ANOMALOUS ATMOSPHERIC CIRCULATIONS FORCED BY VOLCANIC AEROSOLS

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Abstract

During a strong volcanic eruption, the energy balance of the Earth is temporarily disturbed due to the addition of sulphate aerosols to the stratosphere. The selective absorption and reflection of radiation by these aerosols lead to both radiative and thermodynamical effects in the atmosphere. The goal of our study is to identify the anomalous atmospheric circulations generated under these volcanic conditions.

A Principal Component Analysis (PCA) and Combined Principal Component Analysis (CPCA) are first applied to the height and temperature data from the stratosphere at 30 mbar. While PCA extracts the Arctic Oscillation (AO) as a weak volcanic mode, the CPCA performs better and is found to extract a definite volcanic signal with a distinct zonal pattern of circulation. However, the stratospheric volcanic modes are different patterns from the linear PCA modes suggesting that the system’s response to the volcanic forcing is not obvious. The raw data are analysed for comparison.

Application of PCA and CPCA to tropospheric height and temperature revealed only a weak (not statistically significant) volcanic signal, but did extract a strong El Niño signal. Through an Analysis of Variance (ANOVA) technique it is possible to separate the response to volcanic forcing from that due to El Niño.

Combining the 30 mbar and 300 mbar height fields in a vertical CPCA, it is finally possible to extract the volcanic modes at both levels. The resulting tropospheric volcanic mode is shown to have similarities to a composite map of 500 mbar heights representing the difference between years with a strong polar vortex and years with a weak one.
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List of Acronyms

ANOV A Analysis of Variance
AO Arctic Oscillation
CPC Combined Principal Component
CPCA Combined Principal Component Analysis
EOF Empirical Orthogonal Function
ENSO El Niño/Southern Oscillation
GCM General Circulation Model
NAO North Atlantic Oscillation
NCAR National Center for Atmospheric Research
NCEP National Center for Environmental Prediction
PC Principal Component
PCA Principal Component Analysis
PNA Pacific-North America
SAT Surface Air Temperature
SSG Sum of Squares between Groups
SSR Residual Sums of Squares
SST Sea Surface Temperature
SVD Singular Value Decomposition
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Chapter 1

Introduction

1.1 Overview

Weather plays a role in our daily lives and our economic system. Over the past few decades our long term weather, our climate, has become a hot issue as our society develops and our way of life appears to be affecting our global climate. We begin to question the variability that we observe in the climate and ask ourselves whether we are to blame for these changes. However, climate variability is composed of multiple components, whose resolution is a current challenge. This multi-dimensionality to variability is, in part, because in addition to the various sources of variability, there are many components within the climate system which may be affected. One such section is the atmosphere. The variability present in the atmosphere alone can be composed of numerous effects. These effects include natural unforced variability, anthropogenic forced variability, and natural forced variability. It is this last component that will be the focus of this thesis. Natural forced variability in the atmosphere can take on many faces. A change in ocean temperatures, such as during El Niño, can force variability in the atmosphere. Changes in the incoming solar radiation can affect the dynamics of the atmosphere. Volcanic eruptions also fall into the category of natural forcing agents. These are just some of the pieces of the climate variability puzzle.
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1.2 Volcanic Aerosols

Stratospheric volcanic aerosols are the dominant contributor when it comes to short-term radiative forcing (figure 2 in Hansen et al., [5]). We are thus interested in studying their effects in greater detail. Small scale eruptions occur throughout each year, but their effects remain localized. Major eruptions occur less frequently, on average every few decades, but their effects are much more far-reaching. We will focus here on major tropical eruptions with strong vertical plumes. If the eruption is weak and/or the plume is ejected horizontally, then the sulphur dioxide remains in the troposphere and from here it quickly falls or is precipitated out. For this reason, the effects of tropospheric aerosols are short-term effects on the timescale of days or weeks. Strong eruptions with vertical plumes result in the SO$_2$ being injected into the stratosphere where chemical reactions work to convert it into sulphate aerosols. From here, zonal circulations in the atmosphere spread the aerosols into a stratospheric blanket. With tropical eruptions, these circulations can produce a blanket which encircles the globe in a matter of weeks. Stratospheric meridional circulations take 1-2 years to transport the aerosols out of the tropics, poleward through mid-latitudes, and back to the troposphere at higher latitudes where they soon leave the atmosphere (Robock, [11]). It is during this two year window that the aerosols can affect the global climate through the stratospheric absorption of longwave and shortwave radiation which cools the troposphere and warms the stratosphere.

One aim of this thesis is to help decipher the role of volcanoes in the complex phenomenon that is climate variability. Isolating the volcanic signal is a challenge, since it is composed of both a direct radiative effect and an indirect thermodynamical effect. The interactions and relative strength and importance of these two processes further complicates the description of a volcanic signal and its detection from among the variability. The buildup of volcanic aerosols enhances the stratospheric aerosol levels. This enhanced
Chapter 1. Introduction

Layer affects radiation through the scattering and absorption of shortwave radiation and the absorption of longwave radiation (Kirchner and Graf, [8]; plate 1 in Robock, [11]). The shortwave radiation comes from the incoming solar radiation. The primary source of longwave radiation is the radiation emitted by the earth. Through these changes in the radiation the resulting radiative effect of these aerosols is a warming of the stratosphere and a cooling of the troposphere at the surface. The dynamic response, which is a surface warming, is a complex side-effect of the changes in radiation and is thus an indirect effect of the volcanoes. Here, the differential heating of the stratosphere due to the changes in radiation from the aerosol layer results in an enhanced meridional temperature gradient (Graf et al., [4]). This enhanced temperature gradient leads to a strengthening of the stratospheric polar winter vortex as predicted by the thermal wind relationship. The strengthened vortex in turn traps the vertically propagating wave energy in the troposphere. The subsequent changes in the tropospheric circulation may account for the advection of warm air over the continents at mid- and high latitudes producing surface warming (Robock and Mao, [12]). Because the incoming solar radiation is not uniform, the strengths of the radiative and dynamical effects are not uniform across the globe or across seasons. At lower latitudes, in the tropics and subtropics, and in the summer, the radiative cooling effect near the surface is dominant and the dynamic warming effect over the continents is negligible. At higher latitudes, the warming effect in the winter is stronger in places. However, even during the winter months on a hemispheric scale the dynamic warming does not cancel out the radiative cooling effect and the general average is still a tropospheric cooling (Robock, [11]). An additional difficulty in extracting the volcanic signal is that the volcanic forcing appears to excite a natural mode of the stratospheric winter circulation. In some years that have no volcanic influence the stratospheric vortex is also strong. The tropospheric anomaly patterns observable during these years are similar to the patterns that occur in the volcanically forced years (Graf
et al., [4]).

In this thesis we will examine if a forced climate signal can be extracted from the observed variability and then investigate the kinematic response of the atmosphere to the forcing agents. The ability to understand even a small component can help when looking at the entire climate picture. Possible benefits include: explaining changes in the climate record and understanding if and why our climate is changing, as well as predicting the short term effects we can expect the next time a serious eruption occurs.
Chapter 2

Analysis Set-up: Data and Techniques

2.1 Data

The data consist of meteorological observational data that were obtained from the National Center for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) reanalysis project. This project is discussed in more detail in Kalnay et al. [6] and Kistler et al. [9]. One concern that arose was the impact of changes in the observation system, such as the introduction of satellite data, on the accuracy of the reanalysis. Based on the data fields we are using as well as the nature of our analysis, the detected effects of these changes should not affect our results. Another limitation of the reanalysis is that although the accuracy of the system may be estimated, it cannot account for gaps or errors in the original data which will affect all analysis systems. The output gridded fields were categorized based on the relative influences of the measured observational data and the model on their values. Both the geopotential height and the temperature fields were given the designation A, indicating the strong influence that the observations had. This places both variables in the most reliable class, which, although a subjective designation, is a positive sign for our results. It is also possible that these fields may estimate the state of the atmosphere better with the reanalysis than with the observations alone due to the statistical interpolations (Kalnay et al., [6]).

We use the gridded data for geopotential height and temperature. These cover the period from 1958 through to 1998, with a 2.5° x 2.5° grid resolution and 17 available layers.
in the vertical including 7 layers in the stratosphere. All the data are processed through Matlab. This study focuses on the effects in the Northern Hemisphere (NH), so the data are restricted to north of the equator. The volcanic thermodynamic response is strongest during the northern hemisphere winter, so an extended winter consisting of November through March is used. November and March were included to increase the sample size of the data, as the data represented the monthly means. Monthly mean data are used instead of daily data for three reasons. First, the computing resources at the time this work was started were not sufficient to handle data sets as large as those from the daily data, especially not for the entire northern hemisphere. Second, although the comparison with model data is beyond the scope of this thesis, the available model data are run on a monthly time scale and the observational data are chosen to be the same. And last, the effects that we are interested in occur on a longer time scale, not instantaneously, so the monthly data should be sufficient to reveal the atmospheric structure. By using monthly data instead of daily data we can perhaps eliminate some of the chaos in the data and extract a clearer volcanic signal. Also, the monthly averages may aid in removing the non-linearities, facilitating the use of a linear principal component analysis (PCA). This linearization of our study simplifies the procedures that must be carried out on the data as well as the interpretation, without compromising the validity of the results.

As a check, we have looked at the daily data, run through a 10-day filter. The range of the daily data has been reduced to the region from 20°N up to 87.5°N, for computational resource reasons. Also, a standard winter of December, January, and February is used, since sample size is no longer a problem. These data are analysed with the seasonal cycle both included and removed. The seasonal cycle is removed by subtracting the average of the daily means for each calendar day from the data for the appropriate individual days.

In the stratosphere, the daily data are taken at 20 mbar. Spatially, the first three height patterns (from a principal component analysis, explained in section 2.2) with the
seasonal cycle removed are the same as the monthly data results and modes 4 and 5 are flipped in terms of their importance in explaining the variance. With the temperature patterns, the first four spatial modes are the same and mode 6 is mode 5 from the monthly analysis. No discernable volcanic signal appears in the time series by using the daily data instead of the monthly data. Analysis of the daily data with the seasonal cycle included shows the existence of a large artificial oscillation in both the height and temperature variability fields during the first two years. The extreme nature of the oscillation suggests that this is not a physical result. Accordingly, the somewhat zonal pattern associated with this time series may not lead to any valid physical conclusions. Removing the seasonal cycle removes the artificiality, leaving the question of what was in the data originally to cause the anomaly. Removing the first two winters also accomplishes the goal of eliminating the artificial oscillations. The first three resulting height patterns are comparable to the monthly data results, and mode 4 is like mode 5 from the monthly analysis. With the temperature fields, the first four spatial patterns are the same. Again, no discernable volcanic signal appears in the daily data time series.

In the troposphere, the daily data are taken at 500 mbar. Spatially, the first five PCA height patterns with the seasonal cycle removed are the same as the monthly data results taken at 300 mbar. With the temperature modes, no accurate comparison could be made between the 500 mbar daily data and the 300 mbar monthly data with the seasonal cycle removed. A comparison to the monthly data at 500 mbar shows the same patterns for modes 4 and 5. Also, the second and third daily modes are similar to the first and second monthly modes. No discernable volcanic signal appears in the time series of the daily data of either height or temperature with the seasonal cycle removed. Analysis of the daily data with the seasonal cycle included again shows a large artificial oscillation in both the leading height and temperature time series during the first two years. Removing the first two winters removes the artificial oscillation, but somehow also masks the seasonal cycle.
Now, the seasonal cycle does not appear distinctly in any of the leading height modes and only explains 15% of the variance in the temperature modes.

Due to computer resource restrictions, a combined principal component analysis (explained in section 2.2) cannot be performed. However, because the leading modes in the separate analyses remain mostly unchanged, we can assume that the results in the combined analysis will also not change noticeably from the monthly results.

The volcanoes chosen had to release enough sulphate aerosols into the stratosphere to produce a global effect. The tropical volcanoes during the data record which met this requirement were Agung in Indonesia on March 17, 1963, El Chichon in Mexico on April 3, 1982, and Mount Pinatubo in the Phillipines on June 15, 1991. The two-year window following each eruption is defined as the volcanic years as this is the period when the effects are detectable. All remaining years are defined as non-volcanic years. The stratosphere observational data are taken at 30 mbar and the troposphere observational data are taken at 300 mbar. The main focus is on the geopotential height fields, although the temperature field is used as the secondary variable in the combined analyses. These data are analysed with the seasonal cycle both included and removed. The seasonal cycle is removed by subtracting the average of the monthly means for each calendar month from the data for the appropriate individual months.

2.2 Principal Component Analysis

Climate data sets are large multi-dimensional structures that need to be simplified for us to extract the information we need. One popular statistical tool to use is Principal Component Analysis (PCA). This technique finds the k-dimensional hyperplane that gives the best fit to an m-dimensional set of data (when k<m and hopefully k≪m). The leading principal component (PC), or mode, is the spatial pattern which accounts for
the maximum variance in the data. This spatial pattern, or loading, is also called the empirical orthogonal function (EOF). The spatial pattern for PC 1 is accompanied by a time series which describes its oscillation in time over the course of the data record. The second leading mode accounts for the maximum variance in the remaining data with the restriction that it is uncorrelated to the first mode. The magnitude of the contours of a spatial pattern are important when the pattern is considered in conjunction with its time series. In a given month, the time series represents the weighting given to the corresponding pattern, such that the sum of all the weighted spatial patterns totals the normalized observed pattern for that month.

Observational data are only ever available as a single time series with no possibility of ensemble averaging the results. Consequently, if the data are noisy the results could be confounded by chaos. The potential for confounding by noise is particularly true in a principal component analysis (PCA) on a single observational field, and could explain why PCA might not clearly bring out the volcanic signal. However, if two fields are related or simultaneously affected by some forcing, then doing a combined principal component analysis (CPCA) with this pair of fields might help to bring out the signal by finding the coherent variability and removing some of the noise. We must rely on techniques such as CPCA to provide a way of combining multiple fields of observational data to find a clearer signal. This technique simultaneously performs PCA on two different data sets, and the result is a set of spatial patterns for each field with common time series. The leading modes thus obtained represent variability common to both fields. We use two different pairings. The first pairing shows how different fields at the same level are similarly affected. The second pairing shows how the same field at different levels are similarly affected.
2.3 Analysis of Variance

An analysis of variance (ANOVA) procedure is used to test the significance of the volcanic signal. ANOVA is conducted comparing the volcanic and non-volcanic years from the time series obtained from the PC analysis. Each time series is divided into two groups, where \( k \) represents the number of groups and \( i \) indexes the various groups. Here, one group is for volcanic years \( (i = 1) \) and one group is for non-volcanic years \( (i = 2) \). Within each group the data are further subdivided into five subgroups,\(^1\) where each month represents a different subgroup. \( l_i \) represents the number of subgroups within group \( i \), while \( j \) indexes the various subgroups. The data within the subgroups are the observations. Define \( n_{ij} \) to be the number of observations in group \( i \) and subgroup \( j \), with \( m \) indexing the observations. Here, each observation is the time series value from a different year and is given by \( y_{mij} \). There are 6 observations per subgroup (ie. month) for the volcanic years \( (n_{1j} = 6 \text{ for all } j) \) and 34 observations per subgroup for the non-volcanic years \( (n_{2j} = 34 \text{ for all } j) \). We are using this allocation of the data to try to ensure that the observations within a subgroup are independent of one another.

Define the following means:

Subgroup mean:

\[
\bar{y}_{ij} = \frac{\sum_{m=1}^{n_{ij}} y_{mij}}{n_{ij}}
\]  

Group mean:

\[
\bar{y}_i = \frac{\sum_{j=1}^{l_i} \sum_{m=1}^{n_{ij}} y_{mij}}{\sum_{j=1}^{l_i} n_{ij}}
\]  

\(^1\)By using all five months we assume an amount of independence from one month to the next. However, if we assume the months are dependent, the ANOVA values for all the data can be recalculated using only the non-adjacent months of November, January, and March. While the results change numerically, their significance with respect to the f-ratio percentiles and the volcanic signal still leads to the same conclusions. In fact, the volcanic effect may be more clearly illustrated through these results.
Overall mean:
\[
\bar{y} = \frac{\sum_{i=1}^{k} \sum_{j=1}^{l_i} \sum_{m=1}^{n_{ij}} y_{mij}}{\sum_{i=1}^{k} \sum_{j=1}^{l_i} n_{ij}}
\]  
(2.3)

The sum of squares between groups (SSG) is calculated with the means for each group and the overall mean.
\[
SSG = \sum_{i=1}^{k} \left( \sum_{j=1}^{l_i} n_{ij} \left( \bar{y}_i - \bar{y} \right)^2 \right)
\]  
(2.4)

The residual sums of squares (SSR) within subgroups is calculated with the individual data points and the subgroup means.
\[
SSR = \sum_{i=1}^{k} \sum_{j=1}^{l_i} \sum_{m=1}^{n_{ij}} \left( y_{mij} - \bar{y}_{ij} \right)^2
\]  
(2.5)

If the total number of observations, \( N \), is given by
\[
N = \sum_{i=1}^{k} \sum_{j=1}^{l_i} n_{ij}
\]  
(2.6)
and the total number of subgroups, \( L \), is given by
\[
L = \sum_{i=1}^{k} l_i
\]  
(2.7)
then the f-ratio, \( F \), is given by
\[
F = \frac{SSG/(k - 1)}{SSR/(N - L)}
\]  
(2.8)
where \( k - 1 = 1 \) and \( N - L = 190 \) are the degrees of freedom of SSG and SSR respectively (von Storch and Zwiers, [17]). The distribution of \( F \) is \( F \sim F(k - 1, N - L) \) and is a function of the degrees of freedom of SSG and SSR. Tabulated values for the 95\(^{th}\), 99\(^{th}\), and 99.9\(^{th}\) percentiles of \( F(1,190) \) are 3.89, 6.77, and 11.17 respectively. Each measured f-ratio is compared to these values to get an idea of the strength of the volcanic signal as determined by statistics. An f-ratio value exceeding 11.17 suggests a definite volcanic signal, a value between 6.77 and 11.17 suggests a strong volcanic signal, a value between 3.89 and 6.77 suggests a potential or weak signal, and a value less than 3.89 suggests no measurable volcanic signal.
Chapter 3

An Analysis of Observational Climate Data - Stratosphere

The stratosphere forms the upper atmosphere of the Earth in terms of the layers that are important for our weather. This layer consists of an isothermal region, where the air temperature is constant with height, and a temperature inversion region above that, where the air temperature is increasing with height due to UV absorption by ozone. Vertical motion and hence vertical mixing is reduced in such a temperature environment, which has the effect of stratifying this stratospheric layer. In addition, this temperature structure restricts the effects of the vertical motions of the lower atmosphere, the troposphere, on the upper layer. The stratosphere stretches from around 200 mbar to 1 mbar, which is equivalent to about 11 km to 50 km above sea level. Due to the distance from the surface and the stratification, this upper layer is not directly affected by topography or complex interactions with the land and ocean surfaces. This, however, does not suggest that there is no connection between the upper and lower atmosphere. We will see later how the two layers can tie together. Spatial patterns describing the variability in the stratosphere tend to be simpler than at lower levels. In general, the features are broader with fewer centres. We conduct two separate analyses on the stratosphere alone. The first is the PCA, performed separately on both the geopotential height field and the temperature field. The second is the CPCA, performed on the geopotential height and temperature fields.
3.1 Principal Component Analysis

The first five height modes of the PC analysis at 30 mbar account for a combined 92.6% of the total variance with the seasonal cycle removed. The two leading modes (figure 3.1) account for 71.3% and 9.2% of variance respectively. The EOF 1 pattern is a mostly zonal, hemispherical structure called the Arctic Oscillation (AO) (Thompson and Wallace, [15]; Baldwin and Dunkerton, [2]). Although the AO was originally noted, based on a surface analysis, as a more zonally symmetric feature than the previously defined North Atlantic Oscillation (NAO), there is also a strong coupling with zonal features of the stratosphere. Signatures of the AO at various levels have been produced through regression of the AO index with the geopotential (Baldwin and Dunkerton, [2]). There is strong resemblance of our EOF 1 pattern to the AO signature at 30 mbar. The zonal centre over the pole shows a strong, uniform latitudinal gradient. EOF 2 is a dipolar zonal wave 1 pattern with centres on opposite sides of the north pole. Although the positive centre has larger amplitude and range, the zero-axis lies approximately along 50°W/130°E. EOF 4 is included based on the strength of its volcanic signal, even though it only accounts for 2.8% of the variance. This pattern is characterised by two negative centres and two positive centres.

ANOVA suggests that neither PC 1 nor PC 2 have a significant volcanic signal (table 3.1), although they both potentially have a weak signal. This weak signal, however, could be due to an anomalous few years or some feature other than the volcanoes. ANOVA suggests that PC 4 has a definite volcanic signal. The corresponding time series (figure 3.2) illustrate this more clearly. A volcanic signal could manifest itself in the time series curves as a distinct peak or valley or as an increase or decrease in the variability or in the amplitude of the fluctuations during the volcanic years compared to the fluctuations during the non-volcanic years. A dip in the oscillations of PC 2 in the early 80's and 90's
Figure 3.1: Spatial patterns of the first, second, and fourth EOF modes from a PC analysis of 30 mbar observational height data with the seasonal cycle removed. Contour interval is 0.0025.
Chapter 3. *An Analysis of Observational Climate Data - Stratosphere*

<table>
<thead>
<tr>
<th>Analysis at 30 mbar</th>
<th>With the seasonal cycle</th>
<th>Without the seasonal cycle</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Height PCA</strong></td>
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<td></td>
</tr>
<tr>
<td>PC 1</td>
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<td>4.3</td>
</tr>
<tr>
<td>PC 2</td>
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<td>4.6</td>
</tr>
<tr>
<td>PC 3</td>
<td>1.6</td>
<td>1.1</td>
</tr>
<tr>
<td>PC 4</td>
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<td>17.1</td>
</tr>
<tr>
<td>PC 5</td>
<td>10.2</td>
<td>0.0001</td>
</tr>
<tr>
<td><strong>Temperature PCA</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PC 1</td>
<td>0.03</td>
<td>0.03</td>
</tr>
<tr>
<td>PC 2</td>
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<td>9.0</td>
</tr>
<tr>
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<tr>
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<td>4.7</td>
</tr>
<tr>
<td>PC 5</td>
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</tr>
<tr>
<td><strong>CPCA</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PC 1</td>
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<td>17.5</td>
</tr>
<tr>
<td>PC 2</td>
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<td>30.8</td>
</tr>
<tr>
<td>PC 3</td>
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<tr>
<td>PC 4</td>
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<td>0.2</td>
</tr>
<tr>
<td>PC 5</td>
<td>2.8</td>
<td>12.2</td>
</tr>
</tbody>
</table>

Table 3.1: ANOVA f-ratios for the volcanic signal in the leading stratospheric principal components. The values for the 95th, 99th, and 99.9th percentiles of F(1,190) are 3.89, 6.77, and 11.17 respectively.
Figure 3.2: Time series for the EOF modes shown in figure 3.1. Time series tick marks indicate Novembers. Shaded regions indicate volcanic years.
may contribute to the measured signal, but a visual inspection of the time series shows no noticeable major change during the volcanic years. Although PC 4 is mostly negative during the volcanic years, which may account for the measured signal, this may not be a volcanic effect. The apparent signal in the time series of PC 4 is strongest following the El Chichon eruption and weaker following the Mount Pinatubo eruption, even though the extent and magnitude of the El Chichon eruption was less. Some other effect could have caused the dips in the time series, either alone or in combination with a volcanic effect. Although El Niño is a tropospheric event, perhaps this is the stratospheric manifestation of the signal. Either way, the observed signal is probably not purely volcanic in origin.

The first ten height modes of the PC analysis at 30 mbar account for a combined 98.8% of the total variance with the seasonal cycle included. The two leading modes (figure 3.3) account for 74.5% and 7.5% of the variance respectively, with the seasonal cycle appearing mostly in the first time series (figure 3.4). Also included are the fourth and fifth modes which account for only 4.0% and 2.2% of the variance respectively. EOF 1 is a mostly zonal pattern which is similar to the AO. However, the zero contour is more extensive than the signature of the AO at this level. This zonally-symmetric pattern over the pole has a strong resemblance to the leading mode with the seasonal cycle removed. EOF 2 is also similar to the second mode with the seasonal cycle removed. It is a dipolar, zonal, wave 1 pattern with centres on opposite sides of the north pole. However, the zero-axis instead occurs along 75°W/105°E. EOF 4 consists of a positive centre near the pole and two negative centres on near opposite sides, not quite lined up along the 90°W/90°E axis. EOF 5 is similar, but with the three centres roughly lined up along the 0°/180° axis. Despite some similar spatial patterns, the time series in this analysis bear little resemblance to the time series with the seasonal cycle removed. The first mode shows a volcanic signal (table 3.1), but this weak signal is not apparent in the time series. The definite signal in PC 4 may be attributable to the dips during the El Chichon and
Figure 3.3: Spatial patterns of the first, second, fourth, and fifth EOF modes from a PC analysis of 30 mbar observational height data with the seasonal cycle included. Contour interval is 0.005.
Figure 3.4: Time series for the EOF modes shown in figure 3.3. Time series tick marks indicate Novembers. Shaded regions indicate volcanic years.
Mount Pinatubo volcanic periods. However, there is no apparent effect during the Agung volcanic period. Again, the response is strongest following the El Chichon eruption, suggesting that some other effect besides the volcanic aerosols contributed to all or part of the perceived response. This again suggests that the signal is probably not purely volcanic in origin, although volcanic aerosols may still play a minor role. The slightly zonal parts of the pattern may account for some of the measured volcanic response. Interestingly, though, the spatial pattern of PC 4 is comparable to the pattern in the daily data that shows the artificial variability, implying that we cannot trust the volcanic signal seen in this monthly data mode since it is unlikely to be physical. While the averaged monthly data may eliminate the artificial variability from the beginning of the corresponding time series, the validity of EOF 4 is still questionable. Also, since EOF 5 is the next mode, the volcanic signal measured by ANOVA may not be physical in this mode either. Note that this problem is not apparent in the data with the climatology removed.

Scatterplots of the leading time series (PC 1, PC 2) only show a non-random distribution by separating the volcanic years into separate months (figure 3.5). However, there are now too few points in each group and the statistical significance is lost from the scatterplot. As a result, we lose the ability to reach a legitimate conclusion and cannot attribute any non-randomness to a specific forcing. Here, the winter months (December, January, and February) show PC 1 positive and the shoulder months (November and March) show PC 1 to be negative. The tendency of each of the months is similar in the non-volcanic years (figure 3.6), so it is most likely a seasonal cycle effect.

The impact of the volcanic aerosols on the stratospheric temperature field differed from the effects on the height field. The first five temperature modes of the PC analysis at 30 mbar account for a combined 90.1% of the total variance with the seasonal cycle removed, while the two leading modes (figure 3.7) account for 61.9% and 14.0% of the
Figure 3.5: Scatterplot of 30 mbar observational height data, during volcanic years, projected onto the planes spanned by the first and second EOF patterns of the PC analysis with the seasonal cycle included. The data has been separated into months.
Figure 3.6: Scatterplot of 30 mbar observational height data, during non-volcanic years, projected onto the planes spanned by the first and second EOF patterns of the PC analysis with the seasonal cycle included. The data has been separated into months.
variance respectively. The EOF 1 pattern is a mostly zonal structure and resembles the AO signature on the temperature field at this level. A comparison with the leading height EOF pattern (figure 3.1) shows a marked similarity in spatial structure. In addition to the zonal symmetry, the centre over the pole shows a strong, latitudinally uniform latitudinal gradient. EOF 2 is a dipole pattern with centres on opposite sides of the North Pole. Although not exactly symmetrical, the dipole has a zero-axis approximately along 75°W/105°E. EOF 5 is a mostly zonal pattern, except near the pole where there is a negative centre flanked by two positive centres.

ANOVA suggests that PC 1, the zonal AO mode, has no volcanic signal and PC 2, the dipole, shows a strong volcanic signal (table 3.1). In fact, a stronger volcanic signal appears in PC 5, although this mode accounts for only 2.5% of the variation. The two leading time series (figure 3.8) do not clearly illustrate the existence of a volcanic signal. However, in PC 5 a decrease in the amplitude of the fluctuations during one volcanic period as well as a large jump at the end of another volcanic period could account for the observed signal in this mode. Unfortunately, it may not be possible to attribute these changes to volcanic aerosols, due to the sporadic nature of the time series changes.

When the seasonal cycle is included, the first five temperature modes of the PC analysis at 30 mbar account for 92.8% of the total variance, with the two leading modes (figure 3.9) accounting for 70.6% and 10.3% respectively. The EOF 1 pattern is again mostly zonal in structure, with a uniform latitudinal gradient and resembling the AO. There is negligible change in the leading mode with the seasonal cycle included and removed. Again, EOF 2 is a dipolar pattern with centres on opposite sides of the north pole, although this time the zero-axis runs approximately along 85°W/95°E. EOF 5 is again a somewhat zonal pattern, except near the pole where there is a positive centre flanked by two negative centres.

The seasonal cycle appears most strongly in the leading time series, although it is still
Figure 3.7: Spatial patterns of the first, second, and fifth EOF modes from a PC analysis of 30 mbar observational temperature data with the seasonal cycle removed. Contour interval is 0.005.
Figure 3.8: Time series for the EOF modes shown in figure 3.7. Time series tick marks indicate Novembers. Shaded regions indicate volcanic years.
Figure 3.9: Spatial patterns of the first, second, and fifth EOF modes from a PC analysis of 30 mbar observational temperature data with the seasonal cycle included. Contour interval is 0.005.
detectable in the other time series (figure 3.10). However, we can observe a resemblance in the oscillations of these time series and those with the seasonal cycle removed by comparing the corresponding time series. Of greatest interest are the plateaus that appear during the volcanic years in the time series of PC 5. The differences between the volcanic years and the non-volcanic years make it believable to attribute these changes to volcanic aerosols.

ANOVA also shows little change between the analysis with the seasonal cycle included and the analysis with the seasonal cycle removed. Here, we see that PC 1, the zonal AO mode, shows no volcanic signal while PC 2, the dipolar mode, shows a strong volcanic signal (table 3.1). The one definite volcanic signal occurs in PC 5 with the seasonal cycle included (as was also evident in the time series). The signal in PC 5 is so strong that it raises the question of whether or not this is actually a new mode, a volcanic mode. Unfortunately, because this is observational data it cannot be checked with the volcanic aerosol effects eliminated, so we cannot answer whether this mode would still be there without the volcanic forcing. Even though this mode only accounts for 2.4% of the total variance, the importance of its role in the volcanic circulations may be significant. Additionally, the volcanic significance of this mode decreases with the removal of the seasonal cycle, which could indicate that the volcanic and seasonal effects are somehow tied together.

3.2 Combined Principal Component Analysis

During the extended winter we expect that the thermodynamic effect of the volcanic aerosols will be strong enough to play a role. Recall that under the dynamical effect there is an increased equator to pole temperature gradient and a strengthened polar vortex that corresponds to an increased equator to pole height gradient. Since the dominant change
Figure 3.10: Time series for the EOF modes shown in figure 3.9. Time series tick marks indicate Novembers. Shaded regions indicate volcanic years.
in the temperature field and the height field is similar, perhaps the volcanic aerosols affect the two fields in a related way. To test this, we conduct a stratospheric CPC analysis of height and temperature, both with the climatology removed and then included. The height modes are presented and analysed in detail. Both the height and temperature spatial patterns for the first ten modes are shown in Appendix A.

When the climatology is removed, the first height mode (EOF 1) (figure 3.11) has a stronger zonal symmetry than the corresponding PCA mode. In addition, the structure of the latitudinal gradient differs from the AO as seen in PCA mode 1 (figure 3.1). EOF 2 is again dipolar in structure, but the overall spatial extent of the pattern appears to be much greater than in the PCA mode 2. The negative centre does not appear as focused as in the PCA mode. Also, both centres have shifted further south, although they are still over North America and Europe. These two leading modes account for 33.5% and 13.2% of the variance respectively. The first ten modes account for a total of 89.1% of the total variance. Both of these CPCA modes show a definite volcanic signal (table 3.1), in particular in the second mode. This definite volcanic signal is also apparent in the time series curves (figure 3.12). The time series for CPC 2 shows anomalous negative peaks in the first year of each volcanic period followed by a return to the pre-volcanic state in the second year of each volcanic period. The time series for CPC 1 also shows anomalous negative peaks during the volcanic period, but they are not as significant compared to the rest of the time series. Additionally, these two time series show a distinct similarity in their oscillations, especially during the volcanic years, which suggests some sort of coupling across these first two modes. Although the two modes are uncorrelated, they may not be independent (Monahan et al., [10]) and the response to volcanic forcing may project onto multiple linear modes. The fifth principal component (CPC 5) was included in this analysis due to the definite volcanic signal that it measured (table 3.1), even though CPC 5 only accounts for 6.8% of the total variance. EOF 5 (figure 3.11) shows a
Figure 3.11: Spatial patterns of the first, second, and fifth height EOF modes from a CPC analysis of 30 mbar observational height and temperature data with the seasonal cycle removed. Contour interval is 0.002.
Figure 3.12: Time series for the EOF modes shown in figure 3.11. Time series tick marks indicate Novembers. Shaded regions indicate volcanic years.
negative centre near the pole, similar to the one observed in CPC 2. The corresponding
time series (figure 3.12) shows the same anomalous negative peaks in the volcanic years
as the leading two time series, including a significant drop at the start of each period.

The volcanic signal in the CPC analysis can be clearly illustrated through the use of
scatterplots. These scatterplots (figure 3.13) show the distribution of points in the planes
spanned by (CPC 1, CPC 2), (CPC 1, CPC 5), and (CPC 2, CPC 5). The first column
shows how these three components relate during non-volcanic years. With the seasonal
cycle removed from this data, any tendencies in the height or temperature fields due
to seasonal effects should not be visible. During the non-volcanic years the distribution
of points shows no significant bias towards positive or negative quadrants. The second
column shows the relationships during the volcanic years. To emphasize the observed
effect, the data are restricted to the first winter following the three eruptions. Although
the aerosol effects last for up to two winters, the dissipation of the aerosols is less in the
first year and thus we can expect the volcanic effect to be stronger and clearer. In the
second year, although the signal may still be statistically measureable, a shift back to
the non-volcanic state is already visually apparent in the time series (figure 3.12). With
this restriction, a clear pattern emerges where all three components are always negative
or at least mostly negative during the first volcanic winter.

A composite using CPCA height modes 1, 2, and 5 is created to further examine
how these patterns, which collectively seem to represent the volcanic signal, change as a
whole. These three EOF patterns, with the seasonal cycle removed, are added together for
each volcanic month based on their relative strengths as given by the corresponding time
series values. The first winter following the Mount Pinatubo eruption yields the strongest,
clearest pattern, although the other volcanic winters yield similar results. Figure 3.14
shows this mostly zonal pattern which may be a product of volcanic activity. EOF
1 appears to have the strongest influence, resulting in the mostly zonal pattern with
Figure 3.13: Scatterplots of 30 mbar observational height and temperature data projected onto the planes spanned by the first, second, and fifth EOF patterns of the CPC analysis with the seasonal cycle removed. Column one contains data from non-volcanic years. Column two contains data from the first winters following the volcanic eruptions.
Figure 3.14: Composite height EOF patterns constructed for the first winter following the Mount Pinatubo eruption using PCs 1, 2, and 5 from a CPC analysis of 30 mbar observational height and temperature data with the seasonal cycle removed. Contour interval is 0.25.
a strong, latitudinally non-uniform, latitudinal gradient. Another key feature of this pattern is the strong incursion over North America, which reflects the contributions of both EOF 2 and EOF 5.

With the climatology included, the first height mode from the stratospheric CPC analysis of height and temperature (figure 3.15) is comparable to EOF 1 with the seasonal cycle removed (figure 3.11). It is fairly zonally symmetric, but with a slight shift from over the north pole. It also has a latitudinally non-uniform latitudinal gradient. We expect that the first mode would extract the spatial patterns that account for the maximum variance common to both fields. Because the leading time series of the coupled modes does not show a seasonal cycle as strong as that seen on the time series of the second mode (figure 3.16), this suggests that height and temperature do not vary together strongly on the seasonal cycle. Instead, their common variations may be based on some other factor. This may explain the small change in EOF 1 with the removal of the seasonal cycle. The second mode contains the seasonal cycle, as indicated by the time series. There are two centres in the second height mode, a strong minimum over the Pacific and a milder minimum over western Europe. This pattern bears no resemblance to the AO or to the previously discussed PCA and CPCA EOF 2's. The first ten modes account for a combined 90.8% of the total variance, with the first four modes accounting for 29.6%, 21.9%, 9.5%, and 9.3% respectively. All of these CPCA modes show a strong volcanic signal (table 3.1), with the second mode being the strongest and most definite. On top of the seasonal cycle variations, there are other changes in the time series of CPC 2 including the drops in the second volcanic years. The general trend in the first two time series appears to be quite similar, although opposite, suggesting the same sort of coupling between those modes that was apparent with the seasonal cycle removed. Of note, the dipolar pattern which appeared in the second stratospheric PCA mode with the climatology removed now appears in the fourth leading component. The time series
Figure 3.15: Spatial patterns of the first four height EOF modes from a CPC analysis of 30 mbar observational height and temperature data with the seasonal cycle included. Contour interval is 0.002.
Figure 3.16: Time series for the EOF modes shown in figure 3.15. Time series tick marks indicate Novembers. Shaded regions indicate volcanic years.
Figure 3.17: Composites of averaged raw 30 mbar height data with the seasonal cycle removed for (a) the first volcanic winters and (b) non-volcanic winters. Contour interval is 10.

of these two also have similar features, although the CPCA time series has less noise. Although CPC 4 shows a strong volcanic signal, the time series (figure 3.16) does not have an immediately obvious volcanic influence.

3.3 Raw data analyses

Composites are also created from the raw data anomalous from the seasonal cycle (figure 3.17). Here, no statistical analyses are performed, although the seasonal cycle is removed. Recall that the volcanic winters are the two winters following each of the eruptions and the non-volcanic winters are all the remaining winters. The volcanic composite contains only the first of the volcanic winters following each of the eruptions and is constructed by averaging together the data from all of the appropriate volcanic months. Because of the strength of the Mount Pinatubo eruption, the third winter following that eruption is excluded from the non-volcanic composite. Thus, the non-volcanic composite is the average of the months in all of the non-volcanic winters except for the 93-94
winter following Mount Pinatubo. Unlike a single EOF, these composites are not simply oscillations of a single spatial pattern, but are instead the average of the realizations of the natural data anomalous from the seasonal cycle for both the volcanic and non-volcanic years as defined above. Note the similarities in the spatial structures. Both patterns show a centre off-set from the pole, but the contours are opposite. Unfortunately, this may be more a product of the calculation process than of the data themselves. The reason for this is that with the seasonal cycle removed the sum of all the months is zero everywhere. Since only 4 years (20 months) out of 50 years are not included in the analysis, we expect the remaining data to sum to near zero. As a result, the two spatial patterns must be opposite in sign. There are only 15 volcanic months and 165 non-volcanic months, which will automatically result in much smaller magnitudes for the non-volcanic contours. There is no clear way around this problem when the seasonal cycle has been removed. That these patterns are reverse clearly suggests which state is the volcanic state. In the volcanic years there is a decrease in height near the pole and an increase in the tropics corresponding to a strengthening of the polar night jet. In the non-volcanic years on average the reverse occurs. Physically, the raw data shows the same atmospheric structure in volcanic years as the statistical analyses.

Composites are also presented for the raw stratospheric height data with the seasonal cycle included (figure 3.18). These results show the true structure of the atmosphere and not the anomalous structure. The low is over the pole with the heights increasing towards the equator. The biggest difference between the two structures is the number of contours, which indicates the approximate magnitude of the equator to pole height gradient. A larger gradient suggests a stronger polar vortex in the volcanic years, which is exactly what we expect to see, based on the previous results. One thing to note is that there exist other forcings, besides the volcanic aerosols, which can excite the strong vortex state. In particular, the strong vortex can also occur during non-volcanic years.
Figure 3.18: Composites of averaged raw 30 mbar height data with the seasonal cycle included for (a) the first volcanic winters and (b) non-volcanic winters. Contour interval is 200. For (a), the inner and outer contours are 22,400 gpm and 23,800 gpm respectively. For (b), the inner and outer contours are 22,600 gpm and 23,600 gpm respectively.

As a result, during the non-volcanic years the data are averaged over both years with a stronger polar vortex and years with a weaker vortex, unlike the average of only strong vortices that occurs in the volcanic case.

One additional technique used on the raw data to try and combat this problem with the seasonal cycle, is to perform a bootstrap analysis. More importantly, the bootstrap analysis can indicate the statistical significance of the difference between the volcanic and non-volcanic years in both the height and temperature patterns. Because the volcanic period is defined based on three years of five months, each sample of the bootstrap analysis is also chosen as a collection of three winters. Every combination of three winters, from either the height or the temperature record, is considered exactly once for a total of 9880 possible combinations in each record. Each group of fifteen months is then averaged together to form a single height or temperature composite. In order to perform the bootstrap analysis, we need to choose a variable to measure the difference between volcanic
Chapter 3. An Analysis of Observational Climate Data - Stratosphere

Figure 3.19: (a) A histogram of the maximum height difference in three winter composites constructed from the raw 30 mbar height data and normalized based on the total number of points. (b) The difference between the normalized number distribution based on all years and the normalized number distribution based on the non-volcanic years. The solid vertical line marks the median value and the dashed vertical line marks the value using the first volcanic winters.

and non-volcanic years. A stronger polar vortex in volcanic years suggests that the difference between the height maximum and the height minimum is an appropriate measure. So, we represent each composite numerically with the value that indicates the maximum height (or temperature) difference in each composite. We did not use correlation coefficients to compare the various composites, because the correlation coefficients may be small when two patterns differ spatially, even if they have essentially the same structure.

The results of calculating these maximum differences are shown in histograms in figures 3.19 and 3.20. These histograms are normalized based on the total number of points. In addition, the differences are calculated using only combinations of non-volcanic winters, which results in 5456 possible combinations. The resulting non-volcanic histograms have a different shape than when all the years are used. To illustrate this, the normalized distribution for non-volcanic years is subtracted from the normalized distribution for all years and the result is plotted in (b) in figures 3.19 and 3.20. These curves show that a
Figure 3.20: (a) A histogram of the maximum temperature difference in three winter composites constructed from the raw 30 mbar temperature data and normalized based on the total number of points. (b) The difference between the normalized number distribution based on all years and the normalized number distribution based on the non-volcanic years. The solid vertical line marks the median value and the dashed vertical line marks the value using the first volcanic winters.

<table>
<thead>
<tr>
<th>Bootstrap analysis</th>
<th>With the seasonal cycle</th>
<th>Without the seasonal cycle</th>
</tr>
</thead>
<tbody>
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<td>Height field</td>
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<td>73.7</td>
</tr>
<tr>
<td>Temperature field</td>
<td>91.2</td>
<td>85.1</td>
</tr>
</tbody>
</table>

Table 3.2: Percentile values for the volcanic difference in the bootstrap analysis in the stratosphere at 30mbar.

larger height (or temperature) difference is favoured in the volcanic years, which relates to a stronger polar vortex. The statistical significance of the volcanic influence on height and temperature patterns is measured by the volcanic percentile, the percentage of the bootstrap results that are less than the volcanic difference. The volcanic difference, which is the result obtained from using the first winter from each of the three volcanic periods, is thus compared against the rest of the results from the bootstrap procedure (table 3.2). The percentiles show that with the original data for both height and temperature, the
significance of the volcanic structure is clear. With the climatology removed, the results are still reasonable, but the difference may be partly tied in to the seasonal cycle.

When looking at the raw stratospheric temperature data, a pattern which is not strictly zonal appears. This is different from what we might initially expect to see, based on the radiative theory which predicts an enhanced meridional temperature gradient due to the latitudinal differences in heating. The same procedure is used on the temperature data as was used for the height data, with the results with the seasonal cycle included and removed shown. A dipole-like structure is apparent with the seasonal cycle included (figure 3.21), showing a low near the pole and a high over the North Pacific. We see that the low is deeper and the high is stronger in the volcanic years, perhaps corresponding to a stronger polar vortex on average in the affected years. One important thing to note is that in the PC analysis of stratospheric temperature, the leading zonal mode shows no volcanic signal (table 3.1) while the second mode is dipolar and shows a strong volcanic signal.
Figure 3.22: Composites of averaged raw 30 mbar temperature data with the seasonal cycle removed for (a) the first volcanic winters and (b) non-volcanic winters. Contour interval is 0.4.

both with the seasonal cycle included and removed. A noisy dipolar structure is apparent in the raw data when the seasonal cycle is removed (figure 3.22). The zero contours are in comparable locations in both the volcanic and non-volcanic years, as well as the maxima and minima, although the signs are opposite. The low centred over the Arctic/North Atlantic oceans suggests a cooling and deepening of the temperature gradient in places during the volcanic years, although again the dipole complicates the gradient structure. During the non-volcanic years, the weak signal suggests an averaging out of all the years. As in figure 3.21, the result seems indicative of a strengthened temperature gradient structure in volcanic years which may perhaps result in a strengthened polar vortex.

To check if the temperature results do suggest a strengthened polar vortex, we determine the vertical gradient of the anomalous geostrophic wind (figure 3.23). First, the anomalous temperature field (not shown) is calculated by taking the difference between the raw temperature composite in volcanic years and the composite in non-volcanic years (figure 3.21), both including the seasonal cycle. The result, corresponding to the possible
effect of the volcanic forcing, has a dipole structure. Using the Coriolis parameter, $f$, to scale the anomalous temperature gradient, obtained from the anomalous temperature field, yields vectors proportional to the gradient of the geostrophic wind (figure 3.23). Again, there is a dipole structure. Recall that the leading volcanic modes in the PC analysis and the CPC analysis show a zonal pattern which seems to differ from these raw temperature dipole patterns. Despite this apparent inconsistency, note that the raw composite incorporates all modes, not just the zonal patterns. The zonal average of the gradient of the geostrophic wind is shown in figure 3.24. With the exception of the mid-latitudes around 40°N, the zonal average is directed eastward, indicating that even with the addition of the extra modes in the raw composites we can still see an increase in the zonal jet.
Figure 3.24: A plot of the zonal average of figure 3.23. Arrows indicate a scaled magnitude and direction. The data has a 5° latitudinal spacing extending from 30°N to 85°N.
Chapter 4

An Analysis of Observational Climate Data - Troposphere

The troposphere forms the lower atmosphere between the tropopause, which is the boundary with the stratosphere, and the Earth's surface. The tropospheric layer contains our weather. In general, the temperatures in this layer decrease with height. As a result, situations with unstable atmospheric lapse rates can be found which can lead to the formation of giant convective cells of rising and descending air. These vertical motions keep the region well mixed. This layer of the atmosphere is directly influenced by the surface topography and land/ocean contrasts. As a result, the troposphere is more chaotic in nature than the stratosphere and the spatial patterns of atmospheric circulations can be quite complex. Sometimes, the spatial patterns can distribute in a manner that can be described geographically, such as the AO or the NAO. But, sometimes there are too many intricacies for a simple description of the pattern. This also affects our ability to detect similarities in the patterns obtained using different methods.

Unlike in the stratosphere, there are various other atmospheric phenomena present in the troposphere which can also force the tropospheric circulations. Numerous effects occur simultaneously on various length scales and various time scales giving more potential for the volcanic signal to be confounded. This makes it more difficult to extract a single, specific signal, especially if the volcanic effect is not dominant in one of the first few modes. For example, if the volcanic effect manifests itself in a spatial pattern that is not as strong and does not appear among the leading modes, or if the volcanic pattern is a combination of the spatial patterns instead of a single one, and is thus hidden, then even
if the volcanic effect is strong it will be difficult to isolate. One potentially confounding large scale lower atmosphere phenomenon is the El Niño/Southern Oscillation (ENSO), which occurs roughly every 3-7 years. Although there are many forcings present, El Niño is the most important. Some forcings occur on a somewhat continual basis, but El Niño is semi-periodic and is important due to the overlap of the El Niño years with the volcanic years. Each volcanic period coincides with an El Niño year. In particular, a strong El Niño occurred at the same time as the El Chichon eruption. El Niño manifests as a warm sea surface temperature (SST) anomaly in the eastern equatorial Pacific. The Southern Oscillation is the seesaw of atmospheric pressure measured between Darwin and Tahiti. The correlation in the timing of reversals of both the El Niño and Southern Oscillation features suggest that they may be part of the same oscillation of the ocean-atmosphere system. The atmospheric effects of El Niño include a shift in the Walker circulation and a weakening of the easterly trade winds. These weakened easterlies allow the eastward current to strengthen and carry warm surface water towards South America. This flow deepens the thermocline and helps to suppress the upwelling of cold water in the eastern Pacific and thus feedback to maintain the warm SST anomaly.

The oceanic events characterizing El Niño may be confined to the equatorial Pacific region, but the atmospheric effects have a much more global scale (Trenberth et al., [16]). For example, the warmer water can add both warmth and moisture to the atmosphere, changing the global wind and precipitation patterns. Some of these atmospheric anomalies in the circulations may appear in the PC modes we extract in our volcanic analysis. This can cause a significant confounding in our ability to detect the volcanic signal. Various methods have been used in the literature to try to isolate the volcanic and El Niño signals. By studying observed correlations between the high-frequency surface temperature anomalies in the Pacific and the Southern Oscillation Index (SOI) series, Robock and Mao [13] established a linear regression relationship between these
two variables. Then, this linear regression was used to remove the ENSO signal from the high-frequency surface temperature variations. Kirchner and Graf [8] used an analysis with perpetual January general circulation model (GCM) data for four different experiments to examine the effects of the control case, the volcanic case (with changes to the heating rate and shortwave radiation), the El Niño case (with added SST anomalies) and the volcanic/El Niño combined case. These model results were compared to observed data. Yang and Schlesinger [18] performed empirical data analyses on observed surface air temperature (SAT) anomalies over land and SST anomalies over the ocean to detect and separate the volcanic and El Niño signals. Composites were made for the volcanic years (the first two years after an eruption) and for El Niño years and La Niña years with the volcanic years both included and excluded. Singular value decomposition (SVD) was used to detect and remove the El Niño signal in defined spatial regions.

Here, we wish to apply our current method of detecting the volcanic signal to also detect the El Niño signal. This way, we are looking at the generated EOF patterns to determine which ones have a volcanic signal, an El Niño signal, both, or neither. ANOVA is thus applied to the tropospheric data using El Niño years and non-El Niño years as determined from a listing of warm and cold episodes by season from the Climate Prediction Center of the National Center for Environmental Prediction (NCEP) [3]. The El Niño years are taken to be 1965, 1972, 1982, 1986, 1987, 1991, 1992, 1994, and 1997, where the calendar year corresponds to the November/December of the extended winter. The significance thresholds for ANOVA with El Niño and with the volcanic years are the same.

Three separate analyses are conducted on the troposphere alone. The first two are the PC analysis of the geopotential height field and the PC analysis of the temperature field. The third is the combined PC analysis performed on the geopotential height field and temperature field. Only the height CPC patterns are presented and analysed in
Chapter 4. An Analysis of Observational Climate Data - Troposphere

detail. The temperature CPC patterns are included in Appendix B, along with the height patterns.

4.1 Principal Component Analysis

The first ten height modes of the PC analysis at 300 mbar account for a combined 79.3% of the total variance with the seasonal cycle removed. Figure 4.1 shows the five leading EOFs which account for 24.2%, 11.6%, 10.4%, 8.2%, and 6.2% of the total variance respectively, as indicated. EOF 1 is indicative of the AO signature at this level of the troposphere. There is an elongated positive centre over the pole, with one maximum over the pole and another around the southern edge of Greenland, and a small component stretching out over Eurasia. The negative band is marked by four centres over eastern Asia, the north Pacific, the east coast of North America, and western Europe. Dipole-like structures characterize much of EOF 2, which has similarities to the Pacific-North America (PNA) pattern. There is a strong high over the North Pacific along with a weak low, a mild high over the eastern US coast with a strong low over northern Canada, and a strong high over the Arctic/Scandinavia with a mild low over central Asia.

ANOVA indicates only a weak volcanic signal in the first mode, while none of the other four leading modes exhibit any volcanic signal (table 4.1). However, PCs 3, 4, and 5 all show strong El Niño signals. The volcanic and El Niño signals are in distinct modes, suggesting that in this PC analysis the two signals do not confound each other in the leading modes. Unfortunately, because no mode exhibits a strong volcanic signal, another method is needed to determine the tropospheric volcanic response. The time series for the two leading modes (figure 4.2) illustrate the lack of a clear volcanic signal. The time series for the three El Niño modes are shown in figure 4.3.

The first ten height modes of the PC analysis of the unaltered data at 300 mbar
Figure 4.1: Spatial patterns of the first five EOF modes from a PC analysis of 300 mbar observational height data with the seasonal cycle removed. Contour interval is 0.005.
### Analysis at 300 mbar

<table>
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<tr>
<th></th>
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</thead>
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<tr>
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<td></td>
</tr>
<tr>
<td>PC 1</td>
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<tr>
<td>PC 2</td>
<td>3.3</td>
<td>2.7</td>
</tr>
<tr>
<td>PC 3</td>
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</tr>
<tr>
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</tr>
<tr>
<td>PC 5</td>
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<td>0.06</td>
</tr>
<tr>
<td><strong>Temperature PCA</strong></td>
<td></td>
<td></td>
</tr>
<tr>
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<td>4.1</td>
</tr>
<tr>
<td>PC 2</td>
<td>5.2</td>
<td>5.5</td>
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<tr>
<td>PC 3</td>
<td>4.4</td>
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<tr>
<td>PC 4</td>
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<td>0.5</td>
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<tr>
<td>PC 5</td>
<td>2.6</td>
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<tr>
<td><strong>CPCA</strong></td>
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<tr>
<td>PC 1</td>
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<td>0.4</td>
</tr>
<tr>
<td>PC 2</td>
<td>0.3</td>
<td>5.5</td>
</tr>
<tr>
<td>PC 3</td>
<td>5.5</td>
<td>4.3</td>
</tr>
<tr>
<td>PC 4</td>
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<td>0.02</td>
</tr>
<tr>
<td>PC 5</td>
<td>5.5</td>
<td>2.8</td>
</tr>
</tbody>
</table>

Table 4.1: ANOVA f-ratios for the volcanic and El Niño significance tests in the leading tropospheric principal components. The values for the 95th, 99th, and 99.9th percentiles of $F(1,190)$ are 3.89, 6.77, and 11.17 respectively.
Figure 4.2: Time series for the two leading EOF modes shown in figure 4.1. Time series tick marks indicate Novembers. Shaded regions indicate volcanic years.
Figure 4.3: Time series for EOFs 3, 4, and 5 shown in figure 4.1. Time series tick marks indicate Novembers. Shaded regions indicate volcanic years.
account for a combined 83.7% of the total variance. Figure 4.4 shows the five leading EOFs with the seasonal cycle included, which account for 30.9%, 15.0%, 8.2%, 7.4%, and 5.8% of the total variance respectively. The AO signature appears in EOF 2. There is an elongated negative centre over the pole and a zonal band of positive centres around it. The PNA pattern appears in EOF 3. However, PC 4, while not looking spatially like the PNA pattern, does show more of an El Niño response temporally than PC 3. This suggests that either the PNA is split between these two modes with some of the effects represented by each mode or the response to El Niño does not project mainly on to the PNA. EOFs 2, 3, 4, and 5 bear a strong spatial resemblance to EOFs 1, 2, 3, and 4 respectively from the PC analysis with the seasonal cycle removed (figure 4.1). The corresponding time series (figures 4.5 and 4.6) are virtually identical in three of these four modes. An explanation for the striking similarities may lie in the strength of the seasonal cycle in the leading mode, as suggested by the first time series where the annual oscillation is strongly evident. This seasonal cycle mode has its strongest maximum over the north Pacific and a weaker maximum over north-eastern North America, as well as weak minima over both northern Europe and Alaska. ANOVA again only indicates a weak signal in the first two modes, with none of the next modes exhibiting any volcanic signal (table 4.1). A mild El Niño signal appears in PCs 3, 4, and 5, so again the two signals are in distinct modes. A closer look at the leading time series does not illustrate a visible volcanic signal overlaid on the seasonal cycle.

In both analyses of the tropospheric heights, note that the ANOVA response for the volcanoes and for the El Niños appear in completely distinct modes. This, in part, suggests that we can identify the true response to El Niño. While the El Niño signal is typically associated with the PNA (Trenberth et al., [16]), we saw the PNA pattern in modes which showed no stronger than a mild El Niño signal. Perhaps the atmospheric response to El Niño is different from what is currently believed. The answer to that,
Figure 4.4: Spatial patterns of the first five EOF modes from a PC analysis of 300 mbar observational height data with the seasonal cycle included. Contour interval is 0.005.
Figure 4.5: Time series for the two leading EOF modes shown in figure 4.4. Time series tick marks indicate Novembers. Shaded regions indicate volcanic years.
Figure 4.6: Time series for EOFs 3, 4, and 5 shown in figure 4.4. Time series tick marks indicate Novembers. Shaded regions indicate volcanic years.
The first ten temperature modes of the PC analysis at 300 mbar account for a combined 77.6% of the total variance with the seasonal cycle removed. The two leading modes, which account for 36.4% and 9.0% of the total variance respectively, are shown in figure 4.7. EOF 1 shows a near-zonal structure which is indicative of the AO signature at this level. There is a strong zonal maximum, not quite centred over the pole, with a weak band of minima equatorward.

ANOVA indicates only a weak volcanic signal in each of the first two modes, while none of the next three exhibit any volcanic signal (table 4.1). However, ANOVA indicates a definite El Niño signal in the second mode and a strong El Niño signal in the third mode. In particular, the strength of El Niño in the second mode dominates over the weak volcanic signal. The time series for this second mode (figure 4.8) illustrates the origin of the ANOVA results. There are multiple large changes in amplitude, two of which occur during the volcanic periods, but all of which occur during El Niños.
Figure 4.8: Time series for the EOF modes shown in figure 4.7. Time series tick marks indicate Novembers. Shaded regions indicate volcanic years.
The first ten modes of the PC analysis of the unaltered temperature data at 300 mbar account for a combined 84.4% of the total variance. Only the three leading modes, which account for 41.4%, 17.0%, and 5.8% of the total variance respectively, are shown in figure 4.9. The AO signature appears in EOF 2. There is a weak zonal minimum centred near the pole and a strong positive band equatorward. EOFs 2 and 3 bear a similar spatial resemblance to EOFs 1 and 2 from the PC analysis with the seasonal cycle removed (figure 4.7). The time series for PC 3 (figure 4.10) shows a strong similarity to that of the corresponding PC 2 (figure 4.8). While the PC 2 time series with the seasonal cycle shows similarities to the PC 1 time series without, the differences may lie in the seasonal cycle that is evident in PC 2, particularly during the 70's. The leading mode is clearly the seasonal cycle mode, as its time series contains most of the seasonal cycle. This first mode may thus account for the similarity of the remaining modes to the analysis when the seasonal cycle is removed.

ANOVA again only indicates a weak volcanic signal in the second and third modes (table 4.1). A definite El Niño signal is apparent in the third and fourth modes. These apparent signals occur in the same spatial patterns as in the analysis with the seasonal cycle removed. Perhaps the weak volcanic signal in PC 3 results from the strong El Niño signal. The weak volcanic signal is not evident in the time series of PC 2. However, taking into account both temperature analyses, we can hypothesize that the volcanic effects project onto a modified AO temperature pattern.

4.2 Combined Principal Component Analysis

The three leading modes from a CPC analysis of tropospheric height and temperature are shown in figure 4.11. When these patterns are compared to the PC analysis (figure 4.1) we can see that CPC 2 is like a modified AO, while CPC 3 is like a modified PNA
Figure 4.9: Spatial patterns of the first three EOF modes from a PC analysis of 300 mbar observational temperature data with the seasonal cycle included. Contour interval is 0.005.
Figure 4.10: Time series for the EOF modes shown in figure 4.9. Time series tick marks indicate Novembers. Shaded regions indicate volcanic years.
Figure 4.11: Spatial patterns of the first three height EOF modes from a CPC analysis of 300 mbar observational height and temperature data with the seasonal cycle removed. Contour interval is 0.004.
pattern. The first mode, CPC 1, does not resemble any of the PCA modes and could represent a new mode isolated through the coupling. It shows effects over the Pacific and North America. The second and third time series (figure 4.12) also show similarities to their corresponding PC time series (figure 4.2). The leading time series appears to contain a shift in the mean. In the years prior to 1976 the mean is positive. In the years subsequent to 1976 the mean is distinctly negative. This is interesting, because there was an acknowledged climate shift that occurred in 1976-77. If this is a representation of the shift, further study of this mode may tell us what changed during the shift. There is the possibility that our observed shift may have occurred due to a change in data collection methods, but satellites were introduced later than our observed change. However, this CPC analysis does not improve our ability to detect a pure volcanic signal. Instead, the two leading modes, which account for 22.0% and 14.8% of the total variance respectively, show definite El Niño signals (table 4.1). While CPC 2 also shows a mild volcanic signal, this may be due to strong El Niños during the volcanic years, since ANOVA analyses variability based on years with forcing compared to years without forcing. Although CPC 3 explains only 6.3% of the variance, it is the one mode which shows a mild volcanic signal and no El Niño signal. It could represent the main volcanic mode, but the lack of a strong volcanic signal leaves these results inconclusive.

Unlike the PCA results, the EOF height patterns from the CPC analysis in the troposphere are mostly different with the seasonal cycle included and removed (figure 4.13). However, although the patterns are too noisy to make any conclusive visual comparison with the PCA height modes (figure 4.4), there are a couple of similarities. The leading mode, CPC 1, is similar to the leading PC mode. The annual oscillation is strongly evident in the time series (figure 4.14) of this seasonal cycle mode. This could account for the similarities. CPC 3 is like a modified AO while CPC 5 is like a modified PNA pattern. The two leading modes, which account for 31.3% and 14.8% of the total variance
Figure 4.12: Time series for the EOF modes shown in figure 4.11. Time series tick marks indicate Novembers. Shaded regions indicate volcanic years.
Figure 4.13: Spatial patterns of the first, second, third, and fifth height EOF modes from a CPC analysis of 300 mbar observational height and temperature data with the seasonal cycle included. Contour interval is 0.004.
Figure 4.14: Time series for the EOF modes shown in figure 4.13. Time series tick marks indicate Novembers. Shaded regions indicate volcanic years.
respectively, have time series which oscillate with concurrent and opposite large changes in amplitude. There is no apparent volcanic origin to these effects, but the lack of a volcanic signal and the definite El Niño signal (table 4.1) do suggest the origin. Interestingly, it is again the two modified spatial patterns, CPCs 3 and 5, which have a weak volcanic signal. These are the same modes which showed a weak volcanic signal with the seasonal cycle removed. CPC 3 has a mild volcanic signal and a mild El Niño signal, so it is unclear what effects are taking place. So, even with the seasonal cycle included, our ability to detect a pure, clear volcanic signal in the troposphere has not improved.

4.3 Raw data analyses

Composites are created using the raw tropospheric height data with no statistical analyses performed, following the same procedure used in the stratosphere. Results are shown both with the seasonal cycle removed (figure 4.15) and included (figure 4.16). With the seasonal cycle removed we can see some general similarities between the two composites in

Figure 4.15: Composites of averaged raw 300 mbar height data with the seasonal cycle removed for (a) the first volcanic winters and (b) non-volcanic winters. Contour interval is 10.
Figure 4.16: Composites of averaged raw 300 mbar height data with the seasonal cycle included for (a) the first volcanic winters and (b) non-volcanic winters. Contour interval is 200. The inner and outer contours are 8,400 gpm and 9,600 gpm respectively for both composites.

The global structure of the heights. Again, the same problem of the data summing to zero occurs here. A more detailed contouring of the non-volcanic years (not shown) reveals five maxima and three minima. These centres are in the same approximate locations as in the volcanic years as expected and they are opposite in sign. Although the spatial structure in the troposphere is much more complex than in the stratosphere, we can still see the same decrease in height over the pole and increase in the tropics during volcanic years. However, the volcanic composite also resembles the El Niño response with minor modifications. This may not be surprising, as the three volcanic winters used are also El Niño winters. Even though the extended winter in 63-64 is not included in the El Niño years, an El Niño did occur during part of that period. As a result, the raw data for volcanic years in the troposphere does contain an El Niño response also. This confounding problem may not be avoidable.

One thing that is evident from both of these figures is that the seasonal cycle seems to play a stronger role in the troposphere than in the stratosphere. When the seasonal
cycle is included in the raw composite, the spatial structures for the volcanic years and for the non-volcanic years are virtually identical. The orientation of the troughs and crests correspond to each other. Further, in absolute numbers, the heights are so similar that the contour lines shown represent identical values. It is possible with the strength of the seasonal cycle that the volcanic signal is hidden by other influences. This was also seen in the PC analysis with the seasonal cycle included, where ANOVA only detected the volcanic signal in the seasonal cycle mode. So, we again see in the troposphere that there is a greater potential for confounding of the volcanic signal. It is thus unclear what valid conclusions we can draw from these raw composites.

The composites created by averaging together the raw temperature data from the troposphere have a much different result than in the stratosphere, even though the same procedure is used. When the seasonal cycle is included the result is a very zonal structure (figure 4.17), quite unlike the dipole structure observable in the stratosphere. The spatial structures for the volcanic years and for the non-volcanic years are virtually identical,
Figure 4.18: Composites of averaged raw 300 mbar temperature data with the seasonal cycle removed for (a) the first volcanic winters and (b) non-volcanic winters. Contour interval is 0.2.

including the absolute values of the contours. Only a subtle difference is noticeable over North America south of 30°N. Perhaps the volcanic signal is hidden by the seasonal cycle combined with other influences. Recalling the PCA results, the mode with the volcanic signal (PC 2) also shows signs of the seasonal cycle in its times series. Removing the seasonal cycle results in a much more complex structure (figure 4.18). Although the zero contour appears to have numerous differences between the volcanic and non-volcanic cases, a more detailed contouring of the non-volcanic years (not shown) reveals maxima and minima, with the signs reversed, in the same approximate locations. Despite the complexity of the volcanic pattern it bears a similarity to the El Niño pattern. This may again be explained by the El Niños that occurred during the three volcanic winters that were used.

The bootstrap analysis is applied to the troposphere height and temperature data, both with the seasonal cycle included and removed. Table 4.2 shows the volcanic percentiles obtained by comparing the volcanic difference against the rest of the results from
Bootstrap analysis

<table>
<thead>
<tr>
<th></th>
<th>With the seasonal cycle</th>
<th>Without the seasonal cycle</th>
</tr>
</thead>
<tbody>
<tr>
<td>Height field</td>
<td>96.6</td>
<td>86.1</td>
</tr>
<tr>
<td>Temperature field</td>
<td>93.5</td>
<td>99.5</td>
</tr>
</tbody>
</table>

Table 4.2: Percentile values for the volcanic difference in the bootstrap analysis in the troposphere at 300mbar.

Figure 4.19: (a) A histogram of the maximum height difference in three winter composites constructed from the raw 300 mbar height data and normalized based on the total number of points. (b) The difference between the normalized number distribution based on all years and the normalized number distribution based on the non-volcanic years. The solid vertical line marks the median value and the dashed vertical line marks the value using the first volcanic winters.

The volcanic difference is the result from using the combination of the first winter from each of the three volcanic periods. Here, we see that the volcanic difference is significant in all four cases. A histogram with the number distribution for the original height data (figure 4.19) and the original temperature data (figure 4.20) with the seasonal cycle included illustrates these results. A graph of the distribution difference between the analysis for all years and the analysis for the non-volcanic years shows a tendency towards a larger height difference in the volcanic years. Based on the
Figure 4.20: (a) A histogram of the maximum temperature difference in three winter composites constructed from the raw 300 mbar temperature data and normalized based on the total number of points. (b) The difference between the normalized number distribution based on all years and the normalized number distribution based on the non-volcanic years. The solid vertical line marks the median value and the dashed vertical line marks the value using the first volcanic winters.

confounding problems seen in the raw composites, it is perhaps surprising to have such strong significances. As mentioned previously, the troposphere experiences effects from El Niño and SST forcings which may affect the reliability of these results as being purely volcanic. It may be the combination of volcanic forcing and El Niño forcing in the three volcanic winters which strengthens the difference and sets it apart from the remaining winter combinations.

4.4 Discussion

Although the analysis in the troposphere did not yield the same strong results that were obtained in the stratosphere, it did provide some useful results. The ANOVA procedure on the PCA height fields clearly separated the volcanic response and the El Niño response both with the seasonal cycle included and removed. The CPC analysis of height and temperature showed a real strong El Niño signal in the two leading modes, indicating
that the coupled response is that of El Niño.

When the analysis is restricted to the troposphere, the El Niño signal is too prominent. So, to find the volcanic signal in the troposphere the next step is to link the tropospheric fields with the stratospheric fields through a vertical CPC analysis. The results follow in the next chapter.
Chapter 5

An Analysis of Observational Climate Data - Vertical Analysis

5.1 Combined Atmosphere

So far we have looked at both the stratosphere and the troposphere separately. But, these two layers may tie together, possibly with one directly affecting the other. The stratosphere shows a strong volcanic signal, but the volcanic signal in the troposphere is mostly confounded by El Niño. By performing CPCA on the height fields at both the stratospheric and the tropospheric levels (a vertical CPCA) we can observe the spatial patterns that result when the two levels are forced to tie together.

The leading stratospheric mode, EOF 1s (figure 5.1), with the seasonal cycle removed is very zonal and has spatial similarities to the leading height mode from the stratospheric CPCA (figure 3.11). EOF 2s, the second stratospheric mode, is less zonal and more closely resembles the AO at 30 mbar. This mode is comparable to the first mode from the stratospheric PCA on heights (figure 3.1). The third mode, EOF 3s, has some dipole characteristics with a high over North America and a low over eastern Europe and eastern Asia. The leading tropospheric mode, EOF 1t (figure 5.2), resembles a modified NAO. Although there are some differences, this pattern is most comparable to the leading height mode from the tropospheric PCA (figure 4.1), which is a representation of the AO. One important new structure in this mode is the dipole that occurs over eastern Asia. When we compare EOF 1t to results beyond our own analysis, we find another similarity. Graf et al. [4] produced a pattern by taking the spatial difference between the
Figure 5.1: Spatial patterns of the first three EOF modes from a CPC analysis of 30 mbar and 300 mbar observational height data with the seasonal cycle removed, shown at 30 mbar. Contour interval is 0.002.
Figure 5.2: Spatial patterns of the first three EOF modes from a CPC analysis of 30 mbar and 300 mbar observational height data with the seasonal cycle removed, shown at 300 mbar. Contour interval is 0.002.
Chapter 5. An Analysis of Observational Climate Data - Vertical Analysis

<table>
<thead>
<tr>
<th>Vertical CPCA</th>
<th>With the seasonal cycle</th>
<th>Without the seasonal cycle</th>
</tr>
</thead>
<tbody>
<tr>
<td>PC 1</td>
<td>15.8</td>
<td>26.6</td>
</tr>
<tr>
<td>PC 2</td>
<td>18.0</td>
<td>28.6</td>
</tr>
<tr>
<td>PC 3</td>
<td>1.0</td>
<td>0.3</td>
</tr>
<tr>
<td>PC 4</td>
<td>0.6</td>
<td>0.4</td>
</tr>
<tr>
<td>PC 5</td>
<td>7.8</td>
<td>1.2</td>
</tr>
</tbody>
</table>

Table 5.1: ANOVA f-ratios for the volcanic and El Niño significance tests in the leading combined tropospheric and stratospheric height principal components. The values for the 95th, 99th, and 99.9th percentiles of $F(1, 190)$ are 3.89, 6.77, and 11.17 respectively.

Northern Hemisphere height anomaly at 500 mbar in months with a strong stratospheric polar vortex and the anomaly in months with a weak vortex. Even though their analysis is at 500 mbar and ours is at 300 mbar, a similarity in the spatial structures can still be observed, most notably that dipole over eastern Asia. Although it may not be clear whether the NAO or the AO is a more representative structure for the volcanic mode, the eastern Asia dipole is evident in both the analysis of the volcanic forcing and the analysis of the strong vortex years.

The combined leading mode shows a definite volcanic signal (table 5.1) and accounts for 26.2% of the coupled variance. The common time series (figure 5.3) illustrates the origins of this signal. However, the strength of the El Niño signal in the leading mode, although not as strong as the volcanic signal, confounds a possible explanation for the peaks in the volcanic periods as solely due to volcanic activity. There is no volcanic signal in the second or third modes, which account for 16.5% and 7.7% of the variance respectively. The second time series shows the same climate shift that we observed in one of the modes in the troposphere analysis (PC 1 of figure 4.12). Note the negative spike in the winter of 76-77 in the first time series. This spike is also present in the time
Figure 5.3: Time series for the EOF modes shown in figure 5.1 and figure 5.2. Time series tick marks indicate Novembers. Shaded regions indicate volcanic years.
series of PC 2 in figure 4.12. The corresponding EOF 2t (figure 5.2) shows the same spatial structure as EOF 1 in figure 4.11. This shows that the relative importance of PC 1 and PC 2, in explaining the coupled variance, has flipped in the vertical CPC analysis from the results of the troposphere CPC analysis. This change in the leading mode due to the change in the coupled fields suggests that the climate shift has its origins in the troposphere while the volcanic effects have their origin in the stratosphere.

Interestingly, the leading mode with the strongest volcanic signal (extracted by CPCA in the stratosphere and PCA in the troposphere) in each of the two separate levels is extracted as the leading mode and the most significant volcanic mode in the combined vertical analysis. This, along with the strength of the volcanic signal in the first combined mode, suggests the possibility that the height fields at 30 mbar and 300 mbar are linked under the influence of volcanic aerosols. However, as the strong El Niño signal indicates, there is always the possibility that some other phenomenon that is occurring more frequently than the volcanoes could account for the link between the layers. This leaves open the question of how the two layers are linked. One possibility, presented in a model study by Shindell et al. [14], is that the changes in the stratospheric dynamics induced by effects such as volcanic forcing can influence the propagation of planetary waves from the troposphere to the stratosphere. The result is a change in both the stratospheric energy and the propagation of tropospheric energy.

The vertical CPC analysis with the seasonal cycle included has one mode (PC 2) with a definite volcanic signal and no El Niño signal (table 5.1). It also includes one mode (PC 5) with a weaker volcanic signal and no El Niño signal. While the ten leading modes account for 83.2% of the coupled variance, this second mode accounts for 18.2%. The leading mode accounts for 29.7% of the coupled variance. Although PC 1 exhibits a strong volcanic signal, the El Niño signal is even stronger. EOF 1s in the stratosphere has two centres, a weak minimum over northern Europe and a stronger minimum over Alaska.
(figure 5.4). Equatorward of these centres, the pattern shows a strong zonal symmetry. EOF 2s in the stratosphere shows the same zonal symmetry near the pole that appears in the leading mode with the seasonal cycle removed (figure 5.1), except that the zonal symmetry breaks down further away from the pole. This breakdown of symmetry has similarities to the second mode with the seasonal cycle removed. EOF 3s has a similar general structure to the second mode with the seasonal cycle removed, although the location of the centres and the extent of the features differ. In the troposphere, EOF 1t (figure 5.5) also shows a strong low over Alaska, although the remainder of the spatial structure is much noisier. The second mode, EOF 2t, is again a combination of the first two modes with the seasonal cycle removed (figure 5.2). The corresponding time series (figure 5.6) illustrate the volcanic signal with a clear bias towards the positive for all volcanoes. The leading mode (CPC 1) clearly contains the seasonal cycle. In addition, there seems to be either a modulation of the seasonal cycle with a 40-year period or a shift in the mean.
Figure 5.4: Spatial patterns of the first three EOF modes from a CPC analysis of 30 mbar and 300 mbar observational height data with the seasonal cycle included, shown at 30 mbar. Contour interval is 0.002.
Figure 5.5: Spatial patterns of the first three EOF modes from a CPC analysis of 30 mbar and 300 mbar observational height data with the seasonal cycle included, shown at 300 mbar. Contour interval is 0.002.
Figure 5.6: Time series for the EOF modes shown in figure 5.4 and figure 5.5. Time series tick marks indicate Novembers. Shaded regions indicate volcanic years.
Chapter 6

Summary and Conclusions

The intended goal of this thesis was to determine the role of volcanic aerosols in atmospheric circulations and climate variability. We were able to achieve a separation of the volcanic signal, to some extent. We also discovered that the methods we were using helped to extract other climatological and atmospheric signals. A summary of the observed signals for all modes with at least a weak volcanic significance according to ANOVA is shown in table 6.1 for the stratosphere, table 6.2 for the troposphere, and table 6.3 for the combined vertical analysis.

A Principal Component Analysis (PCA) of 30 mbar stratospheric heights extracts the Arctic Oscillation (AO) as the leading mode and a dipole as the second mode, both of which are weakly volcanic modes. The time series associated with the PCA modes do not show a clear association with the volcanoes as does the Analysis of Variance (ANOVA) which shows a weak volcanic signal. It is still possible that these modes illustrate part of the volcanic picture, or a modified volcanic picture. A PCA on 30 mbar stratospheric temperature also extracts the AO as the leading mode, but with no trace of a volcanic signal. Of greatest significance is the strong volcanic signal in PC 5 (both with the seasonal cycle removed and included) which may be a new, volcanic mode. If this is the case, this pattern could be significant in terms of the volcanic circulations. There are also indications that the volcanic and seasonal effects are tied together.

The success of the Combined Principal Component Analysis (CPCA) in extracting a very strong volcanic signal in the stratosphere suggests that the upper level temperature
<table>
<thead>
<tr>
<th>Field(s)</th>
<th>Mode</th>
<th>Seasonal cycle</th>
<th>ANOVA significance</th>
<th>Signal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Height</td>
<td>PC 1</td>
<td>with</td>
<td>weak</td>
<td>unknown signal</td>
</tr>
<tr>
<td></td>
<td>PC 4</td>
<td>with</td>
<td>definite</td>
<td>mixed signal anomalous daily mode - not physical largest response after El Chichon</td>
</tr>
<tr>
<td>Height</td>
<td>PC 5</td>
<td>with</td>
<td>strong</td>
<td>unknown signal no response after Mount Pinatubo may be affected by anomalous mode</td>
</tr>
<tr>
<td></td>
<td>PC 1</td>
<td>without</td>
<td>weak</td>
<td>unknown signal</td>
</tr>
<tr>
<td></td>
<td>PC 2</td>
<td>without</td>
<td>weak</td>
<td>unknown signal</td>
</tr>
<tr>
<td></td>
<td>PC 4</td>
<td>without</td>
<td>definite</td>
<td>mixed signal largest response after El Chichon</td>
</tr>
<tr>
<td>Temperature</td>
<td>PC 2</td>
<td>with</td>
<td>strong</td>
<td>unknown signal</td>
</tr>
<tr>
<td>Temperature</td>
<td>PC 5</td>
<td>with</td>
<td>definite</td>
<td>** new volcanic mode ** linked to seasonal cycle</td>
</tr>
<tr>
<td>Temperature</td>
<td>PC 2</td>
<td>without</td>
<td>strong</td>
<td>unknown signal</td>
</tr>
<tr>
<td>Temperature</td>
<td>PC 5</td>
<td>without</td>
<td>strong</td>
<td>mixed signal generally sporadic nature marked jump after El Chichon</td>
</tr>
<tr>
<td>Height and Temperature</td>
<td>CPC 1</td>
<td>with</td>
<td>definite</td>
<td>volcanic signal</td>
</tr>
<tr>
<td>Height and Temperature</td>
<td>CPC 2</td>
<td>with</td>
<td>definite</td>
<td>volcanic signal drop in second volcanic years</td>
</tr>
<tr>
<td>Height and Temperature</td>
<td>CPC 3</td>
<td>with</td>
<td>strong</td>
<td>unknown signal</td>
</tr>
<tr>
<td>Height and Temperature</td>
<td>CPC 4</td>
<td>with</td>
<td>strong</td>
<td>unknown signal</td>
</tr>
<tr>
<td>Height and Temperature</td>
<td>CPC 1</td>
<td>without</td>
<td>definite</td>
<td>volcanic signal negative dips in all volcanic years</td>
</tr>
<tr>
<td>Height and Temperature</td>
<td>CPC 2</td>
<td>without</td>
<td>definite</td>
<td>volcanic signal negative dips in all volcanic years</td>
</tr>
<tr>
<td>Height and Temperature</td>
<td>CPC 5</td>
<td>without</td>
<td>definite</td>
<td>volcanic signal negative dips in all volcanic years</td>
</tr>
</tbody>
</table>

Table 6.1: A summary of the signals and the time series responses in the stratosphere for all of the analysis modes that have at least a weak volcanic signal measured by ANOVA.
### Table 6.2: A summary of the signals and the time series responses in the troposphere for all of the analysis modes that have at least a weak volcanic signal measured by ANOVA.

<table>
<thead>
<tr>
<th>Field(s)</th>
<th>Mode</th>
<th>Seasonal cycle</th>
<th>ANOVA significance</th>
<th>Signal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Height</td>
<td>PC 1</td>
<td>with</td>
<td>weak</td>
<td>unknown signal</td>
</tr>
<tr>
<td></td>
<td>PC 1</td>
<td>without</td>
<td>weak</td>
<td>unknown signal</td>
</tr>
<tr>
<td></td>
<td>PC 2</td>
<td>with</td>
<td>weak</td>
<td>unknown signal</td>
</tr>
<tr>
<td></td>
<td>PC 3</td>
<td>with</td>
<td>weak</td>
<td>El Niño signal</td>
</tr>
<tr>
<td></td>
<td>PC 1</td>
<td>without</td>
<td>weak</td>
<td>unknown signal</td>
</tr>
<tr>
<td></td>
<td>PC 2</td>
<td>without</td>
<td>weak</td>
<td>El Niño signal</td>
</tr>
<tr>
<td></td>
<td>CPC 3</td>
<td>with</td>
<td>weak</td>
<td>mixed signal</td>
</tr>
<tr>
<td>Temperature</td>
<td>CPC 1</td>
<td>with</td>
<td>weak</td>
<td>unknown signal</td>
</tr>
<tr>
<td></td>
<td>CPC 2</td>
<td>without</td>
<td>none</td>
<td>climate shift mode</td>
</tr>
<tr>
<td></td>
<td>CPC 3</td>
<td>without</td>
<td>weak</td>
<td>unknown signal</td>
</tr>
</tbody>
</table>

### Table 6.3: A summary of the signals and the time series responses for all of the vertical analysis modes that have at least a weak volcanic signal measured by ANOVA.

<table>
<thead>
<tr>
<th>Field(s)</th>
<th>Mode</th>
<th>Seasonal cycle</th>
<th>ANOVA significance</th>
<th>Signal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Height at 30 mbar and 300 mbar</td>
<td>CPC 1</td>
<td>with</td>
<td>definite</td>
<td>mixed signal</td>
</tr>
<tr>
<td></td>
<td>CPC 2</td>
<td>with</td>
<td>definite</td>
<td>volcanic signal</td>
</tr>
<tr>
<td></td>
<td>CPC 5</td>
<td>with</td>
<td>strong</td>
<td>unknown signal</td>
</tr>
<tr>
<td></td>
<td>CPC 1</td>
<td>without</td>
<td>definite</td>
<td>mixed signal peaks after Agung, El Chichon</td>
</tr>
<tr>
<td></td>
<td>CPC 2</td>
<td>without</td>
<td>none</td>
<td>climate shift mode</td>
</tr>
</tbody>
</table>
and height fields are affected by the volcanic aerosols in a related way. The time series of the combined height and temperature volcanic modes show a visible change during the volcanic years. A similarity in the oscillations of the leading zonal and dipolar modes with the seasonal cycle removed suggest a possible coupling of the modes. Although the modes are uncorrelated by construction, they may not be independent (Monahan et al., [10]). The response to volcanic forcings may thus project onto multiple linear modes. The appearance of the seasonal cycle in the second mode suggests that stratospheric height and temperature vary together most strongly on some factor other than the seasonal cycle.

In looking at the raw data, we can observe a larger equator to pole height gradient in the volcanic years, indicating an increase in the strength of the polar vortex. The temperature structure is much more complex and does not yield a clear picture of what is happening to the equator to pole temperature gradient. The bootstrap analysis shows that the volcanic response as shown by the raw composites is significant, particularly when the original data is used without removing the seasonal cycle.

The analysis of the troposphere is complicated by the presence of El Niño events. We made no attempt to remove El Niño, but rather we tried to distinguish the El Niño signal and the volcanic signal using ANOVA. A PCA of 300 mbar tropospheric heights extracts the AO signature as the leading non-seasonal cycle mode, with a weak volcanic signal. ANOVA applied to the associated time series separates the modes that show an El Niño signal from those that show the volcanic signal, showing that PCA of tropospheric heights combined with ANOVA is able to clearly separate the volcanic response and the El Niño response. Of note, the Pacific-North America (PNA) pattern shows little or no El Niño signal, contrary to Trenberth et al. [16] that the two are associated. This analysis provides a start for a more in-depth look at this curious result. The PCA of 300 mbar tropospheric temperatures is less clear in its separation of the El Niño and volcanic
responses. However, the modified AO temperature pattern did show a weak volcanic signal distinct from El Niño.

In the troposphere, the CPCA of height and temperature was successful in extracting a very strong El Niño signal, indicating that the coupled response is mainly influenced by El Niño. Interestingly, it is only the mode which resembles a modified PNA pattern that shows a weak volcanic signal and no El Niño signal. The CPCA was also able to extract a mode that contains a representation of the climate shift of 1976-1977 in its time series. This mode provides a beginning for further investigation into the climate shift.

The strength of the seasonal cycle and the El Niño signal prove to be too much when looking at the raw data spatial composites, and the pattern of the volcanic response is not clearly defined from the influences of the other forcings. The bootstrap analysis does indicate that the volcanic composite is significant compared to the general result, although the El Niños that occurred in the volcanic years may have helped to strengthen both the signal and the significance.

A vertical CPCA on the height fields extracted one particularly interesting pattern in the troposphere which is a representation of a modified NAO with the addition of a dipole over eastern Asia. This reproduces a pattern produced by Graf et al. [4] related to months with a weak polar vortex subtracted from months with a strong polar vortex. The related stratospheric mode is a strong zonal pattern. An El Niño signal, though weaker, partly confounds this potential volcanic mode, but the eastern Asia dipole appears to be a key feature in the troposphere. With the seasonal cycle included, the vertical CPCA extracts a volcanic mode which appears to combine the leading modes without the seasonal cycle.
Bibliography


Appendix A

Stratosphere Plots
Table A.1: ANOVA f-ratios for the volcanic signal in the leading stratospheric principal components. The values for the 95th, 99th, and 99.9th percentiles of F(1,190) are 3.89, 6.77, and 11.17 respectively.
Figure A.1: Spatial patterns of the first four height EOF modes from a CPC analysis of 30 mbar observational height and temperature data with the seasonal cycle removed. Contour interval is 0.002.
Figure A.2: Spatial patterns of the next six height EOF modes from a CPC analysis of 30 mbar observational height and temperature data with the seasonal cycle removed. Contour interval is 0.002.
Figure A.3: Spatial patterns of the first four temperature EOF modes from a CPC analysis of 30 mbar observational height and temperature data with the seasonal cycle removed. Contour interval is 0.004.
Figure A.4: Spatial patterns of the next six temperature EOF modes from a CPC analysis of 30 mbar observational height and temperature data with the seasonal cycle removed. Contour interval is 0.004.
Figure A.5: Spatial patterns of the first four height EOF modes from a CPC analysis of 30 mbar observational height and temperature data with the seasonal cycle included. Contour interval is 0.002.
Appendix A. Stratosphere Plots

Figure A.6: Spatial patterns of the next six height EOF modes from a CPC analysis of 30 mbar observational height and temperature data with the seasonal cycle included. Contour interval is 0.002.
Figure A.7: Spatial patterns of the first four temperature EOF modes from a CPC analysis of 30 mbar observational height and temperature data with the seasonal cycle included. Contour interval is 0.004.
Figure A.8: Spatial patterns of the next six temperature EOF modes from a CPC analysis of 30 mbar observational height and temperature data with the seasonal cycle included. Contour interval is 0.004.
Appendix B

Troposphere Plots
Table B.1: ANOVA f-ratios for the volcanic and El Niño significance tests in the leading tropospheric principal components. The values for the 95th, 99th, and 99.9th percentiles of \( F(1,190) \) are 3.89, 6.77, and 11.17 respectively.
Appendix B. Troposphere Plots

Figure B.1: Spatial patterns of the first four EOF modes from a PC analysis of 300 mbar observational height data with the seasonal cycle removed. Contour interval is 0.005.
Figure B.2: Spatial patterns of the next six EOF modes from a PC analysis of 300 mbar observational height data with the seasonal cycle removed. Contour interval is 0.005.
Figure B.3: Spatial patterns of the first four EOF modes from a PC analysis of 300 mbar observational height data with the seasonal cycle included. Contour interval is 0.005.
Appendix B. Troposphere Plots

Figure B.4: Spatial patterns of the next six EOF modes from a PC analysis of 300 mbar observational height data with the seasonal cycle included. Contour interval is 0.005.
Figure B.5: Spatial patterns of the first four height EOF modes from a CPC analysis of 300 mbar observational height and temperature data with the seasonal cycle removed. Contour interval is 0.004.
Figure B.6: Spatial patterns of the next six height EOF modes from a CPC analysis of 300 mbar observational height and temperature data with the seasonal cycle removed. Contour interval is 0.004.
Figure B.7: Spatial patterns of the first four temperature EOF modes from a CPC analysis of 300 mbar observational height and temperature data with the seasonal cycle removed. Contour interval is 0.004.
Figure B.8: Spatial patterns of the next six temperature EOF modes from a CPC analysis of 300 mbar observational height and temperature data with the seasonal cycle removed. Contour interval is 0.004.
Figure B.9: Spatial patterns of the first four height EOF modes from a CPC analysis of 300 mbar observational height and temperature data with the seasonal cycle included. Contour interval is 0.004.
Figure B.10: Spatial patterns of the next six height EOF modes from a CPC analysis of 300 mbar observational height and temperature data with the seasonal cycle included. Contour interval is 0.004.
Figure B.11: Spatial patterns of the first four temperature EOF modes from a CPC analysis of 300 mbar observational height and temperature data with the seasonal cycle included. Contour interval is 0.004.
Figure B.12: Spatial patterns of the next six temperature EOF modes from a CPC analysis of 300 mbar observational height and temperature data with the seasonal cycle included. Contour interval is 0.004.