Cyclones of Subtropical Origin in the Southwest Pacific A Climatology and Aspects of Movement and Development

by

Susanne Sandra Schröder

Cyclones of Subtropical Origin in the Southwest Pacific A Climatology and Aspects of Movement and Development

by
Susanne Sandra Schröder

Wellington 2009

A thesis
submitted to Victoria University of Wellington
in fulfilment of the requirements of the degree of
Doctor of Philosophy
in
Geophysics

Institute of Geophysics
School of Geography, Environment and Earth Sciences
Victoria University of Wellington
Wellington, New Zealand/Aotearoa

Für Opa

Abstract

A comprehensive study on cyclones of subtropical origin (STCs) in the Southwest Pacific is carried out. A brief history of the damage caused by STCs in New Zealand between 1990 and 2005 is given. It shows that approximately 2 to 3 times a year STCs come into the vicinity of New Zealand, mostly affecting the North Island and causing predominantly flood damage.

A climatology is compiled with a cyclone track database covering 21 years, providing an overview of the behaviour and characteristics of STCs in this region. Distinct annual and seasonal patterns in frequency, tracks and intensity are revealed. Some of these patterns resemble those of tropical cyclones, in particular those undergoing extratropical transition, while others resemble those of extratropical cyclones in this region. In addition, it is shown that there is a significant increase in the number of summer STCs, which coincides with an increase in sea surface temperatures in the area.

The structure and processes involved in the development of STCs are investigated in more detail using data from the United Kingdom Meteorological Office (UKMO) global model spanning 5 years (1999 to 2003). An analysis of the upper-level flow shows that STCs are steered into midlatitudes by upper-level baroclinic waves, in general through interaction with an upper-level trough.

Differences in the structure and development of STCs can be attributed to the fact that upper-level baroclinic waves are able to propagate far into the subtropics in this region. This is also the reason for the existence of three types of STCs, when differentiating by characteristics of their development process. Type 1 STCs are very similar to extratropical cyclones in structure and development. The structure and the development process of Type 3 STCs resemble more those of tropical cy-

clones. The initial development of Type 2 STCs is similar to that of Type 3, but they then undergo a transition, found to be very similar to that of tropical cyclones undergoing extratropical transition.

Interseasonal variations in the upper-level flow over the Southwest Pacific are reflected in the behaviour and characteristics of STCs and subsequently the occurrence of the three types of STCs. During the colder seasons baroclinic waves frequently propagate relatively far into the subtropics in this region. This means STCs not only have a high chance of being picked up by an upper-level trough and undergoing extratropical transition, they are also able to actually form in the vicinity of a trough. Thus, during that time most STCs tend to be either Type 1 or 2. On the other hand, during summer, when baroclinic waves only occasionally propagate into the subtropics, there is a higher frequency of Type 3 STCs.

In terms of weather-related threats to New Zealand, the interaction with an upper-level trough is the cause for STCs coming into the vicinity of New Zealand, while the high rain rates that accompany them, and that are the cause for the extensive, mostly flood-related, damage, are attributed to their place of origin.

Acknowledgment

I would like to thank everyone who contributed to my work and my time here at NIWA and Victoria University.

First of all, thanks to my supervisors Dr. M. Revell and Dr. J. McGregor for initiating the project, organising funding and guiding me in finding my story.

I am also very grateful to Dr. M. Sinclair for his much appreciated interest, as well as his help, in particular for letting me use his software, being available for questions and his quick replies.

Particular thanks also to Dr. J. Renwick, W. Gray, R. Turner and S. Dean for their valuable advice on various topics ranging from Matlab or other programming problems to more scientific questions.

Also many thanks to the IT team at NIWA. I was very impressed with their exceptionally prompt and helpful service.

I also have to thank K. Keay and Dr. I. Simmonds for providing a cyclone track database, even though it was not used for the investigations presented here.

On a personal level, Katja, Anne and Joy thank you so much for your moral support, especially during hard times. It is great to have such good friends. Also thanks to Dr. J. Hellyer for her proof reading expertise.

I also would like to thank my office mates Joe and Natalie for their Matlab advice and providing such a great working atmosphere during the last stage of my study.

Also, thanks to J. Kidston for providing one of the figures used here.

Thanks to 'Beany' for the graphical design of one the figures and as always his moral support. Thanks also goes to my parents for their support and understanding.

I also want to thank NIWA for sponsoring me, including the much appreciated extension, and Victoria University for the PhD completion scholarship.

Contents

1 Introduction

The subjects of investigation in this study are cyclones of subtropical origin (STCs[1]) in the Southwest Pacific. The aim is to provide a comprehensive study of STCs in this region, including a climatology and a detailed analysis of their movement and development. Of particular interest are those that come into the vicinity of New Zealand.

Storms in general are one of the most common severe weather events in New Zealand and in the past have caused considerable damage, as they are often accompanied by strong winds and/or heavy rain. One of the most memorable and devastating storm events in New Zealand history is the Wahine storm (Ex-Tropical Cyclone Giselle) in 1968 (Hill, 1970). The strong winds associated with this cyclone caused the sinking of the inter-island ferry Wahine, which lead to the loss of 51 lives. In more recent history, in February 2004 a cyclone event caused extensive flood and wind damage in the lower North Island, in particular in the region around Wellington. The damage was categorised as being more severe than that by Ex-Tropical Cyclone Bola in 1988. Apart from the millions of dollars in insurance payouts, there was one life lost at sea (McGavin, 1990-2005).

In order to minimise damage by any cyclone, accurate forecasts of these events are necessary. One foundation for successful forecasting is a detailed understanding of all the processes involved in the development of a cyclone. Another is a good

[1] A list of abbreviations and mathematical symbols can be found in the back pages of this study.

coverage with observational data. Due to a lack of observational data in the Southern Hemisphere an extensive investigation of Southern Hemisphere cyclones was almost impossible until the late 1970s. The introduction of satellite data at that time brought a major improvement in cyclone identification and classification in the Southern Hemisphere.

Since then cyclones in the Southern Hemisphere have been the object of numerous studies. This includes cyclones in the Southwest Pacific and, in particular, in the Tasman Sea region. Often the latter have been investigated as part of climatologies of Southern Hemisphere cyclones (e.g. Jones and Simmonds, 1993; Sinclair, 1994; Simmonds and Keay, 2000a,b). According to these studies, the Tasman Sea is a favoured place for the formation and intensification of cyclones.

In addition to the climatologies there have been several other studies investigating either a certain group of cyclones or single events in the Southwest Pacific, in particular the Tasman Sea region. Holland et al. (1987) and Leslie et al. (1987), for example, examined the development of cyclones forming along the east coast of Australia and determined the existence of different types among this group of cyclones. The focus of a study by Revell and Ridley (1995) was the development process of a particular low forming on the east coast of Australia and intensifying over the Tasman Sea. A study by Sinclair and Revell (2000) classified cyclones in the Southwest Pacific region, differentiating by upper-level flow pattern prior to intensification. Furthermore, several studies have examined cyclones undergoing explosive intensification[2], as they are a common feature in the Tasman Sea and New Zealand region. Apart from a study by Leslie et al. (2005), this type of cyclone has mainly been investigated as part of climatologies on Southern Hemisphere cyclones (e.g. Sinclair, 1995a,b; Lim and Simmonds, 2002).

[2]The original definition of an explosive intensification of a cyclone is a pressure drop of an average 1 hPa per hour over a 24 hour period (Sanders and Gyakum, 1980). In recent studies an additional latitude criterion has been included (Lim and Simmonds, 2002; Leslie et al., 2005).

One of the most comprehensive studies of cyclones in the Southwest Pacific was carried out by Sinclair (1993b, 2002, 2004). The objects of his investigations were tropical cyclones (TCs) undergoing extratropical transition. Occasionally TCs travel south out of the tropics and subtropics and into higher latitudes. Typically once they move into midlatitudes they decay. An explanation as to why this occurs is given in chapter 2 of this study, where conceptual models of the development of different types of cyclones are discussed in more detail. However, in the Tasman Sea region it is common for these TCs to link up with an upper-level trough or pre-existing low and then reintensify. These Ex-TCs can be quite destructive, as in the case of Cyclone Giselle in 1968 (Wahine storm) or Cyclone Bola in 1988 (Sinclair, 2002).

Apart from these studies of extratropical transition, most studies of cyclones in the Tasman Sea and New Zealand region, including those mentioned above, have concentrated on extratropical cyclones (ETCs). This is most likely because the majority of cyclones in this area are of midlatitudinal origin. However, there are also a number of cyclones, apart from TCs, that migrate from the subtropics into this region. These cyclones, in this study referred to as STCs (cyclones of subtropical origin, not including TCs), can cause just as much damage as ETCs or TCs.

For example, in June 2004 a STC brought heavy rain to the north of New Zealand, which caused severe flooding and slips leading to road closures across the region. In some areas strong winds lifted roofs, uprooted trees and destroyed power lines (McGavin, 1990-2005).

Since STCs cause considerable damage much more frequently then Ex-TCs, it is surprising that to date they have largely been neglected in the literature. Even Sinclair (2002, 2004) only considered TCs when he investigated extratropical transition over the Tasman Sea region.

The only study of cyclones of subtropical origin in the Tasman Sea region was carried out by Qi et al. (2006). However, their interest was only in heavy rain events and their impact on Australia. That is why the focus of this study here is on STCs in the Southwest Pacific. In addition, of particular interest are those that migrate into midlatitudes and come into the vicinity of New Zealand.
Considering the fact that STCs form in similar latitudes to most TCs, it is very likely that their development process is similar. It is also not unreasonable to assume that when such STCs move into midlatitudes, they undergo a similar process to that of extratropical transition, which occurs in TCs when they migrate into midlatitudes. Verifying this is one of the interests in this study. Other questions addressed in this study are:

- How many STCs actually form annually in the region north of the Tasman Sea and how frequently do they move into midlatitudes and ultimately into the vicinity of New Zealand? Are there any interseasonal variations in their behaviour and characteristics?
- Which mechanisms are responsible for the movement of STCs into midlatitudes?
- What are the dynamics during the development of STCs, in particular during their formation and intensification? Are there any differences among STCs? Are there any interseasonal variations?
- How closely does the development of STCs resemble that of a typical ETC or TC?

A more detailed discussion of the main points of investigation regarding the dynamical processes is given in chapter 2, after discussing conceptual models of the development of STCs. Chapter 3 discusses data and methods used in this study. In the first result chapter, chapter 4, the impact these cyclones have on New Zealand is verified. This is done by analysing damage reports provided by McGavin (1990-2005). Then, in chapter 5, a climatology of patterns in behaviour and characteristics of STCs is compiled. This is followed by investigating of the influence of the upper-level flow on the behaviour and characteristics of STCs in chapter 6. In chapter 7, the structure and the development process of STCs are examined. The final conclusions are presented in chapter 8.

2 Theoretical Background

As mentioned in the introduction, STCs (cyclones of subtropical origin that are not tropical cyclones) have largely been neglected in studies on cyclones in the Southwest Pacific. On the other hand, there are many studies that have investigated the behaviour and characteristics of ETCs (extratropical cyclones) and TCs (tropical cyclones), of the latter in particular those that undergo extratropical transition. Thus, the objects of investigation in this study are STCs in the Southwest Pacific and their characteristics and behaviour. The aim is not only to compile a climatology, but also to examine in more detail the mechanisms responsible for their movement into midlatitudes and the dynamical processes during their development.
As the name implies, subtropical cyclones develop in the subtropics. According to the AMS meteorological glossary[3], these are cyclones in subtropical and tropical latitudes that have characteristics of TCs and ETCs.
A specific aim in this study is to determine to what extent the development of STCs resembles that of ETCs or TCs. To do that, a good understanding of the development process of both TCs and ETCs is required. Thus, the following two sections describe the development processes of both of these cyclone types. Then, the likely importance of TC and ETC features in the development of STCs in the Southwest Pacific is discussed.

[3] webpage: http://amsglossary.allenpress.com/glossary/search?id=subtropical-cyclone1

2.1 Tropical Cyclones

'Tropical cyclone' is the general term for cyclones that develop over tropical and subtropical waters of the Indian and South Pacific Oceans[4] and which display surface winds exceeding 64 knots. Detailed descriptions of the development process of TCs can be found in Wallace and Hobbs (2006) or Terry (2007). The latter specifically examines TCs in the Southwest Pacific, in particular their development and impact on the environment.

The development of TCs is driven by the extraction of heat energy from the ocean at high temperatures. A relatively warm underlying ocean is therefore essential for the development of TCs. Sea surface temperatures (SSTs) above 26.5°C are required. In addition, the warm oceanic top layer should be relatively deep, as Ekman divergence and the resulting upwelling in the ocean, which are caused by the development of TCs, lead to a cooling of the top oceanic layer (Wallace and Hobbs, 2006).

In the initial stage the structure of a TC is poorly organised, but then becomes very symmetrical. Typical TC features are a warm core and large-scale convection organised symmetrically around the surface centre. The warm core enables TCs to draw energy from the ocean surface. The main reason for the symmetry and the rotational nature of TCs is the Coriolis Effect. The Coriolis Force causes the converging air to spiral around the surface centre of the cyclone. Since the Coriolis Force approaches zero toward the equator, its effect is negligible near the equator. This is why only a few TCs develop in close proximity to the equator, despite the otherwise suitable conditions for TC development. In fact, the majority of TCs develop in latitudes between 10°S and 20°S.

Another typical feature of a TC is a decrease in cyclonic geostrophic vorticity with height. Due to the warm-core structure, the slope of the pressure surfaces decreases

[4] In the Atlantic Ocean region these cyclones are referred to as hurricanes. In the North Pacific they are called typhoon.

with height. Thus, with increasing height the geostrophic wind and therefore the cyclonic geostrophic vorticity grow weaker (Wallace and Hobbs, 2006).

As the air converges on the surface, it picks up heat and moisture from the underlying ocean and then rises. Through rising, the air is cooled adiabatically. This forces the moisture in the air to condense.

According to Terry (2007), it is important that in the vicinity of the storm the moisture content in the mid-troposphere is high. In that case saturation and therefore condensation of the moisture in the rising air masses occurs rapidly. Such conditions can generally be found in the tropics and subtropics over the oceans. If the air in the mid-troposphere were to be dry, it would be able to 'soak up' the moisture in the rising air and prevent condensation. The latter is likely to occur when moist air is transported into a dry environment, as for example moving from the subtropics into midlatitudes or from the ocean over land.

Most of the latent heat released in the development of TCs is from convective processes. Studies on TCs, such as those by Anthes (1977) and Sinclair (1993a), have shown that strong latent heating rates from convection, in particular in the upper part of the troposphere, are a typical feature in the development of TCs.

The latent heat released by condensation results in warming of the rising air. It lessens adiabatic cooling and allows the air to rise faster. This, in connection with upper-level divergence directly above the surface centre, which removes the air from the column, enforces further convergence on the ground.

The demise of a TC is either caused by a move over cool waters or land or by vertical wind shear (Terry, 2007). The former two will lead to a reduction of, or even cut off, the heat and moisture supply at the surface. The wind shear can cause the displacement of the upper-level divergence away from above the surface centre and therefore destroy the efficient removal of air from the cyclone core. Both of these events, the movement over cool waters and the vertical wind shear, typically occur when TCs move into midlatitudes. That is why TCs generally decay when leaving the tropics and subtropics.

However, there are exceptions. In some instances TCs re-intensify after having moved into midlatitudes. Detailed investigations of this phenomenon discovered that such TCs undergo a transition, generally referred to as extratropical transition, during which their development processes change from those of a TC to those of an ETC (extratropical cyclone).

Because such cyclones have been the cause of substantial damage, such as in the case of Cyclone Bola in New Zealand in 1988 (Sinclair, 1993a), the process of extratropical transition in TCs has been the subject of numerous studies (e.g., Harr and Elsberry, 2000a,b; Hart, 2003; Hart et al., 2006). The particular interest of studies by Sinclair (1993b,a, 2002, 2004) has been the Southwest Pacific region, where extratropical transition in TCs is a common feature. Sinclair (2002) in particular gives a very graphical and detailed description of the extratropical transition processes.

2.2 Extratropical Cyclones

ETCs develop in midlatitudes. In contrast to the tropics and subtropics, where the heat energy from the ocean dictates the development of cyclones, in midlatitudes the main driving force is a strong horizontal temperature gradient.

The difference in the mechanisms that drive the development of ETCs and TCs is reflected in their structure. The most pronounced differences are the lack of symmetry in the structure of ETCs, the absence of a warm core and the presence of strong vertical wind shear. The aforementioned horizontal temperature gradient has the warm air located to the east and the cold air to the west of the surface centre. Also, for ETCs the geostrophic height gradient increases with height. Accordingly the associated geostrophic winds and therefore geostrophic vorticity grow stronger with height.

The development of ETCs is driven by thermal processes, such as low-level temperature advection (TADV) and adiabatic and diabatic processes, and upper-level vorticity processes, such as vorticity advection (VADV) and divergence (DIV). Fundamental to the development of ETCs is the link between the upper and lower level processes via vertical motions.

The large-scale flow pattern in the upper atmosphere of the midlatitudes is characterised by eastward moving baroclinic waves consisting of ridges and troughs. At the surface the pattern consists of separate cells, referred to as highs and lows. The development of an ETC is generally initiated when the downstream region of an upper-level trough moves over a region of strong low-level baroclinicity[5].

Vorticity is a quantity often used in Meteorology as a measure for the rotation of an air particle, in particular when describing the development process of ETCs. By taking the Lagrangian of the geopotential height fields, the geostrophic relative vorticity ζ is gained. For synoptic-scale motions, where the twisting, tilting and vertical vorticity advection terms can be neglected in the upper levels, local changes in the geostrophic relative vorticity $\partial\zeta/\partial t$ are achieved either through VADV (vorticity advection; first term on the left hand side of Eq. 2.1) or through DIV (divergence; second term on the left hand side of Eq. 2.1).

$$\frac{\partial \zeta}{\partial t} \approx - \underbrace{\mathbf{V} \cdot \nabla(\zeta + f)}_{vorticity\ advection} - \underbrace{(\zeta + f)\, \nabla \cdot \mathbf{V}}_{divergence} \tag{2.1}$$

Here, f is the Coriolis parameter and $\mathbf{V}$ the horizontal wind vector.

[5]Baroclinicity refers to a state of the atmosphere where height and thickness contours intersect one another, so that the geostrophic wind flows across the isotherms and temperature advection can occur.

In storm-following coordinates Eq. 2.2 can be written as:

$$\frac{\delta\zeta}{\delta t} \approx -\underbrace{\mathbf{V}-\mathbf{C}\cdot\nabla(\zeta+f)}_{vorticity\ advection} - \underbrace{(\zeta+f)\,\nabla\cdot\mathbf{V}}_{divergence} \tag{2.2}$$

with $\delta/\delta t$ the change following the storm and $\mathbf{C}$ the moving velocity of the storm. According to Sinclair and Revell (2000), when using storm-relative winds ($\mathbf{V}-\mathbf{C}$) the upper-level cyclonic VADV is much better correlated with central pressure tendencies at the surface than when using Eulerian winds.

Fig. 2.1 shows a schematic illustration of the mechanisms involved in the development of a typical ETC. As the wind blows clockwise (in the Southern Hemisphere) around the surface centre of a forming cyclone, warm air is advected east of the low, under the upper-level ridge. The warming leads to an increase in thickness of the atmospheric layer between the 1000 hPa pressure surface and 500 hPa pressure surface. The increase in thickness results in height rises aloft and therefore strengthening of the upper-level ridge. It also leads to divergence in the ridge aloft. West of the low, under the upper-level trough, cold air is advected, resulting in a thickness decrease of the atmospheric layer and sinking motions beneath the trough. The sinking motions, in turn, are connected to convergence in the trough. Both the thickness increase in the ridge and the decrease in trough lead to an amplification of the upper wave.

The divergence in the ridge and convergence in the trough are both associated with local changes in the vorticity. In the Southern Hemisphere, troughs (ridges) are represented by relative minima (maxima) in the geostrophic relative vorticity field. In the trough and ridge the flow is normal to the vorticity gradient. Therefore, the increase of anticyclonic (cyclonic) vorticity in the ridge (trough) is solely associated with divergence (convergence), caused by rising (sinking) air.

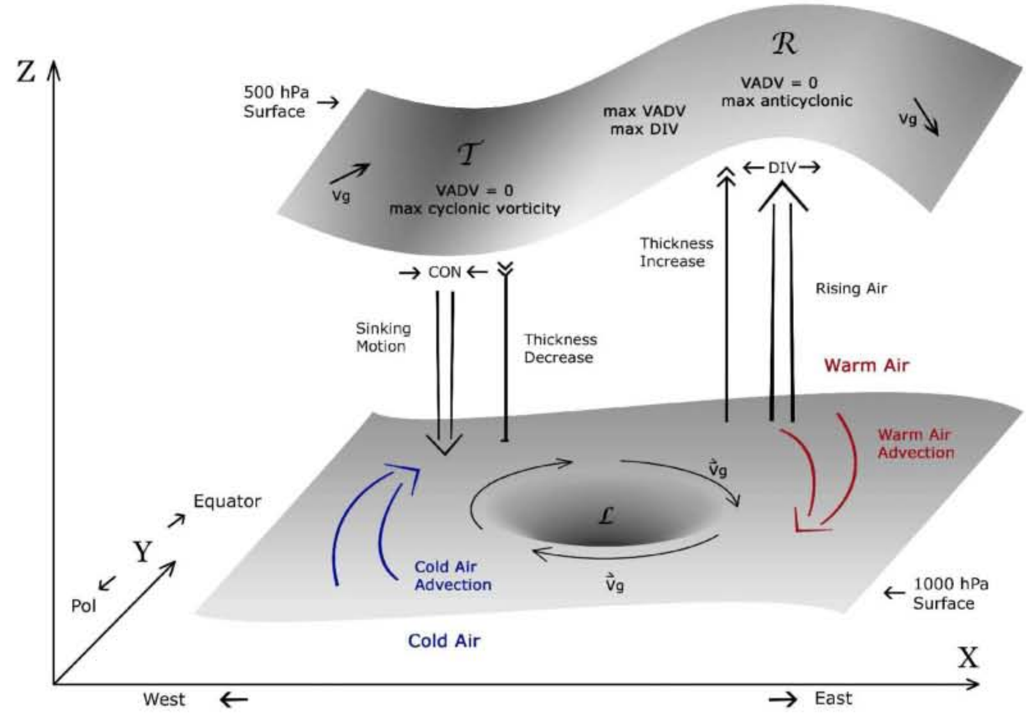

Figure 2.1: *Schematic illustration of conceptual model of the development of an extratropical cyclone in the Southern Hemisphere. See text for more details. Courtesy of F. R. Schroeder (Graphic Designer).*

The increasing anticyclonic vorticity in the upper-level ridge and cyclonic vorticity in the upper-level trough increase the vorticity gradient between trough and ridge and therefore enforce cyclonic VADV between the two. Since, according to Sinclair (2002), $\delta\zeta/\delta t$ is small compared to VADV or DIV in upper-levels, Eq. 2.2 is reduced to:

$$-\frac{1}{(\zeta+f)}\mathbf{V}-\mathbf{C}\cdot\nabla(\zeta+f)\;\approx\;\nabla\cdot\mathbf{V} \tag{2.3}$$

This means an increase in upper-level cyclonic VADV between the trough and ridge is associated with increasing divergence aloft, which enforces rising motions in the atmospheric layer beneath. This leads to a pressure fall at the surface and therefore to further deepening of the surface low, which in turn causes stronger convergence at the ground.

These processes continue as long as the upper and lower waves are in the correct relative phase. As mentioned earlier, the development of ETCs is initiated when the surface low is located downstream of an upper-level trough so, essentially, when the upper-level wave lags a quarter of a wavelength behind the lower wave. At this stage TADV is strongest. This alignment also generates the strongest intensification in ETCs. When the upper wave catches up with the lower wave, the intensification phase in the life cycle of an extratropical cyclone ends (Carlson, 1991).

Even this simplified description of the mechanisms for the development of an extratropical cyclone clearly demonstrates the strong interaction between low-level thermal and upper-level vorticity processes through vertical motions. In reality the whole development process of an extratropical cyclone is even more complex, as other processes, such as diabatic processes, need to be considered (Carlson, 1991).

As discussed in the previous section, the release of latent heat is a fundamental process in the development of TCs. In contrast, diabatic processes are generally not the dominating factors in the development of ETCs; however, they are important (Carlson, 1991). The release of latent heat counters the adiabatic cooling effect in the rising air, and thus helps to maintain or even increase the horizontal thermal gradient. This can increase the baroclinic instability, which subsequently enables further deepening of the low.

In contrast to TCs, where the release of latent heat mostly comes from deep cumulus convection, in ETCs the majority of latent heat released stems from large-scale ascent (Holton, 1992). According to Rausch and Smith (1996), maximum latent

heating rates in ETC development are found in the lower levels between 850 hPa and 700 hPa.
As latent heating rates and vertical velocities are directly linked, increased latent heat release through large scale ascent in the development of ETCs leads to an increase in the vertical velocity near the surface (Carlson, 1991). According to Eq. 2.4, this results in an increase in convergence at the surface centre (Carlson, 1991).

$$-\nabla \cdot \mathbf{V} \approx \frac{\partial w}{\partial p} \tag{2.4}$$

Explosive cyclogenesis is an example where diabatic processes have a significant influence on the development of ETCs. Studies have shown that a strong contribution due to the release of latent heat is for the most part responsible for the rapid intensification of those cyclones (e.g., Gyakum, 1983; Kuo et al., 1991; Rausch and Smith, 1996; Lackmann, 2002; Leslie et al., 2005). Modelling of such cyclone events indicates that without the high amount of latent heating, the rapid development would not have taken place (e.g., Orlanski and Katzfey, 1987; Reeder et al., 1988). Orlanski and Katzfey (1987) also found that prior to the rapid intensification, the contribution from the release of latent heat did not play an important role in the development of these cyclones.

2.3 Subtropical Cyclones

The subtropics typically span the latitudes between 15° and 30°. Naturally, toward the equator the atmosphere becomes warmer and moister, the ocean warmer and the influence of upper-level baroclinic waves more unlikely.

Most TCs form in the latitude band between 10° and 20°. This means some STCs develop in the same latitudes as TCs. Thus, it is not unreasonable to think that the development of STCs in these latitudes might display TC features, such as a warm core, strong surface fluxes, high latent heating rates from convection in upper levels and a lack of upper-level vorticity advection.

Under the right conditions STCs can develop into TCs (Davis and Bosart, 2003). However, the conditions during the development of the STCs investigated here were apparently not favourable enough for them to achieve the intensity of TCs. For example, according to recent work by Dr. M. Sinclair[6] (personal communications; hereafter referred to as MS), in the subtropics the relationship between SSTs and cyclones is often quite weak during intensification. He argues that this is most likely because the oceanic mixed layer is often relatively shallow here. Any region of warm water, which may have encouraged the formation of a STC, is often quickly cooled by Ekman divergence and upwelling in the oceans, which is created by the cyclone itself.

A study by Davis and Bosart (2003), which investigates tropical transition in STCs and ETCs over the Atlantic, found that transition did not take place when the cyclone moved over cooler water or the vertical wind shear did not drop below a certain threshold. As discussed earlier, both the movement over cooler water and strong vertical wind shear are also reasons for a TC to decay.

However, apparently not all STCs, after failing to develop into TCs, simply decay. As mentioned in the introduction, STCs frequently cause significant damage in New Zealand. This means at least some STCs leave the subtropics and migrate into midlatitudes. One interest in this study is to determine what mechanisms are responsible for the movement of STCs into midlatitudes, and what causes a STC to migrate into the vicinity of New Zealand.

[6]Current affiliation: Embry-Riddle Aeronautical University, Prescott, Arizona

As soon as STCs move into midlatitudes, one would expect their development to be more like that of ETCs. It is therefore very likely that such STCs undergo a transition in their development process when moving into midlatitudes, which could be similar to that of extratropical transition of TCs. The aim here is to verify the occurrence and analyse the process of extratropical transition in STCs.

2.3.1 Influence of Regional Climatic Features

The area investigated here has certain climatic features that most likely influence the behaviour and characteristics of STCs. One such feature is the seasonal variation in the upper-level flow in the Southwest Pacific.
The upper-level jets over the Southwest Pacific show strong seasonal variations in strength and location. Typically, only the polar front jet is clearly visible in long-term averages in the Southern Hemisphere during summer. It is located, as a single maximum and a continuous band, at approximately 45°S (top plot in Fig. 2.2, courtesy of J. Kidston[7]). During the colder seasons the jet splits over part of the Southern Hemisphere near Australia (bottom plot in Fig. 2.2). It displays a strong and dominant subtropical maximum near 25°S and another maximum (polar frontal) further south near 60°S over the Southwest Pacific. This phenomenon is known as the 'split jet' and has been investigated by numerous studies, such as Gallego et al. (2005) and Bals-Elsholz et al. (2001).
Studies, such as those by Hoskins and Ambrizzi (1993) and Nakamura and Shimpo (2004), have shown that upper-level jets can act as wave guides, in particular in the Southwest Pacific. This means that, for example, the subtropical jet inhibits the midlatitudinal baroclinic waves from propagating north of the jet. Thus, the location of the subtropical jet gives an indication as to how far midlatitudinal baroclinic waves

[7]Current affiliation: NIWA, Wellington, New Zealand

are able to propagate into the subtropics.

An analysis of the 500 hPa height fields over the Tasman Sea region shows that during winter when the jet is located near 25°S, troughs frequently, on average 14 times a season, propagate north of 30°S. Occasionally, approximately 4 times a season, these troughs propagate north of 25°S. A typical winter situation of the

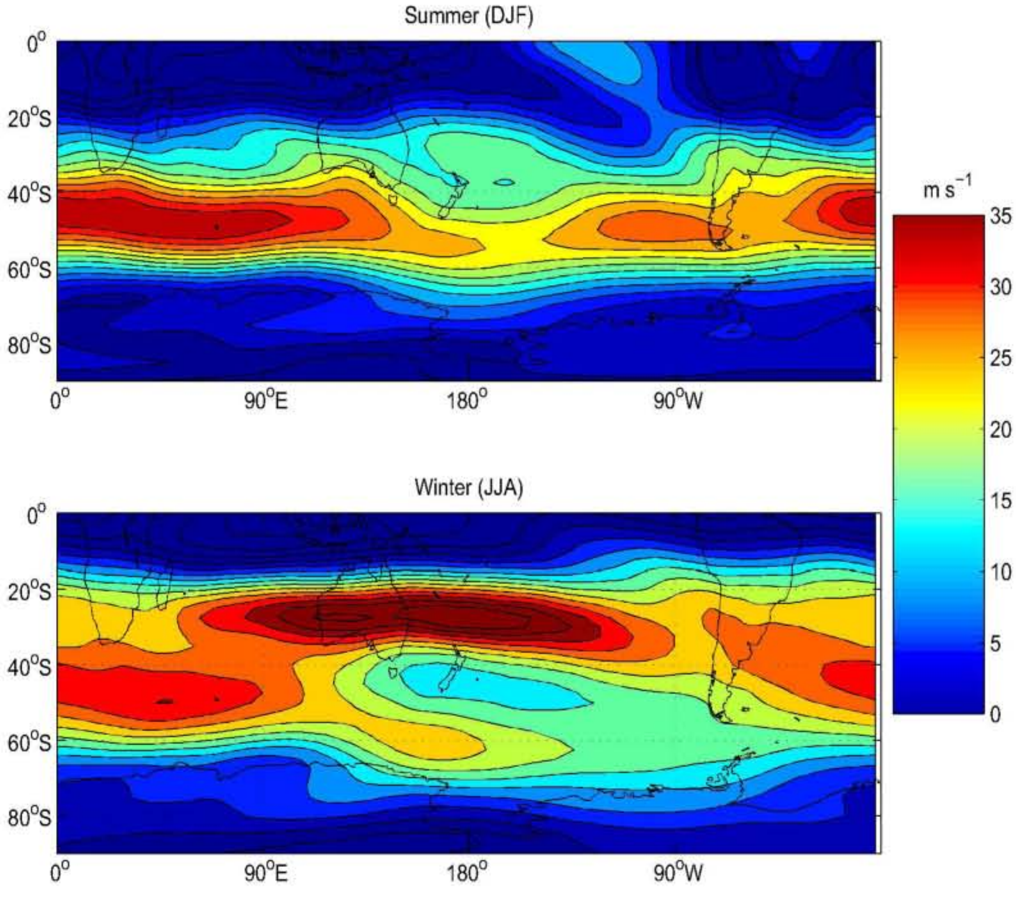

Figure 2.2: *Climatology of horizontal wind speed [ms^{-1}] at 300 hPa in the Southern Hemisphere during summer (top) and winter (bottom). Derived from the NCEP/NCAR reanalysis for the period from 1979-2005. Courtesy of J. Kidston.*

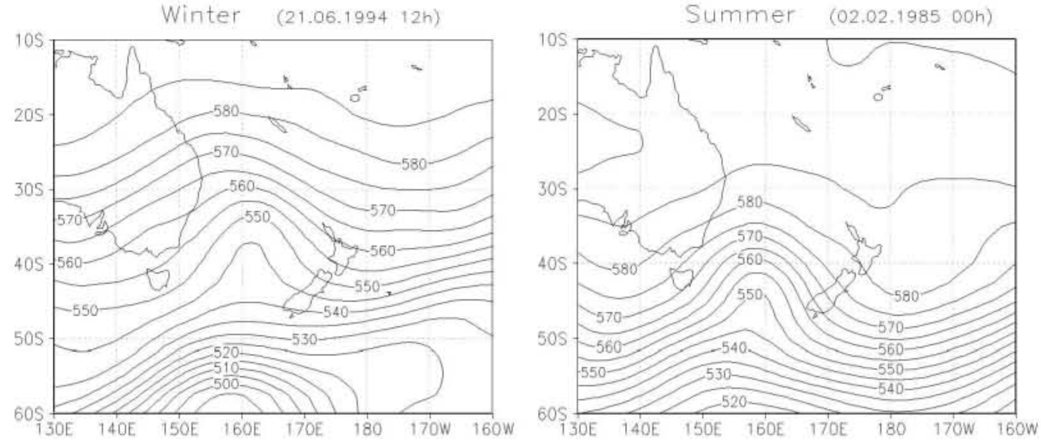

Figure 2.3: *Example of 500 hPa height field [dam] with a typical trough situation in the Tasman Sea region during winter (left) and during summer (right). Derived from the NCEP/NCAR reanalysis for the period between 1985 and 2005.*

500 hPa height fields over the Tasman Sea is shown in the left hand plot in Fig. 2.3 (from 21.06.94 12h). As can be seen, the trough over the Tasman Sea extends well north of 25°S.

In summer troughs generally only extend north of 30°S in this region approximately 5 times each year and only once a year does a trough reach north of 25°S during summer. The right hand plot in Fig. 2.3 shows a typical summer situation, with a trough located over the Tasman Sea (from 02.02.85 00h).

It is suspected that in particular during the colder seasons, when troughs frequently propagate into the subtropics in the Southwest Pacific region and are able to interact with a developing STC, the development of STCs shows predominantly ETC features. In fact, it is very likely that there are STCs whose whole development is driven by low-level baroclinicity and is therefore very similar to that of ETCs. A similar phenomenon is found on the Northern Hemisphere near Hawaii. In their investigation of Kona storms[8] Otkin and Martin (2004) showed that, in particular during the colder months, upper-level extratropical disturbances propagate far into the subtropics in this region of the Pacific Ocean and initiate the development of these low-level cyclonic disturbances.

It is also suspected that the coupling with an upper-level trough is the reason STCs migrate into midlatitudes. In general, the movement of cyclones is strongly dictated by the background flow in the atmosphere, which essentially is represented by the vertically averaged horizontal wind in the troposphere. The level at which the horizontal wind field matches that of the vertically averaged horizontal wind is generally referred to as 'steering level'. Typically this is the 500 hPa level (Wallace and Hobbs, 2006).

In the tropics and subtropics the background flow is predominantly characterised by easterly Trade Winds directed toward the equator (Terry, 2007). Thus, cyclones on the Southern Hemisphere in those latitudes, such as TCs, display a strong southeasterly component in their movement (Wallace and Hobbs, 2006).

In contrast, the mean flow in midlatitudes is characterised by westerlies. As a result, the movement of cyclones in those latitudes often features a strong westerly component. However, as discussed earlier, the flow in midlatitudes is also characterised by baroclinic waves. A high amplitude wave can cause significant deviations from the predominantly westerly mean flow and those deviations are then translated onto the movement of ETCs (Wallace and Hobbs, 2006).

As previously discussed, in the Southwest Pacific region midlatitudinal baroclinic waves frequently propagate relatively far into the subtropics, in particular during the colder seasons. In those instances the flow in the subtropics takes on midlati-

[8] According to Otkin and Martin (2004), ' 'Kona' is a Polynesian adjective meaning leeward and is used to describe the conditions in which the usually persistent trade wind easterlies are replaced by southerly winds and rain squalls so that locations ordinarily in the trade wind lee of mountain ranges are exposed to onshore winds.'

tudinal features. During that time there is a high chance for STCs to couple with a trough. In such cases the cyclones would be 'steered' south, and most likely into midlatitudes, by a northwesterly flow underneath the eastern flank of the trough.

2.4 Main Points of Investigation

The first aim of this study is to compile a climatology analysing spatial and temporal patterns in the behaviour and characteristics of STCS. The main objective of the second part in this study is to examine the development process of STCs, in order to determine to what extent it resembles that of ETCs or TCs. The detailed points of that part of the investigation are to:

- Determine what mechanisms are responsible for the movement of STCs into midlatitudes and ultimately the vicinity of New Zealand.
- Investigate possible classification of STCs differentiating by their development processes.
- Verify the existence of STCs that feature strong ETC characteristics during their whole development. This also includes the investigation of the frequency of such events and seasonal variations.
- Determine whether there are any cases of tropical transition. This refers to STCs whose formation is similar to that of ETCs, but which then transition into cyclones with predominantly TC features.
- Compare the development process of STCs that move into midlatitudes to that of ETCs. Determine whether the former, even when in midlatitudes, are driven more by diabatic processes than ETCs.

- Examine how the dynamics during the development of STCs influence the behaviour and characteristics of STCs, such as intensity.
- Verify the occurrence of extratropical transition in STCs. This includes investigations of frequency, influence on the development of STCs in terms of length of lifetime and intensity, as well as seasonal variations.
- Examine the change in dynamical processes during the development of STCs with changing latitude. Of particular interest is how this is affected by the change in season.

3 Data and Procedures

In this chapter, data used in this study, including the cyclone track databases, are described. This is followed by an explanation of some of the methods employed for analysing and visualising the data.

3.1 Dataset

The investigations in chapters 6 and 7 regarding the upper-level flow and development of STCs were carried out with data from the United Kingdom Meteorological Office (UKMO) global model (e.g. Cullen, 1993) and a cyclone track database derived from that data set. A more detailed description of this cyclone track database, including the tracking method, is given in section 3.2.2.

The UKMO model data are collected from operational model output and sent in real time to the Meteorological Service of New Zealand, and thence, since late 1997, to NIWA for archiving. For this study data from November 1998 until December 2003 are used.

The record at NIWA has several, generally short, missing data periods resulting from failure in real-time data transfer or archiving. An attempt to retrieve the missing data from the Meteorological Service of New Zealand was unsuccessful.

The UKMO model data provide twice daily analyses on 10 pressure levels with a horizontal resolution of $1.25° \times 1.25°$. A list of the available parameters can be found in Tab. 10.1 in Appendix II.

As can be seen in the table, the relative humidity (RH) is only available on the lower 4 levels (1000 hPa to 500 hPa). However, for the dynamical equations described in section 3.3.3 and used in chapter 7, RH is also needed at 300 hPa. As the humidity is near zero and the changes in RH are relatively low above 500 hPa, it was decided to use the values of RH at 500 hPa for 300 hPa as well. The error is generally small. The vertical velocity ω, which was also needed for the dynamical equations, was not provided for the 400 hPa surface. Instead, it was derived via interpolation from the level below (500 hPa) and the level above (300 hPa).
In addition, in August 2002 the UKMO changed the vertical velocity from ω to the z-component of the velocity, w. So for cases after August 2002, ω was derived from w with Eq. 3.1 (e.g. Holton, 1992).

$$\omega \approx -\frac{g\,p\,w}{R\,T} \tag{3.1}$$

Here, p represents the pressure, T the temperature, g is the gravity and R is the gas constant for dry air.

The UKMO data was chosen over the NCEP/NCAR[9] and ECMWF[10] data for the investigations in chapters 6 and 7 because of its higher horizontal resolution, despite the other two data sets being available for longer time periods. The higher horizontal resolution of the UKMO data is more suitable for the investigations in chapter 6 and 7 regarding the dynamical processes during the development of cyclones.

[9]National Center for Atmospheric Research and National Centers for Environmental Prediction.
[10]European Centre for Medium Range Weather Forecasts.

3.2 Cyclone Tracks

The original cyclone track database derived from the UKMO model data was compiled by Dr. R. Turner and Dr. J. Renwick[11] (personal communications; hereafter referred to as TR). Even though the higher horizontal resolution of the UKMO data is of advantage for the dynamical investigations, the 5 years covered by the cyclone track database are not sufficient to compile a comprehensive climatology, in particular when looking at interannual and seasonal patterns. Thus, it was decided to use a cyclone track database provided by Dr. M. Sinclair[12] (personal communications; hereafter referred to as MS) for the climatology presented in chapter 5, as it covers a substantially longer time period.
It is acknowledged that the use of different data sets can lead to different findings. For example, Pezza and Ambrizzi (2003) discovered a negative trend in the number of ETCs in the Southern Hemisphere toward the end of the last century. In a similar study, Sinclair et al. (1997) determined a positive trend. Pezza and Ambrizzi (2003) argue that this difference is caused by the use of different data sets and methods of identifying and tracking cyclones used for the climatology.
However, here it is shown that the broad results of the climatology, when compiled with either cyclone track database, are very similar. It provides confidence that the findings from the climatology in chapter 5 can be linked to the findings from chapters 6 and 7.

The following two sections describe the different methods used to identify and track cyclones for each of the two databases. Then the process of excluding TCs (tropical cyclones) is briefly explained. This is followed by a discussion of the cyclone selection criteria applied in this study.

[11] Current affiliations: NIWA, Wellington, New Zealand

[12] Current affiliation: Embry-Riddle Aeronautical University, Prescott, Arizona

3.2.1 MS Cyclone Track Database

This cyclone track database was compiled by MS with twice daily reanalyses from NCEP/NCAR with a horizontal resolution of $2.5° \times 2.5°$ and his tracking software (Sinclair, 1994, 1995b). Instead of local minima in the sea level pressure (SLP) field, minima in the 1000 hPa vorticity field were used to identify a cyclone. According to Sinclair (1994, 1997b), using the mean sea level pressure at the centre of a cyclone as a measure of its intensity can be misleading, especially when a cyclone travels across a rapidly dropping background pressure field. In cases like this, the rapid drop in central pressure can be caused by the movement across a changing falling background pressure rather than by an actual intensification of the cyclone, as shown by an example in Sinclair (1995b). The geostrophic relative vorticity (GVOR) was found to be a more reliable measure of cyclone intensity.

The cyclones in the MS database are tracked automatically by using an algorithm first developed by Murray and Simmonds (1991a,b) and later modified by Sinclair (1994). Details can be found in Sinclair (1994, 1995b). The MS cyclone track database contains date, position, GVOR and the pressure at the cyclone centre, radius and circulation for each tracked cyclone.

The original database covers the period from January 1950 to April 2006. However, as mentioned in the introduction, in the late 1970s satellite data were introduced. A study by Lim and Simmonds (2002) found an increase in the number of cyclones in the Southwest Pacific in the early 1980s, which the authors think to be connected to the introduction of the satellite data. To avoid a potential bias caused by the change in data, it was decided to only use cyclone tracks from the MS database between January 1985 and April 2006 for the investigations in this study.

3.2.2 TR Cyclone Track Database

TR established a cyclone track database as part of a study on the performance of two forecast models in the Tasman Sea by TR (personal communications[13]). The original database contained time, position and central pressure for each track point of every rain producing weather system from November 1998 to December 2000 in the Tasman Sea area.
The systems were divided into 5 different categories:

Type A - Low pressure systems that developed between 30°S and 45°S and/or traversed the Tasman Sea

Type B - Frontal systems that brought strong Northwest flows across New Zealand

Type C - Less organised mesoscale or convective systems that resulted in heavy rainfall over the upper North Island of New Zealand

Type D - Subtropical depressions that formed north of 30°S

Type E - Ex-Tropical cyclones

For this study only type A (in this study referred to as extratropical cyclones or ETCs) and type D (in this study referred to as cyclones of subtropical origin or STCs) are of interest.
For the purposes of this study the database was extended until the end of 2003. In addition, every cyclone that formed north of 30°S, not only those that produced rain in New Zealand, was included.
In order to maintain continuity in the data, TR's method was used to identify and track cyclones from 2001 to 2003. Following TR, cyclones were detected automatically as a local minimum in the SLP field and then tracked manually.

[13]Part of their findings are published in Turner et al. (2003).

Also, for the purposes of this study, after the initial identifying and tracking of the cyclones, minima in the 1000 hPa GVOR fields were calculated for each track point. Those minima were then used to mark the position of the centre of the cyclones and their intensity. This follows the idea by MS, who found GVOR to be a more reliable measure of intensity for a cyclone.

In addition, minima in the 1000 hPa GVOR fields were calculated up to 24 hours before the initial start of each cyclone track, because according to Sinclair (1994), another advantage of using GVOR as a measure of cyclone intensity is an earlier detection of cyclone formation. The analysis in this study confirms this. In over 80% of cases from the TR database, a minimum in GVOR was found 6 to 12 hours prior to the first occurrence of a minimum in SLP field as defined by TR.

Furthermore, the MS method also provides a better tracking ability in higher latitudes. It was found that it is easier to distinguish between closely located centres by using GVOR in those latitudes, where the system density is very high. This ultimately leads to discrepancies in terms of track length between the two cyclone track databases. Since they were compiled from data on different sized grids, a comprehensive comparison between the two databases, in particular in regard to cyclone position, is not possible. However, in chapter 5 it is shown that discrepancies in the two databases have no significant effect on the broad results of the climatology.

3.2.3 Exclusion of Tropical Cyclones

The methods by TR and MS of identifying and tracking cyclones do not distinguish between different types of cyclones, such as ETCs and TCs. As mentioned in the introduction, the interest in this study is on cyclones of subtropical origin, with the exception of TCs. The latter, in particular those that move into midlatitudes and undergo extratropical transition, have already been studied extensively for the Tasman Sea area (Sinclair, 1993a, 2002, 2004). It was therefore decided not to include TCs in the study. They were separated from STCs by using the TC databases from the Meteorological Service of New Zealand and the University of Hawaii[14]. This lead to the exclusion of 100 cyclones from the MS database for the period between January 1985 and April 2006.

3.2.4 Area of Investigation

The interest in this study is on cyclones of subtropical origin, with particular emphasis on those that come into the vicinity of New Zealand. This strongly dictated the boundaries of the investigation area.

The area where STCs originate that are investigated here is shown in Fig. 3.1 (grey shaded area). It spans the Coral Sea, east coast of Australia, parts of the Southwest Pacific and the Fiji Sea.

The subtropics are defined here as the region between 15°S and 30°S. The southern boundary was set to 30°S following TR. The northern boundary of 15°S was chosen to avoid some of the uncertainty around whether an identified minima in the vorticity field qualifies as a cyclone centre. Near the equator the calculation of vorticity is not very reliable, due to the small Coriolis parameter. Thus, most minima in the GVOR field identified north of 15°S are probably fictional artefacts of the small Coriolis parameter. It was found that during the 21 years investigated here, only 6% of identified cyclones in the MS database that formed north of 15°S migrated into midlatitudes and therefore could reliably be considered to be a true cyclone.

Investigations showed that cyclones forming east of 180°E rarely move into the vicinity of New Zealand. Thus, the eastern boundary for the investigation was set to 180°E.

[14]webpage: http://www.solar.ifa.hawaii.edu/Tropical/

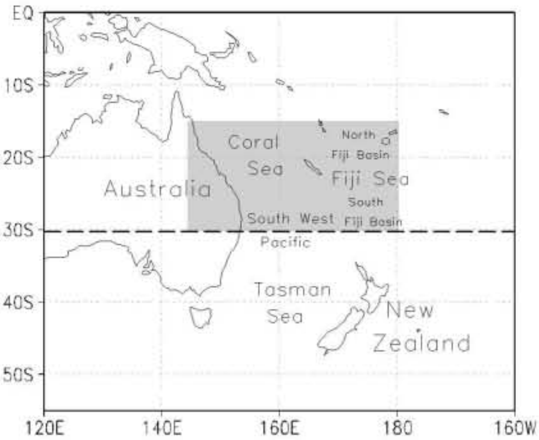

Figure 3.1: *Area of investigation. The area where STCs investigated in this study form is shaded grey.*

As a result of the limited availability of the vertical velocity ω in the UKMO data set (only available between 150°E and 240°E), the western boundary of the domain was set to 145°E.

Widening the investigation area naturally increases the total number of STCs. However, the increase of the number of STCs that come into the vicinity of New Zealand, which are of particular interest here, is considered negligible. When the area is widened by 5° to either the west or east, the number of STCs that come into the vicinity of New Zealand increases by less than 5%. By widening the area by an additional 5° the increase is less than 1%.

3.2.5 Cyclone Selection Criteria

In order to further minimise a bias caused by possible artefacts in the vorticity fields, certain thresholds for cyclone centre GVOR are applied. The criteria were chosen following Sinclair (1995a) and MS (personal communication).

Selection criteria for cyclones from the MS database:

- A cyclone has to form in the area specified in the previous section.
- A cyclone has to have at least 4 track points during its entire lifetime. A track point is defined as a point in space and time. It marks the location of a cyclone centre at a certain time during the lifetime of that cyclone.
- A cyclone has to have spent at least 3 track points in the area between 145°E and 185°E.
- A cyclone has to have a centre GVOR of at least -2*$10^{-5}s^{-1}$ or below for each track point, to avoid artefacts in the vorticity field.
- The minimum threshold of maximum intensity (lowest centre GVOR) during the whole life cycle is -3*$10^{-5}s^{-1}$.

After applying the selection criteria, the relevant subset of the MS database covering the period from January 1985 to April 2006 contains 322 STCs.

As cyclones for the TR database were identified and tracked using minima in SLP fields, and the data from which the tracks were derived are on a different sized grid than for the MS database, different selection criteria for the intensity had to be used. However, the same criteria for the investigation area and the number of track points apply.

Selection criteria for cyclones from the TR database:

- The minimum threshold for the maximum intensity (lowest centre pressure) during the whole lifetime of a cyclone is set to 1012 hPa .

- After the initial identifying and tracking of the cyclones, minima in the 1000 hPa GVOR fields were calculated for each track point. The minimum threshold of maximum intensity (lowest centre GVOR) during the whole life cycle is -4*$10^{-5}s^{-1}$.

Additional criteria for cyclones from the TR database:

- As the aim is to investigate the development process of STCs, cyclones have to have more than 2 track points from formation to maximum intensity.
- If due to gaps in the data sets, 2 or more track points were missing during the intensification period of a cyclone, that cyclone was not used for the detailed investigations in chapters 6 and 7.

Using these selection criteria, the TR database, covering the period from November 1998 to December 2003, contains 67 STCs. A list of all STCs from the TR database can be found in Tab. 10.2, Tab. 10.3 and Tab. 10.4 in Appendix II. Due to missing data, only 56 of these cases were eventually investigated in full in chapters 6 and 7 (numbered cases in list in Appendix II).
For the same time period approximately 130 cyclones formed in the midlatitudinal area between 30°S and 45°S, and 145°E and 180°E. Of these (also referred to as ETCs), 38 were analysed in detail and used for a comparison with STCs in chapter 7. This number was considered large enough to make statistically relevant statements about ETCs. Initially only 20 ETC events were chosen for the comparison. Almost doubling the number of ETC cases produced no significant changes in the results. This confirmed that the sample size is sufficient and the results are representative for ETCs in the Tasman Sea area.

The same criteria for intensity and track length as for STCs from the TR database were applied to ETCs. The selection of the sample ETCs was random. A list of all ETC cases from the TR database used in the investigations in chapter 7 can be found in Tab. 10.5 and Tab. 10.6 in Appendix II.

3.3 Analysing and Visualising Methods

The following sections describe the procedures that were applied to analyse the data. They include visualisation tools, such as system density plots, and equations, in particular those needed to analyse the dynamics during formation and intensification of cyclones.

3.3.1 Intensification Rate

As explained earlier, in this study minima in the GVOR (geostrophic relative vorticity) field were used to determine intensity and position of a cyclone. Following Sinclair (1994) the geostrophic relative vorticity ζ_g is derived as the Laplacian of the geopotential Φ, from the 1000 hPa height fields:

$$\zeta_g = \frac{1}{f}\left[\frac{1}{(a\cos\phi)^2}\frac{\partial^2\Phi}{\partial\lambda^2} + \frac{1}{a^2}\frac{\partial^2\Phi}{\partial\phi^2}\right] \tag{3.2}$$

with the Coriolis parameter, f ($\equiv 2\Omega sin\phi$), where Ω is the angular speed of the rotation of the earth and ϕ the latitude in radians. a is the mean radius of the earth and λ the longitude in radians.

For this study the intensification rate ir was calculated as the centred time difference of GVOR at 1000 hPa at the centre of a cyclone (Eq. 3.3).

$$ir_t = \zeta_{g(t+1)} - \zeta_{g(t-1)} \tag{3.3}$$

Positive values for the intensification rate indicate a weakening of the cyclone. Negative values represent a strengthening (intensifying).

3.3.2 Thermal and Vorticity Processes

As discussed in chapter 2, some STCs are likely to feature ETC characteristics in their development. The main processes typically involved in ETCs are thermal processes, such as low-level TADV (temperature advection), ADIAB (adiabatic processes) and DIAB (diabatic processes), as well as upper-level vorticity processes, such as VADV (vorticity advection) and DIV (divergence).

In order to determine to what extent the development of STCs is similar to that of ETCs, the contribution by the above processes is examined and compared with those during the development of an average ETC. The method used in this study follows Sinclair (2004). It provides the opportunity to assess the individual contribution of each of the processes mentioned above to the intensification of a cyclone, as well as the interaction between the processes.

The method in Sinclair (2004) is based on the Petterssen-Sutcliff theory. It uses the thickness tendency equation (Eq. 3.4) and the geopotential tendency equation at a pressure p (Eq. 3.5) in storm-following coordinates. Sinclair and Revell (2000) found that storm-relative winds $(\mathbf{V} - \mathbf{C})$ for upper-level cyclonic VADV are much better correlated with central pressure tendencies at the surface than the more commonly

used Eulerian winds. Here, $\mathbf{V}$ is the horizontal wind and $\mathbf{C}$ the translation velocity of the moving cyclone, which is obtained as centred differences from the cyclone track coordinates. In order to exclude the movement of the storm, the Eulerian local rate of change $\partial/\partial t$ is replaced by $\delta/\delta t \; - \; \mathbf{C}\cdot\nabla$, where $\delta/\delta t$ is the change following the storm.
For the latter, Sinclair (2004) replaced $\delta\zeta_p/\delta t$ in the vorticity equation with its geopotential equivalent $\delta/\delta t(\nabla^2\Phi_p/f)$. He then took the inverse Laplacian ∇^{-2} of both sides and multiplied it by the Coriolis parameter f.

$$\begin{aligned}\frac{\delta}{\delta t}(\Phi_p - \Phi_b) &= \underbrace{R\int_p^{p_b}[-(\mathbf{V}-\mathbf{C})\cdot\nabla T]\,d\,\ln p}_{TADV} \\ &+ \underbrace{R\int_p^{p_b} S\omega\,d\,\ln p}_{ADIAB} + \underbrace{R\int_p^{p_b}\frac{\dot{Q}}{c_p}\,d\,\ln p}_{DIAB}\end{aligned} \tag{3.4}$$

$$\frac{\delta\Phi_p}{\delta t} \approx \underbrace{\nabla^{-2}[-f(\mathbf{V}-\mathbf{C})\cdot\nabla(\zeta+f)]}_{VADV} + \underbrace{\nabla^{-2}[-f(\zeta+f)\nabla\cdot\mathbf{V}]}_{DIV} \tag{3.5}$$

The bottom layer (in this study at 1000 hPa) is represented by the geopotential Φ_b, while the top layer (in this study at 300 hPa) is represented by Φ_p. Also, $S \; = \; -T\partial ln\;\Theta/\partial p$ is the static stability parameter, with potential temperature Θ. $\dot{Q}/c_p$ is the diabatic heating rate, where $\dot{Q}$ is the latent heating rate of condensation and c_p the specific heat of dry air at constant pressure. A more detailed description can be found in Sinclair (1993b, 2004).

The three processes contributing to thickness tendency changes in Eq. 3.4 are TADV, ADIAB and DIAB. The two main processes contributing to geostrophic tendency changes in upper levels are VADV and DIV. A more detailed description of the processes and their interaction during the development of an ETC was given earlier in chapter 2.
By substituting Eq. 3.5 into Eq. 3.4, the tendency of the 1000 hPa height (Eq. 3.6) is obtained.

$$\begin{aligned}\frac{\delta\Phi_{1000}}{\delta t} \approx & -\underbrace{R\int_p^{1000}[-(\mathbf{V}-\mathbf{C})\cdot\nabla T]\,d\ \ln p}_{TADV} \underbrace{- R\int_p^{1000} S\omega\,d\ \ln p}_{ADIAB} \\ & -\underbrace{R\int_p^{1000}\frac{\dot{Q}}{c_p}\,d\ \ln p}_{DIAB(LH)} + \underbrace{\nabla^{-2}[-f(\mathbf{V}-\mathbf{C})\cdot\nabla(\zeta+f)]_p}_{VADV} \\ & + \underbrace{\nabla^{-2}[-f(\zeta+f)\nabla\cdot\mathbf{V}]_p}_{DIV} \end{aligned} \tag{3.6}$$

As can be seen from this equation, 1000 hPa height falls, which result in the deepening of a cyclone, occur in connection with warm TADV, sinking motions (associated with adiabatic warming) and diabatic heating, e.g. the release of latent heat, and with cyclonic VADV (negative in Southern Hemisphere) and divergence in the upper levels. On the other hand cold TADV, rising motions (associated with adiabatic cooling) and diabatic cooling, and anticyclonic VADV (positive in Southern Hemisphere) and convergence in the upper levels lead to 1000 hPa height rises.

The uncertainties of the estimates of each term on the right hand side (rhs) in Eq. 3.6 were found to be too high to reliably estimate the net sum of all processes (personal communications with MS). However, the relative contribution to the intensification of the cyclone by a process can be derived by correlating each term on the rhs of Eq. 3.6 with the actual deepening rate of that cyclone. The deepening rate is derived directly from the 1000 hPa height field. First the 1000 hPa heights are averaged over a 5° radius around the cyclone centre. Then the deepening rate is calculated following the storm as a centred time difference from the area average. As the deepening rate on the left hand side (lhs) of Eq. 3.6 is determined as a time centred difference over 24 h, a 1-2-1 filter was applied to the rhs terms of the equation for consistency. Experiments by MS (personal communications) have shown this to give better closure between the lhs and rhs of Eq. 3.6.
For this study the terms from Eq. 3.6 were available as part of a software package that contains equations for several meteorological parameters and processes, and that was kindly provided by NIWA (National Institute of Water and Atmospheric Research, New Zealand). This software package was used in several papers by MS, such as Sinclair (1993b), Sinclair and Revell (2000) and Sinclair (2004).

3.3.3 Latent Heat

As described in chapter 2, strong latent heating rates in the upper levels from deep convection are a distinct feature in the development of a TC (Anthes, 1977; Sinclair, 1993a). In comparison, most of the latent heat released in the development of ETCs stems from large-scale ascent and the maximum heating rates are generally found in the lower levels (e.g., Rausch and Smith, 1996; Carlson, 1991).

The distinct difference in the latent heating rates is used here to help determine the extent to which the development of a STC resembles that of a TC or ETC.
The latent heating rates from large scale ascent $\dot{Q}/c_p$ (here referred to as LSHR) and those by convective processes (here referred to as CHR) are both also provided by the software mentioned above. It is assumed that $\dot{Q}/c_p$ arises from the release of latent heat through condensation during resolved saturated ascent (Sinclair, 2004). According to Sinclair (1993a), the resolved saturated ascent is calculated following Haltiner and Williams (1980). Precipitation is presumed to commence for relative humidity above 60%, as suggested by Haltiner and Williams (1980).
According to Sinclair (1993b), for the calculation of latent heat released by convection, the parameterisation of the convectional processes is based on the Kuo parameterisation scheme, with some adjustments by Edmon and Vincent (1976).

3.4 Summary

This concludes the description of data and some of the methods used in this study. As shown, cyclone tracks are essential for the investigations in this study. The tracks used here are provided by two existing databases. From those the relevant subsets were extracted using the criteria listed and explained in section 3.2.5. The suitability of those criteria is tested in chapter 5. This chapter also contains a climatology compiled with the cyclone tracks discussed in section 3.1. In chapter 6, the UKMO data is used to analyse the influence of the upper-level flow on the behaviour and characteristics of STCs. The final results chapter, chapter 7, investigates the structure and development process of STCs using the methods described in sections 3.3.2 and 3.3.3.

4 Impact of STCs on New Zealand

In the introduction to this study it was stated that although STCs (cyclones of subtropical origin) occur less frequently than ETCs (extratropical cyclones), they are responsible for causing significant damage in New Zealand. To support this statement, an example of a STC that caused severe flooding and wind damage in the north of New Zealand was given. In this chapter a more detailed examination of the impact STCs have on New Zealand is carried out.
First a brief description of the source for the damage reports on STCs in New Zealand is given. Then the characteristics of the damage caused by STCs are studied in more detail by analysing the type of damage, its frequency and the regions in New Zealand most affected. In addition, in order to get a measure of the severity of damage, actual insurance payouts in New Zealand from STC events are investigated.

4.1 Data Source for Damage Reports

The analysis presented here is based on the quarterly reports by T. McGavin[15] in the New Zealand Meteorological Society Newsletter (McGavin, 1990-2005). These articles give an overview of weather events and their effects on New Zealand, including synoptic information and damage reports from affected areas. The sources for his

[15] Current affiliation: Meteorological Service of New Zealand, Wellington, New Zealand

damage reports are a mixture of news items on TV and newspaper articles from the Dominion Post and the NZ Herald on the web.

The articles by McGavin (1990-2005) were chosen because they provide a clear picture of the impact these cyclones have in terms of actual damage, compared to observational data. The selection of the cases presented in the articles is relatively subjective. According to McGavin (personal communications), in general a case is included in the articles if it was reported to have caused damage in New Zealand or if it was unusual from a climatological point of view.

The reports cover damage by wind and rain. In the articles, the term 'heavy rain' refers to rainfall rates of more than 5 mm per hour or totals exceeding about 75 mm in 24 hours (personal communications with T. McGavin). 'Gale force winds' generally refers to mean wind speeds over 30-35 knots (56-65 km/hr).

The reports do not necessarily give an indication of where a cyclone originated. However, with the help of weather charts in the articles, it was possible to match some of these cyclone events to cases from the MS database. With this information it was then possible to determine whether a cyclone mentioned in the articles formed north of 30°S and could be classified as a STC. The reports on those cyclone events were then analysed in more detail.

4.2 Characteristics of Reported Damage

According to the MS database, 46 STCs came into the vicinity of New Zealand[16] during the period from 1990 to 2005. This is an annual average of approximately 3 STCs.

[16]Refers to cyclones that pass within 250 km of New Zealand or cross New Zealand.

Of those 46 cyclones, 38 are mentioned in the articles by McGavin (1990-2005) as having caused some kind of damage in New Zealand. The remaining 8 cyclones were apparently not covered by the media, most likely because they caused no significant damage.

4.2.1 Spatial Analysis

A detailed analysis of all reports reveals that the North Island of New Zealand is the region most affected by STCs (Fig. 4.1), in particular Northland, Coromandel Peninsula and the area around Gisborne. A map of New Zealand showing the places mentioned in this section can be found in Fig. 4.2.
The fact that STCs predominantly affect the North Island of New Zealand is not surprising, considering that STCs form in the subtropics and therefore are most likely to approach New Zealand from the north. According to the reports, damage

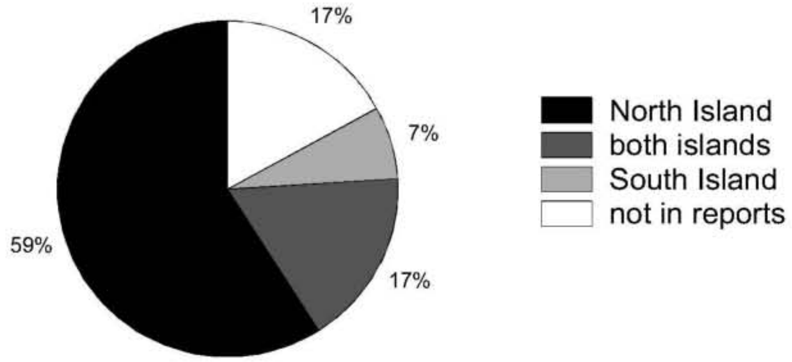

Figure 4.1: *Regional distribution of reported damage in New Zealand by cyclones of subtropical origin from the MS database as mentioned in McGavin (1990-2005). 'not in reports' refers to STCs from the MS database that are not mentioned in the articles by McGavin (1990-2005).*

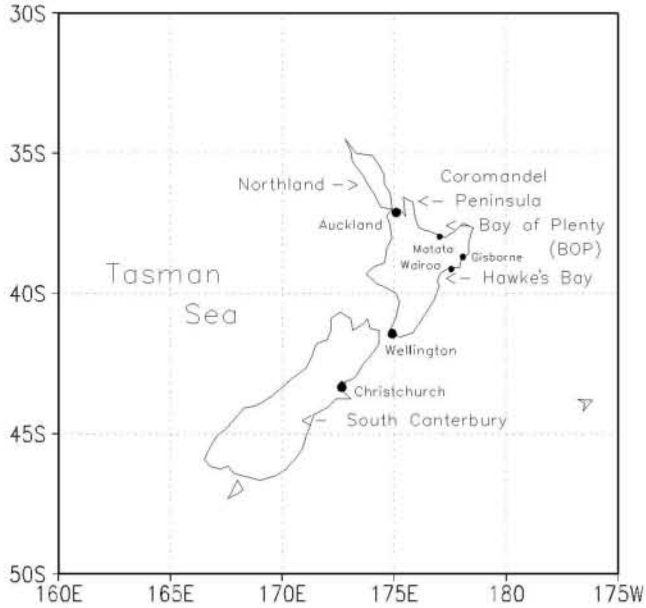

Figure 4.2: *Map of New Zealand highlighting the places mentioned in this section.*

caused by STCs frequently occurs along a particular route starting in Northland, passing over Coromandel Peninsula, the Bay of Plenty (BOP) and finally the area around Gisborne. This indicates a preferred track of STCs when coming into the vicinity of New Zealand. On a few occasions only regions on the east coast of the North Island, near Gisborne and Hawke's Bay, are affected.
The pie chart in Fig. 4.1 also shows that the impact of STCs is not restricted to the North Island. In 24% of cases damage was reported for the South Island. Further analysis reveals that in those cases the STCs moved across the Tasman Sea and approached New Zealand from the west. This is in general more typical for so-called 'Meteorological Bombs'. These are cyclones undergoing rapid intensification, which, as mentioned in the introduction, is a common feature in the Tasman Sea region. According to a study by Leslie et al. (2005), these cyclones, which are mostly of mid-

latitudinal origin, intensify over the Tasman Sea and then approach New Zealand from the west, thereby predominantly affecting the South Island.
Furthermore, the majority of damage in New Zealand associated with STCs occurs in coastal regions. On only 3 occasions during the 5 years covered by this study did STCs cause damage inland by moving directly across the central North Island.

4.2.2 Type of Hazards

An analysis of the type of hazards typically connected with STCs found that all 38 STCs from the MS database mentioned in the articles by McGavin (1990-2005) were associated with heavy rain (Fig. 4.3). Qi et al. (2006) made the heavy rainfall a selection criterion when they investigated cyclones of subtropical origin and their impact on Australia. For the majority of STCs analysed here, the heavy rain resulted in extensive flood damage.
Further analysis reveals that in only a few cases were the floods caused by extremely heavy rainfall of short duration. More often the floods were the result of prolonged periods of rain from slow moving or stationary lows (e.g. October 2005, McGavin (1990-2005)). In a few instances extremely bad floods were caused by multiple cyclone events over a short period of time, which were not always of subtropical origin (e.g. June 1992, McGavin (1990-2005)).
The analysis also showed that only 12 of the 38 STCs were accompanied by strong winds (Fig. 4.3) that led to wind related damage. In comparison, most of the damage caused by ETC events is wind related.
According to the data, the majority of the 12 STCs with strong winds formed in winter. In contrast to the wind damage caused by STCs, flood related damage shows no significant interseasonal variations.

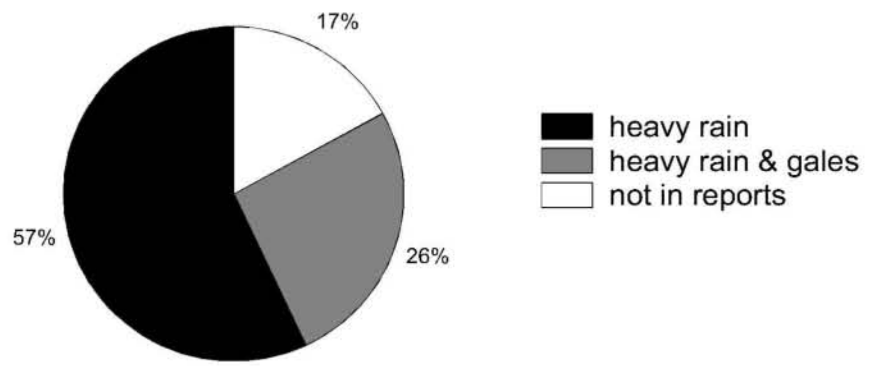

Figure 4.3: *Distribution of reported heavy rain and gale force wind events throughout New Zealand by cyclones of subtropical origin from the MS database as mentioned in McGavin (1990-2005).*

The lack of seasonal variations in heavy rain events is most likely caused by a lack of significant seasonal variations in the moisture associated with STCs. The latter can most likely be attributed to the fact that STCs originate in the subtropics, where it is relatively warm and moist all year round. So, it is suspected that when STCs leave the subtropics, they drag the moist air along with them into midlatitudes. A detailed analysis of the moisture associated with STCs is carried out later in this study.

4.3 Insurance Payouts

To get an even better understanding of the severity of the damage caused by STCs, insurance payouts for claims that arose from damage caused by STC events were studied. Of the 46 STCs that, according to the MS cyclone track database, came into the vicinity of New Zealand, 7 events are listed by the Insurance Council

Year	Location		Type of Hazard	Season	Payouts
1994	South Canterbury	MS 116	Flood	Su	1.5
1997	Wairoa	MS 171	Flood	Wi	0.5
1997	Northland	MS 172	Flood	Wi	1.2
1998	North and South Island	MS 184	Flood/Storm	Wi	11.8
2004	Eastern Bay of Plenty	MS 292	Flood	Wi	17.6
2005	BOP Tauranga/Matata	MS 309	Flood	Au	28.5
2005	Gisborne/East Cape	MS 314	Flood	Sp	0.7

Table 4.1: *Original insurance payouts [million dollars] for claims from 7 STCs during the period from 1990 to 2005 (Figures from Insurance Council of New Zealand website: www.icnz.org.nz/current/weather). Third column shows case number for matching STC event from MS data base. Su = Summer (DJF), Au = Autumn (MAM), Wi = Winter (JJA), Sp = Spring (SON).*

of New Zealand as having cost the insurance industry significant amounts in claims (Tab. 4.1, Figures from Insurance Council of New Zealand website: www.icnz.org.nz/current/weather). The total insurance payout for these 7 events was approximately $62 million. As can be seen from the table, those payouts stem mostly from damage caused by floods. At over $28 million, which is almost half the total amount of insurance payouts from all 7 events, the flood in Matata in May 2005 appears to have been the most damaging case of the 7 events in terms of property losses.

According to that same Insurance Council list, another 26 flood events occurred between 1990 and 2005 (see table at: www.icnz.org.nz/current/weather), resulting in an additional $107 million in insurance payouts. This means STCs made up only

21% of the total number of disasters resulting in extensive flood related damage during those 16 years. However, the insurance payouts from those 7 events amounted to almost 40% of the total payouts for flood related damage during that time period.

4.4 Discussion

Although the reports by McGavin (1990-2005) are quite subjective, they clearly depict the impact STCs, and in particular their associated moisture, have on New Zealand.

To date this group of cyclones in the Southwest Pacific region has largely been neglected in the literature. However, as just shown these cyclones can occur 2-3 times a year and can cause property losses in the millions of dollars. The frequency and magnitude of damage by STCs in New Zealand emphasises the importance of a detailed understanding of the mechanisms involved in the development of these cyclones and warrants a comprehensive study of these cyclones. In the following chapter a detailed climatology on their behaviour and characteristics, including frequency, movement and intensity, is presented. After that the mechanisms of their movement and intensification are investigated in more detail.

5 Climatological Overview

In this chapter a climatology of the behaviour and characteristics of STCs (cyclones of subtropical origin, not including TCs) in a region of the Southwest Pacific[17] is compiled.

The aim of the first section in this chapter is to analyse seasonal and interannual variability in frequency, movement and intensity of STCs. Particular emphasis is given to those STCs that come into the vicinity of New Zealand. The findings will provide the necessary background required for the investigations in the following chapters, where the mechanisms that determine the movement and development of STCs, in particular the dynamics during formation and intensification, are considered.

In the second section the robustness of the climatology is evaluated. First, the sensitivity to the cyclone selection criteria, which are listed in section 3.2, is examined. Then, the sensitivity of the climatology to the use of different cyclone track databases is assessed. This is to ensure that findings from the climatology can be linked to findings from the following chapters, for which a different cyclone track database is used. An explanation for the use of two different cyclone track databases was given in chapter 3.

[17] A map outlining this area is given in Fig. 3.1 in section 3.1.

5.1 Seasonal and Interannual Variability

Initially the climatology of STCs was compiled using the TR database. However, it was found that the period of 5 years covered by that database was insufficient to derive conclusive interannual or even interseasonal patterns. Accordingly, it was decided to use the MS database for the compilation of the climatology. A description of how cyclones were identified and tracked and the selection criteria applied in this study can be found in section 3.2.

The 21 years covered by the MS database not only provide the opportunity to investigate seasonal and interannual variations in the behaviour and characteristics of STCs, but also the opportunity to analyse temporal trends in the occurrence of those cyclone events.

In the following sections, spatial and temporal patterns in the formation[18], movement and intensification[19] of STCs are investigated. Then temporal trends in the number of STCs are examined. The section concludes with an analysis of the influence of the El Niño-Southern Oscillation phenomenon (ENSO) on the behaviour and characteristics of STCs.

5.1.1 Cyclone Genesis

According to the MS cyclone track database, a total of 322 STCs formed in the subtropics, north of the Tasman Sea and New Zealand, between January 1985 and April 2006. This is an annual average of approximately 15 STCs a year. A detailed description of the cyclone selection criteria applied in this study can be found in section 3.1.

[18]Formation, as well as cyclone genesis, refers to the first track point of each cyclone.

[19]Intensification refers to all track points from formation to maximum intensity.

Preferred regions for STC genesis are highlighted in the system density plots in Fig. 5.1. Using density plots to visualise the spatial distribution of cyclones was suggested by Sinclair (1994) and Simmonds and Keay (2000b). Here, the density plots are compiled by dividing the grid into 5° by 5° boxes, which are centred on each grid point on a 2.5° by 2.5° grid. Then the number of cyclones forming in a box is determined for each box. It was decided not to include a latitude adjustment for each box, since the area analysed here only spans 15°S to 30°S.

As can be seen, the majority of STCs form over the Fiji Sea. Other areas of increased STC formation are southeast of New Caledonia and over the Coral Sea.

According to Fig. 5.2, the greatest fraction, approximately 1/3 of STCs, forms during autumn, followed by summer. Throughout the study, summer is defined as December, January and February (DJF), autumn as March, April and May (MAM), winter as June, July and August (JJA) and spring as September, October and November (SON).

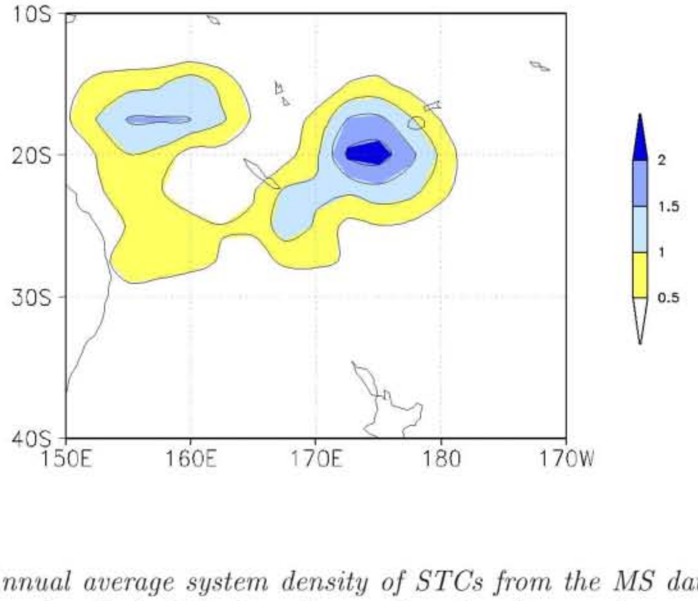

Figure 5.1: *Annual average system density of STCs from the MS database at formation. System density is defined as the number of cyclone centres per grid box (5° by 5°). Contours are in intervals of 0.5 cyclones per grid box.*

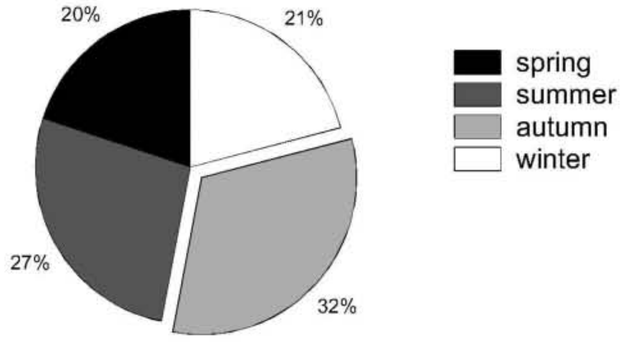

Figure 5.2: *Seasonal distribution [%] of STCs from the MS database at formation. For definitions of the seasons see text.*

The seasonal composites of the system density at formation in Fig. 5.3 reveal that during summer and autumn the formation of STCs is considerably higher over the Fiji and Coral Seas than during the other two seasons. This is similar to findings for TCs in this region. Studies found that most TCs also form during summer and early autumn, with increased genesis in particular over the Coral and Fiji Seas (e.g. Terry, 2007).

A possible explanation for the higher number of STCs during summer and autumn over the Fiji Sea could be the higher SSTs (sea surface temperatures) in the region. In chapter 2 it was argued that the formation of some STCs most likely resembles that of TCs. Thus, SSTs above 26.5°C would favour the formation of those STCs. According to the seasonal composites of SSTs in Fig. 5.4, during summer and autumn SSTs over the Fiji Sea are on average above 27°C. In comparison, during winter and spring SSTs are in general below 26°C in this region.

Correlating the seasonal[20] and spatial average of SSTs in the Fiji Sea[21] with the number of STCs forming in the area yields a correlation coefficient of 0.28. This

[20]3 month averages for the 21 years.

[21]Area between 17.5°S to 22.5°S and 167.5°E to 177.5°E.

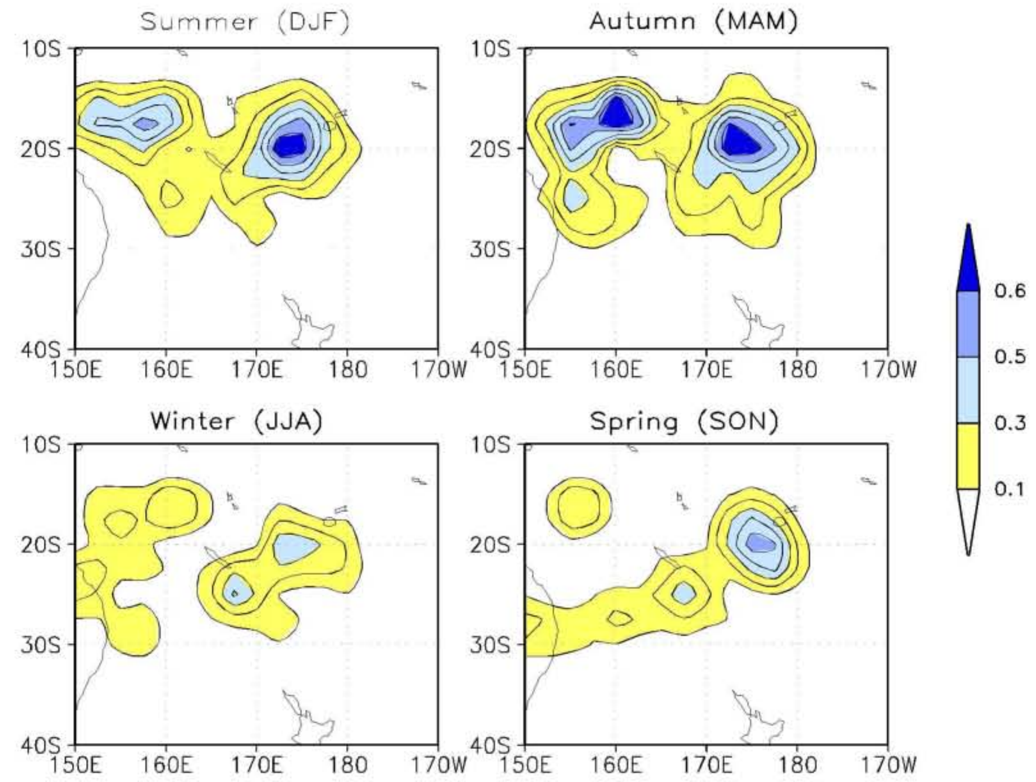

Figure 5.3: *Seasonal composites of average system density of STCs from the MS database at formation. System density is defined as the number of cyclone centres per grid box (5° by 5°). Contours are in intervals of 0.5 cyclones per grid box.*

coefficient is considered statistically significant on the 95% level. It means approximately 8% of the variations in both time series are related.

The relatively low correlation can be explained when considered alongside the discussions in chapter 2 regarding the propagation of baroclinic waves into the subtropics in this region, in particular during the colder seasons. It is believed that in those instances the development of STCs is driven by baroclinicity in the same way as that of ETCs. Thus, it is possible for STCs to develop despite low SSTs.

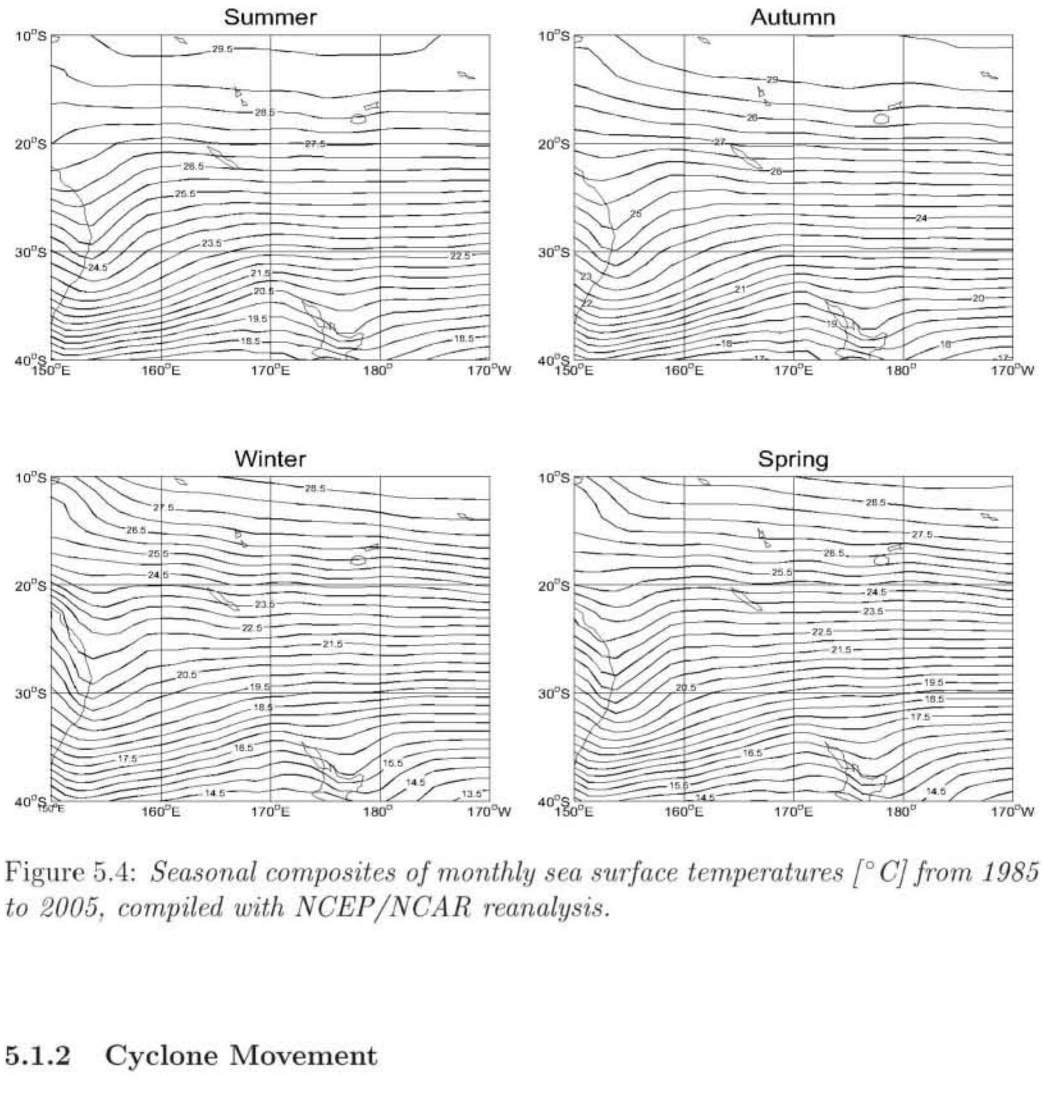

Figure 5.4: *Seasonal composites of monthly sea surface temperatures [° C] from 1985 to 2005, compiled with NCEP/NCAR reanalysis.*

5.1.2 Cyclone Movement

According to the discussions in chapter 2, the movement of cyclones is strongly influenced by the background flow in the atmosphere. Fig. 5.5 features the average motion vectors for the surface centres of all STCs from the MS database. The motion vector plot was created in the same way as the system density plots. Only here, instead of counting the number of cyclones in a box, the average motion vectors of any STCs moving through a box are calculated.

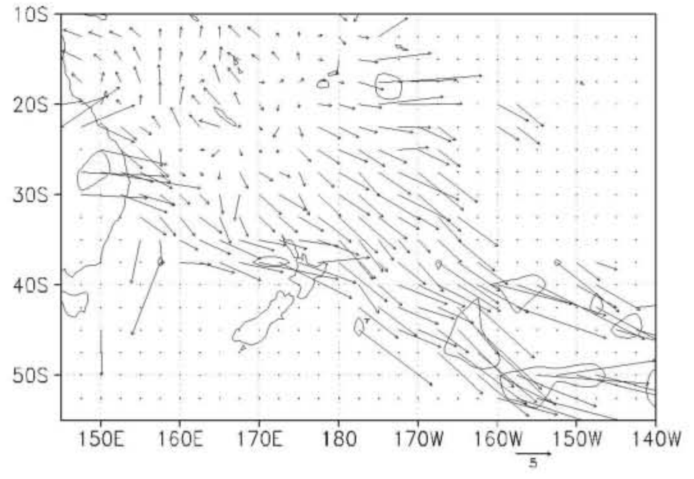

Figure 5.5: *Average motion vectors [kt] for the surface centres of all STCs from the MS database. Only averages calculated with more than 2 values are displayed. All others are set to zero. Speeds above 10 kt are contoured in 10 kt intervals.*

As can be seen, north of 20°S the movement of STCs has on average a south-easterly component with a relatively slow speed. This is consistent with the easterly Trade Winds, which are directed toward the equator. South of 20°S the movement takes on a north-westerly component, turning more northerly with increasing latitude and increasing in speed as well.

The plots of STC tracks[22] in Fig. 5.6 reflect the features of the system density in Fig. 5.3 and the motion vector plots. They show a large density of tracks over the Coral and Fiji Seas. The southeast movement, as well as the relatively low speed, tend to keep STCs forming in the lower latitudes in the region. On the other hand, the turning direction and increasing speed south of 20°S explain the number of STCs leaving the subtropics. In fact, approximately 50% of all STCs, on average 8 per year, move into midlatitudes[23] at some stage during their lifetime.

[22]The path a cyclone follows is called cyclone track.

[23]Defined as moving south of 30°S.

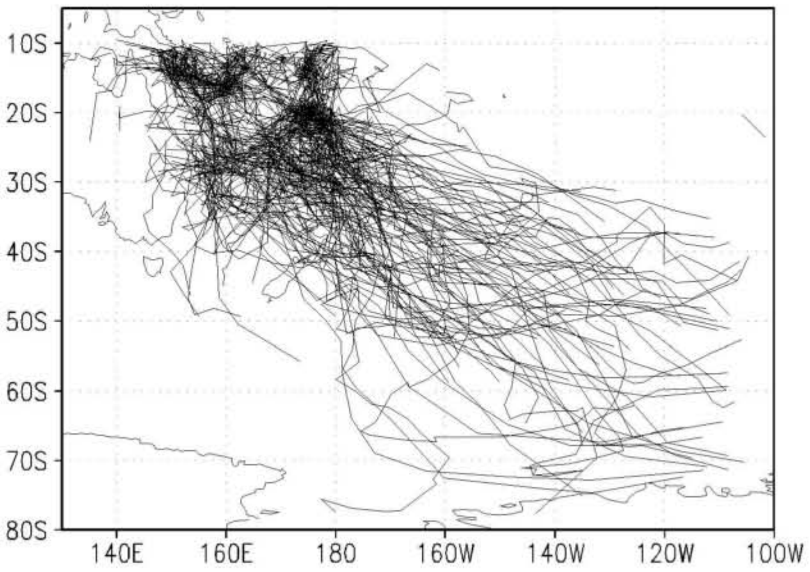

Figure 5.6: *Cyclone tracks of all STCs from the MS database.*

The seasonal composites of the cyclone motion (Fig.5.7) and tracks (Fig.5.8) show distinct differences between summer and winter. They reflect the seasonal differences in the background flow, which were discussed in chapter 2. They are also consistent with findings for other cyclones in this region (e.g. Sinclair, 1994).
During winter, the movement of STCs turns from southeast to northwest 5° further north than during summer. In addition, in comparison to summer STCs the speed is much greater. However, the movement is also slightly more zonal. The latter accounts for the greater number of STCs east of 160°W during winter (Fig. 5.8).
On average STCs are most likely to move into midlatitudes during winter, whereas summer STCs tend to stay in the subtropics (Tab. 5.1). A likely explanation is the fact that, as discussed in chapter 2, during winter baroclinic waves propagate much more frequently and much further into the subtropics than during summer. Thus,

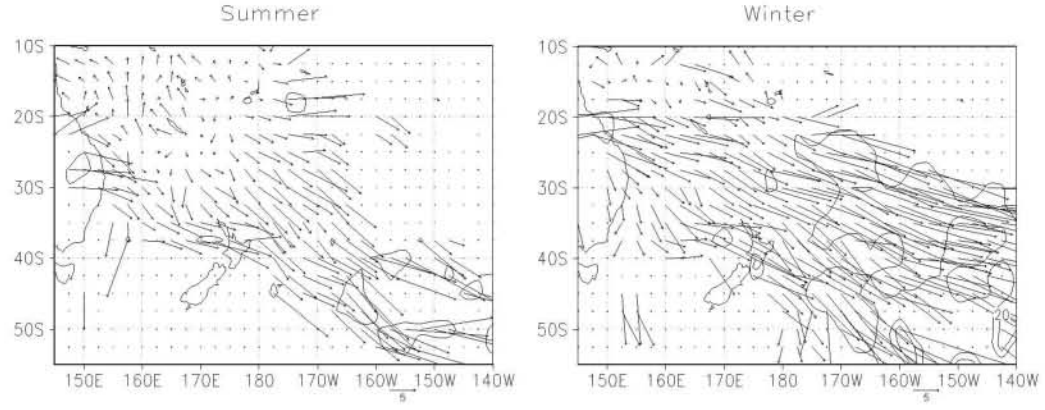

Figure 5.7: *As in Fig. 5.5, only here seasonal composites of motion vectors [kt] during summer (left) and winter (right).*

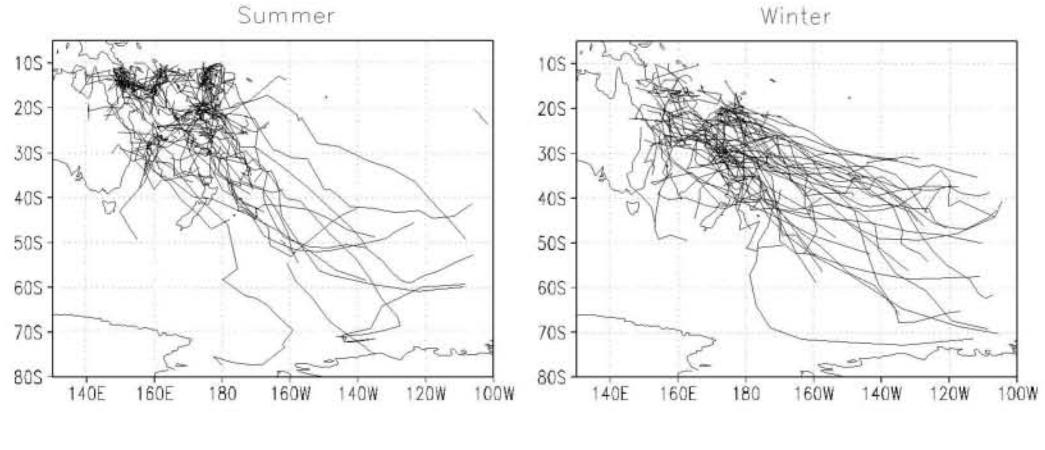

Figure 5.8: *As in Fig. 5.6, only here seasonal composites of tracks during summer (left) and winter (right).*

	Summer	Autumn	Winter	Spring
Total	88	102	67	65
Annual average	4	4.7	3.2	3.1
	(± 2.8)	(± 2.1)	(± 1.7)	(± 2.1)
Moving south of 30°S (total)	32	41	51	35
	36%	40%	76%	54%
In vicinity of New Zealand (total)	15	15	21	14
	17%	15%	31%	22%
Average speed	11.1	12.3	16.8	14.4
	(±3.7)	(±4.6)	(±4.8)	(±4.9)

Table 5.1: *Seasonal frequency of STCs from the MS database (total, annual average, total moving south of 30°S and into vicinity of New Zealand). Seasonal average speed [kt] of STC movement (bottom row). Values in brackets represent standard deviations. Percentages are fractions of season total.*

during that time of year the surface centres of STCs are more likely to couple with a trough and be steered south into midlatitudes than during summer.

A seasonal analysis shows that winter is also the season when STCs are most likely to come into the vicinity of New Zealand (Tab. 5.1, row 4). According to the tracks in Fig. 5.9, only a small fraction of STCs cross the country. Many STCs, in particular during winter, pass just to the north of New Zealand. This is consistent with the discussions in chapter 4, according to which most damage was reported in the northern half of the country, in particular in Northland, Coromandel Peninsula and the Bay of Plenty. As indicated by the damage reports, STCs rarely cross the South Island or come into close proximity of it.

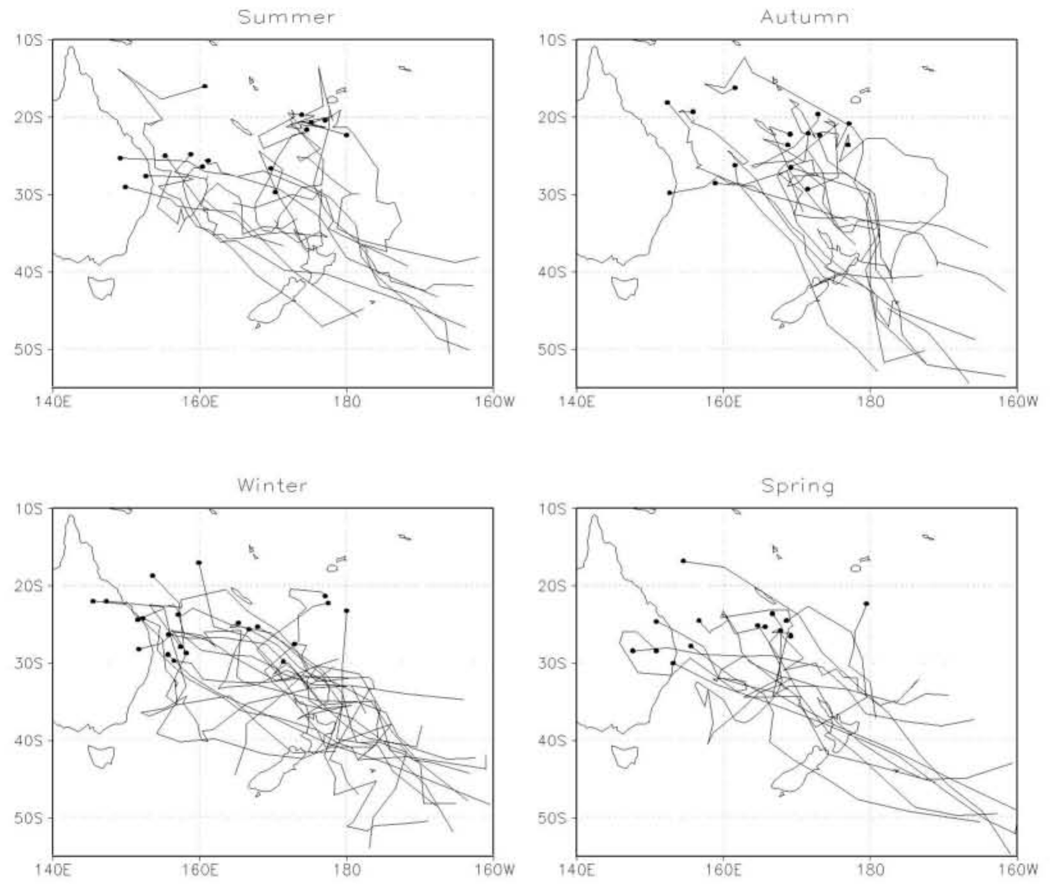

Figure 5.9: *Seasonal composites of STC tracks from the MS database that came into the vicinity of New Zealand. Location of cyclone genesis for each cyclone is marked with a dot.*

A look at the point of origin of the STCs that come into the vicinity of New Zealand reveals that, although it was shown most STCs form over the Fiji Sea, only a small fraction of those migrate into the vicinity of New Zealand. The majority of STCs that come into the vicinity of New Zealand form off the east coast of Australia. Another cluster can be found south of New Caledonia, in particular during winter and spring.

5.1.3 Length of Track and Intensification Period

There are no significant seasonal differences in the track length[24] of STCs. On average STCs exist for 7 days.

However, there are differences between the lifespan of STCs that stay in the subtropics and those that move into midlatitudes at some point during their life cycle. The average duration of the former is approximately 5 days shorter than that of the latter. Fig. 5.10 depicts the number of cyclones as a function of the number of days a cyclone exists (rounded down to the nearest full day). As can be seen in the plot, STCs that stay in the subtropics (black bars) are concentrated to the

[24]Refers to lifespan of a cyclone, covering all track points from formation to decay.

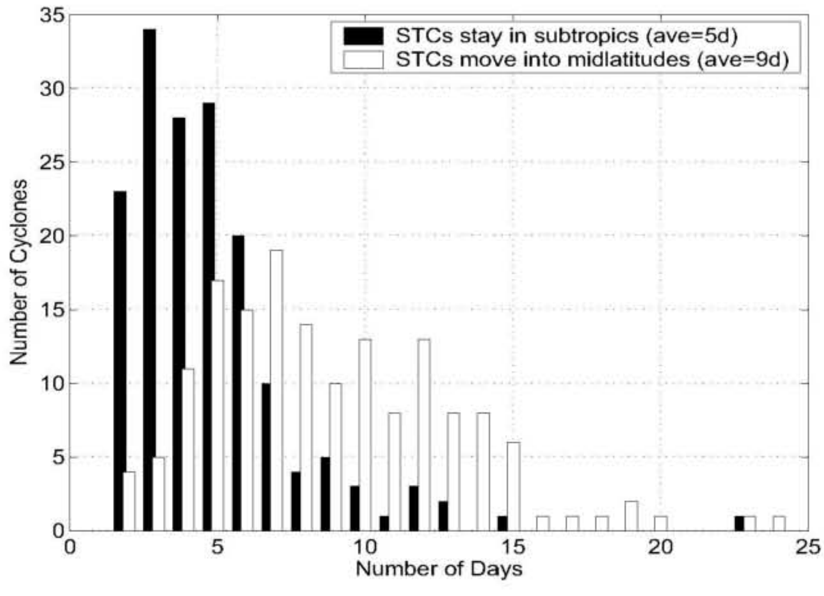

Figure 5.10: *Frequency distribution of duration in days (rounded down to the nearest full day) for STCs from the MS database. STCs that stayed in the subtropics are represented by black bars and those that moved south of 30°S by white bars.*

left of the graph, towards the shorter durations, with the majority of these STCs only existing for between 2 and 7 days. In comparison the distribution of STCs that move into midlatitudes (white bars) is much more widely spread. The majority of these cyclones exist for between 4 and 14 days.
Similarly the duration of the intensification periods[25] differs for STCs that remain in the subtropics and those that move into midlatitudes, the former being 3 days and the latter 5 days.
Considering the discussions about the conceptual models of STC development, likely explanations for the generally short lifespan of STCs that stay in the subtropics include a relatively shallow oceanic mixed layer and the absence of an upper-level trough during intensification. Although the warm ocean surface might be a contributing factor to the formation of STCs over the Coral and Fiji Seas, the shallowness of the warm oceanic layer may not only explain why STCs do not develop fully into TCs, but may also be the reason for the early demise of some STCs. In addition, STCs tend to migrate poleward, where the waters are cooler. This would also destroy any link with the SSTs. If an STC is not picked up by an upper-level trough, it will just decay, hence the generally short lifespan of STCs that stay in the subtropics. If a STC is picked up by a trough, there is a chance that the cyclone will undergo extratropical transition, thereby prolonging its lifespan and intensification period.

5.1.4 Intensification Rates and Maximum Intensity

According to Fig. 5.11 (plot on the left), regions of increased STC intensification can be found just off the east coast of Australia near 30°S and to the east of New Zealand over the South Pacific south of 30°S. The plot shows the average intensification

[25]The intensification period covers all track points from formation to maximum intensity.

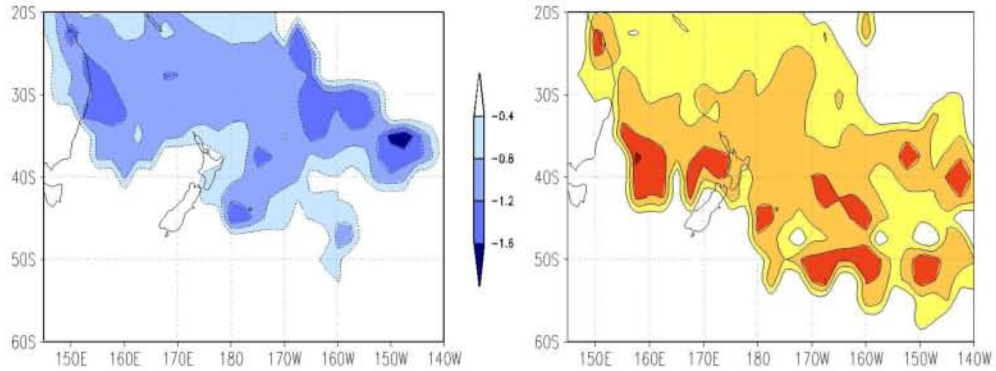

Figure 5.11: *Average intensifications rates [$*10^{-5}s^{-1}$ per day] for all STCs from the MS database. Left plot: only negative values, which represent the strengthening of cyclones. Right plot: only positive values, which represent the weakening.*

rates, using only negative values, which represent the strengthening of a cyclone. The plots were created in the same way as the system density and motion vector plots. A description of how the intensification rates are calculated can be found in chapter 3.3. The increased intensification off the east coast of Australia near 30°S is particularly strong during winter (Fig. 5.12). Similar findings were shown by several other studies, such as Sinclair (1995a, 1997b). Sinclair (1995a) attributes the increased cyclogenesis to the strong horizontal temperature gradient in that area, which is caused by the warm ocean currents along the east coast of Australia and the cold continent during winter.

Regions where STC weakening is prevalent, eventually leading to their demise, can be found off the east coast of Australia near 23°S, over the Tasman Sea, just to the west of New Zealand, and to the east of New Zealand over the South Pacific south of 40°S (Fig. 5.11, plot on the right). Except for the region on the east coast of Australia near 25°S, most regions of STC weakening occur downstream of increased intensification. This is consistent with findings by other studies, such as Sinclair

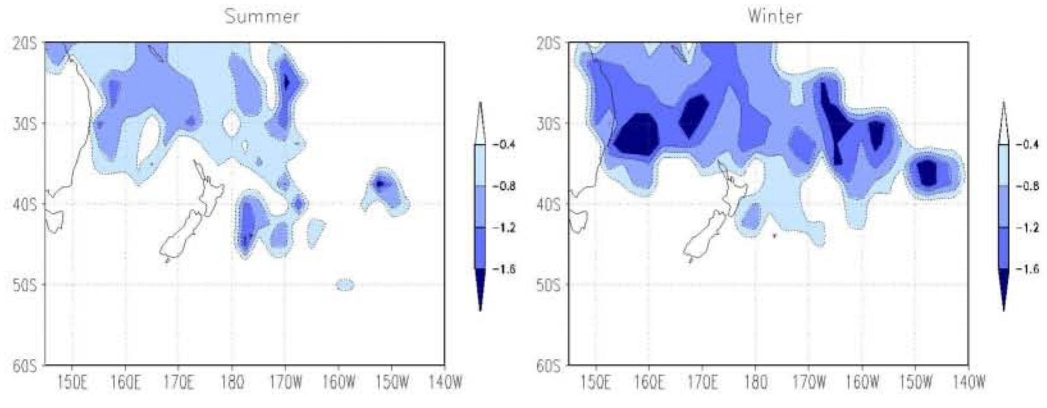

Figure 5.12: *As in the left hand plot in Fig. 5.11, only here seasonal composites of STCs strengthening during summer (left) and winter (right).*

(1995a). The increased prevalence of STCs weakening off the east coast of Australia near 25°S appears to be a summer occurrence (Fig. 5.13). Summer is also when TCs tend to decay in this area after making landfall (e.g. Terry, 2007).

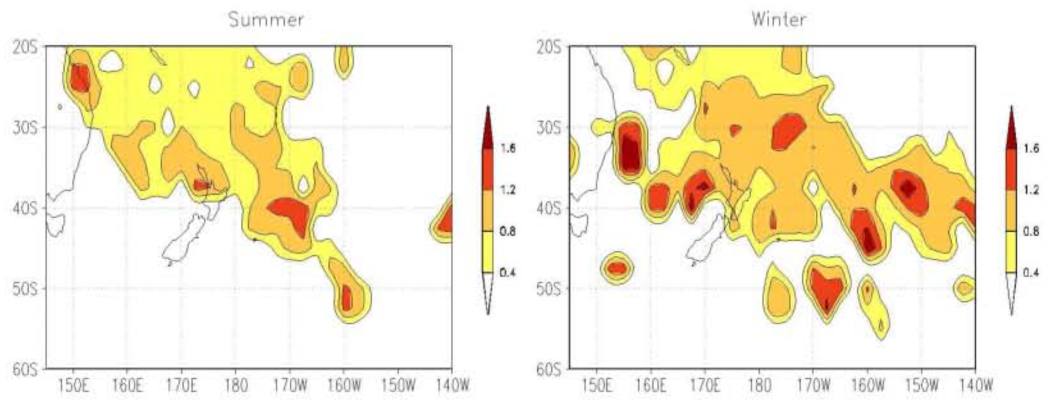

Figure 5.13: *As in the right hand plot in Fig. 5.11, only here seasonal composites of STCs weakening during summer (left) and winter (right).*

Considering that the strongest intensification rates occur south of 30°S, it is not surprising that STCs that move into midlatitudes are on average more intense than those that stay in the subtropics. One also has to keep in mind that TCs, which are a subgroup of cyclones originating in the subtropics and which cover the intense part of the spectrum, are not considered here. Thus, the intensities of STCs that remain in the subtropics are on average not that high.
This is supported by Fig. 5.14. The composites depict the location and approximate values of maximum intensities for STCs that stay in the subtropics (top plot) and for those that move into midlatitudes (bottom plot). As can be seen from the bottom plot, more than 60% of the STCs that move into midlatitudes have a maximum intensity above the average (blue circles). Moreover almost all of them attain their maximum intensity south of 30°S. In comparison, less than 10% of STCs that stay in the subtropics reach maximum intensities above average. The majority of these STCs have a maximum intensity below the average (red crosses).
The analysis of seasonal variations in the maximum intensities found that STCs are on average most intense during winter (Tab. 5.2). This is consistent with earlier findings, which showed that the majority of winter STCs move into midlatitudes and that these STCs are generally more intense than those that remain in the subtropics (Tab. 5.1, row 2). The same can be said of summer STCs. As shown earlier, summer

Summer	Autumn	Winter	Spring
-4.3 (± 1.3)	-4.4 (± 1.4)	-5.6 (± 1.9)	-4.6 (± 1.1)

Table 5.2: *Seasonal average maximum intensity [$*10^{-5}s^{-1}$] of STCs from the MS database. Values in brackets represent standard deviations.*

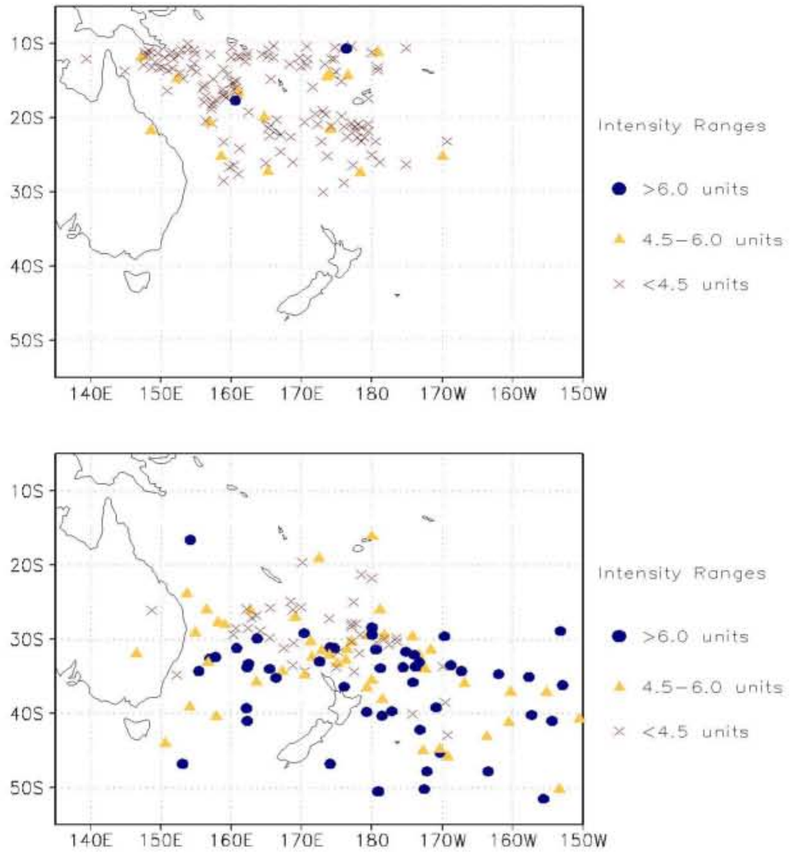

Figure 5.14: *Location of maximum intensity for STCs from the MS database that stay in the subtropics (top) and those that move into midlatitudes (bottom). Separation into three different intensity ranges: above 6.0 units = more than one standard deviation above average (blue circles); between 4.5 and 6.0 units (orange triangles); below 4.5 units = less than one standard deviation below average (red crosses). 1 unit* $= -10^{-5}s^{-1}$.

STCs tend to stay in the subtropics and STCs that remain in the subtropics are relatively weak.

Similar seasonal variations in frequency and maximum intensity apply to STCs coming into the vicinity of New Zealand (plots not shown here). In short, STCs are most likely to come into the vicinity of New Zealand during winter, and these STCs are generally more intense than during the other three seasons. This is consistent with the findings in the articles by McGavin (1990-2005), which reported increased occurrence of wind damage by STCs in New Zealand during winter.

Further analysis reveals that approximately 40% of STCs that came into the vicinity of New Zealand had already reached their maximum intensity and were therefore already in the decaying stage of their development. This is consistent with the area of increased weakening just to the west of New Zealand. Therefore, the potential damage in New Zealand from those cyclones could be even greater if they were to arrive in the vicinity of New Zealand while still in their intensifying stage.

5.1.5 Temporal Trends

As mentioned earlier, on average 15 STCs form annually in the subtropics north of the Tasman Sea. According to Fig. 5.15, there appears to be an increase in the number of STCs between 1985 and 2005. However, the positive trend indicated is not statistically significant at the 95% level. The annual fluctuations are too great for the length of time series to establish a statistical significant trend over the 21 year period.

Similar results are found for trends in the number of STCs moving into midlatitudes and into the vicinity of New Zealand. In both time series the positive trend indicated is again not considered statistically significant at the 95% level. This is also attributed to the strong annual fluctuations. These plots can be found in Fig. 9.1 and Fig. 9.2 in Appendix I.

Simmonds and Keay (2000a) showed in their study on ETCs in the Southern Hemisphere that there has been an increase in intense cyclone events between 1958 and 1997. At the same time they also found a decrease in the total number of cyclones during the same time period. Simmonds and Keay (2000a) argue that since the

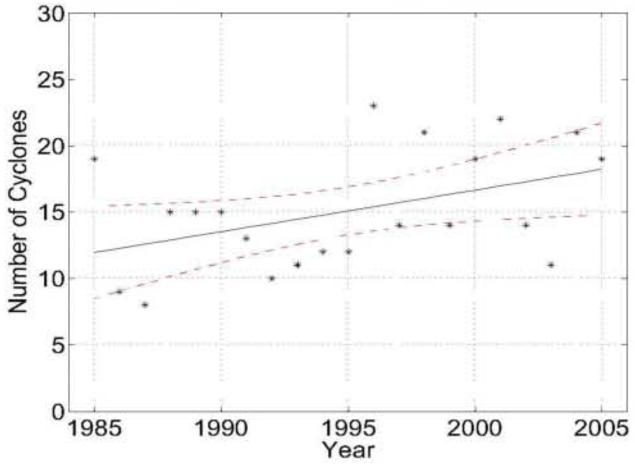

Figure 5.15: *Annual frequency of STCs from the MS database (black stars) between 1985 and 2005, including trend lines (solid black line) and 95% confidence intervals (dashed red lines) of the trend.*

number of cyclones decreases but their intensity increases, cyclones are more efficient with their energy transport between equator and pole.

The investigations here show neither a statistically significant negative trend in the overall number of STCs, nor an increase in the number of intense STCs that can be considered statistically significant at the 95% level (Fig. 5.16). 'Intense' refers to cyclones with a maximum intensity of more than one standard deviation above the average.

The main cause for the large standard deviation in the number of intense STC events appears to be one extreme outlier, an unusually high occurrence during 1990. The outlier is due to an unusually high number of intense winter STCs that year. An analysis of the 500 hPa height fields reveals that during the winter of 1990 an unusually high number of high amplitude baroclinic waves propagated across the Tasman Sea. The troughs in these waves most likely coupled with the winter STCs, steered them into midlatitudes and caused their strong intensification.

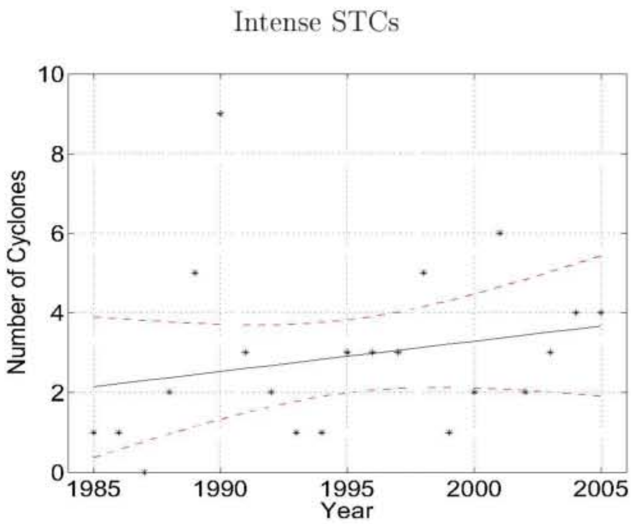

Figure 5.16: *Annual frequency of intense STCs from the MS database (black stars) between 1985 and 2005, including trend lines (solid black line) and 95% confidence intervals (dashed red lines) of the trend. 'Intense' refers to intensities more than one standard deviation above average.*

Based on the seasonal composites of the number of STCs in Fig. 5.17, the positive trend in the number of STCs can be considered statistically significant on the 95% confidence level. There are indications that the increase in summer STCs could in part have been caused by an increase in SSTs. As discussed earlier, there appears to be a link between the SSTs and the number of summer STCs, in particular over the Fiji Sea. According to a study by Roemmich et al. (2006), which investigates the mass and heat budgets in the Southwest Pacific, there has been an increase in SSTs since the early nineties.

The time series of summer STCs also features a noticeable outlier with an unusually high number of STC events during the summer of 2001. Further analysis reveals that the majority formed over the Fiji Sea. Considering earlier discussions, it is possible that the unusually high number that year was caused by increased SSTs. The

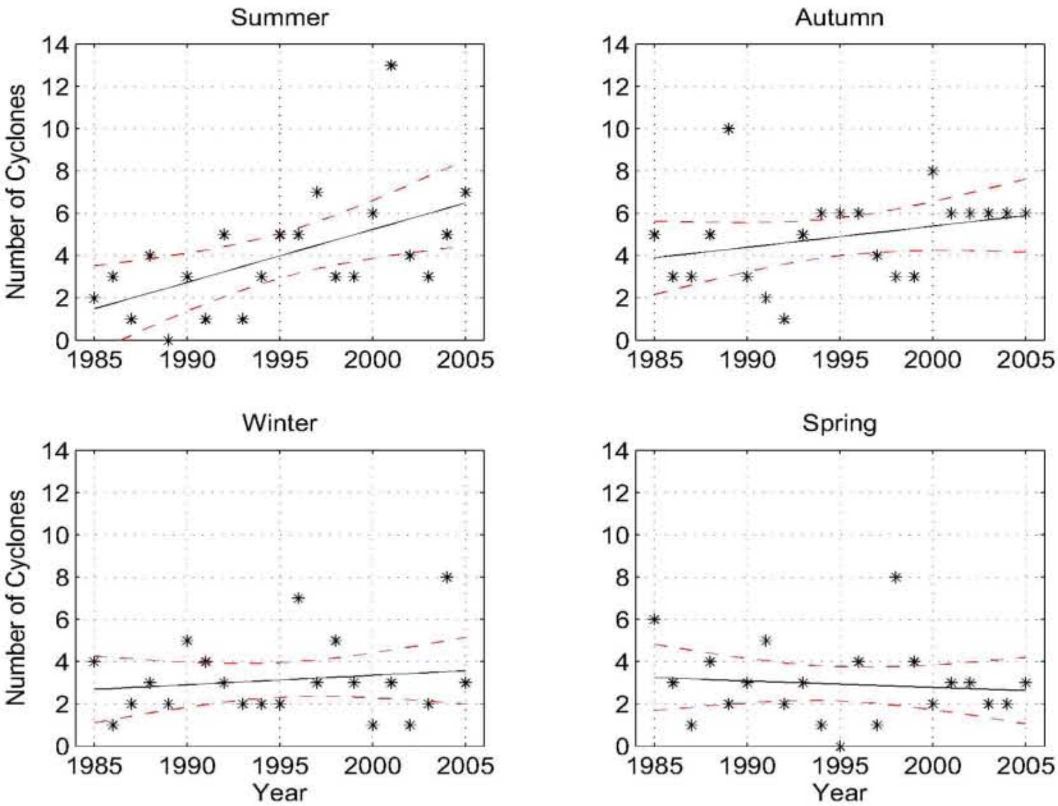

Figure 5.17: *Seasonal composites of the annual frequency of STCs from the MS database (black stars) between 1985 and 2005, including trend lines (solid black line) and 95% confidence intervals (dashed red lines) of the trend.*

positive SST anomalies confirm increased SSTs in that region during that summer. As can be seen in Fig. 5.18, SSTs over the Fiji Sea were on average 1°C warmer than usual during the summer of 2001. In addition, an analysis of the 500 hPa height fields revealed that at the same time, fewer than the usual 5 troughs propagated into the subtropics. This means the development of STCs during that summer was unlikely to have been driven by baroclinicity.

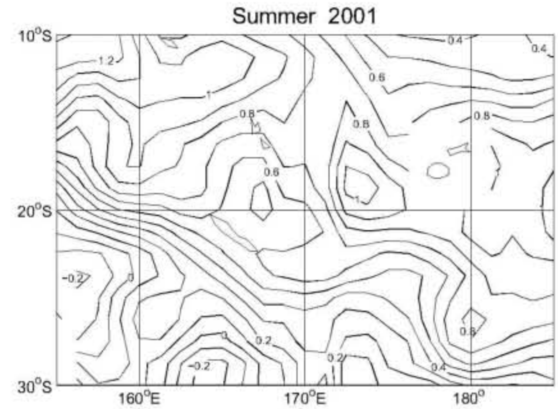

Figure 5.18: *Average sea surface temperature anomalies [°C] for summer 2001 (DJF), compiled with NCEP/NCAR reanalysis.*

5.1.6 Influence of ENSO

As shown in Fig. 5.15, there are strong fluctuations in the annual number of STC events between 1985 and 2005. In the Southwest Pacific interannual variations in the climate are often linked to the El Niño-Southern Oscillation (ENSO) phenomenon. ENSO is a global coupled ocean-atmosphere phenomenon. El Niño and La Niña refer to temperature fluctuations in the surface waters of the tropical eastern Pacific Ocean. The Southern Oscillation reflects fluctuations in the air pressure difference between Tahiti and Darwin, Australia.

During El Niño the air pressure difference between Tahiti and Darwin is smaller than normal, due to higher than usual pressure over Darwin. This leads to a decrease in the easterly Trade Winds, and consequently a warming of the central and eastern Pacific Ocean. Studies such as Sinclair (1995b) and Pezza and Ambrizzi (2003) have found that during such times the formation of cyclones increases over the eastern Pacific.

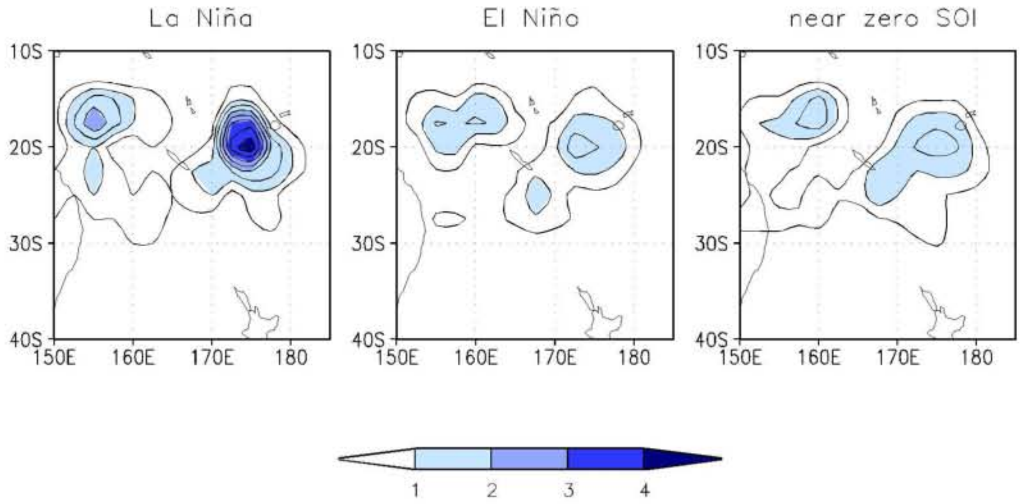

Figure 5.19: *Composites of average system density of STCs from the MS database at formation during La Niña (left), El Niño (middle) and near zero SOI (right) between April 1985 and May 2005. System density is defined as the number of cyclone centres per grid box (5° by 5°). Contours are in intervals of 0.5 cyclones per grid box. Each plot is normalised with the number of years each phase of the ENSO occurred.*

On the other hand, during La Niña the pressure over Darwin is lower than normal, which leads to an increase in the pressure difference. As a result the Trade Winds are relatively strong, whereas the westerlies are weakened. During that time, cyclone formation is concentrated over the western Pacific (Sinclair, 1995b; Pezza and Ambrizzi, 2003). Sinclair (1995b) linked the increased cyclone genesis northwest of New Zealand during La Niña to the increased SSTs in the Southwest Pacific during that phase of the ENSO.

Findings here are consistent with that theory. The composites in Fig. 5.19 show that more STCs form in the subtropics north of Tasman Sea during La Niña than during El Niño. The density plots were compiled as in Fig. 5.1. However, here the plots are normalised by the number of years[26] each ENSO phase occurs during the

[26]Refers to ENSO years, which start in May and continue through to April the following year (Salinger et al., 2001).

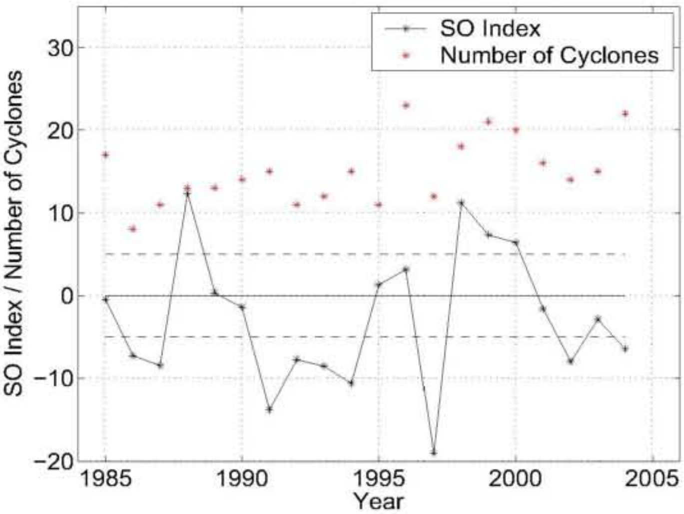

Figure 5.20: *Annual number of STCs from the MS database (red stars) and annual average of SOI (black line and stars) between 1985 and 2005.*

21 year period. El Niño refers to years with a Southern Oscillation Index (SOI) below -5 (Fig. 5.20). La Niña years have a SOI above 5. All other years are referred to as 'near normal SOI'. The SOI was obtained from the Australian Meteorological Bureau[27] (AMB), which uses the Troup SOI. It is the standardised anomaly of the Mean Sea Level Pressure difference between Tahiti and Darwin. AMB multiplies the Index by 10, so the value of the SOI can be quoted as a whole number.

The correlation between the annual average (ENSO years) of the SOI and the number of STCs yields a correlation coefficient of 0.53. This indicates that approximately 28% of the variances in the two time series are related.

In his study on TCs undergoing extratropical transition, Sinclair (2002) found a connection between the variations of the SOI and the movement of these cyclones. He attributed the more southward movement of cyclones during La Niña to the fact

[27]http://www.bom.gov.au/climate/glossary/soi.shtml

	La Niña	El Niño	Near zero SOI
Number of years	4	9	7
Total number of STCs	72	120	109
Annual average	18 (± 3.6)	13 (± 3.9)	15 (± 3.8)
Total moving south of 30°S	38	57	51
Annual average	9.5 (± 1.7)	6.3 (± 1.4)	7.3 (± 2.5)
Total moving into vicinity of NZ	16	21	19
Annual average	4 (± 0.8)	2.3 (± 1.2)	2.7 (± 1.7)

Table 5.3: *Number of STCs from MS database during different ENSO phases between May 1985 and April 2005. Annual average was obtained by dividing the total number of STCs from each phase by the number of years each phase occurred between May 1985 and April 2005. Number in brackets represent standard deviations. Years are 'ENSO-years' which start in May and go to April the following year.*

that during that phase of the ENSO, the Pacific Trade Winds are quite strong and the westerlies are relatively weak. This makes a more southward movement possible. In comparison, during El Niño the Trade Winds are relatively weak, and the strong westerlies lead to a stronger eastward movement.

Here, the same effect is seen for STCs. According to the rose plots in Fig. 5.21, during La Niña the movement of STCs has a stronger southward component compared to the other two ENSO phases.

The more southward movement of STCs and the higher number of STCs that form during La Niña both account for the high number of STCs that move into midlatitudes compared to the other two ENSO phases (Tab. 5.1).

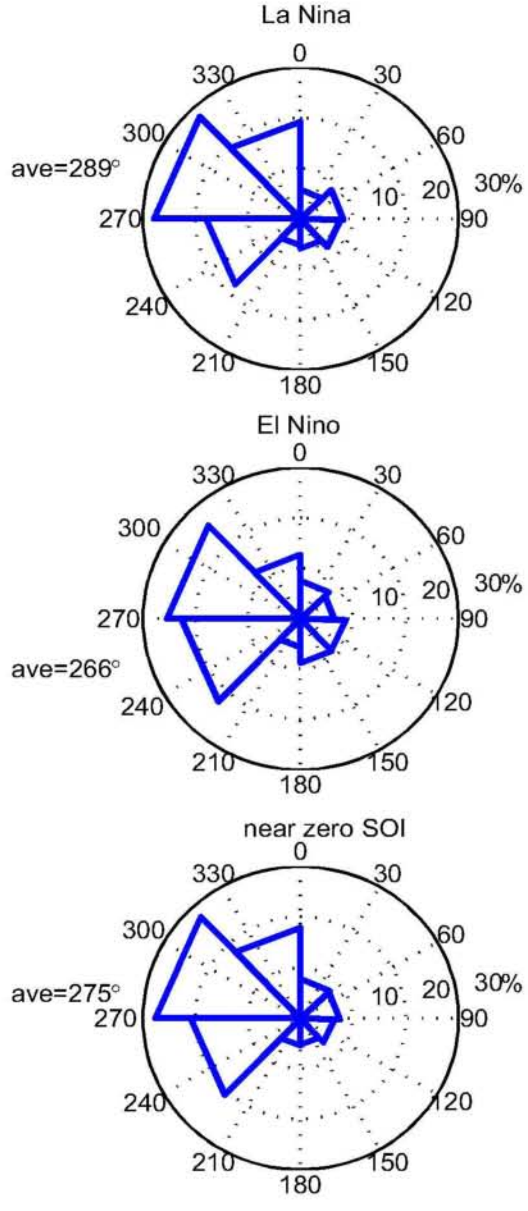

Figure 5.21: *Distribution of directions [°] STCs from the MS database come from during La Niña (top), El Niño (middle) and near zero SOI (bottom). The size of triangle represents the frequency of each direction as a percentage [%]. There are 8 different directions, each ranging over 45°.*

This also applies to the number of STCs that come into the vicinity of New Zealand. As with the total number of STCs, there is a link between the annual number of STCs that come into the vicinity of New Zealand and ENSO. According to Tab. 5.1, STCs are more likely to come into the vicinity of New Zealand during La Niña. The the correlation between the two time series indicates that approximately 30% of the variances in both time series are related.

5.2 Robustness of Climatology

Here, the robustness of the climatology is evaluated. First it is shown that the chosen cyclone selection criteria (listed in section 3.2) are appropriate for the investigations presented here and then that altering the criteria would not significantly affect the results of the climatology.
It is also shown that the use of different cyclone databases does not affect the broad results of the climatology. This sensitivity test was mainly done to ensure the findings from the climatology can be linked to the findings in the following chapters.

5.2.1 Sensitivity to Cyclone Selection Criteria

Altering the cyclone selection criteria, such as the boundaries of the investigation area, maximum intensity or track length, leads to an increase or decrease in the number of cyclones in the data set. The purpose of this section is to verify the influence on the seasonal and interannual patterns of the climatology described in section 5.1, in particular for STCs that come into the vicinity of New Zealand.

Boundaries for the Area of STC Formation

Since the cyclone tracks from the MS database were available for a larger area than used in this study, the opportunity was taken to test the sensitivity of the climatology to the boundaries of the investigation area chosen for this study. A map outlining the boundaries of the investigation area is shown in Fig. 3.1.
As discussed in chapter 3, widening the investigation area naturally increases the number of STCs. However, it causes no significant changes in the broad results of the climatology, particularly with regard to the number of STCs coming into the vicinity of New Zealand.

Threshold for Track Length

Lowering the minimum number of track points during the life cycle of a STC by one down to 3 was also found to have no significant effect on the climatology and its seasonal and annual patterns. Again, the overall number of STCs increases, but the increase in the number of STCs that migrate into midlatitudes or into the vicinity of New Zealand is even less than when extending the boundaries. This is consistent with the fact that STCs with short lifespan are those that remain in the subtropics.

Threshold for Maximum Intensity

Lowering the minimum threshold for maximum intensity only shifts the greatest seasonal fraction of STC occurrences from autumn to summer. This is consistent with the finding that summer STCs are in general less intense than those during the other seasons. Again, no significant changes were found in the other results of the climatology as presented in section 5.1.

5.2.2 Sensitivity to Cyclone Track Database

The fact that two cyclone track databases are used in this study provides an excellent opportunity to verify whether the findings of the climatology are influenced by the choice of database.

Due to the limited availability of the TR database, the comparison between the two databases can only carried out for the period between January 1999 and December 2003.

As can be seen in Tab. 5.4, for those 5 years the TR database, with a total of 62 STCs, contains approximately 22% less cyclones than the MS database with its 80 STC events. As a result, there are on average only 12 STCs in the TR database per year in comparison to the 16 from the MS database. However, the trends within both time series over the 5 year period are very similar, with an increase in the first 3 years and a sudden decrease in the last 2 years (Fig. 5.22).

It was found that the low number of STCs in the TR database is due to a lower number of STCs that remain in the subtropics, as the number of STCs moving into

	MS database	TR database
Total	80	62
Annual average	16 (± 4.4)	12 (± 2.3)
Moving south of 30°S (total)	37	37

Table 5.4: *Frequency of STCs from the MS database and TR database (total, annual average and total moving south of 30° S) between January 1999 and December 2003. Values in brackets represent standard deviations.*

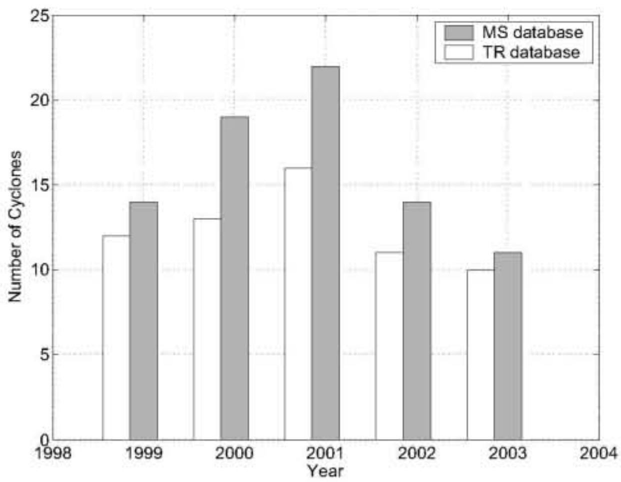

Figure 5.22: *Annual number of STCs between January 1999 and December 2003 from the TR database (white) and MS database (grey).*

midlatitudes is the same for both databases (Tab. 5.4). This can most likely be explained by the fact that, as shown earlier, STCs that remain in the subtropics are in general shorter lived than those that move into midlatitudes. In addition, on average the track length of cyclones from the MS database is approximately 2 days longer than those from the TR database. One reason for the discrepancies in the track length is the earlier detection of cyclone formation in the method by MS, explained in chapter 3. Another reason is the better tracking ability of the MS method in higher latitudes. Due to the high system density in those latitudes, it is easier to distinguish between closely located centres by using GVOR. Hence, the MS method is on occasions able to track a cyclone for longer.

With the exception of these discrepancies in the total number of STCs and the track lengths, there are no significant changes in the broad findings of the climatology, in particular regarding the seasonal patterns in frequency, tracks and intensity, when the TR database is used.

5.3 Summary and Conclusions

In the first part of this chapter, an overview of the seasonal and interannual variations in the frequency, movement and intensity of STCs in the Southwest Pacific region was given. The main findings are:

- An annual average of 15 STCs form in the subtropics north of the Tasman Sea and New Zealand. The majority of them originate over the northern Fiji Sea. Other areas of slightly increased STC genesis can be found over the Coral Sea and just south of New Caledonia.

- The largest portion of STCs form during autumn. However, there has been a statistically significant increase in the number of summer STCs between 1985 and 2005.

- Approximately 50% of STCs move into midlatitudes at some point during their lifetime, the greatest number during winter. STCs that remain in the subtropics are generally less intense than those that leave the subtropics. Most of the latter cyclones reach their maximum intensity after having moved into midlatitudes. This is partly attributed to the longer intensification period of the former, as well as to the strong deepening rates found south of 30°S.

- On average winter STCs move faster and are more intense than those in the other three seasons. The higher speed during winter is associated with interseasonal variations of the upper-level flow in this area. The higher intensification of winter STCs is most likely attributable to the fact that the majority of them move into midlatitudes, which generally leads to further intensification.

- Approximately three STCs come into the vicinity of New Zealand per year. The largest number of these cyclone events occurs during winter and they predominantly affect the north of the North Island.

- There are no significant trends in the overall number of STCs, either for those that move into midlatitudes or those that come into the vicinity of New Zealand. However, there is a statistically significant trend in the number of summer STCs, which appears to be linked to an increase in SSTs in the region.

- ENSO has a similar influence on the behaviour of STCs as it has on TCs undergoing extratropical transition in the Southwest Pacific. The interannual variations in the number of STCs can partly be attributed to the influence of the ENSO. More STCs form during La Niña than during an El Niño or a near zero SOI phase. In addition, the movement of STCs has a much stronger southward component during La Niña than during the other two phases of the SOI. This accounts for the higher number of STCs moving into midlatitudes and coming into the vicinity of New Zealand during La Niña.

The results of the climatology for the behaviour of STCs that come into the vicinity of New Zealand explain the findings from the previous chapter on the impact of STCs on New Zealand. Cyclone tracks in the vicinity of and across New Zealand are consistent with damage reports discussed in chapter 4.

The climatology clearly shows well-defined patterns in the overall behaviour of STCs in the Southwest Pacific region. Some of these patterns, such as those caused by the influence of the ENSO, are similar to those for other groups of cyclones, in particular to those of TCs undergoing extratropical transition in the same region. Other patterns, such as the increased weakening of STCs at the northeastern coast of Australia, resemble those of TCs in this region, whereas the increased intensification of STCs off the east coast of Australia south of 30°S is similar to findings on ETCs in the area. These similarities to patterns found for ETCs and TCs in this region can be seen to indicate certain similarities in the development process of STCs to that of ETCs and TCs, which would concur with the discussions in chapter 2.

Findings regarding the seasonal patterns in the location of cyclone genesis further support the ideas about the development process of STCs discussed in chapter 2. During summer, when SSTs are above 26.5°C over the Fiji and Coral Seas, the number of STCs forming in these areas is significantly higher than during the colder seasons. This link is supported by a statistically significant correlation between the number of STCs and SSTs in the area. In addition, there has been an increase in the number of summer STCs, which coincides with an increase in SSTs in the region. This indicates that the formation of these STCs is linked to SSTs, which is consistent with the idea that the formation of STCs, at least for those over the Fiji Sea, strongly resembles that of TCs. On the other hand, south of 25°S SSTs are too low to be linked to cyclone development. However, in particular during the colder seasons, baroclinic waves frequently propagate north of 30°S. Thus, the formation and intensification of STCs in those latitudes most likely resemble that of ETCs. In chapter 7 the development process of STCs is investigated in more detail.

The marked seasonal variations, in particular the movement into midlatitudes, are attributed to seasonal variations in the upper-level flow. A more detailed investigation of the movement into midlatitudes is carried out in the following chapter.

The second objective of this chapter was to determine how the results of the climatology are affected by the choice of the cyclone selection criteria and the use of different cyclone track databases. It was shown that the climatology is very robust and the choice of the cyclone selection criteria applied here was appropriate.
Using the TR database instead of the MS database, which shortens the investigation period, leads to no significant changes in the broad results of the climatology. It provides confidence that the findings in this chapter can be linked to findings from the following chapters, which will investigate the movement of STCs and the dynamical processes involved in their development during formation and intensification.

6 Influence of the Upper-Level Flow Pattern

This chapter focuses on the influence of the upper-level flow on the behaviour and characteristics of STCs.

First, the importance of baroclinic waves to the movement of STCs into midlatitudes is investigated. In the climatology in the previous chapter it was shown that the majority of STCs migrate into midlatitudes. In the discussions of those findings it was suggested that the mechanism behind that movement into midlatitudes is the coupling of the surface centre with an upper-level trough. Here, this is investigated in more detail.

In the second part of this chapter, the possibility of classifying STCs using the upper-level flow above the surface centre of a cyclone during its development is discussed. Similar classifications have been applied in a number of studies on ETCs in an attempt to organise the wealth of differences in structure and development found among ETCs (e.g. Evans et al., 1994; Sinclair and Revell, 2000). As the main aim of this thesis is to investigate the development process of STCs and determine similarities to that of ETCs and TCs, it is hoped to use this kind of classification to differentiate STCs by their development process.

According to the discussions in chapter 2, the presence of an upper-level trough approximately a quarter of a wavelength to the west of the surface centre is typical only to the development of ETCs, whereas TCs develop in the absence of upper-level baroclinic waves. Thus, the absence or presence of an upper-level trough in the vicinity of the surface centre of a STC can be seen as an indication of its development to be similar to either TCs or ETCs respectively. Therefore, 500 hPa height fields and 300 hPa wind fields above the surface centre during the development of each STC are investigated to determine whether they can be used to classify the cyclones.

As explained earlier, from this point onward the TR cyclone database is used for the investigations. Although this database covers considerably fewer years than the MS cyclone database, higher horizontal resolution of the UKMO data is more suited to these investigations. In addition, the results from the previous chapter show that the findings made in this chapter are representative of the general behaviour of STCs in this region.

6.1 Cyclone Movement

To determine the importance of baroclinic waves to the movement of STCs into midlatitudes, the 500 hPa height fields above the surface centre of STCs during their development are analysed, specifically in terms of whether there is a coupling with an upper-level trough[28] prior to moving into midlatitudes. In addition, a closer look is taken at the movement of STCs into the vicinity of New Zealand.

6.1.1 Movement into Midlatitudes

As mentioned earlier, the TR cyclone track database contains 67 STCs for the period from November 1998 to December 2003. Due to gaps in the dataset, only 56 are investigated in more detail in this and the following chapter.

[28]For convenience, an upper-level trough will from here on be referred to simply as a trough.

According to the data, 42 of the 56 STCs analysed here moved into midlatitudes at some point during their lifetime. The analysis of the 500 hPa height fields reveals that in all 42 events the surface centre of these cyclones was located in the vicinity of a trough prior to moving south of 30°S. The term 'in the vicinity of a trough' refers to situations where the surface centre of a cyclone is either located approximately a quarter of a wavelength to the east of the upper-level trough or directly underneath the trough.

Of the 42 STCs, 26 had actually formed in the vicinity of a trough, 22 of them approximately a quarter of a wavelength to the east of a trough and 4 directly underneath a trough. An example of each of the two scenarios can be seen in Fig. 6.1, which shows the 500 hPa height fields above the surface centre of two STCs during formation. In case 44 the surface centre is located beneath the eastern flank of a trough (plot on the left). In case 33 the surface centre is directly beneath the trough axis (plot on the right). The high number of STCs forming in the vicinity of a trough is not surprising, since it was shown in chapter 2 that, particularly during

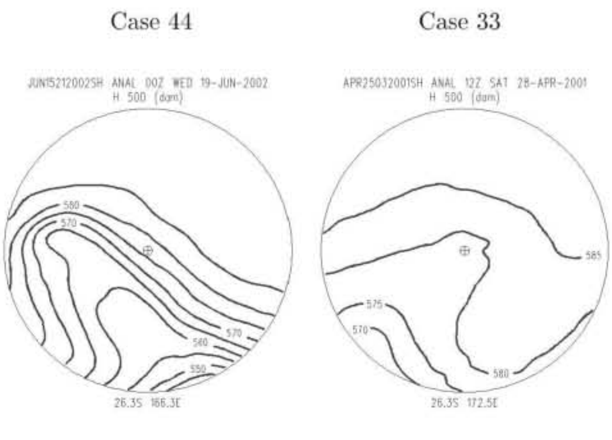

Figure 6.1: *500 hPa height field [dam] during the formation of case 44 (left) and case 33 (right) from the TR database. The plots are cyclone centred with a 20° radius around the surface centre, which is marked with a cross in a circle.*

the colder months, baroclinic waves frequently propagate far into the subtropics in this region. As mentioned earlier, a similar phenomenon can be found in the Northern Hemisphere in the Pacific Ocean near Hawaii, where the development of the so-called Kona storms in the subtropics is initiated by upper-level baroclinic disturbances (Otkin and Martin, 2004).

The remaining 16 cases of the 42 that migrated into midlatitudes did not form in the vicinity of a trough, but did move into the vicinity of one at some point during their development before leaving the subtropics. As can be seen in Fig. 6.2, in every case a trough could be found in the vicinity of a surface centre north of 30°S. Sinclair (2004) found a similar phenomenon when investigating extratropical transition in TCs in the Southwest Pacific. In most cases the onset of extratropical transition in TCs, during which an upper-level trough moves into the vicinity of the surface low, occurs north of 30°S. On only a few occasions was extratropical transition in TCs initiated south of 30°S.

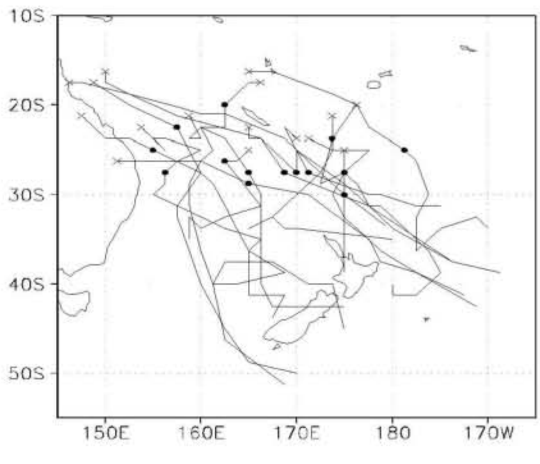

Figure 6.2: *Cyclone tracks of all STCs from the TR database that moved into midlatitudes, but did not form in the vicinity of a trough. Crosses mark the location of cyclone genesis. Circles mark the location where a trough was first found in the vicinity of the surface centre.*

However, the presence of an upper-level trough in the vicinity of the surface centre of a STC is not a definite indication that it will migrate into midlatitudes. 7 of the examined STCs remain in the subtropics despite being in the vicinity of an upper-level baroclinic wave at some point during their lifetime.

In some cases, such as case 52, the cyclone is relatively short lived and dissipates before reaching 30°S. Fig. 6.3 shows the 500 hPa height fields of case 52 (from the

Case 52

(red track in Fig. 6.5)

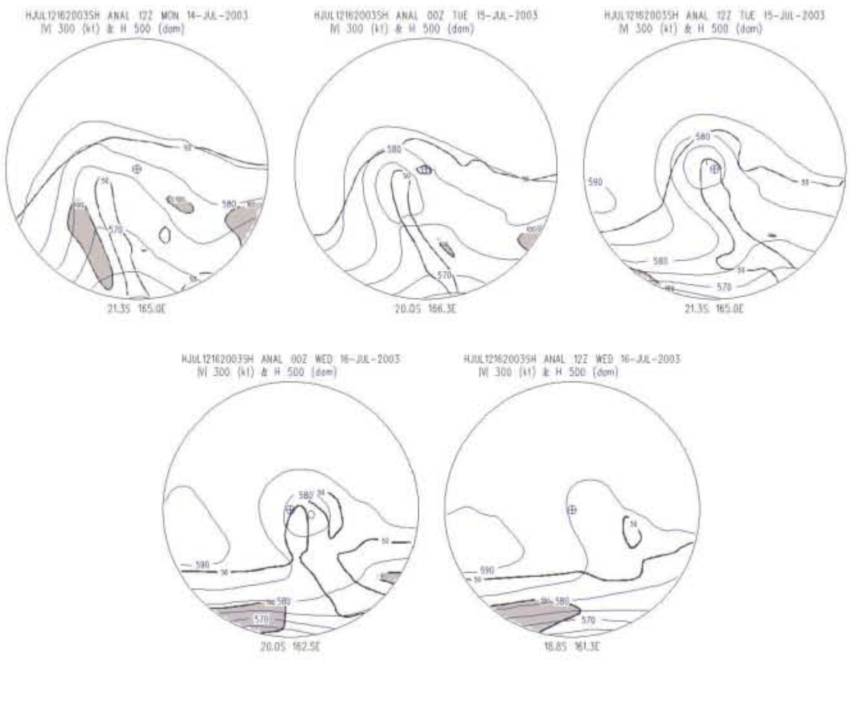

Figure 6.3: *500 hPa height fields [dam] and 300 hPa horizontal wind fields [kt] above surface centre of case 52 from the TR database. Height contours are blue. Isotachs are black, with values greater than 100, 150 and 200 kt shaded. The plots are cyclone centred with a 20° radius around the surface centre, which is marked with a cross in a circle.*

TR database). As can be seen, the upper-level wave above the surface centre was relatively weak to begin with. It eventually cut off and then dissipated quickly, at which point the cyclone decayed.

In case 11 (from the TR database), the subtropical jet apparently acted as a barrier, preventing an interaction between an approaching trough and an existing low. The plots of the 500 hPa height fields in Fig. 6.4 show that for the entire time during intensification, the surface centre of case 11 is located north of the jet whilst a trough is approaching from the southeast. However, throughout the intensification of the cyclone, the trough remains south of the jet. Thus, the trough is not able to interact with the surface centre and unable to steer the cyclone south and possibly

Case 11

(brown track in Fig. 6.5)

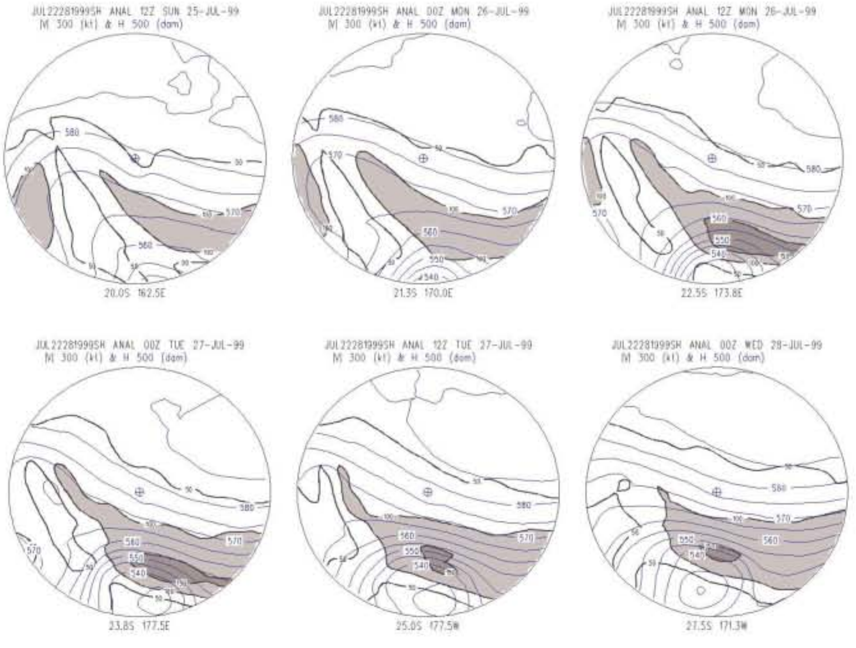

Figure 6.4: *As in Fig. 6.3, only here for case 11 from the TR database.*

into midlatitudes. As a consequence, the cyclone stays in the subtropics. However, the zonal flow north of the jet sweeps the cyclone to the east, where the cyclone eventually decays (brown track in Fig. 6.5).

6.1.2 Movement into the Vicinity of New Zealand

The likelihood of a STC coming into the vicinity of New Zealand is dictated by the location of cyclone genesis combined with the form of the upper-level flow. According to the climatology in chapter 5, approximately 3 STCs come into the vicinity of New Zealand annually. As shown by the tracks in Fig. 5.9 in chapter 5, the most common scenario is for these STCs to form at the east coast of Australia or just south of New Caledonia and then be steered by a north-westerly flow across the Tasman Sea toward New Zealand.

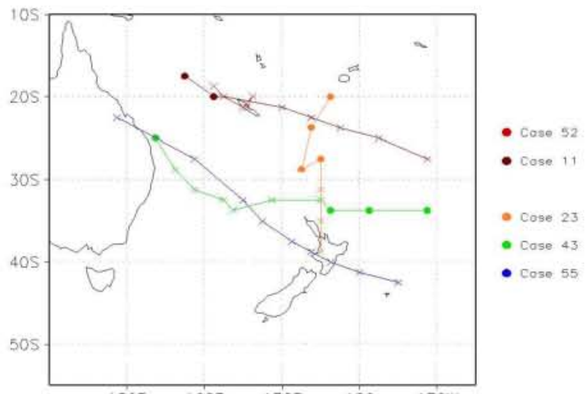

Figure 6.5: *Selected cyclone tracks of five different STCs from the TR database between 1998 and 2003. Crosses mark track points for which the 500 hPa height and 300 hPa horizontal wind fields are analysed in more detail in Fig. 6.3, Fig. 6.4, Fig. 6.6, Fig. 6.7 and Fig. 6.8.*

Case 55 from the TR database is a typical example for this. This STC formed over the east coast of Australia at approximately 23°S already in the vicinity of a trough. This trough then steered the cyclone southeast across the Tasman Sea toward New

Case 55

(blue track in Fig. 6.5)

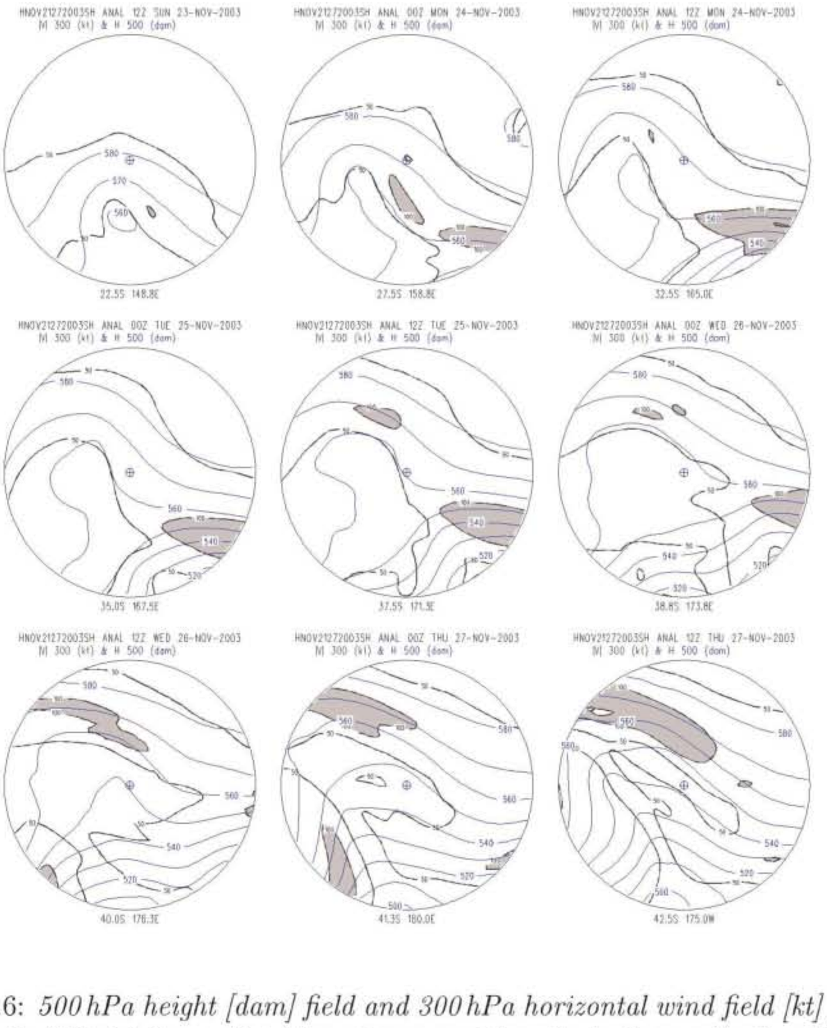

Figure 6.6: *500 hPa height [dam] field and 300 hPa horizontal wind field [kt] for case 55 from the TR database. Height contours are blue. Isotachs are black, with values greater than 100, 150 and 200 kt shaded. The plots are cyclone centred with a 20° radius around the surface centre, which is marked with a cross in a circle.*

Zealand, where the cyclone eventually crossed the southern part of the North Island (blue track in Fig. 6.5). The 500 hPa height fields can be found in Fig. 6.6.

A slightly different flow, for example a more zonal one, and a STC forming in the same area avoids New Zealand. According to the discussion in the climatology in chapter 5, such a more zonal flow is typical during an El Niño phase of the SOI. And as shown in the climatology, during that time STCs are less likely to come into the vicinity of New Zealand.

An example for this is case 43 (from the TR database), which occurred in winter 2002 during a strong El Niño. As can be seen in Fig. 6.5 (green track), the cyclone formed in the same area as case 55. However, in comparison the flow was more

Case 43

(green track in Fig. 6.5)

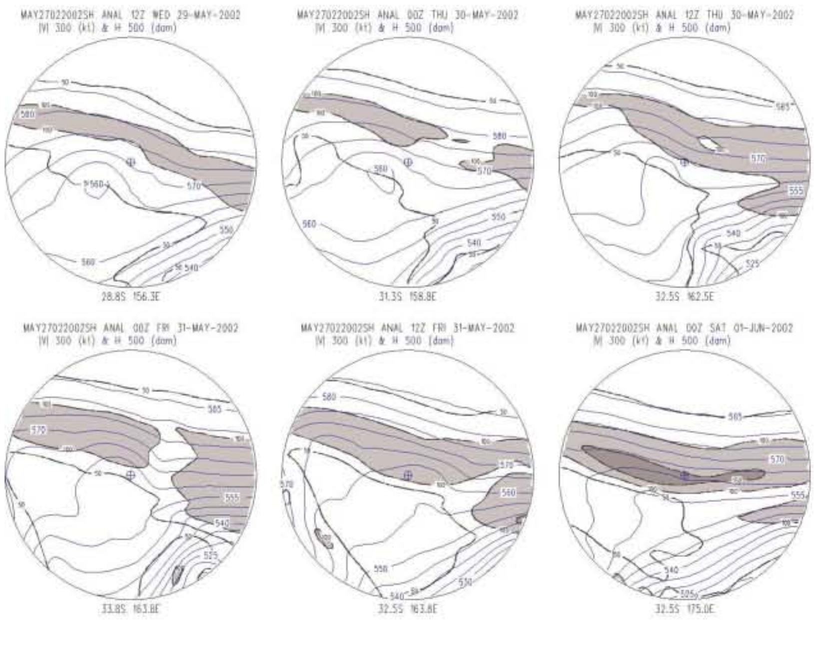

Figure 6.7: *As in Fig. 6.6, only here for case 43 from the TR database.*

zonal, due to a flatter wave (Fig. 6.7 in Appendix I). As a result the movement in the case of cyclone 43 has a stronger eastward component, which caused the cyclone to avoid New Zealand.

As also noted in the climatology, although the greatest fraction of STCs forms over the Fiji Sea, only a small percentage of those come into the vicinity of New Zealand. For a STC that originates over the Fiji Sea to affect New Zealand, the upper-level flow has to have a predominantly southward component. This occurs only occasionally, when the trough is tilted heavily to the east. An example for this is case 23 (from the TR database). The 500 hPa height fields in Fig. 6.8 for this case show that the height contours above the surface centre are aligned meridionally, which causes a northerly flow. The track in Fig. 6.5 (orange) confirms the straight southward movement, which eventually brings the cyclone into the vicinity of New Zealand.

Considering recent discussions about troughs reaching relatively far into the subtropics during the colder seasons, it is not surprising that cyclones over the Fiji Sea are most likely to be steered into the vicinity of New Zealand during those seasons.

Case 23

(orange track in Fig. 6.5)

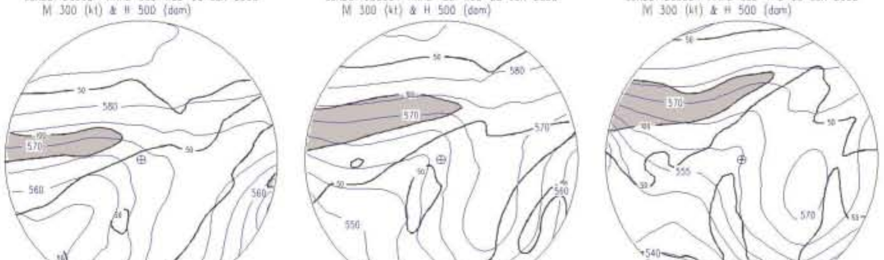

Figure 6.8: *As in Fig. 6.6, only here for case 23 from the TR database.*

The example just shown (case 23) was such a cold season STC, having occurred in early winter 2000. This type of cyclone is in part responsible for the frequent damage reported in connection with STC events in the north of the North Island of New Zealand.

6.2 Cyclone Classification

In the previous section it was shown that the majority of STCs feature an upper-level trough in the vicinity of their surface centre either during formation or at a later stage of their development. However, there are some cases where throughout the whole development the surface centre was never in the vicinity of a trough. It is possible to use the difference in the 500 hPa height fields above the surface centres of STCs to classify these cyclones. By using the presence of an upper-level trough in the vicinity of the surface centre during the development of STCs to differentiate, these cyclones can be separated into three groups. In the following, characteristics of the upper-level flow above the surface centre of the three types are discussed in more detail.

6.2.1 Type 1

The analysis of the 500 hPa height fields reveals that 29 of the 56 STCs from the TR database form in the vicinity of an upper-level trough and remain in the presence of an upper-level trough throughout their entire lifetime. These 29 cyclones are referred to here as Type 1. For 25 of these cases the surface centre is located approximately a quarter of a wavelength to the east of the trough. An example for this was shown in Fig. 6.1.

Using the classification applied in a study by Sinclair and Revell (2000) to ETCs, Type 1 STCs can be divided further into groups when differentiating by the relative location of the upper-level jet stream during formation. Sinclair and Revell (2000) used this classification on cyclones in the Southwest Pacific, more specifically on cyclones forming in the area from 150°E to 150°W and 25°S to 50°S. This means there is an overlap in latitude between their study and this one of 5 degrees. It is therefore not surprising to see that their classification method can be applied to the STCs investigated here, in particular to those forming south of 25°S.
As can be seen in Fig. 6.9, the majority of Type 1 STCs form between 25°S and 30°S. However, there are 10 cases that originate north of 25°S, two even forming north of 20°S. The generally high number of Type 1 STCs and the formation of some of them as far north as 20°S can be attributed to the fact that baroclinic waves are able to propagate far into the subtropics in this region.

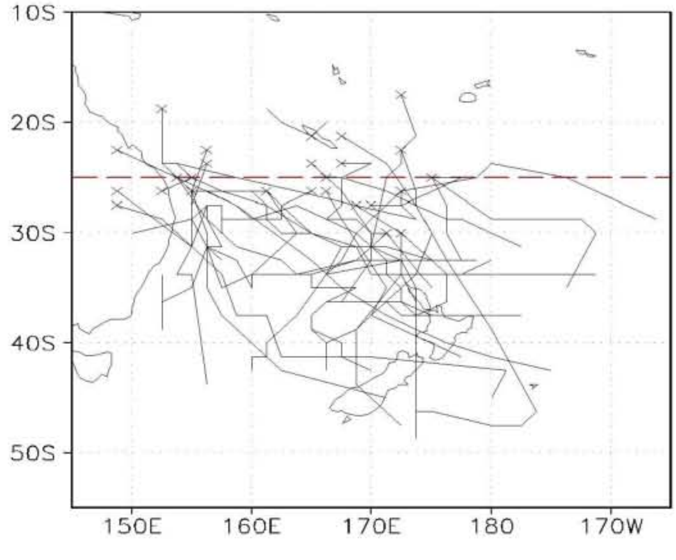

Figure 6.9: *Cyclone tracks of all Type 1 STCs from the TR database. Crosses mark the location of cyclone genesis for each cyclone. The red line marks 25°S.*

Three of the four categories from Sinclair and Revell (2000) involve direct coupling with the upper-level jet stream. The first group, referred to as class U by Sinclair and Revell (2000), contains cyclones that form beneath the poleward exit region of a 300 hPa jet stream that is located upstream of the trough. An analysis of the 500 hPa height fields and 300 hPa wind fields revealed that 12 of the 29 Type 1 STCs

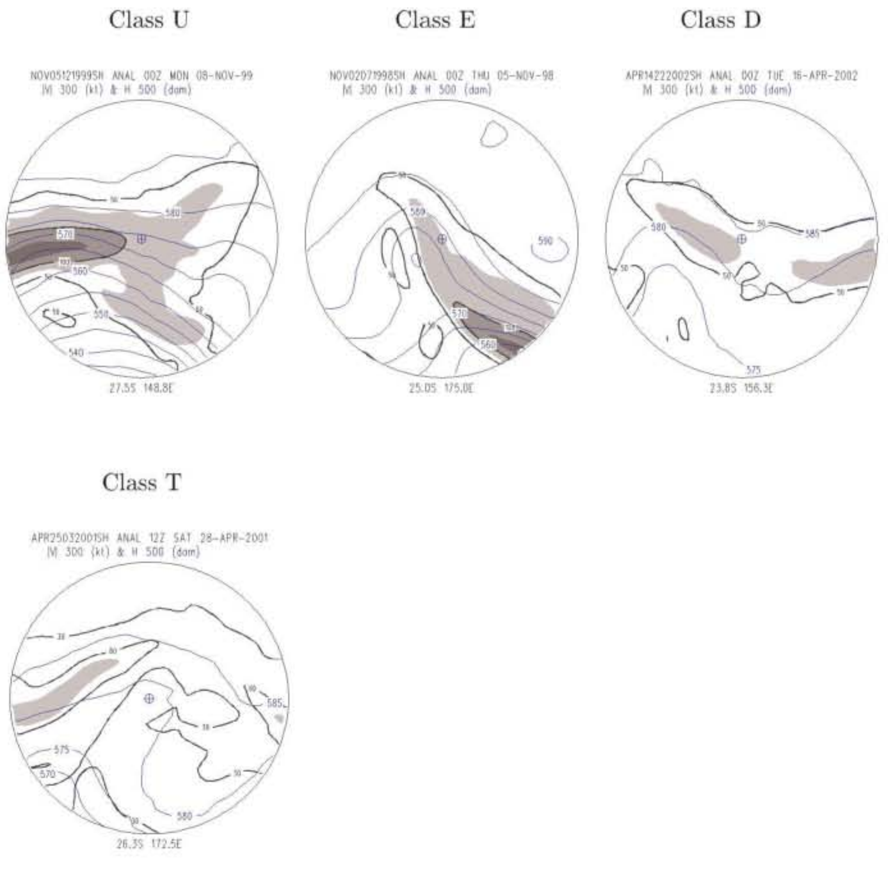

Figure 6.10: *500 hPa height fields [dam] and 300 hPa height fields [kt] during formation for an example of class U (case 14 from TR database), class E (case 1), class D (case 41) and class T (case 33). The height contours are blue. The isotachs are black in 50 kt intervals, with values greater than 70, 100 and 130 kt shaded. The plots are cyclone centred with a 20° radius around the surface centre, which is marked with a cross in a circle.*

fit this category. An example of the typical upper-level height and wind field during formation of cyclones from this class is case 14 from the TR database (Fig. 6.10). In the second group, referred to as class E by Sinclair and Revell (2000), are cyclones that form beneath the equatorward entrance region of the upper-level wind maximum, with the jet downstream of the trough. It was found that 8 of the 29 Type 1 STCs belong to this category. Case 1 from the TR database is an example for this upper-tropospheric flow signature during formation (Fig. 6.10).

The third category that involves direct coupling with the jet stream is referred to as class D by Sinclair and Revell (2000). The cyclones in this category form beneath the exit region of the jet. In addition, just as for class E, the jet is located downstream of the trough. Only 5 STCs fulfil these criteria. An example for this class is case 41 from the TR database (Fig. 6.10).

The fourth group, referred to as class T by Sinclair and Revell (2000), shows no coupling with the upper-level jet during the formation of cyclones. In general the surface centre of these cyclones is located almost directly beneath a high amplitude trough and the jet is located more than 800 km equatorward of the surface low. 5 of the 29 Type 1 STCs belong to this group. Case 33 from the TR database represents an example for this upper-level flow signature (Fig. 6.10).

6.2.2 Type 2

There are 20 STCs that do not form in the vicinity of a trough, but where a trough can be found in the vicinity of the surface centre at a later stage during their development. Here, these cyclones are referred to as Type 2.

The absence of a trough in the vicinity of the surface centre during the formation of these 20 cases and the presence of one later on suggests that these STCs have undergone a change in their development processes. When moving into midlatitudes some TCs undergo a process called extratropical transition. As mentioned in the introduction, extratropical transition is defined as the process where the characteristics of cyclone development change from that of a TC to that of an ETC. Here, it is assumed that a similar process occurs in Type 2 STCs.

A more detailed analysis reveals that in 2 of the Type 2 cases, once the trough is in the vicinity of the surface, the cyclone decays. It is possible that this is the reason for the decay. In one case, after the encounter with the first trough the cyclone starts to decay, but then begins to reintensify after a second trough moves into the vicinity. This means there are 18 STCs from the TR database that potentially underwent extratropical transition.

Of those 18 STCs, 17 continued to intensify once a trough moved into the vicinity of the surface centre. Actual reintensification, as frequently occurs in TCs undergoing extratropical transition, only occurred in 3 STCs. This is mainly because STCs are in general not that intense to begin with. Thus, the transition tends to increase their intensity (Tab. 6.1). In contrast, according to Sinclair (2002), Ex-TCs generally do not reach the intensity they had during their TC stage.

The first time a trough can be found in the vicinity of a surface centre, which most likely is the onset of extratropical transition, occurs north of 30°S for all Type 2 STCs (Fig. 6.11). As mentioned earlier, this is very similar to what was found by Sinclair (2004) for TCs in this region.

	before	after
maximum intensity	-17.6 ($\pm$ 3.4)	-36.6 ($\pm$ 7.1)

Table 6.1: *Average maximum intensity [$*10^{-5}s^{-1}$] for Type 2 STCs from the TR database before and after a trough is located in the vicinity of their surface centre. Numbers in brackets are standard deviations.*

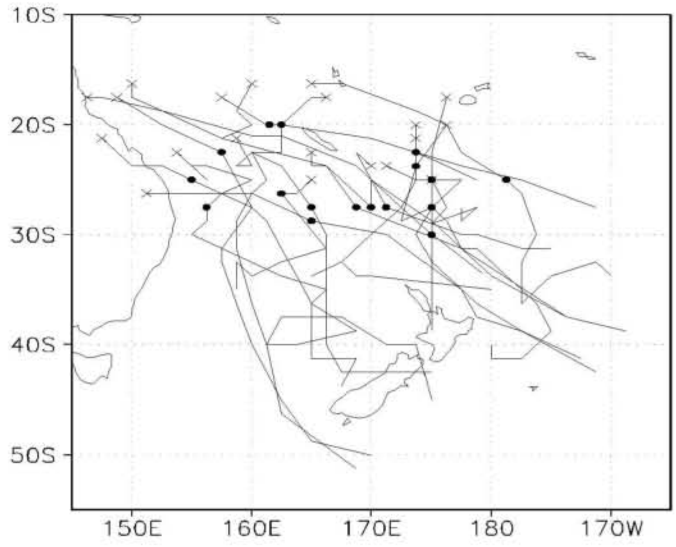

Figure 6.11: *As in Fig. 6.9, only here all Type 2 STCs. In addition, the circles mark the location when a trough first moves into the vicinity of a cyclone.*

The fact that, for the most part, this already occurs in the subtropics can also be attributed to the fact that upper-level baroclinic waves are able to propagate far into the subtropics in this region.

6.2.3 Type 3

According to the data, 7 of the 56 STCs never feature a trough in the vicinity of their surface centre throughout their whole lifetime. These STCs are referred to as Type 3.

The tracks of the 7 STCs can be found in Fig. 6.12. As can be seen, the majority form over the Fiji Sea or nearby. None of them move south of 30°S.

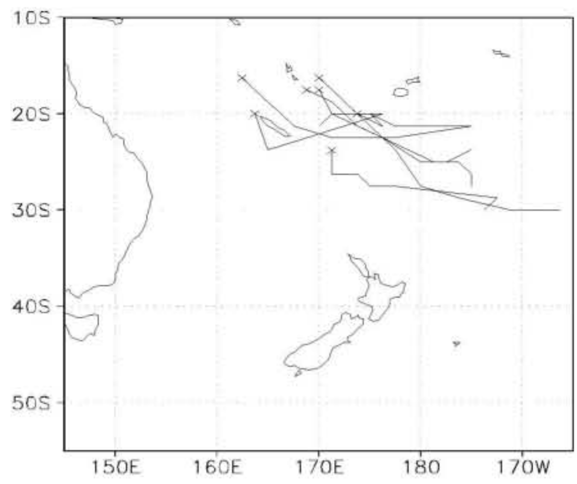

Figure 6.12: *As in Fig. 6.9, only here all Type 3 STCs.*

Of the 7 Type 3 STCs, 4 occurred during summer and none during winter. This means winter STCs generally feature a trough in the vicinity of their surface centre at some stage during their development and are either Type 1 or 2 STCs. This concurs with the phenomena discussed in chapter 2, that upper-level baroclinic waves propagate much more frequently into midlatitudes during winter than summer.

6.3 Summary and Conclusions

One key issue in this chapter was to establish whether upper-level baroclinic waves are responsible for the movement of STCs into midlatitudes and the vicinity of New Zealand. To that end, the 500 hPa height fields above the surface centre of each STC were analysed.

The main finding is:

- All STCs that move into midlatitudes feature a trough in the vicinity of their surface centre prior to moving south of 30°S.

It can be said that the absence of a trough in the vicinity of surface centres during the development of STCs can be seen as an indication that the cyclone will stay in the subtropics.

Differences in the upper-level flow pattern above the surface centre of STCs can be used to classify STCs. By using the upper-level flow above the surface centre during the development of STCs, it is possible to divide them into 3 main categories.

- Type 1 STCs are cyclones that form in the vicinity of an upper-level trough and remain in the presence of an upper-level trough throughout their entire lifetime. The majority, 29 of all 56 cases investigated here, belong to that category. This type of STCs can further be divided into groups when differentiating by coupling with the upper-level jet stream. This method of classification has previously been used on ETCs in this region.

- Type 2 STCs do not form in the vicinity of a trough, but a trough can be found in the vicinity of the surface centre at a later stage during their development. Of the 56 STCs, 20 fit this category. 18 of them continue to intensify after the surface centre is coupled with a trough.

- Type 3 STCs never feature a trough in the vicinity of their surface centre throughout their whole lifetime. Only 7 of the 56 STCs fit this category.

The occurrence of Type 1 and 2 STCs is attributed to the fact that upper-level baroclinic waves frequently propagate into the subtropics in this region, in particular during the colder seasons. A similar phenomenon has already been found in other parts of the world, such as in the Northern Hemisphere over the Pacific Ocean near Hawaii. As in the case of cyclones in that region, the presence of a trough in the vicinity of the surface centre of Type 1 STCs throughout their entire lifetime indicates that the development process of these STCs is similar to that of ETCs. It also means that there are no cases of tropical transition, at least not in the sample group investigated here.

The absence of a trough in the vicinity of the surface centre of Type 3 STCs throughout their whole development makes it very likely that their development resembles more that of TCs.

The fact that there is no trough in the vicinity of the surface centre during the formation of Type 2 STCs, but there is one at some point later during their development, supports the idea of extratropical transition in STCs.

In none of the Type 1 or 2 STCs was a transition from extratropical to tropical observed. However, that does not mean this does not occur in this region; it might only be very rare.

A detailed investigation of the development processes of each of the three types of STCs is carried out in the following chapter. The aim is to determine to what extent the development process of each type resembles that of ETCs or TCs. This includes investigating likely changes in the dynamical processes during the development process of Type 2 STCs and determining whether they undergo extratropical transition.

7 Development Process of STCs

In this chapter the development process of STCs is under investigation.
In the previous chapter, differences in the upper-level flow pattern above the surface centre of STCs were used to classify them into 3 types. The nature of those differences in the upper-level flow indicates differences in structure and development between the three types. Here, these differences are investigated in more detail. Particular emphasis is given to determining to what extent the development of each type resembles that of either ETCs or TCs. To that end, the development process during the intensification[29] of each STC type is analysed individually.
Changes in the atmospheric conditions with latitude, such as increasing moisture content toward the equator and the presence of upper-level baroclinic waves in mid-latitudes, are very likely reflected in the behaviour and characteristics of STCs. Thus, another aim in this chapter is to examine the latitude stratification of the development processes found in STCs. Particular interest is given to seasonal variations, since, as has been discussed earlier, there are strong seasonal variations in the upper-level flow pattern in this region.

As in the previous chapter, the investigations in this chapter are carried out with cyclones from the TR cyclone database and the UKMO model data.

[29] As before, refers to all track points between formation and maximum intensity.

7.1 Type 1 STCs

According to the definition in the previous chapter, Type 1 STCs feature a trough in the vicinity of their surface centre[30] throughout their entire life cycle. As this is a ETC feature, it indicates that the development of Type 1 STCs most likely strongly resembles that of an ETC.

The first section takes a look at the structure of Type 1 STCs and compares it with that of ETCs. For the comparison, a sample group of ETCs from the Tasman Sea area is used. More information on this sample group can be found in chapter 3. Then, the development process of these cyclones is investigated in more detail by analysing the contribution of thermal and vorticity processes to their intensification, using the method discussed in chapter 3.3.

7.1.1 Structure

The upper-level flow pattern above the surface centre during the development of Type 1 STCs indicates a similar structure to that of ETCs investigated here. This is further supported by the composites of the 300 hPa height and 1000 hPa to 500 hPa thickness fields for Type 1 STCs (left) and ETCs (right) during intensification in Fig. 7.1. For both groups of cyclones the thickness contours are aligned in a wave-like pattern, indicating a strong zonal thermal gradient at the surface centre, with cold air (decreased thickness) to the west and warm air (increased thickness) to the east of the centre. The upper-level trough and ridge system is aligned accordingly, with the trough located above the cold air and the ridge above the warm air.

[30]As in chapter 6, this refers to situations where the surface centre of a cyclone is either located approximately a quarter of a wavelength to the east of the upper-level trough or directly underneath the trough.

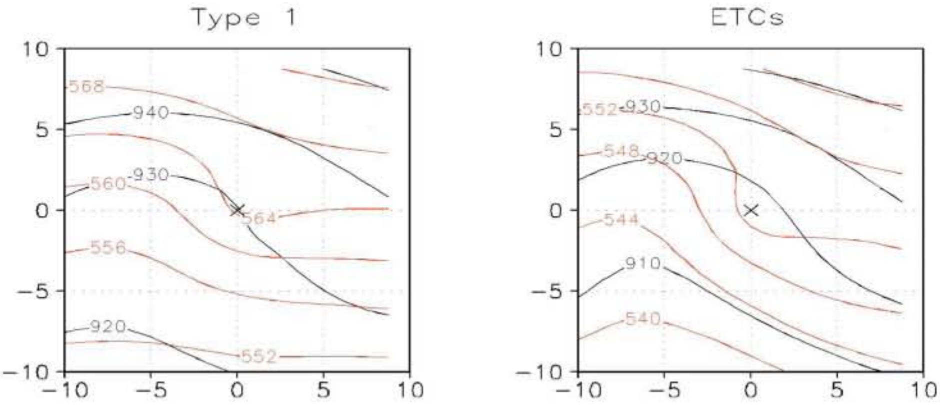

Figure 7.1: *Composites of 300 hPa height fields [dam] (black contours) and thickness of the 1000 hPa to 500 hPa layer [dam] (red contours) for Type 1 STCs (left) and ETCs (right) from the TR database. 300 hPa height contours are in 10 dam intervals. Thickness contours are in 4 dam intervals. Plots are cyclone centred. The centre is marked with a cross. The units on the x and y-axis are in degrees.*

This concurs with the discussions of the development process of ETCs carried out in chapter 2, and also with what can be found in the literature, such as Wallace and Hobbs (2006) or Carlson (1991). However, there are variations in the development process among ETCs, and several studies have used those to classify ETCs. One such classification by Sinclair and Revell (2000) was discussed in chapter 6, where it was discovered that the classification can also be applied to Type 1 STCs. Thus, the differences in structure and development shown by Sinclair and Revell (2000) to occur between their different types of ETCs are also likely to be found in Type 1 STCs. However, the aim here is only to determine to what extent the development of STCs, in this case Type 1, resembles that of ETCs and TCs. Further differentiating the development of Type 1 STCs was not deemed necessary for the purpose of this study.

A marked difference between Type 1 STCs and ETCs that is of interest here can be seen in the vertical profile of latent heating rates from large-scale ascent during intensification of the cyclones in Fig. 7.2. The heating rates are averaged over a 5° radius around the cyclone centre for each level (850 hPa, 500 hPa, 400 hPa and 300 hPa).

Similar in shape to vertical profiles of latent heating for ETCs that appear in other studies and literature, such as Rausch and Smith (1996) and (Carlson, 1991), the highest heating rates for both Type 1 STCs and ETCs can be found near 700 hPa. However, overall the heating rates for Type 1 STCs are on average higher than those for ETCs, in particular in the lower levels. The cause is the higher low-level moisture influx for the former.

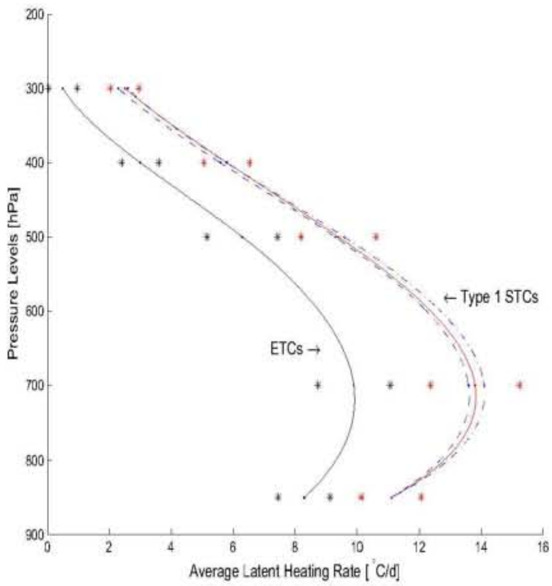

Figure 7.2: *Vertical profiles of latent heating rates from large scale ascent [°C/day] associated with the intensification of Type1 STCs (red line) and ETCs (black line) from the TR database. Also, composites of heating rates during the intensification of Type 1 STCs, while in midlatitudes (blue dashed line) and while in subtropics (blue dashed-dotted line) are shown. Stars indicate confidence intervals at the 95% level. See the text for more information.*

As can be seen in the composites of the 850 hPa horizontal moisture flux $q\mathbf{v}$ and divergence $\nabla \cdot q\mathbf{v}$ in Fig. 7.3, the convergence of moisture just southeast of the surface centre is considerably stronger during the intensification of Type 1 STCs than for ETCs. The moisture convergence occurs southeast of the surface centre, in the region of warm-air advection, thickness increase and large-scale ascent. The higher moisture influx for Type 1 STCs is attributed to their place of origin, as the atmosphere in the subtropics is much warmer and moister than in midlatitudes.

Large latent heating rates from large-scale ascent during the intensification of Type 1 STCs can also be found once the cyclones move into midlatitudes (blue dashed line in Fig. 7.2). Even though slightly lower when in midlatitudes than when in the subtropics (blue dashed-dotted line), they are still significantly higher than those found in ETCs. This is attributed to the fact that the cyclones carry the warm and moist air masses from the subtropics with them when they move into midlatitudes.

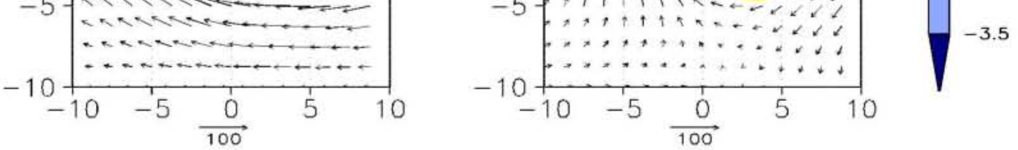

Figure 7.3: *Composites of 850 hPa horizontal moisture flux [10^2 mm/h per 100hPa] and divergence (shaded) for Type 1 STCs (left) and ETCs (right) from the TR database. Plots are cyclone centred. The centre is marked with a cross. Units on x and y-axis are in degrees.*

7.1.2 Development Process

As discussed in chapter 3, to determine to what extent the development of a STC resembles that of an ETC, the contribution by thermal and upper-level vorticity processes to the intensification of the cyclones is investigated. This is done following the method by Sinclair (2004). A detailed description of the method and equations used can be found in chapter 3.3.

The plots in Fig. 7.4 show the average 1000 hPa height changes (hereafter only referred to as height changes) by the two vorticity processes from Eq. 3.6, VADV (vorticity advection) and DIV (divergence), during the intensification of Type 1 STCs and ETCs. As described in section 3.2.3, height changes refer to 1000 hPa height falls (hereafter only referred to as height falls), which are associated with the deepening of a cyclone, and 1000 hPa height rises (hereafter only referred to as height rises), which are connected to the weakening of a cyclone. The height changes represent the individual contribution of each process to the deepening of a cyclone. The composites are cyclone centred. Height falls are coloured blue and height rises are red.

According to Fig. 7.4, the height changes by upper-level vorticity processes during intensification of Type 1 STCs are very similar to those of ETCs. The composites for both Type 1 STCs and ETCs show that upper-level VADV causes strong height falls directly above the surface centre, which is located approximately a quarter of a wavelength to the east of the trough axis. The height falls by VADV are partially offset by the height rises associated with the divergence term. As discussed in chapter 2, increasing divergence aloft enforces rising motions in the atmospheric layer beneath, which results in pressure falls at the surface and therefore further deepening of the low.

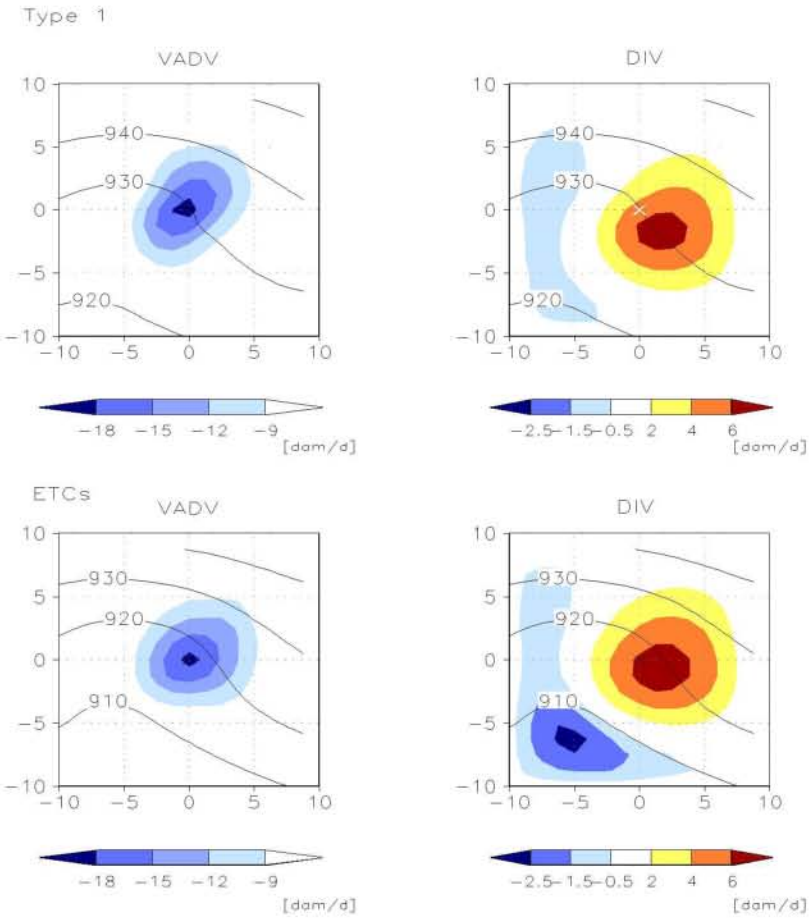

Figure 7.4: *Composites of 1000 hPa height changes [dam/d] by upper-level vorticity processes (shaded) and 300 hPa height fields [dam] (black contours) for Type 1 STCs (top row) and ETCs (bottom row) from the TR database during intensification. Left: vorticity advection (VADV), right: divergence (DIV). Plots are cyclone centred with 1000 hPa height falls coloured blue and 1000 hPa height rises red. 300 hPa height contours are in 10 dam intervals. Units on the x and y-axis are in degrees.*

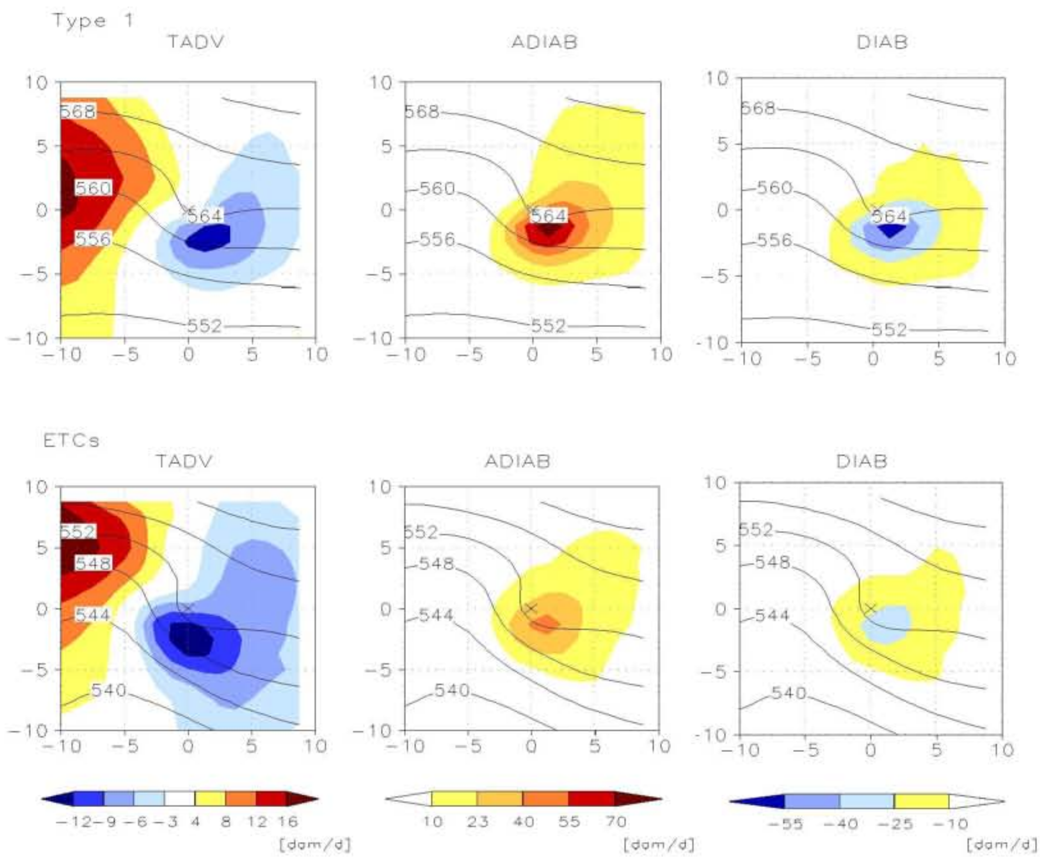

Figure 7.5: *Composites of 1000 hPa height changes [dam/d] by the three thermal processes (shaded) and thickness of the 1000 hPa to 500 hPa layer [dam] (black contours) for Type 1 STCs (top row) and ETCs (bottom row) from the TR database during intensification. Left: temperature advection (TADV), centre: adiabatic processes (ADIAB), right: diabatic processes (DIAB). Plots are cyclone centred with 1000 hPa height falls coloured blue and 1000 hPa height rises red. Thickness contours are in 4 dam intervals. Units on x and y-axis are in degrees.*

The other processes from Eq. 3.6 contributing to the development of ETCs are thermal and include TADV (temperature advection), ADIAB and DIAB (adiabatic and diabatic processes). The composites in Fig. 7.5 show the individual contribution by each of the three thermal processes during intensification of Type 1 STCs and ETCs. In particular the height changes by TADV for both Type 1 STCs and ETCs show a very similar behaviour. In both cases the height changes by TADV feature a dipole in the vicinity of the surface centre, in accordance with the 1000 hPa to 500 hPa thickness. Just southwest of the surface centre the increased thickness, which is associated with warm TADV, causes height falls at the surface. To the west, in the area of thickness decrease, the cold TADV leads to height rises at the surface. As discussed in chapter 2, the dipole in TADV enhances the upper-level trough-ridge system, which in turn increases the upper-level VADV and DIV above the surface centre.

A look at the other two thermal processes in Fig. 7.5 reveals that in both cases, in the region of warm TADV, height rises by adiabatic cooling are almost offset by height falls caused by diabatic heating. However, both height falls by DIAB and height rises by ADIAB are considerably stronger during the intensification of Type 1 STCs. As discussed in the previous section, the strong diabatic processes can be attributed to the higher moisture content in the atmosphere during the development of Type 1 STCs. As ADIAB are directly linked to DIAB via vertical motions, height changes by the former increase as well.

By comparing the relative contributions of each process, the dominant processes during the intensification of a cyclone can be determined. The relative contribution of a process is derived by correlating each term on the rhs of Eq. 3.6 with the intensification rate of the cyclones. The intensification rate is the net sum of the height changes by all processes and incorporates the interaction between those processes.

Here the intensification rate is directly derived from the 1000hPa height tendency[31]. It is then correlated with the average over a 5° radius around the cyclone centre of the height changes by each process for each track point during intensification.
The correlation coefficients for Type 1 STCs and ETCs can be found in Tab. 7.1. The table also includes correlation coefficients from the correlation between the intensification rates and latent heating rates from upper-level convective processes (CHR). The correlations with the latent heating rates at 500 hPa and 300 hPa are always almost identical. Thus, they are listed only once in Tab. 7.1. Also, only correlation coefficients that are significant at the 95% level are displayed.
According to Tab. 7.1, the contributions by all 5 processes from Eq. 3.6 to the intensification of Type 1 STCs are equally strong. In comparison, the intensification of ETCs is mainly driven by upper-level vorticity processes. The strong contribution by the diabatic processes is as mentioned earlier attributed to the fact that Type 1 STCs originate in the subtropics, which is a much warmer and moister environment

[31] A description for this can be found in section 3.2.1.

	TADV	ADIAB	DIAB	VADV	DIV	CHR	
Type 1 STCs	0.29	-0.35	0.32	0.34	-0.3	-	106
ETCs	-	-	-	0.32	-0.34	-	112

Table 7.1: *Correlation coefficients from correlation between intensification rates and height changes by thermal and vorticity processes for Type 1 STCs and ETCs from the TR database during intensification. In addition, correlation coefficients from correlation between intensification rates and latent heating rates from upper-level convection. More information on this can be found in the text. Only correlation coefficients that are significant at the 95% level are displayed. The last column shows the number of data points used for the correlations in the corresponding row.*

than midlatitudes. However, there is no significant contribution by the release of latent heat through convective processes in the upper levels to the intensification of either Type 1 STCs or ETCs.

7.1.3 Associated Rain

In the previous section, the influence of the high moisture content in the air masses involved in the development of Type 1 STCs was discussed. However, the high moisture content not only affects the intensification process, but, even more importantly, is also reflected in the precipitation associated with the cyclones.
As discussed earlier, the vertical profiles in Fig. 7.2 show that latent heating rates in Type 1 STCs are higher than in ETCs not only when the former are in the subtropics, but also when in midlatitudes. This accounts for the higher rain rates found for Type 1 STCs in comparison to ETCs, even when the former are in midlatitudes (Fig. 7.6).

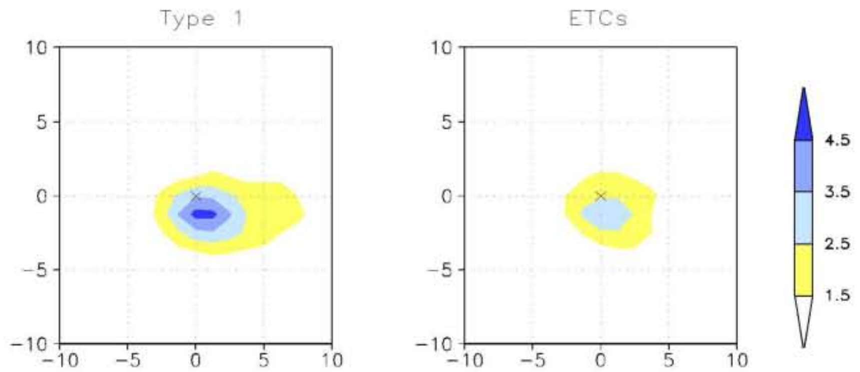

Figure 7.6: *Composites of rain rates [mm/6 hours] for Type 1 STCs, while in midlatitudes (left), and ETCs (right) from the TR database during intensification. Plots are cyclone centred. The centre is marked with a cross. Units on x and y-axis are in degrees.*

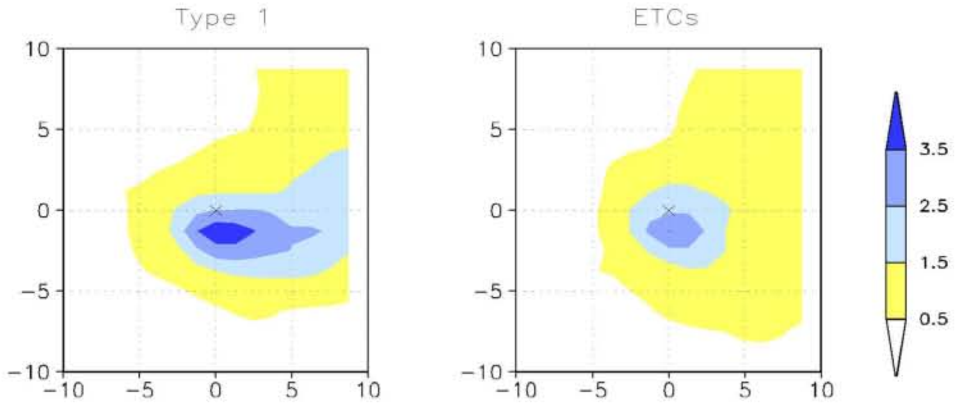

Figure 7.7: *As in Fig. 7.6, only here rain rates [mm/6 hours] for Type 1 STCs (left), and ETCs (right) from the TR database after maturity.*

In addition, even after the cyclones reach maturity rain rates are relatively high in STCs. In fact, they are just as high as those found in ETCs during intensification (Fig. 7.7). This explains why, as shown in chapter 4, most STC events, despite being already in their decaying stage, cause extensive flood damage in New Zealand.

7.2 Type 3 STCs

In contrast to Type 1 STCs, the surface centre of Type 3 STCs is never in the vicinity of an upper-level trough. The absence of a trough is seen as an indication that the development of Type 3 STCs most likely more closely resembles that of TCs. As for Type 1 STCs, first the structure of Type 3 STCs is analysed and then their development process.

7.2.1 Structure

As indicated by the upper-level flow pattern and further supported by the plots in Fig. 7.8, the structure of Type 3 STCs differs considerably from that of ETCs, and subsequently from that of Type 1 STCs. Most importantly, there is no pronounced zonal temperature gradient at the surface centre during the intensification of Type 3 STCs. The thickness contours are aligned more zonally and not in such a strong wave-like pattern as seen for ETCs. However, there is an area of increased thickness just at the surface centre of Type 3 STCs. This indicates a warm core, which is a typical TC feature. As described in chapter 2, the warm core enables the extraction of energy from the ocean in the form of heat and moisture.
Just as was seen for Type 1 STCs, due to the high moisture content in the air in the subtropics, latent heating rates from large-scale ascent are considerably higher in Type 3 STCs than those found in ETCs (Fig. 7.9, left hand plot). Also, whereas

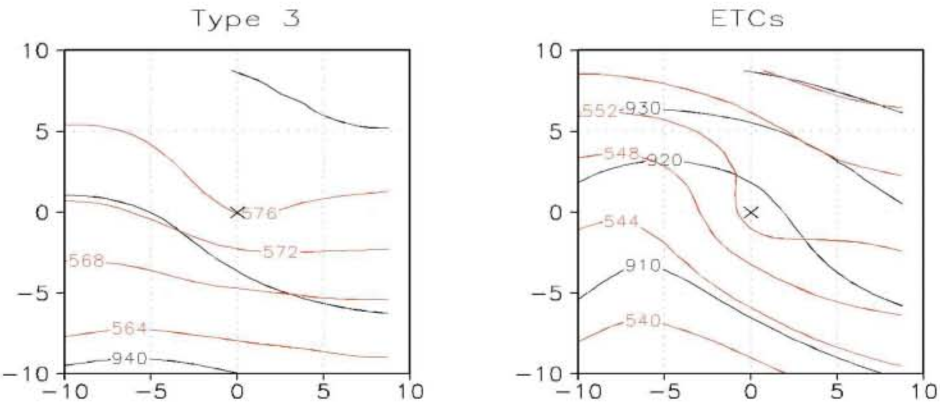

Figure 7.8: *As in Fig. 7.1, only here composites of 300 hPa height fields [dam] (black contours) and thickness of the 1000 hPa to 500 hPa layer [dam] (red contours) for Type 3 STCs (left) and ETCs (right) from the TR database.*

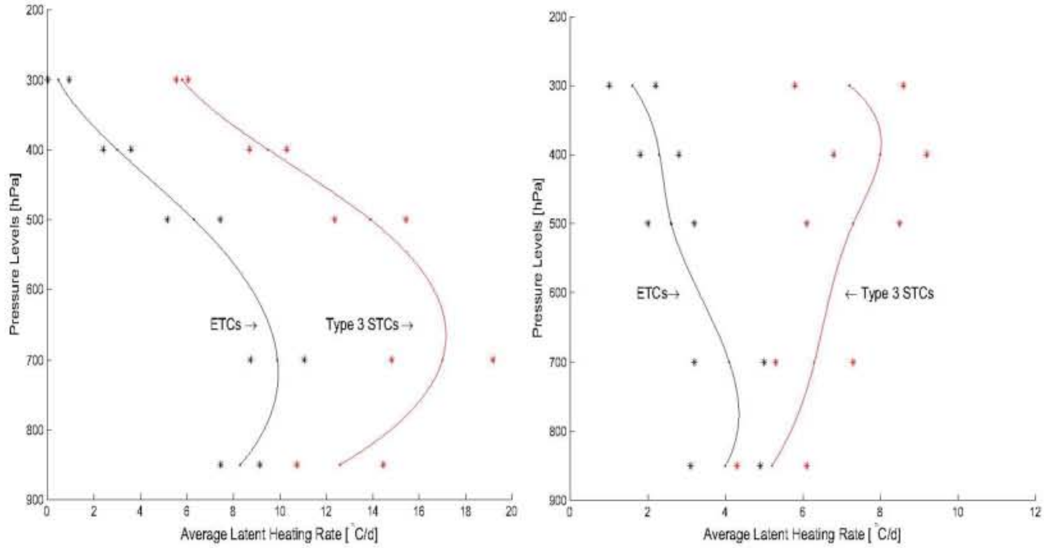

Figure 7.9: *Vertical profiles of latent heating rates from large scale ascent [°C/day] (left plot) and from convective processes [°C/day] (right plot) associated with the intensification of Type1 STCs (red lines) and ETCs (black lines) from the TR database. Stars indicate confidence intervals at the 95% level.*

the highest heating rates in ETCs can be found near 700 hPa, for Type 3 STCs they occur higher up in the atmosphere, closer to 600 hPa. The reason for this is that, due to the warm and moist environment in the subtropics, air masses have to rise higher to release latent heat.

In addition, latent heating rates from convective processes are also much higher in Type 3 STCs, in particular in upper levels (Fig. 7.9, right hand plot). For ETCs those heating rates decrease with height, whereas for Type 3 STCs they increase, with a maximum near 400 hPa. The latter is very similar to vertical profiles of latent heating from convective processes seen for TCs (Anthes, 1977; Sinclair, 1993a).

7.2.2 Development Process

In accordance with the difference in structure, the development process of Type 3 STCs differs from that of Type 1 STCs and ETCs. As the surface centre of Type 3 STCs is generally located to the north away from the influence of any upper-level trough, the weak height falls by upper-level vorticity advection to the southwest of the surface centre are unlikely to affect the development of these cyclones (Fig. 7.10). As explained earlier, the height falls by VADV are most effective when located directly above the surface centre.

Due to the lack of horizontal temperature gradient, there is no dipole in the contribution by TADV, only a region of height falls by warm-air advection southeast of the surface centre. However, there are strong height changes by diabatic and adiabatic processes in the same region.

According to the correlation coefficients in Tab. 7.2, those height changes by DIAB and ADIAB make a significant contribution to the development of Type 3 STCs. Approximately 18% of the variations in the time series of both height changes and intensification rates are related. On the other hand, in contrast to Type 1 STCs, there is no significant contribution by VADV or TADV. However, there is a significant contribution to the intensification of Type 3 STCs from the release of latent heat from convective processes in upper levels, which is typically found in TC development (Anthes, 1977).

TADV	ADIAB	DIAB	VADV	DIV	CHR	
-	-0.43	0.43	-	-	0.43	24

Table 7.2: *Correlation coefficients as in Tab. 7.1, only here for Type 3 STCs from the TR database.*

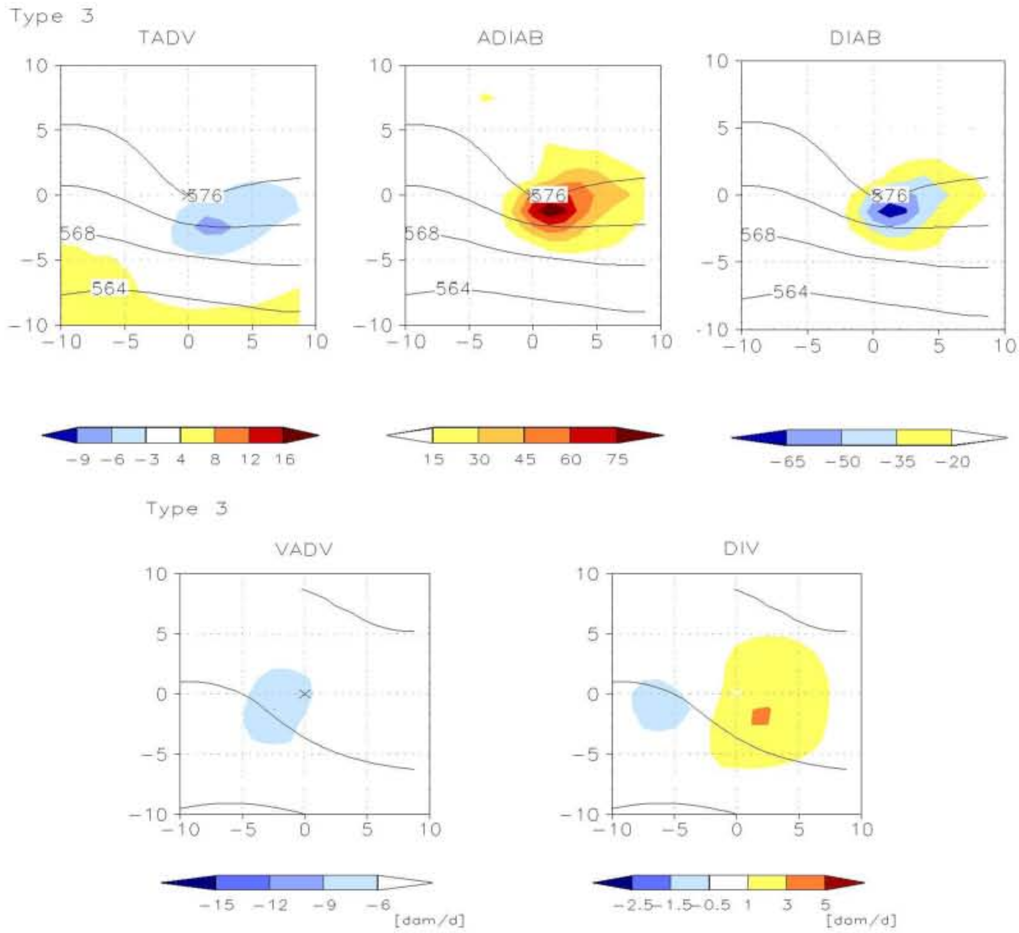

Figure 7.10: *Composites of 1000 hPa height changes [dam/d] by the three thermal processes (shaded and thickness of the 1000 hPa to 500 hPa layer [dam] (black contours) (top row) as in Fig. 7.5 and composites of 1000 hPa height changes [dam/d] by upper-level vorticity processes (shaded) and 300 hPa height fields [dam] (black contours) (bottom row) as in Fig. 7.4, only here for Type 3 STCs from the TR database.*

7.3 Type 2 STCs

According to the definition in chapter 6, there is a change in the upper-level flow pattern above the surface centre of Type 2 STCs. First the absence, then the presence of an upper-level trough in the vicinity of the surface centre indicate a change in the development process of these cyclones, which might resemble that of extratropical transition found in TCs, when moving into midlatitudes. In the following sections, the changes in structure and development of Type 2 STCs are analysed.

7.3.1 Structure

As indicated by the changes in the upper-level flow pattern above the surface centre during the development of Type 2 STCs, there are changes in the whole structure of these cyclones. Before an upper-level trough moves into the vicinity of the surface centre[32], the structure very much resembles that of Type 3 STCs. The thickness contours show a lack of zonal thermal gradient and a greater tendency for increased thickness directly at the surface centre, a sign for a warm core (Fig. 7.11). After the encounter with a trough, the thickness contours take on a strong wave-like pattern and tighten near the centre, which indicates a zonal thermal gradient, similar to that seen for Type 1 STCs and ETCs in Fig. 7.1.

Another indication of changes in the structure are the differences in the latent heating rates from large-scale ascent and convective processes before and after encountering a trough (Fig. 7.12). In general, latent heating rates by large-scale ascent decrease only slightly after the encounter with a trough. However, as seen for Type 3 STCs, the maximum heating rates can be found closer to 600 hPa for Type 2 STCs before the encounter with a trough. Afterwards the maximum lowers to 700 hPa.

[32] Here, also referred to as before an encounter with a trough.

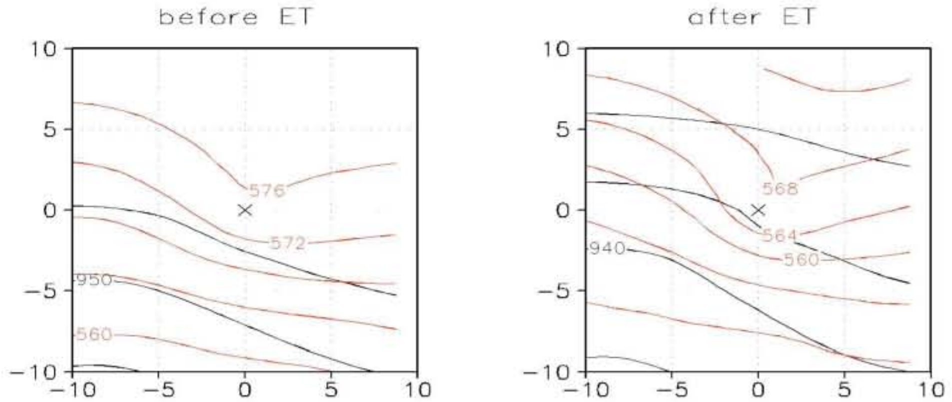

Figure 7.11: *As in Fig. 7.1, only here composites of 300 hPa height fields [dam] (black contours) and thickness of the 1000 hPa to 500 hPa layer [dam] (red contours) for Type 2 STCs before (left) and after (right) the encounter with a trough.*

The changes in latent heating rates from convective processes are even more pronounced, in particular in upper levels. Before the encounter the latent heating profiles are very similar to those of Type 3 STCs, in particular that from convective processes. The heating rates increase with height, displaying a maximum near 400 hPa. After the coupling with a trough, the heating profiles strongly resemble those of ETCs, with a decrease in the upper levels.

The decrease in latent heating rates after the encounter with a trough can be explained with the movement into midlatitudes, which most Type 2 STCs tend to do after coupling with a trough. Even though the cyclones drag the moist and warm air with them from the subtropics, there is some loss of moisture on the way, similar to that seen in the latent heating rates for Type 1 STCs once they move into midlatitudes.

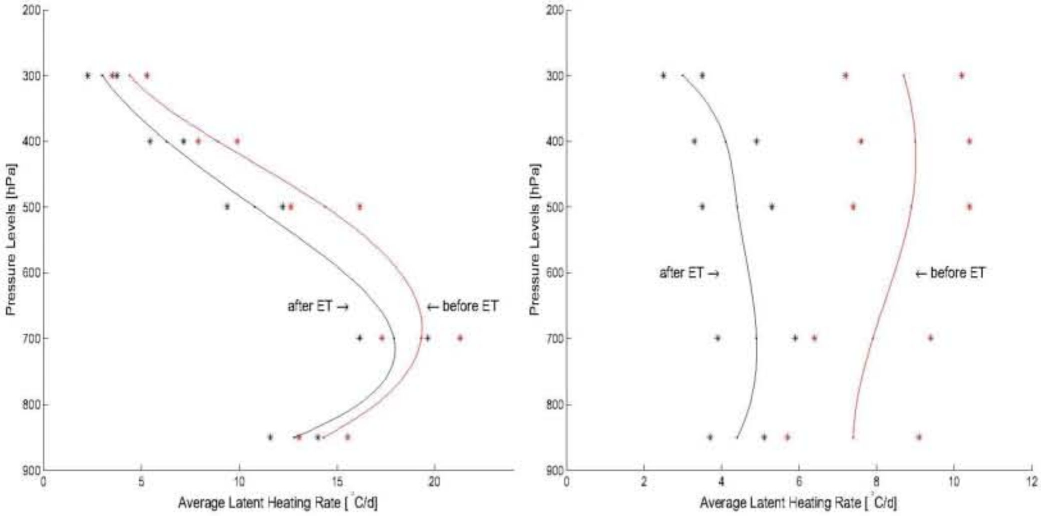

Figure 7.12: *Vertical profiles of latent heating rates from large scale ascent [°C/day] (left) and convective processes [°C/day] (right) associated with Type 2 STCs from the TR database before (red lines) and after (black lines) encountering an upper-level trough. 'ET' is the abbreviation for encounter with a trough. Stars indicate confidence intervals at the 95% level.*

7.3.2 Development Process

As noted, before the encounter with a trough the surface centres are not located beneath the eastern flank of a trough, but generally to the northeast. This means the height falls by VADV associated with these troughs do not occur directly above the surface centre, and are therefore unlikely to affect the intensification of Type 2 STCs during that stage of their development, as was seen for Type 3 STCs. A correlation between the height falls by VADV and the intensification rates confirms that there is no significant contribution by upper-level VADV to the intensification of STCs during the first stage of intensification (Tab. 7.3).

After the surface centre has moved beneath the eastern flank of a trough, the height falls by VADV occur almost directly at the surface centre, which is similar to Type 1 STCs. And just as for the latter, the contribution by VADV in Type 2 after the encounter is partially offset by the divergence term. The composites of height changes by upper-level vorticity processes for Type 2 STCs after the encounter with a trough

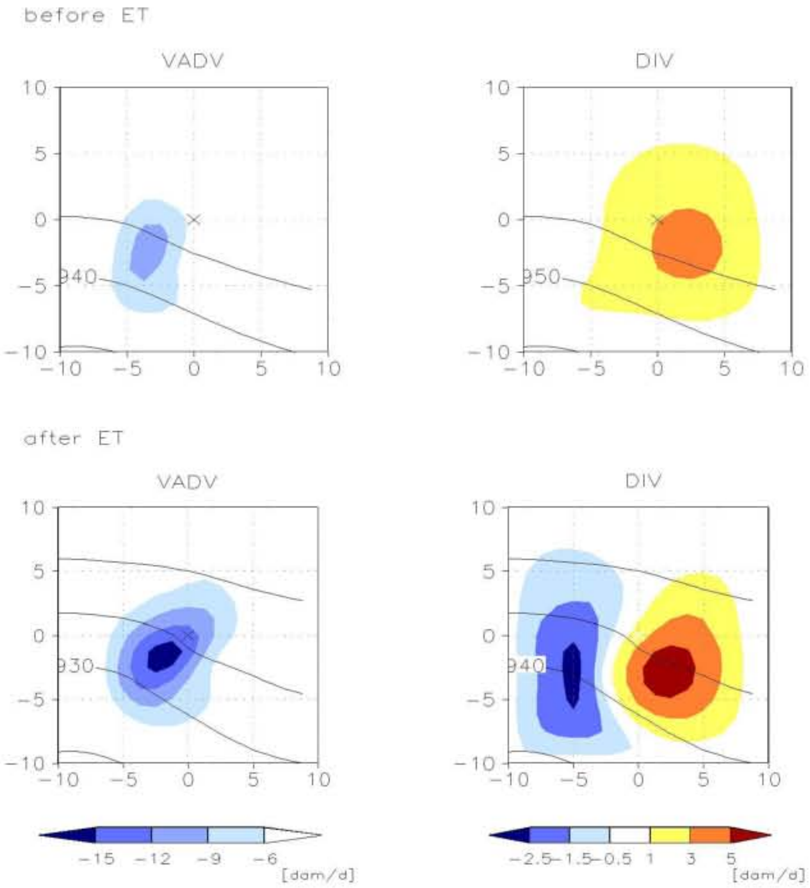

Figure 7.13: *Composites of 1000 hPa height changes [dam/d] by upper-level vorticity processes (shaded) and 300 hPa height fields [dam] (black contours) as in Fig. 7.4, only here for Type 2 STCs from the TR database before encountering an upper-level trough (top row) and after encountering a trough (bottom row). 'ET' is the abbreviation for 'encounter with a trough'.*

strongly resemble those for TCs after having undergone extratropical transition in this region (Sinclair, 2004). The correlation coefficients from Tab. 7.3 confirm a strong contribution by VADV to the intensification of Type 2 STCs during the second stage of intensification.

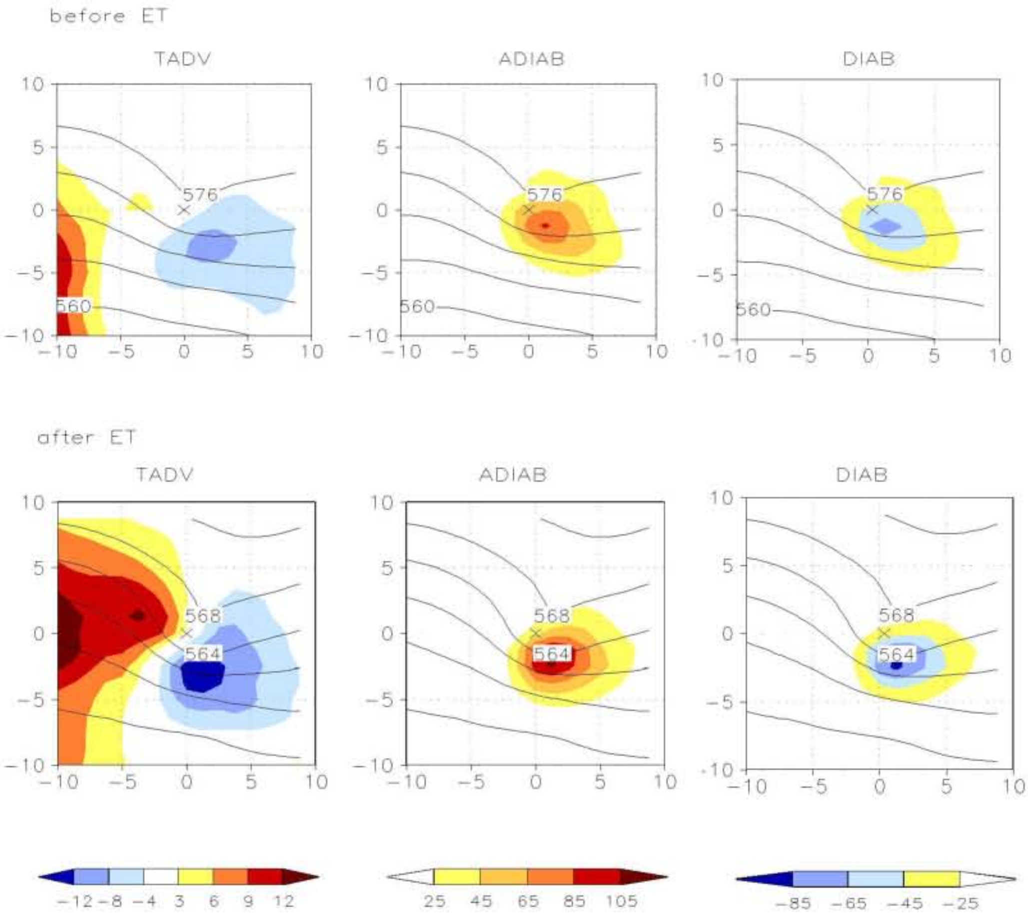

Figure 7.14: *Composites of 1000 hPa height changes [dam/d] by the three thermal processes (shaded and thickness of the 1000 hPa to 500 hPa layer [dam] (black contours) as in Fig. 7.5, only here for Type 2 STCs from the TR database before encountering an upper-level trough (top row) and after encountering a trough (bottom row). 'ET' is the abbreviation for 'encounter with a trough'.*

The differences in the contribution by TADV between both stages of the intensification of Type 2 STCs are slightly stronger height falls by warm TADV to the southeast of the surface centre and additional height rises by cold TADV after the encounter with a trough in comparison to before. However, Tab. 7.3 reveals that there is no significant correlation between intensification rates and height changes by TADV either before or after the encounter with a trough.

	TADV	ADIAB	DIAB	VADV	DIV	CHR	
before ET	-	-0.55	0.56	-	-	0.56	40
after ET	-	-	-	0.30	-0.2	-	42

Table 7.3: *Correlation coefficients as in Tab. 7.1, only here for Type 2 STCs from the TR database before and after the encounter with a an upper-level trough. 'ET' is the abbreviation for 'encounter with a trough'.*

However, there is a significant correlation, similar to that for Type 3 STCs, between DIAB and ADIAB processes and the intensification of Type 2 STCs before the encounter with a trough, whereas after the encounter no significant correlation is observed. As seen for the height changes by the upper-level vorticity processes, the height changes by the thermal processes for Type 2 STCs after the encounter closely resemble those for TCs after transition. This is an indication that, at least after the transition, the development of TCs and Type 2 STCs is very similar (Sinclair, 2004). The effect of the transition is also very similar, causing a prolonging of the lifespan and directing the cyclones into midlatitudes. However, while in STCs the transition simply leads to a continuation of intensification, the majority of TCs actually reintensify, which is due to the fact that STCs are not as intense before the transition.

7.4 Latitude Stratification

Here, the changes in the development of STCs with latitude are examined in more detail. The investigation focuses on the five processes from Eq. 3.6, which include the three thermal processes of TADV, ADIAB and DIAB and the two upper-level vorticity processes, VADV and DIV. In addition, latent heating rates caused by convective processes are examined, in particular those in the upper levels.
First the latitude profile of the individual contribution by each process from Eq. 3.6 is examined, including seasonal variations. Then, in order to determine the dominant process during the development of STCs, the relative contribution of each process is analysed. This includes a discussion of the effect of the changes in development process on the actual intensification rates and maximum intensities, and linking this to findings from the climatology in chapter 5.

7.4.1 Individual Contribution by each Process

As can be seen from the composites of height changes from VADV, DIV, TADV and DIAB in Fig. 7.15 and Fig. 7.16, there is a distinct change with latitude. Due to the fact that upper-level baroclinic waves are midlatitudinal feature, and only occasionally propagate into the subtropics, the influence of upper-level vorticity processes to the development of STCs decreases toward the equator. North of 20°S, the surface centre of STCs is generally located far to the north of any troughs. Thus, any height falls by troughs occur to the south of the surface centres with little chance of influencing the development of the cyclones. However, the further south the cyclones move, the closer the height falls by VADV move to the surface centre. At the same time the height rises by DIV increase. Between 30°S and 35°S

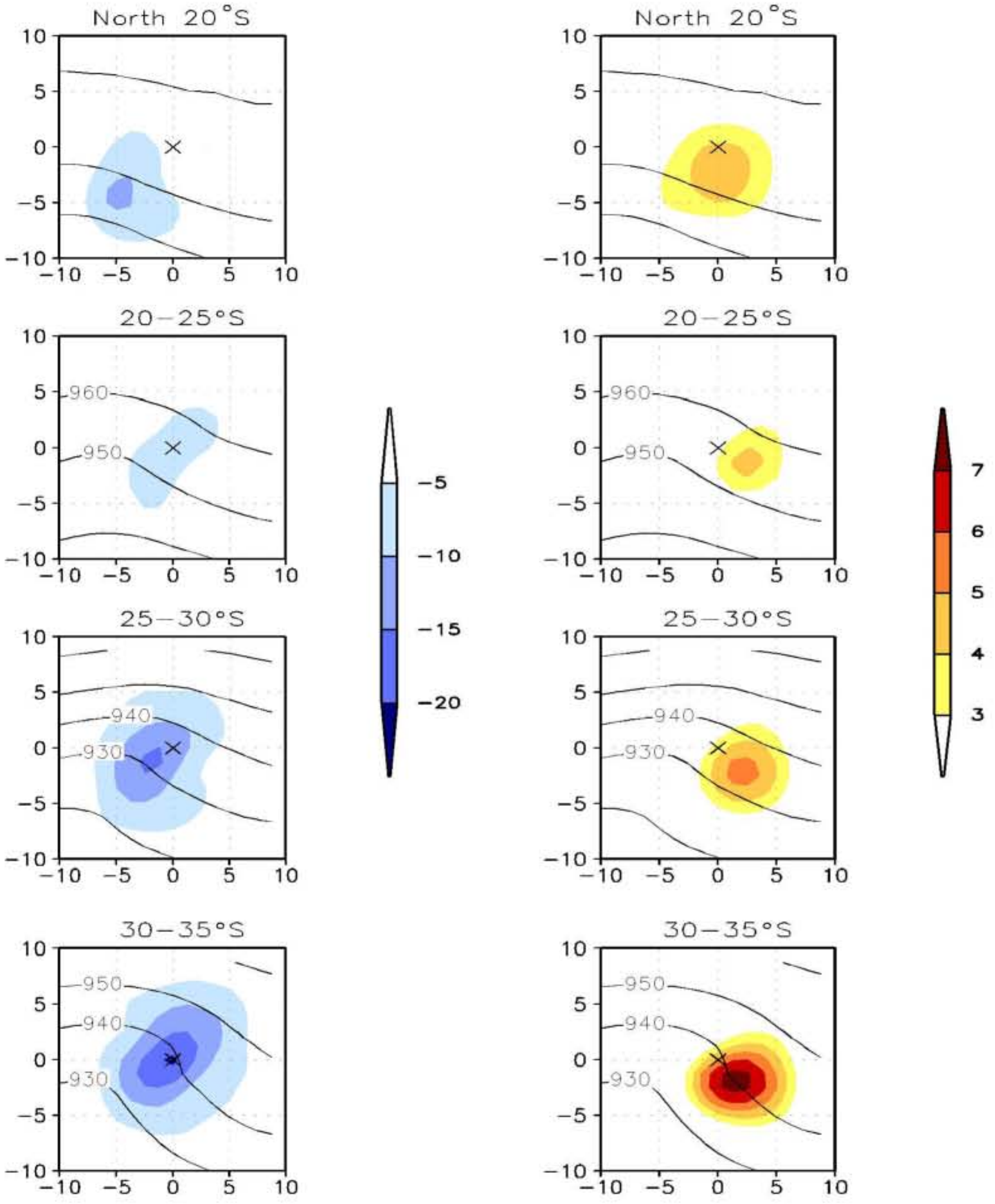

Figure 7.15: *Composites of 1000 hPa height changes [dam/d] by upper-level VADV (left, shaded) and DIV (right, shaded) and 300 hPa height fields [dam] (black contours) during intensification of STCs from the TR database for different latitude ranges.*

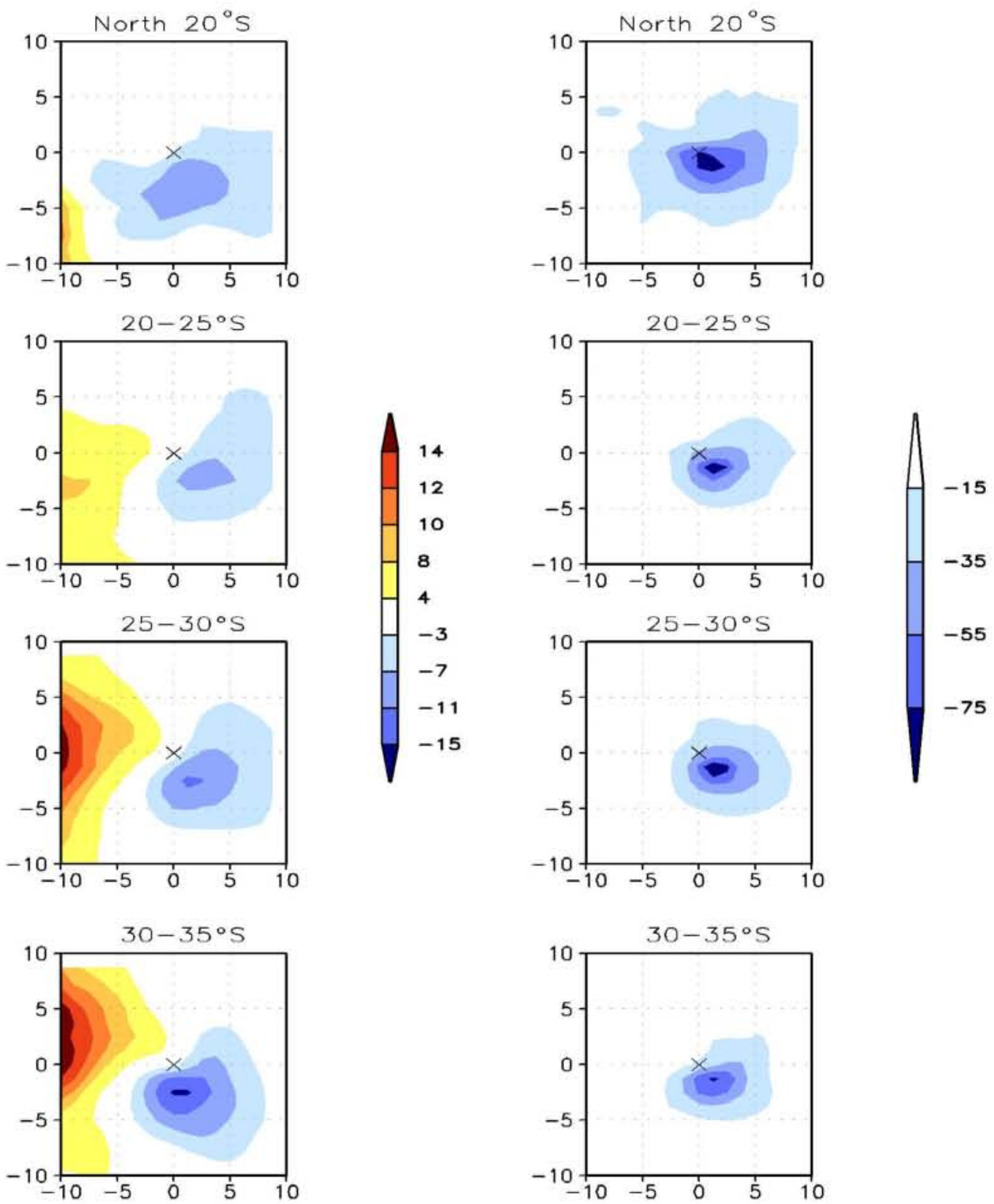

Figure 7.16: *Composites of 1000 hPa height changes [dam/d] by TADV (left) and DIAB (right) during intensification of STCs from the TR database for different latitude ranges.*

height falls by VADV generally occur directly above the surface centre, where they are most efficient and are also partially offset by the height rises by DIV.

Accordingly the thermal gradient associated with an upper-level trough and ridge system above the surface centre of a cyclone increases accordingly toward the pole. North of 20°S there are only height falls by warm-air advection to the southeast of the surface centre, whereas between 30°S and 35°S there is a distinct dipole, with additional height rises to the west.

In comparison, the changes in height falls by DIAB with latitude are not very pronounced. The strength of the height falls are relatively constant across the latitudes,

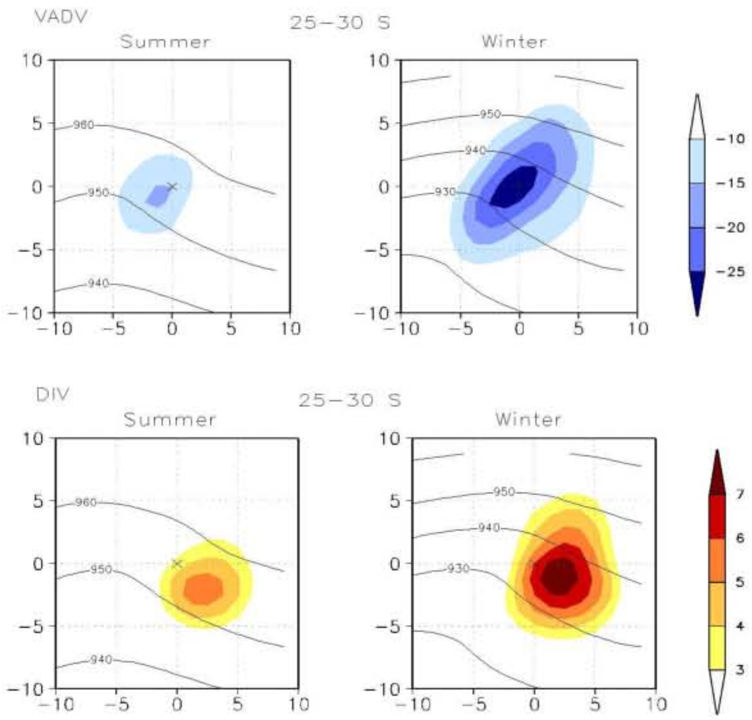

Figure 7.17: *Seasonal composites of 1000 hPa height changes [dam/d] by upper-level VADV (top, shaded) and DIV (bottom, shaded) and 300 hPa height fields [dam] (black contours) during intensification of STCs from the TR database for summer (left) and winter (right).*

only the size of the area covered by the height falls increases toward the pole. The fact that the values of height falls by DIAB are still strong in the midlatitudes can again, as mentioned earlier, be explained by the cyclones dragging the air masses along from the subtropics.

The seasonal variations in the upper-level flow pattern in this region suggest that there are seasonal variations in the latitude stratification of the height changes by most of the processes, in particular those by upper-level vorticity processes. As discussed earlier, during winter upper-level baroclinic waves frequently propagate north of 30°S into the subtropics, whereas during summer this only occurs occasionally.

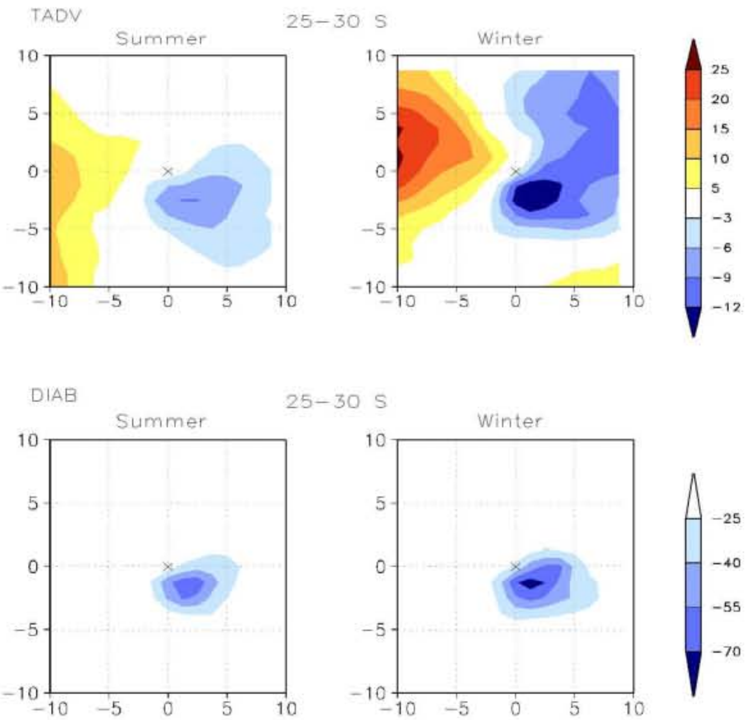

Figure 7.18: *Seasonal composites of 1000 hPa height changes [dam/d] by TADV (top) and DIAB (bottom) during intensification of STCs from the TR database for summer (left) and winter (right).*

Seasonal composites in Fig. 7.17 confirm that during winter strong height falls by upper-level VADV occur directly above the surface centre in the latitudes between 25°S and 30°S. In contrast, during summer those height falls are much weaker and are located to the southwest of the surface centre. At the same time the height rises by DIV are much weaker.

In accordance with the differences in contribution by upper-level vorticity processes, there are differences in the height changes by TADV between summer and winter (Fig. 7.18). During the latter there is a strong dipole in height rises and falls at the surface centre of STCs, whereas during summer there are only height falls by TADV to the southeast of the surface centre. In contrast, there appears to be no pronounced seasonal influence on the contribution by DIAB.

7.4.2 Relative Contribution by each Process

As described earlier, to determine the dominant process during the intensification of a cyclone, the relative contribution of each process has to be determined, which is achieved by correlating each term on the rhs of Eq. 3.6 with the intensification rate of the cyclones.

The changes in the individual contribution by each process with latitude already indicate a latitudinal change in the development process of STCs. The correlation coefficients in Tab. 7.4 show that the change is very gradual. North of 25°S the development of STCs is mainly driven by thermal processes, similar to that of TCs. On the other hand, south of 35°S VADV is the dominant process, similar to the development of ETCs. Sinclair (2004) had similar findings, in particular for the upper-level vorticity processes, when he investigated extratropical transition in TCs in this region.

	TADV	ADIAB	DIAB	VADV	DIV	
20°S - 25°S	-	-.50	.52	-	-	56
25°S - 30°S	.38	-.40	.36	.32	-.20	90
30°S - 35°S	.39	-.50	.45	.51	-.38	48
35°S - 40°S	.58	-.37	.28	.50	-.25	26

Table 7.4: *Latitude stratification of correlation coefficients from correlation between intensification rates and height changes by thermal and vorticity processes for STCs from the TR database during intensification. Only correlation coefficients that are significant at the 95% level are displayed. The last column shows the number of data points used for the correlations in the corresponding row.*

The area between 25°S and 35°S appears to be a transition zone, where the contributions by all processes are on average of similar magnitude. The width of the transition zone is attributed to the interseasonal variations of the upper-level flow patterns in this region. Since in winter the troughs are frequently able to propagate far into the subtropics, strong contributions by VADV to the development of STCs occur north of 30°S during that time. Whereas during summer, due to the lack of upper-level baroclinic waves in the subtropics, the development is driven more by diabatic processes.

The variations in the development process of STCs with changing latitude are reflected in the intensification rates of STCs. The latitude profile of the intensification rates in Fig. 7.19 was derived by averaging the intensification rates for STCs and ETCS respectively for 5 latitude ranges each spanning 5°. It shows that on average intensification rates are strongest between 30°S and 35°S, the latitude range where the strongest relative contribution by VADV and the second strongest relative contributions by DIAB can be found (refer to Tab. 7.4).

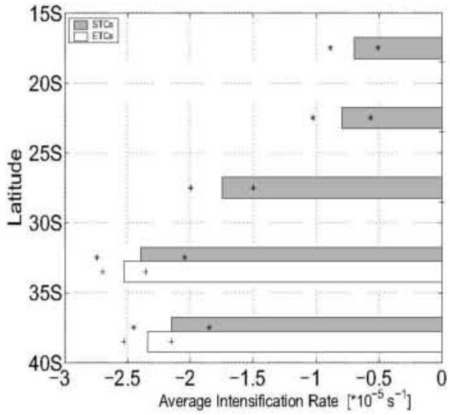

Figure 7.19: *Latitude profile of average intensification rates [$*10^{-5}s^{-1}$ per day] during the intensification of STCs and ETCs from the TR database. Stars and crosses represent confidence intervals.*

The lowest intensification rates associated with the intensification of STCs can be found north of 25°S. According to previous findings, in these latitudes the release of latent heat provides the greatest contribution to the intensification of STCs. Thus, the low intensification rates indicate that the release of latent heat alone is not sufficient to achieve strong intensification rates during the development of STCs. This concurs with the fact that Type 2 STCs after transition and Type 3 STCs do not achieve high enough intensities to be considered TCs.

On the other hand, south of 25°S, with an increasing contribution by VADV, the average intensification rates increase. Apparently the interaction with a trough and therefore a strong contribution by VADV is essential for high intensification rates in STCs. This is consistent with findings from the climatology, which showed that STCs that remain in the subtropics are generally weaker than those that move into midlatitudes.

A comparison with the intensification rates of ETCs reveals that while both types of cyclones are in the same latitudes, there are no significant differences. This means the difference in the development process, according to which the development of STCs is also strongly influenced by diabatic processes, appears not to be reflected in the intensification rates. This would indicate that the diabatic processes compensate for the slightly lower contribution by VADV.

7.5 Summary and Conclusions

The objective of this chapter was to investigate the development process of STCs. First the structure and development for each STC type was analysed separately in detail and compared to that of ETCs and TCs to determine to what extent the development resembles that of either of the two. Then, changes in the development of STCs with latitude were investigated.

In chapter 6, differences in upper-level flow above the surface centre of STCs were used to classify them into 3 types. Findings in this chapter show distinct differences in structure and development process between the 3 types.

The development of Type 1 STCs, with their surface centre in the vicinity of an upper-level trough (a typical ETC feature), strong thermal gradient and their development driven by upper-level vorticity advection, strongly resembles that of ETCs. However, due to the high moisture content in the air masses involved in their development, latent heating rates from large-scale ascent are much stronger than those found in ETCs. Those higher latent heating rates not only affect the intensification of Type 1 STCs, but are also reflected in the associated precipitation. In general rain rates associated with the development of Type 1 STCs, even when in midlatitudes, are considerably higher than those found in ETCs.

In contrast to Type 1 STCs, Type 3 STCs develop without a trough in the vicinity of their surface centre. They feature a warm core instead of a zonal temperature gradient. Apart from the warm core, which is typically seen in TCs, Type 3 STCs also feature strong latent heating rates from convection in upper levels.

Type 2 STCs undergo a transition in their development process. Initially their structure and development is very similar to that of Type 3 STCs. However, after coupling with an upper-level trough, the structure and development changes, resembling more that of Type 1 STCs. The whole transition process is very similar to that of TCs undergoing extratropical transition in this region, only Type 2 STCs are not as intense as TCs before the transition.

The differences in the development process between the 3 types are reflected in their intensification rates and subsequently in their maximum intensities. When compared to Type 3 STCs, Type 2 STCs are in general more intense. The transition in Type 2 STCs tends to prolong their lifespan, which subsequently leads to further intensification.

The change in atmospheric conditions with latitude is reflected in the development process of STCs. North of 25°S, where the moisture content in the atmosphere is very high and where there is an absence of upper-level baroclinic waves, diabatic processes, in particular the release of latent heat by convection in upper levels, dominate the development process of STCs.

As the contribution by diabatic processes decreases toward the pole, which is mostly attributed to the decreasing moisture content in the air, the contribution by VADV increases. Once south of 35°S, VADV takes over as the dominant process in the development of STCs in this region.

The latitudes between 25°S and 35°S are a zone of transition, where the contribution by all processes can be equally strong. The width of the transition zone is attributed to the interseasonal variations in the upper-level flow over the Southwest Pacific. During the colder seasons, troughs are able to propagate further into the subtropics and strong contributions by VADV can occur in lower latitudes, whereas in summer troughs generally do not move north of 30°S. Thus, during the summer months the dominance of diabatic processes in the development of STCs can be found much further south.

The change in the development process of STCs with changing latitude also explains the seasonal variations in the intensity of STCs found by the climatology in chapter 5. The lack of contribution by VADV, which apparently is needed for high intensification rates in STCs, explains the low intensity of summer STCs. On the other hand, during the colder seasons, when troughs frequently propagate far into the subtropics, strong contributions by upper-level VADV to the intensification of STCs are very likely. This explains why winter STCs are on average relatively intense.

8 Final Discussions and Conclusions

First a brief summary of the findings from the investigation in this study is given. Then the results are discussed. The study is concluded with a discussion of ideas for possible future work.

8.1 Summary

In this study a comprehensive investigation of STCs (cyclones of subtropical origin) in the Southwest Pacific was carried out. Whereas ETCs and TCs in this region have been investigated in numerous studies, STCs have largely been neglected in the literature. In chapter 4 it was shown that this group of cyclones can frequently, 2-3 times per year, be the cause of extensive damage in New Zealand, with property losses in the millions of dollars. The damage is mostly flood related, caused by the heavy rain that accompanies these cyclones. It demonstrates the need to have a good understanding of the behaviour and characteristics of these cyclones.
The main aims in this study were to give an overview of the characteristics and behaviour of STCs and then examine their movement and development process in more detail.

The climatology in chapter 5, compiled with a cyclone track database covering 21 years, established patterns in the behaviour and characteristics of STCs, thereby already answering some of the questions from the introduction.

- Annually approximately 15 STCs form in the subtropics north of the Tasman Sea and New Zealand region, most of them over the Fiji and Coral Seas.

- The majority of STCs form during autumn. However, there has been a significant increase in summer STCs over the last 10 years, which can be linked to an increase in SSTs in the area.

- Approximately 3 STCs come into the vicinity of New Zealand per year, most of them during winter. The majority of them originate at the east coast of Australia or just south of New Caledonia.

- ENSO has a strong influence on the annual variations in the behaviour of STCs. During La Niña more STCs form in the subtropics north of New Zealand and their movement has a stronger southward component than during El Niño. Thus, more STCs tend to migrate into midlatitudes and the vicinity of New Zealand during a La Niña phase.

In chapter 6, it was shown that STCs are steered into midlatitudes and ultimately into the vicinity of New Zealand by upper-level baroclinic waves, generally through interaction with an upper-level trough.

In the same chapter, it was shown that STCs can be classified into 3 types when differentiating by the upper-level flow above the surface centre of a cyclone. Those differences in the upper-level flow indicate differences in the development process of STCs. In chapter 7, those differences where analysed in more detail. This included a comparison of the structure and the development process of each type with those of ETCs and TCs in order to determine to what extent they are similar.

Type 1

These are STCs that form in the vicinity of a trough and then continue to interact with a trough throughout their entire lifetime. Their structure and development process is very similar to that of ETCs. The surface centre is located just to the east beneath an upper-level trough and in a region of a strong zonal temperature gradient at the surface. The development is dominated by strong upper-level vorticity advection.
However, in comparison to ETCs, the development of Type 1 STCs is also driven by diabatic processes. The strong influence of diabatic processes on the development of Type 1 STCs, even when they are in midlatitudes, is attributed to their place of origin and the fact that they tend to carry the warm and moist air masses from the subtropics along with them when moving into midlatitudes. The high moisture content in the air masses involved in the development of Type 1 STCs is also the reason why these cyclones are generally accompanied by heavy rain.

Type 2

These STCs lack the presence of an upper-level trough in the vicinity of their surface centre in the early stages of their development, but encounter one some time later.

In most instances the approaching trough couples with the existing surface low and sets off extratropical transition. As a result, those STCs continue to intensify and generally move into midlatitudes. However, on occasion they decay shortly after coming into the vicinity of the upper-level trough.
Before coupling with a trough, the structure of Type 2 STCs resembles that of TCs, featuring a warm core and deep convection. During that stage diabatic processes dominate the development. After the transition, however, their structure and development resembles that of ETCs.

Type 3

These STCs never encounter and interact with an upper-level trough. They display typical TC features, such as a warm core, high latent heat release by convection in upper-levels and the absence of an upper-level trough. However, the conditions are not favourable enough for them to develop into TCs. It is assumed that either the surface fluxes are not strong enough or the vertical wind shear is too strong.

A detailed study of the changes in the development process of STCs with latitude revealed the following:

- The varying atmospheric conditions in the subtropics with changing latitude are reflected in the development process of STCs. North of 25°S tropical cyclone features dominate the development process of STCs. However, the intensification rates achieved mainly by diabatic processes are not very strong, which concurs with the fact that STCs do not reach the high intensities of TCs. South of 35°S extratropical features take over the development. In comparison the intensification rates are much higher here. Apparently strong contributions by VADV are essential to achieve high intensification rates in STCs.

- Between 25°S and 35°S lies a transition zone, where the development process of STCs changes. The width of that zone is attributed to the interseasonal variations in the upper-level flow in this region. During the colder seasons upper-level baroclinic waves are able to propagate far into the subtropics. As the result, strong contributions by VADV can occur in relatively low latitudes, which accounts for the high intensity of winter STCs. In summer, troughs generally do not move north of 30°S. Thus, the development of summer STCs is generally dominated by diabatic processes, which explains their low intensity.

8.2 Discussion and Conclusion

The fact that upper-level baroclinic waves are able to propagate into the subtropics in this region is reflected in the characteristics, behaviour and development process of STCs and it is subsequently the reason for the existence of Type 1 and 2 STCs. The literature shows that this phenomenon is not unique to this region. In the subtropics in the North Pacific near Hawaii, the development of the so-called Kona storms is initiated by baroclinic waves that propagate into the subtropics. And, as in the Southwest Pacific region investigated here, this occurs more often during the colder seasons.

The differences in structure and development among the three types of STCs are reflected in other characteristics and behaviour, such as lifespan and intensity. The coupling with a trough leads to a longer lifespan and, subsequently, intensification period for Type 1 and 2 STCs. In comparison Type 3 STCs are much shorter-lived. In addition, Type 3 STCs tend to be much weaker than the other two types. Apparently the contribution by upper-level VADV is needed to achieve strong intensification rates in STCs.

Seasonal variations in the upper-level flow pattern in the Southwest Pacific are not only reflected in the development process of STCs, but also in the frequency with which each STC type occurs. Type 1 and 2 STCs are mostly found during the colder seasons, due to the fact that troughs are able to propagate into the subtropics during that time and STCs are able to form in the vicinity of a trough or are likely to couple with one at a later stage. On the other hand, Type 3 STCs occur mostly during summer, when baroclinic waves can only occasionally be found in the subtropics.

The findings here suggest that the transition Type 2 STCs undergo is similar to that of extratropical transition by TCs in this region. Essentially, TCs are just on the higher end of the intensity spectrum of all cyclones that undergo extratropical transition. Since most TCs occur during summer, and STCs are more likely during autumn, STCs are more likely to undergo extratropical transition, as they have a higher chance to couple with a trough, since troughs propagate relatively farther into the subtropics during the colder seasons.

On the basis of the findings in this study, it can be said that even though it is possible to easily classify cyclones that develop south of 30°S as ETCs and one can be relatively certain of the main characteristics of their development process, for cyclones originating north of 30°S it is not that straightforward to make assumptions about their development processes. However, their origin almost guarantees that they are accompanied by heavy rain, which essentially is what causes the most damage in New Zealand.

In their study on the performance of two forecast models in the Tasman Sea, TR (personal communication) showed that occasionally both the UKMO and the ECMWF model have difficulties with accurately forecasting their Type D cyclones (in this study STCs). The fact that both models have problems with the forecasting of this type of cyclones shows that this is not a model-specific issue. Findings here offer a possible explanation for some of these forecast errors. Sinclair (1997a) found that models have difficulties predicting the onset of extratropical transition in TCs, more specifically whether an approaching trough is going to couple with an existing surface low or cause its decay. Here, it was shown that extratropical transition also occurs in STCs and that on occasion a STC decays when approached by a trough. Thus, it is not unreasonable to suggest that some of the difficulties in forecasting STC events in this region are linked to problems forecasting the onset of extratropical transition.

The ability of upper-level baroclinic waves to propagate into subtropics and subsequently of troughs to pick up STCs is of great importance in terms of weather-related threat to New Zealand. The coupling with an upper-level trough is what brings STCs into the vicinity of New Zealand, and the moisture that they carry with them from their place of origin is the reason for the extensive flood damage frequently caused by STC events.

If baroclinic waves were to increase in amplitude and were to propagate further into the subtropics, not only might more STCs form in the vicinity of a trough, but also more STCs would most likely undergo extratropical transition. This would potentially increase the number of STCs migrating into midlatitudes and the vicinity of New Zealand. This would lead to an increase in heavy rain events over New Zealand and subsequently more flood related damage.

In terms of climate change, according to the IPCC (Intergovernmental Panel of Climate Change) reports, so far no assumptions about future changes in the upper-level flow can be made, as models are currently not capable of producing reliable simulations of this.

When investigating the future behaviour of STCs, one has to keep in mind the distinct differences in the development process among STCs. Since the development process of Type 2 STCs before transition and Type 3 STCs resembles that of TCs, it is likely to see some parallels between the future behaviour of TCs and those STCs. According to the IPCC reports, most climate change scenarios predict an increase in SSTs. However, despite the link to SSTs, there is no evidence for an increase in TC events (Terry, 2007). This is due to the fact that the development of TCs is not only influenced by SSTs. On the other hand, there is evidence for an increase in the intensity of TCs (Emanuel, 2005; Terry, 2007). Since the development process of Type 2, at least in part, and 3 STCs is similar to that of TCs, this could also mean an increase in their intensity. In some cases the increase might be high enough to put an STC into TC category.

At the current time no viable prediction of the future behaviour of STCs in this region can be made. Evidently much more work has to go into that area of research.

8.3 Future Work

During the course of this study, a number of ideas for future work were formed.

As mentioned earlier, Type 2 and 3 STCs are cyclones of subtropical origin that, despite having TC features, did not develop into TCs. Future work could examine in more detail what keeps these STCs from fully developing into TCs, including whether it is mainly due to the lack of sufficient surface fluxes, or mainly due to vertical wind shear that is too strong.

Another idea would be to take a closer look at the forecasting of STC events. As mentioned in the previous section, occasionally models have difficulties forecasting STC events in this region. According to TR (personal communication), generally the models tend to overestimate the intensity of these systems. Poor forecasting of STC events, in particular in regard to intensity, was also mentioned by Qi et al. (2006), when they investigated heavy rain events affecting Australia. Preliminary analysis during the investigation for this study here regarding the forecast of STCs confirms occasionally significant forecast errors for STCs not only in regards to intensity, but also location of track. It is suspected that, aside from the difficulties predicting extratropical transition, another cause for the forecast errors, in particular in terms of overestimated intensity, might be the handling of moisture in the models. Future work could investigate this in more detail.

Furthermore, the use of different cyclone track databases in this study initiated the idea for another study. In addition to two cyclone track databases used here, a third cyclone track database was available. This one was compiled by K. Keay and Dr. I. Simmonds (hereafter referred to as KS), who used their own tracking software and the ERA40 data from ECMWF, which is available 4 times daily on a $2.5^\circ \times 2.5^\circ$ grid. As mentioned in chapters 3 and 5, there is a discrepancy in the total number of STCs from the MS and TR database. The number of STCs in the KS database also differs. It would be interesting to know what the cause for this is, in particular the reason for differences between the MS and KS database. However, since both not only used different tracking software, but also different data sets, it is impossible to determine the direct cause for the discrepancy at this stage. One option would be to run each tracking software with the same dataset, to see whether the discrepancy is caused by the different tracking method. The second option would be to run either tracking software on both datasets. This would show if the different datasets are responsible for the discrepancy.

[4]Current Affiliations: University of Melbourne, Australia

9 Appendix I

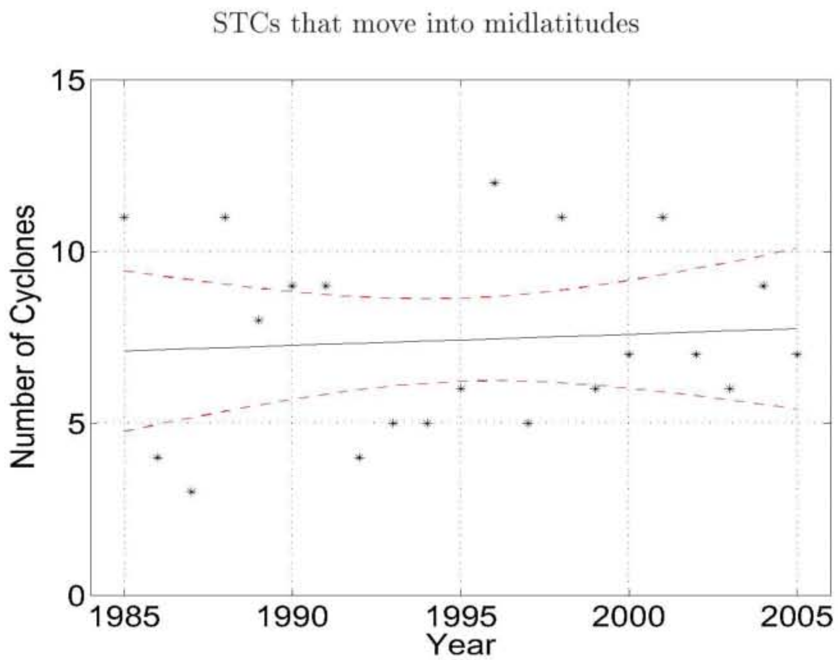

Figure 9.1: *Annual frequency of STCs from the MS database (black stars) that move into midlatitudes, including trend lines (solid black line) and 95% confidence intervals (dashed red lines) of the trend.*

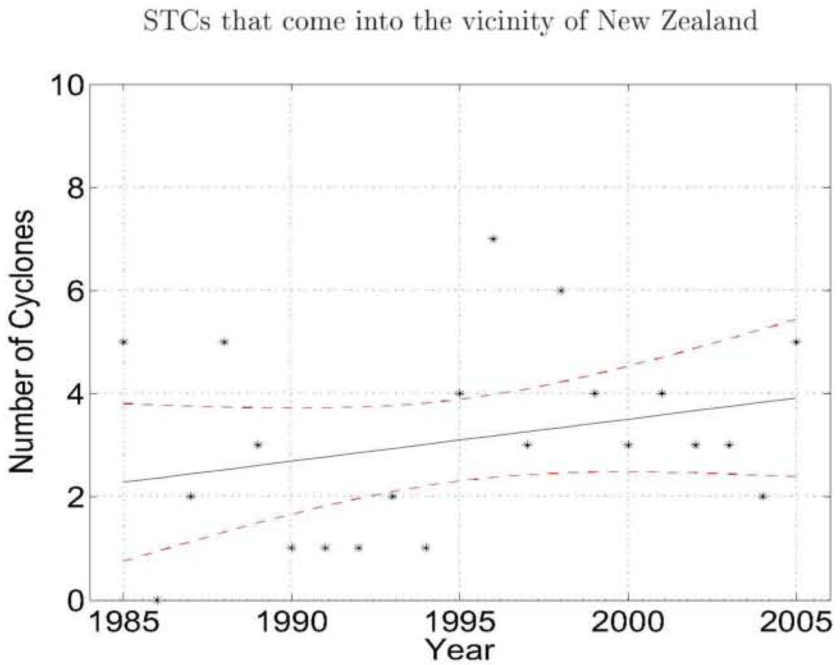

Figure 9.2: *Annual frequency of STCs from the MS database (black stars) that come into the vicinity of New Zealand, including trend lines (solid black line) and 95% confidence intervals (dashed red lines) of the trend.*

10 Appendix II

Parameter	Levels
SLP	Ground
H	1000, 850, 700, 500, 400, 300, 250, 200, 150, 100
T	Ground, 850, 700, 500, 400, 300, 250, 200, 150, 100
U/V	Ground, 850, 700, 500, 400, 300, 250, 200, 150, 100
OMEGA*	1000, 850, 700, 500, 300
W**	1000, 850, 700, 500, 300
RH	1000, 850, 700, 500
Rain	Total

Table 10.1: *Available analyses fields from the UKMO model data from November 1998 to December 2003.*
Levels [hPa], Ground = Z(0), Total = sum over whole column. (*) - available until July 2002. (**) available from August 2002.

CN	Date	Season	Area	Track	max GVOR	Type
1	05.11.-06.11.98	Sp	SFB	S30	16.5	1
	12.11.-14.11.98	Sp	SFB	N30	–	–
2	17.11.-22.11.98	Sp	SWP	VNZ	36.6	1
3	25.11.-30.11.98	Sp	ECA	VNZ	37.1	1
4	14.12.-20.12.98	Su	CS	VNZ	39.4	2
5	23.12.-26.12.98	Su	SWP	S30	22.8	2
6	07.03.-15.03.99	Au	SFB	S30	27.2	2
7	10.04.-13.04.99	Au	SFB	S30	17.2	2
8	10.05.-13.05.99	Au	CS	VNZ	54.5	1
9	20.05.-26.05.99	Au	CS	VNZ	69.9	2
10	09.07.-19.07.99	Wi	CS	VNZ	40.4	2
11	24.07.-28.07.99	Wi	CS	N30	27.1	2
12	12.09.-17.09.99	Sp	NFB	VNZ	28.3	1
13	31.10.-06.11.99	Sp	NFB	S30	41.6	1
14	08.11.-12.11.99	Sp	ECA	VNZ	53.9	1
15	04.12.-07.12.99	Su	CS	N30	22.0	3
16	18.12.-22.12.99	Su	ECA	VNZ	46.0	2
17	26.12.-03.01.00	Su	ECA	VNZ	29.9	2

Table 10.2: *List of STCs from the TR database between November 1998 and December 1999;*
Info on: Start and End Date, Season, Area of Formation, direction of movement (track), maximum GVOR [-10^{-5} s^{-1}] during whole lifetime of each cyclone and Type of STCs as defined in chapter 6. Case without a number have 2 or more track points of missing data.

CN	Date	Season	Area	Track	max GVOR	Type
18	04.01.-08.01.00	Su	NFB	N30	12.3	3
	21.02.-03.03.00	Au	NFB	N30	–	–
	28.02.-03.03.00	Au	CS	N30	–	–
19	28.04.-30.04.00	Au	CS	N30	40.9	2
20	30.04.-03.05.00	Au	CS	N30	30.9	3
21	09.05.-14.05.00	Au	SFB	VNZ	44.3	1
22	09.06.-12.06.00	Wi	CS	S30	49.0	2
23	26.06.-28.06.00	Wi	NFB	VNZ	33.1	2
24	18.10.-21.10.00	Sp	SFB	N30	26.8	1
25	30.10.-06.11.00	Sp	CS	VNZ	24.6	1
	22.11.-24.11.00	Sp	CS	N30	–	–
26	05.12.-08.12.00	Su	SFB	S30	18.2	1
27	04.01.-08.01.01	Su	SFB	N30	25.1	3
28	08.01.-12.01.01	Su	SWP	S30	18.1	1
29	15.01.-17.01.01	Su	NFB	N30	16.1	2
30	29.01.-01.02.01	Su	SFB	VNZ	29.1	2
31	08.02.-13.02.01	Su	NFB	VNZ	20.5	2
	10.02.-15.02.01	Su	CS	N30	–	–
	19.02.-25.02.01	Su	CS	N30	–	–
32	03.03.-09.03.01	Au	SWP	N30	39.3	1
	01.04.-03.04.01	Au	SWP	N30	–	–
33	28.04.-03.05.01	Au	SFB	S30	52.2	1
34	02.05.-07.05.01	Au	NFB	VNZ	35.6	1
35	07.05.-10.05.01	Au	SWP	S30	18.0	1
36	11.06.-15.06.01	Wi	SFB	S30	30.2	1
37	02.07.-08.07.01	Wi	SWP	S30	61.6	1
38	05.11.-07.11.01	Sp	SFB	VNZ	26.5	1
39	13.12.-17.12.01	Su	NFB	N30	13.5	2

Table 10.3: *List of STC cases from the TR database during 2000 and 2001; info as in Tab. 10.2.*

CN	Date	Season	Area	Track	max GVOR	Type
	01.01.-08.01.02	Su	NFB	N30	–	–
40	13.01.-18.01.02	Su	CS	S30	20.2	2
	07.02.-08.02.02	Su	SFB	N30	–	–
41	16.04.-22.04.02	Au	SWP	S30	40.1	1
42	10.05.-13.05.02	Au	NFB	N30	19.9	3
43	29.05.-02.06.02	Au	CS	S30	21.9	1
44	19.06.-21.06.02	Wi	SWP	VNZ	57.3	1
45	26.06.-28.06.02	Wi	SWP	VNZ	37.0	1
	14.08.-19.08.02	Wi	NFB	S30	–	–
	24.08.-27.08.02	Wi	CS	N30	–	–
46	21.10.-24.10.02	Sp	CS	N30	25.8	3
47	15.01.-18.01.03	Su	NFB	N30	15.6	3
48	26.03.-31.03.03	Au	SFB	VNZ	28.6	1
49	05.04.-10.04.03	Au	NFB	S30	32.3	2
50	15.05.-18.05.03	Au	SWP	S30	26.6	1
51	24.06.-29.06.03	Wi	CS	S30	66.5	2
52	14.07.-16.07.03	Wi	NFB	N30	27.8	1
53	15.08.-22.08.03	Wi	CS	VNZ	46.6	1
54	18.10.-25.10.03	Sp	CS	S30	24.8	2
55	23.11.-27.11.03	Sp	ECA	VNZ	29.2	1
56	05.12.-11.12.03	Su	ECA	S30	56.7	1

Table 10.4: *List of STC cases from the TR database during 2002 and 2003; info as in Tab. 10.2.*

CN	Date	LAT	max GVOR
1	08.01.-10.01.99	36	29.1
2	28.01.-30.01.99	39	20.2
3	17.02.-19.02.99	45	28.7
4	02.03.-06.03.99	30	54.6
5	27.03.-30.03.99	36	42.1
6	21.04.-27.04.99	35	44.6
7	27.04.-02.05.99	35	30.4
8	03.06.-06.06.99	43	34.6
9	09.06.-13.06.99	34	26.5
10	30.06.-05.07.99	34	30.5
11	31.07.-04.08.99	43	25.5
12	12.08.-16.08.99	38	43.5
13	10.09.-15.09.99	43	27.1
14	04.10.-08.10.99	38	20.2
15	18.10.-22.10.99	33	58.6
16	23.10.-26.10.99	29	37.6
17	15.11.-18.11.99	33	20.1
18	25.11.-30.11.99	43	21.3
19	11.12.-14.12.99	36	31.7
20	29.12.-03.01.00	38	31.8

Table 10.5: *List of selected ETC cases from the TR database during 1999. Info on: Start and End Date, Latitude location at formation and maximum GVOR [-10^{-5} s^{-1}] during whole lifetime of each cyclone.*

CN	Date	LAT	max GVOR
21	03.01.-08.01.00	41	30.0
22	28.06.-04.07.00	33	34.4
23	07.07.-11.07.00	43	24.3
24	10.07.-14.07.00	30	27.4
25	28.10.-31.10.00	39	31.3
26	07.12.-12.12.00	41	17.2
27	27.04.-29.04.01	37	17.7
28	10.05.-12.05.01	41	19.4
29	12.06.-14.06.01	37	61.6
30	19.10.-23.10.01	34	40.1
31	27.10.-30.10.01	33	20.0
32	12.11.-14.11.01	36	32.7
33	18.11.-23.11.01	30	39.8
34	12.01.-15.01.02	31	24.2
35	12.01.-15.01.02	41	24.2
36	18.05.-21.05.02	38	30.9
37	02.04.-07.04.03	34	25.3
38	18.08.-21.08.03	40	23.5

Table 10.6: *List of selected ETC cases from the TR database during 2000 and 2003; info as in Tab. 10.5.*

Glossary of Abbreviated Terms

ADIAB	Adiabatic Processes
Au	Autumn
BOP	Bay of Plenty
CG	Cyclone Genesis
CHR	Latent Heating Rates from Convective Processes
DIAB	Diabatic Processes
DIV	Divergence
CN	Case Number
CS	Coral Sea
ECA	East Coast of Australia
ECMWF	European Centre for Medium Range Weather Forecasts
ENSO	El Niño-Southern Oscillation
ET	Encounter with an upper-level trough
ETC	Extratropical Cyclone
Ex-TC	Ex-Tropical Cyclone
GVOR	Geostrophic Relative Vorticity
IPCC	Intergovernmental Panel on Climate Change
KS	K. Keay and Dr. I. Simmonds
LSHR	Latent Heating Rates from Large Scale Ascent
MS	Dr. M. Sinclair
N30	North of 30°S
NCAR	National Center for Atmospheric Research
NCEP	National Centers for Environmental Prediction

NCEP/NCAR	see NCEP and NCAR
NFB	North Fiji Basin
NIWA	National Institute of Water and Atmospheric Research
NZ	New Zealand
RH	Relative Humidity
S30	South of 30°S
SFB	South Fiji Basin
SH	Southern Hemisphere
SLP	Sea Level Pressure
SOI	Southern Oscillation Index
Sp	Spring
SST	Sea Surface Temperature
STC	Cyclone of Subtropical Origin, not including TCs
Su	Summer
SWP	Southwest Pacific
TADV	Temperature Advection
TC	Tropical Cyclone
TR	Dr. R. Turner and Dr. J. Renwick
TS	Tasman Sea
UKMO	United Kingdom Meteorological Office
VADV	Vorticity Advection
VIC	Victoria University of Wellington, New Zealand
VNZ	Vicinity of New Zealand
Wi	Winter

Mathematical Symbols

a	Mean radius of the earth
c	Correlation coefficient
c_p	Specific heat at constant pressure
f	Coriolis Parameter
g	Gravitational acceleration
ir	Intensification rate of GVOR
p	Pressure
$q\mathbf{v}$	Horizontal moisture flux
w	Vertical wind component (z-component)
$\mathbf{C}$	Speed of storm
$\dot{Q}$	Latent heating rates of condensation
$\dot{Q}/c_p$	Diabatic heating rate
R	Gas constant for air
RH	Relative humidity
S	Static stability parameter
T	Temperature
$\mathbf{V}$	Horizontal wind vector
ζ	Absolute vorticity
ζ_g	Geostrophic relative vorticity (GVOR)
λ	Longitude
ϕ	Latitude
ω	Vertical velocity
Θ	Potential temperature
Φ	Geopotential
Ω	Earth rotation

List of Figures

List of Tables

References

Anthes, R. A., 1977: A Cumulus Parameterization Scheme Utilizing a One-Dimensional Cloud Model. *Mon. Wea. Rev.*, **105**, 270–286.

Bals-Elsholz, T. M., E. H. Atallah, L. F. Bosart, T. A. Wasula, M. J. Cempa, and A. R. Lupo, 2001: The Wintertime Southern Hemisphere Split Jet: Structure, Variability, and Evolution. *J. Climate*, **14**, 4191–4215.

Carlson, T. N., 1991: *Mid-Latitude Weather Systems*. HarperCollins. 211-212.

Cullen, M. J. P., 1993: The unified forecast/climate model. *Meteorological Monographs*, **122**, 81–94.

Davis, C. A. and L. F. Bosart, 2003: Baroclinically Induced Tropical Cyclogenesis. *Mon. Wea. Rev.*, **131**, 2730–2747.

Edmon, H. J. J. and D. G. Vincent, 1976: An application of two tropical parameterization schemes of latent heat release in middle latitudes. *Mon. Wea. Rev.*, **104**, 1141–1153.

Emanuel, K., 2005: Increasing destructiveness of tropical cyclones over the past 30 years. *Nature*, **436**, 686–688.

Evans, M. S., D. Keyser, L. F. Bosart, and G. M. Lackmann, 1994: A satellite-derived classification scheme for rapid maritime cyclogensis. *Mon. Wea. Rev.*, **122**, 1381–1412.

Gallego, D., R. Ribera, R. Garcia-Herrera, E. Hernandez, and L. Gimeno, 2005: A new look for the Southern Hemisphere jet stream. *Clim. Dyn.*, **24**(6), 607–621.

Gyakum, J. R., 1983: On the Evolution of the QE II Storm. II: Dynamic and Thermodynamic Structure. *Mon. Wea. Rev.*, **111**, 1156–1173.

Haltiner, G. J. and R. T. Williams, 1980: *Numerical Prediction and Dynamic Meteorology*. John Wiley and Sons. 477pp.

Harr, P. A. and R. L. Elsberry, 2000a: Extratropical Transition of Tropical Cyclones over the Western North Pacific. Part I: Evolution of Structural Characteristics during the Transition Process. *Mon. Wea. Rev.*, **128**, 2613–2633.

Harr, P. A. and R. L. Elsberry, 2000b: Extratropical Transition of Tropical Cyclones over the Western North Pacific. Part II: The Impact of Midlatitude Circulation Characteristics. *Mon. Wea. Rev.*, **128**, 2634–2653.

Hart, R. E., 2003: A Cyclone Phase Space derived from Thermal Wind and Thermal Asymmetry. *Mon. Wea. Rev.*, **131**, 585–616.

Hart, R. E., J. L. Evans, and C. Evans, 2006: Synoptic Composites of the Extratropical Transition Life Cycle of North Atlantic Tropical Cyclones: Factors Determining Posttransition Evolution. *Mon. Wea. Rev.*, **134**, 553–578.

Hill, H. W., 1970: The precipitation in New Zealand associated with the cyclone of early april 1968. *N.Z. J. Sci.*, **13**, 641–662.

Holland, G. J., A. H. Lynch, and L. M. Leslie, 1987: Australian East-Coast Cyclones. Part I: Synoptic Overview and Case Study. *Mon. Wea. Rev.*, **115**, 3024–3036.

Holton, J. R., 1992: *An Introduction to Dynamic Meteorology; Third Edition*. Academic Press, Inc. Pp 511.

Hoskins, B. J. and T. Ambrizzi, 1993: Rossby Wave Propagation on a Realistic Longitudinally Varying Flow. *J. Atmos. Sci.*, **50**(12), 1661–1671.

Jones, D. A. and I. Simmonds, 1993: A climatology of Southern Hemisphere Extratropical Cyclones. *Clim. Dyn.*, **9**, 131–145.

Kuo, Y.-H., M. A. Shaprio, and E. G. Donall, 1991: The Interaction between Baroclinic and Diabatic Processes in a Numerical Simulation of Rapidly Intensifying Extratropical Marine Cyclone. *Mon. Wea. Rev.*, **19**, 369–384.

Lackmann, G. M., 2002: Cold-Frontal Potential Vorticity Maxima, the Low-Level Jet, and Moisture Transport in Extratropical Cyclones. *Mon. Wea. Rev.*, **130**, 59–74.

Leslie, L. M., G. J. Holland, and A. H. Lynch, 1987: Australian East-Coast Cyclones. Part II: Numerical Modeling Study. *Mon. Wea. Rev.*, **115**, 3037–3053.

Leslie, L. M., M. Leplastrier, B. W. Buckley, and L. Qi, 2005: Climatology of meteorological 'bombs' in the New Zealand region. *Meteor. Atmos. Phys.*, **89**, 207–214.

Lim, E. and I. Simmonds, 2002: Explosive Cyclone Development in the Southern Hemisphere and a Comparison with Northern Hemisphere Events. *Mon. Wea. Rev.*, **130**, 2188–2209.

McGavin, T., 1990-2005: Notable Recent Weather. *Quart. Newsl. NZ. Meteor. Soc.*, **1-4**.

Murray, R. and I. Simmonds, 1991a: A numerical scheme for tracking cyclone centres from digital data. Part I: Development and operation of the scheme. *Austral. Meteor. Mag.*, **39**, 155–166.

Murray, R. J. and I. Simmonds, 1991b: A numerical scheme for tracking cyclone centres from digital data. Part II: Application to January and July GCM simulations. *Austral. Meteor. Mag.*, **39**, 167–180.

Nakamura, H. and A. Shimpo, 2004: Seasonal Variations in the Southern Hemisphere Storm Tracks and Jet Streams as Revealed in a Reanalysis Dataset. *J. Climate*, **17**, 1828–1844.

Orlanski, I. and J. J. Katzfey, 1987: Sensitivity of Model Simulations for a Coastal Cyclone. *Mon. Wea. Rev.*, **115**(11), 2792–2821.

Otkin, J. A. and J. E. Martin, 2004: A Synoptic Climatology of the Subtropical Kona Storm. *Mon. Wea. Rev.*, **132**, 1503–1517.

Pezza, A. B. and T. Ambrizzi, 2003: Variability of Southern Hemisphere Cyclones and Anticyclones Behavior: Further Analysis. *Amer. Meteor. Soc.*, **16**, 1075–1083.

Qi, L., L. M. Leslie, and M. S. Speer, 2006: Climatology of cyclones over the southwest Pacific: 1992-2001. *Meteor. Atmos. Phys.*, **91**, 201–209.

Rausch, R. L. M. and P. J. Smith, 1996: A Diagnosis of a Model-Simulated Explosively Developing Extratropical Cyclone. *Mon. Wea. Rev.*, **124**(5), 875–904.

Reeder, M. J., A. J. Simmons, M. D. Albright, and P. Unden, 1988: The Role of Latent Heat Release in Explosive Cyclongenesis: Three Examples Based on ECMWF Operational Forecasts. *Wea. and Forec.*, **3**, 217–229.

Revell, M. J. and R. N. Ridley, 1995: The origin and evolution of low-level potential vorticity anomalies during a case of Tasman Sea cyclogenesis. *Tellus*, **47A**, 779–796.

Roemmich, D., J. Gilson, J. Willis, P. Sutton, and K. Ridgeway, 2006: Closing the Time-Varying Mass and Heat Budgets for Large Ocean Areas: The Tasman Box. *J. Climate*, **18**, 2330–2343.

Salinger, M. J., J. A. Renwick, and A. B. Mullan, 2001: Interdecadal Pacific Oscillation and South Pacific Climate. *Int. J. Climatol.*, **21**(14), 1705–1722.

Sanders, F. and J. R. Gyakum, 1980: Synoptic-dynamic climatology of the 'Bomb'. *Mon. Wea. Rev.*, **108**(10), 1589–1606.

Simmonds, M. and K. Keay, 2000a: Variability of Southern Hemisphere Extratropical Cyclone Behaviour 1958-97. *J. Climate*, **13**(3), 550–561.

Simmonds, M. and K. Keay, 2000b: Mean Southern Hemisphere Extratropical Cyclone Behaviour in 40-Year NCEP-NCAR Reanalysis. *J. Climate*, **13**(5), 873–885.

Sinclair, M., 1993a: A Diagnostic Study of the Extratropical Precipitation Resulting from Tropical Cyclone Bola. *Mon. Wea. Rev.*, **121**, 2690–2707.

Sinclair, M., 1993b: Synoptic-Scale Diagnosis of the Extratropical Transition of a Southwest Pacific Tropical Cyclone. *Mon. Wea. Rev.*, **121**(4), 942–960.

Sinclair, M., 1994: An Objective Cyclone Climatology for the Southern Hemisphere. *Mon. Wea. Rev.*, **122**, 2239–2256.

Sinclair, M., 1995a: Climatology of Cyclogenesis for the Southern Hemisphere. *Mon. Wea. Rev.*, **123**, 1601–1618.

Sinclair, M., 1995b: Extended Climatology of Extratropical Cyclones over the Southern Hemisphere. *Wea. and Clim.*, **15**, 21–32.

Sinclair, M., 1997a: Anatomy of Storms. *Tephra*, **16**, 6–13.

Sinclair, M., 1997b: Objective Identification of Cyclones and their Circulation Intensity, and Climatology. *Wea. and Forec.*, **12**, 595–612.

Sinclair, M., 2002: Extratropical Transition of the Southwest Pacific Tropical Cyclones. Part I: Climatology and Mean Structure Changes. *Mon. Wea. Rev.*, **130**, 590–609.

Sinclair, M., 2004: Extratropical Transition of the Southwest Pacific Tropical Cyclones. Part II: Midlatitude Circulation Characteristics. *Mon. Wea. Rev.*, **132**, 2145–2168.

Sinclair, M., J. A. Renwick, and J. W. Kidson, 1997: Low-Frequency Variability of Southern Hemisphere Sea Level Pressure and Weather System Activity. *Mon. Wea. Rev.*, **125**, 2531–2543.

Sinclair, M. and M. Revell, 2000: Classification and Composite Diagnosis of Extratropical Cyclogenesis Events in the Southwest Pacific. *Mon. Wea. Rev.*, **128**, 1089–1104.

Terry, J. P., 2007: *Tropical Cyclones: Climatology and Impacts in the South Pacific.* Springer-Verlag. Pp.220.

Turner, R., J. Renwick, and S. Schoeder, 2003: How good are New Zealand weather forecasts? *Water and Atmosphere.*, **11**(4), 24–25.

Wallace, J. M. and P. V. Hobbs, 2006: *Atmospheric Science. An Introductory Survey*. Elsevier. Second Edition. pp. 483.