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PREDICTION OF THE INTERANNUAL VARIATIONS OF TROPICAL CYCLONE MOVEMENT OVER REGIONS OF THE WESTERN NORTH PACIFIC

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ABSTRACT

The interannual variability of tropical cyclone (TC) movement has been found to be rather significant in certain regions of the western North Pacific. Westward and northwestward moving TCs are found to occur mostly at low latitudes and have the largest interannual variations in the region just east of the Philippines and over the northern part of the South China Sea. The area east of the Ryukyu Islands and south of Japan is identified as having the largest interannual variation of northward moving TCs.

Correlations are made between the annual number of occurrences of TCs in these prescribed regions and the principal components of the monthly mean 850- and 500-hPa zonal wind patterns over the western North Pacific (for the months of November of the previous year to April of the current year). Westward-moving cyclones are found to correlate well with the 850-hPa zonal wind patterns in January and March. Using the principal components associated with these patterns, prediction equations are then developed using the total (dependent) sample and the jackknife method (simulating an independent sample). The predictions made with both the dependent and 'independent' samples are found to be very good.

For north-westward moving cyclones, no prediction equation is developed because principal components of the 850- and 500-hPa zonal winds found to be significant can explain less than 30 per cent only of the total variance. However, the February 500-hPa zonal winds correlate well with northward-moving cyclones in the region east of the Ryukyu Islands and south of Japan. Predictions made using the principal components associated with this flow pattern for both the dependent and 'independent' samples give rather good results.

Because all the predictors are between January and March, they can be used operationally to predict the annual number of occurrences of TCs in the predefined regions. As TCs in these regions are likely either to move into the South China Sea or affect Japan, these results should prove useful in the seasonal prediction of TC occurrence in these latter areas.

KEY WORDS Tropical cyclone movement Interannual variability Climate prediction Western North Pacific

1. INTRODUCTION

The movement of a tropical cyclone (TC) is largely related to the environmental flow surrounding the cyclone (Chan and Gray, 1982). Specifically, Chan and Gray (1982) found that the mid-tropospheric flow azimuthally averaged around the TC at 5–7° latitude radius from the TC centre bears a consistent relationship with the TC motion vector. Because this synoptic-scale flow is influenced by planetary-scale circulations that have interannual variations, the movement of TCs can be expected to have similar variations. A knowledge of such variations are important in the seasonal prediction of the occurrence of TCs in a particular region.

In two recent studies, Chan (1990, 1991) found that annual tropical cyclone occurrence over regions of the western North Pacific (WNP) can be predicted by patterns of sea-surface temperature (SST) and the 850- and 500-hPa zonal winds over the entire WNP. These parameters are related to the genesis and

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intensification processes as well as to the 'steering' flow. The present study represents an extension of this previous research by analysing the interannual variations of the direction of TC movement in various regions of the WNP. These variations are correlated with the principal components associated with the monthly mean 850- and 500-hPa zonal wind patterns. Those principal components found to have significant correlations are then used to develop regression equations for predicting the annual number of occurrences of TCs moving in a certain direction in a particular region. Correlations between the direction of TC movement and the SST have also been studied. However, no significant correlation can be identified.

The data and methodology used in this study are described in section 2. Regions with the largest variations in the direction of TC movement are also identified. Correlations between these variations in each of these regions and the principal components of the 850- and 500-hPa zonal winds are given in sections 3 and 4, respectively. The prediction equations obtained from these correlations and their verifications are also presented. The results are then summarized in section 5.

2. DATA AND METHODOLOGY

2.1. Tropical cyclone data

Tropical cyclones over the WNP between 1947 and 1988 form the basic data set for this study. Best tracks of these cyclones are obtained from the Royal Observatory, Hong Kong. These tracks for years prior to 1984 were analysed only in the region west of 160°E. Therefore, this study is limited only to cyclones west of this longitude. This limitation, however, should not restrict the usefulness of the study as most of the TCs over the WNP form, and thus most of their variability occurs, west of 160°E (Xue and Neumann, 1984).

2.2. Wind data and their representation

To correlate TC movement in the WNP with the large-scale environment in the region, the 850- and 500-hPa monthly mean zonal winds are analysed. Data for these parameters are obtained from the US Climate Analysis Center in a gridded format for the region 0–50°N, 90–180°E. The years of coverage are 1975–1988 for the 850-hPa and 1971–1988 for the 500-hPa zonal winds, giving a total of 168 and 228 cases respectively. The horizontal resolution of each parameter is 5° longitude in the zonal direction and between 3·5° and 5° latitude in the meridional direction. The total number of grid points is 228.

The fields of each parameter are represented by a set of empirical orthogonal functions (EOFs) using the method described by Shaffer and Elsberry (1982). The use of eigentechniques in meteorology was first

Table I. Eigenvalues and cumulative percentages of the total variance explained by the first five eigenvectors for the 850- and 500-hPa zonal winds. The sampling errors of the eigenvalues $\delta\lambda$ are estimated using the method of North *et al.* (1982). See text for further details

	Zonal winds at					
	850 hPa			500 hPa		
Eigenvector	Eigenvalue	$\delta\lambda$	Cumulative percentage variance explained	Eigenvalue	$\delta\lambda$	Cumulative percentage variance explained
1	85·87	9·37	38	107·69	10·13	47
2	40·10	4·38	55	35·93	3·38	63
3	16·06	1·75	62	17·16	1·61	71
4	12·52	1·37	68	13·33	1·25	76
5	10·23	1·12	72	8·73	0·82	80

suggested by Lorenz (1956). The basic idea is to represent a meteorological field by a set of coefficients that are determined empirically by projecting many realizations of this field on to a set of orthogonal functions, such that a maximum amount of variance of these realizations can be explained by the first function (eigenvector). The second eigenvector then explains the maximum amount of variance that cannot be explained by the first eigenvector, and so on. In this way, each realization of a meteorological field can be represented by a few coefficients instead of all the grid-point values. This method is also known in other fields as principal component analysis. For a detailed discussion of this technique the reader is referred to Jolliffe (1986). The purpose of using this technique here is to have a simple representation of the wind fields so that correlations with the TC direction of movement can be derived easily.

The eigenvalues and cumulative percentages of the total variance explained by the first five eigenvectors for both the 850- and 500-hPa zonal wind fields are given in Table I. It can be seen that for both fields the first three EOFs are able to explain more than 60 per cent of the total variance of the fields. The possible sampling errors of the eigenvalues $\delta\lambda$ shown in Table I are calculated using the formula suggested by North *et al.* (1982):

$$\delta\lambda = \lambda\sqrt{\frac{2}{N}}$$

where λ is the eigenvalue and N the sample size ($=168$ and 228 for the 850- and 500-hPa zonal winds respectively). It can be seen from Table I that for the first three EOFs, the spacings between the eigenvalues are much larger than the values of $\delta\lambda$, suggesting that the EOFs obtained from the data sample are representative of the actual EOFs (North *et al.* 1982).

The principal components (PCs) associated with these EOFs are therefore used to correlate with the annual number of TCs moving within a particular direction range in a predefined region (to be identified later). For the results to have predictive value, only the PCs between the months of November of the previous year to April of the current year are included in the regression analysis.

2.3. Grouping TCs based on the direction of movement

The WNP ocean basin is first divided into 5° longitude by 5° latitude grid boxes. Within each grid box, TCs that move within a certain range of directions are grouped together. The interannual variations in the number of TCs *with a given range of direction of movement* in a particular grid box or region can then be studied.

Four direction categories are defined based on the Cardinal directions (Table II). These represent the most frequent directions of TC movement in the WNP. Other movements are ignored as they are generally associated with erratic tracks or TCs close to becoming extratropical. The direction of movement is calculated using the $\pm$6-h best-track positions.

2.4. Identifying regions of largest variability

To identify regions that have the largest variability in each of the direction categories defined in Table II, the following procedure is used. For each 5° × 5° grid box, the direction of a particular TC in a given year when it first enters the box is calculated. The number of cases for that year in the particular direction

Table II. Categories of TC movement defined in this study

Direction Category	Range
Westward	270 ± 22·5°
North-westward	315 ± 22·5°
Northward	337·5–360°, 0–22·5°
North-eastward	45 ± 22·5°

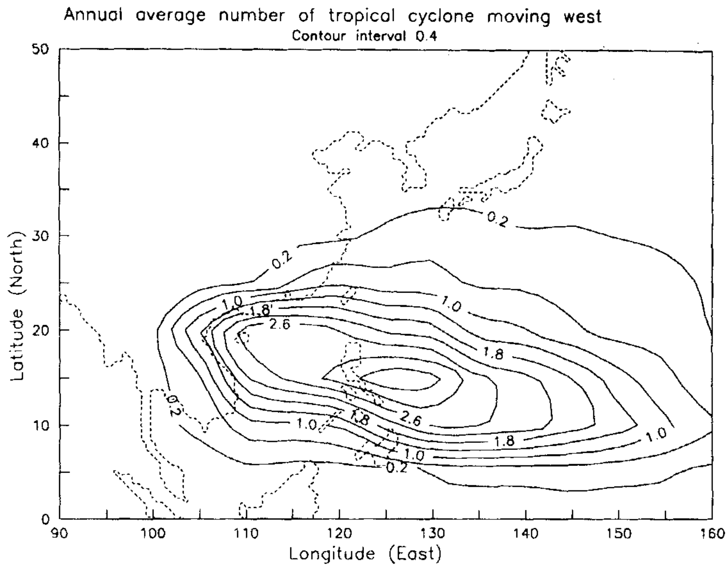

Figure 1. Annual average number of westward moving tropical cyclones over the western North Pacific

category to which this direction belongs is then increased by one. During the transit of the TC through the grid box, if its direction remains in the same category, the number of cases in that category is not increased. However, if the TC changes direction within the grid box such that the new direction belongs to another category, the number of cases for the year in this new category is then increased by one. This procedure therefore counts the *number* of TCs having the same direction (range) within each box in each year. The standard deviation of this number for all the years in the data set is also calculated.

2.4.1. Westward. In the westward category, the axis of maximum average annual occurrence, as expected, is in the tropics (Figure 1) with the centre around (15°N,125°E). The area of large interannual variation, however, occurs slightly south of this axis (Figure 2). At these low latitudes it might be expected that most

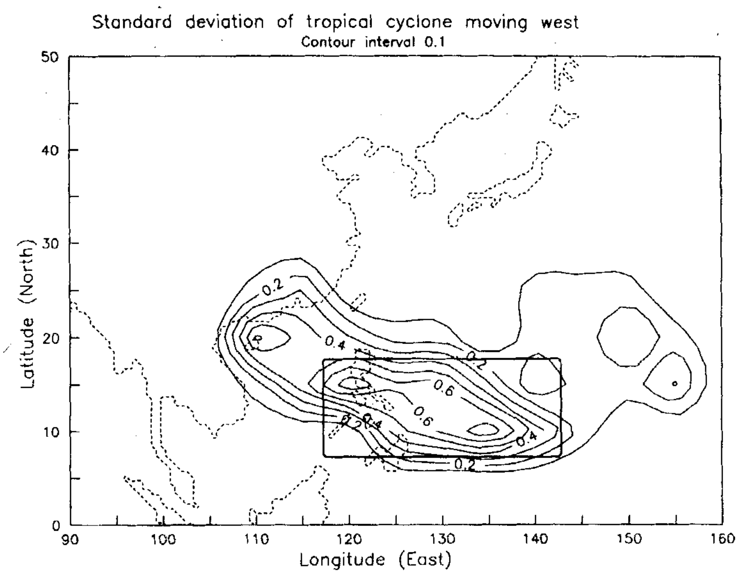

Figure 2. Standard deviation of the annual number of westward moving tropical cyclones over the western North Pacific. The boxed region represents the area within which the annual number of occurrences of these TCs will be further analysed

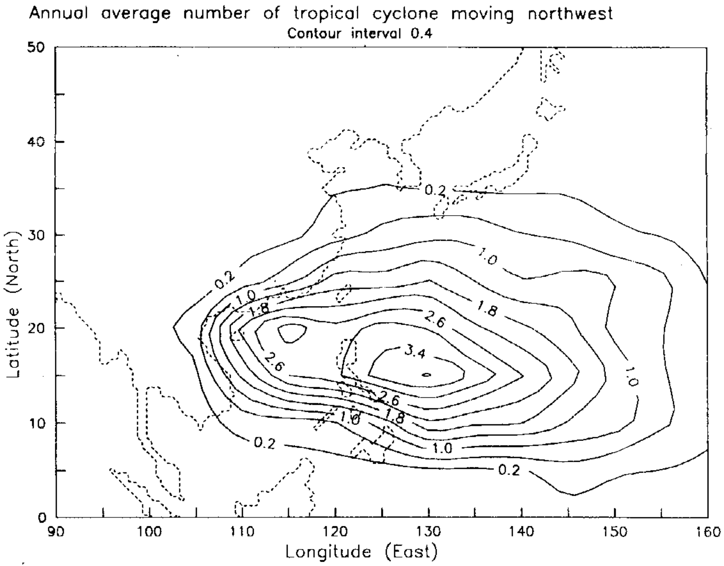

Figure 3. As in Figure 1 except for north-westward moving TCs

of the TCs would be travelling westwards. The existence of such a high value for the standard deviation σ suggests that in some years TCs in these locations do not necessarily have a westward motion. In this region of largest variability (over and east of the Philippines), westward TCs are likely to move into the South China Sea. Therefore, a knowledge of the conditions leading to this variability can be used to develop a prediction equation for the number of TCs entering the South China Sea.

Based on Figure 2, a region of 'maximum interannual variability' bounded by 7·5°N,117·5°E and 17·5°N,142·5°E is defined. For each year, the number of TCs having a westward movement (as defined in Table II) in each 5° × 5° grid box in this region is then totalled. This gives the annual number of occurrences of westward TCs within the region.

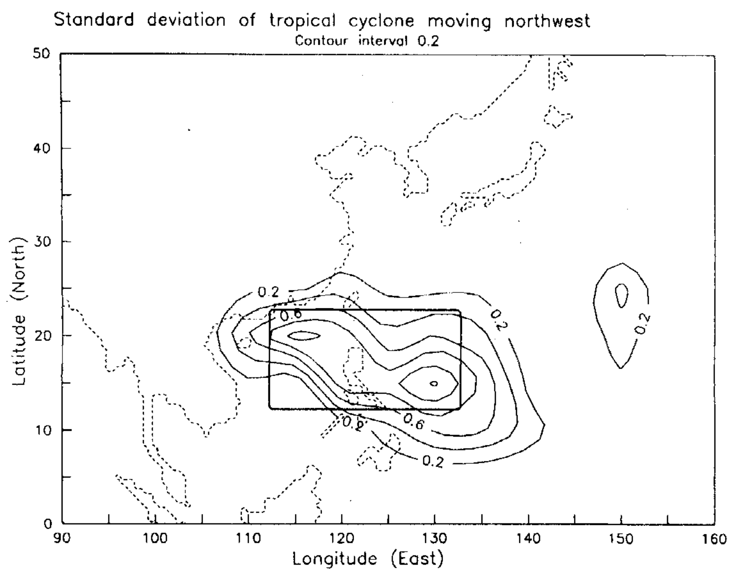

Figure 4. As in Figure 2 except for north-westward moving TCs

2.4.2. North-westward. For TCs moving north-westward, the annual average number again has a primary maximum to the east of the Philippines, with a secondary peak over the northern part of the South China Sea (Figure 3). The regions of largest variability also coincide with these areas of maximum occurrence (Figure 4). The box bounded by 12·5°N,112·5°E and 22·5°N,132·5°E therefore can be defined to represent the region of maximum variability. North-westward moving TCs in this region are likely to make landfall over the South China coast. It therefore would be desirable to be able to predict the interannual variability of these TCs.

2.4.3. Northward. The annual average number of TCs moving northward has a distribution very different to those of the westward and north-westward categories (Figure 5). The entire distribution is shifted northward with a primary maximum east of the Ryukyu Islands and a secondary maximum further east at around the same latitude. Three areas of largest variability can be identified (Figure 6), one over the north-eastern part of the South China Sea, one to the south of Japan, and one much further east, near 150°E. Because the area south of Japan has the maximum variability, TCs within the box bounded by 12·5°N,132·5°E and 27·5°N,137·5°E will be studied. These TCs are likely to affect Japan, so that developing a prediction equation for these TCs could help in the seasonal prediction of TCs affecting Japan.

2.4.4. North-eastward. Consistent with the fact that most north-eastward moving TCs are those that have recurved, the distribution of the annual average number of TCs in this category (Figure 7) shifts further northward compared with those in the northward category. The axis of maximum occurrence is oriented south-west–north-east, with the peak over a region south of Japan. The areas of large variability are quite scattered (Figure 8), with the maximum variability between Taiwan and the Philippines. However, as the annual average number in this latter region is quite small, TCs in this direction category will not be studied further.

2.4.5. Summary. The analyses in these subsections show that although TCs moving in different directions tend to concentrate in certain regions, their number of occurrences can have substantial interannual variations. A knowledge of the conditions that lead to such variations could therefore lead to the prediction of the number of TCs affecting a region likely to be affected by TCs moving within a particular direction range.

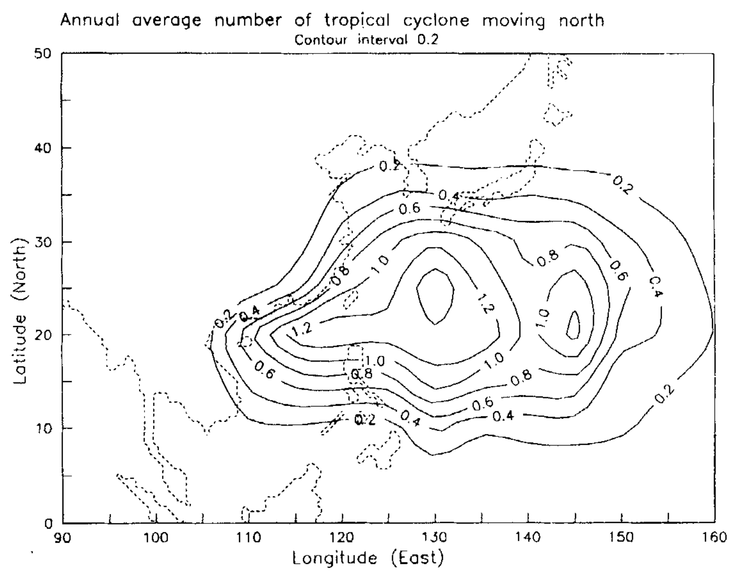

Figure 5. As in Figure 1 except for northward moving TCs

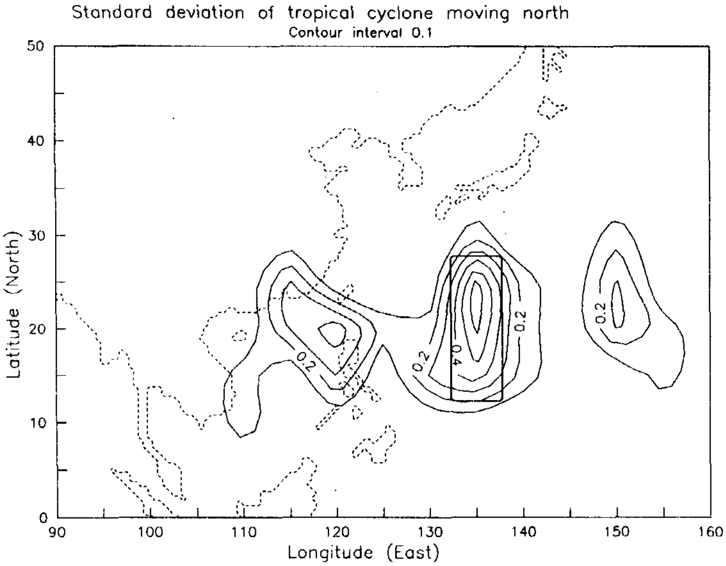

Figure 6. As in Figure 2 except for northward moving TCs

In the following two sections, the annual number of occurrences of TCs in each of the regions defined above will be correlated with the 850- and 500-hPa monthly mean zonal winds in order to determine the most significant flow patterns. Based on these results, prediction equations will be developed and verified using the entire sample (the dependent sample) as well as the jackknife method. The latter method involves removing one data point in the entire sample and then deriving a prediction equation based on the data from the rest of the sample. The number of occurrences of TCs for the year removed from the derivation is then predicted using this equation. This method therefore simulates an independent test of the accuracy of the prediction equation.

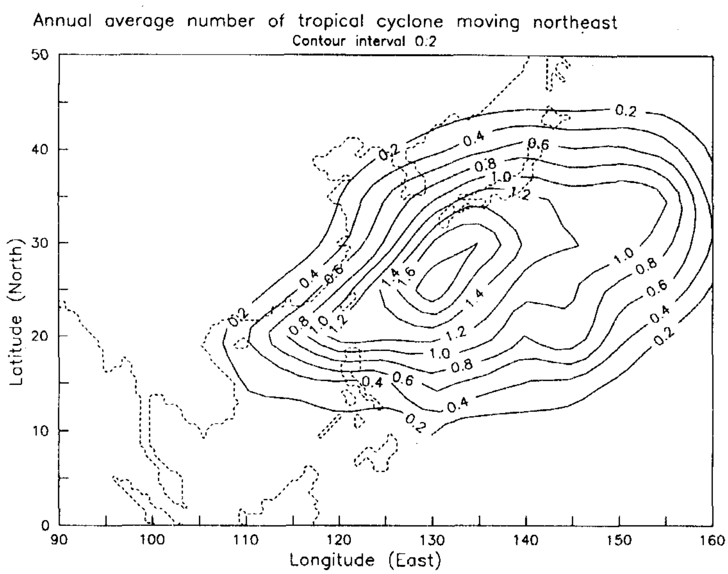

Figure 7. As in Figure 1 except for north-eastward moving TCs

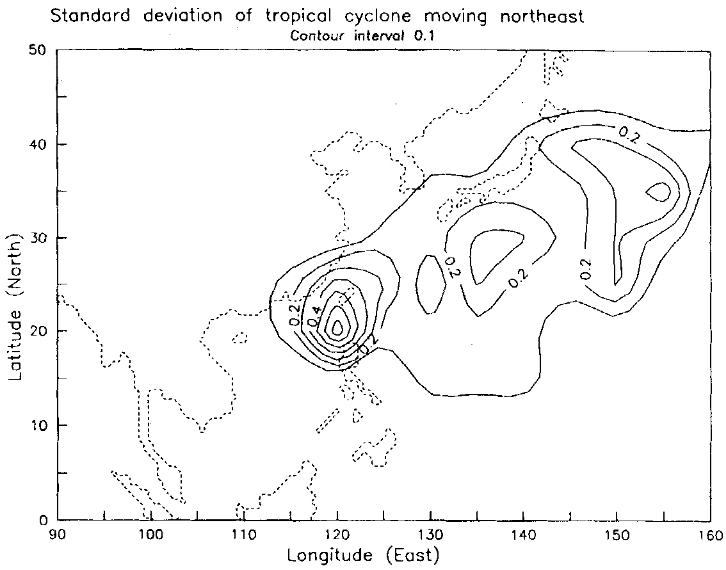

Figure 8. As in Figure 2 except for north-eastward moving TCs

3. CORRELATION WITH 850-hPa ZONAL WINDS

A linear stepwise multiple regression analysis is made between the anomalies in the annual number of TC occurrences within each of the regions defined in section 2 and the PCs associated with the first three EOFs of the 850-hPa monthly mean zonal winds for the months of November of the previous year to April of the current year. The number of potential predictors is therefore 18. Assuming only four or five of these predictors will be chosen, the F-to-enter value is set at 5·0. Because only 14 years of wind data are available (see section 2.1), the regression analysis is performed three times, each using PCs associated with one EOF for all months between November of the previous year and April of the current year. All the selected predictors are then regressed against the annual occurrences one more time in order to obtain the final set of predictors.

Unfortunately, none of the principal components of the 850-hPa monthly mean zonal winds has a significant correlation with northward moving TCs in the region defined in the last section (i.e. east of the Ryukyu Islands and south of Japan). For north-westward moving TCs in the region east of the Philippines and over the South China Sea, only the second principal component in April has a significant correlation. However, it explains a mere 25 per cent of the total variance of the annual occurrence of such TCs. For the westward-moving TCs east of the Philippines, two variables are selected by the regression procedure: the first principal component (labelled as PC1) of March and PC2 of January. These two predictors together explain 64 per cent of the total variance of the annual number of occurrences of westward TCs in this region.

To see if the results for the westward moving TCs are physically meaningful, the EOF1 March patterns for two years in which the numbers of such TCs are very large (39, year 1987) and very small (15, year 1975) are plotted (Figure 9). The patterns for these two years show much stronger easterlies in the tropics in 1987 than in 1975. Therefore, TCs that are in the area east of the Philippines will have a much higher tendency to move westward in 1987 than in 1975. The statistical result therefore appears to be physically reasonable.

Predictions of the annual number of westward TCs in the region east of the Philippines are then made from the two principal components found to be significant (i.e. PC1 of March and PC2 of January) using the entire dependent sample as well as the jackknife method. It can be seen from the results shown in Table III that both types of predictions give similar results although the former, as expected, has a smaller root-mean-square (RMS) error. Other than a few cases, the errors are within half to one standard deviation

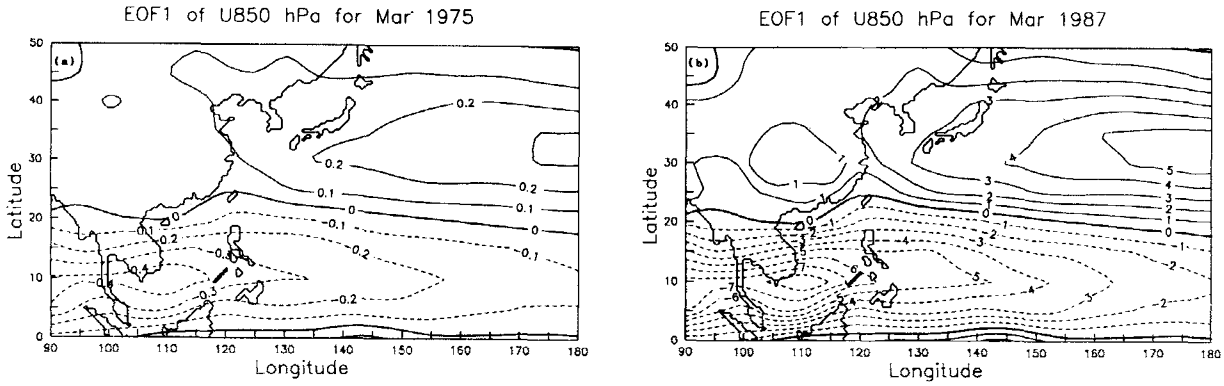

Figure 9. The EOF1 March pattern of the 850-hPa zonal winds for (a) 1975 and (b) 1987

of the observed number of occurrences. The RMS errors are also quite small. This result suggests that by using the 850-hPa zonal winds, the annual number of occurrences of westward TCs in the region over and east of the Philippines can be predicted rather accurately.

4. CORRELATION WITH 500-hPa ZONAL WINDS

The same procedure of choosing the predictors used in the last section is repeated using the principal components of the 500-hPa monthly mean zonal winds. Because 18 years of data are now available (see section 2.1), the F-to-enter value is set at 4·5 in the stepwise regression analysis.

Table III. Prediction of the annual number of occurrences of westward TCs in the region bounded by 7·5°N,117·5°E and 17·5°N,142·5°E using PC1 in March and PC2 in January of the 850-hPa zonal winds. The 'independent' sample result is obtained using the jackknife method. The error of prediction is in parentheses. RMS error = root-mean-square error

		Predicted	
Year	Observed	Dependent Sample	Independent Sample
1975	15	16(+1)	18(+3)
1976	20	22(+2)	22(+2)
1977	21	23(+2)	24(+3)
1978	31	25(−6)	25(−6)
1979	32	33(+1)	33(+1)
1980	32	26(−6)	25(−7)
1981	36	33(−3)	32(−6)
1982	34	29(−5)	29(−5)
1983	24	26(+2)	27(+3)
1984	21	27(+6)	32(+11)
1985	25	30(+5)	30(+5)
1986	35	31(−4)	31(−4)
1987	39	40(+1)	40(+1)
1988	33	36(+3)	38(+5)
Mean	28		
Standard deviation	7·3		
RMS error		3·8	5·1

As might be expected from the discussion in the last section, no principal component of the 500-hPa flow correlates significantly with the westward TCs in the region east of the Philippines. For north-westward moving TCs in this same general region and over the South China Sea, the only PC that has a significant correlation is PC2 of January. However, only 17 per cent of the total variance is explained. If this PC is combined with PC2 of April at 850 hPa (which is found to be significant from the last section), the 500 hPa PC becomes insignificant. Therefore, it appears difficult to obtain a good prediction of the interannual variation of north-westward moving TCs in this region.

Only PC1 of February is found to correlate significantly with the annual number of occurrences of northward moving TCs in the area east of the Ryukyu Islands and south of Japan, explaining 46 per cent of the total variance. As in section 3, the EOF1 February patterns of two years in which the numbers of northward moving TCs in this region are large (6, year 1976) and small (0, year 1973) are compared (Figure 10). It can be seen that in 1976, in which more northward moving TCs occurred east of the Ryukyu Islands, the westerlies are about 50 per cent weaker than in 1973. Therefore, TCs that had recurved had less tendency to move north-eastward or eastward in 1976, and instead moved northward. Again, the EOF patterns give physically meaningful results.

The values of PC1 for February are used to develop prediction equations for the annual number of occurrences of northward-moving TCs in this region using the total sample and applying the jackknife method. The results of the predictions (Table IV) show that they are rather good. Most of the predictions are within ± 1 of the observed number of occurrences and the RMS error is less than one standard deviation of this number. Thus, even with one predictor, the annual number of occurrences of northward moving TCs in the region south of Japan can be predicted rather accurately.

5. SUMMARY AND CONCLUSIONS

This study analyses the interannual variations of tropical cyclone (TC) movement over regions of the western North Pacific. Such variations are found to be rather significant in certain regions. Just to the east of the Philippines, the annual number of TCs moving westward is the largest and also has the largest annual variation. The distribution and variability of north-westward moving TCs are similar. However, for northward moving TCs, the maximum interannual variability occurs just to the east of the Ryukyu Islands to the south of Japan.

A box is defined to include the area with the largest variability of TC movement for each of the direction categories. The annual number of occurrences of TCs moving within the specified direction category is found to correlate significantly with the monthly mean 850- and/or 500-hPa zonal wind patterns as represented by a set of empirical orthogonal functions. For westward moving cyclones in the area over and just to the east of the Philippines, correlation is the highest with the 850-hPa zonal winds in January and March. Using the principal components associated with these flow patterns, prediction equations are derived

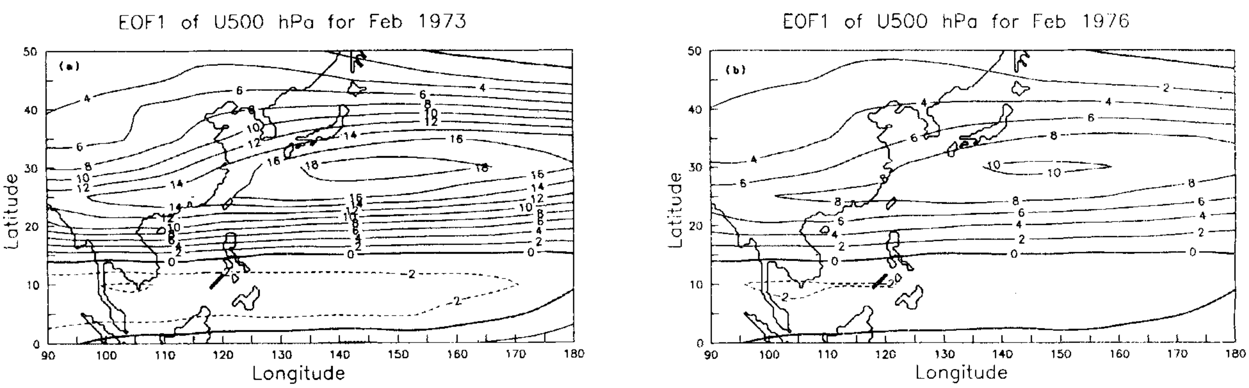

Figure 10. As in Figure 9 except for EOF1 of February at the 500-hPa level for (a) 1973 and (b) 1976

Table IV. As in Table III except for northward moving cyclones in the region bounded by 12·5°N,132·5°E and 27·5°N, 137·5°E using PC1 of February. The predictions from the dependent and independent samples are the same

Year	Observed	Predicted
1970	1	2(+1)
1971	4	4(0)
1972	4	4(0)
1973	0	1(+1)
1974	1	3(+2)
1975	5	4(−1)
1976	6	6(0)
1977	1	0(−1)
1978	2	2(0)
1979	6	6(0)
1980	2	3(+1)
1981	3	1(−2)
1982	5	4(−1)
1983	3	2(−1)
1984	3	1(−2)
1985	0	3(+3)
1986	1	3(+2)
1987	6	3(−3)
1988	0	1(+1)
Mean	2·8	
Standard deviation	2·1	
RMS error		1·5

to predict the annual number of occurrences of westward moving TCs in the region just east of the Philippines. Predictions are made for the total sample and using the jackknife approach to simulate an independent sample. In both cases, the predicted numbers are found to be very good with root-mean-square (RMS) errors of less than one standard deviation of the observed number of occurrences.

For north-westward moving TCs over the South China Sea and in the area east of the Philippines, although significant correlations are found from the 850- and 500-hPa zonal winds, the principal components are able to explain less than 30 per cent only of the total variance. Therefore, no prediction equation is developed for these TCs.

The 500-hPa zonal winds in February are found to have a significant correlation with northward moving TCs in the area east of the Ryukyu Islands and south of Japan. The predictions made using principal components of these flow patterns also give RMS errors of less than one standard deviation of the observed number of occurrences.

Because all the predictors are from the months of January through to March, these results can be applied operationally to predict the annual number of occurrences of TCs moving within a certain direction range in the predefined regions. These TCs are likely to affect areas further downstream: the South China Sea for westward moving TCs and Japan for northward moving TCs. Therefore, the present results should prove to be of value to the seasonal prediction of TC activity in each of these two downstream areas.

The method of using an EOF representation of the zonal winds in winter to predict the annual number of TCs moving within a certain directional range has not been attempted before and therefore should be tested operationally. It should be pointed out, however, that the present results are based on a 14- to 18-year sample, and when more years of data are available some refinements of the prediction equations may be necessary.

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