Meridional temperature gradients and the mid-latitude storm track.

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Abstract:

The southern hemisphere's atmospheric circulation experiences several annual and seasonal changes that are well documented and studied. The teleconnections between different variables are verified and used to explain variability in everyday climate and weather. Theories using physics are taught and published in textbooks to help us understand the connectivity and complexity of such a system. One theory is the meridional temperature gradient has a direct impact on the storm track. This thesis investigates that theory using the ERA-Interim dataset.

The temperature gradient is a direct result of the temperature field, and depending on the latitudes you decide in which to constrain your gradient, the gradient experiences several changes. In the high latitudes, the southern annual oscillation created a two peaked pattern; the mid-latitudes display the expected seasonal mono peak pattern. The strong correlations seen in the high latitudes means that the gradient is driven by the patterns experienced at higher latitudes.

The independence of behaviours displayed by the ocean sectors led to the research investigating the influences, looking at not just the hemisphere, but also each basin separately. The Pacific and Indian Ocean showed in several results to act independently from one another, in temperature gradients, wind field, and storm track position.

The strong correlations between the temperature gradient and the wind field, as well as the storm track field show that the two are connected, as the theory suggests. If temperatures rise in the tropics, or decrease in the poles, then the temperature gradient will steepen. The pressure gradient force increases which pushes the thermal wind balance poleward, shifting the position of the westerlies. The area with the largest variation in the wind speed becomes the storm track, which would also shift poleward.

Climatic factors such as the southern oscillation index, southern annular mode or Indian Ocean dipole show slight correlations with the temperature field, but have little to no influence on the temperature gradient itself.

Precipitation levels in New Zealand are highly variable due to the nature of the countries location and topography. What was found was little connection between the northern part of the country and the storm track. However, closer proximity to the storm track, such as the south of the country, do experience a small amount of variation due to the storm tracks influence.

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"You are braver than you believe, stronger than you seem,
and smarter than you think."

Christopher Robin, **Winnie the Pooh**

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Chapter 1 : Introduction

1.1: Overview

The circulation of the Earth's atmosphere is a complex and integrated process that incorporates several different variables including temperature, pressure, wind, and moisture. Modelling is used to give visual representations of the relationships and the interconnectedness of the atmosphere that are already established. The spatial relationships that exist reflect the laws of physics as applied to a rotating sphere heated unevenly by solar radiation.

The 'textbook' idea, or the physics of the atmosphere, states that the north-south temperature gradient influences the storm track and the mean strength of is a one-way flow system as made popular by the explanations seen in introductory textbooks, such as that by Wallace and Hobbs (2006). A steepened temperature gradient means a poleward shift, and strengthening of the westerlies and mid-latitude storm track, based on the physics of geostrophic balance.

This research will investigate the extent to which a shift in the temperature gradient, whether it be a steepening or a weakening of the gradient, will cause a resulting shift in the mid-latitude storm track due to increasing or decreasing height of the air column with temperature, the pressure plane and the zonal winds. The steeper the gradient, the further south the mid-latitude storm track will shift. This would, in theory, create a change in the precipitation experienced in New Zealand. We investigate these linkages using observational data. We also determine the meridional gradient changes throughout the year and how that is expressed in terms of changes in the atmospheric circulation.

Climate change has become one of the greatest challenges facing humans in the foreseeable future. Rising temperatures impact the gradient and the storm track, but the extent of this is up for debate? There is a need to better understand how all the elements in the earths system work together, how the impact of one will impact the rest of the system, and how the climate system may change in the future. This thesis is not about climate change or the ability to forecast any changes, rather, it strives towards a greater understanding of the circulation of the Southern Hemisphere. A complete understanding will give rise to more accurate models and forecasting in the future.

1.2: Main questions to be answered

The main focus is the change in the meridional temperature gradient in the Southern Hemisphere atmosphere. How does the temperature gradient change throughout the year? Does it experience annual variation, and to what extent? Where does it change the most and the

smallest? By asking these questions, this research will establish a frame work for investigating patterns that may emerge due to outside influences not included in the annual variations.

This raises further questions. How different is the gradient between the sea surface and different levels of the atmosphere? How much of a difference? Which has the largest variation; which has the least? Establishing how the levels vary allows for a more focused research on specific levels and climatic processes.

How do climatic processes such as the El Niño Southern Oscillation (ENSO), Southern Annular Mode (SAM) and the Indian Ocean Dipole (IOD) impact the temperature gradient? These are large scale processes that make up a significant amount of variability in certain sectors of the Southern Hemisphere.

To what extent does the gradient have an influence on the storm track? Does the climatic factors have any influence on the storm track? It has been established through the literature that an increase in the gradient will result in the shift of the zonal winds. Zonal winds are an area that experiences large amounts of energy and where the storm track resides. The extent of this shift is what needs to be identified.

Does the storm tracks movement have any influence on the rainfall in New Zealand? In what location does it influence the most? The mid-latitude storm track sits to the south of New Zealand and, therefore, the location allows for research into whether any of the shifts or changes in the precipitation as a direct result of the shifting storm track.

1.3: Aim of this research

The circulation in the Southern Hemisphere experiences significant variability which has been well documented. The present day circulation of the Southern Hemisphere has many climatic processes that can change the temperatures and gradient both spatially and temporally. The aim of this research is to investigate thermal wind balance in the real atmosphere in the Southern Hemisphere by looking at the climatology of the temperature gradient, and to investigate how the temperature gradient affects the winds and storms, how these changes are brought about and if the low latitudes or high latitudes are the main drivers.

The temperature gradient in the Southern Hemisphere is a quantity that experiences annual, seasonal, and daily changes, both spatially and temporally. The aim of this research is to clearly document how the spatial and temporal changes to the gradient occur and the impact this has on other variables. What impacts the temperature gradient the most? Both the high and low latitudes selected will have a seasonal cycle themselves and, therefore, must be evaluated for

the strength of their individual correlation to the temperature gradient. Spatially, different parts of the earth will show different patterns of temperature gradient and, therefore, how the gradient changes in different locations are also included in this study.

Through the physics of geostrophic balance, there must be a consequent change in the zonal winds with a shift in the temperature gradient. This shift will be recorded in the datasets chosen for this study (3.1.1, 3.1.2) and will be correlated against the temperature gradients to show if there is a correlation, either negative or positive. An increase in storminess of the zonal winds should represent the mid-latitude storm track, an area of high energy wind events. This area would have increased wind speed and storm events.

The last section of the thesis will be looking for correlation in the precipitation on New Zealand, whether it has an impact or not. New Zealand is a topographically variable landscape. As such, a large correlation is not expected, due to the stronger variables in New Zealand's precipitations, such as orographic rainfall, ex-tropical storms and rain shadow regions.

Chapter 2 : Background

This chapter gives an overview of the atmosphere, and the variables that will be studied in this thesis. The object is to give a small overview and previous research of each individual part, and allow for understanding of the Southern Hemispheres circulation. Also explained is atmospheric levels that were selected for the study, based on the reasoning given in this chapter. As mentioned previously (1.1), the ‘textbook’ idea, as documented by the likes of Wallace and Hobbs (2006), is that the change in temperatures will result in a shift of the storm track and a change in the westerlies. How other atmospheric processes such as El Niño and the Southern Annular Mode impact these changes will also be reviewed.

2.1: General circulation:

The earth’s curvature creates imbalances in the amount of solar radiation absorbed at the surface and, therefore, the heating (Hartmann, 2015; Lee, 1952) . With the tilt of the earth’s axis being around 23° (Davis & Brewer, 2009), a surplus of solar radiation is found in the tropical areas between approximately 30° north and south latitude. At the poles, the same amount of radiation is spread out over a larger area due to the curvature of the earth, and there is a net loss (Rind, 1998). The earth’s system must then transfer energy poleward to achieve a minimum energy state.

The rotation of the earth around the axis also influences the general circulation. The further the distance from the axis of rotation, the faster the rotation experienced. Therefore, the rotation speed varies with latitude (Starr, 1948). With the earth trying to balance the temperature inequalities caused by the solar radiation variance, the poleward movement of wind flows faster than the land underneath it, becoming a westerly. Conversely, equatorward winds from the poles move slower than the land beneath it and therefore become an easterly (Schneider, 2006). The change of wind directions has resulted in 3 different cells in each hemisphere: the Polar, Ferrell and Hadley cells (Schneider, 2006; Starr, 1948).

The Hadley and Polar cells are thermally direct cells, which transport momentum upwards into the atmosphere and outwards towards the poles (H. Ding, Greatbatch, & Gollan, 2015; Hadley, 1735). The Ferrell cell is thermally indirect, transporting momentum downwards into the lower heights of the atmosphere and equatorward (X. Y. Liu & Liu, 2012). Therefore, the atmosphere gains momentum from 30° towards the equator, which acts to slow the rotation of the earth, but also loses momentum poleward of 30° , which acts to speed up the rotation of the earth (Richter & Rasch, 2008).

The Earth's climate will always try to come to an equilibrium. The geostrophic balance between the Coriolis force and the pressure gradient force, as well as the earth being hydrostatic, create a strong pressure gradient (Phillips, 1963).

The change in pressure and temperature between the tropics and the poles means that a parcel of air will want to flow directly to the pole. However it cannot do this as the rotation of the earth means that the Coriolis force will try and push the package of air to the east as it moves toward the pole (Holton, 1973; Phillips, 1963). When these two forces equalise, it means there is a geostrophic balance (Phillips, 1963), and the parcel of air flows at right angles to the pressure gradient, so a westerly flow.

From this geostrophic balance comes the thermal wind balance (Holton, 1973).

The north–south temperature gradient is directly entwined in the north–south pressure gradient. If we think of pressure surfaces as a plane, the height of that plane is proportional to the temperature below it. The depth of the air column will be proportional to the mean temperature experience at a certain latitude (Holton, 1973). Because the Tropics experience warmer temperatures, the height of the air column is quite high, whereas, at the poles, the air column is shorter in comparison (Phillips, 1963). The change in height means that a given pressure surface slopes downwards towards the pole. Higher in the atmosphere, the slope of the pressure surfaces increases, so the pressure gradient force increases with height, leading to stronger westerly winds at higher altitudes (lower pressure). Thermal wind balance encapsulates the relationship between the horizontal temperature gradient and the vertical gradient in wind speed.

Presently, tropical expansion is causing movement of warm tropical temperatures, both in the atmosphere and the oceans, into the low mid-latitudes. Tropical expansion is the poleward movement of the tropical waters into the mid-latitudes. This is occurring through the increased warming of the tropics as a feedback of the greenhouse effect (Zhang & Li, 2014). With the increase of greenhouse gases in the atmosphere, tropical expansion will continue to occur into the mid-latitudes. This will cause a change in the gradients experienced in the Southern Hemisphere, and therefore the poleward movement of energy as the earth tries to come to an equilibrium (Yamagata et al., 2003). Geostrophic balance and thermal wind balance will react with the increasing temperatures by increasing the gradient height between the poles and the tropics. This will cause a strengthening of the westerly winds, and a shift the mid-latitude storm track. To what extent the temperature gradient has on the storm track and the westerlies will be the focus of this research, as well as exploring the interannual variability in the temperature gradient and what influences that, and the overall climatology of the temperature gradient.

Coriolis force is created due to the rotation of the earth, in a west to east direction around the polar axis (Sturman & Tapper, 2006). This force deflects air as it moves across the earth's surface, making it an apparent force. The deflection to the left in the Southern Hemisphere creates a westerly acceleration for air moving toward the pole (Sturman & Tapper, 2006). In the northern hemisphere, this deflection is to the right, a westerly acceleration for air moving toward the pole.

Geostrophic balance is the equilibrium of both the pressure gradient force explained above, and the Coriolis force, also explained previously, represented in Equation 2.1. The geostrophic balance is where both forces equalise and wind flows parallel of the isobars as seen in figure 2.1 (Sturman & Tapper, 2006).

Figure 2.1: Diagram showing the Coriolis Effect. The path of the object moving from the centre (O) in a straight line towards the edge of the image (P1). Rotation means that the object is deflected so its path ends at P2 instead. The rotation causes the curved path. Image from Hay (2016)

Figure 2.2: diagram showing the influence of both the Coriolis force (CF) and the pressure gradient force (PGF) between two different pressure values acting on a parcel of air. In reality, no one parcel of air would be influenced only by these two variables. At the beginning of the movement, the Coriolis force is less than that of the pressure gradient force, and so the parcel moves more towards the lower pressure band. As the parcel moves further towards the lower pressure, there is an increase in the amount of Coriolis force applied on that air parcel, until they are finally even, meaning the wind travels parallel to the isobars.

For geostrophic balance to occur, equation 2.1 must be accurate. The pressure gradient force must become equal to the force exerted as the Coriolis force on a parcel of air (Wallace & Hobbs, 2006).

$$PGF = CF$$

Equation 2.1: Equation showing the true statement for geostrophic balance, where PGF stands for pressure gradient force, and CF stands for Coriolis force.

The steeper the gradient of the slope, the faster the winds. At the surface, this is a softer gradient than the steep ones experienced in the upper atmosphere (Holton, 1973; Starr, 1948). Higher in the atmosphere, the pressure slope is steepened as explained above, causing stronger pressure gradient force, stronger winds, and stronger Coriolis force which is proportional to the strength of the winds. The higher atmosphere experiences larger Coriolis force, and the pressure gradient force is also in action. For this reason the winds are stronger higher in the atmosphere than on the earth's surface. If the mean temperature were to decrease closer to the poles, then the height of that pressure plane would decrease as well. This decrease in height would create a steepened gradient, increased pressure gradient force, and increased Coriolis force, leading to increased westerly winds (Phillips, 1963).

$$V_g = \frac{1}{(f\rho)} \frac{dp}{dn}$$

Equation 2.2: Equation to find the establishment of geostrophic balance. V_g represents the geostrophic wind associated with geostrophic balance, f is the Coriolis parameter, ρ is the air density, dp is the horizontal pressure and dn is the horizontal distance.

Vertical gradients in the westerlies are products of the thermal wind balance, as well as zones of increased wind activity, such as the mid-latitude storm track. This storm track should follow the north–south temperature gradient as it is the direct result of the balancing between the temperature differences (Holton, 1973). If the gradient is steepened, then there should be movement in the mid-latitude storm track to reflect that.

Thermal wind balance is the resulting process. The concept of thermal wind is that any changes in wind speed, or wind direction are related to the horizontal temperature gradient (Sturman & Tapper, 2006). Similar to the aforementioned geostrophic wind, the forces acting on the wind must come to an equilibrium, in this case, the temperature and the pressure patterns (Sturman & Tapper, 2006). Equation 2.3 shows us that the temperature plays a significant role in the calculation of thermal winds (Randall, 2015).

$$\frac{du}{dz} = \frac{g}{fT} \frac{dT}{dy}$$

Equation 2.3: equation to state thermal wind relationship with the vertical and horizontal component of wind, where u is the westerly wind speed component, u is the westerly wind direction component, z is height, g is the acceleration due to gravity, f represents the Coriolis force, T is temperature, and x and y representing the distance from west to east, and north to south direction respectively (Sturman & Tapper, 2006)

In this thesis, the primary focus is the changes in the temperature gradient in between 30°S and 65°S, responding both to the temperature and the pressure variations (Randall, 2015). Different latitude limits were investigated, which is explained in Chapter 4. However, between 30°S–65°S was the main latitudinal band included as the results. This is more characteristic of the mid-latitudes and closer to the poles where there is more heterogeneity in the atmosphere, than in the tropics, which exhibits barotropic behaviour, just responding to the change in pressure.

2.2 Climatic Processes

The circulation of the Southern Hemisphere has a significant amount of variability. The Southern Hemisphere has little land mass in comparison to the northern hemisphere. The continents of Australasia, Africa and South America are the only major land masses that are present in the southern latitudes (Renwick, 2002) which reduces continental heating. Antarctica is also a contributing land mass. However, it is not evenly distributed over the South Pole, and, for that reason, the latitudes that exclude Antarctica from the data have been chosen. There is more land and ice mass in the Indian Ocean high latitudes and less in the Pacific high latitudes.

Large open ocean basin processes can change over time and location. The ocean surface and the atmosphere are coupled in the tropics (Bell & Goring, 1998; Kevin E Trenberth et al., 1998). In the Pacific Ocean basin, the largest climatic process recognised is the El Niño Southern Oscillation (ENSO) (McPhaden, Zebiak, & Glantz, 2006). In the Indian Ocean, the Indian Ocean dipole is a significant variable in the temperature gradient anomalies (Ashok, 2004; Guo, Liu, Sun, & Yang, 2015), and in the Southern Ocean, the southern annular mode (SAM) creates significant variability in the high and mid-latitudes (Kidston, Renwick, & McGregor, 2009; Yuan & Li, 2008).

2.2.1: Southern Annular Mode

The SAM is the leading contributor to Southern Hemisphere climate variability explaining approximately 20-30% of the weekly, monthly, and yearly variance in the extratropical atmospheric flows (Gillett, Kell, & Jones, 2006). Sea ice extent and distributions, temperatures and southern ocean SST variation are linked to the SAM. Recently, the SAM has shown a trend towards positive phase events in austral summer and autumn, which was previously unprecedented (Arblaster & Meehl, 2006). Ozone depletion has been linked to the positive trend, as its greatest impact occurs at the same time (Sigmond & Fyfe, 2010). Ozone absorbs incoming solar radiation in the stratosphere, so the depletion means that heat is not being absorbed in the atmosphere, resulting in cooling of the stratosphere (Sigmond & Fyfe, 2010, 2014). The meridional temperature gradient is therefore amplified, resulting in an increased stratospheric polar vortex which results in positive SAM events (Schoeberl & Hartmann, 1991). SST in the central Pacific during austral winter and SST anomalies in the eastern tropical Pacific can be correlated to the SAM.

The SAM describes the north–south movement of the westerly belt around Antarctica increasing or decreasing the strength of westerlies over New Zealand and other mid-latitude countries. The positive phase can be characterised by decreased strength of the westerly flows leading to less frequent passage of rain fronts and depression, and more anticyclone blocking east of New Zealand (Kidston et al., 2009; Marshall, 2003). The positive phase shows the movement of the strongest westerlies, and the mid-latitude storm track to the south. During the negative phase, the strong westerly winds move northwards, bringing depressions and frontal systems. Kidston et al. (2009) found that negative SAM brought more trough systems, and positive SAM more zonal and blocking regimes. The tough system is where the surface pressure experiences a bulge of high pressure (Holton, 1973). A blocking system is a large anti-cyclonic system high that can lead to the breakdown of zonal winds, in this case the westerlies (Renwick & Revell, 1999). They are hard to predict and are often associated with extreme weather events.

In the Southern Hemisphere, if a large high pressure system sits in place for five consecutive days, it is classified as a blocking event (K. E. Trenberth & Mo, 1985).

2.2.2: The El Niño Southern Oscillation

Part of the El Niño Southern Oscillation (ENSO) is the shift in the tropical Pacific mean sea surface temperature (SST). ENSO is the 2–7 year cycle which oscillates, not consistently, between unusually warm and cold sea surface temperatures in the tropical Pacific (McPhaden et al., 2006; K. E. Trenberth & Hoar, 1997) and the corresponding east-west oscillation in mean sea level pressure and the strength of the trade winds. In an El Niño, the tropical Pacific trade winds weaken, with an increase in the atmospheric pressures in the Western Pacific, and decreasing in the Eastern Pacific. Warming in the Eastern equatorial Pacific migrates across the central Pacific into the west, reducing the ocean upwelling. This reduces the Bjerknes feedback, reinforcing the conditions as the El Niño develops (McPhaden et al., 2006). The Bjerknes feedback was a concept published by Jacob Bjerknes which stated that the normal Pacific characteristic was for the east Pacific to be 4-10 degrees cooler than in the West, despite receiving the same solar insolation (Bjerknes, 1969; Zheng, Fang, Yu, & Zhu, 2014). The ENSO process can be seen as a feedback system. Temperature gradients can influence the strength of winds, which can help push warmer waters westward, cooling the eastern waters, which then increase the temperature contrast and gradient (Cane, 1985). K. E. Trenberth (1997) observes that this feedback mechanism is causation of the ENSO signal. In a La Niña, these conditions would be reversed. As mentioned above, the ENSO system is not an annual phenomenon, and it does not alternate from an El Niño to La Niña and back: it oscillates between the two on different time scales (McPhaden et al., 2006).

It is the accepted theory that the equatorial western Pacific warm pool has warmed and expanded eastward, with the SST in the western Pacific increasing by 1.5°C per century (Z. Y. Liu & Huang, 2000). An and Jin (2001) state that the SST in the east has increased more than in the west, with increased El Niño events and the increased CO² levels creating more favourable conditions for El Niño. The western Pacific warm pool experiences an increase in the SST, but it is weaker as it has a deeper mixing layer in the ocean (Abram, McGregor, Gagan, Hantoro, & Suwargadi, 2009), whereas the eastern Pacific displays a stronger increase in SST due to its shallow mixing layer. Increased upwelling of cold water due to the vertical temperature gradient compensates for the radiative warming (Wang, 2001). Increases in the SST gradient between the east and the west will create La Niña-like responses.

2.2.3: Indian Ocean Dipole

The Indian Ocean Dipole (IOD) is confined to the Indian Ocean basin and describes an east-west dipole in SST across the tropical Indian Ocean. The event starts with the anomalies in the sea surface temperatures near the south east of the basin, and the strong ocean atmosphere interaction of the tropical Indian Ocean (Guo et al., 2015; Saji, Goswami, Vinayachandran, & Yamagata, 1999). Similar to the factors contributing the formation of ENSO, the IOD relies on an anomaly in the sea surface temperatures (Guo et al., 2015). Positive SST to the east will result in stronger westerly winds, where as a negative SST will result in the opposite (Guo et al., 2015). The dipole has three phases, a positive, negative and a neutral phase. The positive phase sees sea surface air temperatures in the western Indian Ocean greater than usual, with the east having corresponding cooler temperatures. The conditions would be reversed in a negative phase (Guo et al., 2015).

2.3: Sea surface temperatures:

Figure.2.3 Image showing sea surface anomalies in February 2015. Note the large warm patches in the eastern pacific, associated with an El Nino event, and the eastern Indian Ocean associated with a weak positive Indian Ocean dipole. This was selected as a random example. This image is using the ERA-Interim 700hPa data set, created in MATLAB.

The Southern Hemisphere circulation can be classified as zonally symmetric, as a result of the lack of land mass situated south of 40°S, the shape and location of Antarctica over the pole (Jones, Raper, & Wigley, 1986). The graduated temperature from the equator to the Southern Ocean allows for the study of the horizontal meridional gradient. Some studies have suggested that the gradient can also be influenced by large climatic systems, such as ENSO, which modulates temperature in the tropics (Chiang & Sobel, 2002).

There is a natural temperature gradient between the tropics and the Antarctic within the oceans and the atmosphere. This is due to the natural disparity in solar radiation, with higher temperatures in the low latitudes and low temperatures in the high latitudes (Legates & Willmott, 1990). The resulting variance in the Southern Hemisphere, as well as the lack of land mass, creates a banded gradient in the Southern Ocean and those connecting to it.

The resulting warming of the sea surface due to the increase in overall temperatures will at some point meet the southern part of the gradient which will be influenced by the high latitudes' freezing temperatures (Rind, 1998). There is also a large seasonal change to the position of the SST gradients which is expected given the change of solar radiation and warming in the mid-latitudes with the change of season (Schneider, 2006). Most of the change in the gradient comes from the cooling and warming of the latitudes selected, which largely happens in the transition to the autumn and the spring months. The temperatures in summer and winter stabilise during the season.

The ENSO signal is also well established in the East Pacific, with sea surface temperature anomalies centred around 50°S 135°W (Fig 2.3) which is associated with enhanced equatorward flow, seen as positive polarity, with positive sea surface temperature anomalies east of the main centre around the southern tip of South America (Holland & Kwok, 2012). The ENSO signal will then be present in the data for the Pacific Ocean and the East Pacific. The Indian Ocean exhibits both the signal from the ENSO mechanism as well and the Indian Ocean dipole (Ashok, 2004),

2.4: Air Temperatures

The central focus of this thesis is the air temperature data, the gradients and the latter's implications on the Southern Hemisphere circulation. As mentioned above, the increase of CO₂ in the atmosphere has created atmospheric warming on all levels, and there should be a resulting increase in temperature. The physics of the atmosphere and the meridional temperature gradient suggest that a visible change should first appear in the atmosphere, and then, through coupling with the oceans, in the SST. The expansion of warm tropical temperatures into the sub-tropics means that there will be a steepening of the pressure gradients as explained in the climatic section of this chapter (2.2).

Atmospheric pressure surfaces 700 hPa (AT7), 850hPa (AT8), and 1000 hPa (AT1) were selected for this thesis. AT7 and AT8 were chosen as suitable lower tropospheric fields for calculation of temperature gradients. They are in the free atmosphere but are low enough to influence the structure of zonal winds through much of the troposphere. AT8 (approximately

1500 metres above sea level) and AT7 (approximately 3000 metres above sea level) were high enough not to be influenced by land mass, but still by the overall temperature gradient from the surface (Nicol et al., 2000). AT1 was selected as a close surface representation of the atmosphere, as the sea surface temperature field exhibited missing values where there was no ocean. AT1 varies in height with latitude, but in most places, AT1 is just above the earth's surface. Three heights were selected so that the vertical dimension of the atmosphere could be included.

The air temperature gradients also experience a similar pattern to the sea surface temperatures. However, they experience a larger variation between the high and low latitude components. They also experience a much larger shift from cold to warm. This is due to the fact that the ocean takes a lot longer to process and shift than the atmosphere. According to Randall (2015), The increased moisture in the lower atmosphere means that AT1 shows the gradients and signals this shift more clearly than the higher levels of the atmosphere.

The gradient itself has a semi-annual oscillation (SAO) which has a larger peak in October and a smaller peak in March (Walland & Simmonds, 1999). This is because the two phases of seasonal change shift out of alignment (Walland & Simmonds, 1999). The rates of cooling and heating between the different latitudes differ, causing disparities between the minimum and maximum temperatures experienced. This typically occurs when the high latitude component has a rapid change in comparison to the mid-to-low latitude component (Vanloon, 1967).

The temperatures in the tropics and subtropics have increased faster than in the Southern Ocean, causing a steepening in the north–south temperature gradient. As explained earlier, this would result in the stronger westerlies. If there is any change, it will be evident in the atmosphere as it has a faster response time than in the oceans.

2.5: Storm Tracks

Storm tracks are the regions of the middle latitudes where the storms most commonly occur and tend to follow the strongest westerly winds. The winds shift with the seasons, and are strongly modulated by the Southern Annular Mode, on time scales from days to decades. Gan and Wu (2015) suggest that it is the winds and the strength of them that dictate the storm track position. In the wintertime, there is an observed equatorward shift, in both the hemispheres. These claims will be assessed in chapter 5 of this thesis.

Storm tracks are generally considered as a narrow area, where there is disturbance and high energy in the prevailing wind patterns (Gan & Wu, 2015). High energy events will move with pressure gradients as well as Coriolis force. These events then try to come into geostrophic

balance, where the Coriolis force and the pressure gradient force become equal, creating westerly flow on average. Stronger winds will create high energy eddies, feeding the energy to the storm systems (Gan & Wu, 2015). As well as experiencing the seasonal cycle of movement mentioned above, there is also a shift due to other climate mechanisms such as ENSO.

The meridional temperature gradient, as discussed earlier, has an impact on climatic processes, storm tracks in the Southern Hemisphere being one of them. Due to the disparity of pressures and temperatures, the energy which flows down gradient would create strengthened westerlies. Any changes to the spatial patterns of storm tracks, or their intensity, would be visible in climatic patterns and regional weather (Gan & Wu, 2015).

SAM alters the north-south movement of the westerly belt around Antarctica, increasing or decreasing the strength of westerlies over New Zealand. The positive phase can be characterised by lower than normal pressures over Antarctica which brings the westerly belt closer to the continent. During the positive phase, two jet streams can be observed, one hugging close to the coast of Antarctica and the other equatorward of New Zealand. A negative phase would involve higher pressures located further away from the continent, and the westerly belt moving equatorward. There is only a single, more connected jet mode in a negative SAM, with the jet south of New Zealand migrating equatorward. There is no peak in the frequency of the SAM; it can flip from positive to negative in the matter of days. The signal for the SAM is the most obvious in the summer months.

2.6: New Zealand

New Zealand is a collection of islands that sits in an intersection zone of several climatic phenomena, which means that the country's different regions experience different levels of precipitation. New Zealand sits between 34–47°S and therefore experiences prevailing westerly winds, as well as the large scale climatic events such as ENSO and SAM.

El Niño creates on average stronger south-westerlies, colder temperatures and increases in rainfall in the south-west and drier conditions in the north-east. La Niña causes on average more frequent north-easterlies and the climate is in general warmer and milder.

During a positive SAM, New Zealand experiences decreased storm activity and westerlies, which are increased over the Southern Ocean, resulting in drier, warmer conditions. During a negative SAM, the storm track moves equatorward causing increased westerlies and storminess in New Zealand. (Ummenhofer & England, 2007) ascertained that 80% of the rainfall trend in regions of the North Island, and 30–60% of the rainfall trend on the South Island west coast could be explained by the resulting changes in the climate by SAM.

The interpretation of the precipitation pattern of New Zealand regions varies with different definitions. Three regions were identified by Salinger and Mullan (1999); the northern and central regions of the North Island, the eastern coasts of both the North and South Islands, and the west coast of the South Island. However, in this thesis, seven locations have been selected around New Zealand with the hypothesis that they will experience different impacts from the changing storm track locations based on where they sit in relevance to that storm track.

The top of the North Island region is a sub-tropical climate zone, with a prevailing south westerly wind. Winter patterns are dominated by the tropical storms which can bring heavy rainfall from the east and northeast. The central North Island is sheltered by the high country to the south and east, which has less wind. The south west coast is exposed to the prevailing westerly winds, with high topography often creating orographic rainfall, which would increase the precipitation levels. The east coast of the South Island is sheltered by the high topography of the Southern Alps, but experiences southerly storms as well.

2.7: Overview

Everything in the earth's system is interconnected. As discussed through the chapter, the physics behind the circulation and movement of the Southern Hemisphere has been well established. The physics are known, and the theory has been written about in several overviews of the circulation system. This research is to document the theory, and to visually emphasise the relationships between the different variables of the atmospheric system. All the aspects discussed play a part in the circulation and will be used to determine changes to the temperature gradients, and the mid-latitude storm track.

Chapter 3 : Data

3.1: Data collection

All the gridded data, such as the atmospheric and sea surface temperatures, were downloaded from the ERA Interim data set (Dee et al., 2011). Once again to reduce inaccuracies, data that was recorded previous to the satellite era was excluded to reduce inaccuracy in the data, therefore, data processed and analysed was between 1979 and the end of 2016. This was one of the key reasons that this dataset was selected, as it does not contain data pre satellite era. All data was downloaded into a NetCDF format and structured through MATLAB.

Time series data, such as the climatic variables, were downloaded from the NOAA earth system laboratory (NOAA, 2017), in a NetCDF file, and once again, read into MATLAB.

3.1.1: Sea Surface Temperature

The data set selected is a monthly mean produced by finding the mean of the daily observations, and put into a $2.5^{\circ} \times 2.5^{\circ}$ latitudinal by longitudinal grid. The sea surface data is limited to areas in the ocean, and therefore there are missing values represented by Not a Number (NaN).

3.1.2: Air Temperature

For this thesis, only three atmospheric pressures were selected, 700 hPa, 850 hPa, and 1000 hPa.

850 hPa (AT8) is approximately 1500m above the earth surface, although this varies with latitude. Lower latitudes will have AT8 at higher height, and the high latitudes will have it closer to the surface. AT8 is high enough in the atmosphere to lie above surface effects.

700 hPa (AT7) is approximately double the height of AT8, once again varying with latitude. The reason AT7 was selected to look at large scale climatic processes in the mid-troposphere, it is often used to find the connections between the surface and the upper atmosphere.

Both AT7 and AT8 were selected because they are in the free atmosphere. This means that any impact of the friction from the earth's surface is negligible and therefore the data is a true indication of the workings of the atmosphere.

1000 hPa (AT1) is just above the earth's surface, and, although it is influenced by continental heating, does not exclude land mass from the dataset. It was selected as a fast response variable that could show the impacts of the surface on the larger scale atmospheric processes. Unlike oceans, the air warms and cools at a quick rate, and the seasonal variability is more pronounced.

The three pressure levels are gridded 2.5° by 2.5° latitude and longitude. The data goes up till December 2016, so that the data is in a complete year format. Once again, the data was separated into months of the year and seasons using MATLAB.

Anomalies were then calculated for both the months and the seasons, once again using the MATLAB code. Anomaly data was then correlated against other data of the same format.

3.1.3: Sea Ice Edge

The high-resolution sea ice extent data is of $1^\circ \times 1^\circ$ longitudinal grid, which was processed in Matlab to find the sea ice edge: the data is the latitude in which the sea ice cover stops exceeding the 15% threshold. This data was retrieved from the National Snow and Ice Data Centre (NSIDC) (Fetterer, Knowles, Meier, & Savoie, 2016). The sea ice extent data is formatted in a binary format, with 1 representing the grids that contain sea ice, and 0 representing the areas, that did not. The 15% threshold states that the grid cell is covered by at least 15%. This is not a standard for all sea ice extent data, as each can be modelled on a different threshold.

As the sea ice data was going to be compared to other data, the anomaly of the latitudinal difference was needed. For this research, the anomalies from the seasonal cycle was created by taking the mean for each month, and subtracting those means off the individual months in the time series.

The sea ice data was used to determine the latitudinal limits of the temperature gradient. While it was used in the preliminary stages of the thesis, it does not feature in the results of this thesis.

3.1.4: Wind data

The data selected was the u component, or the zonal winds at 300hPa level. Once again the anomalies from the seasonal averaged were calculated using the same technique as previously explained above (Chapter 3.1.3).

3.1.5: Storm Track Data

Using the same ERA-Interim dataset as the wind frequency data, an estimate of storm track activity was calculated from twice daily 300hPa heights. The height fields were high pass filtered with an 81-point Lanczos filter (Duchon, 1979) with half power point at 7 days. The monthly standard deviation of the resulting high frequency height fields, the variability on time scales of less than 7 days, were calculated, with the resulting data set showing the high frequency variability in the circulation. The latitude in which these maximum variability occurs was labelled as the storm track, with the idea that the region where the height field fluctuated the most on a daily to weekly timeframe would be the turbulent storm track area.

3.1.6: Southern Annular Mode data

This data comes in a 58x13 matrix, with each column representing each month of the year, and the 13th column as a yearly mean. The index is calculated by the position of the stronger than average westerly wind position compared at 40°S and 65°S. A positive index values corresponds with stronger than average westerlies in the higher latitudes. The SAM dataset came from the NOAA earth science laboratory (NOAA, 2017).

3.1.7: Southern Oscillation Index data

The Southern Oscillation Index (SOI) is a standard index based on the sea level pressure differences between Tahiti and Darwin, Australia, specifically to identify an El Niño or La Niña pattern. The index focuses on sea level pressures, which correspond with the sea surface temperatures. The data is in a 58x13 matrix, with each row representing a year from 1957 until 2015. Each column from one to twelve represent each month of the year, and the thirteenth column representing the annual index. A positive phase of the SOI represents above average air pressures in Tahiti and below average air pressures experienced and Darwin. Prolonged positive SOI coincides with a La Niña. The SOI dataset came from the NOAA earth science laboratory (NOAA, 2017).

3.1.8: Indian Ocean Dipole data

The Indian Ocean Dipole index is based on the sea level pressure changes experienced between Java to the East, and the African continent to the west. Once again, the sea level pressures are an indicator for the change in sea surface temperature. The data is in a 34x13 matrix, with the rows representing the years of data from 1981 until 2015, with the first twelve columns representing each of the months of the year, and the thirteenth column the yearly average. The IOD dataset came from the NOAA earth science laboratory (NOAA, 2017).

3.1.9: Precipitation

As previously discussed, New Zealand has several different climatic nodes across the country. Its location in the Southern Ocean means that different parts of the country will experience different climatic changes. Therefore, several different locations around the country that will experience different climatic processes. All precipitation data was collected from the National Institute of Water and Atmospheric Research's (NIWA) National Climate Database, CliFlo. CliFlo is a web based system that allows access to the over 6500 climate stations in New Zealand, including those that are no longer in service. Historic records are still available. CliFlo also has the option to download the already statistically calculated the monthly mean from the high resolution data, including some resolutions of 10 minutes. One of the main criteria used to

select a site for further research was a continuous record from 1979 to January 2015. The biggest reason for this is because a change in the location of the climate station would mean that the environmental impacts could change, and as a result, a trend that was not there would be falsely represented.

The data was structured in a simple matrix format, with each column representing a single year, and each row the months. This format is to keep the data similar to those shown in the previously mention climate data, where time, specifically years, is the last variable in the matrix. This was done to reduce confusion, and allow for an order to be created when data was collected from different agencies and or formats. The locations data sets (Table 1) were imported as numeric matrixes into MATLAB, where they were saved in the data pack labelled ‘precipitation’.

Location	Longitude	Latitude	Missing Data
Russell	174.12°E	-35.265°S	Nov, 2015
Mokairau, Gisborne	178.24°E	-38.475°S	Feb, Dec, 2014
Longbush, Wairarapa	175.60°E	-41.20°S	None
Christchurch	172.6°E	-43.53°S	Apr, May 2014, Mar 2015
Hokitika	170.98°E	-42.71°S	Aug, Dec 2014
Milford sound	167.92°E	-44.67°S	None
Invercargill	168.33°E	-46.417°S	None

Table 1: Table showing the location names and co-ordinates of the climate stations used for the precipitation analysis. These seven locations were selected to show the variation in the precipitation in the different coasts and latitudes of New Zealand. The missing data was replaced with the monthly sum of daily values from the same dataset.

3.2: Data Manipulation

All the data and figures in this thesis have been created and calculated from the above data collections. Where possible, the origins of the data were similar, or from government data stores to reduces inaccuracy and changing formats. Having the data read into MATLAB through similar systems meant that there was the ability to manipulate the data with similar codes. The learning of MATLAB programming was essential for this research, and took a significant amount of time to become proficient at it.

The first way was to import the data in a structure that was easy to use and able to be used in conjunction with other formats. The data was processed in MATLAB for both the sea surface temperature data and the atmospheric levels data. Where possible, the use of the data was restricted from 1979 when the use of satellite increased the accuracy.

3.2.1: Reading in the data

The nature of the NetCDF files that were being used to store the data meant that they had to be read into the MATLAB programme and structured ease of use. The example given is the MATLAB code (Documentation 1), 'tgraderai_1000850700', used to structure the atmospheric data, and a similar code to structure the sea surface temperature gradient. In this code, the reading of four key elements are done and structured into one structure. Time was used, in this case days since 01/01/1900, which allowed for the accurate date of the data to be connected to the data. The longitude and latitude have also been connected to the data, making the data into a grid pattern. The final element was the data itself, the data at each grid cell, which was recorded in degrees Celsius, as a monthly average. The rows representing the latitude of the data, the columns representing the longitude of the data, and the third dimension was the time, in this case, each month. The air temperatures were similar to this structure. The attribute 'level' was included, as there were 3 levels of the atmosphere included into the structure, creating a fourth dimension of spatial relevance.

```
% finding the data
fname=['era-interim-temperatures-1000-850-700-1979-2016.nc'];
%establishing the datasets that we want to look at
levs=[1000 850 700];
for ilevel=1:3
    lev1=levs(ilevel);
    t=read_netcdf_latlon('file',fname,'field','t','level',lev1);
    %Data in Kelvin, change to °C
    t.data=t.data-273.15;
    switch lev1
        case 1000
            t1=t;
            save temp1000 t1
        case 850
            t8=t;
            save temp850 t8
        case 700
            t7=t;
            save temp700 t7
    end
    %Establish the parameters, Gradient and areas to look at
    north=[-32 -28];
    south=[-67 -63];
    hemis=[0 360];
    Pacific=[150 282];    % Longitude range
    Indian=[39 120];
    Atlantic=[320:360 1:15];    % Longitude range
    eastpac=[210 280];    % Longitude range
    westpac=[150 210];    % Longitude range% Longitude range
```

```

la=t.latlon(:,1);
lo=t.latlon(:,2);

sectors={hemis,Pacific,Indian,Atlantic,eastpac,westpac};
nsec=length(sectors);
tall=NaN(t.nt,3*nsec);
%Creating the gradient
for i=1:nsec
    sector1=sectors{i};
    if sector1(1)<sector1(2)
        losel=lo>=sector1(1) & lo<=sector1(2);
    else
        losel=lo>=sector1(1) | lo<=sector1(2);
    end
    seln=((la>=north(1) & la<=north(2)) & losel);
    sels=((la>=south(1) & la<=south(2)) & losel);
    tn=mean(t.data(:,seln),2);
    ts=mean(t.data(:,sels),2);
    tg=tn-ts;
    tall(:,(1:3)+(i-1)*3)=[tn ts tg];
end
%Bring the data all together
tgrad=t;
tgrad.data=tall;
tgrad.sectors=sectors;
tgrad.sector_names={'Hemisphere','Pacific','Indian','Atlantic','EastPacific','West
Pacific'};
tgrad.ns=[north south];
tgc=month_clim(tgrad);
%Save the outputs
fout=sprintf('erai_t%i_gradient_3565_monthly',lev1);
switch lev1
    case 1000
        tgrad1=tgrad;
        tgc1=tgc;
        save(fout,'tgrad1','tgc1')
    case 850
        tgrad8=tgrad;
        tgc8=tgc;
        save(fout,'tgrad8','tgc8')
    case 700
        tgrad7=tgrad;
        tgc7=tgc;
        save(fout,'tgrad7','tgc7')
end
end

```

Documentation 1: The MATLAB code used to separate data into the three categories described earlier. Please note this code is specifically for the atmospheric heights of 1000, 700 and 850hPa. The code does not vary significantly for the other data sets.

3.2.2: Datasets

From the code mentioned previously, each variable had three saved sections. Tgc, tgrad and t. At each height, these then had the number representative of the height: for example 850 hPa became tgc8.

T represents the gridded data set, in this case temperatures. In the case of the storm track it becomes z and in the case of the winds, the horizontal component is u. This is where the temperature data has been structured into three main parts. The first one is time. Each data point has been processed changing it from days since 01/01/1900 into a time that can be called upon by the user, with a year and month. It also has latitude longitude values processed to allow for mapping. Lastly, the data has been converted to degrees Celsius and saved into its respective heights or variable.

tgrad is used to find the temperature gradient between two latitudes. As previously stated the entire dataset in t has been given latitude and longitude values. The monthly temperature gradient is calculated as the difference in temperatures between the selected latitudes. The tgrad is then put into sectors of the data, and averaged over those areas. The sectors are discussed below in 3.2.3.

Tgc is the average climatology of the gridded data set. It takes the average of each month from the temperature gradient to create an overall temperature gradient pattern. Tgc also includes another four columns at the end, for each of the different seasons, summer, autumn, winter and spring.

Each variable is saved in its own structure, and can be loaded before any processing is done. This code can be rerun if there is a cause to change the latitudes of the temperature gradient.

3.2.3: Ocean Data sets

The average of the hemisphere as a whole was not all that was being investigated. As a result, the data had to also be separated into the individual ocean basins. Atlantic (40°W-15°E), Indian (39°E-120°E) and the Pacific (150°E-80°W). The Pacific was separated into the Western Pacific (150°E- 150°W) and the Eastern Pacific (150°W-80°W), as the size of the basin meant that there could be some dampening of any signals that were being investigated. The land mass of the Southern Hemisphere meant that it was very easy to establish the oceanic boundaries. In the section under 'establishing parameters', the different sectors are established, and the longitudes in which they are including are within the square brackets beside them. The code has been written so that almost any file can be run through it, therefore keeping the defined

boundaries the same. As seen in documentation 1, the longitude limits of the basins were defined.

3.2.4: Gradients

To reduce any interference with regional climatic factors when looking at the gradients, nine gradients were selected and deployed. At the low latitudes, 20°S, 25°S, and 30°S were selected and in the high latitudes were 60°S 65°S, and 70°S, and then correlated at each. With the temperature gradient being banded, it was important to see how the interpretation could change based on the gradient selected, and how these changed in each of the basins. As the gradients were our primary focus of the thesis, it was important to cover all the possible outcomes.

To find the gradient between each of these pairs of latitudes gradients was a simple calculation, as discussed in 3.2.2, and shown in Appendix 1 and Chapter 4.2. The high latitude temperature was subtracted away from the low latitude temperature to find the difference, which can be seen in the code. As the temperatures change, the gradient would increase if the temperature gradient was steepening, and decrease if the gradient was shallowing out.

The gradient was also calculated with seasonality. Summer months were classified and December, January and February. Autumn months were defined as March, April and May. Winter months are defined as June, July and August. Finally, the spring months are defined as September, October and November. Once again, these calculations were assimilated into the code

3.2.5: Correlation between the variables

To understand how the temperature gradient impacts the surrounding temperatures, the temperature gradient (tgrad) was correlated to the original temperatures (t). This was carried out by creating a MATLAB code that took the time series for each sea surface temperature grid point and correlated it to the temperature gradient time series to find the correlation. As the MATLAB ‘corrcoef’ function returns a 2x2 matrix, the result from each grid point was then entered into a blank matrix.

```
function correlmap=corrmap(data,tseries,regress,n1,n2)
```

Documentation 2: Correlation code used for a majority of the work

In the code above (Documentation 2), the data would be represented by the gridded monthly data, in this case t: the time series (tseries) would be represented by the temperature gradient (tgrad). To find the correlation you would just input those two arguments. If you were after regression maps, then you would but substitute ‘true’ where variable “regress” sits.

3.2.6: Climatic factors

The climatic factors include the SOI index, the SAM index, and the DMI. Once it was read into MATLAB, these climatic factors were processed in the same way, becoming time series data. The DMI has only been recorded in the NOAA dataset since 1982 and, therefore, does not have the same length of time series as SAM or SOI. The three climatic drivers were correlated against the anomalies of each seasonal temperature gradient, explained in 3.2.4. Each gradient at each level, SST, AT1, AT8, and AT7. Each climatic driver was correlated using the MATLAB correlation coefficient, included in the 'corrmap' function. Each ocean basin was also correlated against each of the climate drivers.

3.2.7: Sea ice extent and the temperature gradients

The Sea Ice Extent (SIE) is not a time series data, but rather a gridded dataset. Two calculations were done in relation to SIE: SIE against the temperature gradient, and SIE against the temperature at the lower latitudes. SIE was found to have little influence on the overall pattern of the circulation, but the impact it would have on the sea surface temperatures, particularly in the Indian Ocean sector. This was visible when the gradients were checked for sensitivity. After this finding, SIE was no longer used.

3.2.8: Temperature gradients and the Zonal Winds

The analysis on the impact of the temperature gradient on the zonal winds was done by correlating the temperature gradient as a time series against the zonal wind gridded data. This was done using MATLAB code similar to that explained in 3.2.6.

3.2.9: Storm track

The storm track shows the area of the highest variability in wind speeds. The actual dataset is the latitude in which the highest variability occurs. Three sets of data for the storm tracks were created. Due to the variability of the individual longitudinal positions, some smoothing was implemented to the data to reduce the outliers of the data. The first set of data has had no smoothing. The second set of data has had smoothing of 11 points, this means that the middle point, number 6, has been averaged from the previous five and following five longitudinal data points. The third data set is the original storm track and smoothed by 21, smoothed by 10 on each side of the original data point (Documentation 3).

```
% make empty array big enough to hold smoothed data
stormsm21 = zeros(455,120);
for i = 1:455
```



```
% go through each row, smooth it and then rotate the result because  
% smooth() creates a column instead of a row  
stormsm21(i,:) = smooth(storm.data(i,:),21)';  
end
```

Documentation 3: Smoothing of the storm track code.

When graphed this can represent the southern mid-latitude storm track. The average position for the storm track was calculated using the mean function on MATLAB. This was then plotted as a monthly average.

3.2.10: Precipitation and the storm track.

The precipitation was already downloaded as a time series, and therefore could be easily correlated with the storm tracks. The precipitation is data collected from one point in the region of interest, and therefore can only be a representation of the impact that the position of the storm track has on regions of New Zealand. Because the position of the southern mid-latitude storm track varies along the longitudes, and so correlation was done by correlating the time series of each location with the time series of each longitude near New Zealand. The Storm track data is in 3° longitudes, starting at 147°E, with 3° intervals until -165°W. Each correlation was then input into a matrix for each location, which was then plotted as a correlation matrix.

3.2.11 Overview

The data selected for this thesis has been structured for ease of use, and downloaded from the same sources, where possible to keep accuracy. The data was used in codes that allowed for a variety of data to be used. Comparing results will show genuine changes in the data. The use of a data manipulation program was unavoidable due to the size of the data sets available, MATLAB was selected due to the large amount of online help.

Chapter 4 – Results

The results of this thesis have been calculated and projected using the MATLAB program, as explained in chapter 3.2. These results will show connections and spatial variations, with explanation primarily based around the provided figures. A small explanation will be given as to why these results were derived.

The annual variation of the temperature gradients demonstrates large variations in the annual cycle, and different heights of the atmosphere show different patterns. Looking closer at the temperature gradients, the selected latitudes have also been evaluated to allow for a reasonable gradient to be used in further research. These gradients were then correlated and regressed against the temperature fields to see in which areas influenced the temperature gradient as a whole, and if ocean basins correlated with each other or if they were separated from the other ocean basins.

In chapter 2.1, it was established the steeper the temperature gradient, the more energy in the system and the faster the winds and the thermal wind balance. The zonal winds show a strong correlation in the strength and mean position when compared to the temperature gradient. The Indian Ocean shows the strongest zonal winds, but also, shows little to no correlation with the other oceans. This may be due to the steepened gradient of having the tropical warm pool in the East, and having the Antarctic coast in lower latitudes than elsewhere in the high latitudes.

Finally, trying to relate the storm track and its position to New Zealand, the precipitation was correlated against the storm track position. The expected was seen, the locations selected that were south of the country had higher correlations than the northern ones. But also, unsurprisingly, that all the stronger correlations were to the longitudes west of the country.

The results section is to show evidence of the relationship between the temperature gradients and the circulation of the Southern Hemisphere, with direct reasons as to why the patterns are present. The discussion will go into further detail.

4.1: Average hemispheric temperature gradient

The natural temperature gradient varies throughout the year, but in different ways at different vertical levels (Fig.4.1). As discussed in 3.1, temperatures studied are from four levels. The SST, AT1, AT8 and AT7. These levels all show different patterns in their annual behaviour.

Figure 4.1: Seasonal cycle of temperature difference (°C) between 30°S and 65°S latitude, averaged around the Southern Hemisphere. Each monthly value is an average over the 38 years from 1979 to 2016. The four panels are (top to bottom) 700hPa, 850hPa, 1000hPa, and sea surface temperature. These gradients were calculated using the ERA-Interim data. The y-axes have been adjusted to show the pattern of change in each plot.

Between 30°N and 30°S, the temperatures in the tropics are stable, both annually and spatially. Through the seasons, there is an expansion poleward of the warm temperatures in the summer, and a recession of colder temperatures in the winter. This is seen as the boundary between the predominantly more baroclinic and the more barotropic processes on the planet (Holton & Hakim, 2012). 65°S was chosen for the higher latitudes due to its position in relation to the Antarctic continent. The higher latitudes have a complex relationship with the Antarctic continent, with the latitude of the Antarctic coast varying around the hemisphere, and sea ice extent exhibiting large seasonal variation (Simmonds, 2015). For example, the Indian Ocean when 70°S was selected to look at the gradient, the SST could not be recorded as it recording over the Antarctic coast. As AT1 is just above the surface, the sea ice might also impact those results. 60°S did not show the full extent of the gradient, and missed a significant amount of the cooling. 65°S was decided as the best suited latitude for the gradient to be examined.

The temperature gradient at AT7 displays a semi-annual oscillation, with the larger peak occurring in September, and the smaller peak in April. The smallest gradient is in the summer, in December/January. Overall, the temperature gradient does not oscillate to a large magnitude, with the difference between minimum and maximum average temperature gradient being 2.62°C. The semi-annual oscillation can be seen in the pattern of the AT7, and this has been well documented by G. A. Meehl (1991). The SAO is due to the position of the circumpolar trough and how it contracts and expands with the changing of the seasons, winter and summer respectively. As explained in several papers, the SAO is a prominent pattern in the high latitudes; G. A. Meehl (1991) and Vanloon (1967) demonstrate that the pattern is a feature of the 50°–65° latitudinal gradient. As the gradient selected includes this range, the pattern has presented itself in the data.

The annual temperature gradient from 30-60 (Fig 4.2) removes the SAO pattern significantly (Fig 4.3), creating a single dip in the data. The magnitude of the gradient is also reduced by removing the higher latitude.

Figure 4.2: Seasonal cycle of temperature difference (°C) between 30°S and 60°S latitude, averaged around the Southern Hemisphere. Each monthly value is an average over the 38 years 1979-2016. The four panels are (top to bottom) 700hPa, 850hPa, 1000hPa, and sea surface temperature. These gradients were selected using the ERA-Interim data.

Figure 4.3: Seasonal cycle of temperature difference (°C) between 60°S and 65°S latitude, averaged around the Southern Hemisphere. Each monthly value is an average over the 38 years 1979-2016. The four panels are (top to bottom) 700hPa, 850hPa, 1000hPa, and sea surface temperature. These gradients were selected using the ERA-Interim data.

The temperature gradient found at the atmospheric pressure level of AT8 also exhibits the semi-annual oscillation, with the maxima and minima at the same time of year as AT7. However, the AT8 shows a larger magnitude of change between the higher and lower gradients, with a difference of 3.8°C. As discussed in the previous paragraph, the SAO pattern has been removed with the reduction of the gradient (Fig 4.2). Instead of reducing the temperature gradient in the middle of summer, the smaller latitudinal difference results in an increase in the gradient. These findings are consistent with the arguments made by G. A. Meehl (1991) and Vanloon (1967). It is quite clear that the reduction in the temperature gradient in December is a pattern that occurs in the higher latitudes (Fig 4.3).

Unlike those higher in the atmosphere, AT1 exhibits a single maximum and a single minimum when looking at figure 4.1. It has an expected seasonal steeping of the gradient from February to August. The largest annual change in the temperature gradient is evident at AT1, or almost surface level. During the year, the gradient can vary by 5°C , with the peak occurring in August, and the minimum in December. Figure 4.3 shows that a majority of the that gradient pattern is from 60°S – 65°S , as the trend is almost completely opposite in figure 4.2 when compared to figure 4.1; the peak occurs in February, and the minimum occurs in June. Both gradients (30°S – 60°S and 60°S – 65°S) have an impact on the overall pattern. The 60°S – 65°S gradient (Fig 4.3) has a larger influence, with the overall pattern being similar to that shown in the 30°S – 65°S gradient (Fig 4.1). The gradient pattern of 30°S – 60°S (Fig 4.2) allows for the peak to be moved to later in the year. If the latitudes 60°S – 65°S were not included in the gradient, then AT1 would exhibit a similar pattern to that of the higher atmosphere levels.

The change in the pattern between AT1 and the higher levels of the atmosphere could be due to the Antarctic influence. Significantly colder temperatures are blown offshore from the continent by katabatic winds, and in some areas, due to the pressure changes by climatic processes such as the SAM. This would mean that the temperatures and near earth signals would be representative of the Antarctic influence rather than that of the hemispheric influence. In this case, the sea ice and the Antarctic continent would be interfering with the temperature signal, significantly cooling the air temperatures quickly. There would therefore be no differentiation in the heat budget.

The SST shows a peak in the temperature gradient around March, and a minimum around August. The magnitude of the change (3.1°C) is relatively similar to the upper atmosphere. It shows no correlation to the SAO due to the longer response time exhibited by the oceans. It displays the expected pattern with a smooth seasonal signal (Fig 4.1). Figure 4.2 shows a similar pattern, with a more plateaued high in the summer. Figure 4.3 however does not show the same seasonal pattern. The pattern emerging in the high latitudes (Fig4.3) shows a reduced peak in the winter months, and a slow reduction in the temperature.

According to G. A. Meehl (1991), the SAO pattern is due to the transition from heat gain to heat loss in the late summer (March) and the heat loss to heat gain in the winter (August). The SAO pattern emerges because the higher latitudes have a different heat budget in the latitudes 50° and 65° (Taschetto, Wainer, & Raphael, 2007). The influence of the Antarctic on the high latitude temperatures has been well established. The variation in the surface pressure between the Antarctic continent and the mid-latitude surface pressures are due to the changing temperatures, as well as the influence of the circumpolar trough (G. A. Meehl, 1991; Vanloon,

1967), an band of low pressure surrounding the Antarctic continent(Turner, Marshall, & Lachlan-Cope, 1998).

Figure 4.4: Annual behaviour of the temperature gradients between 30°S–65°S in the different ocean basins, compared to the hemispheric gradient pattern. Four levels were selected (From top left) 700hPa, 850hPa, 1000hPa, and SST. The blue line represents the hemispheric average of the temperature gradient. This graph is to show that looking hemispherically will not give you a clear image on the variation of the temperature gradient and how that can be used to physically show the 'textbook' idea. This is evidence that ocean basins should be reviewed as separate datasets.

Different oceans have different gradient patterns, as shown in Fig 4.4, and as such, must be considered separately for any data analysis. There is a clear change in the pattern when we look at the AT1 behaviour, which was also seen in Figure 4.1, the AT1 shows a single peak in the winter months, while the higher levels of the atmosphere show a two peaked structure, especially specifically in the Indian Ocean, which will be explained later in this chapter. The variation in the temperature gradient, specifically 12°C between the East Pacific and the Atlantic show that the temperature gradient is not a fixed value and that variations should be discussed, as all heights show significant variations away from the hemispheric mean. To see the results of the different latitudes selected in the sensitivity testing, refer to the appendix.

The change in the pattern experienced in AT1, as seen in figure 4.4 shows that the temperatures experience an opposite pattern than those of AT7 and AT8. As the Indian Ocean experiences the largest change of pattern, it can be inferred that the influence of Antarctica has resulted in cooling/heating in the high latitudes to occur at the same rate as cooling/heating in the low

latitudes during the changing of the season. AT1 is the surface level of the atmosphere, and therefore has greater connectivity with the ocean interface. As the advance and retreat of sea ice in the Southern Ocean being the largest seasonal change, this would be communicated through the SST and AT1. The influence of the different latitudes on the temperature gradient is explored in 4.2.

4.2: Average temperature gradients at different latitudes

Figure 4.5: Seasonal cycle of the temperature, as well as the temperature gradients of different latitude bands averaged over the Southern Hemisphere. Each monthly value is the average over the 38 years 1979-2016. The four rows represent 700hPa, 850hPa, 1000hPa, and sea surface temperature. Each column represents a different latitude band (left to right) 20°-60° latitude south, 25°-65° latitude south, and 30°-70° latitude south. The blue lines in each graph represent the temperature gradient. The red line represents the low latitude of the gradient, and the orange line represents the high latitude. These gradients were calculated using data from the ERA Interim dataset (Dee et al. 2011)

Looking at the variation of the temperature gradient of the different latitudes (Fig. 4.2), it is evident that there is considerable sensitivity to the choice of latitudes for calculation. As figure 4.5 shows, a variation between 10° of latitude can have a visible impact on the emerging pattern of the gradient. Figure 4.5 shows these difference between three latitudinal gradients; 20°–60°, 25°–65° and 30°–70°.

The temperature gradient shows that the maximum gradient occurs in the winter time. Both the low and high latitudes experience a decrease in temperatures; the lower latitude does not experience the same drop in temperature as the high latitude. Both show strong negative correlations with the overall gradient, which is evident in all the atmospheric gradients, to different magnitudes (Fig 4.5). The semi-annual oscillation is visible in many of the graphs, but is more prominent in the 30°S–70°S gradients (Fig 4.5). The peaks of the oscillation coincide with the increase or decrease of the temperatures experienced at the higher atmosphere. The lower temperatures experienced in the higher latitudes stabilise through the mid-year, between

the decrease in the temperatures coinciding with the start of the Southern Hemisphere Autumn, and the increase of temperatures, coinciding with the start of the southern Spring.

The SST however does not show the semi-annual oscillation, and the overall temperature gradients correlate to the low latitudes quite strongly. The variation experienced by the SST is minimal, and heavily dependent on the behaviour of the low latitudes. Unlike the variations experienced in the atmosphere, the variation in the high latitudes is minimal, just 2.6°C , compared to the change in the low latitudes of 3.77°C . Due to the lack of variation in both the high and low latitudes, and the high latitudes sitting around the 0°C mark, the overall temperature gradient and the low latitude temperatures plot to almost the same point on all three of the SST graphs. This thesis will therefore primarily focus on the patterns and reactions of the atmosphere, rather than the SST.

Unlike the temperature gradients from the levels of the atmosphere, the peak being at the end of summer/beginning of autumn, and the minimum in the late winter, the opposite gradient pattern emerges, with an increase in summer and a decrease in winter. Instead of the high latitudes changing to a larger magnitude than the lower, it is the equatorial latitudes that have the larger and quicker decrease or increase in temperature.

Chapter 4.1 demonstrated that the high latitudes have a significant impact on the gradient pattern throughout the year. 70°S in some areas is covered in sea ice or is in fact part of the Antarctic continent. For this reason, the SST gradient recorded between 30° – 70° may not be a true indication of the ocean temperatures. In the Indian Ocean, the Antarctic continent is located further equatorward than elsewhere in the Southern Hemisphere. Conversely, areas such as the Pacific Ocean experiences more open ocean than other areas. In the atmosphere, AT1 is surface level, and therefore may also exhibit interference from the Antarctic continent or the sea ice. At AT7 or AT8, if the high latitude for the gradient covers the Antarctic continent, such as in the Indian Ocean, then these data sets may also show incorrect patterns, as the height of ice on Antarctica can reach heights of over 4km. This explains the lack of pattern in the SST in winter months.

4.3: Average Temperature gradients in the different ocean basins

The oceans around the world vary in size, depth and climatic influences. In this section, the focus on the separate ocean basins is to explain the semi-annual oscillation, and visualise the different patterns in each basin. The reason basins were chosen was to reduce the impact of continental heating. The three oceans included are the Indian Ocean (40°E – 120°E), the Atlantic Ocean (40°W – 15°E) and we have split the Pacific Ocean into two zones, the west Pacific Ocean

(155°E to -150°W) and the East Pacific Ocean (-150°W to -80°W). The correlations are provided next to the temperature of the single latitudes.

4.3.1: The Atlantic Ocean

Figure 4.6: Seasonal cycle of the temperature, as well as the temperature gradients of different latitude bands averaged over the Atlantic Ocean basin, which extends from 40°W-15°E. Each monthly value is the average over the 38 years 1979-2016. The four rows represent 700hPa, 850hPa, 1000hPa, and sea surface temperature. Each column represents a different latitude band (left to right) 20°-60° latitude south, 25°-65° latitude south, and 30°-70° latitude south. The blue lines in each graph represent the temperature gradient. The red line represents the low latitude of the gradient, and the orange line represents the high latitude.

The Atlantic Ocean has strong negative correlation in the atmospheric gradients, and relatively strong positive correlation in the SST gradients. All gradients show the seasonal cycle throughout the year, to a lesser magnitude in the SST (Fig. 4.6). The gradient at all atmospheric and ocean levels is steepest between August and September, which is intuitive in the winter. The Atlantic Ocean displays a larger variation in the high latitudes in reference to temperature than the average world temperatures. The semi-annual oscillation does not appear strongly in the Atlantic Ocean, however, the temperature gradient between 30°S -70°S at an atmospheric height does display a levelled out gradient in the winter month.

4.3.2: The Indian Ocean

Figure 4.7: Seasonal cycle of the temperature, as well as the temperature gradients of different latitude bands averaged over the Indian Ocean basin, which extends from 39°E-120°E. Each monthly value is the average over the 38 years 1979-2016. The four rows represent 700hPa, 850hPa, 1000hPa, and sea surface temperature. Each column represents a different latitude band (left to right) 20°-60° latitude south, 25°-65° latitude south, and 30°-70° latitude south. The blue lines in each graph represent the temperature gradient. The red line represents the low latitude of the gradient, and the orange line represents the high latitude.

The Indian Ocean also shows strong positive correlations in the SST gradients, and strong negative correlations in the atmospheric gradients. The strong seasonal cycle is once again visible, stronger in the atmospheric gradients (Fig. 4.7). One of the dominant features of these graphs, again specifically in the atmospheric gradients is the strong semi-annual oscillation signal. While other graphs demonstrate the steepest gradient occurring around August-September, the peak in two of these graphs, specifically 30°S -70°S at AT8 and AT1, shows the peak at the beginning of the winter months, in April - May. This strong signal appears at a similar time as the one shown on the hemispheric gradients. In the atmospheric gradients, the role of the high latitudes has a larger impact on the overall gradient than that of the low latitudes.

The Indian Ocean has a large boundary with landmass. Unlike the other oceans studied, the north of the Indian Ocean is bounded by landmass, whereas the Pacific and the Atlantic both have north and south components to it. Landmass is quicker and more proficient at heating and this could influence the atmospheric temperatures experienced in the Indian Ocean. To the East of the Indian Ocean, the Pacific warm pool is situated, which would translate into atmospheric temperatures through the ocean atmosphere interactions which has the warmest waters of the earth. To the south of the Indian Ocean basin, the continent of Antarctica, specifically East Antarctica which lies further equatorward than the rest of Antarctica's coastline. The high latitude selected (65°S) sits close to the coastline of East Antarctica; sitting within the bounds

of the sea ice extent. Because 70°S is covered by the Antarctic coast in the winter months, there could be no measurements in the winter months.

4.3.3: The Western Pacific Ocean

Figure 4.8: Seasonal cycle of the temperature, as well as the temperature gradients of different latitude bands averaged over the Western Pacific Ocean basin, which extends from 150°E - 150°W . Each monthly value is the average over the 38 years 1979-2016. The four rows represent 700hPa, 850hPa, 1000hPa, and sea surface temperature. Each column represents a different latitude band (left to right) 20°S - 60°S latitude south, 25°S - 65°S latitude south, and 30°S - 70°S latitude south. The blue lines in each graph represent the temperature gradient. The red line represents the low latitude of the gradient, and the orange line represents the high latitude.

The Western Pacific Ocean does not display the semi-annual oscillation, instead showing a large curve with a flattened peak. This is especially visible in the 30°S - 70°S category. In the other categories, the change in the gradient does not have as much variation, which is represented by the low and high latitudes having similar responses to the seasonality (Fig. 4.8). When the peaks are evident, these are typically in August/September. The SST in the western Pacific show a trend, it does not decrease over the Southern Hemisphere winter month. This gradient change is easily explained: Antarctic Sea ice would be in this location, which has skewed the results.

4.3.4: The Eastern Pacific Ocean

Figure 4.9: Seasonal cycle of the temperature, as well as the temperature gradients of different latitude bands averaged over the East Pacific Ocean basin, which extends from 150°W-80°W. Each monthly value is the average over the 38 years 1979-2016. The four rows represent 700hPa, 850hPa, 1000hPa, and sea surface temperature. Each column represents a different latitude band (left to right) 20°-60° latitude south, 25°-65° latitude south, and 30°-70° latitude south. The blue lines in each graph represent the temperature gradient. The red line represents the low latitude of the gradient, and the orange line represents the high latitude.

This trend is similar to the western Pacific, in as much that the magnitude of change in these areas are not to the same extent as those experienced in the other ocean basins. And once again, the SST gradients, especially for 30°S -70°S may be skewed as sea ice is found around 70°S. Not all the graphs show a mono peak, more the SST (Fig. 4.9). The higher atmosphere shows more of the SAO pattern, not demonstrating the typical seasonal pattern, but rather variation throughout the year. Both the Pacific basins show a reduced difference between the lower and high latitudes when compared to the Atlantic and the Indian Ocean.

4.3.5: The Pacific Ocean

Figure 4.10: Seasonal cycle of the temperature, as well as the temperature gradients of different latitude bands averaged over the Pacific Ocean basin, which extends from (150°E-80°W). Each monthly value is the average over the 38 years 1979-2016. The four rows represent 700hPa, 850hPa, 1000hPa, and sea surface temperature. Each column represents a different latitude band (left to right) 20°-60° latitude south, 25°-65° latitude south, and 30°-70° latitude south. The blue lines in each graph represent the temperature gradient. The red line represents the low latitude of the gradient, and the orange line represents the high latitude.

The Pacific as a whole shows two dynamics. AT1 and SST shows a mono peak at apposing times of the year, SST in the autumn, and AT1 in the late winter. In the free atmosphere, both AT7 and AT8 show the SAO pattern apart from the AT7 at 20°S-30°S. Once again the SST temperature gradient between 30°S-70°S shows inaccurate behaviour due to the sea ice extent during the winter months (Fig. 4.10).

4.3.6: Overall

The overall pattern shows that the Indian Ocean has the largest annual changes, and these are easily recognisable in the hemispheric temperature gradients. The Pacific basins, although separated, show a similar pattern throughout the year, and the Atlantic demonstrates the ideal gradient pattern expected.

4.4 – Variability of the gradient in relation to climatic drivers

Field correlation maps have been calculated for each of the gridded data sets to allow for each grid point to be correlated to the climatic driver over time, looking for an overall spatial pattern. In this case, it was done for the anomalies in temperature gradients for AT7, AT8, and AT1.

Histograms were also used to show the spread of the temperature gradient and the occurrences of the 20th and 80th percentile of SAM, SOI and IOD events.

The SOI represents the phase of the ENSO, where a negative number means El Niño conditions and a positive number is recognised as La Niña conditions. If there is a warming in the ocean due to El Niño conditions, then it will appear to be a negative correlation with temperature, and vice versa.

4.4.1: Southern Annular Mode

Although SAM is a significant factor in climate variability, it mainly focuses on the strength and variability of the winds and the storminess in the mid-latitudes. The correlation between the temperature field and the SAM was not expected to be large, however the SAM does respond to changes in the temperature gradient. The largest correlation are expected in the high latitudes as the SAM is most active near the Antarctic continent (Fig. 4.11).

Figure 4.11: Graphs showing the correlation between the Southern Annular mode (SAM) and (from top left to bottom right); AT7, AT8, AT1, and SST. Each line represents 0.02 correlation. Black lines represent 0 correlation. Red signifies the positive correlation and blue the negative. These numbers are not statistically significant as correlations over 0.3 are significant at the 5% level

4.4.1.1: SST and the Southern annular Mode

The SST does not demonstrate the typical SAM pattern expected, but instead, shows an apparent randomisation of the correlations. This is due to the SST around the Antarctic coast showing irregularities in the data due to the sea ice in the area. The strength of the correlations is weak, with no correlation being above $r=0.1$. In context to the results, the largest correlations can be found in the low latitudes in the Pacific region.

4.4.1.2: AT1 and the southern annular mode

The correlation calculated is weak, and shows the typical SAM pattern around the Antarctic coast. The strongest positive correlation is found in the south Pacific, with $r=0.1077$. The strongest negative correlation is found in the over the South American continent, where $r=-$

0.0910. As previously noted, the largest correlations are found in the Southern Hemisphere. The largest correlations appear in areas that experience the changes in the SAM pattern, such as the one in the Pacific Ocean.

4.4.1.3: AT8 and the southern annular mode

The correlations found at 850 hPa are similar to those seen at 700hPa. Once again, the correlations resemble the typical SAM pattern, with 3 distinct areas of negative correlation and 3 areas of positive correlations. The strongest positive oscillation can be found in the in the high latitudes of the south east Pacific, between New Zealand and South America, with $r=0.13$. The strongest negative correlations are in the high latitudes of the south Atlantic with a correlation of $r=-0.1596$.

4.4.1.4: AT7 and the southern annular mode

The correlations of AT7 mirror those of AT8, including position of the strongest positive and negative correlations. The positive correlation maximum is weak, at just $r=0.0906$, but a strengthening of the negative correlation of -0.1986 . AT7 follows the pattern of the lower atmospheric pressure levels, and have been used to see if the occurrences. Looking at figures 4.12 and 4.13, the spread of the larger positive SAM coincide with the larger temperature gradients on the annual scale, which is represented in the winter histogram, which is when the SAM is strongest.

Figure 4.13: Histogram showing the annual spread of temperature gradients (x axis) and the frequency (y axis). The top histogram represents the top 20 percentile of SAM, representative of the negative Southern Annular Mode. The second histogram is the top 80 percentile of SAM recordings, representative of positive Southern Annular Mode. Both show the temperature gradients during those years. The bottom shows the complete list of temperature gradients for the recorded time. This figure is designed to see if either positive or negative represent the largest or smallest temperature gradients.

Figure 4.12: Histogram showing the left) summer and right) winter spread of temperature gradients (x axis) and the frequency (y axis). The top histogram represents the top 20 percentile of SAM, representative of the negative Southern Annular Mode. The second histogram is the top 80 percentile of SAM recordings, representative of positive Southern Annular Mode. Both show the temperature gradients during those years. The bottom shows the complete list of temperature gradients for the recorded time. This figure is designed to see if either positive or negative represent the largest or smallest temperature gradients.

4.4.2: Southern Oscillation Index

Figure 4.14: Graphs showing the annual correlation between the Southern Oscillation Index (SOI) and (from top left to bottom left); AT7, AT8, AT1, and SST. Each line represents 0.1 correlation. Black represents 0 correlation; red signifies the positive correlation and blue the negative.

4.4.2.1: SST and the Southern Oscillation Index

The majority of the correlation in reference to the SOI and the temperatures will be negative, as a positive SOI is a La Niña, which cools the temperatures rather than warms it. The strongest correlations are found in the Pacific Ocean, as the SOI is a predominantly Pacific Ocean response (Fig. 4.14). The strongest correlations of the Oscillation index are in the later months of the year: August to December. It also produces the highest variability of the correlations, with almost no correlation in reference to the east Pacific low latitudes, but a strong positive relationship with the West Pacific.

4.4.2.2:AT1 and the Southern Oscillation Index

AT1 shows the typical ENSO pattern in the correlation, with positive correlation in the west Pacific Ocean, and negative correlations in the Eastern Pacific, with a max value of $r=0.406$ and $r=-0.645$ respectively. This shows that an El Niño will warm significant portion of the Eastern Pacific. During a La Niña, there will be a warming in the Western Pacific. Visibly, minimal impact that the Atlantic and the Indian Ocean.

4.4.2.3:AT8 and the Southern Oscillation Index

Similar to the pattern explained in 4.4.2.1, where an El Niño will increase temperatures in a majority of the Pacific Ocean region, with a maximum correlation of $r=-0.591$. A La Niña will result in a warming of the oceans below the sub-tropical convergence zone, stretching from the Indonesian warm pool, the north east of New Zealand, with a correlation $r=0.396$. At this height, there is a minimal warming of the Indian and Atlantic Oceans.

4.4.2.4:AT7 and the Southern Oscillation Index

At the higher level of the atmosphere, there is more interaction with the SOI in the Indian and Atlantic Ocean sectors. Similar to the results of the higher atmospheres, the largest correlation to El Niño is in the West Pacific, around 200° longitude, with a correlation value of $r=-0.6097$, while the La Niña has a weaker correlation, of $r=0.275$. The Atlantic shows a weak relationship with the SOI, whereas the Indian Ocean shows a positive relationship in the mid-latitudes, and a negative relationship with the low latitudes.

The spread of the occurrences in figures 4.15 and 4.16 show no major correlations again with the temperature gradient. There may be a weak shift during a positive and negative SOI, however, it is not enough to change the shape of the spread of the temperature gradient.

Figure 4.15: Histogram showing the annual spread of temperature gradients (x axis) and the frequency (y axis). The top histogram represents the top 20 percentile of SOI, representative of the El Nino. The second histogram is the top 80 percentile of SOI recordings, representative of La Nina. Both show the temperature gradients during those years. The bottom shows the complete list of temperature gradients for the recorded time. This figure is designed to see if either positive or negative represent the largest or smallest temperature gradients.

Figure 4.16: Histogram showing the left) summer and right) winter spread of temperature gradients (x axis) and the frequency (y axis). The top histogram represents the top 20 percentile of SOI, representative of the El Nino. The second histogram is the top 80 percentile of SOI recordings, representative of La Nina. Both show the temperature gradients during those years. The bottom shows the complete list of temperature gradients for the recorded time. This figure is designed to see if either positive or negative represent the largest or smallest temperature gradients.

4.4.3: Indian Ocean Dipole

Figure 4.17: Graphs showing the correlation between the Indian Ocean Dipole (IOD) and (from top left to bottom left); AT7, AT8, AT1, and SST. Each line represents 0.03 correlation. Black represents 0 correlation; red signifies the positive correlation and blue the negative. 4.4.3.1: SST and the Indian Ocean Dipole. These numbers are not statistically significant as correlations over 0.3 are significant at the 5% level

4.4.3.1: SST and the Indian Ocean Dipole

The Indian Ocean Dipole shows the strongest correlation in the later months of the year, specifically, September through to December, with a correlation of $r=0.34$ (Fig. 4.17). Focusing on the Indian Ocean, there is a strong positive relationship to the west of the basin, with little to no correlation in the extreme east. Large correlations in the East Pacific and the high latitudes of the South East Pacific are also visible. However, as previously explained, the temperature gradient in the Indian Ocean are independent form the Pacific, and vice versa. Therefore the correlation between the two ocean basins may be due to a similarity of changes within each basin. Much like the ENSO system, there is a shift in the ocean thermocline in the Indian Ocean,

which will account for the higher correlations in the Indian Ocean, than in the Pacific or the Atlantic.

The extent of the connection between the Indian Ocean and the Pacific is debated in scientific reviews as to whether they are independent or not concerning the IOD and the ENSO. Allan et al. (2001) state that there is a relationship between them, with a correlation of $r=0.54$ when looking at the factor that start the processes. However, Saji, Ambrizzi, and Ferraz (2005) state that the IOD is independent from the Pacific influence, with its own triggers.

In the earlier months of the year, there are reasonable correlations in similar areas with a much muted signal. Except for the large area of strong correlation south of Western Australia. This correlation is only evident in the ‘spring months’.

4.4.3.2: AT1 and the Indian Ocean Dipole

The Indian Ocean dipole does not exhibit a relationship to the temperature field, in any of the atmospheric pressure fields. The positive correlations are typically over the oceans, and the negative over the landmasses. As there is a clear distinction at AT1, continental heating will play a part.

4.4.3.3: AT8 and the Indian Ocean Dipole

Once again the IOD signal is significantly small, with the largest negative correlation over the Atlantic, at $r=0.32$. This negative correlation is linked to the low correlation that occurs over the African Continent. The Pacific warm pool north of Australia shows almost no correlation, and the Indian and Pacific show weak positive correlations.

4.4.3.4: AT7 and the Indian Ocean Dipole

AT7 has some differentiation between the oceans and the IOD. The Atlantic Ocean is the only area in the Southern Hemisphere that has annual negative correlation with the IOD index. The rest of the hemisphere experiences weak positive correlations, or no correlation at all.

Figures 4.18 and 4.19 show the least amount of change to the spread of the temperature gradients, in fact, they look exactly the same in shape. This shows that a strong IOD has no impact on the strength of the temperature gradient.

Figure 4.18: Histogram showing the annual spread of temperature gradients (x axis) and the frequency (y axis). The top histogram represents the top 20 percentile of IOD, representative of the negative Indian Ocean Dipole. The second histogram is the top 80 percentile of IOD recordings, representative of positive Indian Ocean Dipole. Both show the temperature gradients during those years. The bottom shows the complete list of temperature gradients for the recorded time. This figure is designed to see if either positive or negative represent the largest or smallest temperature gradients.

Figure 4.19: Histogram showing the left) summer right) winter spread of temperature gradients (x axis) and the frequency (y axis). The top histogram represents the top 20 percentile of IOD, representative of the negative Indian Ocean Dipole. The second histogram is the top 80 percentile of IOD recordings, representative of positive Indian Ocean Dipole. Both show the temperature gradients during those years. The bottom shows the complete list of temperature gradients for the recorded time. This figure is designed to see if either positive or negative represent the largest or smallest temperature gradients.

4.5 – Temperature field and the temperature gradient

In this section, the temperature gradient is correlated against the Southern Hemisphere temperatures. In areas of high correlation, higher temperatures of that area will cause a

steepening of the temperature gradient. Negative correlations mean that an increase in the temperature causes a reduction in the temperature gradient.

This was produced to show the relationship between the temperature field and the temperature gradient. In this study, how the different ocean basins behave and which areas have the largest impact on the regions temperature gradient, and if a large area of impact, which oceans are connected and correlate with the other.

4.5.1 –Southern Hemisphere temperature gradient and atmospheric temperatures

Annual hemispheric correlation between the temperature gradient and the temperature field

Figure 4.20: Field correlation of the temperatures of each grid point and the temperature gradient averaged annually over the Southern Hemisphere. The black line represents a zero correlation; each blue line represents negative correlation; Red represents positive correlation. Each line is at an interval of 0.1 correlation. The four panels represent each of the levels of the atmosphere, 700hPa, 850hPa, 1000hPa, and SST.

The overall atmospheric temperature gradient of the hemisphere shows extensive regions of small positive correlation over lower latitudes, and larger and more significant negative correlations at higher latitudes (Fig. 4.20). At AT7, the highest positive correlation sits just over New Zealand, with a correlation of 0.3; at AT8, it drops to 0.2 and is located west of Australia. The highest negative correlation sits south of New Zealand and Australia, which is the same for the AT8. The positive correlations at AT1 are extremely weak and unevenly distributed. Unlike

in the higher levels of the atmosphere, the banded structure does not show clearly. The higher levels of the atmosphere are in the free atmosphere, which means that they are not significantly impacted by the surface exchanges. This would explain why the higher levels show the banded pattern, rather than the uneven distribution of AT1. AT1 pattern is due to the changes in the surface, specifically continental warming. AT1 is also influenced by the interactions between the atmosphere and the ocean surface. Despite the variations, the mid- to high- latitudes show the negative relationship and the low latitudes show the positive relationship. The Pacific temperatures show the smallest correlation with the hemispheric temperature gradient.

There are strong negative correlations that are present in the same location as AT7 and AT8, to approximately the same strength. The results are consistent with the textbook idea. A steeper gradient is the result of an increase in temperature in the tropics and decrease in temperature in the polar area. The Indian Ocean typically exhibits the strongest westerly winds, and the gradient is the largest contributor to the strength of those winds. The largest correlation between the gradient and the temperature field would be in the Indian Ocean. The largest correlation is seen to the south-west of the Australian continent, which is explained by the westward movement of the systems due to the prevailing westerly winds and Coriolis force.

This pattern is expected as the temperature gradient is calculated from the temperatures present at 30°S and 65°S. The purpose of comparing the entire hemisphere, is to calculate the areas with the largest correlation to the temperature gradient, as this would represent the area that has a greatest impact on the hemispheric gradient. The hemispheric correlations are quite weak in comparison to those shown in the individual ocean basins, which are shown later in the chapter.

4.5.2- Pacific Ocean temperature gradient and atmospheric temperatures

Annual hemispheric correlation between the Pacific temperature gradient and the temperature field

Figure 4.21: Field correlation of the temperatures of each grid point and the temperature gradient averaged over the Pacific Ocean basin. The black line represents a zero correlation; each blue line represents negative correlation; Red represents positive correlation. Each line is at an interval of 0.1 correlation. The four panels represent each of the levels of the atmosphere, 700hPa, 850hPa, 1000hPa, and SST.

The correlations seen when Pacific Ocean gradient when compared to hemispheric temperature show strong negative relationships in the high latitudes, and positive correlations around 30°S, with negative correlations over the tropical Pacific (Fig. 21). The Pacific shows the one of the highest correlation in the high latitudes at the atmospheric height of AT7, with a negative correlation of 0.9. There is a suggestion of a wave-like structure over the south Pacific, with a positive centre near New Zealand, a strong negative over the central south Pacific, and positive values over the south Atlantic. This is analogous to patterns seen in the height field in associated with ENSO (Renwick, 2002). The positive correlations are weaker than the negative. There is very little correlation at all when comparing the Pacific gradient to the temperatures in the Indian Ocean at all levels focused on in this thesis. While in the Atlantic, the correlation patterns extend into the region, moving poleward.

4.5.3 – Indian Ocean gradient and atmospheric temperature

Annual hemispheric correlation between the Indian temperature gradient and the temperature field

Figure 4.22: Field correlation of the temperatures of each grid point and the temperature gradient averaged over the Indian Ocean basin. The black line represents a zero correlation; each blue line represents negative correlation; Red represents positive correlation. Each line is at an interval of 0.1 correlation. The four panels represent each of the levels of the atmosphere, 700hPa, 850hPa, 1000hPa, and SST.

The Indian Ocean shows an interesting pattern. Unlike previous results, the correlations are mainly over the Indian Ocean, with minimal correlations, both negative and positive, seen in the Pacific or Atlantic Ocean basins (Fig. 4.22). As seen in previous examples, the negative correlations are stronger than the positive correlations, with the strong correlations found off the coast of Antarctica directly poleward of the Indian basin. The strongest positive correlations are found off the west coast of Australia.

4.5.4- Atlantic Ocean gradient and the atmospheric temperatures.

Annual hemispheric correlation between the Atlantic temperature gradient and the temperature field

Figure 4.23: Field correlation of the temperatures of each grid point and the temperature gradient averaged over the Atlantic Ocean basin. The black line represents a zero correlation; each blue line represents negative correlation; Red represents positive correlation. Each line is at an interval of 0.1 correlation. The four panels represent each of the levels of the atmosphere, 700hPa, 850hPa, 1000hPa, and SST.

The Atlantic Ocean shows one of the more interesting set of correlation patterns. It shows the expected pattern of high positive correlations around 30°S and the high negative correlations in the high latitudes (Fig. 4.23). It also shows that there are strong correlation within the Pacific as well, with strong positive correlations in the eastern Pacific, and negative correlations in the western Pacific. This shows the distinct pattern of three positive correlations and 3 negative correlation circling the high latitudes of the southern ocean, similar to zonal wave 3. However, the correlations over the Indian Ocean are weak.

4.5.5 – East Pacific gradient and the hemisphere temperatures

Annual hemispheric correlation between the East Pacific temperature gradient and the temperature field

Figure 4.24: Field correlation of the temperatures of each grid point and the temperature gradient averaged over the East Pacific Ocean basin. The black line represents a zero correlation; each blue line represents negative correlation; Red represents positive correlation. Each line is at an interval of 0.1 correlation. The four panels represent each of the levels of the atmosphere, 700hPa, 850hPa, 1000hPa, and SST.

In the Eastern Pacific Ocean, the pattern looks similar to that of the overall basin, with the greater correlations farther east (Fig. 4.24). Large positive correlations are found in the East Pacific around 30°S and large negative correlations in the high latitudes of the east Pacific basin. There is movement of correlations into the Atlantic Ocean, with positive correlations occurring in the high latitudes of the Atlantic. Minimal correlations occur over the Indian Ocean basin, due to the Pacific wave train (Renwick, 2002).

4.5.6 – West Pacific basin gradient and the hemispheric temperatures

Annual hemispheric correlation between the West Pacific temperature gradient and the temperature field

Figure 4.25: Field correlation of the temperatures of each grid point and the temperature gradient averaged over the West Pacific Ocean basin. The black line represents a zero correlation; each blue line represents negative correlation; Red represents positive correlation. Each line is at an interval of 0.1 correlation. The four panels represent each of the levels of the atmosphere, 700hPa, 850hPa, 1000hPa, and SST.

The typical pattern of positive correlations around 30°S, and negative correlations in the high latitudes, can easily be seen in figure 4.25. The negative correlations are stronger than the positive correlations. Unlike the East Pacific, there is no clear relationship with another basin, even the East Pacific basin does not show a strong signal with the west. What we do see, weak at AT8 but stronger in the AT7, is a large line of negative correlations spreading from the tropics of the west Pacific, across South America and dropping to 30°S.

Each of the ocean basin temperatures show a strong relationship with the temperature gradient within the basin. Despite the temperatures being banded in the Southern Hemisphere, the individual behaviour of each ocean further substantiates the decision to separate the hemisphere into sections.

4.6 – Zonal winds and the temperature gradient

In this section, the anomalies of temperature gradient between 30°S and 65°S have been correlated against the anomalies of the zonal winds. It was expected that we would see a large area of positive correlations in the 50-60 south latitude area as an increase in the temperature gradient would then result in strengthened westerlies further south. The strongest winds are situated in the southern Indian Ocean. In areas of negative correlation, the steeper the temperature gradient result in a weakening of the zonal winds. Strong correlations means that the strength of the winds is strongly connected to the temperature gradient and the temperature field.

4.6.1- Hemispheric influence

Annual hemispheric correlation between the temperature gradient and the 300hPa wind field

Figure 4.26: Field correlation of the zonal winds at each grid point and the temperature gradient averaged over the Southern Hemisphere. The black line represents a zero correlation; each blue line represents negative correlation; Red represents positive correlation. Each line is at an interval of 0.1 correlation. The four panels represent each of the levels of the atmosphere, 700hPa, 850hPa, 1000hPa, and SST.

The temperature gradient of the hemisphere when correlated to the zonal winds for the entire hemisphere shows a definite positive relationship in the lower mid-latitudes. A positive correlation means that the steeper the temperature gradient will also exhibit stronger winds in

these areas (Fig. 4.26). The negative correlations mean a steepening of the temperature gradient will have a resulting weakening of the westerly zonal winds. The strongest correlation is at AT7 just south of New Zealand, with just over 0.5. The overall correlation of the gradient in the upper atmosphere is significantly stronger than at AT1. The pattern of the positive correlations matches with the position of the mid-latitude westerly jet. That strength of the relationship reduces in the lower atmosphere. The negative correlations are over the Antarctica and the tropics and subtropics.

Annual hemispheric regression between the temperature gradient and the 300hPa wind field

Figure 4.27: Maps showing the regression (m/s) between the 300hPa zonal wind field and the temperature gradient on a hemispheric level. The black line represents zero; each blue line represents negative values; Red represents positive correlation. The contour interval is 1m/s. The four panels represent each of the levels of the atmosphere, 700hPa, 850hPa, 1000hPa, and SST.

Regression analysis was completed on the relationship between the temperature gradient of the Southern Hemisphere and the zonal wind field at 300hPa. In figure 4.20, the regression can be seen to follow a similar spatial pattern to that seen in the correlation figure (Fig. 4.27). If the temperature gradient went up by one unit, in this case degrees Celsius, then the winds in the mid-latitudes would experience an increase, some over 2m/, the units of wind. In the high latitudes, there would be a decrease in the winds, specifically over the west of Australia, of the same magnitude.

4.6.2-Pacific Ocean temperature gradient and the zonal winds

Annual hemispheric correlation between the Pacific temperature gradient and the 300hPa wind field

Figure 4.28: Field correlation of the zonal winds at each grid point and the temperature gradient averaged over the Pacific Ocean Basin. The black line represents a zero correlation; each blue line represents negative correlation; Red represents positive correlation. Each line is at an interval of 0.1 correlation. The four panels represent each of the levels of the atmosphere, 700hPa, 850hPa, 1000hPa, and SST.

Breaking up the correlations into that of the basins previously selected, the correlations are substantially increased. Once again, as previously discussed in 4.4.1, the strongest correlations are in the higher levels of the atmosphere, AT7 and AT8, with upwards of $r=0.7$ correlation (Fig. 4.28). Once again, the strongest correlations are coinciding at the location of the mid-latitude storm track. As expected, the Pacific temperature gradient is closely correlated to the behaviour of the winds in the Pacific region. It is expected a shift in the local temperature gradient would result in a local response. This is seen on all there layers of the atmosphere. The minimal to no correlation seen in the Indian Ocean basin. This is in contrast with the correlations seen in the Atlantic Ocean, which seem to continue the correlations through what looks to be the wave train pattern.

4.6.3- Indian Ocean temperature gradient and the zonal winds

Annual hemispheric correlation between the Indian temperature gradient and the 300hPa wind field

Figure 4.29: Field correlation of the zonal winds at each grid point and the temperature gradient averaged over the Indian Ocean Basin. The black line represents a zero correlation; each blue line represents negative correlation; Red represents positive correlation. Each line is at an interval of 0.1 correlation. The four panels represent each of the levels of the atmosphere, 700hPa, 850hPa, 1000hPa, and SST.

The opposite pattern seems to occur in the Indian Ocean when compared to the results from the Pacific Ocean basin; the strongest correlations can be found Indian Ocean basin, specifically to the east of the basin; over Western Australia for the strongest negative correlation can be found, the south of the Australian continent has the strongest positive anomalies (Fig. 4.29). Over the Pacific Ocean, there is little to no correlation at all. Unlike the Pacific pattern, the correlations in the surface (AT1) are quite strong and have a similar pattern to the upper atmosphere.

4.6.4 – Atlantic Ocean temperature gradient and the zonal winds

Annual hemispheric correlation between the Atlantic temperature gradient and the 300hPa wind field

Figure 4.30: Field correlation of the zonal winds at each grid point and the temperature gradient averaged over the Atlantic Ocean Basin. The black line represents a zero correlation; each blue line represents negative correlation; Red represents positive correlation. Each line is at an interval of 0.1 correlation. The four panels represent each of the levels of the atmosphere, 700hPa, 850hPa, 1000hPa, and SST.

The correlations between the Atlantic Ocean and the zonal winds are, as expected, the strongest in the Atlantic Ocean. The strongest correlations coinciding with the mid-latitude storm track. The Indian Ocean displays little to no correlation with the gradient from the Atlantic, but, the Pacific Ocean displays weak correlations patterns (Fig. 4.30). This mirrors the earlier mentioned pattern of the Atlantic Ocean experiencing strong correlation patterns with the Pacific gradient (4.4.3)

4.6.5 – East Pacific Ocean temperature gradient and the zonal wind

Annual hemispheric correlation between the East Pacific temperature gradient and the 300hPa wind field

Figure 4.31: Field correlation of the zonal winds at each grid point and the temperature gradient averaged over the East Pacific Ocean Basin. The black line represents a zero correlation; each blue line represents negative correlation; Red represents positive correlation. Each line is at an interval of 0.1 correlation. The four panels represent each of the levels of the atmosphere, 700hPa, 850hPa, 1000hPa, and SST.

The East Pacific follows a similar pattern in correlations as the overall Pacific Ocean Basin pattern, with similar levels of correlation, just more to the west than the overall. Once again we see the strong positive correlations in the mid-latitudes, surrounded by the strong negative correlations in the tropical eastern Pacific and in the high latitudes of the Pacific (Fig. 4.31). The eastern Pacific gradient also shows a strong positive correlations over the east coast of South America. Once again, the impact of the Pacific is not shown as significant in the Indian Ocean basin in the higher atmosphere levels. However, at AT1, there is a stronger relationship than previously shown in the other variables.

4.6.6 – West Pacific Ocean temperature gradient and the zonal winds

Annual hemispheric correlation between the West Pacific temperature gradient and the 300hPa wind field

Figure 4.32: Field correlation of the zonal winds at each grid point and the temperature gradient averaged over the West Pacific Ocean Basin. The black line represents a zero correlation; each blue line represents negative correlation; Red represents positive correlation. Each line is at an interval of 0.1 correlation. The four panels represent each of the levels of the atmosphere, 700hPa, 850hPa, 1000hPa, and SST.

The west Pacific shows the same pattern as previous correlations between the zonal winds and the temperature gradient, with stronger correlations, both positive and negative in the western Pacific basin (Fig. 4.32). What is also evident is that the correlations cross into the Atlantic basin, but are weak if not non-existent in the Indian Ocean. The strongest correlation is to the positive correlation to the south of New Zealand, with $r=0.73$ at AT7. At AT8 the correlations are similar to those at AT7, with a correlation of $r=0.72$ in the same areas as stated above. AT1 show a weakened pattern of the high atmosphere in the Pacific, but in the Indian Ocean, there is an increase in the correlation strengths.

Overview:

The zonal winds of the Southern Hemisphere and the temperature gradients are well correlated and show that the strength of the zonal winds is dictated mainly by the region of study, as expected from the thermal wind relationship. The Atlantic and Pacific show some connectivity in regards to the zonal winds and temperature gradient. Once again the Indian Ocean acts

independently, with the strong correlations in the Indian Ocean basin and minimal in the other basins.

These results help to visualise how the theory of thermal wind balance is actually expressed in the real atmosphere.

4.7 Storm Track Variability

The strength of the storm track varies strongly in space and in time (Hartmann, 2015). The mid-latitude storm track is an area of increased circulation variability on daily-weekly timescales, associated with large scale changes in geopotential height and pressures. In the different ocean basins, there is a distinctive reaction to the basin of interest. For example, the storm tracks position in the Pacific Ocean has not been influenced by the behaviour of the Indian Ocean.

The mid-latitude storm tracks position varies spatially. Throughout the year, the storm track consistently is poleward between the South America and Australia, or more precisely, where there is more of an interaction with East Antarctica (Fig. 4.33). This is because the temperature gradient is steeper in these areas due to the extending land mass of Antarctica, as explained in 4.3. Over the Pacific Ocean there is an equatorward response to the reduction of Antarctic landmass, as the gradient is not as steep, and the thermal winds and geostrophic balance occurs at lower latitudes than in the Indian Ocean.

However, the position of the storm track does not stay the same throughout the year. In fact, it contracts and extends from its position quite regularly. Below New Zealand for example, the storm track shift by 10 degrees latitude, and can sometimes cross the southern South Island in extreme circumstances.

Figure 4.33: Maps showing the mean position of the storm track at different times of the year. Note the more poleward position between South America and Australia. The storm track is just a way of showing the area of highest energy with storms between 2-8 days variability.

4.7.1: Hemispheric temperature gradient and the storm track

Annual hemispheric correlation between temperature gradient and the storm track field

Figure 4.34: Field correlation of the storm track field at each grid point and the temperature gradient averaged over the Southern Hemisphere. The black line represents a zero correlation; each blue line represents negative correlation; Red represents positive correlation. Each line is at an interval of 0.1 correlation. The four panels represent each of the levels of the atmosphere, 700hPa, 850hPa, 1000hPa, and SST.

Figure 4.34 shows the expected return for the correlation of the average temperature gradient for the hemisphere and the storm track. The mid-latitude storm track is the strongest to the south west of the Australian continent. This is consistent with the more powerful storm track activity positions. There is strong negative relationships between the latitudinal limits, as the temperature gradient according to the theory is part of what justifies the position of the storm track. As the temperature gradient steepens, there will be a poleward shift of the storm track, and therefore reduced storm activity in the extratropical regions. Around the latitudinal limits, so 30°S and equatorward are weak positive correlations, and around 50°S to 65°S is a small area of positive correlations. This is where the storm track typically sits, as shown in figure 4.33. This pattern is similar throughout the levels of the atmosphere and the SST. The regression shows that an increase of 1 degree in the temperature gradient will result in an increase of variability in the positive areas (Fig. 4.35).

Annual hemispheric regression between temperature gradient and the storm track field

Figure 4.35: Field regression of the storm track field at each grid point and the temperature gradient averaged over the Southern Hemisphere. The black line represents a zero regression; each blue line represents negative regression; Red represents positive regression. Each line is at an interval of 1 unit (m/s). The four panels represent each of the levels of the atmosphere, 700hPa, 850hPa, 1000hPa, and SST.

4.7.2: Pacific temperature gradient and the storm track

Annual hemispheric correlation between Pacific Ocean Basin temperature gradient and the storm track field

Figure 4.36: Field correlation of the storm track field at each grid point and the Pacific Ocean basin temperature gradient averaged over the Southern Hemisphere. The black line represents a zero correlation; each blue line represents negative correlation; Red represents positive correlation. Each line is at an interval of 0.1 correlation. The four panels represent each of the levels of the atmosphere, 700hPa, 850hPa, 1000hPa, and SST.

The Pacific Ocean basin temperature gradient shows stronger correlations towards the Pacific Ocean (Fig 4.36). This is because, as previously stated, the temperature gradient has a regional impact. Similar patterns are shown as the hemispheric in terms of correlations, however, the regression shows there would be little to no change in the variability of wind speeds in the tropics (Fig.4.37).

Annual hemispheric regression between Pacific Ocean Basin temperature gradient and the storm track field

Figure 4.37: Field regression of the storm track field at each grid point and the Pacific Ocean basin temperature gradient averaged over the Southern Hemisphere. The black line represents a zero regression; each blue line represents negative regression; Red represents positive regression. Each line is at an interval of 1 unit (m/s). The four panels represent each of the levels of the atmosphere, 700hPa, 850hPa, 1000hPa, and SST.

4.7.3: Indian temperature gradient and the storm track

Annual hemispheric correlation between Indian Ocean Basin temperature gradient and the storm track field

Figure 4.38: Field correlation of the storm track field at each grid point and the Indian Ocean basin temperature gradient averaged over the Southern Hemisphere. The black line represents a zero correlation; each blue line represents negative correlation; Red represents positive correlation. Each line is at an interval of 0.1 correlation. The four panels represent each of the levels of the atmosphere, 700hPa, 850hPa, 1000hPa, and SST.

The correlations in the Indian Ocean, the strength of both the correlations and the regressions are less than those experienced by the hemisphere as a whole. The Indian Ocean, as previously discussed, acts very independently. It does however show a strong positive correlation to the south west of the Australian continent, where the largest variability in wind speed occurs in the storm track (Fig. 4.38). The regression shows a similar pattern (Fig. 4.39).

Annual hemispheric regression between Indian Ocean Basin temperature gradient and the storm track field

Figure 4.39: Field regression of the storm track field at each grid point and the Indian Ocean basin temperature gradient averaged over the Southern Hemisphere. The black line represents a zero regression; each blue line represents negative regression; Red represents positive regression. Each line is at an interval of 1 unit (m/s). The four panels represent each of the levels of the atmosphere, 700hPa, 850hPa, 1000hPa, and SST.

4.7.4: Atlantic temperature gradient and the storm track

Annual hemispheric correlation between Atlantic Ocean Basin temperature gradient and the storm track field

Figure 4.40: Field correlation of the storm track field at each grid point and the Atlantic Ocean basin temperature gradient averaged over the Southern Hemisphere. The black line represents a zero correlation; each blue line represents negative correlation; Red represents positive correlation. Each line is at an interval of 0.1 correlation. The four panels represent each of the levels of the atmosphere, 700hPa, 850hPa, 1000hPa, and SST.

The Atlantic also shows reduced negative correlation in the extratropical latitudes. The presence of the correlation between the south Pacific and the Atlantic pattern associated with the Pacific wave train. Which strongest correlations both negative and positive to the west of the basin, near the Argentinian coast (Fig. 4.40). Regression shows that the area of change is in the mid to high latitudes (Fig. 4.41), with no change in the tropics.

Annual hemispheric regression between Atlantic Ocean Basin temperature gradient and the storm track field

Figure 4.41: Field regression of the storm track field at each grid point and the Atlantic Ocean basin temperature gradient averaged over the Southern Hemisphere. The black line represents a zero regression; each blue line represents negative regression; Red represents positive regression. Each line is at an interval of 1 unit (m/s). The four panels represent each of the levels of the atmosphere, 700hPa, 850hPa, 1000hPa, and SST.

4.7.5: East Pacific temperature gradient and the storm track

Annual hemispheric correlation between East Pacific Ocean Basin temperature gradient and the storm track field

Figure 4.42: Field correlation of the storm track field at each grid point and the East Pacific Ocean basin temperature gradient averaged over the Southern Hemisphere. The black line represents a zero correlation; each blue line represents negative correlation; Red represents positive correlation. Each line is at an interval of 0.1 correlation. The four panels represent each of the levels of the atmosphere, 700hPa, 850hPa, 1000hPa, and SST.

The East Pacific basin once again doesn't show the same strength of correlation or regression as the Pacific as a whole (Fig. 4.36, 4.37, 4.42, 4.43), but it is stronger than the Indian or the Atlantic. The strongest correlation is found in the south of the East Pacific Basin.

Annual hemispheric regression between East Pacific Ocean Basin temperature gradient and the storm track field

4.7.6: West Pacific temperature gradient and the storm track

Annual hemispheric correlation between West Pacific Ocean Basin temperature gradient and the storm track field

Figure 4.44 Field correlation of the storm track field at each grid point and the West Pacific Ocean basin temperature gradient averaged over the Southern Hemisphere. The black line represents a zero correlation; each blue line represents negative correlation; Red represents positive correlation. Each line is at an interval of 0.1 correlation. The four panels represent each of the levels of the atmosphere, 700hPa, 850hPa, 1000hPa, and SST.

When compared to some of the other ocean basins, the West Pacific shows stronger negative and positive correlations (Fig. 4.44). Once again the strongest regression and correlations are in the south West Pacific Ocean basin. The Pacific Ocean when taken into a whole represents stronger correlations than when they are separated into the two basins. The regression shows that changes in the tropics would not be due to the temperature gradient (Fig. 4.45).

Annual hemispheric regression between West Pacific Ocean Basin temperature gradient and the storm track field

Figure 4.45: Field regression of the storm track field at each grid point and the West Pacific Ocean basin temperature gradient averaged over the Southern Hemisphere. The black line represents a zero regression; each blue line represents negative regression; Red represents positive regression. Each line is at an interval of 1 unit (m/s). The four panels represent each of the levels of the atmosphere, 700hPa, 850hPa, 1000hPa, and SST.

4.8: Precipitation of New Zealand and the storm track

Precipitation anomalies averaged over New Zealand have a very weak correlation with the position of the storm track. However, particular locations show coherent patterns of correlation with storm track location. To see how the correlations vary spatially and temporally, correlations are displayed in a matrix. In these matrices, the x axis is the longitude, and the y axis is the months of the year. Each square is a representation of the correlation coefficient between the precipitation experienced at the selected location, and the latitude of the storm track at the given longitude in a specific month. A strong positive (negative) correlation means that the closer position of the storm track is in relation to New Zealand will result in an increase (decrease) in precipitation in that area, represented by the brighter (darker) yellow (blue) colours.

4.8.1: Russell

Figure 4.46: Correlation matrix showing the correlation between the precipitation recorded throughout the year, and the latitude in which the storm track sits at longitudes around New Zealand. Climate station situated -35.265°S 174.121°E . The Red represent positive weak correlations and the blue represents weak negative correlations. As no correlation was over/under ± 0.5 , the relationship was considered weak. Correlations of less than ± 0.1 were removed to show the larger correlations.

Russell is located at the top of the New Zealand's North Island. Out of the locations sampled it is the furthest distance from the Southern Hemisphere storm track. The strongest correlation, $r=0.4019$, can be found in May (Fig. 4.26), at -174°W . The strongest negative correlation can be seen in September, to the east, specifically 147°E to 159°E . The matrix allows us to visually see that the strongest correlations occur from autumn until mid-winter, with positive anomalies to the east of Russell, and the negative correlation to the west of Russell (Fig. 4.46).

4.8.2: Gisborne

Figure 4.47: Correlation matrix showing the correlation between the precipitation recorded throughout the year, and the latitude in which the storm track sits at longitudes around New Zealand. Climate station situated -38.475°S 178.242°E. The Red represent positive weak correlations and the blue represents weak negative correlations. As no correlation was over/under ± 0.5 , the relationship was considered weak. Correlations of less than ± 0.1 were removed to show the larger correlations

Gisborne is the location furthest to the east out of the selected locations for these correlations. It is located on the east coast of the North Island. The strongest positive correlation can be found in March, at -165°W (Fig.4.27), with a correlation of $r=0.565$, and strongest negative correlation in November, at -174°W, with a correlation of $r=0.37$. The strongest positive and negative correlations are in March and April respectively (Fig. 4.47). The longitudes east of Gisborne have larger correlations than those to the west of the location.

4.8.3: Longbush, Wairarapa

Figure 4.48: Correlation matrix showing the correlation between the precipitation recorded throughout the year, and the latitude in which the storm track sits at longitudes around New Zealand. The climate station situated -41.201°S 175.607°E . The Red represent positive weak correlations and the blue represents weak negative correlations. As no correlation was over/under ± 0.5 , the relationship was considered weak. Correlations of less than ± 0.1 were removed to show the larger correlations

Longbush, Wairarapa is the southernmost site in the North Island selected for this study. It has the overall weakest correlations calculated from any of the sites. However, there are slight patterns that emerge. Specifically, January an increasing strength of positive correlations to the longitudes to the east, whereas, in August, there is an increase in the strength of negative correlations (Fig. 4.48). The strongest correlation being a negative one of $r=-0.4253$, in August, with a longitude of 177°E (Fig. 4.28).

4.8.4: Hokitika

Figure 4.49: Correlation matrix showing the correlation between the precipitation recorded throughout the year, and the latitude in which the storm track sits at longitudes around New Zealand. Climate station situated -42.71S 170.98E. The Red represent positive weak correlations and the blue represents weak negative correlations. As no correlation was over/under ± 0.5 , the relationship was considered weak. Correlations of less than ± 0.1 were removed to show the larger correlations

Hokitika is the northern-most site in the South Island of New Zealand, and is directly influenced by the westerly winds. This site shows a band of stronger positive correlation in the months of June and July, and a band of stronger negative correlations in February and March (Fig. 4.49). Hokitika does not show a large correlation with any longitude. The strongest positive correlation is in July with a correlation of $r=0.3988$, and the strongest negative correlation is in March, at 174°E , of $r=-0.3815$.

4.8.5: Christchurch

Figure 4.50: Correlation matrix showing the correlation between the precipitation recorded throughout the year, and the latitude in which the storm track sits at longitudes around New Zealand. Climate station situated -43.53S 172.6E. The Red represent positive weak correlations and the blue represents weak negative correlations. As no correlation was over/under ± 0.5 , the relationship was considered weak. Correlations of less than ± 0.1 were removed to show the larger correlations

Christchurch is only site on the east coast of the South Island of New Zealand. It is more to the west than any of the North Island sites. The positive correlations are more prominent in the first half of the year, and the negative correlations, in the late half of the year (Fig. 4.50). The strongest positive correlation is in March, at 147°E, with a correlation of $r=0.525$, and the strongest negative correlation occurs in December, at 168°E, with a correlation of $r=-0.4469$. The correlations to the west of the site are overall stronger than those on the east side of the site.

4.8.6: Milford Sounds

Figure 4.51: Correlation matrix showing the correlation between the Precipitation recorded throughout the year, and the latitude in which the Storm track sits at longitudes around New Zealand. Climate station situated -43.53S 172.6E. The red represent positive weak correlations and the blue represents weak negative correlations. As no correlation was over/under ± 0.5 , the relationship was considered weak, Correlations of less than ± 0.1 were removed to show the larger correlations

The Milford Sound site is the site furthest to the east out of all the sites. The matrix clearly displays that the latitude of the storm track within the longitudes have a positive correlation with the precipitation measured in the Milford Sound, but the correlations are not to the same magnitude as other sites calculated (Fig. 4.51). To the east of the site, there is a reduction in correlations. The strongest positive correlation occurs in January, at a longitude of 165°E, with a correlation of $r=0.334$, and the strongest negative correlation in March, to the east at -168°W, with a correlation of $r=-0.3714$

4.8.7: Invercargill

Figure 4.52: Correlation matrix showing the correlation between the Precipitation recorded throughout the year, and the latitude in which the Storm track sits at longitudes around New Zealand. Climate station situated -46.417°S 168.33°E . The red represent positive weak correlations and the blue represents weak negative correlations. As no correlation was over/under ± 0.5 , the relationship was considered weak. Correlations of less than ± 0.1 were removed to show the larger correlations

Invercargill is the most southern site selected for this study, making it the closest in proximity to the Southern Hemisphere mid-latitude storm track. The strongest correlations are calculated to be to the west of the site, and very little correlation to the east of the site (Fig. 4.52). Throughout the year, there are bands of correlations, which suggested that there is not an obvious seasonal cycle to the correlations. The largest positive correlation is June, at the longitude of 162°E , with a positive correlation of 0.44. The largest negative correlation is in May, at the longitude of 153°E .

4.8.8 Overview

The correlations between the precipitation and the storm track position are weak in most cases. As New Zealand is impacted by several different climatic processes due to its proximity to the mid-latitude westerlies, the tropics and the polar influences. Each location chosen has varying

forces that act on the amount of precipitation, orographic rainfall on the west coast and the tropical storms from the Tasman Sea in the north. Any variation, such as those seen in the spring and autumn months are weakly statistically significant.

The pattern that emerges when comparing them all together, is that the storm track has significantly more influence on the sites that are located closer to its proximity. Invercargill shows the greatest spread of correlations, and the strongest, but it is the closest locations. The Russell station showed minimal correlations and the weakest. Christchurch also shows minimal correlations because the rainfall on the west coast is typically due to orographic rainfall due to the predominantly westerly winds. Locations to the south and west are more likely to be influenced by the storm track than those to the north and east.

Generally speaking, when the storm track is further north, precipitation is increased. The storm track brings significant variation and energy into the area. The proximity of this area to the southern coast of New Zealand will dictate the variability of the rainfall: impacts of the storm track will be higher than if it is shifted poleward and vice versa. The area of impact isn't a significantly large area, but a gradual build up through the extratropical and mid latitudes which impact a larger area.

Chapter 5 : Discussion

5.1: Theory

The hypothesis behind the thesis is to test and evaluate the ‘text book’ theory about the temperature gradient’s impact on the atmospheric circulation of the Southern Hemisphere. If the temperature gradient were to steepen, then there would be a resulting change in the position and strength of the westerlies, and therefore where the mid-latitude storm track is located. As proven in the previous chapters, there are significant linear relationships between the temperature, temperature gradient, zonal winds, and the storm track, proving the text book theory accurate. However, the amount of variability in the Southern Hemisphere masks the relationship between the two, with other processes acting on the storm track such as climatic processes such as the SAM. The main signals for the correlation and regression are seen to the west of the ocean basin of focus, due to the movement of the energy to the west.

Increased temperatures in the tropics or decreased temperatures in the poles will result in a steepening of the temperature gradient. A steeper gradient will then create stronger pressure gradient force and therefore push the stronger zonal westerly winds further poleward than normal. This would result in a poleward shift of the storm track. Visual representation shows that temperature gradients are connected to the temperature as a source and that there is strong linear correlation between the temperature gradient and the zonal wind.

5.2: The theory in practice.

The strong relationship between the temperature field and the temperature gradients are expected, as the latitudinal picks dictate the area of highest correlation. In this research, the latitude is limited on the 30°S–65°S gradient. As previously shown in chapter 4.1 and appendix 1, the sensitivity of latitudinal limits dictate the annual pattern of the temperature gradient. Several latitudinal limits were tested, with the combination of 25°S, 30°S, and 35°S in the low latitudes and 60°S, 65°S, and 70°S for the high latitudes.

The polar and tropical seas experience different annual influences on their behaviour. The tropics are relatively stable in the temperatures through the year, as the amount of solar radiation does not vary significantly. 25°S showed a small variation due to its proximity to the stable tropical temperatures. 35°S showed significant seasonal variation that often eclipsed the patterns coming through from the high latitudes. 30°S allowed for the annual change to be recorded without the loss of pattern. The shift of the warm temperatures in the low latitudes does have an annual variation caused by the seasonal cycle.

In the high latitudes, the latitudinal limit had to incorporate the variation of the temperatures in the southern ocean, without recording the actual sea ice. 70°S was too poleward, and had issues in many places in the winter months with odd recordings due to the position of the ice, in both the SST and the AT1. This can be seen throughout the figures in chapter 4, where there is a lot of anomalous noise in the correlations, specifically due to the odd recordings around the Antarctic coast. 60°S showed a very different pattern from the one displayed in the higher latitudinal limits, with a weak annual pattern. The strongest pattern on the temperature gradient was the higher latitudes (Fig 4.1.3). As such, the weaker gradient pattern had to be dismissed for a latitude limit that included the Antarctic latitudes, such as 60°S to 65°S.

Despite the claim from several scholars that the pattern is visible between 50°S and 65°S (Gerald A Meehl, Hurrell, & Loon, 1998; Vanloon, 1967) , the gradient patterns demonstrate that this signal is predominantly in the 60°S–65°S latitudinal limit. The pattern is visible in the data analysis. Therefore with the latitudes that are included into this thesis, it will include the SAO pattern. That is not to say that the pattern is exclusively between 60°S and 65°S, but that the pattern is the strongest in those latitudes.

The difference between the latitude limit to constrain the gradient has a significant impact on the results. As the SAO was present significantly between 60°S and 65°S, and any gradient that included the latitudes 60°S to 65°S show the double-peak pattern of the SAO. If the previously discussed latitudes were to be removed, there would be the threat of omitting important evidence of the annual gradient pattern. As the 30°S to 65°S allowed for both the SAO and the mid-latitude variation to come through, it was deemed as the most appropriate choice for this research, after looking at different variations.

The storm track, being tied to the location of the strongest zonal winds should exhibit as a hemispheric response to the temperature gradient. The separation of the data into the ocean basins as established in Chapter 3.2, allowed for the correlation of the storm track position in relation to the temperature gradient in a specific basin. The results show that there is little to no interaction between the Indian Ocean and the Pacific Ocean. These independent basins mean that the temperatures experienced in the region has no impact on the system on the other side. This was confirmed by both correlation of the temperature field against the temperature gradient, and the correlation between the wind field and the temperature gradients. Neither correlation showed any relationship between the Pacific and the Indian Oceans.

The data must be looked at separately rather than hemispherically. The independence of ocean basins means there is a requirement for analysis of the atmosphere to be conducted in sectors.

Averaging data can undermine the patterns and the reactions of the system if the averaging cancels it all out. This is quite visible when there are comparisons between the strength of the correlations between the annual hemispheric relationship, and the stronger relationship between the ocean basins and temperatures, which can be almost doubled (Fig. 4.13 and 4.14). Such results are consistent with the arguments put forward in recent work on tropical-extratropical linkages in the Southern Hemisphere (Clem, Renwick, & McGregor, 2017; Q. Ding, Steig, Battisti, & Wallace, 2012).

As shown in the previous chapter, the correlation between the wind field and the temperature gradient is significant, more so when the relationship is studied at the ocean basin level. The temperature gradient is a direct consequence of the temperature field a rise in temperatures in the tropics or a cooling in the poles would result in a larger temperature gradient, higher wind speeds in the mid-latitudes and reduced wind speeds in the low latitudes. The position of the storm track is defined in this research as the area in which 2 to 8 day variability of the 300hPa height field maximises, which is where the zonal winds are also strongest. As discussed, the strength of the winds will increase if the temperature gradient is steepened.

The storm track would move poleward in the case of increased heating in the tropics or a decrease in temperatures in the poles. We have seen this in Chapter 4, when there is an increase of the temperature gradient there is a subsequent strengthening of the winds, resulting in more turbulent behaviour in the winds. This can be categorised as the storm track. Increase in the temperature gradient means that in this case, the area of highest wind speed and turbulence would shift poleward as the stronger pressure gradient force would be stronger and pull the air parcels quicker towards the pole.

The research and findings of this research were to test the theory of thermal wind balance, and examine how it is expressed in the Southern Hemisphere atmosphere. This thesis has achieved its goal of testing the theory with real world data. It shows the relationship between the temperature and the temperature gradients, as well as the zonal winds.

The climatic variables show a small influence on the temperature field, but the relationship is weak. The SOI has the largest influence on the temperature fields, but in most cases, only to a 5% level. The SAM and IOD show almost no correlation, proving that not all teleconnections are vital to others.

In practice, the results of the theory are true, with some interesting notes to make. The different basins operate largely independently. The wave train across the south Pacific and Atlantic goes

against this conclusion, suggesting that ENSO dynamics play a role in how the temperature gradient varies and how it affects the circulation.

The earth is a complicated system and no one process is going to account for a shift in the dynamics. An interconnected system will show a high correlation in some areas when looking at the Southern Hemisphere ocean by ocean.

5.3: Influence on New Zealand

New Zealand has its special characteristics, with the topography and its location in the westerly wind belt. All this means is that New Zealand is accustomed to inconsistent weather and often turbulent seasons. To explain the variation, the storm track position was calculated and then correlated with the time series of the precipitation in different parts of the country. The results show that any influence to the precipitation in New Zealand comes from the west, which makes sense as any energy would be pushed from the west due to the existence of the westerly winds. Although the linear correlations were small, it was an anticipated outcome. With the variations in the topography in New Zealand, orographic rainfall, ex tropical storms, and Antarctic blast all mean that different areas experience the significant variations of rainfall. For example, the West Coast region of New Zealand experiences the most rainfall in New Zealand due to the influence of orographic rainfall due to the Southern Alps, as well as bearing the brunt of the westerly winds, which brings moisture laden fronts. The North Island receives ex tropical storms that release large amounts of rainfall in specific areas, but not continuously throughout the year. To the East coast of the south island, the east coast receives foehn winds which are dry after dropping large amounts of precipitation on the west coast. It also receives the brunt of Antarctic blasts which are large cold frontal systems. Precipitation is already a variable factor of New Zealand, so even a small correlation is positive. The further south the climate station, the more influence it is by the mid-latitude storm track.

5.4: How is this helpful to future research?

Climate change is one of the biggest problems in human history. It has now become an undeniable fact that the earth is heating up at a rate that is not sustainable. Presently the oceans are taking up a majority of the energy from the increase, however, in many regions have already seen a 1°C increase in atmospheric temperatures. As this research is just a visual representation of the testing of a theory of physics, the principles can be applied to any changes experienced. Presently, the warming that is occurring is significantly in the tropical atmosphere and less so in the Polar Regions.

Higher temperatures in the Tropics, or the low latitudes, would mean an increase in height of the air column, and therefore the pressure plane. As the polar, or high latitudes, do not respond on the same time scale or magnitude, this would create a steepening of the temperature gradient, which is proportional against the pressure gradient. As explained, an increase in the temperature gradient will cause a poleward shift of the strongest westerly winds and, therefore, the areas of the most variability, the mid-latitude storm track, to also shift toward the pole.

Throughout this research, interconnectedness has been a key in reference to the overall physics of the atmosphere. Climate change will cause change to several sectors of the atmosphere and oceans, which has been well established through literature such as the IPCC reports (IPCC, 2013). Using that knowledge, the theory and the physics dictate that the temperature gradient will steepen, the westerlies will increase in energy and the storm track will shift poleward. This will decrease the variability of the southern rainfall of New Zealand attributed to the position of the storm track.

5.5: Future work

This thesis covers a lot of ground work, which can lead on to a number of future studies. For future research, it would be beneficial that climatic processes impact are researched in the separate oceanic basin. Chapter 4 shows that the Pacific Ocean and the Indian Ocean are independent from each other, in that the temperature gradient and storm track in one has little to no impact on the other. For any future work on similar lines to this research would need to include a part where the Pacific and Indian ocean basins are modelled externally from each other. This would allow for more accurate modelling in those specific regions.

For future work, one of the key aspects would be climate change, and the influence its resulting impacts would have on this research. Climate change will increase the temperatures in both the oceans and the atmosphere, and although the atmosphere was the main focus, a change in the sea surface would have other impacts. In the atmosphere, this would result in increased heights of air columns, and therefore the height of the pressure planes. This would directly result in the steepening of the pressure gradient and the strength of the winds, and position of the storm track. This study has not identified any trends in temperature gradients, but an analysis of temporal trends would be an interesting next step.

At the beginning of this research, there was a focus on the Antarctic sea ice and whether it had an influence on the temperature gradient. It was found that it didn't, almost no correlation at all. If there were more time, it would have been interesting to see if climate change and increasing temperatures of the sea surface would have meant warmer SST or cooler with more

melt water. If either were the case, the resulting changes in the atmosphere in the Polar Regions would influence the temperature gradient.

More literature on the subject would be useful to those wanting to further the investigation into the temperature gradient. When investigating the background for this research, there was very little to be found in reference to the behaviour of the temperature gradient, and the physics behind it. Most of the information that was found were in textbooks that were used to understand the theory altogether. Further investigation into the annual and seasonal behaviour would be of use, as well more information on latitudinal limits. In the case of the SAO, there was research into the gradient pattern, but as I explained in Chapter 4.1, the variation in the pattern caused by the SAO was actually a small latitude, between 60°S to 65° showed the majority of the pattern.

If there was more time, the difference between the different latitudinal limits and the temperature gradients would have been the next priority. Although explained in Chapter 4.1 as to why the latitude limits of 30° and 65° were selected were explained, further investigation as to the changes that the different limits would have been useful.

One of the main points that has frequently been highlighted has been the need for increased research in this field. Although physics dictates the theory to work, it is important that factors pertaining to the theory must be researched well for the sake of increased accuracy and understanding. To say in a theory that an increase temperature gradient will result in a poleward shift of the storm track due to the physics is fine, but it should be researched and represented as well.

Although this research focused on New Zealand for the impact of the storm track, there was little result. However, other countries in the mid-latitudes of the Southern Hemisphere must also be included into the research. For example, the countries of Argentina and Chile are both crossed by the mid-latitude storm track, and perhaps there is more of a correlation between the rainfalls in that area than those seen in New Zealand. A change in the position of the storm track in those regions may have a significant impact, although once again, the topography of those locations are just as variable and could count for significant changes in rainfall, more so than in New Zealand.

It would be interesting to apply the same analysis to output of climate models as used in the CMIP5 and other intercomparison experiments, to see if the models capture the same features seen in reanalysis, and to investigate future changes as the climate continues to warm.

5.6: Conclusion

The basic theory made was tested under the scientific hypothesis of this research. An increase in temperatures would result in a steepening of the temperature gradient, and the pressure gradient, which will cause a poleward shift of the storm track and strengthening of mid-latitude zonal winds. One part of the research that didn't show the results expected was the storm tracks influence on the rainfall of New Zealand, which showed minimal correlation in the northern locations, and statistically weak correlations in the absolute south locations. With the poleward shift of the storm track, this influence would decrease further.

In future research, the impact of climate change must become relevant into the theory, and the increase in the atmospheric temperatures to be taken into account. With the theory being shown as accurate, there can be no doubt that an increase in the temperatures in the tropics would result in stronger zonal winds. Although this research focused on New Zealand, other countries in the mid-latitudes would be able to use the findings.

The temperature gradient is expressed in the temperature field, with bigger correlations at high latitudes so that changes in the gradient are driven more by what happens near Antarctica than what happens in the subtropics. The gradient has high correlations with the zonal wind strengths as well as the storm tracks as shown in the correlation and regression maps.

The impact on the temperature gradient and storm track from the climatic factors, SAM, SOI and IOD, was minimal. The wave train pattern shows the influence of ENSO on the temperature system with the pattern emerging between the Pacific Ocean and the Atlantic Ocean basin. IOD and SAM shows almost no impact to the temperature gradient or storm track, with the correlation not meeting the significance level.

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Appendix

Appendix 1:

This appendix is to show the variations and sensitivity of the latitudinal limits selected and how the patterns change depending on the limits selected.

25°S–60°S

Annual hemispheric correlation between temperature gradient and the temperature field

Figure 0.1: Field correlation of the temperatures of 25°S–60°S, each grid point and the temperature gradient averaged over the Pacific Ocean basin. The black line represents a zero correlation; each blue line represents negative correlation; Red represents positive correlation. Each line is at an interval of 0.1 correlation. The three panels represent each of the levels of the atmosphere, 700hPa, 850hPa, and 1000hPa.

Annual hemispheric correlation between temperature gradient and the 500hPa wind field

Figure 0.2 Field correlation of the zonal winds at each grid point and the temperature gradient averaged over the Southern Hemisphere. The black line represents a zero correlation; each blue line represents negative correlation; Red represents positive correlation. Each line is at an interval of 0.1 correlation. The three panels represent each of the levels of the atmosphere, 700hPa, 850hPa, and 1000hPa.

25°S–65°S

Annual hemispheric correlation between temperature gradient and the temperature field

Figure 0.3: Field correlation of the temperatures of 25°S–65°S, each grid point and the temperature gradient averaged over the Pacific Ocean basin. The black line represents a zero correlation; each blue line represents negative correlation; Red represents positive correlation. Each line is at an interval of 0.1 correlation. The three panels represent each of the levels of the atmosphere, 700hPa, 850hPa, and 1000hPa.

Annual hemispheric correlation between temperature gradient and the 500hPa wind field

Figure 0.4: Field correlation of the zonal winds at each grid point and the temperature gradient averaged over the Southern Hemisphere. The black line represents a zero correlation; each blue line represents negative correlation; Red represents positive correlation. Each line is at an interval of 0.1 correlation. The three panels represent each of the levels of the atmosphere, 700hPa, 850hPa, and 1000hPa.

25°S–70°S

Annual hemispheric correlation between temperature gradient and the temperature field

Figure 0.5: Field correlation of the temperatures of 25°S–70°S, each grid point and the temperature gradient averaged over the Pacific Ocean basin. The black line represents a zero correlation; each blue line represents negative correlation; Red represents positive correlation. Each line is at an interval of 0.1 correlation. The three panels represent each of the levels of the atmosphere, 700hPa, 850hPa, and 1000hPa.

Annual hemispheric correlation between temperature gradient and the 500hPa wind field

Figure 0.6: Field correlation of the zonal winds at each grid point and the temperature gradient averaged over the Southern Hemisphere. The black line represents a zero correlation; each blue line represents negative correlation; Red represents positive correlation. Each line is at an interval of 0.1 correlation. The three panels represent each of the levels of the atmosphere, 700hPa, 850hPa, and 1000hPa.

30°S-60°S

Annual hemispheric correlation between temperature gradient and the temperature field

Figure 0.7: Field correlation of the temperatures of 30°S–60°S, each grid point and the temperature gradient averaged over the Pacific Ocean basin. The black line represents a zero correlation; each blue line represents negative correlation; Red represents positive correlation. Each line is at an interval of 0.1 correlation. The three panels represent each of the levels of the atmosphere, 700hPa, 850hPa, and 1000hPa.

Annual hemispheric correlation between temperature gradient and the 500hPa wind field

Figure 0.8: Field correlation of the zonal winds at each grid point and the temperature gradient averaged over the Southern Hemisphere. The black line represents a zero correlation; each blue line represents negative correlation; Red represents positive correlation. Each line is at an interval of 0.1 correlation. The three panels represent each of the levels of the atmosphere, 700hPa, 850hPa, and 1000hPa.

30°S-70°S

Annual hemispheric correlation between temperature gradient and the temperature field

Figure 0.9: Field correlation of the temperatures of 30°S–70°S, each grid point and the temperature gradient averaged over the Pacific Ocean basin. The black line represents a zero correlation; each blue line represents negative correlation; Red represents positive correlation. Each line is at an interval of 0.1 correlation. The three panels represent each of the levels of the atmosphere, 700hPa, 850hPa, and 1000hPa.

Annual hemispheric correlation between temperature gradient and the 500hPa wind field

Figure 0.10: Field correlation of the zonal winds at each grid point and the temperature gradient averaged over the Southern Hemisphere. The black line represents a zero correlation; each blue line represents negative correlation; Red represents positive correlation. Each line is at an interval of 0.1 correlation. The three panels represent each of the levels of the atmosphere, 700hPa, 850hPa, and 1000hPa.

Appendix 2:

This appendix has been created to show the variations of the seasons, that have been discussed in the results however, not included into the chapter.

Summer hemispheric correlation between the temperature gradient and the temperature field

Figure 0.11: Field correlation of the temperatures of each grid point and the temperature gradient averaged over the Hemisphere during the summer. The black line represents a zero correlation; each blue line represents negative correlation; Red represents positive correlation. Each line is at an interval of 0.1 correlation. The four panels represent each of the levels of the atmosphere, 700hPa, 850hPa, 1000hPa, and SST.

Summer hemispheric correlation between the Pacific temperature gradient and the temperature field

Figure 0.12: Field correlation of the temperatures of each grid point and the temperature gradient averaged over the Pacific Ocean basin during summer. The black line represents a zero correlation; each blue line represents negative correlation; Red represents positive correlation. Each line is at an interval of 0.1 correlation. The four panels represent each of the levels of the atmosphere, 700hPa, 850hPa, 1000hPa, and SST.

Summer hemispheric correlation between the Indian temperature gradient and the temperature field

Figure 0.13: Field correlation of the temperatures of each grid point and the temperature gradient averaged over the Indian Ocean basin during summer. The black line represents a zero correlation; each blue line represents negative correlation; Red represents positive correlation. Each line is at an interval of 0.1 correlation. The four panels represent each of the levels of the atmosphere, 700hPa, 850hPa, 1000hPa, and SST.

Summer hemispheric correlation between the Atlantic temperature gradient and the temperature field

Figure 0.14: Field correlation of the temperatures of each grid point and the temperature gradient averaged over the Atlantic Ocean basin during summer. The black line represents a zero correlation; each blue line represents negative correlation; Red represents positive correlation. Each line is at an interval of 0.1 correlation. The four panels represent each of the levels of the atmosphere, 700hPa, 850hPa, 1000hPa, and SST.

Summer hemispheric correlation between the East Pacific temperature gradient and the temperature field

Figure 0.15: Field correlation of the temperatures of each grid point and the temperature gradient averaged over the East Pacific Ocean basin during summer. The black line represents a zero correlation; each blue line represents negative correlation; Red represents positive correlation. Each line is at an interval of 0.1 correlation. The four panels represent each of the levels of the atmosphere, 700hPa, 850hPa, 1000hPa, and SST.

Summer hemispheric correlation between the West Pacific temperature gradient and the temperature field

Figure 0.16: Field correlation of the temperatures of each grid point and the temperature gradient averaged over the West Pacific Ocean basin during summer. The black line represents a zero correlation; each blue line represents negative correlation; Red represents positive correlation. Each line is at an interval of 0.1 correlation. The four panels represent each of the levels of the atmosphere, 700hPa, 850hPa, 1000hPa, and SST.

Winter hemispheric correlation between the temperature gradient and the temperature field

Figure 0.17: Field correlation of the temperatures of each grid point and the temperature gradient averaged over the hemisphere during winter. The black line represents a zero correlation; each blue line represents negative correlation; Red represents positive correlation. Each line is at an interval of 0.1 correlation. The four panels represent each of the levels of the atmosphere, 700hPa, 850hPa, 1000hPa, and SST.

Winter hemispheric correlation between the Pacific temperature gradient and the temperature field

Figure 0.18: Field correlation of the temperatures of each grid point and the temperature gradient averaged over the Pacific Ocean basin during winter. The black line represents a zero correlation; each blue line represents negative correlation; Red represents positive correlation. Each line is at an interval of 0.1 correlation. The four panels represent each of the levels of the atmosphere, 700hPa, 850hPa, 1000hPa, and SST.

Winter hemispheric correlation between the Indian temperature gradient and the temperature field

Figure 0.19: Field correlation of the temperatures of each grid point and the temperature gradient averaged over the Indian Ocean basin during winter. The black line represents a zero correlation; each blue line represents negative correlation; Red represents positive correlation. Each line is at an interval of 0.1 correlation. The four panels represent each of the levels of the atmosphere, 700hPa, 850hPa, 1000hPa, and SST.

Winter hemispheric correlation between the Atlantic temperature gradient and the temperature field

Figure 0.20: Field correlation of the temperatures of each grid point and the temperature gradient averaged over the Atlantic Ocean basin during winter. The black line represents a zero correlation; each blue line represents negative correlation; Red represents positive correlation. Each line is at an interval of 0.1 correlation. The four panels represent each of the levels of the atmosphere, 700hPa, 850hPa, 1000hPa, and SST.

Winter hemispheric correlation between the East Pacific temperature gradient and the temperature field

Figure 0.21: Field correlation of the temperatures of each grid point and the temperature gradient averaged over the East Pacific Ocean basin during winter. The black line represents a zero correlation; each blue line represents negative correlation; Red represents positive correlation. Each line is at an interval of 0.1 correlation. The four panels represent each of the levels of the atmosphere, 700hPa, 850hPa, 1000hPa, and SST.

Winter hemispheric correlation between the West Pacific temperature gradient and the temperature field

Figure 0.22: Field correlation of the temperatures of each grid point and the temperature gradient averaged over the West Pacific Ocean basin during winter. The black line represents a zero correlation; each blue line represents negative correlation; Red represents positive correlation. Each line is at an interval of 0.1 correlation. The four panels represent each of the levels of the atmosphere, 700hPa, 850hPa, 1000hPa, and SST.