble the intense northeasterly wind pattern during cold

surge events. At $\tau=48$ h the significant acceleration has already occurred and the cold surge pattern of strong northeasterlies streaking down the South China Sea is well established. A correlation of the time variations of these two rather dissimilar patterns has more significance than that between two similar-pattern, post-onset stages.

The determination of the cold surge mode is done by CCA. In order to be computationally efficient, the entire 14-winter data are first subject to an EOF analysis over the small (South China Sea) domain. Only the first 12 modes of the EOF, which represent 69% of the total variance, are used to reconstruct the surface wind fields. Figure 2 shows the composite of each stage, at 12-h intervals, of the cold surge surface wind field truncated by the 12-EOF mode. These maps resemble the major features of the composites of the total anomalies (departure from 14-winter mean) at their respective stages (not shown). As mentioned in Section 2c, this truncation ensures that those principal components with high correlation but small variance will not contribute to the CCA modes. However, due to the significant smoothing effect of the truncation, the acceleration of northerly wind in the northern South China Sea as indicated in Fig. 2 is about 3 m/s from $\tau 00$ to $\tau 24$,

Table 1. Canonical correlation modes

Mode number	Correlation coefficient	%Variance of τ_{00} Σ (12 EOF)	%Variance of τ_{48} Σ (12 EOF)
1	0.949	14.645	11.071
2	0.869	12.972	18.717
3	0.788	18.440	7.132
4	0.706	3.162	6.432
5	0.645	6.282	14.721
6	0.588	3.836	3.164
7	0.422	10.164	2.913
8	0.358	4.688	3.447
9	0.327	9.214	5.691
10	0.188	3.701	9.951
11	0.130	9.319	11.371
12	0.109	3.579	5.403

Fig. 3. The composite of 8 respective CCA modes derived from τ_{00} – τ_{48} correlation, for τ_{00} (left panel) and τ_{48} (right panel) over the small (South China Sea) domain. The contour interval is 1 m/s. Solid lines indicate negative (northerly) winds. The dotted line in the left panel is -0.5 m/s.

less than the 5 m/s criterion for surge case selection.

The 12 EOF modes for τ_{00} and τ_{48} give rise to 12 pairs of CCA modes according to descending correlation coefficients. Table 1 lists the correlation coefficients and the respective variances of these CCA modes. The τ_{48} CCA modes are then used to define the “cold surge” mode as follows. The composite τ_{48} v_{sfc} anomalies are first projected onto each of the τ_{48} CCA modes. The 8 leading CCA modes are then recombined to form the *basic cold surge mode*, which shall be denoted by the notation V_{48} . (Because the projection, compositing and recombination are all linear operations, this procedure gives the same results as if individual-case τ_{48} v_{sfc} anomalies are projected onto the CCA modes first, then composited and recombined.) Figure 3 shows V_{48} and its counterpart at τ_{00} (which is constructed from the 8 leading CCA modes of the composite τ_{00} v_{sfc} anomaly).

The selection of the number of leading CCA modes for the recombination was based on the ex-

amination of adding successively the trailing CCA modes to the summation of the previous modes. If a filtering criterion of canonical correlation coefficient ≥ 0.5 is used, the summation will be over the first 6 CCA modes. This actually gives as good a representation of the composite τ_{48} anomaly pattern as the summation of the first 8 CCA modes. However, the time sequence of the amplitude of the summation of 8 CCA modes resemble most closely that of the cold surge selection index, v_N . Therefore the first 8 modes are included to form V_{48} , which means that the filtering criterion is set at canonical correlation coefficient ≥ 0.358 , and that 67.6 % of the total variance of the 12 EOF sum is represented. (Because the CCA is computed from the 103 surge cases, which is a subset of the entire data, the percentage variance represented by the V_{48} mode does not equal exactly to the product of the 12-EOF variance and the 8-CCA variance. Nevertheless this product gives an estimate of the fraction of the total variance. Thus approximately half of the total v_{sfc} variance is represented by V_{48} .) It turns out that some of the leading CCA modes do not contribute significantly to V_{48} . For example, the first CCA mode has very little contribution even though Table 1 shows that it has 11 % of the variance. This is because this mode has very little projection onto the composite τ_{48} anomaly. On the other hand, the third CCA mode appears to dominate the V_{48} pattern. Nevertheless, we will not separate our discussion to address individual modes, since the orthogonality in space are somewhat arbitrary and do not imply necessarily orthogonality in physics (different physical mechanisms). Therefore, to ensure that the analysis is physically meaningful, only the combined mode is considered.

c. *Temporal sequence of the surface meridional velocity pattern associated with the cold surge mode*
Once the basic cold surge mode (V_{48}) is defined,

Fig. 4. Time sequence of the fraction of v_{sfc} variance (over the large domain) that is correlated with the V_{48} mode. The contour interval is 10 %. Positive (dashed) and negative (solid) values are defined by the sign of the lag correlation coefficient.

the relationship of any field with this mode may be found by computing the lag correlation between the amplitude variations of V_{48} and the corresponding values of each spatial point of the other field. The correlation coefficients so determined may be used in a number of ways to illustrate the pattern of motion structure changes that may be considered as being related to the cold surge mode.

Figure 4 shows a result of the time-lag correlation between V_{48} and the v_{sfc} winds at different τ 's over the large (western Pacific-East Asia-eastern Indian Ocean) domain. Plotted isoplethes in each panel are values of the square of the correlation coefficient, with the sign of the correlation coefficient attached. This figure gives the time evolution of the fraction of the local v_{sfc} variance that is correlated with the cold surge mode. At $\tau 00$ the only indication of an organized pattern is a dipole in the northwest of the large domain, with a positive (northerly) center near 47°N , 88°E and a negative (southerly) center near 42°N , 110°E . At both centers the fractional variance is a modest 30 %. These are a manifestation of the stronger anticyclone over northern China at the surge onset. At $\tau 12$ the northerly area begins to develop into a northerly surge pattern and moves southward, with the fractional variance increasing to 40 % at the center which is now south of 30°N .

From this time on, the northerly pattern intensifies rapidly and continues to progress southward, so that after $\tau 48$ the entire region of the South China Sea is under its influence. The pattern also develops a northeast-southwest orientation and covers the Indo-China and the Malay peninsulas. The maximum of $>70\%$ maintains a position in the northern South China Sea near 18°N , 114°E , which is close to the v_N location, and its axis extends southwestward to reach the equator near Singapore. The southerly area, keeping its smaller size and the 20–30 % maximum fractional variance, accompanies the southward progression of the northerly center and settles in a position in the northwest corner of the small domain over Burma. The smaller fractional variance for the positive area indicates that the acceleration effect of the anticyclogenesis during cold surges is less for the southerly winds west of the anticyclone center than the northerly winds to the east.

To give a perspective of the development of the “typical” v_{sfc} anomalies (departure from the 14-winter mean) that is related to the cold surge mode in terms of absolute magnitudes, we plot the time sequence of the standard deviation of the v_{sfc} multiplied by its lag correlation coefficient with V_{48} in Fig. 5. The standard deviation is the square root of the total variance, so the evolution of the anomaly

Fig. 5. Time sequence of the composite anomalous v_{sfc} pattern (over the large domain) that is correlated with the V_{48} mode. The contour interval is 1 m/s. Positive (dashed) and negative (solid) values are defined by the sign of the lag correlation coefficient.

patterns is very similar to that of the relative variance fractions shown in Fig. 4. The maximum northerly (negative) anomalous v_{sfc} in the northern South China Sea is near 5 m/s, while the maximum southerly anomalous v_{sfc} speed over Burma is around 2 m/s. These values and positions are reached at $\tau 72-84$, although the northerly anomaly center appear to have further southward progress with time.

4. Velocity potential

a. The 200 mb χ : winter-mean and correlation with the cold surge mode

As discussed in Section 2b, the velocity potential at 200 mb (χ_{200}), with area-mean removed, is used to represent the large-scale divergence in the tropical upper troposphere. Figure 6 shows the 14-winter mean of this quantity over the large domain. The field is smooth and of planetary scale characteristics in the tropics, with an equatorial positive (divergence) zone along 5°S. Its center is located immediately to the east of New Guinea (at 155°E, see Chang *et al.*, 1991), which is just outside of the eastern boundary of the large domain. A negative (convergence) center is located over northern China. The mainly east-west oriented isoplethes give overwhelmingly “Hadley”-type divergent winds emanat-

ing from the equatorial divergence zone toward the midlatitude convergence center. There is also a convergence center northwest of India that is also outside of the large domain.

Figure 7 shows the correlation coefficient between the χ_{200} field and the time series of a V_{48} mode for the 14 winters, without any lag. The latter is constructed from the projection of the V_{48} cold-surge mode onto the 4236 twice-daily v_{sfc} fields in the 14 winters without regard to any τ or cold surge cases. The correlation coefficients are low, which is not surprising, because the χ_{200} data are masked by noises due to data problems and other processes. In spite of the low values, Fig. 7 indicates a smoothed pattern with three centers whose values are ≤ 0.21 . The first two are a positive center (0.15) in the north-west Pacific near 19°N, 137°E and a negative center (0.19) over northern China near 35°N, 118°E. Relatively strong gradients are saddled between this pair of centers, which delineate the upper-level poleward branch of the secondary circulation that is associated with the entrance region of the East Asian jet near Japan during winter.

It is well known that baroclinic processes of the East Asian jet play an important role in the development of the cold surges. The extratropical cyclo- and anticyclo-geneses associated with a strengthen-

Fig. 6. The 14-winter mean velocity potential at 200 mb (with area mean removed) over the large domain. The contour interval is $5 \times 10^5 \text{ m}^2/\text{s}$.

Fig. 7. The correlation coefficient between velocity potential at 200 mb and the V_{48} mode. The contour interval is 0.025.

ing of the jet in the subtropics force a strong pressure gradient that leads to the initiation of strong winds in the upstream region of the South China Sea (Boyle and Chen, 1987). Thus the first two centers are a modest manifestation of a correlation between the jet activity and the cold surge events.

The third correlation center (0.21) is situated in the equatorial region of the South China Sea. It is more remote from the core of the East Asian jet streak. There are some studies that proposed a subsequent relationship whereby a cold surge event lead to an enhanced local Hadley circulation that contributes to the further strengthening of the East Asian jet (*e.g.*, Lau and Chang, 1987), although the possibility that the jet continues its own strengthening process independent of the increased tropical convection cannot be totally ruled out yet. In any case, it is sufficiently judicious to say that, unlike the first two centers in Fig. 7 which are related to the cause of cold surges, the center in the equatorial South China Sea is much more likely a result of the surge events.

Compared to Fig. 6, it is noteworthy that although the equatorial correlation center lies near the axis of the divergence zone, it is situated far away from the 14-winter mean divergence center in the equatorial western Pacific.

b. Temporal sequence of the 200 mb χ associated with the cold surge mode

Figure 8 shows the time-lag correlation coefficient squared and with sign of the correlation coefficient attached, between V_{48} and χ_{200} at different τ 's over the large domain. Therefore it gives the time evolution of the fraction of the local χ_{200} variance that is

correlated to the cold surge mode. The contour interval here is 5 %, half that of Fig. 4 for the v sfc chart. It is obvious that the variance related to the cold surge mode is generally much less in χ_{200} . There are two clearly defined patterns. The first is a pair of divergence-convergence couplet in the northeast region of the large domain. It begins to emerge at τ_{24} and the two center values increase to 15 % of the total local variance at τ_{48-60} before gradually diminishing to $<5\%$ after τ_{96} . This is a reflection of the correlation between cold surge and the increased secondary circulation in the entrance region of the strengthening East Asian jet, as indicated in Fig. 7.

The other is a positive (divergence) area in the equatorial region of the South China Sea. It first appears at τ_{60} with a small 5 % area near Singapore. The area expands continuously with time and covers the entire South China Sea at τ_{132} (5.5 days) with the maximum fractional variance reaching $>25\%$. This is a clear signal of the tropical upper level divergence development following the cold surge. We have continued the correlation to τ_{156} (7.5 days), for which the number of cold surge cases falls to 33, and observed that the value increases continuously to near 50 %.

The development of the "typical" χ_{200} anomalies (departure from the 14-winter mean) that is related to the cold surge mode in terms of absolute magnitudes is given in Fig. 9. This figure shows the time sequence of the standard deviation of the χ_{200} multiplied by its lag correlation coefficient with V_{48} . Again the evolution of the anomaly patterns is very similar to that of the relative variance fractions shown in Fig. 8. The pair of anomalies associated with the East Asian jet is now more obvious in most of the panels. The center values are around

Fig. 8. Same as Fig. 4 except for the 200 mb anomalous (from the respective 14-winter mean) velocity potential, and the contour interval is 5 %.

$10^6 \text{ m}^2/\text{s}$. The equatorial South China Sea anomalous divergence center begin to appear as a separate center at $\tau 36$. Its value attains $10^6 \text{ m}^2/\text{s}$ at $\tau 84$, and continues to increase to nearly twice of this value at $\tau 132$.

The positive (anomalous divergence) area in the tropical region of Fig. 9 resembles a “V” shape with extensions from the equatorial South China Sea northeastward and northwestward. The northeastward extension is a connection with the anomalous divergence southeast of the East Asian jet. The northwest extension indicates a tendency for positive anomaly to occur over the Bay of Bengal, which is most evident during $\tau 48$ – 60 when a separate center is identified. This is an area that is not previously reported in the case studies.

To further examine these correlated patterns, we computed the lag correlation coefficient between χ_{200} and V_{48} without using the 14-winter mean as a reference. The resultant χ_{200} patterns that is related to the cold surge mode is shown in Fig. 10. The difference between this figure and Fig. 9 is that in Fig. 10 the patterns are entirely due to the variations between different cold surge cases, while in Fig. 9 they are due to a combination of the inter-case variations and the anomaly variations. In general the inter-case variations give rise to lower correlation coefficients because the center of reference is

now zero rather than on one side (because we consider only surge cases when the northeasterly v_{sfc} is stronger for larger τ). Thus we would expect that the patterns in Fig. 10 have smaller amplitudes. In addition, there are significant differences in the patterns themselves. The tropical divergence center in the equatorial South China Sea shows up earlier in the sequence. From $\tau 00$ to $\tau 60$ it is most noticeable, but afterwards the positive center is shifted northwest to the Bay of Bengal. (This Bay of Bengal center can be detected beginning from $\tau 48$ when both tropical divergence centers coexist.)

The difference between the patterns in Figs. 9–10 suggests that during earlier stages ($\tau 12$ to $\tau 72$) the equatorial South China Sea divergence is correlated with the intensity of the cold surges. Afterwards Fig. 9 suggests that it is highly correlated with the anomalous condition (occurrences of cold surges), but not sensitive to the relative intensity of each surge case. The Bay of Bengal divergence center, on the other hand, is highly correlated with the intensity of the cold surges, but is less correlated with the anomalous condition. Namely, the probability is high that the occurrence of cold surges induces strong upper-level divergence over the equatorial South China Sea between the Malay Peninsula, Sumatra and Borneo, but the magnitude depends on the surge intensity only during the first three days.

Fig. 9. same as Fig. 5 except for the 200 mb anomalous velocity potential, and the contour interval is $2 \times 10^5 \text{ m}^2/\text{s}$.

The probability for increased upper-level divergence to develop over the Bay of Bengal during cold surges is somewhat lower, but if it develops its magnitude is more sensitive to the surge intensity.

Figure 11 shows the composite total χ_{200} fields at four different stages: $\tau 00$, $\tau 48$, $\tau 96$, $\tau 132$. The respective fractional variance due to the cold surge mode (given in Fig. 8) is also plotted. It is clear that the composite total χ_{200} changes very little from one stage to another in the cold surge, with the exception that at $\tau 132$ a secondary tropical divergence center develops over Borneo. This location is close to the equatorial anomalous divergence center indicated by the overlapped fractional variance isoplethes. The figure shows that the cold-surge related variations do not appear to have any effect on the western Pacific mean center located to the east of the large domain. This is in contrast to the inference drawn by Lau *et al.* (1983) based on relatively weak cold surge cases during the Winter MONEX.

c. Velocity potential at the surface

The surface wind field is also used to compute divergence and velocity potential (χ_{sfc}) to supplement the analysis of the χ_{200} data. Figure 12 shows the typical χ_{sfc} anomaly sequence that is related to the cold surge mode, again based on the lag correlation with V_{48} . The fractional variance (not

shown) is much larger at the surface, with center maxima reaching 40 % at $\tau 48$ and above 50 % at $\tau 108$. In general, the sign of the χ_{sfc} correlation is opposite of that of the χ_{200} shown in Fig. 9, so the upper level anomalous divergence (convergence) are supported by surface anomalous convergence (divergence). However, the pattern of the systematic intensification of the equatorial convergence is not exactly the mirror image of the divergence at 200 mb. There are two centers, one over northwestern Borneo and the other in the eastern Indian Ocean just south of the Bay of Bengal. Although the χ values of the two centers are comparable, the significantly stronger gradient north of the Borneo center indicates that this is a much more significant convergence center. Due to its proximity to the 200 mb anomalous divergence center in the same vicinity, the two centers are highly coupled to give increasingly rising motions during cold surges. The surface center has a smaller spatial scale, which may at least partially due to the better data density and quality, and also the effect of the complex land-sea distribution. An active convection center over the northwestern coast of Borneo has been noted in several previous studies, particularly for its diurnal cycles (*e.g.*, Johnson and Houze, 1987). It thus appears that the apparently rather local Borneo convection system plays an important role in the large scale

Fig. 10. Same as Fig. 9 except for the 200 mb velocity potential without regard to the 14-winter mean, and the contour interval is $2 \times 10^5 \text{ m}^2/\text{s}$.

Fig. 11. Composite of the total 200 mb velocity potential at four stages: τ_{00} , τ_{48} , τ_{96} and τ_{132} . The contour interval is $5 \times 10^5 \text{ m}^2/\text{s}$. The fractional variance correlated to the V_{48} mode (Fig. 8) is superimposed.

tropical divergence variations following cold surges. The surface convergence center in the equatorial Indian Ocean, which is located further south of the 200 mb divergence center over the Bay of Bengal,

overlaps with a center reported in the interannual variation study by Chang *et al.* (1991). However, the significance in this surge-related synoptic scale variation is not clear.

5. Summary and conclusions

In this study we used a 14-winter data set of the U.S. Navy's operational tropical global band analysis between 1974/75 and 1987/88 to study the possible relationship between the development of cold surges in the South China Sea and the variation of tropical divergence from the western Pacific to eastern Indian Ocean. The data are independent of numerical prediction model influences, therefore its divergence field depends on observations only. The surface meridional velocity is used to represent the cold surges. Based on a criterion which depends on the acceleration and sustaining of northerly surface winds in the northern South China Sea, 103 cold surge cases of 3–8 day durations during the 14 winters are identified. The data, with a 12-component empirical orthogonal function truncation, are subjected to canonical correlation and lag correlation analysis. The empirical orthogonal functions are computed with respect to the 14-winter mean.

The canonical correlation between the surface winds during the onset of the surge and 48 h after the onset is used to construct a basic cold

Fig. 12. Same as Fig. 9 except for the surface anomalous velocity potential.

surge mode. This is done by combining the first eight of the 12 canonical components at the 48 h stage. Again the 14-winter mean is used as a reference upon which the canonical components are computed. This mode represents the spatial and time coherent part (and contains approximately half) of the total variance of the freshening of northeasterlies during cold surge events. The time variation of this mode is then lag-correlated with three fields at different stages of the cold surge: the surface meridional velocity, the velocity potential at 200 mb, and the velocity potential at the surface. Special care is taken to remove the area means of the velocity potential at each individual time, so the central values approximate those of smoothed divergence field with minimum influences from boundary condition variations.

The lag correlations give the time evolutions of the three fields after the cold surge develops. The main results are:

1) For a typical cold surge, the anomalous surface northerlies that can be attributed to the cold surge mode are 5 m/s centered in the northern South China Sea, and the anomalous surface southerlies are around 2 m/s over Burma. These correlated anomalies develop within 72 h of the surge onset (the beginning of the freshening of the northeasterlies) and represent over 70 % and 30 %, respectively, of the local variance of the surface meridional winds.

2) The center of the 200 mb tropical divergence anomalies that is correlated with the cold surge mode is located in the equatorial South China Sea near 105°E between the Malay Peninsula, Sumatra and Borneo. This location is considerably to the west of the long-term winter mean divergence center near 5°S, 155°E. Five days after the surge onset, the anomaly accounts for about 25 % of the local variance contained in the divergence data, and it continues to increase to 40–50 % if the surge lasts 7 or 8 days.

3) There is a secondary 200 mb anomalous divergence center over the Bay of Bengal that is correlated with the cold surge mode.

4) While there is a high probability that strong 200 mb divergence develops over the equatorial South China Sea as a result of the cold surge, the magnitude of the increased divergence depends on the surge intensity only during the first three days. The probability for increased 200 mb divergence to develop over the Bay of Bengal following a cold surge is somewhat lower, but if it develops its magnitude is much more sensitive (positively correlated) to the surge intensity, throughout the surge period.

5) In general, the 200 mb anomalous divergence is supported by surface anomalous convergence during a surge event. However, the intensification of the equatorial surface convergence pattern has a smaller scale with two centers, the dominate one over north-

western Borneo and the other in the eastern Indian Ocean south of the Bay of Bengal. Both centers contain up to >50 % of the local variance. The Borneo convergence center is in the proximity of the 200 mb divergence center and is located in the vicinity of the prominent land-sea diurnal convection system studied by Johnson and Houze (1987). It probably reflects the importance of the Borneo convection system in the cold surge-modulated large-scale tropical divergence variations.

In a study mainly concerned with the Winter MONEX, Lau *et al.* (1983) reported that the time-mean 200 mb tropical divergence has a more west center position over the maritime continent during strong winter-monsoon seasons and a more east center position over the western-central Pacific during weak seasons. They postulated that the surges impact the divergence center in both cases. The 14-winter mean in the present study has a 200 mb equatorial divergence center in the western Pacific that corresponds to the weak winter-monsoon season position in Lau *et al.* (1983). However, our results do not indicate that the cold surge mode has any effect on this mean upper-level tropical divergence center. Since their result was based on the relatively weak surge cases during the Winter MONEX, we plan to stratify the data into strong and weak surges in future studies. Also our results indicate different behavior between the first few days after the surge onset and the later periods. It may be worthwhile to stratify the data according to the duration of each surge case to see whether the extended surges have fundamentally different effects even in the early stages. Furthermore, each season may be separated into early and late winters to study the possible effects due to the different planetary scale circulations between November–December and February–March.

There are other possible approaches of using the CCA. Instead of single-point lag correlations, the CCA method itself may be used for direct comparison between different fields. With proper data stratifications, such correlations may allow the use of initial ($\tau=0$) field to estimate the duration and structure evolution of a cold surge. The degree of success of such estimates will shed light on the conditions and degrees the tropical motion can be forced by midlatitude systems. Moreover, it also will be interesting to include the OLR data and the rotational motions at various levels in future studies.

Acknowledgements

This work was supported in part by the National Science Foundation under Grant ATM-9106495, and by the Naval Postgraduate School. We wish to thank Professor Robert Haney for reading the manuscript, and the Fleet Numerical Oceanography Center for providing the tropical global band data.

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南シナ海上の冬モンスーン寒気吹出しと赤道域の大規模発散場に関する統計的研究

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熱帯域のグローバルデータセットを14回の冬（1974/75の冬～1987/88の冬、各11月～3月）について用いて、南シナ海上の寒気吹き出し（cold surge）の出現と、西太平洋～インド洋東部の熱帯域での200 mbと地上の発散場の変動との関係について調べた。データは経験直交関数で展開した12個のモードまでで切断し合成した。各吹き出しの開始（onset）と48時間後の南シナ海上での地上南北風成分間の正準相関分析（CCA）を行なって寒気吹き出しの基本的なモードを決定した。地上の南北風成分の総分散の約半分の寄与をもつ計8つのCCAモードから合成されたこのモードは、寒気吹き出しイベントの時空間でコヒーレントな変動を表現する。このモードと地上の南北風成分、200 mbや地上の速度ポテンシャルとの相関をそれぞれ計算し、吹き出しの影響を議論する。

吹き出し開始から72時間以内に地上の北風成分の偏差は南シナ海北部を中心に 5 ms^{-1} に達し、ビルマ上空で南風偏差が 2 ms^{-1} になる。これらは、それぞれ、領域内の南北風の全分散の70%、30%を表現する。この寒気吹き出しに関連した熱帯域での200 mb面での発散は2つの中心域を持つ。第1の中心はマライ半島、スマトラ島、ボルネオ島の間の南シナ海熱帯域に位置し、それは 155°E 付近の熱帯西太平洋域の長期間の冬の平均場でみられる発散の中心から西側へ約 50° ずれる。第2の中心はベンガル湾付近にある。いずれの領域付近での発散も、吹き出し開始後に増大し、第1の中心付近では5日後にはローカルな変動の25%以上を表現するようになり、もし7～8日続けば40～50%にまで増大する。

200 mb発散の増大は、吹き出しの強さに正相関の関係を持って起きる。しかし、ベンガル湾では、吹き出しの全期間についてこの傾向が認められるが、南シナ海熱帯域では、最初の3日間についてのみ、みられる。地上では、熱帯域で収束（アノマリーとして）が吹き出しイベントを通じて増大し2つの中心へと発達する。第1の中心は200 mb発散中心（アノマリーとして）付近のボルネオ島北西部にあり、ボルネオの日変化する対流システムの影響を反映した可能性がある。もう1つの中心は、ベンガル湾の南の東部インド洋に位置する。いずれの地域付近でも吹き出しに関連した変動は開始2日後には40%、5日後には50%以上

になる。長期間の冬全体で平均した時の上層の発散中心にあたる西太平洋熱帯域では、個々の寒気吹出しイベントの影響は特に認められなかった。