UNIVERSITY OF READING

Department of Meteorology

An Investigation into Possible Interactions between Volcanoes and El Niño.

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A dissertation

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Abstract

A literature review was undertaken to examine all aspects of possible interactions between volcanic activity and El Niños, specifically the impact of volcanoes upon varying aspects of El Niños, the separation of the climate signal of volcanoes from that of the El Niño Southern Oscillation (ENSO) and finally the impact of El Niños upon the level of volcanic activity.

A data analysis was performed in order to further investigate the impact of volcanic activity upon El Niños by comparing the average level of volcanic activity in strong El Niño years with that in other years from 1845 to 2010. The list of strong El Niños was taken from Quinn's (1992) list of El Niños modified and extended by comparison with data from the Multivariate ENSO Index (MEI), Oceanic Niño Index (ONI), the Southern Oscillation Index (SOI) and Cold Tongue Index (CTI). The Volcanic Explosivity Index (VEI) and the Ice core Volcanic Index (IVI) were used as measures of the volcanic activity. A comparison was also made between the evolution of El Niños that occurred within a year of volcanic activity and that of other El Niños using CTI and VEI data records from 1877 to 2010. A two sample 't' test to determine the statistical significance level was used for both sets of analysis.

It appears likely, although not conclusively so, that tropical volcanoes can, if sufficiently explosive, increase the possibility of an El Niño occurring in the year following the eruption especially given the right initial ocean conditions prior to the eruption. The ocean dynamical thermostat mechanism is the most plausible theory.

The results from the data analysis, whilst they cannot be considered statistically significant, are consistently in agreement with the above theory. The relatively short instrumental data record limits the effectiveness of a statistical study.

The ENSO signal must be removed in order to determine the climatic impact of volcanoes. The range of estimates for the ENSO contribution to global tropospheric temperature trends is from 15 to 72%. Methods of removing the ENSO signal include statistical regression, Fourier frequency filtering, a dynamically based filter and the use of Coupled Global Climate models (CGCMs) to estimate the ENSO contribution with the latter two probably the most reliable.

It is considered unlikely that an El Niño can be a cause of volcanic eruptions.

Acknowledgements: I would like to thank my supervisor, Ross Reynolds, for his helpful comments and Fiona Underwood for her advice on statistical methods. I am also grateful to my husband, Paul and children, Emily and Andrew for their moral support and especially for all the cooking!

Glossary

BEST	Bivariate ENSO Timeseries
CGCM	Coupled Global Climate Model
CTI	Cold Tongue Index
DVI	Dust Veil Index
EOF	Empirical Orthogonal Function
ENSO	El Niño/Southern Oscillation
GCM	Global Climate Model
HadISST	Hadley Centre Global sea-Ice coverage and SST
ICOADS	International Comprehensive Ocean-Atmosphere Data Set
IR	Infra Red
IVI	Ice core Volcanic Index
MEI	Multivariate ENSO Index
MODIS	Moderate-Resolution Imaging Spectraradiometer
MSLP	Mean Sea Level Pressure
NCEP	National Centers for Environmental Protection
NH	Northern Hemisphere
NOAA	National Oceanographic and Atmospheric Administration
No-SEN	No Strong El Niño
OI	Oceanic Index
ONI	Oceanic Niño Index
QBO	Quasi Biennial Oscillation
SEA	Superposed Epoch Analysis
SeaWiFS	Sea-viewing Wide Field-of-View Sensor
SEN	Strong El Niño
SH	Southern Hemisphere
SLP	Sea Level Pressure
SOI	Southern Oscillation Index
SST	Sea Surface Temperature
SSTA	Sea Surface Temperature Anomaly
TNI	Trans Niño Index
VEI	Volcanic Explosivity Index
WMO	World Meteorological Organisation

Contents

Chapter 1 Introduction

1.1   Background

When running a simple climate model it was noted that the climatic influence of volcanoes was being overestimated. Upon investigation it appeared that several of the largest eruptions were followed by a strong El Niño which could have countered the cooling effect of the volcanoes. Figure 1 illustrates this possible relationship between volcanic forcing and the occurrence of strong El Niños. It is also worth noting that during periods of prolonged volcanic inactivity strong El Niños were less frequent and, indeed, volcanoes have such widespread global climatic impacts it would seem unlikely that they would not exert some influence upon the El Niño Southern Oscillation (ENSO) cycle.

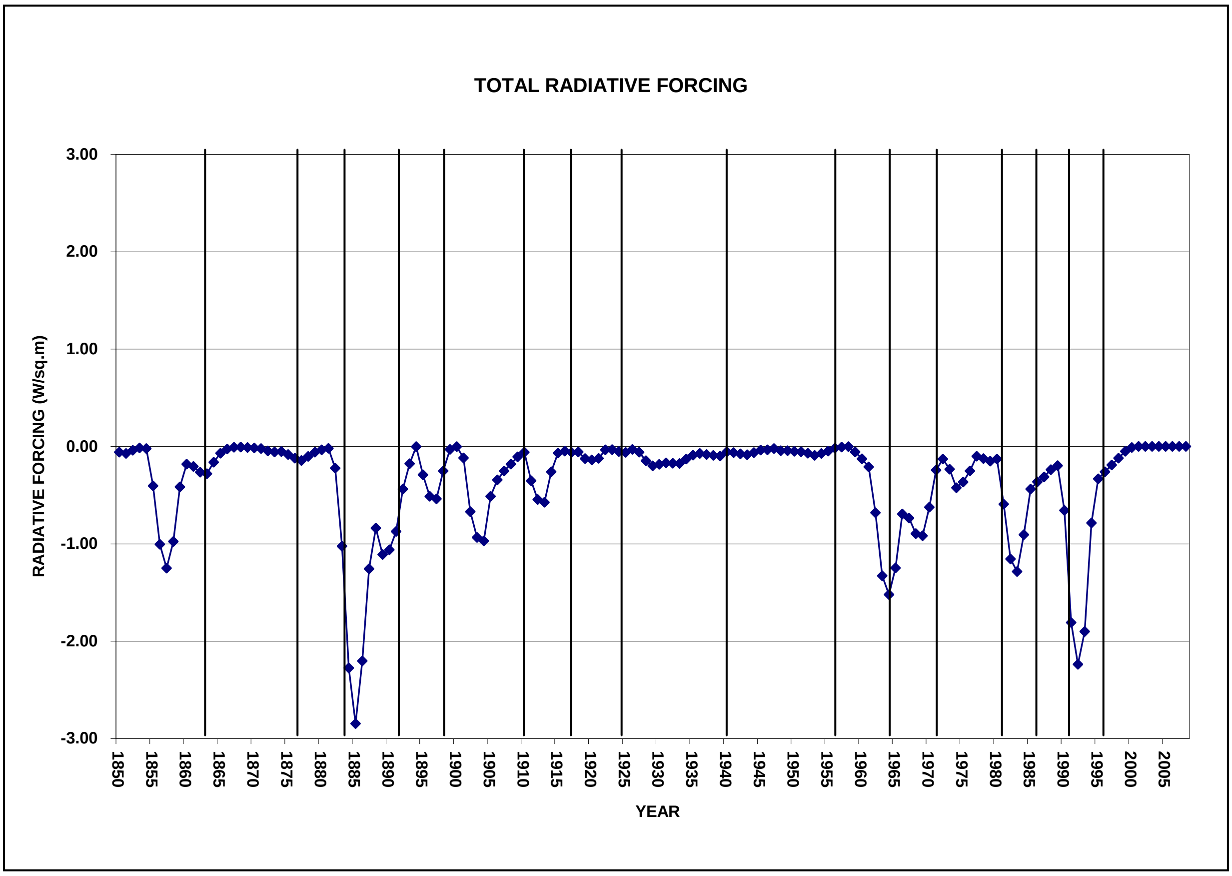

Figure 1: Volcanic radiative forcing with strong El Niño years represented by vertical lines

Given that both volcanoes and El Niños occur on a quasi-periodical basis it is quite possible that the coincidence of strong El Niños with the strongest volcanic eruptions could be just that, a coincidence, but it is worthy of further investigation. This will be addressed by means of both a literature search and data analysis. Volcanoes and El Niños are both very important climate modifiers on the inter-annual timescale with volcanic eruptions tending to lower global temperatures with El Niños showing the opposite tendency. When trying to identify climate trends the volcanic and El Niño climate signatures must be removed in order to determine any underlying tendency. Existing methods of isolating the ENSO signal will be investigated.

Finally, any possible impacts of El Niños on volcanic eruptions are considered.

Before any interactions between El Niño and volcanic eruptions can be evaluated an understanding of both is required and, therefore, background information on El Niño and volcanoes is included in Sections 1.2 and 1.3 respectively.

1.2 Introduction to El Niño Southern Oscillation

1.2.1 What is the El Niño Southern Oscillation?

The El Niño Southern Oscillation is a recurrent, quasi-periodic, anomalous warming/cooling of the tropical Pacific.

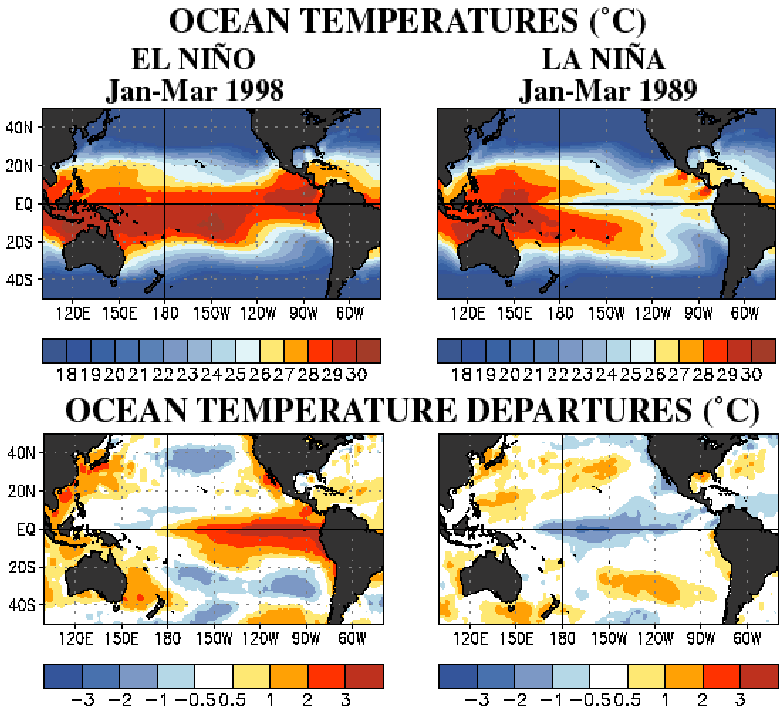

Figure 2: Ocean surface temperatures (top) and anomalies in El Niño and La Niña years. (NOAA, 2010a)

Figure 2 shows the Sea Surface Temperatures (SST) and ocean temperature departures for the warm phase (El Niño) and the cool phase (La Niña). The ENSO cycle has an average period of about four years, although this can vary between two and seven years.

These ocean temperature departures are highly correlated (Figure 3) with large-scale

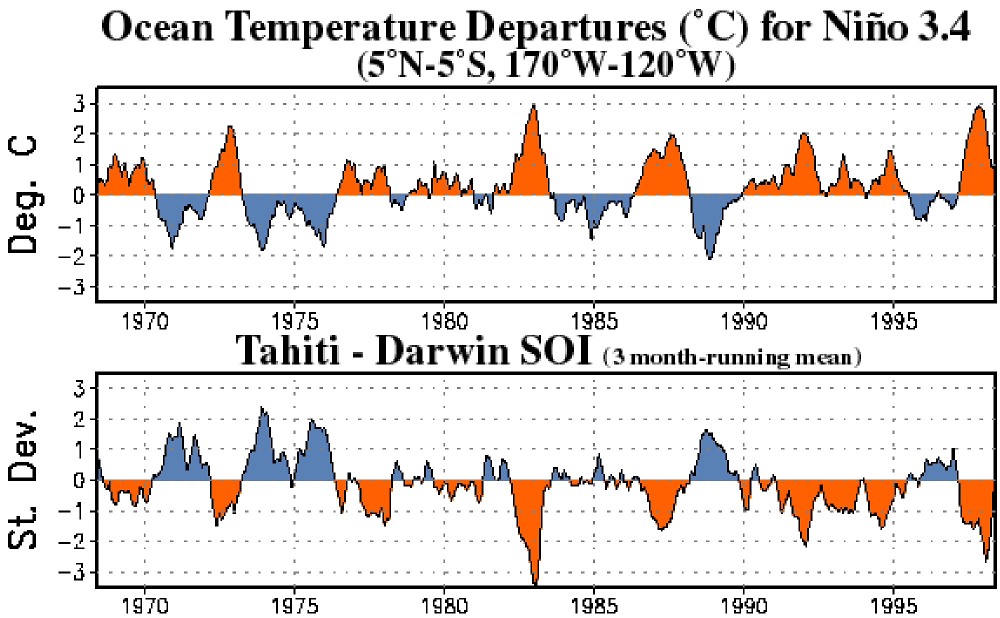

Figure 3: Time series of ocean temperature departures for NINO3.4 compared with the Southern Oscillation Index time series. (NOAA, 2010b)

fluctuations in air pressure that occur between the western and eastern tropical Pacific during El Niño and La Niña phases. This is measured by the Southern Oscillation Index (SOI) (1.2.4), the difference in air pressure anomaly between Tahiti and Darwin. The negative phase of the SOI represents above-normal air pressure at Darwin and below-normal air pressure at Tahiti; with prolonged periods of negative SOI values corresponding to El Niño conditions and vice versa for La Niña episodes. There is considerable variability in the ENSO cycle from one decade to the next with very active cycles in the 1980s and 1990s and a more quiescent period between the 1920s and 1960s. The evolution of an average El Niño also varies over time with striking differences between post 1976 El Niños and those that occurred between 1957 and1972 (Davey and Anderson, 1998).

A typical El Niño usually originates during the north hemisphere spring, reaching its peak in the following northern hemisphere winter and decaying during the course of the following year when it may be followed by a La Niña episode. It must be emphasised that there is a great deal of variation about this norm.

There is no official definition of ENSO phenomena agreed on a global basis as the World Meteorological Organisation (WMO) is still at the working party phase. There have been several attempts at a definition but none have been universally adopted. What follows is by no means an exhaustive list but is intended to convey the level of controversy surrounding the definition.

1. The definition of El Niño proposed by the Scientific Committee on Oceanic Research (1983) and based on climatology from 1956-81 was "El Niño is the appearance of anomalously warm water along the coast of Ecuador and Peru as far south as Lima (12 °S), during which a normalized sea surface temperature (SST) anomaly exceeding one standard deviation occurs for at least four consecutive months at three or more of five coastal stations (Talara, Puerto Chicama, Chimbote, Isla Don Martin, and Callao)."
2. Trenberth (1997) concluded that an El Niño can be said to have occurred if the 5-month running means of sea surface temperature (SST) anomalies in the Niño 3.4 region (5°N–5°S, 120°–170°W) exceed 0.4°C for 6 months or more.
3. Probably the nearest thing to an official definition, is that adopted by agreement between the North American countries of Mexico, the U.S.A. and Canada in 2005 and used by the National Oceanographic and Atmospheric Administration (NOAA, 2010c):

"El Niño: A phenomenon in the equatorial Pacific Ocean characterized by a positive sea surface temperature departure from normal (for the 1971-2000 base period) in the Niño 3.4 region greater than or equal in magnitude to 0.5 degrees C, averaged over three consecutive months."

"La Niña: A phenomenon in the equatorial Pacific Ocean characterized by a negative sea surface temperature departure from normal (for the 1971-2000 base period) in the Niño 3.4 region greater than or equal in magnitude to 0.5 degrees C, averaged over three consecutive months."

1.2.2 El Niño current theory

In order to understand El Niño one must first be familiar with the normal state of the tropical Pacific circulation as illustrated in Figure 4. This circulation pattern is known as the Walker circulation and is driven by SST differences between the western and eastern sides of the Pacific basin. The SSTs are particularly cool on the eastern side of the equatorial Pacific due to meridional advection from higher latitudes and greater depth than the western side. The greatest convection occurs over the warm pool in the western Pacific forming the ascending branch of the convectively driven Hadley-Walker cell. This deep convection causes upper

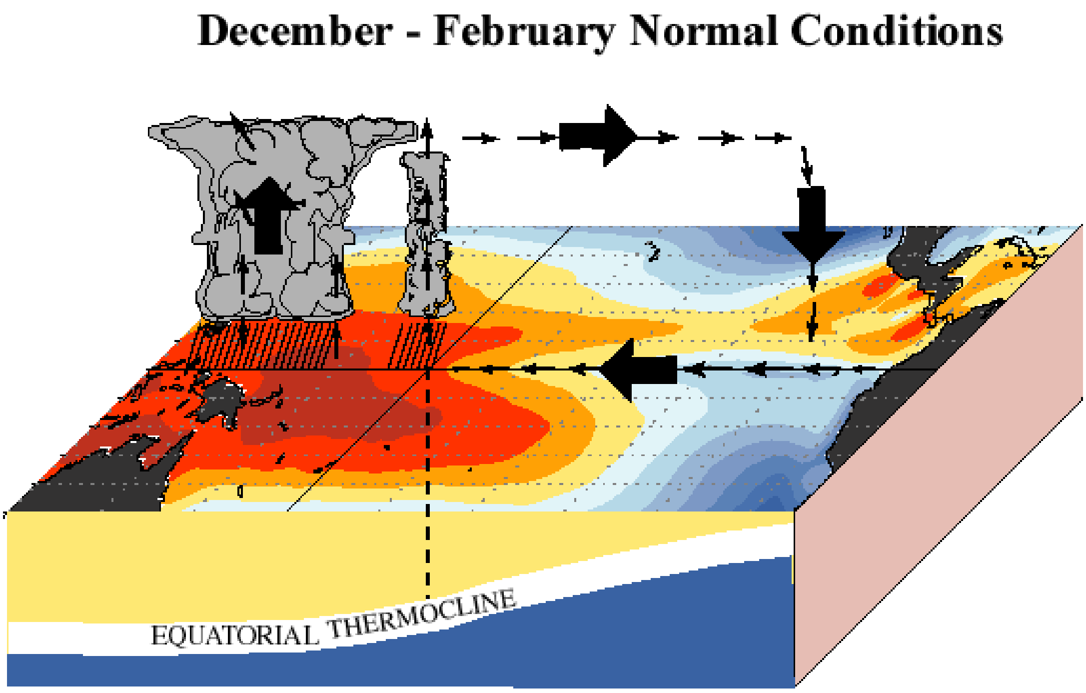

Figure 4: Normal December-February conditions in the equatorial Pacific (NOAA, 2010d)

level divergence and low surface pressure. The descending branch of the Hadley-Walker cell is in the eastern Pacific where the cooler SSTs lead to subsidence and, consequently, high surface pressure. On the equator, as there is no coriolis force, the surface winds respond to this east-west pressure gradient and cause easterly trade winds to blow across the surface of the Pacific whilst the upper level winds are westerly. (University of Reading, MSc Applied Meteorology, Tropical Weather Systems, 2010)

To the north and south of the equator the wind forced ocean currents approximately satisfy

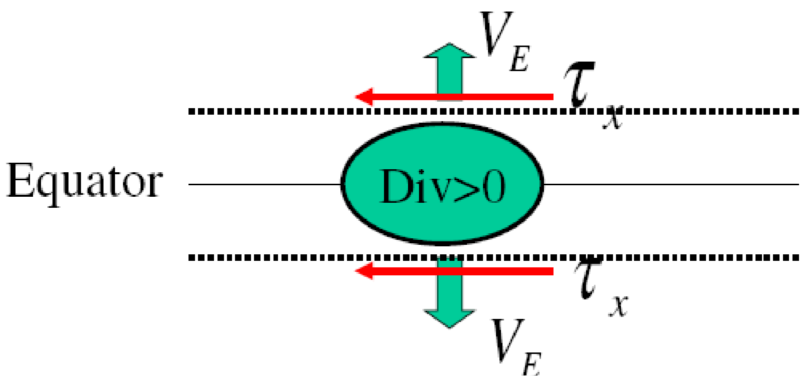

Figure 5: Ekman transport (τ_x = wind stress, V_E = wind forced ocean current) (University of Reading, MSc Applied Meteorology, Tropical Weather Systems, 2010)

geostrophic balance causing the Ekman transport (Figure 5) to be to the right of the wind to the north of the equator and to the left of the wind south of the equator. Easterly trade winds thus mean that the mean Ekman flow is away from the equator causing divergence there. This results in upwelling of water from below and causes cooling at the surface on the equator. (University of Reading, MSc Applied Meteorology, Tropical Weather Systems, 2010)

The warm surface water is separated from the cold, deep ocean waters by the oceanic thermocline, which is normally deepest in the west and slopes upward towards the surface further east. This results in easterly winds causing more cooling in the east as the shallower thermocline means that colder water is up welled. (University of Reading, MSc Applied Meteorology, Tropical Weather Systems, 2010)

During an El Niño event the easterly trade winds slacken due to, for example, westerly wind bursts in the western Pacific. These are normally caused by some external weather event such as the Madden-Julien oscillation or a tropical cyclone. This reduction in the easterly winds causes the SSTs to warm locally as the upwelling of cold water is reduced and also sets up a pressure gradient force in the thermocline. The slope of the thermocline then adjusts, via equatorially trapped baroclinic Kelvin and Rossby waves, to bring the pressure gradient back into balance. Thus the east-west slope of the thermocline is reduced. The increased depth of the thermocline in the east causes the SSTs to rise in the central and eastern equatorial

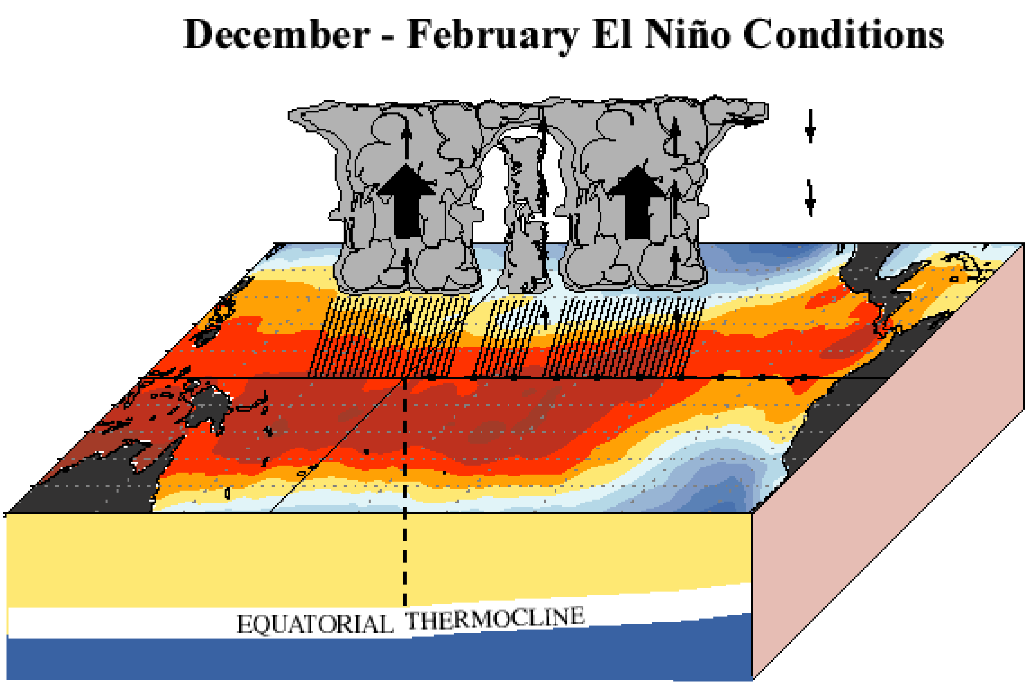

Figure 6: December-February conditions during an El Nino year (NOAA, 2010e)

Pacific as the water that is being up welled is less cold when the thermocline is deeper. These warmer SSTs towards the east cause the convection to move over the central Pacific, as shown in Figure 6, thus weakening the surface Walker circulation which in strong El Niño episodes can be completely absent or even reversed. The increased SSTs in the eastern Pacific result in lower surface pressure there and thus the easterly winds are reduced further causing a feedback loop known as Bjerknes feedback whereby

↓East West SST gradient ⇨ ↓East West SLP gradient ⇨ ↓Wind stress ⇨ ↓ East West SST

There are several theories to account for the termination of El Niño. These include the spring relaxation theory where anomalies decrease as the seasonal cycle catches up, the delayed oscillator theory of Suarez and Schopf (1988), the recharge oscillator theory of Jin (1997) and the west-Pacific oscillator theory of Weisberg and Wang (1997).

1.2.3 Why is El Niño important?

El Niño not only causes changes to weather conditions in the Pacific but can also impact

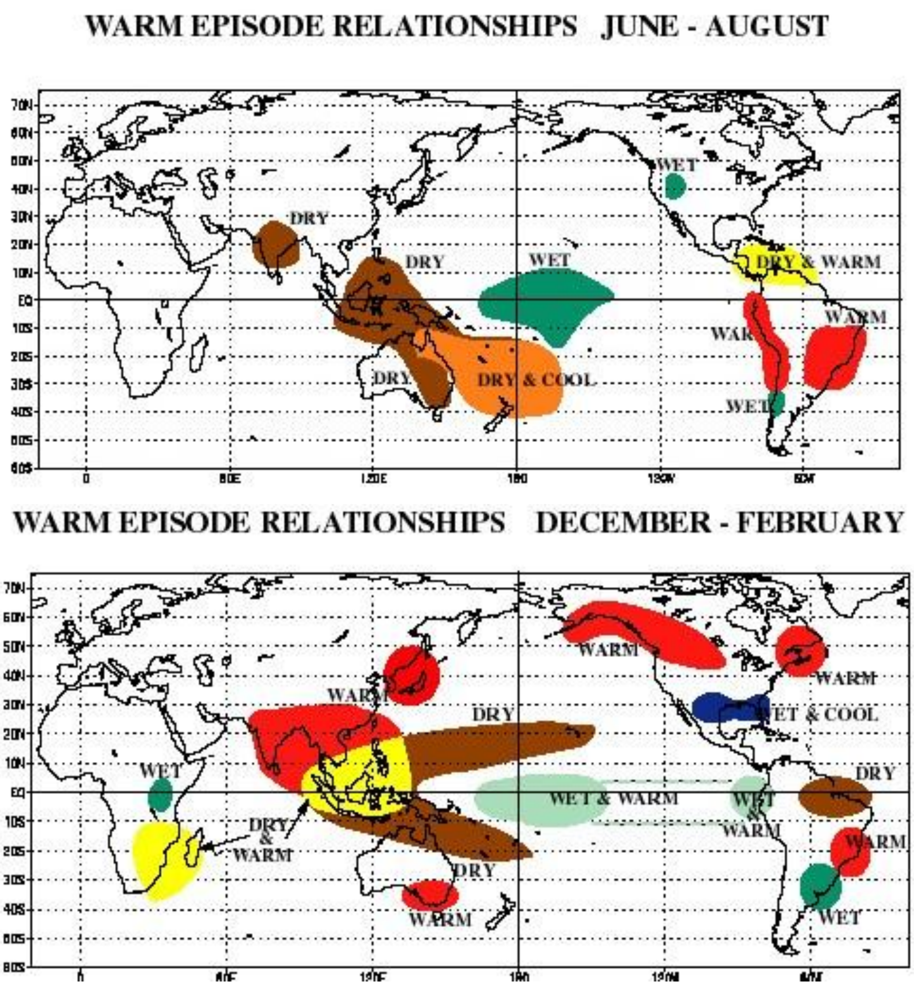

Figure 7. El Nino's influence on global weather for June-August and December-February (IRI, 2010a)

important global weather patterns. Some reasonably predictable weather responses to an El Niño event are shown in Figure 7 although it should be noted that ENSO related weather anomalies are very variable and it would be rare for all these teleconnections to be observed during one event. In the tropical Pacific an El Niño often leads to drought in normally humid regions such as Indonesia and northern Australia and flash floods in normally arid areas like coastal South America. Globally, it has impact upon many important weather patterns such as the Indian monsoon and the North Atlantic hurricane season and, indeed, ENSO indices are used as part of the statistical weather forecasts for these phenomena. It is, therefore, vitally important to be able to predict the phases of ENSO. (IRI, 2010a)

1.2.4 Measures of ENSO

Historically, El Niño was recognized by fisherman off the coast of South America as the appearance of unusually warm water in the Pacific Ocean occurring near the beginning of the year. Records of these warmings and extreme weather events in South America provide early data on ENSO. Prior to historical records, indications of ENSO phases can be found in proxy records such as coral and tree rings. Instrumental records, Darwin and Tahiti Sea Level Pressure (SLP) measurements and SSTs are available from the 19th century. In the late 20th century satellite data and a network of buoys, operated by NOAA, have vastly improved the quality and quantity of data available. The TAO/ TRITON array of buoys positioned across the equatorial Pacific transmit daily temperature, current and wind data in real time (Figure 8).

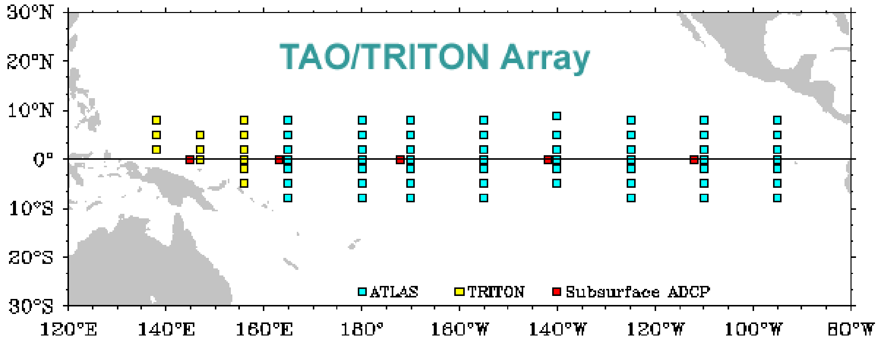

Figure 8. The TAO/TRITON array of buoys in the equatorial Pacific (IRI, 2010b)

There are even more indices for measuring an El Niño than there are definitions and weaker ENSO events may not be represented in all indices. As well as the standard SST indices for the Niño 1+2, Niño 3, Niño 3.4 and Niño 4 regions (Figure 9) there are also several other main indices which are listed alphabetically below.

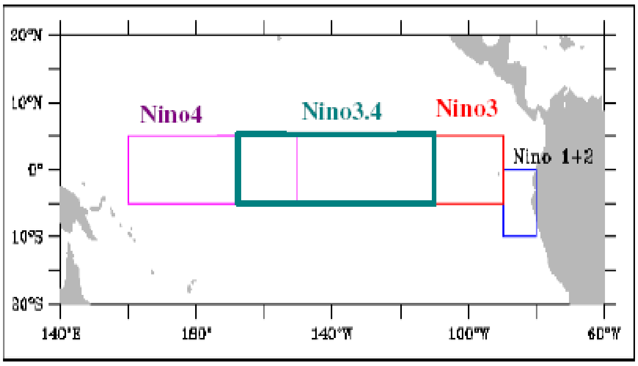

Figure 9. Nino SST regional indices (IRI, 2010b)

The Bivariate ENSO Time series (BEST) is calculated from combining a standardized SOI and a standardized Niño 3.4 SST time series (from the Hadley SST dataset) based on indices from 1871-2001. It is designed to be simple to calculate and to provide a long time period ENSO index for research purposes; combining SSTs with explicit atmospheric processes. Including the SOI, which is better measured historically than the SSTs, reduces the effect of biases in the SST data. (Smith and Sardeshmukh, 2000)

The Cold Tongue Index (CTI) is a measure of the average eastern equatorial Pacific SST anomalies in the region 6N-6S, 180-90W (Figure 10) calculated as the average SST anomaly

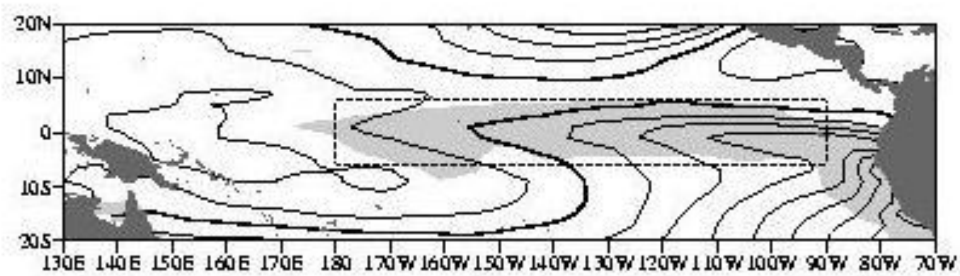

Figure 10: geographical region of Pacific "cold tongue" within the dashed contour. (JISAO, 2010)

in the region minus the global mean SST anomaly. This region, commonly referred to as the “cold tongue”, is characterized by cold SSTs (typically < 26C) in a narrow zonal band centred on the equator in the central and eastern longitudes of the Pacific. The SST observations are taken from the International Comprehensive Ocean-Atmosphere Data Set (ICOADS) version 2.5 with delayed-mode data for 1845-2007 and real-time data for 2008-10 (data is non-continuous prior to the 1870s). Anomalies are calculated with respect to the

1950-79 climatology. In a given month, the CTI value is the average of the available data for all of the 2-degree latitude-longitude grid boxes in the CTI region, weighted by the number of observations in each 2-degree box. The global mean SST anomaly is subtracted from the CTI in order to remove a step jump at the onset of World War II when the method of the marine observations largely changed and to lessen the trend associated with global warming. (JISAO, 2010)

The Multivariate ENSO Index (MEI) which was developed primarily for research purposes combines the six main observed variables over the tropical Pacific. These six variables are: sea-level pressure, zonal and meridional components of the surface wind, surface air temperature, sea surface temperature and the total cloud fraction of the sky. The MEI is calculated separately for each of twelve sliding bi-monthly seasons (Dec/Jan, Jan/Feb up to Nov/Dec). All seasonal values are standardized with respect to each season and to the 1950-93 reference period. Negative values of the MEI represent La Niña and a positive MEI indicates an El Niño. A strong El Niño is defined as one in the top 10% of the MEI rankings. (NOAA, 2010f)

The Oceanic Niño Index (ONI) is defined as the 3 month running mean of NOAA ERSST.v2 SST anomalies in the Niño 3.4 region (5N-5S, 120-170W), based on the 1971-2000 base period (NOAA, 2010g). The strength of the El Niño according to the ONI is described in Table 1.

Table 1: definition of El Niño strength according to the ONI

El Niño Definition	Oceanic Niño Index (ONI)
Weak	0.5 - 0.9
Moderate	1.0 - 1.4
Strong	1.5 - 1.9
Extreme	2.0 +

The Southern Oscillation Index (SOI) is defined as the normalized pressure difference between Tahiti and Darwin. There are several slight variations in the SOI values calculated at various centres e.g. the method used by the Australian Bureau of Meteorology is the Troup

SOI which is the standardised anomaly of the Mean Sea Level Pressure (MSLP) difference between Tahiti and Darwin calculated as follows:

$$SOI = 10\left(\frac{Pdiff - Pdiffav}{SD(Pdiff)}\right)$$

where:

P*diff* = (average Tahiti MSLP for the month) - (average Darwin MSLP for the month), P*diffav* = long term average of Pdiff for the month in question, and SD (P*diff*) = long term standard deviation of Pdiff for the month in question.

The Trans-Niño Index (TNI) time series is calculated from the HadISST (Hadley Centre Global sea-Ice coverage and SST) and the NCEP OI (National Center for Environmental Protection Oceanic Index) datasets. It is the standardized Niña 1+2 minus the Niña 4 with a 5 month running mean applied which is then standardized using the 1950-1979 period. The index is available from 1871 onwards. (Trenberth and Stepaniak, 2001)

1.3 Overview of Volcanic Influences on the Atmosphere and Oceans.

Figure 11. Mount Pinatubo eruption column. Photo by Dave Harlow, 1991 (U.S. Geological Survey) (Smithsonian Institute)

The power of a volcano is graphically illustrated in Figure 11 which shows the eruption column from Mount Pinatubo on June 12th 1991. The column extended to an altitude of 19km and was the first in a series of powerful eruptions that reached a climax on June 15th. Volcanoes of this magnitude and explosivity are important modifiers of climate on a variety of timescales. Less explosive volcanoes also impact climate but generally more locally and on shorter timescales. An understanding of these climate impacts is important both for predicting climate conditions for the years following an eruption and for the detection of anthropogenic climate change.

1.3.1 Atmosphere

The climatic effects of an explosive volcanic eruption are illustrated in Figure 12. Following such an eruption the first effects are due to magmatic material which is ejected as solidified

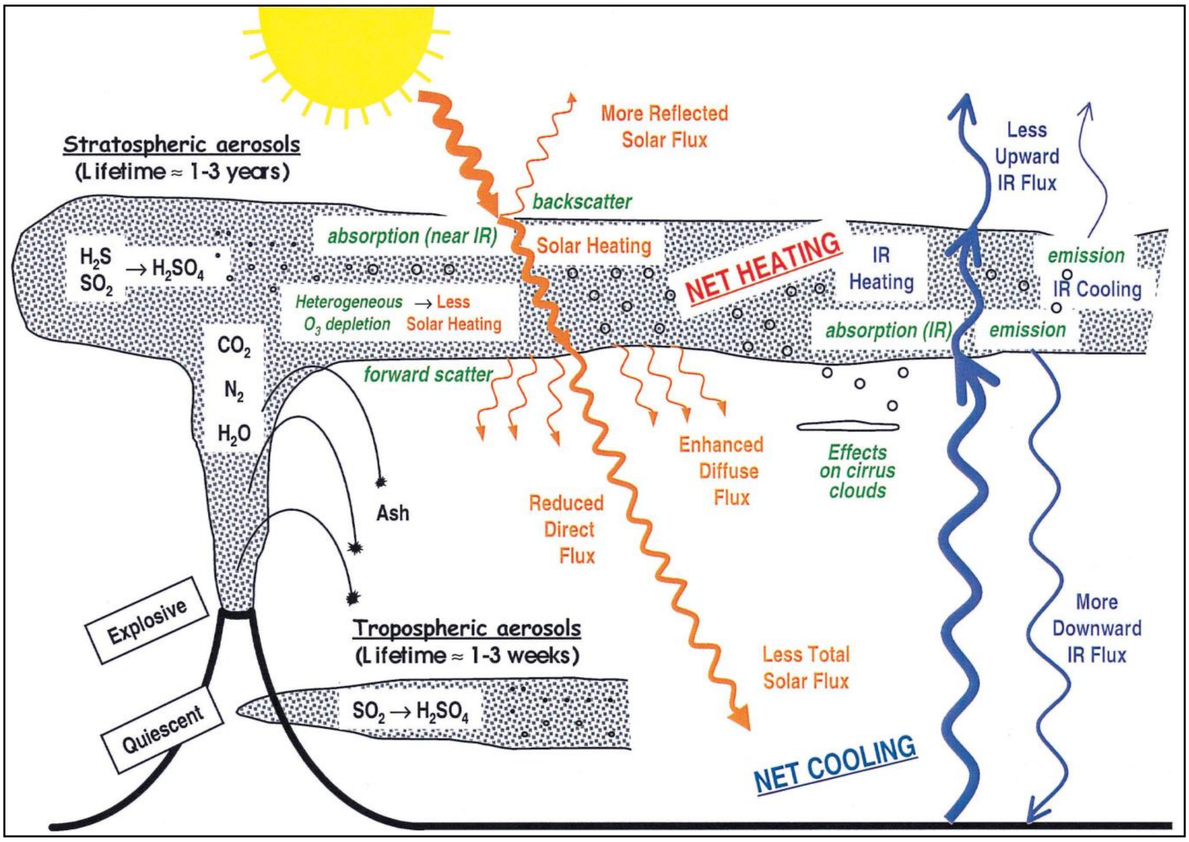

Figure 12: Schematic diagram of volcanic inputs to the atmosphere and their effects. (Robock, 2000)

large particles called ash or tephra. These particles normally remain within the troposphere where they are short-lived and fallout within a timescale of a few minutes to a few weeks. During their lifetime they reduce the amplitude of the diurnal cycle of air surface temperature underneath the tropospheric cloud e.g. the Mount St. Helen’s region cooled by 8°C during the day but warmed by 8°C at night. Small amounts might get into the stratosphere and last there for a few months but these have little climatic impact.(Robock, 2000)

Gases are also emitted during an eruption mostly H_2O, N_2 and CO_2. Of these H_2O and CO_2 are important greenhouse gases but individual eruptions don’t have a significant effect on their concentrations although over many millennia the accumulations have been the main source of the earth’s atmosphere.(Robock, 2000)

The main influence on the climate is the emission of sulphur species mainly SO_2 and occasionally H_2S. It is estimated that 7Mt of SO_2 was emitted from El Chichón and 20Mt from Pinatubo. Within a few weeks of emission these sulphur species react with OH and H_2O in the atmosphere to form H_2SO_4 aerosols. If the eruption is sufficiently explosive these aerosols can reach the stratosphere. Once in the stratosphere the aerosols are advected around the globe within 2 to 3 weeks and can last there for up to 3 years. Although dependent on the wind pattern at the time of the eruption, aerosols from tropical eruptions are normally lifted by the stratospheric meridional circulation, transported towards the poles and then fall back into the troposphere at higher latitudes on a timescale of 1-2 years. The aerosols from high latitude eruptions are not normally advected beyond the mid-latitudes of the eruption hemisphere. (Robock, 2000)

These sulphate aerosol particles scatter solar radiation as they have a radius of around 0.5μm which is approximately the same size as the wavelength of visible light. Some of the light is backscattered, reflecting sunlight back to space and increasing the net planetary albedo. Much of the solar radiation is also forward scattered increasing downward diffuse radiation partly offsetting the large reduction in the direct solar beam. The forward scattering effect can be seen by the naked eye making the normally blue sky a milky white colour. The reflection of the setting sun from the bottom of the dust veil produces the typical volcanic sunset. (Robock, 2000)

At the top of the aerosol cloud the atmosphere is heated by absorption of near infra-red solar radiation. In the lower stratosphere the atmosphere is heated by absorption of upward long wave radiation from the troposphere and the surface. There is also increased Infra Red (IR) cooling due to enhanced emissivity caused by the presence of the aerosols. This cooling is overwhelmed by the heating effect and there is a net heating of the stratosphere.

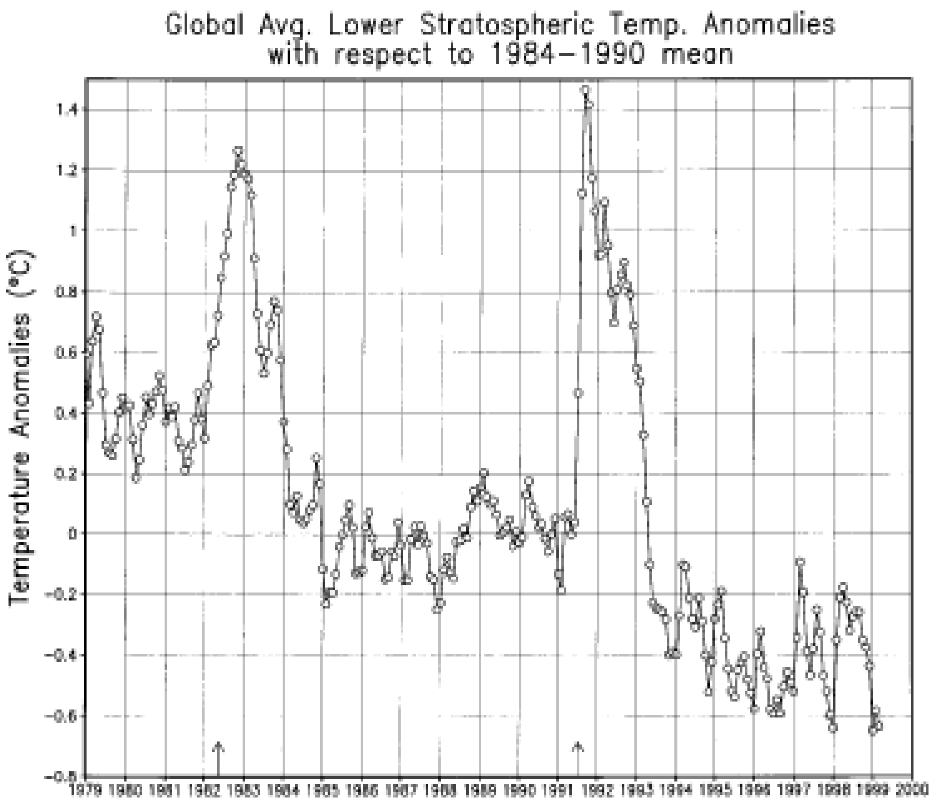

Figure 13. Global average lower stratospheric temperature anomalies with respect to the 1984-1990 mean (Robock, 2000)

Figure 13 shows observations of stratospheric temperatures over the 20 years from 1980-2000 clearly showing temperature peaks following the El Chichón and Pinatubo eruptions. Lower stratospheric heating is much larger in the tropics than at the poles and, therefore, the pole to equator stratospheric temperature gradient is increased. This results in a stronger polar vortex which produces winter warming over Northern Hemisphere (NH) continents. (Robock, 2000)

As in the stratosphere, there could initially be some heating of the troposphere due to the mechanisms described above although the tropospheric aerosols may fallout before the chemical reactions have time to occur. Once the tropospheric aerosol cloud has dispersed there are no significant radiative effects in the troposphere as the reduced downward near-IR is compensated by the additional downward longwave radiation from the aerosol cloud. (Robock, 2000)

At the surface the large reduction in direct shortwave radiation is much greater than the combination of additional downward diffuse shortwave flux and longwave radiation from the aerosol cloud. This net cooling at the surface is responsible for the global cooling effect of volcanic eruptions for several years after major eruptions. The maximum cooling of about 0.1-0.2°C is found approximately 1 year after the eruption. The cooling follows the solar declination but is displaced towards the NH. Land surfaces respond more quickly to radiation perturbations and thus, with its larger land mass, the NH is more sensitive to radiation reduction from volcanic aerosols. Consequently, the maximum cooling in the NH winter is at about 10°N and in summer at 40°N. (Robock, 2000)

Sulphate aerosols in the stratosphere can provide a surface for heterogeneous reactions allowing anthropogenic chlorine to be available for the chemical breakdown of ozone. These reactions would normally only occur on polar stratospheric clouds over Antarctica. A decrease of the ozone concentration results in less ultraviolet (UV) absorption in the stratosphere thereby increasing the surface UV radiation and reducing the aerosol heating effect in the stratosphere. This will only be a problem for as long as anthropogenic chlorine remains in the stratosphere.(Robock, 2000)

Detection and attribution of the volcanic signal is complicated because the climatic signature of volcanic eruptions is of similar amplitude to that of ENSO. It has been demonstrated that the ENSO signal in past climate records partially obscures the detection of the volcanic signal on a hemispheric annual average basis for surface air temperature (e.g. Mass and Portman, 1989).

1.3.2 Ocean

Possibly the most visually dramatic effect of volcanoes upon the ocean is the pumice raft as pictured in Figure 14. These are formed by types of volcanic ash which do not dissolve but instead clump together on the surface of the water. As these rafts cover relatively small areas they probably have little overall impact on climate.

Figure 14 Pumice raft in southern Pacific (NOAA, 2010h)

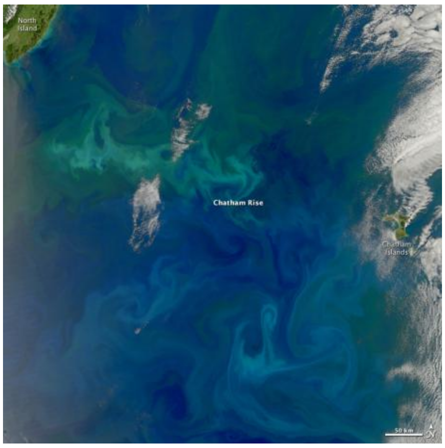

Figure 15.Phytoplankton bloom over Chatham Rise, South Pacific. (NASA, 2010a)

Another visually impressive spectacle is the phytoplankton blooms that can occur in the oceans. Figure 15, although not of volcanic origin, is an example of one of these phytoplankton blooms which can increase the albedo of the ocean surface by 10%. In some parts of the globe these blooms occur on a regular seasonal basis but elsewhere their growth is limited by a lack of nutrients or iron.

Figure 16 indicates the global phytoplankton concentrations in the oceans, red, yellow, and green

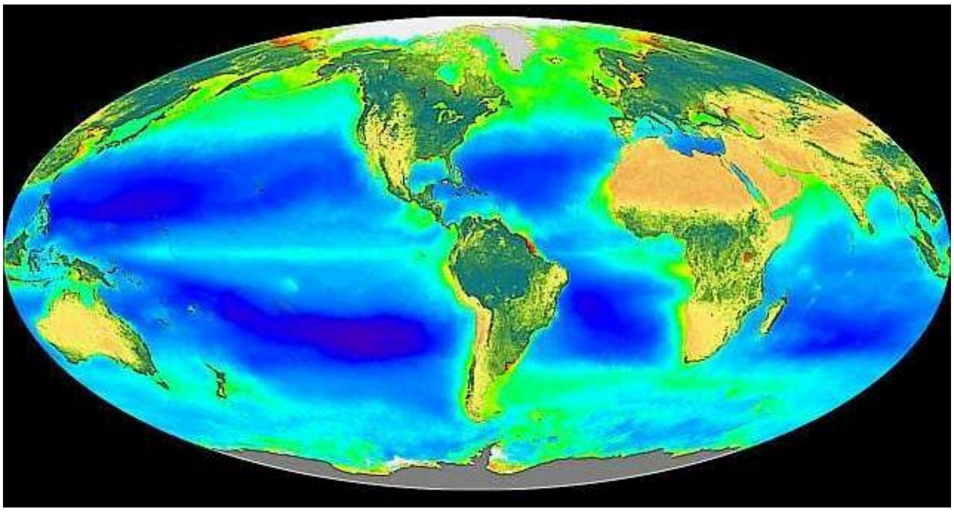

Figure 16. The ocean's average phytoplankton chlorophyll concentration between September 1997 and August 2000. (NASA, 2010b)

pixels show dense phytoplankton blooms, while blues and purples show where there are very little phytoplankton. The Pacific is generally rich in nutrients but low in iron and therefore the phytoplankton concentrations are not very high across much of the Pacific. The effect of the equatorial upwelling bringing nutrients to the surface can be seen across the equatorial Pacific. During an El Niño this effect disappears and during a La Niña event it is enhanced.

A relatively new field of study is the impact that bio-available iron dissolved from offshore deposition of airborne volcanic ash can have on phytoplankton concentrations. The source of this soluble and rapidly delivered iron is believed to be the sulphate and halide salts deposited onto the surface of ash particles. Significant amounts of iron can be released from the ash within 45 minutes of contact implying that a significant fraction is released in the sun-lit surface ocean where it is available for the phytoplankton. If this ash falls into areas of high nutrient but low iron such as the equatorial Pacific it can have a significant impact on phytoplankton concentrations.

Since 1997, satellite-borne detectors such as Moderate-Resolution Imaging Spectraradiometer (MODIS) and Sea-viewing Wide Field-of-View Sensor (SeaWiFS) have provided true colour images of the surfaces of the oceans on a daily basis and these will make it easier to detect phytoplankton blooms in the future. Langmann et al (2010) used MODIS to monitor chlorophyll levels following the 2008 eruption of Kasotochi and saw an increase in the levels as illustrated in Figure 17. This technology was not available for earlier eruptions

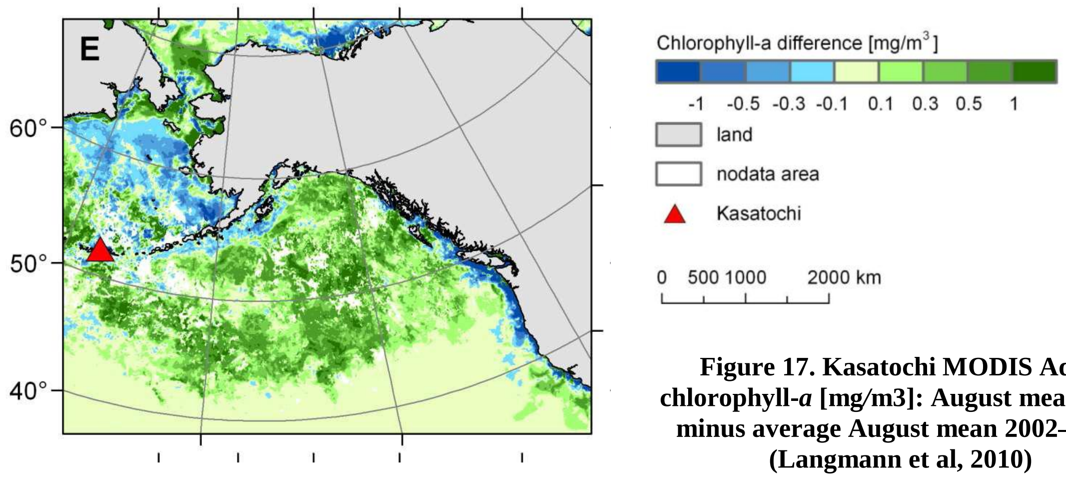

Figure 17. Kasatochi MODIS Aqua chlorophyll-*a* [mg/m3]: August mean 2008 minus average August mean 2002–2007 (Langmann et al, 2010)

but it was noted that Agung in 1963 and Pinatubo in 1991 were followed by a pronounced atmospheric CO_2 drawdown despite the large amount of CO_2 emitted by the volcanoes and it is believed that this was due to biological CO_2 fixation by increased phytoplankton growth in the oceans. (Duggen et al, 2010)

Following atmospheric fallout on the ocean surface, marine sedimentation of ash-grade material occurs by Stokes Law settling for individual grains. Particle aggregation, however, can cause premature sub-aerial fallout of fine-grained ash. After crossing the air-sea interface, vertical settling of the ash clusters is enhanced by absorption of water leading to settling rates of 1–3 orders of magnitude faster than possible by Stokesian settling. It has been demonstrated that when entering a stratified environment these ash particles can decouple from the transporting fluid, whose vertical motions are limited by the stable density gradient. In the ocean, vertical density currents generated by ash-loading and gravitational destabilization of the water column can overcome the strong stable density gradients in the ocean and transport ash particles vertically. (Wiesner et al, 1995, Manville and Wilson, 2004)

Whilst the influence of volcanic radiative forcing only lasts up to about 7 years in the troposphere, in the ocean it can have an influence on the sea level, salinity, deep ocean temperature and the Atlantic meridional overturning circulation for up to a century. A succession of volcanic eruptions over a number of decades can, therefore, produce a cumulative impact on the deep ocean thermal structure. (Stenchikov et al, 2009)

1.3.3 Measuring the Strength of a Volcano

There are several methods of measuring the impact of a volcanic eruption but all have some drawbacks and not all have been updated since they were originally devised.

The Dust Veil Index (DVI) was originally compiled by Lamb in 1970 and is based on historical reports of eruptions, temperature information, estimates of the volume of ejecta, optical phenomena (such as red sunsets) and radiation measurements from 1883 onwards. The DVI is an annual average with 40% of the volcanic loading assigned to the year of the eruption, 30% to the following year, 20% to the year after and 10% to the third year after the eruption. The eruption of Krakatau is considered to have a DVI of 1000. The DVI is not ideal as an indicator of volcanic climate impacts as it uses climate data in its derivation.

The Ice core Volcanic Index (IVI) is a measure of the average acidity or sulphate found in ice cores from both the northern and southern hemispheres as estimated by Robock and Free (1995) and subsequently updated in 2005 (Gao et al, 2008). It is assumed that if sulphate is found in cores from both hemispheres then the source of the eruption was in the tropics. The IVI has the potential to provide a longer time series of volcanic information than the historical record. For the northern hemisphere high latitude eruptions are over represented and the record can only be adjusted to allow for this if their signal can be unambiguously detected.

The Mitchell Index produced by Mitchell (1970) is based on the order of magnitude of the total mass ejected from each volcano. In compiling the index Mitchell made the assumption that 1% of the mass from each eruption formed a stratospheric aerosol layer with a mean residence time of 14 months.

The Sato Index compiled by Sato et al (1993) is a monthly index of average NH and Southern Hemisphere (SH) optical depths at the 0.55µm wavelength. For the earliest period it is based on data on the volume of ejecta, from 1883 to 1978 on optical extinction data and on satellite data from 1979 onwards.

The Volcanic Explosivity Index (VEI) is effectively a geologically based measure of the explosive force of a volcanic eruption. The VEI record was originally produced by Newhall and Self (1982) and has the advantage that it has been maintained and updated until the present day. Under this system the explosivity of a volcano is rated on a scale of 1 to 8 with Krakatau having a VEI of 6. For an eruption with a VEI of 3 it is considered possible that the eruption has produced stratospheric aerosols, for a VEI of 4, under the original definition, stratospheric aerosol production was considered definite and, for VEI greater than 4, a significant quantity of stratospheric aerosols were considered to have been emitted. In practice, however, the use of the VEI as a climatic indicator is not wholly reliable as the amount of stratospheric aerosol produced is not precisely correlated to the strength of the explosive force. For example, Mount St. Helens with a VEI of 5 did not produce much stratospheric aerosol as most of its eruptive force occurred laterally through the flank of the volcano.

Chapter 2 Review of Research into Interactions between Volcanoes and El Niño

2.1 Influences of Volcanoes on El Niño

The strong El Niño of 1982/83 that coincided with the eruption of El Chichón in April 1982 led to speculation on whether the two events could be connected. Initially, statistical analysis was performed on the available instrumental data set but this analysis was found to be flawed. Several early attempts to describe a physical mechanism for a link between volcanism and ENSO were also not widely accepted. Later attempts at statistical analysis using a longer data set with proxy data and a plausible ocean dynamical thermostat model led to more interest in the theory. An uncritical summary of these analyses and theories is contained in sections 2.1.1 to 2.1.17 and will be discussed in 2.4.

2.1.1 Handler (1984)

Handler investigated how often this sequence of events has occurred in the past in order to determine whether the events were related or if it was just coincidental. He studied eleven low latitude (<20˚) eruptions similar to El Chichón that had occurred between 1868 and 1980. He obtained seasonal sea surface temperature data for the region from the equator to 10˚S latitude and 90˚ to 180˚W longitude from Angell (1981) and volcanic eruption data (VEI) from Newhall and Self (1982). Only volcanoes with a VEI greater than 3 were included in the study. As previously discussed, the use of VEI as a measure of stratospheric aerosols is not ideal and, therefore, Handler used Superposed Epoch Analysis (SEA) to remove the random noise. In order to avoid conflicting signals the volcanoes were chosen so that the stratosphere was free of aerosols prior to the eruption and contained only the aerosol from the volcano in question for one or more years after the eruption.

Handler's composite results from the 11 volcanoes, from 2 seasons before the eruption to 8 seasons after, showed that the sea surface temperature anomaly is small during the season in which the eruption occurs but rises to almost 0.5˚C above background for up to 3 seasons afterwards. Handler considered this to be above the 95% level of significance especially when serial correlation of the sea surface temperature data is taken into account. Handler did a similar analysis of 20 high latitude volcanoes over the same period. For these volcanoes, again the sea surface temperature anomaly is small during the season of eruption, but this time the temperatures are *cooler* than normal for up to 5 seasons following the eruption.

Again, taking serial correlation into account, Handler considered the results significant at greater than 95%. Handler noted that if both low latitude and high latitude aerosols were included in the same data set then they would have cancelled each other out and no significant results would have been obtained. Handler considered that including El Chichón in the list of low latitude aerosols would raise the level of significance of the results to the 99% level.

2.1.2 Schatten et al (1984)

Schatten et al used a simple zonally symmetric model to investigate the effect of a low latitude aerosol, reducing the tropospheric pole to equator temperature gradient, on atmospheric motion. Their model applied the conventional theories of atmospheric super-rotation, in which the super -rotation is considered as a solar driven heat engine via the pole to equator temperature difference. They assumed a constant decrease in the atmospheric heating rate over a 6 month interval. They found a decrease in wind velocity at high altitudes and an increase at low altitudes, as illustrated in Figure 18, resulting in the transport of angular momentum from high altitudes down towards the surface and ultimately increasing the westerly zonal wind velocity. They also believed that an initial moderation of the horizontal temperature contrast resulting in a lessening of temperature extremes (i.e. a more maritime climate) could result from the change in circulation. Applying these conclusions to the eruption of El Chichón and given the location of El Chichón in the low latitudes the authors considered that its eruption would primarily influence low latitude temperatures thereby reducing the tropospheric pole to temperature gradient and thus increasing the westerly zonal wind velocity. At this date the "westerly wind burst" theory as a trigger for El Niño was only a controversial hypothesis and although the authors did mention this theory they went on to state that the more well established relationship to explain an El Niño

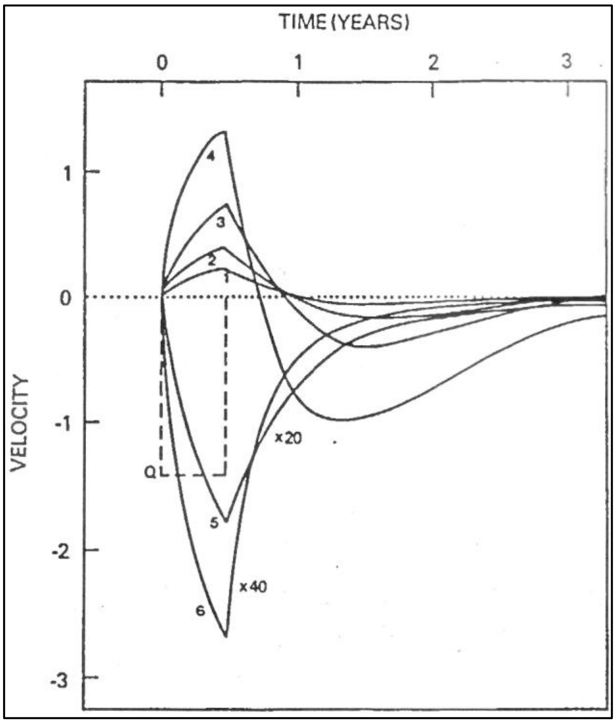

Figure 18: wind velocity at different altitudes from (1) 2km to (6) 100km. Q represents the period over which the solar input is reduced (Schatten et al, 1984).

was the warming of the central Pacific which they hypothesised could be triggered or augmented by volcanic activity. In conclusion, while accepting that their analysis was an oversimplification, they believed that as their model conserved angular momentum and utilised the thermal wind equation the phenomena they described might not be overly model dependent and that their results were qualitatively consistent with the observations. The 2 initial effects predicted by the model were the redistribution of angular momentum to lower altitudes and the moderation of temperature extremes.

2.1.3 Handler (1986)

Handler (1986) is an extension of the work in Handler (1984). The same volcanoes were considered (including El Chichón), some extra statistical analysis was performed (such as a chi squared test) but essentially the conclusions from this aspect remained unchanged. The results of the SEA are shown in Figure 19. When the other volcanoes of VEI ≥ 4 that occurred between 1868 and 1982 were included in the results Handler believed that in total the stratospheric aerosols from volcanoes could account for over half of ENSO events. He suggested that given the limitations of the use of VEI as a measure of stratospheric aerosols (see 1.3.3) it is possible that some volcanoes of VEI = 3 can produce stratospheric aerosols. His analysis of ice core records from Greenland (from Hammer et al, 1980) appeared to back this up as there are groups of years where sulphuric acid has been found in the ice but no volcano of VEI ≥ 4 was observed. He considered that stratospheric aerosols satisfy a number of the conditions required as a trigger for ENSO events (Barnett, 1985) namely:

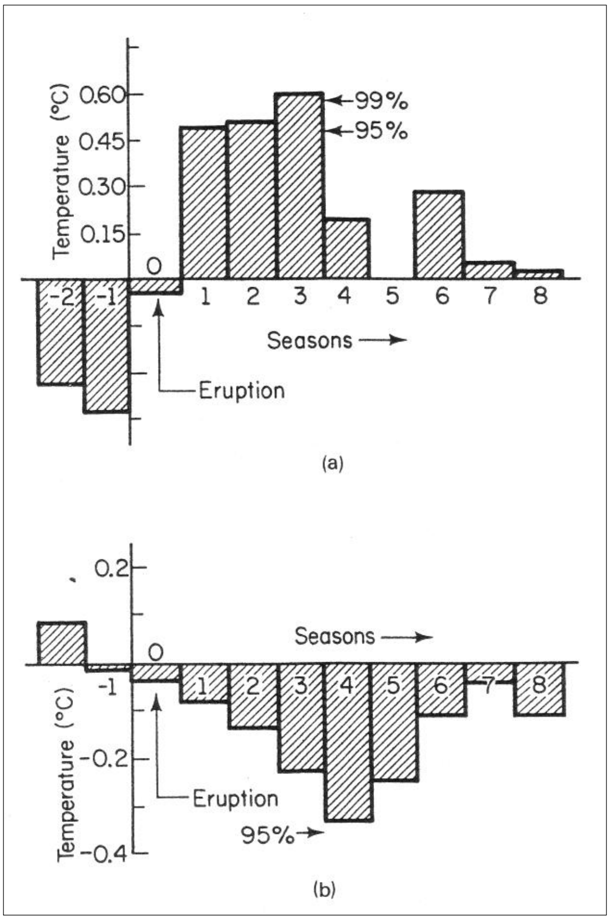

Figure 19. Handler's SEA for (a) 12 low latitude eruptions and (b) 21 high latitude eruptions.

- they occur randomly in time.

- They persist for a number of years.
- They can divert enough solar energy to cause global scale climatic change.
- They are not linked to the solar cycle.
- They precede the climate events which they trigger.

He concluded that there is a very strong association between low latitude stratospheric aerosols and ENSO years and between high latitude stratospheric aerosols and non-ENSO years.

2.1.4 Strong (1986)

In 1986 Strong presented a paper to the American Geophysical Union, the abstract of which is available. He took volcanic aerosol information for the previous 110 years and demonstrated a relationship between tropical eruptions and increased SSTs in the eastern equatorial Pacific which he thought would occur when volcanic aerosols are trapped for several months in a zonal belt around the tropics because of stratospheric easterlies. If the SSTs were below average at the time of the eruption then the effect is more pronounced and the effect can be seen for up to 18 months following the eruption with SST increases along the equator averaging about 0.8°C. He believed that the effect of the eruption was to modify processes already underway, in particular, he thought that the El Chichón eruption led to the enhancement of the 1982/3 El Niño.

2.1.5 Hirono (1988)

Following on from Handler's analysis of climatic data Hirono (1988) attempted to find a physical mechanism for the possible relationship between aerosols in the atmosphere and El Niño type events with particular reference to the El Chichón eruption of 1982 and the Agung eruption of 1963. Knowing (from Cane and Zebiak, 1985) that a prolonged westerly wind burst of 2m/s near the central Pacific would be required to initiate an El Niño Hirono investigated the variations in the atmospheric winds that could be produced by aerosol heating in the early period following the El Chichón eruption using a simple model constructed by Gill (1980). From lidar measurements and Global Climate Model (GCM) results of Giorgi and Chameides (1986) it was estimated that for several months after the eruption of El Chichón a substantial proportion of the aerosols remained near Mexico and the subtropical eastern Pacific. These aerosols, which were gradually falling through the upper troposphere, caused atmospheric heating due to the absorption of visible solar radiation and terrestrial longwave radiation so producing a pressure difference. The results from the model run suggested that the initial local atmospheric heating would produce a westerly component to the wind near the equatorial central Pacific if the centre was at about 100˚W and the dissipation factor (representing the Rayleigh friction and Newtonian cooling) was of the order of 0.1. The model was also run assuming a subsequent zonal distribution of aerosols for several months around a centre at about 16˚N. This also produced a westerly wind component along the equator. For a dissipation factor of the order of 0.01 this zonal forcing of the wind was about 1m/s thus Hirono concluded that if there is also moisture feedback the wind forcing would be sufficient to trigger or amplify an El Niño. Because of the pressure differential between the eastern and western Pacific the local forcing produced by Agung on the western edge of the Pacific would produce an easterly wind component which would act to suppress El Niño but the subsequent zonal forcing would amplify El Niño. In fact Agung was followed by a weak El Niño.

2.1.6 Parker 1988

Parker tested Handler's results from the 1986 paper by repeating the SEAs using seasonal east tropical Pacific SST anomalies from the U.K. meteorological office data set, thus testing the robustness of the results to variations in the data. The data set covered the Pacific east of 170°W and between 20°N and 20°S. The eruption dates were the same as those selected by Handler (1986).

The results from the analysis including the significance levels were similar to those from Handler but Parker believed that the results warranted further statistical investigation as the distribution did not appear to be Gaussian and to apply the test to a non-Gaussian distribution would result in over-estimated significance at the extremes. To circumvent this he used the Monte Carlo sampling method, producing 80,000 composites, each one consisting of a SEA with 12 random start dates. The composites with similar initial SSTs to those seen prior to the eruption date in the composite of the 12 volcanic years were then compared to

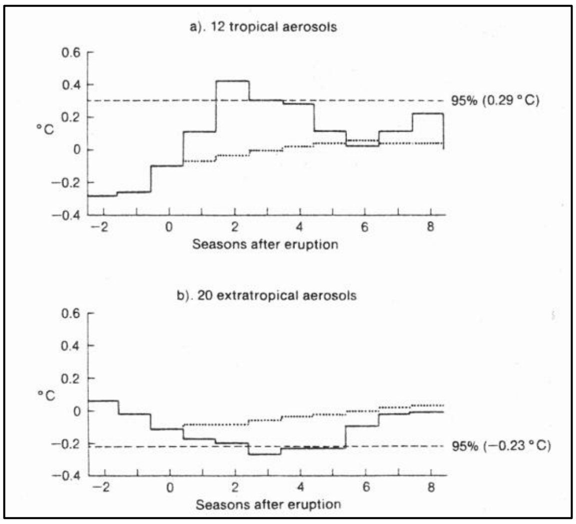

Figure 20: superposed epoch analyses of SSTs in the east tropical Pacific (20N -20S, E of 170W). The dotted lines are expectation values from the Monte Carlo analysis (Parker, 1988)

the volcanic composite. Figure 20 shows that the rise in SSTs seen for the volcanic composite is not seen for the average of the other composites that started out with similar SSTs but which did not experience a volcanic eruption. Parker repeated the work using a subset of the volcanic eruptions and produced similar but more significant results.

Parker believed that his work had increased the confidence in the statistical significance of Handler's results but accepted that the available record of volcanic eruptions was small from a statistical point of view, that selection of the events could influence the results in a SEA and that the development of a physically realistic model would be needed to prove or disprove any relationship between explosive volcanism and El Niño.

2.1.7 Nicholls (1988)

Nicholls expressed concerns over some aspects of Handler's work (1986), principally disputing his claim that volcanic eruptions precede ENSO. Nicholls pointed out that, of the 12 eruptions analysed by Handler, 8 occurred in the March to June period by which time any ENSO event should already have been initiated and thus would not satisfy causality. Nicholls performed his own SEA of monthly mean Darwin pressures but over a longer period than Handler starting 12 months before the eruption and continuing for 12 months afterwards.

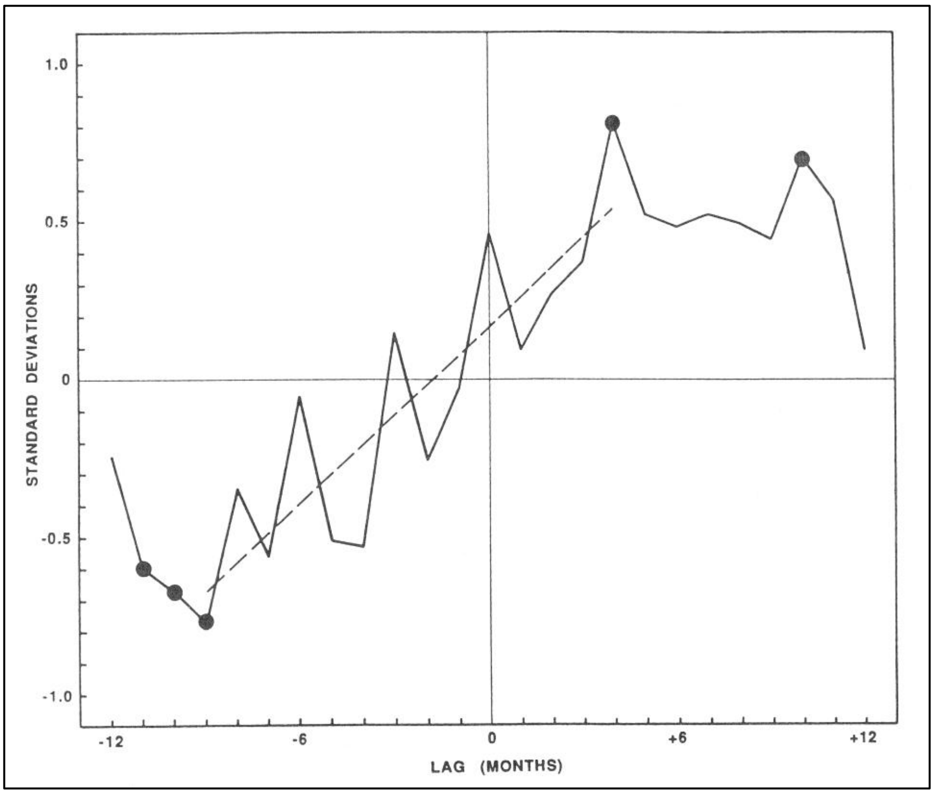

Figure 21: Nicholls' superposed epoch analysis of standardised monthly mean Darwin surface pressures. Solid dots indicate points significant at the 5% level and the dashed line is the regression line using data between lags -9 and +4 months. (Nicholls, 1988)

Nicholls used 10 low latitude volcanoes for his study leaving out the two earliest volcanoes examined by Handler as he considered the Darwin pressure data to be suspect prior to 1898. To measure the statistical significance of the results Nicholls used the Monte Carlo approach which provided 50,000 separate values of Darwin pressure averaged over 10 months. On examining the frequency distribution of these means five percent had an absolute value exceeding 0.6 standard deviations so this value was used as the two-sided five percent significance level for the SEA. His results (Figure 21) showed that above average Darwin pressures tend to follow low latitude volcanic eruptions as already found by Handler (1986). He also found, however, that 9, 10 and 11 months prior to the eruption date there are significant negative anomalies in Darwin pressure. The pressure then rises (before the eruption) and the positive anomalies in the months following the eruption appear to be just a continuation of this trend. Due to the small data sample (10 volcanoes) Nicholls believed it likely that these results could be just a fluke but assuming that they were not he proposed three possible explanations of the link:

- some other phenomenon caused both the Darwin pressure anomalies and the eruptions.
- Low latitude eruptions cause ENSOs but to reach this conclusion one would have to assume that the anomalies prior to the eruptions are due to chance but the positive anomalies following the eruptions are significant. As the anomalies are of similar magnitudes Nicholls considered that it would not be reasonable to assume this and that, therefore, no causality could be implied.
- The fact that the upward trend in Darwin pressure begins well before the eruption tends to support the theory that ENSOs cause eruptions. Nicholls did not suggest a physical mechanism for this.

Nicholls final conclusions were that the most likely explanation for the observed relationship between ENSO and eruptions was that it was due to chance and the least likely explanation is that low latitude volcanic eruptions cause ENSOs.

2.1.8 Handler (1989)

Handler proposed a physical mechanism for a link between El Niño and volcanic eruptions. He postulated that the decrease in solar radiation caused by the volcanic eruption induces El Niño by the anomalous transfer of air mass from the oceanic anticyclones to the Southern Eurasian land mass as follows:

- the volcanic eruption causes a decrease in the amount of solar radiation reaching the Eurasian continent.
- This causes the Eurasian continent to cool relative to the oceans leading to less air mass transferred out to the oceans in the spring and summer and a quicker transfer of air mass back in to the continent in autumn and winter.
- This leads to anomalously high SLP over the land relative to the ocean similar to that of the negative phase of the Southern Oscillation.
- Under these conditions the Pacific anticyclones will have lower central pressure and thus the easterly component of the winds moving out of the anticyclones will be weaker.
- Weaker easterly winds along the equator are the forerunner of El Niño.

2.1.9 Handler and Andsager (1990)

Handler and Andsager tried to answer some of the questions raised by Nicholls (1988) by using Monte Carlo techniques to re-examine the statistical significance of the composite SST and SOI anomalies before and after a low latitude volcanic eruption. The Monte Carlo method involved generating 10,000 randomly generated composites to compare against the composite created from the volcanic eruption years. The same data set from Handler (1986) was used for the reanalysis but the composite was extended to 8 seasons before and after the eruption date. It should also be noted that the dates of some of the eruptions reported in Handler's previous papers (1984 and 1986) were incorrect. These dates have been corrected in this paper and Handler believed that as they only affect the values of the composite slightly they do not

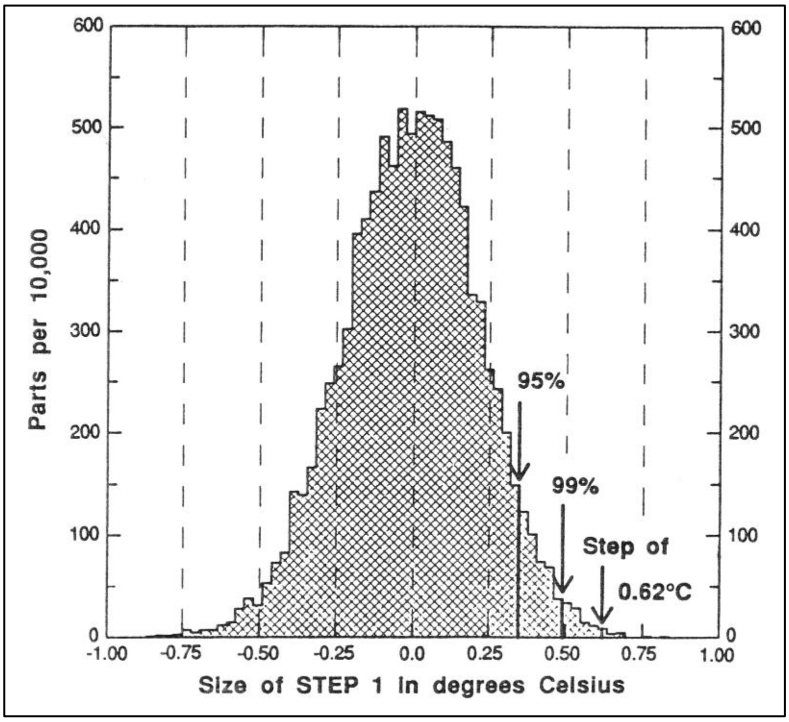

Figure 22: frequency distribution of the temperature anomaly STEP increase across the key date from the Monte Carlo simulation (Handler and Andsager, 1990)

change the conclusions reached in Handler (1984 and 1986). The composite SST anomalies (SSTA) showed that prior to the eruption there are cool SSTAs and after the eruption there are warm SSTAs with a step of 0.62˚C between season -1, immediately prior to the eruption, and season +1, immediately afterwards. Handler and Andsager calculated that the probability of a step of 0.62°C or larger occurring by chance is 21 in 10,000 for their Monte Carlo sample (Figure 22). They also produced a composite of SOI anomalies which showed a predominance of positive anomalies before and up to 1 month after the eruption anomalies for the following 2 years some of which were significant at the 95% level. The gradual increase in Darwin pressure prior to an eruption seen in Nicholls composite was not seen in Handler and Andsager's SOI composite. Their conclusion was that their results were as predicted by the volcanic hypothesis that states that low-latitude volcanic eruptions are the immediate and only cause of El Niño.

2.1.10 Nicholls (1990)

Nicholls responded promptly to Handler and Andsager (1990). He expressed concern over the use of composites which could be dominated by just one event, principally the very large El Niño that occurred in the same year as the eruption of El Chichón, and decided instead to do a case by case study of low latitude eruptions. For this study he investigated eruptions that occurred between 1935 and 1984, a period when he considered the ENSO and volcanic records were reasonably reliable.

Looking at volcanoes from this period in detail he discovered that of the 6 eruptions included in Handler and Andsager's composite only half were followed by an El Niño (2 of them only weak El Niños), two eruptions were followed by cooling and the final one, El Chichón in 1982, occurred after the onset of the El Niño of that year.

Analysing the list of El Niños between 1935 and 1984 he found that of the 13 moderate or strong El Niño events that occurred during this time period only 3 were preceded (within 6 months) by a low-latitude volcanic eruption. Whilst accepting Handler's (1986) proposal that some volcanic eruptions could have gone unreported he thought it highly unlikely that 10 eruptions could have gone unnoticed especially as, from the work in measuring stratospheric aerosols of Castleman et al (1974) and Sedlacek et al (1983), no *major* low-latitude injections were observed that could not be attributed to known eruptions.

He then went on to investigate the 6 eruptions from Handler's composite that occurred before 1935 and concluded that of these eruptions only one (Taal in 1911) actually occurred before an El Niño. He also expressed concerns over Handler and Andsager's use of the SOI as he was concerned over the accuracy of the Tahiti record prior to 1935 and felt that this justified his use in Nicholls (1988) of just the Darwin pressure for his composite.

His final conclusions were that low-latitude volcanic eruptions were not the only cause (and probably not even a cause) of El Niño and that uncritical acceptance of composites can lead to wrong conclusions.

2.1.11 Robock and Free (1995)

Robock and Free compared the IVI with ENSO records as a small part of their overall paper on ice cores as an index of global volcanism. They calculated the correlation coefficients between the volcanic record in the ice core and the Southern Oscillation Index to be -0.17 for the Northern hemisphere and 0.06 for the Southern hemisphere and concluded there was no evidence for any influence of volcanic eruptions on El Niño. Figure 23 compares the IVI with the SOI.

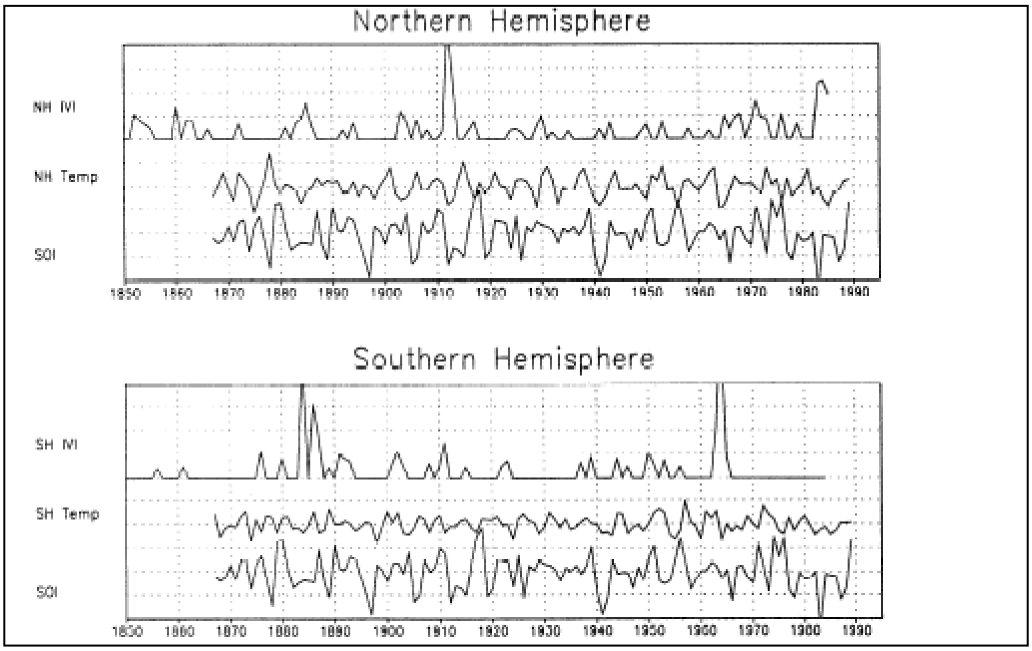

Figure 23: Northern Hemisphere and Southern Hemisphere IVI compared to the 6-month lagged SOI. Tick marks and grid lines are 1 standard deviation apart for IVI and SOI. (Robock and Free, 1995)

2.1.12 Robock et al (1995)

Robock et al performed a General Circulation Model (GCM) evaluation of Hirono's (1988) mechanism for the triggering of El Niño by the El Chichón ash cloud. Hirono himself had used a fairly simple model with an unnaturally smooth aerosol distribution and simple heating profile which meant that his theory was not generally accepted. Graf et al (1992) had already shown that a uniform zonal distribution of aerosols would not initiate an El Niño so

Robock et al restricted their investigations to the initial cloud of aerosol that formed over the eastern Pacific. They used the National Centre for Atmospheric Research Community Climate Model 1 (modified by the Lawrence Livermore National Laboratory to calculate the solar radiative effects of aerosols) with a grid spacing of 4.5° in latitude, 7.5° in longitude and 12 vertical levels. To produce 2 independent control simulations the model was run starting November 1st 1981 through to April 30th 1982 using observed SSTs and 2 different sets of initial conditions. There were no direct measurements of the aerosol cloud in the eastern Pacific so they had to make estimates as to the horizontal extent and optical depth of the cloud. They assumed that the aerosol cloud in the troposphere above the eastern Pacific largely consisted of ash particles as volcanic sulphate aerosols take several weeks to form and would have been unable to produce immediate significant heating. Preliminary runs of the GCM showed a high sensitivity to the vertical distribution of the aerosols and as there were no observations of the vertical structure they used 3 different profiles: one with the aerosols concentrated in the upper troposphere, one with them in the mid-troposphere and one with the particles in the lower troposphere. The maximum heating rate for each profile was about 1.5K per day. They also ran the model with a control case with no aerosols.

Each of the perturbed simulations was begun on April 1st 1982 with a horizontal distribution of the aerosols over the eastern Pacific Ocean from 0-30°N and 60-150°W which corresponded to the location of the El Chichón cloud from satellite observations. The model was run for 30 days with constant aerosol forcing and the average results from the last 8 days of the run were as follows:

- for aerosols in the upper troposphere a cyclonic circulation developed in the upper part of the troposphere due to the lower pressure and subsequent upward motion in the region of aerosol heating but a compensating anti-cyclonic circulation developed beneath it which enhanced the trade winds and thus would not contribute to an El Niño which requires a slackening of the trade winds.

- The profile with mid-tropospheric aerosols resulted in upward motion in the region of the aerosols leading to the development of a cyclonic circulation and a decrease of the easterly trade winds at the surface.

- The aerosols in the lower troposphere acted to suppress the normal convective heating and this reduction in convective heating more than compensated for the direct heating from the aerosol and therefore there was no net heating of the column and no dynamical response.

Robock et al concluded that only mid-tropospheric aerosols would produce a reduction in the easterly trade winds and then only in the eastern Pacific but as it is believed that only trade wind reductions in the western Pacific will produce El Niños the near simultaneous occurrence of an El Niño and the eruption of El Chichón was just a coincidence.

2.1.13 Clement et al (1996), Cane et al (1997)

These two papers will not be described in detail as they looked more generally at the potential response of ENSO to radiative forcing, particularly that due to the rise in anthropogenic greenhouse gas concentrations. It is worth mentioning, however, the ocean dynamical thermostat mechanism described in these studies as it is referred to in several later papers.

This mechanism causes a cooling (heating) in the eastern Pacific in response to a general heating (cooling) of the tropical Pacific. This is due to different responses to the forcing; in the east it is much harder to change the SSTs by radiative forcing alone due to the strong upwelling and sharp thermocline. In contrast, in the west, the deeper thermocline makes it easier to change the SSTs so given a uniform reduction in incoming radiation such as that caused by a volcanic dust veil the SSTs will cool faster in the west reducing the zonal SST gradient. Due to the Bjerknes feedback mechanism (1.2) this change in the SST gradient will result in a slackening of the trade winds which can ultimately lead to El Niño-like conditions.

2.1.14 Self et al (1997)

Self et al decided to test the hypothesis that El Niño events are caused or enhanced by volcanic eruptions using 2 methods:

- a case by case comparison over the last 150 years of the strongest 16 El Niños with the characteristics of the largest concurrent volcanic eruption.
- A comparison of the timing of strong El Niño events with the stratospheric optical depth perturbation record.

The compilation of ENSO events from Quinn et al (1978), Quinn and Neal (1992) and NOAA (1994) was used to identify the strongest El Niños of the past 150 years. Only the strongest El Niños were used to avoid signal to noise problems. They then selected the eruptions that were the largest, most explosive and most likely to produce stratospheric aerosols that occurred in the year and previous year of the 15 strongest El Niños. Their comparison showed that for 5 of the strong El Niño events no known significant eruption occurred at the critical time for triggering the event and for 7 others although an eruption did occur in the relevant period the eruption was not believed to have produced a significant quantity of stratospheric aerosols. This just left the 1883 Krakatau, 1982 El Chichón and 1991 Mount Pinatubo eruptions which all produced large aerosol clouds and occurred at around the time of a strong El Niño. Not enough information was available on the strong 1884 ENSO event to evaluate the Krakatau case but on closer examination of the other 2 cases it was shown that positive SST anomalies in the central tropical Pacific occurred prior to the eruptions of El Chichón and Mount Pinatubo although the 1991-1992 warming event did increase greatly after the eruption of Mount Pinatubo. This seemed to rule out the possibility that the eruptions were the cause of the El Niños.

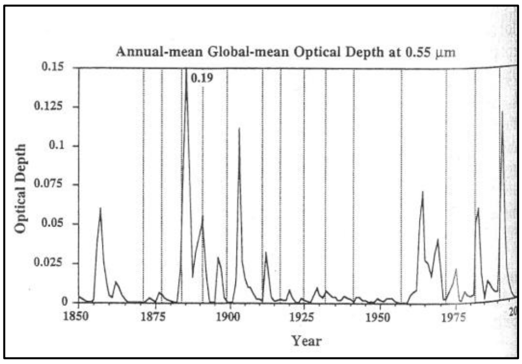

Figure 24: global mean optical depth with the strongest El Nino years marked by vertical dashed lines (Self et al, 1997)

Figure 24 shows the record of stratospheric optical depth perturbations and El Niño years used by Self et al. They believed that this record shows that many strong El Niños have occurred at times when volcanic stratospheric aerosols were at or near background levels and they could see no general relationship between the onset of an El Niño and periods of increased stratospheric optical depth. They did note that 3 of the strongest aerosol depth perturbations in the tropics were associated with strong El Niños but, as the El Chichón aerosol cloud was less than half the size of the Mount Pinatubo cloud and yet the El Niño that occurred in the El Chichón year was much larger, they believed that if amplification of El Niño by volcanic aerosols is possible it is by no means a direct relationship.

2.1.15 Adams et al (2003)

During the late 1990s and early 21st century much research was done on the possible response of ENSO to increased greenhouse gas concentrations using coupled ocean-atmosphere GCMs. The results from these experiments, whilst not agreeing in the details, did show that ENSO is sensitive to radiative forcing. In particular the paper by Clement et al (1996) (2.1.13) introduced a plausible ocean dynamical thermostat mechanism for an ENSO-like response to radiative forcing and predicted positive eastern tropical Pacific SST anomalies in response to negative surface radiative forcing. These findings prompted further interest in the relationship between volcanic radiative forcing and ENSO. Adams et al (2003) felt that they could overcome the criticisms of past work (such as the small number of volcanoes evaluated not giving sufficient statistical robustness) by relying on the much longer data record provided by proxy based reconstructions of both explosive tropical eruptions and El Niño.

They used 2 independent measures of past volcanic activity which are already well documented, the VEI and a discretised version of the IVI assigning values from 1 (weak) to 8 (strong) to correlate with the values of the VEI. The reconstruction of past cold season NIÑO3 indices was based on proxy climate indicators such as tree rings, ice cores, corals and historical documents. This reconstruction is available back to 1649 and was cross-validated with independent early instrumental data showing a high degree of skill. They also used a proxy-based reconstruction of the winter SOI based on ENSO sensitive Mexican and south-western U.S.A. tree ring data which is available back to 1706. They considered that these 2 reconstructions were largely independent and, therefore, would represent reasonable estimates of the respective indices. A SEA was then used to evaluate the composite response of the ENSO indices to volcanic forcing.

Initially they used the same data as Handler and Andsager (1990) and not surprisingly they produced similar results. They found that if they excluded several eruptions such as El Chichón from their list the results were not reproduced which they believed showed that the instrumental record did not provide a sufficient sample size to provide a definite conclusion as just one large event could influence the whole composite. They then ran SEA experiments over the pre-instrumental period for a variety of selection criteria. Several of the results are shown in Figure 25. In general, their analyses indicated a positive, El Niño like, NIÑO3 composite response in the several years following explosive low-latitude eruptions with the results being most consistent (21 out

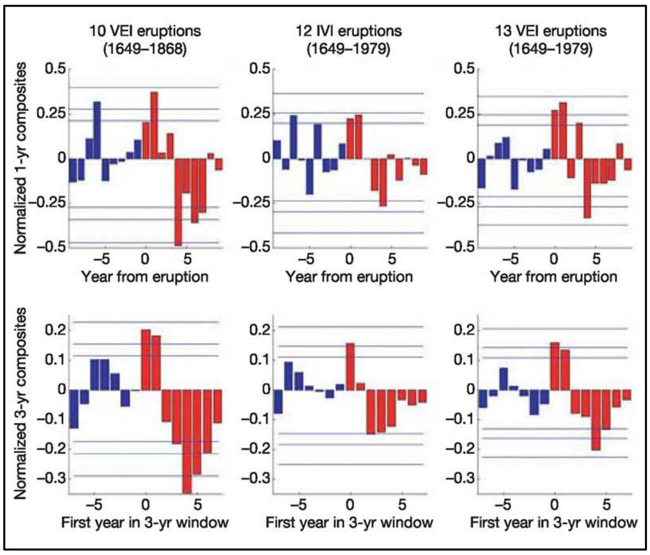

Figure 25. Reconstructed cold season Nino 3 SEA results (Adams et al, 2003)

of 22 positive responses being significant at the p=0.05 level) when 3 year composites are considered. They also noted a statistically significant rebound into a La Niña like state following the initial El Niño like response.

They also determined the fraction of volcanic events followed within the first year by an El Niño like response. The results of this analysis indicated that the likelihood of an El Niño event following an eruption in the subsequent cold season is significantly above that based on chance alone and roughly doubles the probability of an El Niño.

Their final conclusions were that explosive tropical eruptions do not trigger all El Niño events but that volcanic forcing influences the coupled ocean-atmosphere towards a state whereby El Niño like conditions are favoured followed by a weaker reversal into La Niña like conditions.

2.1.16 Mann et al (2005)

Mann et al extended the previous work on the effects of anthropogenic forcing upon ENSO to also investigate the response of ENSO to natural radiative forcings due to explosive volcanism and solar variations over the previous 1000 years. In this summary we will concentrate on their results for volcanism.

The experiments were run on the Zebiak and Cane (1987) intermediate complexity model of the tropical Pacific coupled ocean-atmosphere system. This model does not include extra-tropical feedbacks, large-scale monsoonal responses or cloud radiative feedbacks but to use a GCM was considered too computationally expensive. The radiative forcing was input into the model in the form of an anomalous surface heat flux into the ocean mixed layer. The model was run for 3 different scenarios (a) volcanic forcing only, (b) solar forcing only and (c) combined solar and volcanic forcing. They used a 100 member ensemble each initialised with different random initial conditions to isolate the signal due to forcings from the internal variability of the model. The magnitudes of volcanic forcings were taken from the work of Crowley (2000). All volcanic eruptions were assumed to have occurred during the January of the eruption year and the resultant forcing was assumed to remain uniform for the following 12 months. Only tropical eruptions were considered. From their results in Figure 26 an El Niño-like response can be observed in response to each tropical volcanic forcing event. When the model was run with fewer ensemble members a response to the largest volcanic eruptions could still be seen although the signal was lost amongst the model's internal variability for the weaker eruptions.

They also performed a SEA to identify the NIÑO3 response to tropical forcing using proxy reconstructions of volcanic forcing and ENSO indices. Their results were very similar to those achieved by Adams et al (2003) with a tendency for El Niño conditions in the year of eruption. They estimated the probability of an El Niño event (NIÑO3 anomaly ≥ 1°C) in the year following a large eruption (radiative forcing exceeding -4 Wm^{-2}) at 63%, for eruptions with radiative forcing between -2 and -4 Wm^{-2} they put the probability at 55%. This is in contrast with the probability over all years of 33%.

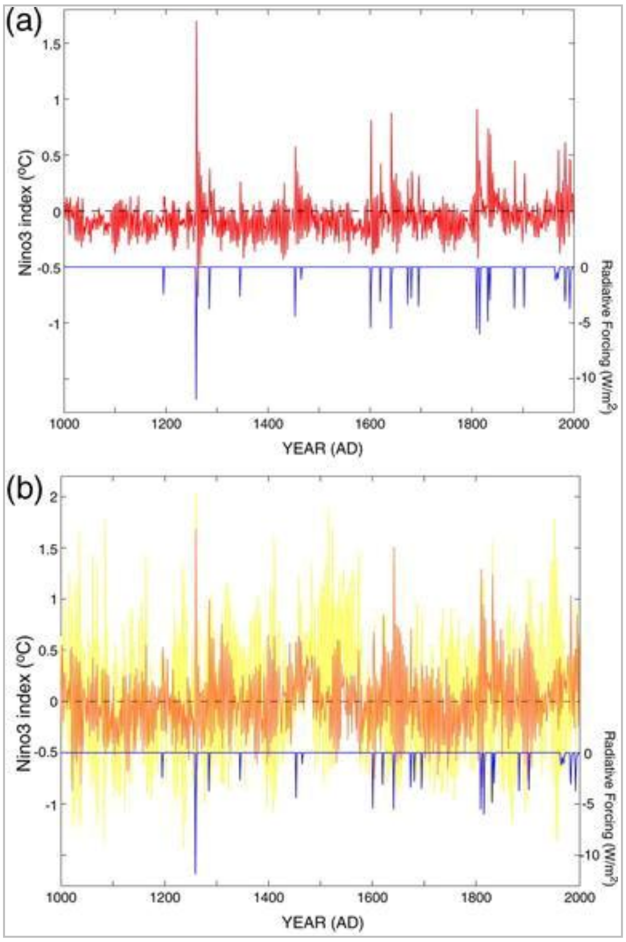

Figure 26: Ensemble-mean Niño-3 response to tropical volcanic forcing experiments over the period 1000–1999A.D. (a) Response (red; anomaly in °C relative to 1000–1999A.D. mean; scale provided on left axis) based on ensemble of 100 realizations. Radiative forcing (blue) is shown in W m^{-2} (scale provided on right axis). (b) Comparison of ensemble-mean responses to volcanic forcing [as in (a)] based on smaller ensembles of 20 (orange) and 5 (yellow) realizations. (Mann et al, 2005)

Finally, they went on to compare the 100 member ensemble mean NIÑO3 response to the combined solar and volcanic forcings from 1000 to 1999A.D. with a record of ENSO from oxygen isotopes found in fossil corals from Palmyra in the tropical central Pacific. Despite uncertainties with the dating of the corals and in the scaling from the isotope level to a SST index, which meant that the model and observations could not be compared in detail, some longer term SST tendencies could be seen in both model and observations, most notably, cold late 12th/early 13th century central/eastern tropical Pacific SSTs and warm late 17th/early 18th century central/eastern tropical Pacific SSTs. The authors noted that the absence of large El Niño events in the earlier period and numerous large El Niños in the latter period coincided with a lack and an abundance, respectively, of large volcanic eruptions during those periods.

2.1.17 Emile-Geay et al (2008)

Emile-Geay et al provided corroboration of the earlier work of Adams et al (2003) and Mann et al (2005) using records of volcanic forcing from Crowley (2000) and the model of Zebiak and Cane (1987) to explore the quantitative relationship between explosive volcanism and ENSO. The ocean model domain was restricted to 124°E-80°W and 29°S-29°N so that only tropical influences were considered. The cloud cover fraction in the model was held constant at 50% and all eruptions were assumed to occur in January of each year and stay constant for 12 months. The aerosol veil's spatial extent was uniform throughout the model domain.

The model was run to test the response to radiative forcing for 200 ensemble members each with its own set of random initial conditions. As in Mann et al (2005) the model showed that a strong volcanic cooling seems to produce a warming in the eastern equatorial Pacific within a year of the eruption with noticeable effects for up to 24 months afterwards. This, they considered, was the result of the ocean thermostat mechanism of Clement et al (1996) as described in paragraph 2.1.13. It should be noted that in individual simulations an El Niño may or may not occur but the tendency of the ensemble mean to higher SSTs indicates that warm events are favoured.

They also repeated, with similar results, the work of Adams et al (2003) to determine the fraction of volcanic events followed within the first year by an El Niño like response but with the eruption list adjusted to use the eruptions from Crowley (2000).

Another aspect of their work was to construct a phase diagram for ENSO regimes using the previously described 200 member ensemble. For this phase diagram they used the radiative forcing for each year between 1000 and 1998 A.D when the forcing was negative to estimate the NIÑO3.4 SST index for the January to December of the *following* year. Their criterion for one of their simulations to exhibit El Niño characteristics was for the NIÑO3.4 SST anomaly to be greater than 0.5°C for at least 6 consecutive months. They then plotted, for each year, the fraction of ensemble members that went into an El Niño versus the corresponding volcanic forcing. From the results shown in Figure 27 they identified 3 regimes:

1. for a volcanic dimming of less than $1Wm^{-2}$ the model is essentially unperturbed by the negative forcing and the likelihood of an El Niño event in any given year never exceeds 0.43 and the average likelihood is 0.29.

2. For a dimming of greater than 4 Wm^{-2} all plotted points are above the normally expected limit of 0.43 and therefore they considered this to be a forced regime to which all major eruptions of the millennium belong.
3. Finally, they considered dimming of between 0.8 Wm^{-2} and 4 Wm^{-2} to be a transition regime where the likelihood of an El Niño is sometimes but not always above the threshold of 0.43.

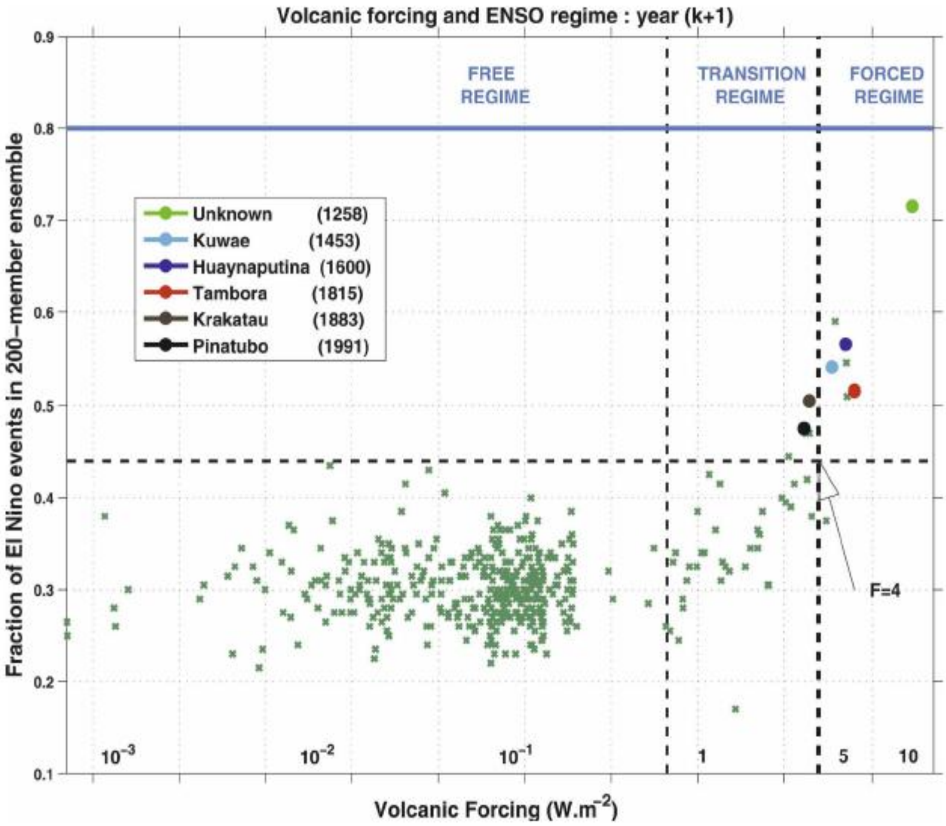

Figure 27: ENSO regimes as a function of the intensity of volcanic cooling showing the fraction of the ensemble members that went into an El Niño event in the year following the eruption. (Emile-Geay et al, 2008)

Except for a few events with a large number of ice core records it is difficult to estimate the error in volcanic forcing. An uncertainty of about 30% has been estimated when sufficient records do exist and, therefore, Emile-Geay et al re-ran the model with the volcanic forcing weaker by 30%. The same basic qualitative results were obtained but the forced regime commenced at -3.3Wm^{-2}.

Plotting volcanic cooling against the average of the maximum NIÑO3 SSTs from the 200 ensemble members showed that the average maximum size of El Niño events is raised for volcanic forcing that falls into the transition and forced regimes although they are not raised outside the model's range of internal variability.

They then went on to investigate the eruption of 1258/9 A.D., possibly the strongest eruption of the millennium, in more detail. This eruption occurred at the time of prevailing La Niña conditions caused by increased solar activity during the medieval climate anomaly. Whilst the precise location of this eruption has not been pinpointed evidence for it has been found in 9 northern hemisphere ice cores, 6 southern hemisphere ice cores and also in Lake Malawi sediments. The presence of sulphates in both northern and southern hemisphere ice cores appears to point to a tropical origin, El Chichón (Mexico) and Quilotoa (Ecuador) are both possible candidates. Evidence from the ice cores suggests that this volcano would have produced a negative forcing of -8.9 to -11.4 Wm^{-2} leading the model to predict a NIÑO3 anomaly of approximately 1.5°C. 75% of the ensemble members predicted an El Niño would follow the eruption (increasing the likelihood almost 2.5 times), 71% predicting a moderate El Niño (3 times greater than chance) and 47% a strong El Niño (6 times greater than chance).

They then used the following paleoclimate records to see if they could find any evidence of an El Niño in the late 1250s:

- the North American Drought Atlas (a 2000 year tree ring chronology)
- tree ring widths from El Assiento, Chile
- titanium contents in Cariaco Basin sediments
- fine grain lithics from sediment core off the Peruvian coast

All of these proxies did show evidence of an El Niño occurrence in 1258/9 and the conjunction of all these records led them to conclude that there was an El Niño event in 1258/9.

Emile Geay et al (2008) concluded that explosive volcanism does not trigger El Niño events but, for a dimming larger than 1 Wm^{-2}, it can increase the likelihood of an event by 50% on average and also favour higher amplitudes.

2.1.18 Summary

A short historical summary of the major work to date is included below for ease of reference.

- Handler (1984, 1986) Handler and Andsager (1990) proposed a volcanic hypothesis that low-latitude volcanic eruptions are the immediate and only cause of El Niño! Used statistical methods.

- Nicholls (1988, 1990) disputed their findings pointing out that in many cases the SST warming started before the eruptions.
- Hirono (1988) suggested a physical mechanism whereby local and zonal heating in the troposphere caused by volcanic aerosols from El Chichón could produce a westerly component to the wind. Used a simple model.
- Robock et al (1995) tested Hirono's model using a GCM and concluded it would not produce the required westerly winds in the western Pacific.
- Robock and Free (1995) found no significant correlation between the volcanic record in ice cores and the Southern Oscillation Index.
- Self et al (1997) found no general correlation between volcanic aerosol perturbations and strong El Niños
- Adams et al (2003) used proxy records from 1649 to perform a statistical analysis and concluded that the probability of an El Niño occurring was doubled following a volcanic eruption.
- Mann et al (2005)/Emile-Geay et al (2008) used a climate model to determine that explosive volcanic activity raises the likelihood of El Niño by 50% due to the "thermostat "mechanism.

2.2 Impact of El Niño on the climatic signature of volcanoes.

It is widely recognised (e.g. Angell, 1990, Mao and Robock, 1998, Robock, 2000, Santer et al, 2001, Penland and Matrosova, 2006, Compo and Sardeshmukh, 2010) that the ENSO signal must be isolated and removed in order to more accurately estimate the global climatic impact of volcanoes (and other climate variations such as anthropogenic warming). Although other phenomena such as the quasi-biennial oscillation (QBO) can also cause noise in the climate system (e.g. Angell, 1997) ENSO is the largest signal in the climate system on inter-annual timescales (Compo and Sardeshmukh, 2010). Isolating such contributions is challenging, especially with the existing ambiguities in the definition of ENSO discussed in section 1.2.1. There is a wide range of estimates for the contribution of ENSO to trends in global tropospheric temperature anomalies, most studies lie in the 15 to 30% range (e.g. Santer et al, 2001) but some have put it at as much as 72% (McLean et al., 2009).

There are several methods used to remove the ENSO signal and these are described here with a few examples.

One of the earlier methods commonly used, by, for example, Angell (1990) and Mao and Robock (1998), is linear regression of an ENSO index or on the amplitude of the dominant empirical orthogonal function (EOF) of tropical SST variability. Angell (1990) adjusted the annual global temperature deviations in the tropospheric 850-300hPa layer from 1958 to 1989 based on the linear regression line shown in Figure 28 which compares the global temperature variations previously described with the annual SST anomalies in the eastern equatorial Pacific. As there is a 2 season lag between equatorial SST changes and global tropospheric temperature changes this lag was incorporated into the regression. Angell (1990) found that 55-60% of the annual variance of global tropospheric temperature was accounted for by ENSO-related effects.

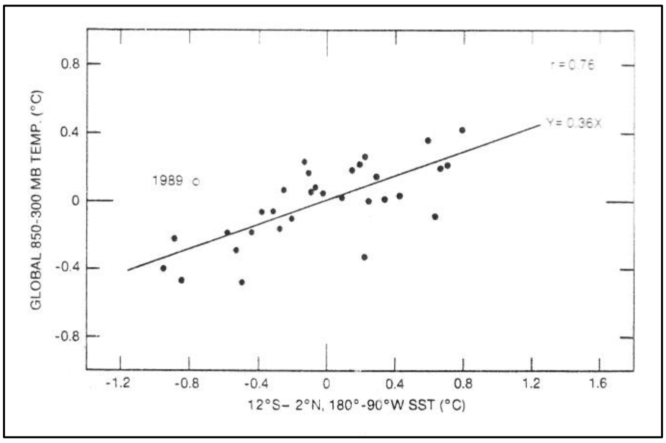

Figure 28: linear regression used by Angell (1990)

Another method for eliminating the ENSO signal involves Fourier frequency filtering (e.g., Parker et al, 2007). It assumes that most of the ENSO signal is found in the 4 to 7 year (or 2 to 6 year depending on the study) frequency band and removes those frequencies from the time series of interest.

Some more recent analyses (e.g. Penland and Matrosova, 2006, Compo and Sardeshmukh, 2010) have considered ENSO as an evolving dynamical process rather than as a simple statistical index. These methods use a dynamically based filter to separate SSTs into 3 dependent components: the evolving El Niño signal, the global tropical trend and the background. The filter is based on the work of Penland and Sardeshmukh (1995) who demonstrated that tropical SSTs could largely be represented as a stable linear process maintained by stochastic forcing such that:

$$\frac{d\mathbf{x}}{dt} = \mathbf{Bx} + \xi$$

where the ith component, $x_{i,}$ of $\mathbf{x}$ is the sea surface temperature anomaly at location i and ξ_i is the contribution to the dynamics from the stochastic forcing at location i. Utilising this method to analyse the 136 year (1871-2006) Hadley sea ice and sea surface temperature dataset Compo and Sardeshmukh (2010) found that ENSO contributed up to 40% of the total warming trend.

Ocean-atmosphere coupled climate models could be used to estimate the ENSO related background noise but many current models have difficulty representing the tropical variability associated with ENSO (e.g. Newman et al, 2009) which compromises the estimations of the ENSO related component in model simulations.

2.3 Influence of El Niño on volcanic activity.

2.3.1 Nicholls (1988)

This paper is described in detail in paragraph 2.1.7 but in the context of this section it is worth re-iterating the result from Nicholls' SEA that showed the Darwin sea level pressure rising prior to the eruption date although he concluded that this was almost certainly a fluke.

2.3.2 Robock (2000)

Robock, as part of his review paper on volcanic eruptions and climate, observed that some volcanoes were preceded by El Niños and cited Rampino et al (1979) who had suggested that climatic change could cause volcanic eruptions by changing the stress on the Earth's crust due to glaciation and deglaciation. Rampino et al had noted that in many cases volcanic eruptions have been preceded by periods of cooling rather than the eruptions being the cause of the cooling as might have been expected. They speculated whether the cooling and glaciation could trigger the explosive eruptions or if some outside factor, such as orbital variations, affected both the volcanism and climate. Although most of their work was concerned with the effects of global cooling they did also mention the theory that during deglaciation the sea floor is depressed due to the redistribution of water and there is a corresponding upwarp and shift of stress to the land masses.

Robock also speculated on whether the increases to the Earth's rotation rate due to applied wind stresses (such as during El Niño) as described by Marcus et al (1998) could produce an extra lithospheric stress. He did emphasise, however, that these speculations had not been proven.

2.4 Discussion

2.4.1 Influences of Volcanoes on El Niño

The original statistical work of Handler (1984, 1986), Handler and Andsager (1990) and

Parker (1988) has now been largely discredited. This is partly due to Handler's volcanic hypothesis interpretation of his results. As this is easily disproved by a simple examination of individual El Niños showing that not all El Niños are preceded by volcanic eruptions and not all volcanic eruptions are followed by El Niños the credibility of his hypothesis was thrown into serious doubt. His explanation for this was that volcanic eruptions in remote locations can go unreported but, for his hypothesis to be correct, 31 major unreported low latitude eruptions would be required to have occurred during his period of investigation. Whilst there is little doubt that some volcanic eruptions have gone unobserved (even as late as 1990 a stratospheric aerosol cloud of unknown origin was observed) it is unlikely that there could have been such a high number of such events. Handler's detractors also pointed out the ability of Chen et al (2004) to predict the El Niños of the last 146 years without knowledge of radiative forcing. It can, therefore, be fairly safely concluded that the volcanic hypothesis is not correct.

Parker whilst producing very similar results was much more circumspect in his conclusions and, in fact, if the actual results of Handler are examined, rather than his conclusions, they are more convincing. Although there are still problems with the statistical methodology (due to El Chichón dominating the composites and the short instrumental data record) what the composites actually show is an increase in SSTs following an eruption and not necessarily the occurrence of an El Niño. Given the later research which suggested that only large eruptions can influence El Niños the domination of the early composites by the El Chichón eruption may be a real effect. One oft-quoted criticism of the statistical results was the fact that in some cases the El Niño had already started before the eruption occurred but an examination of SST records (see Appendix) indicates that in about 10% of years between 1877 and 2010 there has been warming in the NH spring that has not led to an El Niño later in the season and, therefore, the early warming may not have led on to an El Niño in the absence of volcanic activity. The later statistical analysis of e.g. Adams et al (2003) is more robust (assuming that the proxy records can provide the precision required for work of this nature) with a longer data record and is much more widely accepted.

Given the short instrumental data record, uncertainties in the proxy record and other competing influences upon ENSO which can cause the volcanic signal to be lost there is probably not much more that can be learnt from statistical analysis. In order to prove a connection between explosive tropical volcanism and a viable physical mechanism needs to be proposed and tested on a Coupled Global Climate Model (CGCM). The early attempts at modelling whilst looking promising were based on simple models e.g. Schatten's model was zonally symmetric, didn't explain why the response would be so rapid or why the response should occur mainly in the Pacific (Robock, 2000). It is also not clear if the reduction in the stratospheric pole/equator temperature gradient was included in his model. Handler's mechanism was never tested by a model and Hirono's proposed mechanism, when tested by a GCM, failed to produce a zonal wind in the right region. It must be noted, however, than even the GCM simulation was a simplification as the model was run separately for aerosols at different levels in the troposphere whereas in practice the aerosols would be falling throughout the depth of the troposphere. The ocean dynamical thermostat theory has achieved a lot of credibility but again needs to be tested on a CGCM. The use of a relatively simple model has the advantage that it allows the examination of a long dataset but the incompleteness of the model physics does not represent all the complexities of the climate system such as cloud feedbacks and thermocline ventilation. There are also issues with uncertainties in the forcings and the dataset. Some preliminary experiments have been conducted by Stenchikov et al (2007) on the CGCM of the Geophysical Fluid Dynamics Laboratory (GFDL CM2.1) and found a weak but not conclusive El Niño response to volcanic forcing but more work needs to be done in this area as many CGCMs can not accurately predict ENSO at present although they are improving rapidly.

The final conclusions from this part of the literature review are that whilst there is no definitive answer it appears likely that, although by no means the sole cause of or influence upon El Niños, tropical volcanoes can, if sufficiently explosive, increase the possibility of an El Niño occurring in the year following the eruption. Further experiments need to be conducted on GCGMs that can accurately model ENSO to confirm or disprove the current ocean dynamical thermostat theory.

2.4.2 Impact of El Niño on the climatic signature of volcanoes.

From the plethora of methods and results it can be seen that whilst there can be little doubt that isolating the ENSO signal is essential for any form of climate diagnostic there is still a lot of work to be done in the field with matters being complicated by ambiguities in the definitions of El Niño. Probably the best results at present can be obtained using a dynamically based filter which better represents the differing facets and variability of El Niño. One advantage of using this method is that whilst the statistics of ENSO have changed over time the basic dynamics have not. The regression methods have several problems associated with them such as:

- they assume that the rate of temperature lag occurs uniformly across the globe which may not be the case (Alexander et al, 2002).
- They assume a standard El Niño SST pattern whereas at least 6 different ENSO evolution patterns have been observed (Penland and Matrosova, 2006).
- No ENSO unrelated climatic variations will be represented in the ENSO index used for the regression.
- It does not allow for the identification of physical phenomena, such as the development and decay phases associated, with ENSO dynamics.

For Fourier frequency filtering the high level of variability in the ENSO signal means that it is unlikely that the entire ENSO signal will be eliminated and, also, this method will remove non-ENSO signals within the band. The combination of these 2 factors can compromise the physical interpretation of results. Future development of ocean-atmosphere coupled climate models, better able to reproduce ENSO phenomena, will probably eventually produce the best estimate of the ENSO signal.

2.4.3 Influence of El Niño on volcanic activity

The composites of Nicholls (1988) show the Darwin pressure already rising prior to the volcanic eruption but this was not seen in any other composites and Nicholls himself dismissed the effect as probably a fluke due to the limited dataset.

Although El Niño years are generally warmer than average it would take a prolonged multi-year El Niño to achieve a significant degree of deglaciation so it is unlikely that an El Niño could cause volcanic eruptions via the method described in Rampino et al (1979).

Despite the fact that angular momentum changes associated with ENSO related wind anomalies can cause changes to the rotation rate of the Earth (Marcus et al, 1998) there is no evidence that they could cause lithospheric stress.

Therefore, with the present state of knowledge, it can be concluded that the case for ENSO causing volcanic eruptions is weak.

Chapter 3 Data Analysis

3.1   Data Set

The list of strong El Niños was taken from Quinn's (1992) list of El Niño events during the past 500 years which has been considered as the major reference for any long term analysis of ENSO. His identification of El Niño years was based upon historical records for the earlier centuries and on SST measurements at stations along the Peru coast for the instrumental period. His earlier studies (1978, 1987) were based on unusual occurrences such as thunderstorms, heavy rainfall, and /or flood conditions on the north Peruvian coast and adjacent waters but in 1992 he also identified a link between the Nile flood and ENSO and this data was used to update his list of El Niños. This latest list was used as the basis of the data for the data analysis but was updated to include El Niños up to and including 2010 using MEI, ONI, SOI and CTI data (see 1.2.4). The criteria used here for classifying an El Niño as strong was for it to meet the "strong" criteria for at least 2 of these data sets.

For the more detailed investigation into different aspects of El Niño the CTI dataset was chosen as it provided the longest record for a statistical analysis. The ONI and MEI indices are only available from 1950 onwards and, although the SOI record is available from 1866, it has more monthly variation than the CTI and, therefore, it is more difficult to detect trends. This is presumably because the SLP is more influenced by external weather events than SSTs which have a longer response time. The CTI was compared with the ONI for the years for which both were available and they were found to be in good agreement with each other. The CTI is available from 1845 but much data is missing for the early years and so the analysis was carried out from 1876 onwards.

The VEI and IVI were found to be the best maintained indices of the level of volcanic activity and they were, therefore, both used for the analysis. Although the VEI is not a completely reliable indicator of the quantity of aerosols reaching the stratosphere it is much more detailed record than the IVI which only shows up the most explosive eruptions and cannot give the precise date of eruption. It was also considered that the use of the 2 separate indices might show up differences which could provide an indication as to whether the El Niño was influenced by aspects of volcanism other than just the stratospheric aerosols.

The use of proxy data would have provided a much longer and therefore more statistically significant data set but all the analysis was done within the period of the instrumental data record due to concerns over uncertainties in the proxy record which might not provide the degree of precision required to determine that the volcano and the El Niño occurred in the same year.

3.2 Analysis

Firstly, a two sample 't' test (with a significance level of $p \leq 0.05$) was used to compare the level of volcanic activity in Strong El Niño (SEN) years with that in all other (no-SEN) years. This analysis was performed for years from 1845 (the beginning of the instrumental period) to 2010 and all possible combinations of the geographical regions, strengths of volcanoes and time periods as listed in Table 3 and Table 2 for the IVI and VEI measures of volcanic activity respectively .

Geographical regions were defined as follows:

- tropical - all regions between latitudes 30°N and 30°S.
- Tropical Pacific - all regions between latitudes 30°N and 30°S and longitudes east of 110°E and west of 70°W
- Tropical west Pacific - all regions between latitudes 30°N and 30°S and longitudes east of 110°E and west of 180°.
- Tropical east Pacific - all regions between latitudes 30°N and 30°S and longitudes east of 180° and west of 70°W.

For the time period, year 0 was classed as the year of El Niño onset (or the year being analysed for the non- El Niño years), year -1, the previous year etc. As aerosols can remain in the stratosphere for up to 3 years, time periods as far back as year -3 were included and the cumulative VEI for these years was calculated.

Table 2: IVI dataset

Region	Year
Global	El Niño Year 0
Tropical	El Niño Year 0

This relatively small dataset was used for the IVI as it provides less detail than the VEI.

Table 3: VEI dataset

Type of volcano	Region	Year
All	Global	Year 0
Volcanoes likely to produce stratospheric aerosols (i.e. with a VEI > 3)	Tropical	Year 0 - Year -1
	Tropical Pacific	Year 0 - Year -2
	Western Tropical Pacific	Year 0 - Year -3
	Eastern Tropical Pacific	

For the second part of the investigation a two sample 't' test (again with a significance level of $p \leq 0.05$) was used to see if there were any significant differences for various aspects of El Niños for those that occurred in volcanic years and those that occurred in the absence of volcanic activity. An El Niño was considered to have occurred in a volcanic year if a tropical volcano of VEI>3 erupted during the course of the El Niño or during the previous year.

The aspects of El Niño that were studied were: the length of the El Niño, the rate of onset (in the form of the SST change from April to August of El Niño year 0, the SST change from August to December of El Niño year 0 and the number of months from the typical spring onset date in April until the maximum SST was reached) and the maximum SST anomaly recorded for the El Niño. The standard deviation (SD) of the time to reach the maximum temperature was also noted.

In calculating the length of the El Niño the number of consecutive months with an SST anomaly greater than 0.5°C was recorded, with allowance made for a break of not more than one month with a positive anomaly < 0.5 °C.

3.3 Results

Table 4 contains the results for the first part of the analysis where the level of volcanic activity (as measured by the VEI) in SEN years was compared with that in no-SEN years.

The third column allows one to compare the percentage of years for each dataset in which volcanic activity has occurred. The final column shows the percentage change in the average volcanic activity between SEN and no-SEN years for each data combination e.g. if the average VEI during SEN years is 5 and for no-SEN it is 4 then the percentage change recorded in the table would +25%. A similar but least detailed analysis was done for the IVI and the results for this are in Table 5.

For the second part of the analysis aspects of El Niño for volcanic and non-volcanic years are compared, as described earlier, and the results are tabulated in Table 6.

Finally, an investigation was carried out to see if there was any connection between the phase of ENSO at the time of an explosive tropical eruption (VEI ≥4) and the subsequent occurrence of an El Niño within a year of the eruption date. The amount of data in each subset was too small for any meaningful statistical analysis but the results are listed in Table 7 to allow a comparison to be made. The CTI data from the Appendix was used for this with El Niño conditions considered to be an SST anomaly greater than +0.5˚C, La Niña conditions an anomaly of more than -0.5˚C and normal conditions anything between El Niño and La Niña conditions.

Table 4: comparison of volcanic activity between SEN years and no-SEN years (measured by VEI)

Strength of volcano	Region	Percentage of years which have volcanic activity in current and previous year		Year	Percentage change in volcanism for SEN year compared to no-SEN years.	
		SEN Year	No-SEN Year		Change	p-value
All	Global	100	94	Year 0	+28	0.50
				Year 0 - Year -1	+24	0.35
				Year 0 - Year -2	+13	0.52
				Year 0 - Year -3	+4	0.90
	Tropical	96	84	Year 0	+49	0.17
				Year 0 - Year -1	+34	0.14

Strength of volcano	Region	Percentage of years which have volcanic activity in current and previous year		Year	Percentage change in volcanism for SEN year compared to no-SEN years.	
		SEN Year	No-SEN Year		Change	p-value
All (contd.)	Tropical (contd.)			Year 0 - Year - 2	+10	0.58
				Year 0 - Year - 3	-2	0.88
	Tropical Pacific	96	79	Year 0	+69	0.10
				Year 0 - Year - 1	+38	0.12
				Year 0 - Year - 2	+15	0.43
				Year 0 - Year - 3	+3	0.85
	Western Tropical Pacific	87	73	Year 0	+35	0.29
				Year 0 - Year - 1	+21	0.41
				Year 0 - Year - 2	+3	0.88
				Year 0 - Year - 3	-5	0.77
	Eastern Tropical Pacific	48	34	Year 0	+113	0.36
				Year 0 - Year - 1	+47	0.42
				Year 0 - Year - 2	+24	0.55
				Year 0 - Year - 3	-7	0.81
Volcanoes likely to produce stratospheric aerosols i.e. VEI> 3	Global	52	32	Year 0	+71	0.27
				Year 0 - Year - 1	+68	0.26
				Year 0 - Year - 2	+0	0.30

Strength of volcano	Region	Percentage of years which have volcanic activity in current and previous year		Year	Percentage change in volcanism for SEN year compared to no-SEN years.	
		SEN Year	No-SEN Year		Change	p-value
Volcanoes likely to produce stratospheric aerosols i.e. VEI> 3 (contd.)	Global (contd.)			Year 0 - Year - 3	-4	0.42
	Tropical	43	20	Year 0	+180	0.21
				Year 0 - Year - 1	+119	0.15
				Year 0 - Year - 2	+42	0.43
				Year 0 - Year - 3	+15	0.71
	Tropical Pacific	39	20	Year 0	+267	0.16
				Year 0 - Year - 1	+110	0.22
				Year 0 - Year - 2	+51	0.40
				Year 0 - Year - 3	+16	0.72
	Western Tropical Pacific	26	13	Year 0	+228	0.09
				Year 0 - Year - 1	+146	0.16
				Year 0 - Year - 2	+89	0.25
				Year 0 - Year - 3	+47	0.40
	Eastern Tropical Pacific	22	7	Year 0	+708	0.14
				Year 0 - Year - 1	+180	0.30
				Year 0 - Year - 2	+64	0.53
				Year 0 - Year - 3	+16	0.83

Table 5: a comparison of volcanic activity between SEN years and no-SEN years (measured by IVI)

Region	Percentage change in volcanism for SEN year compared to no-SEN years.	p-value
Global	+281	0.32
Tropical	+329	0.58

Table 6: comparison of aspects of El Niño for volcanic and non-volcanic years

<table>
<tr><th rowspan="2">Type of Year</th><th colspan="2">Length of El Niño (months)</th><th colspan="2">Temperature change (°C)
Apr-Aug of El Niño year 0</th><th colspan="2">Temperature change (°C)
Aug-Dec of El Niño year 0</th><th colspan="3">Time to reach maximum temperature
(months)</th><th colspan="2">Maximum temperature reached during El Niño.
(°C)</th></tr>
<tr><th>Average</th><th>p-value</th><th>Average</th><th>p-value</th><th>Average</th><th>p-value</th><th>Average</th><th>p-value</th><th>SD</th><th>Average</th><th>p-value</th></tr>
<tr><td>Volcanic</td><td>12</td><td rowspan="2">0.88</td><td>0.7</td><td rowspan="2">0.58</td><td>0.4</td><td rowspan="2">0.59</td><td>8</td><td rowspan="2">0.36</td><td>1</td><td>1.8</td><td rowspan="2">0.15</td></tr>
<tr><td>Other</td><td>12</td><td>0.6</td><td>0.5</td><td>9</td><td>4</td><td>1.5</td></tr>
</table>

Table 7: Timing of volcanic eruption in relation to ENSO phase

Year	ENSO phase	El Niño occurrence
1883	Normal	✓
1886	End of El Niño	X
1886	La Niña	X
1890	El Niño	✓
1902	El Niño	✓
1911	Normal	✓
1919	End of El Niño	X
1937	Normal (but during prolonged cool spell)	X
1942	End of El Niño	X
1951	Normal	✓
1963	Normal	✓
1965	El Niño	✓
1966	Just after El Niño	X
1974	La Niña	X
1982	Just before and during El Niño	✓
1990	Normal	X
1991	El Niño	✓

3.4 Discussion

No firm conclusions can be reached from these results as none reach the required level of significance. Given the relatively short instrumental record and the many competing influences upon the ENSO phenomenon, if there is a volcanic signal it may well be lost amongst other noise in the system and, therefore, the lack of firm statistical evidence does not rule out entirely the possibility that volcanic activity does interact in some way with ENSO. In light of this there are some points from the results that are worth noting.

1. For every region there are more SEN years with volcanic activity than no-SEN years, double the amount in the tropical region (Table 4).
2. For all regions the percentage change in volcanism for SEN years when compared to no-SEN years is always positive for the year of the eruption (Table 4).

3. For explosive volcanoes (VEI ≥ 4) the percentage change in volcanism is greater than that seen when less explosive volcanoes are included in the data set (Table 4) which could be taken as an indication that stratospheric aerosols are an important factor.
4. The percentage change in volcanism is greater for tropical eruptions than for the global eruptions (Table 4).
5. 1982 contained 4 major eruptions in total, 3 El Chichón eruptions and 1 volcano in Java. This one year did have a major influence on the mean level of volcanic activity but removing El Chichón from the dataset, whilst reducing the magnitude of the change, did not change the general trends described above.
6. The IVI dataset does show a greater percentage change than the VEI in volcanic activity for SEN years than for no-SEN years (Table 5) which might imply that the stratospheric aerosol loading might be more influential than other volcanic climate impact factors. The IVI dataset is so small, however, that this result probably has no significance.
7. Although the average time from spring onset to maximum temperature is very similar for both volcanic and non-volcanic El Niño years there was much less variation in this factor for the volcanic years (as demonstrated by a comparison of the standard deviations in Table 6).
8. The average maximum SST anomaly is greater for volcanic years (Table 6).

Whilst it must be re-iterated that these results are by no means conclusive they do consistently, if not significantly, agree with the theory that highly explosive tropical volcanic eruptions increase the likelihood of an El Niño occurring within a year of an eruption.

Finally, an examination of Table 7 demonstrates that, during the instrumental period, no explosive tropical volcanoes which have occurred in a cold phase or at the end of an existing El Niño have led on to the subsequent occurrence of an El Niño. Four out of six eruptions that occurred during "normal" conditions were followed by an El Niño and the remaining volcanoes occurred during an existing El Niño although, as mentioned earlier (2.4.1), it is a possibility that these years may not have been El Niño years in the absence of volcanic activity although this would be difficult to prove. If this is a real effect this may possibly be an indication that, if the conditions in the equatorial Pacific are receptive to the initiation of an El Niño, volcanic activity might just tip the balance in favour of the occurrence of an El Niño. On the other hand if the initial conditions are not receptive to the formation of an El Niño the volcanic activity by itself is insufficient to trigger an El Niño.

Chapter 4 Conclusions

Whilst there is no definitive answer from the literature review it appears likely that, although by no means the sole cause of or influence upon El Niños, tropical volcanoes can, if sufficiently explosive, increase the possibility of an El Niño occurring in the year following the eruption. The ocean dynamical thermostat mechanism is the most plausible theory.

The results from the data analysis, whilst they cannot be considered statistically significant, are consistently in agreement with the above theory. The relatively short instrumental data record limits the effectiveness of a statistical study. As the volcanic signal is just one of many competing factors in the evolution of an El Niño lack of firm statistical evidence does not rule out entirely the possibility that volcanic activity does interact in some way with ENSO e.g. Mary Shelley was inspired to write her novel 'Frankenstein' during the gloomy "year without a summer" following the eruption of Tambora. Although there was a definite cause and effect mechanism at play a statistical analysis would never show up a link between teenage authoresses writing horror novels and volcanic activity!

From an examination of the cold tongue index it was noted that not all early season warmings resulted in an El Niño later in the season. It is also theorised that, if the conditions in the equatorial Pacific are already receptive for the onset of an El Niño, then volcanic activity might provide the final impetus required to initiate the El Niño. It would appear that if the initial conditions are not receptive to the formation of an El Niño the volcanic activity by itself is insufficient to trigger an El Niño.

It is without question that isolating the ENSO signal is essential for any form of climate diagnostic and not just for determining the climatic impact of volcanoes. There is still a lot of uncertainty with a range of estimates of the ENSO contribution to global tropospheric temperature trends from 15-72%. Methods of removing the ENSO signal include statistical regression, Fourier frequency filtering, a dynamically based filter and the use of CGCMs to estimate the ENSO contribution with the latter two probably showing the most promise.

It has been theorised that ENSO can cause volcanic eruptions but this is highly speculative and it can be concluded that it is unlikely that an El Niño can be a cause of volcanic eruptions.

Chapter 5 The Future

ENSO and in particular the interactions between it and volcanic activity can be considered an unsolved problem at the present. In the future as the time series of accurate and detailed measurements of both ENSO and volcanic activity increases then, so too, will our knowledge. Improvements to CGCMs to allow them to more accurately model ENSO will help to prove or disprove the ocean dynamical thermostat theory and to allow the ENSO signal to be removed from the climatic record with more accuracy.

Some other aspects that would be worth investigating are listed below.

1. Test the ocean dynamical theory for volcanic eruptions occurring during different phases of ENSO to see if this does have a bearing on the likelihood of an El Niño occurrence.
2. A tropical volcano will cool the tropical region more than the polar region thereby reducing the surface pole/equator temperature gradient. As the latitudinal extent of the Hadley cell and, consequently, the position of the subtropical jets is, to an extent, dependent upon this gradient one possible future piece of work would be to model the effect of the volcanically induced surface pole/equator temperature gradient reduction upon the tropical circulation both under normal conditions and during El Niño conditions when an abnormal Hadley cell prevails. The model could also include the increase in the stratospheric pole equator temperature gradient due to stratospheric heating.
3. Most studies into the climatic effects of volcanoes are primarily interested in stratospheric aerosols. Although the ash does not remain long enough in the atmosphere to have more than a short lived local climatic influence it would be interesting to see what effect the ash could have once it is deposited into the oceans. Some studies have suggested that it could cause a phytoplankton bloom thereby altering the albedo of the ocean by up to 10% and also that it can increase vertical mixing. Future work could include a study to determine if the ash could alter the sea surface temperature and, therefore, possibly have an influence upon ENSO for volcanoes in the right area.

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Appendix - Data

Data Sources

CTI: http://www.jisao.washington.edu/data/cti/

IVI: http://climate.envsci.rutgers.edu/IVI2/

MEI: http://www.esrl.noaa.gov/psd/people/klaus.wolter/MEI/mei.html

ONI: http://www.cpc.ncep.noaa.gov/products/analysis_monitoring/ensostuff/ensoyears.shtml

SOI: http://www.cru.uea.ac.uk/cru/data/soi/soi.dat

VEI: http://www.ngdc.noaa.gov/hazard/volcano.shtml

Cold Tongue Index

Key
Temperatures indicative of a Strong El Niño
Temperatures indicative of a Moderate El Niño
Temperatures indicative of a Weak El Niño
Temperatures indicative of a La Niña
Explosive Tropical Volcanic eruption

CTI values in hundredths of ˚C

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1876	64	-78	-135	-127	-54	-12	79	69	37	106	109	46
1877	138	36	57	166	90	**204**	63	180	184	238	224	223
1878	184	107		81	52		12	27	-12	-45	11	-74
1879	-24	36	-7	-76	-22	-24	-77	-59	19	-101	-92	-7
1880	-249	5	-1	173		4	51	12	57	110	56	26
1881	44	10	62	47	29	35	72	1	78	-12	63	-33
1882	-25	-45	42	33	39	-12	-70	-45	23	-52	-48	-63
1883	-62	-27	79	81	116	4	18	**-1**	21	14	82	-32
1884	-52	-1	8	-11	133	100	36	30	102	92	149	106
1885	88	62	21	27	57	81	17	7	111	123	133	68
1886	**101**	-16	-55	-22	3	-71	-55	**-74**	-16	-57	-66	-95
1887	-52	-93	6	5	3	-21	-1	30	87	2	48	17
1888	118	81	86	78	109	93	97	90	168	180	218	195
1889	248	189	63	48	70	32	-21	-61	-156	-101	-151	-72

1890	-43	28	-95	2	-2	-32	-27	-22	-1	5	-74	38
1891	46	30	14	97	68	79	43	104	-25	40	68	3
1892	14	-3	-1	-28	-22	-50		-25	-95	-109	-98	-82
1893	-90	-122	-82	-43	-57	-23	-27	-54	-54	-31	-40	-48
1894	-44	29	-46	-39	18	-14	64	-8	-1	-50	9	-46
1895	-7	-58	17	26	48	76	33	48	96	87	119	85
1896	84	20	58	34	39	53	141	155	109	133	186	200
1897	169	153	64	-43	-7	27	75	-30	21	-11	-17	-48
1898	7	-54	-58	-32	-1	-24	-26	-64	-4	-27	-43	-52
1899	-37	-15	-68	21	11	24	42	88	110	132	**178**	166
1900	147	150	103	72	98	91	84	51	16	84	20	55
1901	59	29	1	38	10	18	-50	-19	26	24	45	24
1902	52	62	68	77	**94**	111	212	**175**	177	**205**	217	188
1903	189	157	117	35	49	8	-31	-54	-27	-12	-45	-67
1904	1	20	42	2	21	74	125	138	75	144	132	146
1905	167	116	147	129	185	189	133	137	194	164	138	118
1906	144	68	34	73	25	-26	-37	-98	-36	-57	-78	-16
1907	-20	-43	-57	-5	28	42	92	22	93	34	61	55
1908	-13	73	18	-13	-1	-52	-59	-1	-84	-35	-59	-65
1909	-46	-106	-11	-22	-66	-51	-26	-95	-49	-95	-95	-127
1910	-71	-33	-91	-113	-44	-40	-16	-60	-49	-7	-48	-19
1911	**-48**	-61	-49	-32	52	37	118	123	131	133	181	225
1912	165	115	93	113	46	-14	18	-34	40	24	-7	-5
1913	-7	29	28	6	3	52	51	37	62	54	91	130
1914	125	74	73	91	61	37	78	72	166	84	131	70
1915	67	118	102	50	120	101	-76	128	-3	-63	-66	-53
1916	10	49	-35	53	5	-11	-82	-155	-76	-149	-97	-75
1917	-80	26	-25	40	0	34	-41		55	0	-155	-69
1918	22	-45	12	-30	62	94	103	116	133	99	226	233
1919	126	180	49	33	**78**	52	18	19	84	38	32	105
1920	82	-87	96	18	96	92	31	-9	51	13	-5	0
1921	6	32	-56	-3	-41	-5	2	-27	44	2	-20	29
1922	-40	9	22	32	38	-41	-9	-29	-11	-72	-42	-2
1923	-25	-38	21	24	53	56	64	61	107	95	105	87
1924	47	43	43	-13	-30	-18	-55	-64	-69	-55	-60	-45
1925	-54	-36	1	2	10	46	60	81	87	80	131	119
1926	125	93	88	89	84	12	50	3	-15	-45	-36	-42
1927	26	38	-36	-39	19	4	-19	17	33	50	25	47
1928	33	19	12	27	39	-29	14	7	14	0	7	17

1929	-28	-12	36	31	39	52	29	33	66	50	54	39
1930	48	40	35	54	54	26	86	80	120	123	166	162
1931	170	106	96	93	59	24	20	15	-28	-46	-42	-46
1932	-8	25	62	33	99	57	17	15	23	7	7	9
1933	-1	36	-8	12	-36	-43	-63	-68	-38	-102	-76	-86
1934	-51	-43	-21	18	13	-8	-6	20	6	-15	1	-50
1935	-63	-51	-3	-25	-17	-4	-15	31	29	29	24	6
1936	32	30	25	46	26	-21	-24	-16	11	20	-8	-6
1937	-31	-22	-2	21	**-3**	17	7	-6	4	-15	18	-12
1938	-56	-9	-58	-69	-60	-92	-109	-61	-87	-7	-77	-40
1939	-6	17	-39	77	39	54	73	67	60	-37	-3	27
1940	104	98	84	-5	81	55	50	23	53	50	80	119
1941	120	122	102	108	109	116	110	66	50	52	83	93
1942	95	**61**	26	40	2	3	-38	-87	-120	-90	-123	-115
1943	-129	-116	-100	-80	-62	-10	-7	12	0	-68	-58	-47
1944	-47	-23	-12	23	21	1	24	19	26	-44	-36	-33
1945	-57	-43	-108	-131	-29		-77	-31	-28	-38	-33	30
1946		14	-24	28	50	-49	-52	-65	44	-33	-28	48
1947	45	35	27	35	47	47	-25	-21	-25	-43	-22	-7
1948	38	39	58	52	39	-32	-70	-22	-35	-46	-1	16
1949	-65	44	-1	62	30	-26	-21	-42	-82	-108	-129	-57
1950	-119	-131	-44	-67	-74	-51	-103	-54	-88	-87	-101	-30
1951	**-38**	-41	-24	58	60	4	142	120	71	115	154	109
1952	64	22	-9	35	-3	-41	-42	-48	-31	-30	-47	-26
1953	39	34	50	95	72	56	50	15	92	26	50	15
1954	-10	-1	14	-81	-95	-99	-104	-95	-96	-108	-81	-87
1955	-25	17	-46	-47	-85	-87	-96	-66	-109	-137	-183	-148
1956	-114	-53	-40	-10	-20	-7	-24	-50	-47	-43	-68	-57
1957	-55	-2	39	66	102	124	149	118	108	82	120	126
1958	136	118	87	36	22	44	35	19	-21	3	8	2
1959	5	9	43	46	22	-12	-23	-23	-22	41	9	9
1960	2	-6	18	10	4	-17	-23	-13	18	-28	-53	-27
1961	-3	50	6	-12	-7	19	-34	-41	-76	-101	-25	-25
1962	-13	8	-25	-81	-46	-17	-28	-27	-31	-33	-48	-69
1963	-35	**-28**	13	10	13	26	63	78	74	71	84	91
1964	72	16	-15	-62	-102	-108	-45	-59	-40	-50	-62	-77
1965	-11	11	33	52	109	132	130	160	**146**	153	153	140
1966	126	78	35	**1**	-19	-14	11	**-7**	-25	-2	-48	-54
1967	-39	-20	-28	-22	15	31	-19	-93	-84	-69	-54	-50

1968	-73	-82	-82	-45	-47	-5	30	48	42	44	58	74
1969	75	40	41	52	103	71	27	67	69	92	92	112
1970	69	21	-14	4	-30	-71	-118	-90	-71	-63	-101	-71
1971	-110	-79	-58	-38	-31	-33	-37	-64	-41	-58	-57	-74
1972	-17	-12	14	62	89	108	161	177	158	189	191	214
1973	163	52	20	-41	-53	-72	-112	-107	-82	-83	-80	-107
1974	-106	-77	-58	-12	-20	12	-1	6	-4	**-64**	-58	-65
1975	-21	-35	-15	12	-26	-69	-61	-64	-76	-78	-79	-122
1976	-100	-30	-11	4	48	86	84	133	110	117	109	68
1977	94	54	44	-22	-3	5	21	0	11	41	50	60
1978	57	51	-4	-35	-36	-47	-41	-65	-19	6	8	33
1979	-13	17	14	30	38	35	7	23	66	55	59	36
1980	39	22	22	17	46	57	0	-5	22	-7	35	40
1981	-60	-56	-22	-34	-7	-2	-38	-48	10	-12	-27	24
1982	31	-6	**11**	**31**	**74**	100	77	106	171	183	243	269
1983	225	167	147	134	196	153	108	89	78	-15	-41	-64
1984	-28	-5	2	-30	-49	-89	-25	-18	-10	-76	-41	-77
1985	-67	-72	-71	-57	-72	-58	-57	-26	-53	-39	-42	-41
1986	-50	-12	-11	-16	-26	-19	21	26	41	20	95	89
1987	123	117	105	110	124	117	127	134	157	123	102	94
1988	39	19	-8	-46	-125	-156	-135	-94	-57	-104	-106	-108
1989	-85	-55	-81	-67	-33	-17	-58	-32	-15	-18	-27	-29
1990	-13	**13**	3	-15	29	-1	-1	23	17	18	-2	-16
1991	19	2	2	-1	50	**82**	66	56	46	97	112	139
1992	151	143	109	109	111	48	34	11	18	-4	14	24
1993	23	39	50	85	102	92	70	60	80	76	69	44
1994	25	-2	-4	-10	16	29	11	41	62	88	108	92
1995	77	65	10	-14	-26	-13	-27	-45	-50	-63	-76	-68
1996	-54	-66	-51	-64	-44	-41	-24	-32	-35	-39	-40	-71
1997	-44	-29	-8	34	96	115	163	196	222	219	253	235
1998	216	161	121	73	57	-26	-74	-68	-56	-105	-128	-159
1999	-157	-122	-90	-100	-69	-76	-76	-95	-74	-98	-132	-150
2000	-151	-123	-81	-43	-46	-58	-52	-50	-40	-61	-70	-83
2001	-69	-64	-41	-28	-29	-16	-7	-18	-11	-25	-32	-49
2002	-16	-1	-2	4	21	55	55	64	95	90	128	106
2003	82	47	29	-26	-62	-46	-15	-22	2	19	21	24
2004	18	-4	-23	-25	-3	-5	11	29	52	45	56	49
2005	67	38	17	-3	9	-4	-10	-14	-8	-14	-57	-85
2006	-65	-46	-51	-27	-2	-4	-1	31	61	62	94	93

2007	55	15	-7	-25	-30	-36	-45	-50	-72	-121	-137	-119
2008	-157	-128	-98	-86	-58	-53	-14	-6	-24	-35	-37	-75
2009	-59	-61	-54	-15	23	17	30	39	67	66	103	119
2010	111	85	58	30	-11							