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VARIATIONS IN TYPHOON LANDFALLS OVER CHINA

By

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Special thanks to my advisor James Elsner, without his guidance none of this would be possible. Thank you to my other advisors Tom Jagger and Tony Stallins for their wonderful advice and help. Finally thank you to Kam-biu Liu from Louisiana State University for providing the historical data used in this study.

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ABSTRACT

The inter-annual variability of typhoon landfalls in China is investigated using historical and modern records. A north-to-south anti-correlation in yearly activity is confirmed from the historical records. When activity over Guangdong is high, it tends to be low over Fujian and vice versa. This spatial variation is identified in the modern record using a factor analysis model, which delineates the southern provinces of Guangdong, and Hainan from the northern provinces of Fujian, Taiwan, Zhejiang, Shanghai, Jiangsu, and Shandong. An index of annual activity representing the degree to which each year follows this pattern of activity is used to identify correlated climate variables. A useful model that includes sea level pressure differences between Mongolia and western China and SST over the midlatitude NW Pacific during the summer explains 27% of the inter-annual variability of the index. Physically, we suggest that a stronger than normal north to south pressure gradient increases the surface easterly wind flow over northern China, this coupled with lower SST over midlatitude NW Pacific, favors typhoons taking a more southerly track toward Hong Kong.

CHAPTER 1

INTRODUCTION

A tropical cyclone is a non-frontal synoptic scale low-pressure system over tropical or sub-tropical waters with organized thunderstorm activity and a cyclonic (counterclockwise) wind circulation at the surface. Tropical cyclones with sustained surface winds of less than 17 ms^{-1} are called “tropical depressions”. Once the tropical cyclone reaches winds of at least 17 ms^{-1} they are typically called a “tropical storm” and assigned a name. Tropical cyclones with sustained wind speeds of at least 33 ms^{-1} are known in the western North Pacific (WNP) as typhoons and known as hurricanes over the eastern North Pacific and North Atlantic.

Typhoons are among the most destructive of all natural disasters. When Typhoon Wanda hit Hong Kong in 1962, damage and casualties were widespread, 130 people were killed and at least 53 were missing. Approximately 72,000 people were left homeless. Sea water from the storm surge flooded at least 869 acres of farm land. Typhoon Wanda had maximum sustained winds of 37 ms^{-1} and gusts of 72 ms^{-1} in the harbor, with a record-setting gusts of 79 ms^{-1} at one of Beijing's mountain peaks (Tate's Cairn). More recently in 2003, Typhoon Nepartak brought torrential rains and strong winds to the west coast of Hainan causing $197 million dollars (US) in economic losses. More than 1.7 million people were affected and 800 homes were destroyed. Typhoon Nepartak damaged acres of cropland and killed an estimated 400 livestock (Xinhua News Agency-20th November 2003). The economic loss in China from typhoon-generated storm surge averaged over the three costliest events since 1990 amounts to $2.7 billion USD (Kentang 2000). Understanding the nature and causes of variability in tropical cyclone activity over China is an important step toward improving risk assessment.

The earliest historical records of tropical cyclones anywhere in the world are probably from China, where the documentary history spans about 3500 years. The record length and the quality of these historical data vary from region to region. Yet, from a very early period the Chinese were aware of the essential features of typhoons, including their attendant storm surges. Meticulous records documented the frequency of tropical cyclone landfalls over parts of China (Louie and Liu 2003). In particular, the availability of records from two provinces in China (Chan and Shi 2000; Liu et al 2003) provide a unique opportunity to compare patterns of typhoon landfall activity across the centuries. Records of tropical cyclone activity from the second half of the 20th century follow from advances in satellite and aircraft reconnaissance. These modern records support a spatially more comprehensive analysis of typhoon activity in China, but are temporally more limited. Thus in the present work we make use of both the historical and modern records of typhoon landfalls.

Approximately one third of all tropical cyclones originate over the WNP, making it the most prolific of the tropical cyclone basins. The WNP basin produces tropical cyclones year round, however the active season extends from May through November with a peak in late August or early September. The modern record, from 1945–2003, indicates that on average 28 tropical cyclones occur in the WNP each year. Approximately 61% of these become typhoons. Most WNP tropical cyclones track west-northwestward at low latitude (i.e. 15°N latitude or lower). Approximately one-third continue on west-northwestward track and make landfall in east Asia south of about 25°N latitude. A larger portion of the remaining two-thirds turn northward, gain latitude, and eventually turn eastward as they enter the mid-latitude westerlies (Lander 1996; Shanghai Typhoon Institute 1990).

Numerous climatological studies of WNP typhoon activity are available (Wu and Lau 1992; Lander 1994; Chan 1994; Chan and Shi 1996; Lander and Guard 1998; Chan et al. 1998; Chen et al. 1998; Chan and Shi 2000; Wang and Chan 2002). These studies focus on factors affecting the variability in overall tropical cyclone (TC) activity. In general, tropical cyclones form over the warm oceans where sea surface temperature (SST) are higher than 26.5°C. Environmental conditions that control formation, development and movement of tropical cyclones include SST, vertical wind shear, thermodynamic stability and mid-tropospheric moisture (Gray 1968; 1979; Emanuel 1988; Molinari and Vollaro 1989; DeMaria et al. 2001). Large-scale atmospheric and oceanic factors also play a role in typhoon activity.

During El Niño events, when sea-surface temperatures (SSTs) in the central and eastern equatorial Pacific are higher than normal, tropical cyclones are relatively more likely to form east of about 160°E longitude (Lander 1994). Chan (1985) notes that typhoons tend to form farther east during El Niño events and are consequently more likely to remain east of China. This we refer to as the "ENSO-typhoon" hypothesis. The corollary is that typhoons are relatively more likely to effect China during La Niña years (Saunders et al. 2000). The ENSO-typhoon hypothesis was verified by an analysis of historical and modern data in Elsner and Liu (2003). Wu et al. (2004) found a significant relationship between late season landfalls over China and ENSO and Ho et al. (2004) infer that changes in typhoon tracks are associated with the westward expansion of the subtropical northwestern Pacific high (SNPH). Thus there is consensus among researchers that large scale climate patterns affect TC genesis regions and subsequent tracking. However, agreement has not been reached on how large-scale circulation pattern influence the landfall variability. Here we address this question directly. More specifically, in this study we are interested in examining the case for a north-south anti-correlation in typhoon activity along the coast of China. This interest is prompted by the work of Liu et al. (2003) who speculated an inverse relationships across latitudes between the frequency of typhoons occurring over northern China to those occurring over Guangdong Province in the south (Liu et al. 2003). A similar anti-correlation across latitudes in U.S. hurricane frequency was noted and explained in Elsner et al. (2000).

We begin with an examination of the historical record using log-linear regression. This suggests a possible north-south variation in typhoon activity. The modern record is subsequently analyzed to examine this variation in greater spatial detail. Here we employ a factor analysis model. Output from the model is then used to study possible climate factors that might influence this variation. Data sources and methods are described in chapter 2. Chapter 3 outlines the historical inverse relationship that exist between tropical cyclone landfall frequencies over China. Chapter 4 describes the factor analysis including a test of statistical significance. Chapter 5 examines large-scale atmospheric patterns that are correlated with a factor score index. Chapter 6 is a discussion of the results and chapter 7 provides some concluding remarks.

CHAPTER 2

DATA

What causes variations in the frequency of typhoons over China? In order to describe and model the spatial variability in typhoons, this study makes use of both modern and historical typhoon records and modern atmospheric data obtained from the U.S. NCAR/NCEP reanalysis project. The area examined is the WNP extending to the Chinese coastal provinces of Guangdong (including Hong Kong), Fujian, Zhejiang, Shanghai, Jiangsu, Shandong including the islands Hainan and Taiwan (Figure 2.1). In this section we describe the historical and modern data sources and provide a brief description of the analysis methods. We begin with the historical records from Guangdong and Fujian.

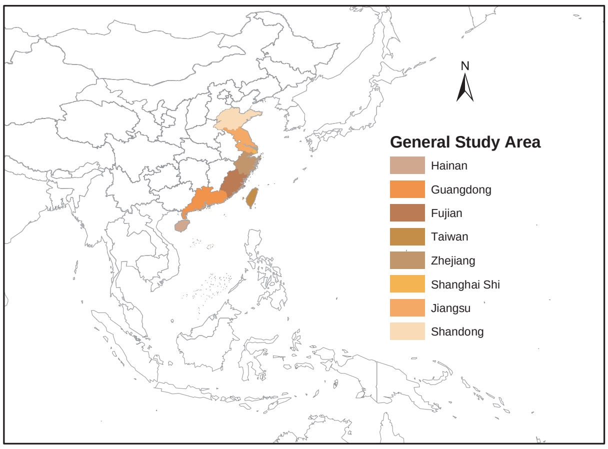

Figure 2.1. The western North Pacific (WNP) tropical cyclone basin. The coastal provinces of China are labeled.

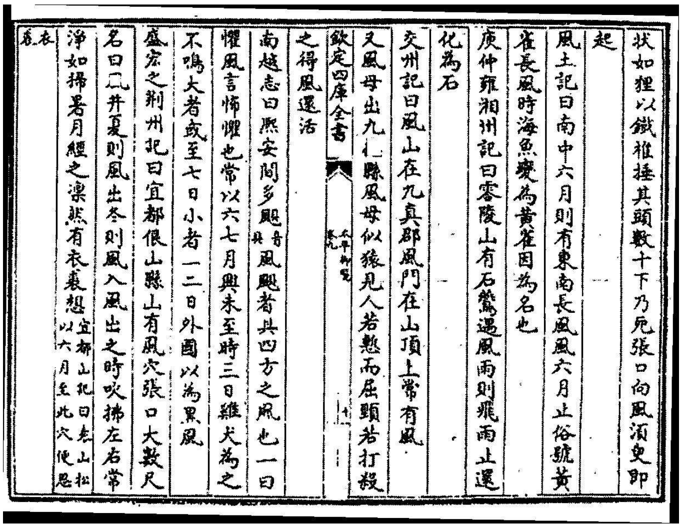

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Figure 2.2. The fragment of *Nayue Zhi (Records of the South)*on *jufeng*(typhoon),quoted in *Tai Ping Yu Lan (Tai-ping Reign-period Imperial Encyclopaedia).* Used in Louie and Liu 2003.

2.1 Historical Typhoons over Guangdong and Fujian Province

The historical typhoon data used in this study are obtained from Liu et al. (2003) and kindly provided by Kam-biu Liu. According to their study, records of past typhoon activity are available in two groups of Chinese historical documents. First, since the Northern Song Dynasty (AD 960-1126), the Chinese government has kept a continuous record of typhoon strikes reported by local administrative authorities (Louie and Liu 2003, Liu et al. 2003). The second source comes from local gazettes (*Fang Zhi*) an example page from one of he gazettes is reproduced in Figure 2.2. These gazettes were written or last updated during the 19th and 20th centuries, although some date back as early as the mid 16th century (Louie and Liu 2003). According to Louie and Liu (2003), the compilation of gazettes contain a catalog of major cultural and natural events, including typhoon strikes. Annual counts of typhoons affecting the Guangdong Province for the years 1000–1909 were made available as were counts affecting the Fujian Province for the years 1000–1920. It is likely that counts are underestimated prior to 1600 and that storms much weaker than typhoon intensity are likely not recorded. We consider only the common years of 1600–1909 (310 consecutive years) for the present analysis.

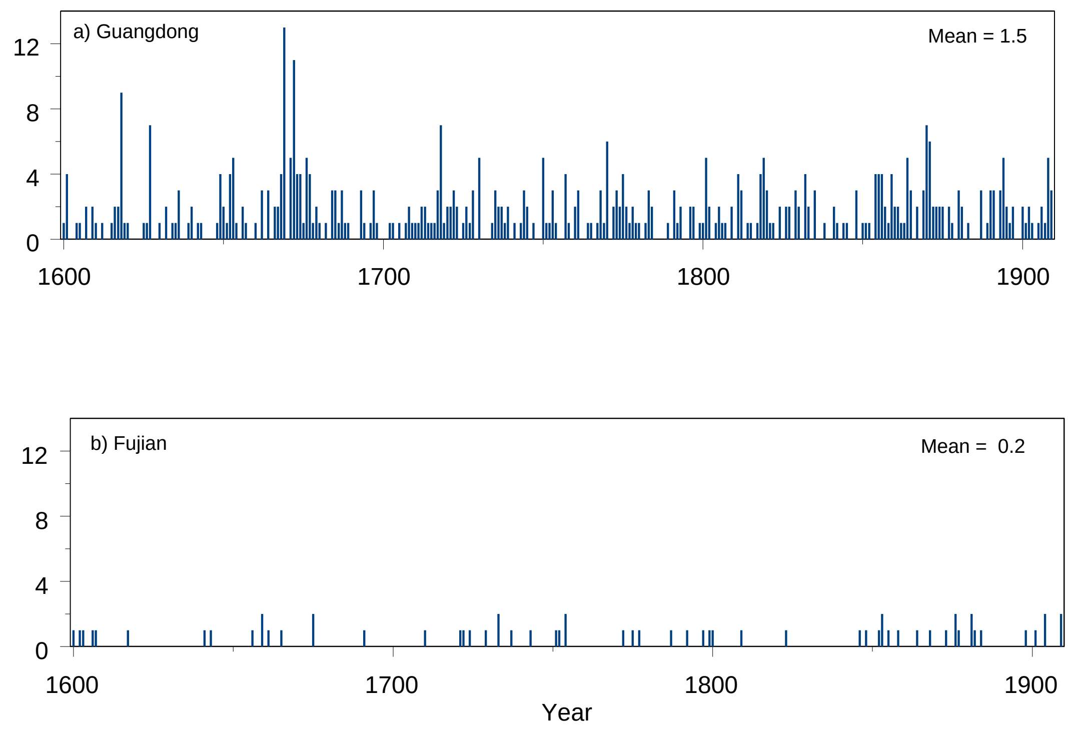

Figure 2.3. Annual counts of Guangdong and Fujian Province typhoons for the years 1600–1909. The counts were extracted from historical documents.

Figure 2.3 shows time series plots of the annual counts for both Guangdong and Fujian. While we analyze the time series' separately, it is likely that some storms are counted in both provinces. Collectively there are 539 storms. This equates to an average rate of 1.7 storms/yr. Guangdong experiences considerably more storms compared with Fujian, with an average rate of 1.5 per year and a maximum of 13 storms in a single year. This compares to an average rate of 0.2 per year and a maximum of 2 in a single year. In this study we are specifically interested in the co-variability of landfalls across the two provinces.

2.2 Modern Typhoon Records

The modern typhoon record consist of 6-hourly positions (latitude and longitude in tenths of a degree) and intensities (5 kt intervals of maximum sustained (1-minute average) wind speed) for all western North Pacific tropical cyclones. The values are based on *Annual Tropical Cyclone Reports* issued by the Joint Typhoon Warning Center (JTWC) in Hawaii. Extracted from these records is an annual count of tropical cyclones that made landfall over the period 1945–2003 between the months of May to December. Landfalls are counted by coastal province including Guangdong (with Hong Kong), Fujian, Zhejiang, Shanghai, Jiangsu, Shandong and including the islands of Hainan and Taiwan.

For each province, a count is added to the annual total if a storm reached typhoon intensity (33 ms^{-1}) somewhere over the WNP and subsequently made a direct passage through the province. In this way, more than one province may count a single storm. Also, the storm is counted even if the winds at the time of passage through the province are less than typhoon intensity. Direct passage is defined as the straight line path connecting 6-hr positions of the storm's circulation center. Counts are determined with the help of a geographic information system. A total basin-wide count of the number of typhoons is also used in the analysis to compute relative frequencies. The WNP basin extends from the international dateline to Asia.

These data show 61% of all WNP tropical cyclones reach typhoon intensity. Furthermore, out of the 963 tropical cyclones that formed, 405 (42%) made landfall over at least one of China's coastal provinces including the islands of Hong Kong, Taiwan and Hainan. Guangdong sees the most storms with an average annual rate of 1.8 per year. Its neighbor to the north has an annual rate of 1.2 per year which compares with 1.3 per year for Hainan and 1.4 per year for Taiwan. The northern provinces have fewer typhoons. The average annual rate for Zhejiang is 0.6. This compares with 0.1, 0.2, and 0.1 for Shanghai, Jiangsu, and Shandong, respectively. The annual counts are plotted as time series' in Fig. 2.4. Here we see the large inter-annual variations in counts. Before modeling these data we change the annual counts to relative frequencies based on the total number of storms occurring over the WNP basin.

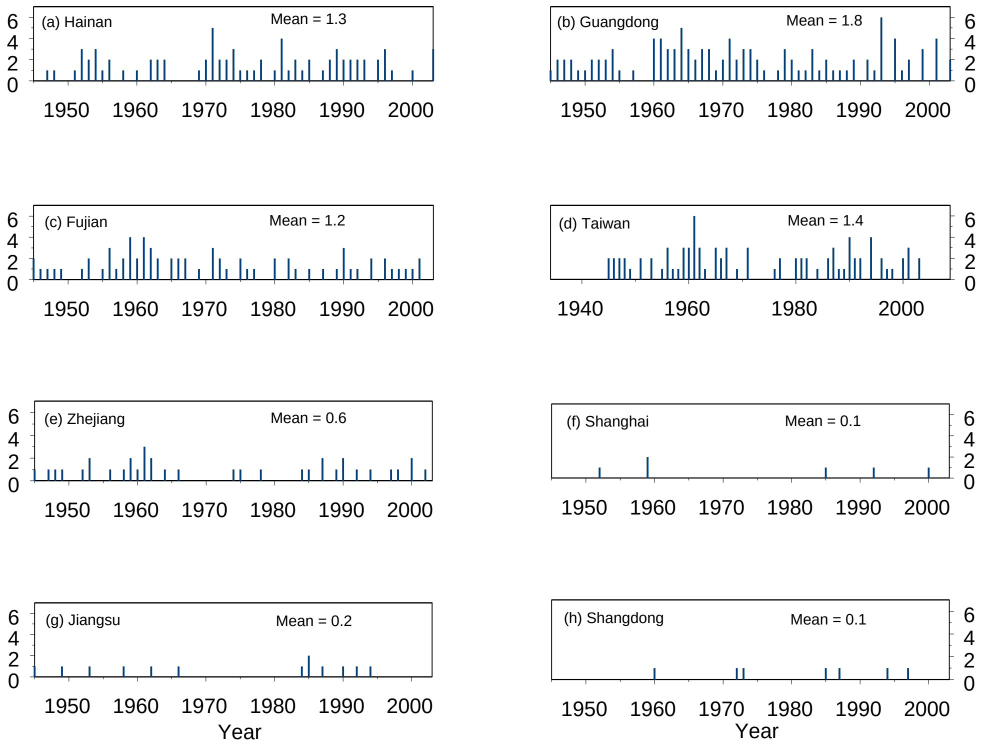

Figure 2.4. Annual counts of typhoons over the period 1945–2003 separated by coastal provinces. The counts are extracted from the modern records using a geographic information system.

2.3 ENSO and the Pacific Decadal Oscillation

Two large-scale atmospheric/oceanic index variables are used in the study to investigate possible relationships to the pattern of China landfalling typhoons. The El Niño-Southern Oscillation (ENSO) refers to systematic variations of the ocean and atmosphere characterized by sea-surface temperature (SST) and sea-level pressure (SLP) changes in the tropical Pacific Ocean. El Niño is the warm oceanic phase, which results in warming of SST's in the eastern tropical Pacific. The opposite phase, La Niña, results in cool SST's in the same region of the eastern Pacific. The atmospheric component of ENSO is characterized by zonal SLP variation called the Southern Oscillation. The Southern Oscillation Index (SOI) represents the difference in SLP's between Tahiti and Darwin, Australia.

Early work on variations in typhoon activity over the WNP have indicated a relationship with ENSO. During El Niño conditions TC formation tends to shift farther to the east (Lander 1994) and their subsequent tracks tend to be toward higher latitude (Elsner and Liu 2003), thus we speculate that variations in the SOI will correlate with the typhoon landfall pattern. Monthly values of the SOI are obtained from NOAA-CIRES Climate Diagnostics Center (CDC), Boulder, Colorado, from their website at http://www.cdc.noaa.gov/. The Pacific decadal oscillation (PDO) is a persistent atmospheric pressure pattern over the North Pacific Ocean with energy on the decadal time scale. It is the dominant factor in monthly SST variability in the North Pacific (north of about 20N latitude) (Mantua et al. 1997). A PDO index (PDOI) is defined as the leading principal component of North Pacific monthly SST variability (poleward of 20°N latitude). The warm phase (positive values of the PDOI) of the PDO is characterized by negative sea surface temperatures and positive sea level pressure in the north Pacific.

2.4 NCEP/NCAR Reanalysis Data

Additional atmospheric and ocean data are used in this study to investigate possible relationships to the pattern of China landfalling typhoons not explained by ENSO or the PDO. The National Centers for Environmental Prediction-National Center for Atmospheric Research (NCEP/NCAR) reanalysis data is provided CDC. The data are the result of an elaborate analysis/forecast system employed to perform data assimilation using observational data from 1948 to present. The data are divided into six categories, pressure level, surface, surface flux, other flux, tropopause level and sigma level data (Kalnay et al. 1996). The present study utilizes two datasets, first the pressure level data at the surface in order to examine possible influences on coastal typhoon patterns. In particular we are interested in the large-scale atmospheric surface pressure patterns across Asia and the Pacific that might influence the probability of typhoon landfall over China. Monthly data are obtained from the CDC and averaged over the months of May through November. Figure 2.5 shows the average sea-level pressure pattern during the typhoon season.

The second dataset obtained from the NCEP/NCAR reanalysis are SST over the middle latitudes of the NW Pacific. These data were examined in order to ascertain whether or

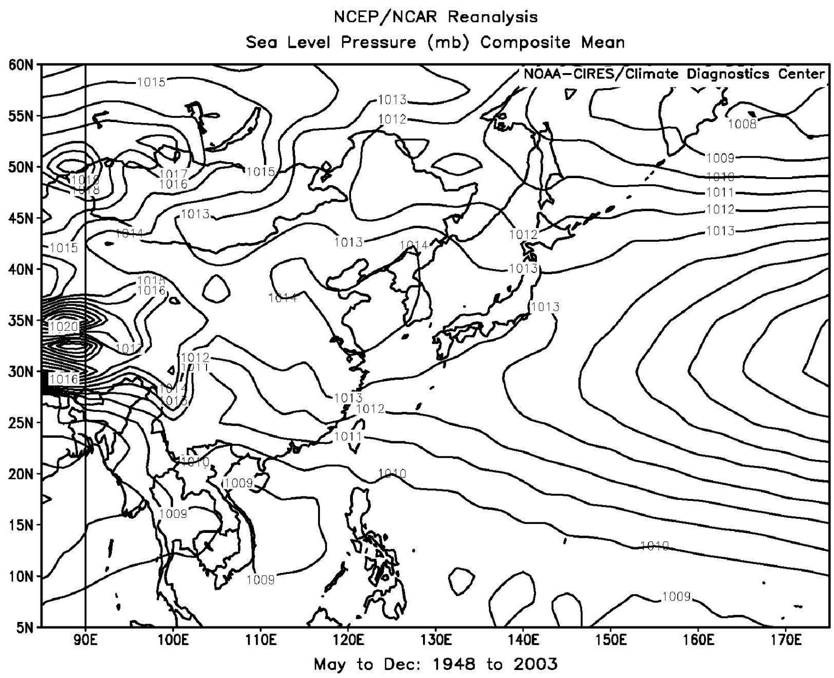

Figure 2.5. Average sea-level pressures over the WNP during the typhoon season. Values for sea-level pressure are given in hPa.

not anomalous SST in the NW Pacific are related to tropical cyclone steering mechanisms and thus the probability of landfalls over China. Figure 2.6 shows the average SST in the midlatitude NW Pacific, for this study that area is 30°N to 60°N and 150°E to 180°W.

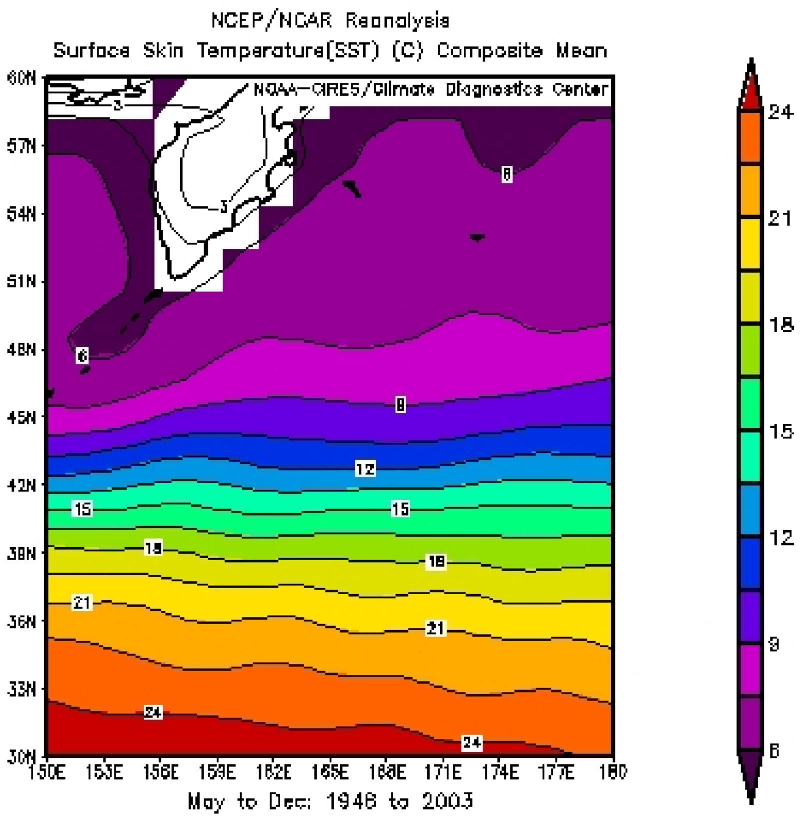

Figure 2.6. Average SST over the middle latitudes of the NW Pacific during the summer (June–August). Values for sea-surface temperatures are given in °C.

CHAPTER 3

ANTICORRELATION BETWEEN GUANGDONG AND FUJIAN TYPHOON ACTIVITY

We begin the analysis with an examination of the historical counts of typhoons. The historical counts of typhoons affecting Guangdong and Fujian provide a long record for examining co-variability between these two regions. A close-up look at Fig. 2.3 indicates years of above average activity over Guangdong appear out of phase with years of above average activity over Fujian. The Pearson correlation coefficient verifies this with a value of -0.35.

Another way to see this inverse relationship is with conditional probabilities. A conditional probability is the probability of an event given the occurrence of some other event. For instance Guangdong experiences less TC given Fujian has at least one TC, this is suggestive of an inverse relationship. Figure 3.1 shows the probability of Guangdong typhoons conditioned on Fujian typhoons. The graph shows that when Fujian experiences an increase in TC frequency there tends to be a decrease in the number of storms that impact Guangdong.

Although the Pearson correlation provides a quantitative estimate of this anticorrelation, it is influenced by overall trends in the data. Thus a better way to quantify the relationship is with a Poisson regression model. This helps us control for year. The arrival of TC on the coast can be considered a Poisson process (Elsner et al. 2001; Solow and Moore 2000; Parisi and Lund 2000; Elsner and Kara 1999; Bove et al 1998). Poisson log-linear regression, like binomial logistic regression, is a generalized linear model (GLM). A GLM is a probability model in which the mean of a response variable is related to explanatory variables through a regression equation. An ANOVA with results displayed in Table 3.1 suggest that different distributions for Guangdong (Gd) when Fujian (Fj) is larger.

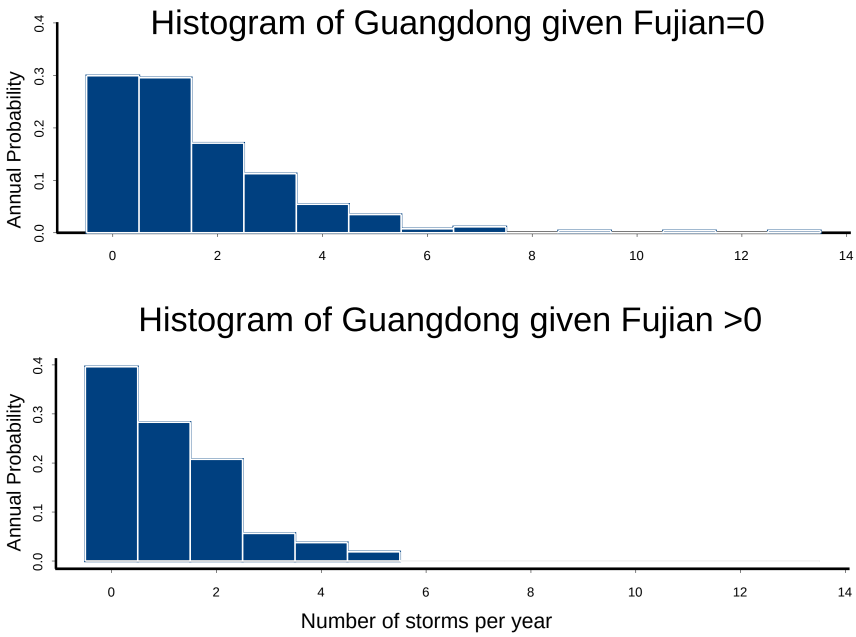

Figure 3.1. The annual probability of Guangdong typhoons conditioned on Fujian typhoon activity. The plots suggests a decreasing chance of a Guangdong strike with increasing Fujian activity.

Table 3.1. Analysis of Deviance Table

	Df	Deviance Resid.	Df	Resid. Dev	F Value	Pr(F)
NULL			309	574.4175		
Fujian Count	1	9.3246	308	566.0928	4.7711	0.02969

Table 3.2. Results of GLM

	Value	Standard Error	t-value
(Intercept)	0.4874	0.4850	10.0500
Fujian Count	-0.3380	9.791461	-2.8690

Table 3.2 shows the result of the log-linear regression of Fujian on Guangdong, it gives a significant t-value and a negative value of the coefficient of Fujian. This indicates that not only is there a relationship to the response, but a negative or anticorrelation is present. These results are important since they will be compared with the modern record.

CHAPTER 4

SPATIAL CO-VARIABILITY IN CHINA LANDFALLS

Typhoons typically form and track westward toward China, as they approach the coast they sometimes curve northwestward steering clear of China. Thus, on average, direct hits on the northern provinces are less likely than hits on the southern provinces. To lessen this disparity in counts between Guangdong and the northern provinces, we combine the counts from Shanghai, Jiangsu, and Shandong. Figure 4.1 shows the annual typhoon rates in the the six regions, including the combined northern provinces which are labeled as SJS.

To normalize the annual counts we use relative frequency, where the relative frequency of a tropical cyclone is calculated by dividing the annual count by the total number of typhoons to occur in the WNP basin for the entire season. Relative frequencies are obtained for the 6

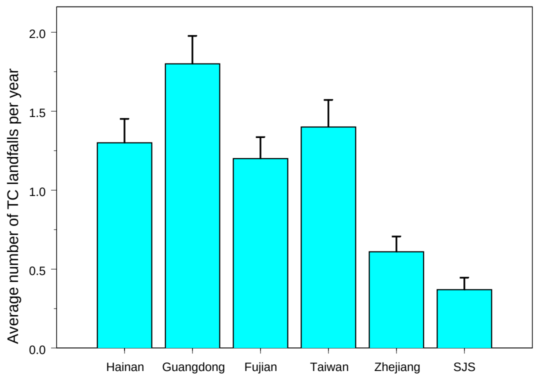

Figure 4.1. The average annual rate of tropical cyclones affecting coastal provinces of China. The rates are obtained by counting storms that made direct passage over the region. The period of record extends over the period 1945–2003.

Table 4.1. Matrix of correlations in annual typhoon frequencies.

	Hainan	Guangdong	Fujian	Taiwan	Zhejiang	SJS
Hainan	1.000	0.139	-0.268	-0.274	-0.197	-0.143
Guangdong		1.000	-0.190	-0.348	-0.357	-0.296
Fujian			1.000	0.595	0.436	0.350
Taiwan				1.000	0.386	0.158
Zhejiang					1.000	0.523
SJS						1.000

coastal regions. Correlations in annual frequencies between each of the regions is shown in Table 4.1. The matrix of values (correlation matrix) is in order from south to north, with Hainan southernmost and the region of SJS northernmost. On balance the correlations are positive indicating that when activity is high in one province it tends to be high in another or vice versus. The exception is Guangdong and Hainan. When typhoon activity is high over the south it tends to be lower over the north. Interestingly, the cutoff between negative and positive correlation occurs between the provinces of Guangdong and Fujian. Thus the negative correlations indicate an inverse relationship in activity between the north and south. Next, as a way to describe and quantify this overall pattern in annual typhoon frequencies we employ a factor analysis model.

4.1 Factor Analysis Model

A factor analysis model attempts to approximate the correlation matrix, with the object being to decide if the data are consistent with a prescribed structure. Factor analysis is used to study patterns of relationships among many dependent variables; this is unlike regression where one looks at many independent variable. The purpose of employing a factor analysis model is to describe if possible, covariance relationships among many variables in terms of a few underlying, but unobservable random quantities called factors. Factors that contribute to correlation structure observed in the correlation matrix are the dependent variables being observed. The single factor model is composed of a response vector (R) that is equal to the single vector of factor loadings (F) times the factor scores (s) plus an error vector (e). The factor model formula is $R = F^{*}s + e$, where the random variable (s) has mean 0 and variance 1. The errors (e) is a random vector with uncorrelated components that are also uncorrelated with s, having mean 0 and variances less than 1. The response vector R is the centered and scaled proportion term. The expected value of R is zero and the variance is equal to the transpose of the single vector factor loadings F times F plus the diagonal of the variances, Var(R)=$F^T * F + diag(\sigma^2)$. The factor loadings are estimated using maximum likelihood methods. Once factor loadings are determined scores are estimated using generalized least squares fitting the response R using $\frac{1}{uniqueness}$ as weights with the factor loadings as the predictors. In the context of this work the dependent variables are the annual typhoon frequencies in the 6 regions of coastal China.

Since we are only concerned about a leading factor we adapted a one factor model. Model solutions are the same whether we use a principal component or maximum likelihood method. The resulting factor loadings are plotted in Fig.4.2. As expected they show a north-south split with opposite signs on the loadings for Guangdong and Hainan compared to Fujian, Taiwan, Zhejiang and SJS. The split occurs between Guangdong and Fujian. Thus the factor analysis model appears to capture the main correlation structure of annual typhoon activity along the China coast and the results are consistent with the inverse relationship noted in the historical counts.

The magnitude of the factor score represents the degree to which the year represents the dominate co-variability in relative typhoon frequencies. The time series of 59 factor scores is called the factor score index (FSI). A plot of the FSI is shown in Fig 4.3. Positive values of the FSI indicate a propensity for storms to recurve and track north of the Tropic of Cancer. Where as negative values of the FSI indicate the opposite effect with a larger relative frequency of landfalls occurring over regions south of the Tropic of Cancer.

A plot showing the tracks of typhoons during a year with a large positive value for the FSI and a year with a large negative value for the FSI is given in Fig.4.4. Evident is the fact that years with many recurving, higher latitude typhoons are years with few non-recurving, lower latitude typhoons and vice versa. This result was inferred based on the analysis done on the historical record, and confirmed using the modern record.

4.2 Statistical Significance of the Factor Analysis Model

Since there are no direct methods to test the factor analysis results we employ a Monte Carlo simulation. Simulations are performed to test whether the split in landfall frequency

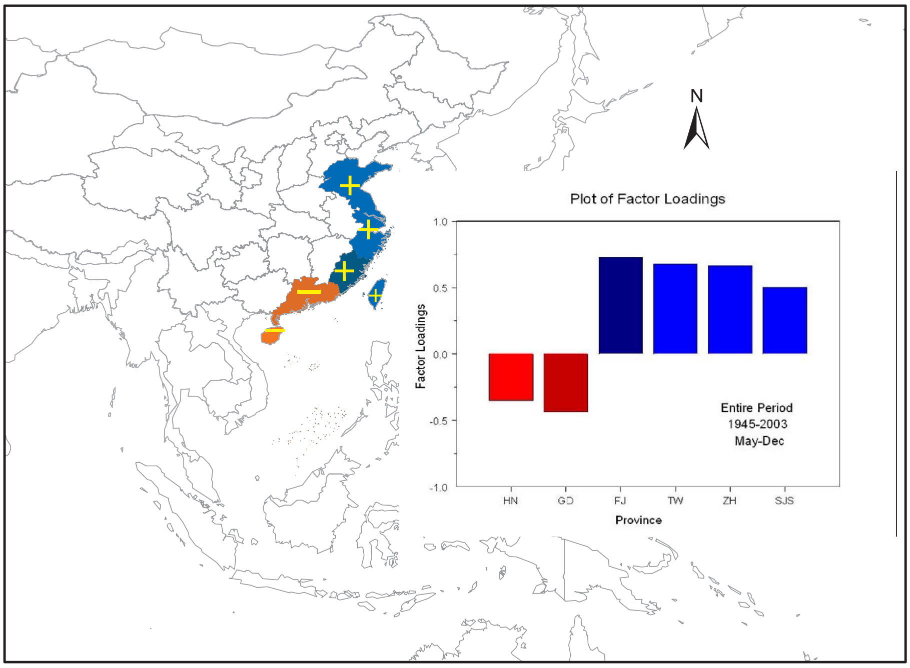

Figure 4.2. Values of the factor loadings from a factor analysis model using a maximum likelihood method. The sign on the factor loading is plotted in the corresponding map region.

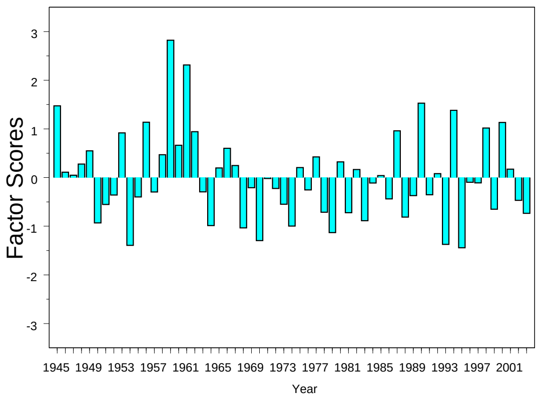

Figure 4.3. A factor score index (FSI) obtained by linearly projecting the factor loadings onto the annual frequencies using regression.

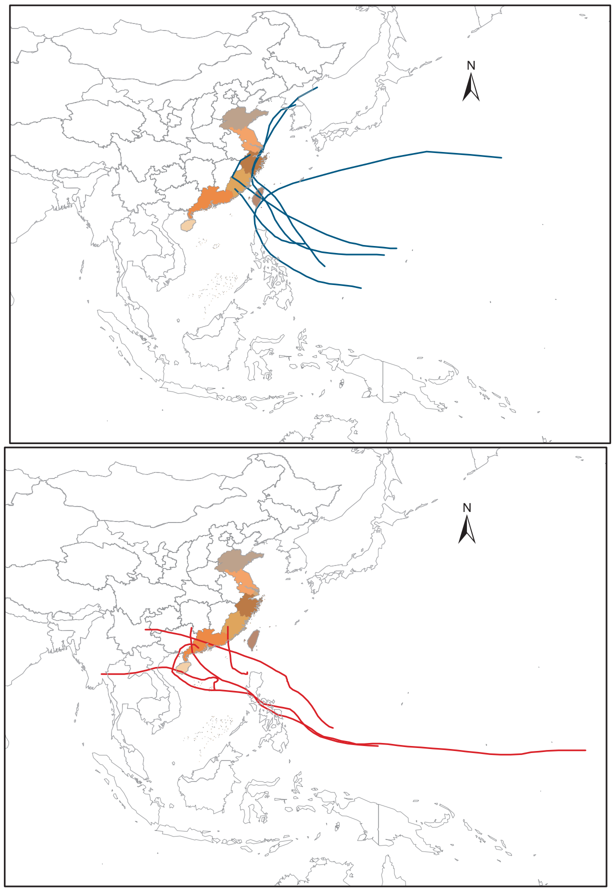

Figure 4.4. Largest positive (top map) and negative values of the FSI

could have occurred by chance. The annual frequency of storm occurrences in each province is randomized with respect to year. For example in 1945 the the relative frequency of Guangdong typhoons was 8 percent, but under a randomization it is 13 percent. One can constrain all the rows and columns and simulate the possible combinations of counts and assign probabilities to them. This is based on work from Patefield (1981) which gives an efficient method of generating r x c tables with given row and column totals. Referred to here as the r2dtable, it allows you to generate all the tables satisfying a set of fixed margins. The r2dtable format allows for a multinomial sampling scheme where the sample data is randomized (by simulation) with new data having the same marginal totals. In the context of this study the relative frequencies of landfalls are randomized n=100 number of times. Samples are drawn from the conditional distribution of the table given the margins.

Rows are the yearly seasonal basin totals and the columns are the annual region totals, an additional column of the sum of all season basin wide activity out of TC that did not affect any part of the study area is also included. Using the Simulation method assumptions are made about the data, in this case the number of storms in each year and the proportion of storms in the basin for each province stay constant, only the relative frequency of landfalls per region change in value for each simulation. From these assumptions we simulate 100 times the number of storms for each province for each year. For every simulation we run N=1000 times a one factor (mle) factor analysis and keep the factor loadings. Included also in the output (N=1000) are the values for the intercept and slope that result from a linear regression of the loadings against the order North to South of the regions. Then we run some tests on the simulation results.

An initial estimate of the values of the data are generated from the modern record data. Using a Monte-Carlo sample to estimate the probability of getting a results as strong or stronger than what we observe by chance. This value is then probability of a Type I error, that is the probability of rejecting the null hypothesis, when in fact it is true. The null hypothesis is that the magnitude of the slope is zero, corresponding to no relationship between provinces. Another words, the North-South one factor split observed in the modern record data is random. The expected slope for north to south based on the factor analysis is .2112. The number of samples in the Simulation (N=1000) with the absolute value of the slope greater than or equal to .2112 under the independence assumption is 6 so the p-value is 6/N where N=1000 samples or .006. The null hypothesis that the magnitude of the slope is zero is rejected. The small p-value indicates that the observed North-South one factor split does not occur at random. This bolsters our claim that there is a relationship between the factor loadings for each province.

CHAPTER 5

RELATION TO LARGE-SCALE CLIMATE PATTERNS

The above modeling study indicates geographic variation in typhoon landfall frequency over China on an interannual basis. In years with above normal landfall activity over Guangdong and Hainan, there are fewer storms over Fujian and provinces to the north. What causes this variation and can it be explained by variations in atmospheric and ocean variables?

The coherent north-south signal in China landfalls is expressed as a value for the FSI each year. We now turn our attention to the possibility that a portion of the interannual variation in this signal can be predicted based on large-scale climate variations. Specifically, we explore the possibility of statistically explaining the dominant coastal variation in typhoon occurrence with fluctuations in climate patterns. We begin by examining two known large-scale climate variations including the El Niño-Southern oscillation (ENSO) and the Pacific decadal oscillation (PDO).

We find little correlation between the FSI and the ENSO as measured by the SOI. The Pearson's product moment correlation coefficient $r = -0.12$. On the other hand their does appear to be some correlation with Pacific decadal oscillation (PDO), as measured by the PDOI, in fact, $r = -0.20$. It is the dominant factor in monthly SST variability in the North Pacific (north of about 20N latitude) (Mantua et al. 1997). During the warm phase of the PDO there is a departure from the average with negative SST and positive SLP pressure in the northern Pacific. Although this relationship exists, it is not very strong, thus we are motivated to move on and look at other covariates.

Alternatively it has been proposed by Liu et al. (2003) that variations in coastal typhoons might be related to regional climatological connections such as anomalous SST over midlatitude NW Pacific during the typhoon summer and fluctuations in sea-level pressure

Table 5.1. Linear Model

	Value	Standard. Error	t-value	P-value
(Intercept)	-7.6402	3.5816	-2.1332	0.0376
SLP	-0.3651	0.1003	-3.6396	0.0006
SST	0.6015	0.2514	2.3928	0.0203

(SLP) patterns between western China and Mongolia. Ho et al (2004), noted that SST increase in tropical regions of the WNP tend toward decreases in the midlatitude Pacific. This phenomena has an interannual variability. Furthermore it was hypothesized in the study done by Liu et al (2003) that historically lower SST in the midlatitude NW Pacific, especially during the summer season, could displace the predominant storm tracks to the south.

We begin by looking at the correlation between the FSI and SLP then SST relationships are explored. Results of the correlation between FSI and SLP indicate that SLP differences between Mongolia and western China are significantly negatively correlated to the FSI, $r(FSI, SLP = -0.43)$. An examination of the correlations between SST over the midlatitude NW Pacific during the months June to August and the FSI, results in $r(FSI, SST = 0.31)$, these results collaborate the hypothesis generated from an examination of the historical records. When SSTs are below normal in the midlatitude NW Pacific, values of the FSI are low as shown in Fig 5.1. To illustrate this result further a composite of anomalous SST for years with predominantly southern landfalls is shown in Fig. 5.2, negative values indicate lower than average SST in the midlatitude NW Pacific.

The top portion of Figure 5.3 shows when SLP pressure differences are high indicating relative high pressures over Mongolia and low pressures over western China, FSI values are low. This implies that when the gradient in SLP over Mongolia is greater there is a increase in surface winds in the form of a stronger easterly wind flow over northern China. This increase in surface flow inhibits TC from tracking toward the north therefore there is an increase of landfall activity over Guangdong and Hainan. Also, when SSTs over the NW Pacific are below normal during the summer months, tropical cyclones tend to track farther south and affect the southern provinces of China. The scatter plots shown in Fig 5.1 and Figure 5.3, indicates unequal variance therefore, we focus the result of the correlation

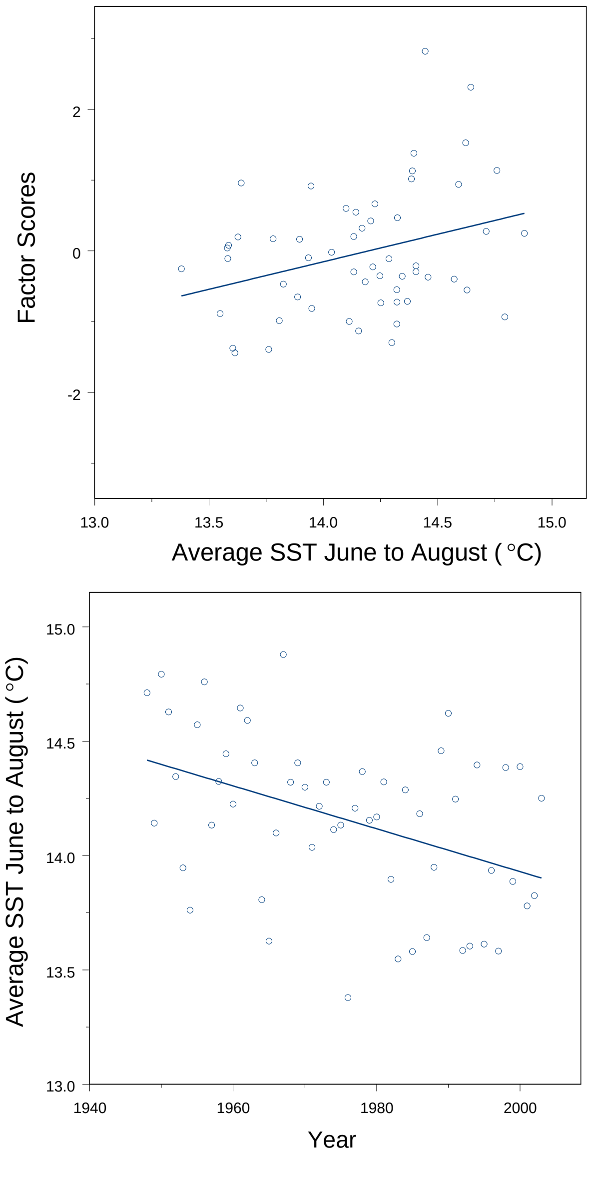

Figure 5.1. SST in the midlatitude NW Pacific during the summer June to August plotted against FSI (top map) SST over time

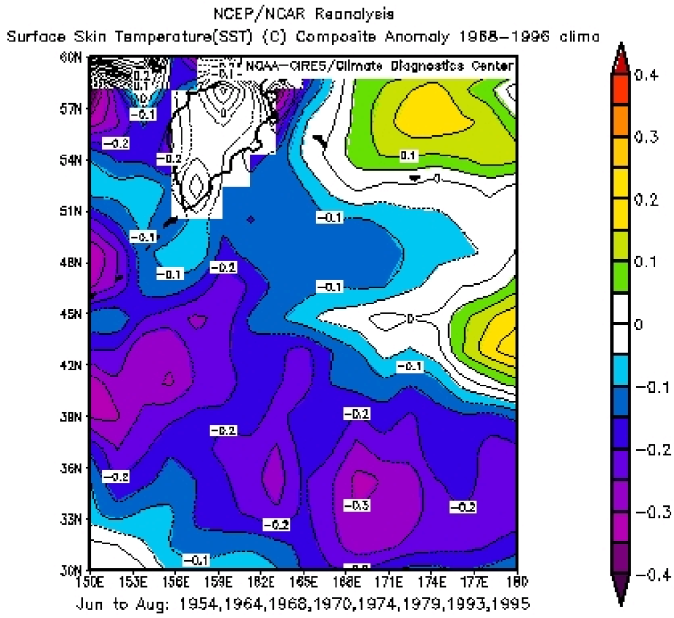

Figure 5.2. Map of anomalous SST over midlatitude NW Pacific for the months of June - August, during years of predominately southern landfalls

matrix by running a weighted linear regression. Here FSI is the response variable and SLP differences between western China and Mongolia, and SST over the midlatitude NW Pacific during the summer are the explanatory variables. The multiple R-squared value was found to be .27. This indicates that 27% of the variability in the FSI is explained by these two variables, the results are listed in Table 5.1.

These results are consistent with the speculation put forth in Liu et al (2003) that typhoons are more abundant across Guangdong when the climate is drier and windier in northern and central China. This coupled with lower SST in the midlatitude NW Pacific during the summer months displace the predominant storm tracks to the south. The bottom portion of Figure 5.3 plots annual pressure changes between western China and Mongolia.

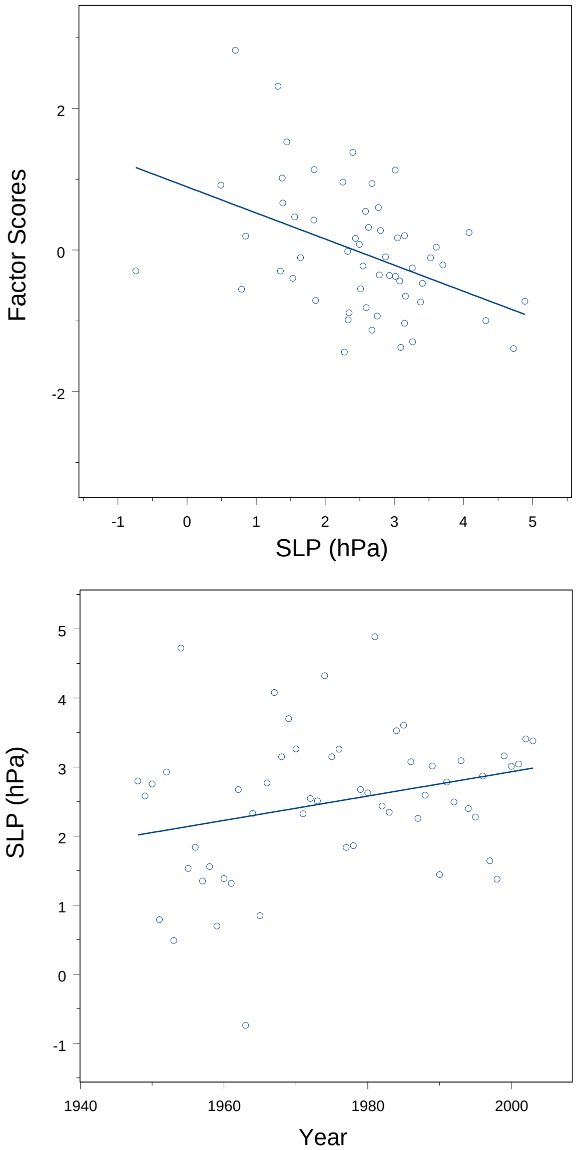

Figure 5.3. North-South variability in SLP between Mongolia and western China (top map) Annual changes in pressures over Mongolia and western China

CHAPTER 6

DISCUSSION

The variability of the typhoon landfall pattern in China is investigated using historical and modern records. The work is motivated by a recent hypothesis of an inverse relationship between the frequency of typhoons over northern China to those over the Guangdong Province in the south (Liu et al. 2001; Elsner and Liu 2003). The study makes use of the modern instrumental record of typhoons over the coastal provinces of China and documentary evidence of typhoons over Guangdong and Fujian. Observational indices of ENSO and the PDO are combined with more local variables to examine climate factors related to the pattern of China landfalls. The originality of this work rests with the examination of both historical and modern landfall records and in the use of a covariability model for identifying the dominant pattern of spatial landfall variability.

The historical records provide a hint at the important landfall pattern by showing a statistically significant negative correlation between the frequency of landfalls over Guangdong and Fujian. When activity over Guangdong is high, it tends to be low over Fujian and vice versa. The relationship is examined using correlation, conditional probabilities, and log-linear regression. The dominant landfall pattern is identified in the modern records of typhoon counts in coastal provinces using a factor analysis model. The model delineates the southern provinces of Guangdong, and Hainan from the northern provinces of Fujian, Taiwan, Zhejiang, Shanghai, Jiangsu, and Shandong. When typhoon activity is high over the southern provinces it tends to be low over the northern provinces. This result is new and provides a way to examine climate influences on geographic variations in typhoon activity. The statistical significance of the factor analysis model is tested using Monte Carlo simulation experiments. An index of annual activity representing the degree to which each year follows this pattern of activity is used to identify correlated climate variables.

The relationship between the dominant spatial pattern of China landfalls, as described by the FSI, and climate is first examined using indices for ENSO and the PDO. Although the SOI is not linearly related to the FSI, their is a weak relationship with the PDO. Examination of additional variables that might explain the landfall pattern indicate that a north-south SLP gradient between western China and Mongolia might be used as a predictor of regional typhoon activity. When the SLP gradient featuring relatively high pressures over Mongolia and low pressures over western China intensifies typhoons are more likely to track westward toward southern China. In contrast, when the SLP gradient weakens, recurving typhoons are more likely to visit the northern provinces of China.

Additionally, ocean surface temperatures over the midlatitudes of the NW Pacific appear to have a correlative affect on China landfalls. When temperatures are cooler than normal, southern China landfalls are relatively more likely. A linear regression model that includes sea level pressure differences between Mongolia and western China and SST over the midlatitude NW Pacific explains 27% of the inter-annual variability of the FSI. Physically, we speculate that a stronger than normal surface pressure gradient increases the easterly wind flow over China forcing the fledgling storms to track westward toward the southern coast. Moreover, colder water over WNP shifts the subtropical high pressure farther to the west and south thus keeping tropical cyclones over lower latitudes and tracking them toward Hong Kong.

CHAPTER 7

CONCLUSIONS

The major conclusions of this study are:

- Historical typhoon records from the Guangdong and Fujian provinces of China dating back to 1600 are inversely correlated on the annual time scale.
- A factor model applied to modern typhoon counts in the coastal provinces of China indicates a north-south split in activity, with the split occurring between Guangdong and Fujian.
- The factor model is statistically significant against a null hypothesis of random distribution of landfalls.
- A factor score index (FSI) provides a time series of the dominant geographical pattern in China landfall activity.
- The FSI is weakly negatively related to both the PDO and the SOI.
- The north-south sea-level pressure gradient over central Asia and sea-surface temperatures over the midlatitude NW Pacific are significant predictors of FSI on an annual basis.

The study can be improved. For example, it would be interesting to examine the geographic pattern of strong typhoons over China. It is likely to be similar to that of the typhoon pattern, but it might be more pronounced. More importantly, it would be revealing to examine the results of a factor model applied to the historical records and make a more detailed comparison with the present results. Unfortunately, typhoon counts for provinces other than Guangdong and Fujian are unavailable at this time. Finally, a closer examination of other atmospheric and oceanic variables might reveal additional relationships with the typhoon landfall pattern.

APPENDIX A

SOFTWARE USED

- ERSI: ArcMap version 8.0. Used to tabulate the direct passage of TC over study area.
- Insightful: Splus version 6.0. Used to create graphs, correlation matrix and to perform factor analysis.
- The R Foundation for Statistical Computing: *R* version 1.9.0. Used to perform simulation(provided by Tom Jagger).
- CDC: Atmospheric and oceanic data obtained from NOAA-CIRES Climate Diagnostics Center (CDC), Boulder, Colorado, from their website at http://www.cdc.noaa.gov/. All maps of variables are directly from the CDC website.

APPENDIX B

SIMULATION CODE

```
> get.prop1
function(x,i) { prop<-x[i,-1]/x[i,1]
y<-as.vector(factanal(prop,factors=1)$loadings) x<-1:length(y)
coef(lm(y~x)) }
> boot(data=e.count1, statistic= get.prop1, R=100)
ORDINARY NONPARAMETRIC BOOTSTRAP
Call: boot(data = e.count1,
statistic = get.prop1, R = 100)
Bootstrap Statistics :
      original       bias    std. error
t1* -0.4454049  0.010682298  0.19043247 t2*  0.2111963
-0.005499302  0.05117334
> get.prop1(e.count1)
(Intercept)           x
 -0.4454049   0.2111963
>wf<-get.e.stats.fisher(e.count1,n=1000)
Result of simulation wf= 1000 simulations...the following is and
example
(Intercept)           x
 -0.5993300   0.2216133
$sim.test[[999]]
(Intercept)           x
 0.19963247 -0.03571522
$sim.test[[1000]]
(Intercept)           x
 -0.2914978   0.1046065
```

```
> FA.ecount1<-get.prop(e.count1)
> FA.ecount1
Loadings: Factor1
Hainan    -0.366
Guangdong -0.429
Fujian     0.742
Taiwan     0.695
Zhejiang   0.643
Shi.J.Sd   0.478
Factor1 SS loadings
1.995
Proportion Var
0.332
```

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