Spatial and Temporal Variability of Phytoplankton Productivity in the Subtropical Front around New Zealand

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ABSTRACT

The association between enhanced phytoplankton productivity and the Subtropical Front (STF) around New Zealand was investigated using remote sensing images derived from the MODIS-Aqua sensor. The STF is a major circumpolar oceanic system that marks the boundary between subtropical and subantarctic water masses. The STF is accompanied by strong physical and nutrient gradients due to the interactions between these water masses and adjacent coastal processes that lead to elevated phytoplankton biomass. The spatial and temporal variability in the position of the STF due to changes in topographic features and water mass properties regulates the conditions required for growth of phytoplankton. This study provides a long-term analysis of spatial and temporal variability in Chlorophyll-a (Chl-a) concentration with respect to variations in the frontal location.

MODIS-Aqua monthly composite images of sea surface temperature (SST) and surface Chl-a concentration from January 2003 to December 2012 were used to estimate the position of the STF and enhanced phytoplankton productivity around the STF to the south and east of New Zealand. The position of the STF mainly followed the shelf-break (between the 200 and 500 m isobaths). The position and strength of the STF changed with season, being located further inshore relative to the 500 m isobath and strengthened during summer, and located further offshore and weakened during winter. Areas of elevated productivity were consistently coincident with the frontal location, with the highest Chl-a concentrations typically occurring inshore of the front. The peak 10-year average concentration along the front was 1 mg/m$^3$ and the peak seasonal average was 1.5 mg/m$^3$. Phytoplankton productivity typically increased heading northward and decreased (< 0.5 mg/m$^3$) with increasing distance from the coast. The locations of enhanced phytoplankton productivity relative to the position of the front varied seasonally. Small patches of high productivity were normally found across regions where the front intensely meandered (e.g. over the Mernoo Saddle and Chatham Rise).

Phytoplankton blooms generally occurred at the STF over the Mernoo Saddle and Chatham Rise, following the spring annual cycle, with the Chl-a concentration increasing during spring and dropping during winter. The mean concentration in the blooms over the Mernoo Saddle varied between 1 mg/m$^3$ and 5 mg/m$^3$, being stronger during autumn. Over the Chatham Rise, mean bloom concentration varied between 1 mg/m$^3$ and 3 mg/m$^3$, being stronger during spring. The spring bloom cycle was very obvious inshore of the front, but weaker in the offshore water. Secondary blooms were observed outside the spring blooms.
during summer or autumn, and were sometimes stronger than the spring bloom within the same year.
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CHAPTER I. GENERAL INTRODUCTION

1.1 Overview

Phytoplankton is a vital part of marine ecosystems, dominating net primary production (NPP) in the global oceans (Field et al., 1998; Han & Takahashi, 2001). Variability in phytoplankton biomass affects biogeochemical cycles, fishery catches, productivity of filter-feeding invertebrates, and climate processes (Falkowski et al., 1998; MacKenzie & Adamson, 2004; Falkowski & Oliver, 2007; Chassot et al., 2010). The physical and chemical changes in the ocean regulate the spatial and temporal variability of phytoplankton abundance (Sullivan et al. 1993). Chlorophyll-a (Chl-a) concentration is a good indicator of phytoplankton biomass as it is found in most eukaryotic phytoplankton and some prokaryotes (including cyanobacteria), and is essential for the absorption of light energy during photosynthesis (Blankenship, 2002; Liu & Wang, 2013). The physical process of vertical mixing controls the mixed layer depth and water column stability, which affect the availability of light and nutrients for photosynthesis (Demnan & Gargett, 1983; Falkowski et al., 1998; Liu & Wang, 2013). These features vary depending on the location, time of year, and global climate fluctuations (Haywood, 2004; Gall & Zeldis, 2011; Hirawake et al., 2011).

New Zealand’s Exclusive Economic Zone (EEZ) is the fourth largest in the world (Blezard, 1980). The primary productivity within the EEZ of New Zealand has an important role in sustaining fisheries production. The South Island of New Zealand affects the physical and chemical properties of the ocean surrounding it, including the Subtropical Front (STF) (Vincent et al., 1991; Haywood, 2004; Jones et al., 2013). The STF is a global front in the Southern Ocean acting as the boundary between Subtropical Water (STW) and Subantarctic Water (SAW) (Heath, 1973, 1981, 1985; Chiswell, 1996; Shaw et al., 1999). The STF is accompanied by strong physical and nutrient gradients (Vincent et al., 1991; Butler et al., 1992; Bradford-Grieve et al., 1997; Nodder et al., 2003; Chiswell et al., 2013), driving the planktonic growth which is linked to the ocean-atmosphere carbon budget (Currie et al., 2011; Jones et al., 2013), food-chain dynamics (Field et al., 1998), global climate change (Murphy et al., 2001), and fishery production (Roberts, 1980; Chassot et al., 2010). Nevertheless, little is known about the association between enhanced phytoplankton productivity and the STF around New Zealand.

Remote sensing of ocean-colour data provides near real-time, long-term, concise, and broad estimates of oceanic parameters. In turn, this facilitates evaluation of oceanic
processes, such as the variability of Chl-a, encompassing a wide variety of spatial and temporal scales (Longhurst et al., 1995; Dogliotti et al., 2009). Chl-a concentration is routinely measured by several remote sensing ocean-colour sensors, for example the MODerate Resolution Imaging Spectroradiometer (MODIS), and the Sea-Viewing Wide Field-of-view Sensor (SeaWiFS). Chl-a measurements from these sensors have been used to assess the spatial and temporal variability of phytoplankton and its interaction with other biological, chemical, and/or physical components of the ocean around the world (Gregg et al., 2005; Sokolov et al., 2006; Sokolov & Rintoul, 2007; Belkin & O’Reilly, 2009; Waite & Mueter, 2013; Liu et al., 2014), and particularly in the New Zealand region (Murphy et al., 2001; Chiswell et al., 2013; Jones et al., 2013).

The main objective of this study is to examine the relationship between enhanced phytoplankton productivity indicated by the surface Chl-a concentration and the STF around New Zealand. This study utilizes the sea surface temperature (SST) and Chl-a concentration images provided by the MODIS-Aqua sensor from 2003 to 2012 to demonstrate the average, inter-annual, and seasonal variability of the position of the STF and phytoplankton productivity.

1.2 Phytoplankton biomass

Phytoplankton refers to the aquatic single-celled organism, which drifts freely in the water and uses light and CO₂ for photosynthesis to obtain energy (Bollmann et al., 2013). There are over 5000 described species of phytoplankton with cell diameters ranging from 1 µm to 100 µm (Blondeau-Patissier et al., 2014). Since photosynthesis uses solar power as its energy source, phytoplankton cells contain pigments that absorb sunlight in certain wavelengths of the spectrum. Chl-a is the dominant pigment found in most species, although other pigments, such as Chl-b and Chl-c, carotenoids, and biliproteins, may also be found. The relative amount of each pigment varies according to the species of phytoplankton (Kirk, 1994). Chl-a concentration is generally used as a direct proxy for the estimation of phytoplankton biomass and abundance (Blondeau-Patissier et al., 2014). Details of the photosynthetic reaction are explained in Jones (2012).
1.2.1 Factors limiting phytoplankton biomass

The biochemical development of biomass from photosynthesis is known as primary production (Bollmann et al., 2010). Phytoplankton production and growth are generally controlled by the availability of light and inorganic carbon in the water column (Bollmann et al., 2013). Sufficient macro- and micro-nutrients are also needed to sustain phytoplankton growth (Falkowski et al., 1998). The availability of light in the ocean water column depends on seasonal fluctuations in the surface irradiance, mixed layer depth, and turbidity (Diehl et al., 2002).

The euphotic zone is the depth of the water column where the light irradiance is greater than 1% of surface light irradiance (Morel, 1988; Jones, 2012). Vertical mixing in the water column transports phytoplankton in and out of the euphotic zone. Water movement, such as ocean currents and upwelling, regulate the fluxes of essential nutrients from deeper water to the euphotic zone, influencing the Chl-a concentration and the phytoplankton community (Falkowski et al., 1998).

Phytoplankton reacts rapidly to fluctuations in nutrient availability (Bollmann et al., 2010). The availability of macronutrients, such as nitrogen and phosphorus, are essential for the production of the nucleus and ribosomes of phytoplankton (Falkowski et al., 1998; Jones, 2012). Dissolved silicate is essential for the growth of diatoms (Liu & Wang, 2013). Micronutrients, including trace metals, such as iron, zinc, and manganese, are also essential for photosynthesis, even though they are only needed in a small amounts (Hawke, 1989; Hassler et al., 2011). In water with low nitrogen and phosphorus concentrations, small phytoplankton cells dominate the community, since they cope with the limited diffusion better than the larger cells (Falkowski & Oliver, 2007).

1.2.2 Phytoplankton bloom

A phytoplankton bloom is generally defined as a rapid growth of phytoplankton in a short time resulting in a significant enhancement in biomass (Skliris & Djenidi, 2006; Liu et al., 2014). Phytoplankton blooms occur in water where the physical factors, such as light and temperature, are favorable, and essential nutrients are available. The bloom is normally a temporary event that subsides once the abundance of essential nutrients is gone, or when
physical conditions are no longer favorable. Hence, they are typically short duration events that may last a few days or up to several weeks (Murphy et al., 2001; Skliris & Djenidi, 2006).

The nutrient enrichment triggering phytoplankton blooms may be delivered from deep water, such as from the upwelling. In this type of bloom, diatoms normally dominate the phytoplankton community (Falkowski et al., 1998). On the other hand, in regions near the shore, essential nutrients are regularly supplied by riverine discharge along the coast (Jones et al. 2013). In addition, a localized bloom may occur caused by deposition of iron-rich aeolian dust (Shaw et al., 2008), or due to episodic events such as storms (Zhang et al., 2013).

1.3 Ocean fronts

Ocean fronts are commonly explained as narrow zones that separate water masses with different characteristics, for example, salinity and temperature (Belkin & Cornillon, 2003). Fronts are formed as different water masses meet, due to a variety of different physical processes, such as river outflows, tidal mixing or ocean upwelling (Acha et al., 2015). These processes generate sharp horizontal gradients in temperature, salinity, nutrients, and other properties of the ocean (Belkin & Cornillon, 2003; Belkin & O’Reilly, 2009). A number of permanent ocean fronts exist in the Southern Ocean (Belkin & Gordon, 1996), that are shown in Figure 1.1. Previous studies have found that the location of the Southern Ocean fronts may vary as the properties of the water masses changes both temporally and spatially (Belkin & Gordon, 1996; Uddstrom & Oien, 1999; Sokolov & Rintoul, 2002, 2007; Hopkins et al., 2010).
Fronts are often associated with enhanced biological productivity (Chiswell, 1994; Bradford-Grieve et al., 1997; Chang & Gall, 1998; Sokolov et al., 2006; Sokolov & Rintoul, 2007). Distributions of seabirds and pelagic fish are often concentrated within frontal zones. For example, Sokolov et al. (2006) found that most dives by king penguin (*Aptenodytes patagonicus*) were located in regions of higher surface Chl-a over the Antarctic Circumpolar Current. During summer months, shearwaters and diving petrels tend to migrate south of New Zealand towards the Subtropical Convergence (STC) and Polar Front (PF) to exploit phytoplankton productivity (Gaskin & Rayner, 2013). Roberts (1980) found the STC across the Chatham Rise was the southern limit for the surface distribution of albacore tuna (*Thunnus alalunga*).
1.3.1 Subtropical Front

In the Southern Ocean, cold, low salinity SAW of the West Wind Drift, meets and sinks beneath warmer, more saline STW derived from the Trade Wind Drift, to form the STF (Heath, 1973, 1981, 1985; Chiswell, 1996; Shaw et al., 1999; Belkin & Cornillon, 2003). The STF is located at approximately 40°S and extends continuously around the Southern Ocean over 25,000 km (Belkin & Gordon, 1996; Hopkins et al., 2010). The STF forms a key mixing zone between these two water masses with distinct physical and biochemical characteristics (Pinkerton et al., 2005). The signature of the STF can be identified by sharp horizontal gradients in surface temperature and salinity (Chiswell, 1996; Shaw & Vennell, 2000).

New Zealand lies across the path of the STF and acts as a barrier. Moving eastward from the Tasman Sea, the STF is deflected southward, before moving northeastward along the continental shelf of the east coast of the South Island, then turning east around the Mernoo Saddle towards the Chatham Rise (Heath, 1981, 1983, 1985; Shaw & Vennell, 2000; Sutton, 2003). East of the Chatham Rise, the STF generally projects southwards as a tongue-like feature (Heath, 1981). The position of the STF south and east of New Zealand is shown in Figure 1.2. The position of the STF within the New Zealand region is likely to be topographically steered by the upper continental shelf (Shaw & Vennell, 2001; Hopkins et al., 2010; Smith et al. 2013). Some studies propose that south of the South Island, the STF directly crosses the Snares Shelf (Garner, 1959; Belkin & Gordon, 1996; Chiswell, 1996; Hopkins et al., 2010), while other studies suggest it passes around the shelf (Jillett, 1969; Heath, 1981, 1985; Uddstrom & Oien, 1999; Smith et al., 2013) (Figure 1.2). East of the South Island, the position of the STF varies seasonally, being located further inshore during summer and offshore in winter (Shaw & Vennell, 2001; Hopkins et al., 2010; Jones et al. 2013).

Enhanced phytoplankton biomass within the STF around the South Island has been reported in previous studies (Vincent et al., 1991; Bradford-Grieve et al., 1997; Murphy et al., 2001; Pinkerton et al., 2005; Jones et al., 2013). The distribution of seabirds and marine mammals is influenced by the presence of enhanced phytoplankton productivity since their prey feed on phytoplankton (Evans, 1982; Degrati et al., 2013; Vaughn et al., 2008). For example, many different species of seabirds breed on the southeast coast of the South Island, for instance, around the Otago Peninsula (O’Driscoll et al., 1998). Hawke (1998) identified seabird species concentrated south of Banks Peninsula in response to the region of higher productivity.
Figure 1.2 The Subtropical Front (STF; shown by the red line) and ocean currents around the New Zealand region. The alternate position for the STF, crossing the Snares Shelf south of Stewart Island (Garner, 1959; Belkin & Gordon, 1996; Chiswell, 1996; Hopkins et al., 2010) is shown by the blue line. The Southland Front (SF) is shown by the green dashed line. SS (Snares Shelf); MS (Mernoo Saddle). Modified from Heath (1981) and Jones (2012).

1.3.2 Southland Front and Southland Current

The Southland Front (SF), the local manifestation of the STF, is a single, well-defined, narrow front passing along the east coast of New Zealand’s South Island (Figure 1.2) (Heath, 1985; Uddstrom & Oien, 1999; Shaw & Vennell, 2001; Hopkins et al., 2010; Smith et al., 2013). The SF is constrained along the continental shelf approximately 30-50 km offshore, and is typically 2 to 10 km wide (Jones et al., 2013). The SF is bathymetrically locked to the shelf-break, in water depths from 200-1000 m (Shaw & Vennell, 2001; Hopkins et al., 2010). There is evidence for spatial and temporal variation in the width and strength of the SF. The front
tends to be wider, with a weaker gradient, in the north of the region (Shaw & Vennell, 2001; Hopkins et al., 2010). Some studies found the front was strongest (highest horizontal temperature gradient) during winter (Chiswell, 1996; Shaw & Vennell, 2001; Hopkins et al., 2010), while others found the front was the strongest during spring and autumn (Uddstrom & Oien, 1999).

The Southland Current (SC) is an induced geostrophic flow associated with the SF. It consists of a mixture of STW and SAW, moving northward along the shelf from Stewart Island to the Chatham Rise (Chiswell, 1996; Sutton, 2003) (Figure 1.2). The SF and SC system is essential in determining the local oceanographic conditions off the southeast coast of the South Island (Sutton, 2003). The SC has been reported to transport mainly STW on the western side of the SF (Jillet, 1969; Chiswell 1996), while Sutton (2003) suggests it consists largely of SAW. The SC separates into two branches once it approaches the Mernoo Saddle where the continental slope becomes less steep (Nelson et al., 2000). The major branch deflects east, flowing south of the Chatham Rise, while another branch passes through the Mernoo Saddle and continues northward along the east coast of the North Island (Heath, 1972).

1.4 Remote sensing of ocean colour

Remote sensing of ocean colour relies on measurements of the concentration of absorbed and scattered photons from within the visible range of the electromagnetic spectrum (McClain, 2009). The amount of absorption differs according to the pigment contained in the phytoplankton present, as phytoplankton species have different pigments, and every pigment has its own absorption spectrum (Kirk, 1994). As Chl-a is the most common pigment found in phytoplankton, ocean colour measurements generally use Chl-a concentration as the index of phytoplankton biomass (Murphy et al., 2001; Jones et al., 2013). An example of Chl-a concentrations measured by remote sensing is shown in Figure 1.3.

Water masses in which Chl-a concentration is measured through remote sensing can be defined as Case 1 and Case 2 waters (Pinkerton et al., 2005). Case 1 waters are those where the spectral data mostly covary with the Chl-a pigments, usually found in open ocean water which is free from terrestrial influences. Case 2 waters are those containing other optically detectable constituents besides Chl-a pigments, including suspended particles or coloured dissolved organic material (CDOM), commonly found in coastal systems and riverine plumes (Pinkerton et al., 2005). Remotely sensed data taken from Case 2 waters pose a problematic
issue due to the presence of these other optical constituents, which do not covary with the phytoplankton pigment concentration. In the near-shore region, coastal bathymetry and riverine discharge are critical factors influencing the spatial pattern of ocean colour observations (Joint & Groom, 2000).

Figure 1.3 A remote sensing image of Chl-a measurements in the New Zealand region (Boyd & Law, 2011)

1.4.1 The inaccuracies and advantages of remote sensing

Remote sensing of ocean colour may have inaccuracies and uncertainties arising from the Chl-a retrieval algorithm (Sullivan et al., 1993; Pinkerton et al., 2005). The atmosphere reduces the irradiance from the water surface and scatters light into the sensor's field of view (Joint & Groom, 2000). Conducting measurements in the near-infrared band minimizes this problem (Gordon & Wang, 1994). However, this approach needs to be modified for turbid water (Case 2 waters) (Moore et al., 1999).

The presence of clouds, contrails from aircraft, and sun glint may limit the observation of the underlying sea surface (Liu et al., 2014). Cloud cover has been the major factor limiting ocean colour observations since it obscures the surface of the sea. Cloud cover may vary spatially and temporally, depending on the location and season (Joint & Groom, 2000). Cloud contamination of ocean colour images becomes more persistent at high latitudes (Uddstrom
An example of a remote sensing image with the presence of cloud contamination is shown in Figure 1.4.

Figure 1.4 Remote sensing image captured by MODIS-Aqua sensor on 1 May 2015. The presence of persistent cloud at high latitude masks the sea-surface, preventing the observation of underlying surface. This condition will result in a limited ocean colour data availability. The area that is not passed over by the MODIS-Aqua orbit track is shown in oblique black lines (retrieved from NASA Earthdata, 10/09/2015).

Despite the limitations and inaccuracies, remotely-sensed ocean colour data have been proved to be very useful in oceanographic research and monitoring (Dogliotti et al., 2009). The synoptic and global data play a fundamental role since they cover the vast and rapidly varying ocean at temporal and spatial scales not possible from conventional platforms (e.g. ship-borne observations) (Pottier et al., 2006; Dogliotti et al., 2009; Jiang et al., 2009). Remote sensing of ocean colour is now the primary tool used in understanding the seasonal cycling and distribution of phytoplankton on regional and global scales (McClain et al., 2002; Gregg et al., 2005; Behrenfeld et al., 2009; Dogliotti et al., 2009; Strutton et al., 2012; Petrenko et al., 2013).

1.5 Study area

This study investigates the spatial and temporal variability of phytoplankton productivity within the STF region to the south and east of the South Island, extending from 43° S to 49° S and from 166° E to 179° W for approximately 1200 km (Figure 1.5). The STF
position within this study area has been demonstrated to vary annually and seasonally (Uddstrom & Oien, 1999; Shaw & Vennell, 2001; Hopkins et al., 2010; Smith et al., 2013), which may affect the fluctuations in phytoplankton productivity. The study area extends from the poleward limit of the STF around the Snares Shelf to the equatorward limit along the Chatham Rise in order to see if there is latitudinal variability in the phytoplankton distribution along the STF. The area of interest extends 100 km from the shore along the east coast of the South Island to obtain a clear picture of the phytoplankton distribution across the shelf break, where the front is likely to be located.

**Figure 1.5** The study area (shaded yellow) along the STF, south and east of the South Island of New Zealand.

### 1.6 Data

#### 1.6.1 MODIS-Aqua ocean colour sensor

The Moderate Resolution Imaging Spectroradiometer (MODIS) instrument aboard the Aqua Satellite Spacecraft provides entire coverage of the earth in two days (Pottier et al., 2006). MODIS-Aqua passes over New Zealand twice within one day (once during the daytime and once at night). The oceanographic application of MODIS-Aqua includes measurements of ocean colour and SST (Minnett et al., 2002). MODIS-Aqua has 36 spectral bands measuring visible, infrared, and microwave wavelengths. Nine spectral bands are used for ocean colour
(bands 8 to 16), while the other bands are used for measuring temperature, properties of clouds and aerosols, and ozone concentration (Pottier et al., 2006). The MODIS-Aqua images of SST and surface Chl-a will be used in this study.

1.7  Thesis objectives and outline

The main objective of this study is to examine the spatial and temporal variability of phytoplankton productivity based on the surface Chl-a concentration within the STF around New Zealand between 2003 and 2012. Off the South Island coast, the STF is particularly interesting because its physical and chemical characteristics strongly influence biological productivity. Phytoplankton biomass and productivity around the STF east of the South Island vary spatially and temporally, with the highest Chl-a concentration normally found along the coast and around the Chatham Rise (Vincent et al., 1991; Bradford-Grieve et al., 1997; Pinkerton et al., 2005; Jones et al., 2013). Chl-a concentration in the STF has been shown to follow the spring bloom cycle (Murphy et al., 2001; Delizo et al., 2007; Chiswell et al., 2013). Most previous studies, however, have only examined variability over relatively short period observation periods (less than five years), and not specifically showed how the phytoplankton distribution varies with respect to the spatial and temporal variation in the position of the STF. The exception is Chiswell et al. (2013), who examined the climatology of surface Chl-a concentration for 13 years. Nevertheless, little is known about the association between enhanced phytoplankton productivity and the STF in the New Zealand region.

In order to understand the association, this study investigates the spatial and temporal variability of the STF and Chl-a concentration along and across the STF. Therefore, there are specific questions that need to be answered beforehand.

1. How does the position of the STF east of the South Island of New Zealand vary spatially and temporally?
2. How does the distribution of Chl-a concentration vary spatially and temporally relative to the position of the STF?

As the region of interest in this study is vast and a long period of observation is needed, this study uses the remote sensing approach. Ocean colour images derived from the MODIS-Aqua sensor are used to examine the average position of the front and the average Chl-a
concentration. This study develops an algorithm to estimate these features along the STF for different time scales of analysis.

The chapters are organized as follows:

Chapter 2 describes the technique applied in the algorithm to estimate the mean position of the STF from the SST satellite data. The mean position of the STF is determined relative to the position of a reference line referred as the nominal STF. The nominal STF was taken as the approximate position of the STF located in previous studies. This section explains the spatial and temporal variability of the mean position and characteristics (SST gradients and SST) of the STF over a ten year period (2003-2012), on inter-annual, and seasonal time scales.

Chapter 3 summarises the spatial variability in phytoplankton productivity along and across the STF, averaged seasonally and over the ten year period. The spatial distribution of Chl-a concentration along the front is examined relative to the mean position of the front for each time scale.

Chapter 4 presents the seasonal variability of phytoplankton blooms over the Mernoo Saddle and Chatham Rise from 2003 to 2012. The characteristics of the phytoplankton blooms, the magnitude, location, and timing are examined for each season for each year. The locations of the bloom are estimated relative to the position of the front.

Chapter 5 presents the summary, conclusions, and recommendation for the future work associated with this study.
CHAPTER II. THE LOCATION OF THE SUBTROPICAL FRONT SOUTH AND EAST OF THE SOUTH ISLAND OF NEW ZEALAND

2.1 Introduction

There is some disagreement about the position of the STF south of the South Island. The front has been observed to directly cross the Snares Shelf south of Stewart Island, turning northeast following the upper continental shelf at depths of 200-300 m (Garner, 1959; Belkin & Gordon, 1996; Chiswell, 1996; Hopkins et al., 2010). Other studies show the STF passing around the Snares Shelf to the south before turning northeast (Jillett, 1969; Heath, 1981, 1985; Uddstrom & Oien, 1999; Smith et al., 2013) (Figure 2.1). Along the east coast of the South Island, the STF consists of a single, narrow front known as the Southland Front (SF) that is spatially stationary, constrained along the continental shelf approximately 30-50 km from the shore in water depths from 200-1000 m (Chiswell, 1996; Shaw & Vennell, 2001; Hopkins et al., 2010, Jones et al., 2013).

The position of the STF off the east coast of the South Island and Chatham Rise greatly varies among seasons (Uddstrom & Oien, 1999; Shaw & Vennell, 2001; Hopkins et al., 2010). The STF is located furthest inshore during summer and furthest offshore during winter (Hopkins et al., 2010). There is also seasonal variability in the intensity of the SF, with the strongest horizontal gradient in the surface temperature during the austral summer and winter (Hopkins et al., 2010). In contrast, Uddstrom & Oien (1999) described the SF as being strongest during austral spring and autumn, and weakest during winter.

Remote sensing observations using satellite SST data have enabled global monitoring of oceanic fronts over time scales ranging from daily to inter-annual (Belkin & Gordon, 1996; Uddstrom & Oien, 1999; Shaw & Vennell, 2001; Belkin & Cornillon, 2003; Sokolov & Rintoul, 2007; Hopkins et al., 2010). In this study, SST information is used to identify the surface expression of the STF. Smith et al. (2013) found that the surface expression of temperature was a good approximation for the position of the front. The surface expression of the front can be analyzed in remotely-sensed SST data using the classical isotherm contouring technique (Butler et al., 1992; Chiswell, 1994). This technique, however, assumes that an oceanic front demonstrates fixed temperature along its frontal line (Shaw & Vennell, 2000). Another technique for investigating the features of thermal fronts is the use of thermal gradients computed from convolution operators (Shaw & Vennell, 2000). Belkin & Reily (2009)
mention two such approaches that are widely accepted to obtain the SST gradient: the gradient method and the histogram method.

This chapter aims to demonstrate the spatial and temporal variability in the position and characteristics (SST and SST gradient) of the STF to the south and east of New Zealand. The mean position of the front will be derived from the location of the maximum SST gradient across the front between 2003 and 2012. Previous studies have indicated there are variations in the position and strength of the front (Heath, 1981; Chiswell, 1994; Uddstrom & Oien, 1999; Shaw & Vennell, 2001; Hopkins et al., 2010). This study, however, uses data from time periods when the position and characteristics of the front have not been investigated.

2.2 Methods

2.2.1 Acquisition of MODIS-Aqua SST images

MODIS-Aqua Level-3 Global Ocean Mapped (v.2014.0) Ocean SST products were retrieved from ERDDAP (http://coastwatch.pfeg.noaa.gov/erddap/index.html) for the 2003-2012 period. These products are processed and distributed by the Ocean Biology Processing Group (OBPG). The Aqua MODIS Level 3 standard mapped image (SMI) products are integer representations of binned data products. This image is a 16-bit, two-dimensional array of an Equidistant Cylindrical projection of the globe. The Level 3 binned products are used to generate mapped data products on 4 and 9 km equirectangular projection. This study used the SST monthly composite images of the night time period (11 micron) processed from the SMI products at 4 km spatial resolution. Details of how the ST estimates are derived and the data processing steps are given by Minnett et al. (2002).

The monthly composite image is a composite constructed to give an image for a “close approximation” as image pixels in a different area are composited from different quantities of data. This approach has the advantage of minimizing the effects of cloud cover since any partial image can contribute information to the monthly composite, so estimates for the whole region of interest can be obtained (Joint & Groom, 2000). The monthly composite images of SST from ERDDAP were obtained in the “.mat” format (MATLAB, 2014). Each pixel of the SST images comprises information of the derived estimates SST (°C) and its metadata that are geolocation (latitudes and longitudes), time (months), and altitude. The altitude was
set to be zero in this study. A total of 120 MODIS-Aqua monthly composite images of SST were used to derive the time series analyses.

2.2.2 The nominal Subtropical Front

As a first step, a nominal line was generated as a starting point to create cross-sectional windows along the front, referred to as the nominal STF. The nominal STF follows the approximate position of the STF estimated in previous studies (Uddstrom & Oien, 1999; Shaw & Vennell, 2001; Hopkins et al., 2010; Smith et al., 2013). The nominal STF generally follows the 500 m isobath that extends for approximately 1200 km from a starting point on the southern edge of the Snares Shelf at 167.34179° E 49.092769° S, and ends on the southern side of the Chatham Rise at 179.63313° E 44.065615° S (Figure 2.1).

![Figure 2.1 The nominal STF (red dashed line) used in the present study. The STF position south of the South Island found in previous studies: passing around the Snares Shelf (black arrow line; used in this study) and crossing the Snares Shelf (blue arrowline).](image)

2.2.3 The rotating-extraction window

A rotating-extraction window (Shaw & Vennell 2000) was built to examine variability in the surface expression of the front. Several extraction windows were generated extending
inshore and offshore of the nominal STF. Shaw & Vennell (2000) demonstrated that the data extracted from a non-rotating window (i.e. positioned irrespective of front orientation) did not always estimate position of the front accurately. Therefore, the extraction windows were rotated perpendicular to the nominal STF.

A schematic diagram of the rotating-extraction window modified from Shaw & Vennell (2000) is shown in Figure 2.2. The spatial coordinates $X'$ and $Y'$ are in terms of the rotating-extraction window and determined from the rotation angle $\theta$. $\alpha$ is the angle between the nominal STF in that window and longitude. The rotation angle $\theta$, the orientation of the extraction window, is defined as $\alpha$ plus 90 degrees (perpendicular to the front line). The process for finding the rotation angle is given below.

Figure 2.2 A schematic of the rotating-extraction window. The nominal STF is shown by the red line. The initial extraction windows are shown by the blue rectangles. The rotated extraction window is shown by black dashed rectangle. The centres of the extraction windows along the nominal STF line are shown by black dots. (Modified from Shaw & Vennell, 2000).

### 2.2.4 Construction of the extraction window

The steps of constructing the extraction window are explained below and shown in a diagram (Figure 2.3a-2.3f). These steps were executed using Matlab R2014b (MATLAB, 2014).

**Step 1.** Once the nominal STF had been digitized in the geographic coordinate system (longitude and latitude) using the digitizer tool, its coordinates were converted to a complex
number-coordinate system (**Figure 2.3a**). A complex number-coordinate system was used to avoid the issue of longitudinal distance varying with latitude.

**Step 2.** The position of the digitized-nominal STF was interpolated using smoothing splines at 500 m resolution (**Figure 2.3b**).

**Step 3.** Points were generated at 20 km intervals along the interpolated line to represent the centre of the extraction windows, resulting in 60 centre points (**Figure 2.3c**). It is recognized that the interval space for the centre of the extraction window would determine how many image pixels fall within each window. Also, if the interval space is smaller than the length of the extraction window, adjacent extraction windows might overlap each other and pixel duplication would occur.

**Step 4.** The extraction window was rotated by angle $\theta$, perpendicular to the nominal STF line as shown in the schematic diagram (**Figure 2.2**). Curvature of the nominal STF means that the adjacent rotated extraction windows may overlap each other, so that data points (pixels) are duplicated (**Figure 2.3d**). (Note: due to the differences in the orientation of the extraction windows, the number of pixels varied among different extraction windows).

**Step 5.** Each extraction window was extended 80 km inshore and 80 km offshore relative to the nominal STF (**Figure 2.3e**). The windows were then divided into strips parallel to the nominal STF, called “bins”, either 10 km wide or 20 km wide (see section 2.2.4 below) (**Figure 2.3e**). The first bin was placed straddling the nominal STF, so that half of the bin extended inshore of the STF and half of the bin extended offshore. The second bin was placed adjacent to the nominal STF, such that it overlapped the first bin, resulting in an area near the nominal STF covered by more than one bin (**Figure 2.4**). This was done to increase the resolution in the region where the SST is likely to have the steepest gradient. All subsequent bins were placed adjacent to each other, with no overlap; hence the data within bins are independent of one another (**Figure 2.4**).

**Step 6.** The nominal STF line and the extraction windows were converted back to the geographic coordinate system (**Figure 2.3f**). Each extraction window is referred to hereafter as a “box”. The algorithm generated 60 boxes of 20 km length along the nominal STF. Boxes were numbered consecutively from 1-60, with box 1 in the south-western limit of the study area and box 60 at the north-eastern limit.
2.2.5 Bin width

There is a compromise in choosing the width of the bin, between more data in the averages and more resolution of the structure across the front. A wide bin will contain a lot of data to average, yet produce fewer bins to resolve the variation across the front. On the other hand, a narrow bin has fewer data but provides more detail across the front. Shaw & Vennell (2000) generated 20 km long by 30 km wide windows to determine the spatial and temporal variability in the position and characteristics of STF over three years. A smaller width of 20 km, however, was used to analyze narrow features such as plumes.

**Figure 2.3** The steps for creating the rotating-extraction windows; (a) Step 1; (b) Step 2; (c) Step 3; (d) Step 4; (e) Step 5; (f) Step 6.
In this study, two bin widths (10 km and 20 km) were trialled, resulting in bins of 20 km x 20 km (approximately 4 pixels x 4 pixels) (Figure 2.4a) and 20 km x 10 km (approximately 4 pixels x 2 pixels) (Figure 2.4b). Bins were identified according to their distance from the nominal STF; a negative distance was assigned to bins inshore of the front, and a positive distance to bins offshore of the front (Figure 2.4a & 2.4b).

The mean SST gradients between 2003 and 2012 were then estimated to compare the performance of the 20 km x 20 km bins (Figure 2.5a) and the 20 km x 10 km bins (Figure 2.5b) along the nominal STF. An edge indicator, the Sobel operator, was applied in the algorithm to obtain the SST gradients from the remote sensing SST images (Simpson, 1990). The Sobel operator consists of two 3x3 convolution masks or kernels (equation 1). These can be combined together to find the absolute magnitude of the gradient at each point.

\[
\begin{align*}
G_x &= \begin{bmatrix}
+1 & 0 & -1 \\
+2 & 0 & -2 \\
+1 & 0 & -1 \\
\end{bmatrix} \quad 
G_y &= \begin{bmatrix}
+1 & +2 & +1 \\
+0 & 0 & +0 \\
-1 & -2 & -1 \\
\end{bmatrix}
\end{align*}
\]

where \(G_x\) and \(G_y\) are two images which at each point contain the horizontal and vertical derivative approximations respectively. The details of gradient computation using the Sobel operator are explained in Simpson (1990) and Belkin & Reily (2009). Due to cloud cover or temporal variation in coverage by MODIS-Aqua, the remote sensing monthly-composite images sometimes comprised an invalid measurement. In order to produce a robust analysis, the invalid measurements were excluded from the estimation.
Figure 2.4 An illustration of the extraction window and the two trialled bin widths, (a) 20 km x 20 km; (b) 20 km x 10 km. The positive and negative signs indicate the offshore and inshore bins, respectively. The SST data points (pixels) derived from the MODIS-Aqua sensor are shown by the green crosses within the bins.

Overall, the boxes were able to show a clear surface expression of the front gradient using both widths trialled (Figure 2.5a & 2.5b). The surface expression of the front derived from the 20 x 20 km bins and the 20 km x 10 km bins were similar to each other. The 20 km x 20 km bin tended to produce lower average values due to the smoothing of the SST gradient.
The 20 km x 10 km bins (Figure 2.5a) produced a finer structure and sharper gradient of the front along and across the nominal STF. The ability to depict fine structure in the surface expression of the front is necessary as the front location may vary temporally and spatially in a narrow band. Therefore, the 10 km bin width was chosen for the remainder of the study.

**Figure 2.5** The mean SST gradient inshore and offshore of the nominal STF (red line), between 2003 and 2012 estimated from the two trialled bin widths; (a) 20 km x 10 km; (b) 20 km x 20 km.

### 2.2.6 Locating and analyzing the front

The surface expression of the front in this study primarily refers to the maximum value of the SST gradient from the monthly-composite SST images. The gradient approach can also
additional insight about the strength and structure of the front at the surface (Hopkins et al., 2010). In this study, the bin containing the highest-mean SST gradient in each box was used to define the location of the surface expression of the front. However, it is also useful to state when there is no front detected, thus SST gradient thresholds were chosen.

This study used specific thresholds for the temperature gradient to define the signature of the thermal front. As the temperature gradient varies northward (Shaw & Vennell, 2001; Hopkins et al., 2010), it is not realistic to only use a single gradient threshold. The nominal STF was therefore divided into five regions: Snares Shelf (boxes 1-16), Southland Front (boxes 17-28), Canterbury Bight (boxes 29-36), Mernoo Saddle (boxes 37-44), and Chatham Rise (boxes 45-60) (Figure 2.6). The thresholds were set at 80% of the mean-maximum SST gradient across the nominal STF in each region between 2003 and 2012. The thresholds for each region were: Snares Shelf (0.035 °C/km), Southland Front (0.04 °C/km), Canterbury Bight (0.45 °C/km), Mernoo Saddle (0.025 °C/km), and Chatham Rise (0.03 °C/km).

If the highest-mean SST gradient in the bin was lower than the threshold, it was assumed not to indicate the surface expression of the front and excluded as a possible frontal location. Hence, there was no front recorded in that particular box and month. The computation was repeated for all boxes along the nominal STF for all monthly-composite SST images, producing 120 estimates of the position of the STF for each box over the ten year period. The mean position of the front over 10 years, in each year, and in each season was examined using these monthly estimated positions. One way ANOVA (Analysis of Variance) tests were used to reveal if there were significant differences in the mean position of the front among seasons and years at the 99% confidence interval.

The surface expression of the front gradient and temperature refer to the SST gradient and the SST value, respectively, in the bin with the maximum SST gradient. Estimation of the mean SST gradient and mean SST were also repeated for all boxes along the nominal STF for all monthly-composite SST images. Their spatial distributions were computed over the same time scales as for the mean position of the front: ten years (2003-2012), inter-annual, and seasonal average.
2.2.7 The presence of neritic fronts

The spatial distribution of the SST gradient along the nominal STF from one monthly image may present multiple filaments of surface expression of the front within the near-shore water. These filaments are normally present off the southeastern coast of the South Island and in the Canterbury Bight. Examples of these features are shown in Figure 2.7. Previous studies have assumed these filaments are the result of frontal instabilities or localized-neritic fronts which are mostly influenced by river outflows (Chang & Gall, 1998; Shaw and Vennell, 2001). Several major rivers are found along the east coast of the South Island of New Zealand, for instance, the Clutha River, which is located approximately 100 km south of the Otago Peninsula. The large volume of freshwater discharge from the Clutha River travels northwards and may reach as far as the Otago Peninsula (Murdoch et al., 1990; Hawke & Hunter, 1992; Jones et al., 2013). Belkin & Cornillon (2003) suggested these localized fronts are associated with salinity fronts induced by freshwater discharge from the river. Hence, in this study, fronts located in near-shore waters (> 40 km inshore relative to the nominal STF) from the southern South Island (box 8) to the southeast of Banks Peninsula (box 39) were assumed not to represent the STF and were excluded as possible frontal locations (“bin masking” in Figure 2.6). This assumption was necessary to maximise the likelihood of identifying the correct position of the actual STF via the maximum SST gradient.
Figure 2.7 The spatial distribution of the SST gradient from one monthly SST image in July 2008. The surface expression of the front is indicated by a strong gradient across the nominal STF (black line). Additional areas with a strong SST gradient (red ellipses) are typically observed within near-shore waters and over the western Chatham Rise (red square).

2.2.8 Sensitivity to the method

The surface expression of the front estimated using the maximum SST gradient across the nominal STF may result in mistakes selecting the true frontal position, for example due to filaments of strong SST gradient away from the nominal STF. This section compares the mean position of the front derived from the location of the maximum gradient and the gradient above the 80th percentile in each box over ten-years. Overall, both techniques demonstrated a similar result for the mean position of the front along the nominal STF south and east of the South Island (Figure 2.8). This similarity may be because masking the near-shore bins eliminated the unrealistically high SST gradients caused by neritic fronts. These high values could be registered as the frontal location, hence, the mean position of the front would be biased inshore. Nevertheless, there was no strong evidence that high inshore gradients have been selected as the frontal location. The comparison resulted in only small differences in the position of the front along the Mernoo Saddle and Chatham Rise (Figure 2.8). This might be due to the presence of multiple filaments of high SST gradient along the northern and southern flank of the Mernoo Saddle and Chatham Rise (e.g. see the red square in Figure 2.7). Thus, the 80th percentile approach may result in selection of the frontal location between these filaments, which is located slightly offshore relative to the frontal position generated from the maximum gradient.
Figure 2.8 The mean value (± 95% confidence interval) of the position of the front from 2003 to 2012. The position of the front was derived from two approaches: the mean location of the maximum gradient, and the mean location of the gradient above the 80th percentile for each box. The mean position of the front is expressed relative to the nominal STF (0 km).

2.3 Results

2.3.1 Mean position of the front relative to the nominal STF over ten years

The ten-year mean position of the front in each box was derived from the 120 monthly images estimating average position of the STF. The surface expression of the front between 2003 and 2012 mostly lay close to the 500 m isobath (Figure 2.9a & 2.9b). Moving north from the southern part of the Snares Shelf, the position of the front was relatively stable, gradually moving towards the shelf break (Figure 2.9a). The variability in the frontal position became slightly greater and the front shifted shoreward south of the Clutha River (Figure 2.9b). The ten-year average frontal position along the east coast of the South Island followed the continental shelf between the 200 and 500 m isobaths. Furthermore, the results show that east of the Otago Peninsula the frontal position was permanently locked to the 500 m isobath (Figure 2.9a). Approaching the Mernoo Saddle, the isobaths diverge and the continental slope becomes less steep. In this region, the position of the front tended to be unstable, intensely meandering between the offshore and inshore waters (Figure 2.9b). The results show the front was positioned furthest offshore relative to the 500 m isobath on the western side of the Mernoo Saddle (box 40) and furthest inshore over the Mernoo Saddle (box 41) (Figure 2.9b). South of the Mernoo Bank, the frontal position followed the southern flank of the
Chatham Rise eastward along the 500 m isobath (Figure 2.9b). The frontal position remained variable along the Chatham Rise, consistent with the less-steep topography.

![Map showing Chatham Rise and surrounding regions](image1)

**Figure 2.9** The mean position of the front in each box from 2003 to 2012 relative to the nominal STF. (a) The map of the mean position of the STF (blue dashed line) and the nominal STF (red dashed line). (b) The mean position of the STF ± 1 standard deviation.
2.3.2 Mean annual position of the front relative to the nominal STF

The annual mean position of the front was derived from twelve monthly images for each year over the ten years. The results suggest the annual mean position of the front was comparable year to year and similar to the ten-year average frontal position (Figure 2.10a & 2.10b). One-way ANOVAs revealed significant differences in the annual average frontal position relative to the nominal STF between years ($F_{9,590} = 4.29, p = 2.04826 \times 10^{-05}$), yet the general trend was similar, following close to the shelf break.

The frontal position was more variable during 2007 over the Snares Shelf and Chatham Rise compared to other years, rapidly meandering between 20 km offshore and 10 km inshore relative to the 500 m isobath (Figure 2.10a). Off the Otago coast, the annual frontal position was similar in most years. However, the front occurred further offshore from northeast of the shelf (box 8-9) to the east coast of Otago during 2005 (Figure 2.10a). The frontal position was greatly variable between years over the Mernoo Saddle. At this site, the frontal position was furthest offshore and inshore during 2004 (Figure 2.10a) and 2012 (Figure 2.10b), respectively. In contrast to other years, the front remained offshore without meandering inshore during 2007 (Figure 2.10a). Eastwards of the Chatham Rise, the front was found furthest inshore (> 50 km relative to the 500 m isobath) in 2011 (Figure 2.10b).
2.3.3 Mean seasonal position of the front relative to the nominal STF

The seasonal mean position of the front was derived from thirty monthly images over the ten years: summer (December-February), autumn (March-May), winter (June-August), and spring (September-November). The results show the surface expression of the front varied seasonally, yet the general spatial pattern was similar among seasons (Figure 2.11). The mean position of the front during autumn and spring were similar to the ten-year average frontal position, in particular along the Southland Front region (Figure 2.11). One-way ANOVAs showed significant differences in the seasonal average of the frontal position relative to the nominal STF among seasons ($F_{3,236} = 10.2, p = 2.42774e-06$). The front was generally positioned furthest offshore during winter, and furthest inshore during summer from the Snares Shelf to the southeast of Banks Peninsula (Figure 2.11). Compared to other seasons, the frontal position during autumn was very different over the Mernoo Saddle to the Chatham Rise. In these regions, the front was furthest offshore during summer and furthest inshore during autumn (Figure 2.11).
2.3.4 The mean SST gradient and SST of the STF over ten years

The ten-year mean SST gradient and SST were derived from 120 monthly-estimates of SST gradient and SST. The mean SST gradient ranged from 0.04 °C/km (Box 39) to 0.09 °C/km (Box 2) (Figure 2.12a), and the mean SST ranged from 9.8 °C (Box 8) to 12.1 °C (Box 44) (Figure 2.12b). The results show that the surface expression of the front gradient and temperature varied spatially, with the SST gradient decreasing and the SST increasing further north. The SST distribution was relatively stable over the Snares Shelf, then became more variable over the Chatham Rise (Figure 2.12b). The front strength fluctuated, being generally weaker on the northeast of the Snares Shelf (0.05 °C/km) and on the western side of the Mernoo Saddle (0.04 °C/km), and stronger southwest of the Clutha river (0.075 °C/km) and on the western flank of the Chatham Rise (0.07 °C/km). Just before the Mernoo Saddle, the SST gradient and SST both dropped, then rapidly increased to 0.07 °C/km and 12 °C respectively over the Chatham Rise (Figure 2.12a & 2.12b). The results show the ten-year average front along the Snares Shelf, Southland Front, and Chatham Rise was delineated by the 10 °C, 11 °C and 12 °C isotherms, respectively (Figure 2.12b). The spatial distribution of mean SST gradient shows the front strength gradually weakened and was more spatially variable eastward of the Chatham Rise.
Figure 2.12 (a) Mean SST gradient and (b) Mean SST, in each box averaged from 2003 to 2012. Bin -1 and bin +1 refer to the bins immediately adjacent to the surface expression of the front.

In each box, the SST gradient and SST value in the bins adjacent to the bin with the maximum SST gradient were extracted to examine the sensitivity of the front identification process (Figure 2.12a & 2.12b). The SST gradient in the bins adjacent to the surface expression of the front in each box differed by between 0.02 °C/km and 0.04 °C/km (Figure 2.12a). The mean SST in the bins adjacent to the front differed by ca. 0.5 °C (Figure 2.12b). The smallest temperature gradient across the front occurred over the Mernoo Saddle (box 40-41) (Figure 2.8b). This finding suggests that the surface expression of the front might be very weak and could be difficult to identify in this region.
2.3.5 The annual mean SST gradient and SST of the STF

The annual mean SST gradient and SST were derived from the twelve monthly estimates of SST gradients and SSTs for each year between 2003 and 2012. The results show the surface expression of the front gradient and temperature varied annually, with a similar spatial distribution trend to the ten-year average (Figure 2.13 & 2.14). The frontal strength and temperature was more variable between years over the Chatham Rise. In this region, the surface expression of the front temperature varied between 11 °C and 13 °C (Figure 2.14a & 2.14b), while the temperature of the front was relatively much lower during 2009 compared to the other years (Figure 2.14b). The frontal strength was strongest during 2008 in all regions (Figure 2.13b). In this year, the frontal strength over the Mernoo Saddle reached above 0.1 °C/km. The front was also stronger than the ten-year average front during 2007 (Figure 2.13a) and 2009 (Figure 2.13b). Overall, the surface expression of the front was delineated with a similar temperature isotherm (ca. 11 °C) along the Southland Front region in all years. However, the front temperature increased dramatically to 13.5 °C in 2011 near Banks Peninsula (box 36) (Figure 2.14b).
Figure 2.13 The annual mean SST gradient in each box. (a) 2003-2007; (b) 2008-2012. The SST gradients were derived from the surface expression of the front temperatures in the annual averaged images.
Figure 2.14 The annual mean SST in each box. (a) 2003-2007; (b) 2008-2012. The SSTs were derived from the surface expression the front temperature in the annual averaged images.

2.3.6 The seasonal mean SST gradient and SST of the STF

The seasonal mean SST gradient and SST were derived from the thirty monthly-estimates of SST gradient and SST between 2003 and 2012: summer (December-February), autumn (March-May), winter (June-August), and spring (September-November). The results show the surface expression of the front gradient and temperature varied seasonally (Figure 2.15a & 2.15b). There was less seasonal variability in the SST gradient off the southern South Island (box 12-16), Canterbury Bight (box 29-32) and Mernoo Saddle (box 36-40) (Figure 2.15a). The greatest seasonal difference in the mean SST was approximately 3.5 °C between summer and winter over the Chatham Rise. The temperature difference was relatively small between summer and autumn (ca. 1.5 °C) and between spring and winter (ca. 1 °C), with the least difference along the Snares Shelf (Figure 2.15b).

Relative seasonal front strength varied over the study area. Along the Snares Shelf, Mernoo Saddle, and Chatham Rise, the front was typically strongest during winter and weakest during summer (Figure 2.15a). The winter front was much stronger in the Snares Shelf region (0.1 °C/km) than along the Mernoo Saddle and Chatham Rise (0.075 °C/km). Over the southern Snares Shelf (box 2-4), the seasonal front gradient during autumn was greater than the seasonal front strength during winter. On the other hand, off the east coast of the South Island the front was strongest during summer (0.08 °C/km) and weakest during winter and spring (0.06 °C/km) (Figure 2.15a). In this region, the front temperature was very different
between seasons; approximately 12 °C - 13 °C during summer and autumn, compared to 9 °C – 9.5 °C during winter and spring (Figure 2.15b).

Figure 2.15 (a) The seasonal mean SST gradient, and (b) SST in each box from 2003 to 2012. The SST gradient and SST were derived from the surface expression of the front gradient and temperature in the seasonal averaged images.

2.4 Discussion

2.4.1 The position of the STF

This study found that the STF was positioned close to the 200 m isobath along the southeastern part of the Snares Shelf, in agreement with the pathway demonstrated in a number of earlier studies (Jillett, 1969; Heath, 1981, 1985; Uddstrom & Oien, 1999; Smith et
The front followed the upper continental slope (at approximately 180 m depth) around the south of the South Island at 49° S. It then gradually approaches the near-shore water of the South Island (between 48° S and 47° S), before becoming aligned with the upper shelf break (200-500 m isobaths) heading northeastward. The inter-annual and seasonal variability of the frontal position were relatively stable along the southern flank of the Snares Shelf but became more variable northeast of the shelf between Stewart Island and the Campbell Plateau. In 2007, the frontal position exhibited intense meandering from the southern flank of the Snares Shelf to the northeast of the Snares Shelf (Figure 2.10a). Belkin & Cornillon (2003) showed that the position of the front varied annually south of the South Island, and that it might follow the shelf break along the 200 m isobath, or be positioned further inshore.

Along the east coast of South Island, the STF was positioned over the shelf break (200 m-1000 m), consistent with the pathway demonstrated in earlier studies (Uddstrom & Oien, 1999; Shaw & Vennell, 2001; Hopkins et al., 2010; Jones et al., 2013). However, between the Clutha River and Cape Saunders, the ten-year average frontal position lay slightly inshore of previously estimated positions, close to the 100 m isobath (Figure 2.16a). The variations in the frontal position gradually increased as the front approaches the Canterbury Bight. Shaw & Vennell (2001) concluded that the minimum and maximum variation in the position of the front occurred off Dunedin and in the Canterbury Bight, respectively. The increasing variability in the frontal position in the north of the study area confirms that east of the South Island, the STF is mainly steered by the bathymetry. In the Canterbury Bight, the continental slope becomes less steep and the position of the front becomes more variable (Shaw & Vennell, 2001; Hopkins et al., 2010; Graham, et al., 2012; Smith et al., 2013). Shaw et al. (1999) suggested that the occurrence of river plumes in the Canterbury Bight might also increase variability in the position of the front. Overall, the mean position of the STF was different between seasons. The STF was located further inshore during summer and offshore during winter, similar to the findings of Shaw & Vennell (2001) and Hopkins et al. (2010) (Figure 2.16b).

South east of Banks Peninsula, the front was deflected into the deeper water south of the Mernoo Saddle. It then meandered, before flowing eastward to the Chatham Rise. Compared to other regions along the front’s pathway, the frontal position became more spatially and temporally variable over the Mernoo Saddle. Even though previous studies did not find the exact same shape of the front pathway over the Mernoo Saddle, they still demonstrated the variability in this region (Heath, 1972, 1981, 1985; Vincent et al., 1991;
Uddstrom & Oien, 1999; Sutton, 2003; Currie et al., 2011). The ten-year average frontal position followed the STF pathway observed by Uddstrom & Oien (1999) during May and August 1993-1998. In these months, the surface expression of the front was identified further inshore at the northern mouth of the Saddle.

The variation in the frontal position over the Mernoo Saddle and Chatham Rise can be explained by the variation in the Southland Current (SC) (Heath, 1971, 1985; Vincent et al., 1991; Shaw & Vennell, 2000, 2001; Sutton, 2003; Hopkins et al., 2010). They observed that the SC may reach close to Kaikoura before deflecting southeast to merge with the STF along the Chatham Rise. This finding supports the observed divergence of the STF along the Mernoo Saddle. The portion of the SC that goes through the saddle is characterised by water with low salinity and temperature, identified as a wisp of SAW on the western edge of the Saddle (Shaw & Vennell, 2000). Hopkins et al. (2010) suggested that the annual variation in the position of the STF was coincident with the seasonal variation in the SAW wisp. They found the SAW wisp moved furthest west (shoreward) during the summer months. This finding might explain the mechanism for the front being positioned furthest inshore to the west of the Mernoo Saddle (box 39) during summer (Figure 2.11).

In this study, the STF was located over the southern flank of the Chatham Rise, following close to the 500 m isobath at 44°S. This result is consistent with the position of the southern STF explained in Heath (1981, 1985), Belkin & Gordon (1996), Chang & Gall (1998), Belkin & Cornillon (2003), Sutton (2003), and Hopkins et al. (2010). The frequency of meanders increased and the frontal position was highly variable over the Chatham Rise. These results confirm that the topographic steering weakens across the Chatham Rise as the continental shelf becomes less steep (Shaw & Vennell, 2001; Hopkins et al., 2010). The STF was positioned furthest inshore (northward) during summer and autumn, and furthest offshore (southward) during winter. Other studies have observed that the STF migrates from the southern flank during spring to the northern flank in the late summer (Heath, 1981; Chiswell, 1996; Uddstrom & Oien, 1999). They explained this northern manifestation of the STF as a result of the advection of warm STW, and the entrainment of surface SAW, which associated with the dynamics of the Wairapa Eddy between 177°E and 180°E.
Figure 2.16 The approximate position of the STF south and east of the South Island of New Zealand estimated in this study and earlier studies. (a) The mean position of the STF between 2003 and 2012 (blue dash), Smith et al., (2013) (orange line), Shaw & Vennell (2001) (black line) and Hopkins et al., (2010) (red line). (b) The seasonal mean position of the front during summer and winter; 2003-2012: summer (red dotted line) and winter (blue dotted line); Hopkins et al. (2010): summer (red line) and winter (blue line).

2.4.2 The characteristics of the STF (SST and SST gradient)

The surface expression of the STF across the Snares Shelf was generally delineated by the 10 °C isotherm between 2003 and 2012, in agreement with Heath (1981, 1985) and Smith et al., 2013. The high gradient values observed over the southern shelf were explained in
Smith et al. (2013) as a result of the front gradient being reintensified once the front encounters the steep sides of the Campbell Plateau. The front gradient over the southern shelf was similar to that observed by Smith et al. (2013), but much greater than Chiswell (1994). Hopkins et al. (2010) suggested that differences in estimates of the SST gradient could be explained by different resolutions of the data, with higher data resolution (> 4 km SST images) resulting in a lower gradient. Although the front gradients differ between studies, all findings show a similar decreasing trend in gradient moving northward (Chiswell, 1994; Hopkins et al., 2010; Smith et al., 2013). This study suggests the front was stronger during autumn and winter, and weaker during spring and summer in this region. The seasonal cycle of the SST northeast of the Snares Shelf is within the SST range measured in Butler et al. (1992) and Chiswell (1994), varying between 10 and 12 °C during summer and autumn, and 9 and 10 °C during winter and spring (Figure 2.15b).

The surface expression of the gradient reintensified from 0.045 °C/km to 0.075 °C/km as the front approaches the southeastern corner of the South Island near the Clutha River, then decreases to 0.05 °C/km towards Cape Saunders. In contrast to this study, Chiswell (1994) found the mean SST gradient between 1989 and 1991 along this region to be stable at 0.02 °C/km. This study suggests that the variability in the spatial gradient might correspond with the presence of neritic water (NW) near the coast, which is characterised by variable seasonal temperature and low salinity due to the freshwater discharge from the Clutha River (Jillett, 1969; Hawke & Hunter, 1992; Shaw & Vennell, 2001; Jones et al., 2013). The surface expression of the STF east of the South Island was typically delineated by the 11 – 11.5 °C isotherm. Seasonal temperature at the front was more variable, ranging from 12 - 13 °C during summer and autumn, to 9 - 10 °C during winter and spring. These findings were also reported in Heath (1972,1975,1981), Chiswell (1994,1996), Uddstrom & Oien (1999), Hopkins et al. (2010) and Currie et al. (2011).

The mean seasonal SST gradient indicated the STF was strongest during summer, and weakest during winter and spring off the east coast of the South Island (Figure 2.15a). The seasonal gradient observed in this study is in agreement with the findings of Uddstrom & Oien (1999) and Hopkins et al. (2010). The surface expression of the temperature increased moving northward, while the temperature gradient decreased, consistent with Shaw & Vennell (2001) and Hopkins et al. (2010). They suggested the northward decrease in the front gradient was consistent with greater instability in the frontal position and increased mixing as the continental shelf is less steep.
The surface expression of the gradient and temperature of the front consistently decreased on the western side of the Mernoo Saddle, just before the front encountered deep water. They then reintensified as the continental slope gets steeper on the eastern side of the Mernoo Saddle. This study found no significant difference in the seasonal front gradient on the western side of the saddle, but increasing variability on the eastern side. Shaw & Vennell (2000) suggested that the variability of the properties of water masses in this region were mainly influenced by the interaction between the southward intrusion of the STW and the northward SAW wisp through the Mernoo Saddle. The surface expression of the temperature was persistently lower on the western side of the saddle compared to the eastern side, probably because the SAW wisp mainly flows along the western edge (Uddstrom & Oien, 1999; Shaw & Vennell, 2000; Sutton, 2003).

The front gradient along the Chatham Rise varied spatially heading eastward, decreasing from 0.07 °C/km to 0.05 °C/km. Even though these gradients are greater than those reported in Chiswell (1994), Hadfield et al. (2007) and Uddstrom & Oien (1999), the spatial trend of the gradient is consistent with those studies (Figure 2.15a). The decrease in the strength of the front is consistent with the greater instability as the continental slope becomes less steep across the Chatham Rise and topographic control weakens eastward (Uddstrom & Oien, 1999; Hopkins et al., 2010). Furthermore, the variability of the surface expression of the front along the southern flank of the Chatham Rise is thought to be driven by the variability in the SC (Chiswell, 1996; Sutton, 2003). The annual and seasonal fronts were generally delineated by the 12 °C isotherm along the southern flank of the Chatham Rise, consistent with Vincent et al. (1991), Bradford-Grieve et al. (1997), Chiswell (1994), Uddstrom & Oien (1999), and Hadfield et al. (2007). There was a little difference in the seasonal temperature of the front, similar to findings that have been reported in Hopkins et al. (2010).

2.5 Conclusions

- The position of the STF mainly followed the shelf-break (between 200 – 500 m isobaths) along the south and east coast of the South Island and Chatham Rise. The bathymetric diversion from the Canterbury Bight to the Mernoo Saddle and across the Chatham Rise resulted in intense meandering of the frontal position and changes in the structure and strength of the front.
• The position and strength of the STF changed dramatically with season. The greatest gradient in the STF off the southern South Island, Mernoo Saddle, and Chatham Rise was typically found during winter, and the weakest gradient was during summer. Contrary to that, off the Otago and Canterbury coasts, the STF was strongest during summer and weakest during winter and spring.

• The surface expression of the STF was typically delineated by different isotherms as the temperature increased northward and changed between seasons. The STF east of the South Island was delineated by the 9 – 10 °C isotherms during winter and spring, 11 – 13 °C during autumn, and 12 – 14 °C during summer. The surface expression of the front temperature over the south of the South Island was less variable, delineated by the 9 °C isotherm during winter and spring, and 10.5 °C during summer and autumn.

• Remote sensing observations using monthly composite images of SST proved to be a robust method for examining the surface expression of the STF. The resolution of the extraction windows and the masking of coastal waters played a key role in determining the true frontal position, as the surface expression of the front gradient may be influenced by adjacent physical features, such as river outflow.
CHAPTER III. SPATIAL AND SEASONAL VARIABILITY IN PHYTOPLANKTON PRODUCTIVITY AROUND THE SUBTROPICAL FRONT TO THE SOUTH AND EAST OF NEW ZEALAND

3.1 Introduction

Fronts are often associated with enhanced phytoplankton productivity and also enhanced biological activity at higher trophic levels (Sokolov et al., 2006; Belkin & O’Reilly, 2009; Acha et al., 2015). Acha et al. (2015) explained a strong relationship between the increased lateral or vertical mixing and nutrient enrichment within the frontal zone, which enhances phytoplankton productivity. Sokolov and Rintoul (2007) found most of the regions of enhanced phytoplankton productivity in the fronts of the Antarctic Circumpolar Current (ACC) (i.e. Subantarctic Front and Polar Front) related to the upwelling of nutrients, which occur when the ACC interacts with the topography. The distribution of phytoplankton in the ACC reflects the influence of the ACC fronts (Sokolov et al., 2006).

The Southern Ocean has been identified as a region with high nutrients but low chlorophyll (HNLC) (Han & Takahashi, 2001; Sokolov & Rintoul, 2007). This is because the low concentrations of trace metals essential for photosynthesis (e.g. iron, copper, and zinc) limit productivity, despite high year-round concentrations of macronutrients (e.g. phosphate and nitrate; Vincent et al. 1991; Hassler et al., 2011; Bender et al., 2016). The zones of high Chl-a concentration in the Southern Ocean are commonly observed in shallow coastal and continental shelf waters, and in the vicinity of fronts, where there is an input of iron from shallow sediments or from upwelling within the frontal zone (Boyd et al., 1999; Moore & Abbott, 2000, Sokolov & Rintoul, 2007).

The marine ecosystem within the STF around New Zealand is accompanied by diverse physical processes, which affect the frontal mixing and nutrient enrichment that support phytoplankton growth (Vincent et al., 1991; Murphy et al., 2001). Previous studies have examined the spatial and temporal variability of Chl-a concentration in the New Zealand region utilizing ship-borne measurements, remote sensing technology or combining both approaches (Vincent et al., 1991; Bradford-Grieve et al., 1997; Murphy et al., 2001; Pinkerton et al., 2005; Jones et al., 2013). Murphy et al. (2001) estimated the concentration of Chl-a around New Zealand using monthly composite images taken from SeaWiFS during September
According to their findings, phytoplankton productivity varied along the STF around New Zealand, with the regions to the east and west of the South Island having the highest Chl-a concentrations. Bradford-Grieve et al. (1997), Pinkerton et al. (2005), and Jones et al. (2013) found the STF water and STW exhibited higher phytoplankton biomass than the SAW. The Chl-a concentration across the SF to the east of Tairaoa Head in Otago rarely exceeded 1 mg/m³ between September 2009 and November 2010, and was typically lower than in other near-shore coastal systems (Jones et al., 2013). A negative gradient of Chl-a concentration was identified with increasing distance offshore off the Otago coast (Currie et al., 2011; Jones et al., 2013).

Those previous studies were able to demonstrate that enhanced phytoplankton productivity was associated with the STF around New Zealand. Nevertheless, they did not specifically show how the spatial and temporal distribution of phytoplankton productivity varied with respect to the variations in the frontal position. This was because they had limited sample locations across the STF and generally only used the approximate region or position of the STF based on previous findings (Vincent et al., 1991; Bradford-Grieve et al., 1997; Chang & Gall, 1998; Murphy et al., 2001; Jones et al., 2013), rather than using the actual position of the front during their observation periods. Moreover, they used relatively short observation periods (e.g. less than five years), which did not show the long-term seasonal variation in phytoplankton productivity. This chapter presents a long-term (i.e. ten year) analysis of the spatial and seasonal distribution of Chl-a concentration around the STF to the south and east of New Zealand, with the aim of understanding the distribution of phytoplankton productivity with respect to the frontal position. The maximum Chl-a concentrations across the STF were also examined to obtain the locations of enhanced phytoplankton productivity relative to the position of the front.

3.2 Methods

3.2.1 Acquisition of MODIS-Aqua Chl-a images

MODIS-Aqua Level-3 Global Ocean Mapped (v.2014.0) Ocean Chl-a products at 4 km resolution were obtained for the 2003-2012 period from ERDDAP (http://coastwatch.pfeg.noaa.gov/erddap/index.html). The surface Chl-a concentration was used as a proxy for phytoplankton productivity within the STF region. A total of 120 MODIS-
Aqua monthly composite images of Chl-a images were used to derive the time series analyses. The monthly composite images of Chl-a were obtained in the “.mat” format constructed in a 4-D matrix. Each pixel of the Chl-a images comprises information on geolocation (latitudes and longitudes), time (months), and Chl-a concentration (mg/m³). Details of how the Chl-a estimates are derived and the data processing steps are given by Dogliotti et al. (2009) and Petrenko et al. (2013).

3.2.2 Estimating and analyzing phytoplankton productivity

The same algorithm that was explained in sections 2.2.3 and 2.2.4 was applied to create boxes extending 80 km offshore and 80 km inshore relative to the nominal STF. Each box was divided into 20 km x 10 km bins. The 10 year mean and seasonal mean Chl-a concentrations were derived within these boxes. The mean position of the front estimated in Chapter 2 was overlaid on the Chl-a concentration image to examine the spatial and seasonal variability in phytoplankton productivity along and across the STF.

This study recognized that unrealistically high estimates of Chl-a concentrations might be found over the near-shore water off the east coast of the South Island. This neritic water (NW) is strongly influenced by the freshwater outflow from several major rivers along the east coast of the South Island (Jillett, 1969; Heath, 1985; Uddstrom & Oien, 1999; Shaw & Vennell, 2000; Jones et al., 2013). Murphy et al. (2001) also found consistently high estimates of Chl-a concentrations in the near-shore water off the east coast of the South Island using the SeaWiFS monthly composite images between 1997 and 2000.

The presence of elevated estimates of Chl-a concentration in near-shore water could be due to the high abundance of nutrients (e.g. silicate) and trace metals (e.g. iron, copper, zinc), which are supplied by the riverine outflow (Butler et al., 1992; Hawke & Hunter, 1992; Jones et al., 2013). However, rivers also transport suspended sediment and inorganic particulates, often resulting in turbid water in the coastal zone (Case 2 waters). Remotely sensed estimates of Chl-a concentration from Case 2 waters are complicated by the presence of these other optical constituents (Joint & Groom, 2000). This condition is not ideal for the MODIS-Aqua Chl-a retrieval algorithm which was developed for open ocean (Case 1) water (Petrenko et al., 2013). In this study, it was recognized that coastal turbidity might affect the estimates of Chl-a concentration in the near-shore water of the east coast of the South Island. Therefore, the near-shore masking of bins that applied in Chapter 2 was also applied in this
chapter when estimating the location of enhanced phytoplankton productivity. The bins from 40 km to 80 km inshore of the nominal STF, from box 8 to box 39, were excluded from analyses. This masking method meant that the remotely-sensed estimates of Chl-a concentration were not biased by the presence of sediment.

3.2.3 Sensitivity to the method

High turbidity in near-shore waters could potentially have led to mistakes in identifying areas of enhanced phytoplankton productivity. Therefore, the sensitivity of the computation method was evaluated by comparing the location of enhanced phytoplankton productivity derived from maximum Chl-a concentration, with the location derived from the 80th percentile of Chl-a concentration (Figure 3.1). A paired 2-sample t-test showed there was no significant difference ($F_{1,118} = 2.00$, $p = 0.1603$) in the mean location of the enhanced phytoplankton productivity derived from the locations of maximum concentration and from the locations of the 80th percentile. The locations that were derived from the maximum concentration tended to be located slightly inshore of the locations derived from the 80th percentile, especially along the east coast of the South Island (Figure 3.1). Nevertheless, both approaches provided similar locations of enhanced phytoplankton productivity along the front. Thus, the maximum concentration approach was used in this chapter.

Figure 3.1 The ten year mean locations of enhanced phytoplankton productivity relative to the frontal location. The mean location of enhanced phytoplankton productivity was derived from the location of maximum concentration (black line) and from the location of the 80th percentile of Chl-a concentration in each box (red line).
3.3 Results

3.3.1 Distribution of phytoplankton productivity along the STF over ten years

The ten-year average Chl-a concentration was derived from the 120 monthly images in each box. The Chl-a concentration varied spatially along the ten-year mean position of the front from 0.2 mg/m³ to 1 mg/m³ (Figure 3.2). The concentration typically increased heading northward and decreased with increasing distance from the coast. The concentrations were generally below 0.5 mg/m³ offshore of the front, and above 0.5 mg/m³ inshore of the front. The estimated Chl-a concentration was persistently high (> 1.5 mg/m³) within 20-30 km from the shore, which was outside the masked area. These concentrations were assumed to be an indication of elevated turbidity, as explained in the previous section. A much broader band of high Chl-a concentration (>0.75 mg/m³) was observed in the region of the Mernoo Saddle, where the frontal location was more variable and located further offshore (Figure 3.2). This band tended to occur within 1 standard deviation (S.D.) either side of the front. A narrow patch (ca. 50 km wide) of high concentration (1 mg/m³) was observed inshore of the front on the western side of the Mernoo Saddle (box 40). Another patch of high concentration (1 mg/m³) coincided with the frontal position off Banks Peninsula (box 35-37), extending 10 km on either side of the front. These patches were generally found in the regions where the front intensely meandered.
Figure 3.2 The mean Chl-a concentration and position of the front in each box from 2003 to 2012. The mean position of the front (± SD) is shown by the red line and red dashed line, respectively. Positive and negative signs on the y-axis indicate the offshore and inshore water relative to the nominal STF, respectively. The masked bins are within the black dashed line. Note: the Chl-a concentrations within the masked bins were not used for the estimates of the ten-year average maximum concentration.

The 10-year mean locations of the front and Chl-a maximum, including the 95% confidence intervals of these means, were estimated for each box (Figure 3.3). The overlapping confidence intervals suggest that the mean location of the front and maximum Chl-a concentration were not significantly different to the south of the South Island, off Banks Peninsula, and east of the Mernoo Saddle to the Chatham Rise. According to this finding, the location of enhanced phytoplankton productivity might coincide with the frontal location near the shelf break. Although their locations were not significantly different (overlapping confidence intervals) over the eastern portion of the Chatham Rise (boxes 55-60), the region of elevated phytoplankton productivity was consistently inshore of the frontal location. In contrast, the mean locations of the front and enhanced phytoplankton productivity were significantly different (non-overlapping confidence intervals) along the east coast of the South Island (box 20-32) and on the western flank of the Mernoo Saddle (box 40). In these regions, the average maximum concentrations were located much further inshore relative to the frontal position (Figure 3.3). The locations of enhanced phytoplankton productivity were more variable over the Mernoo Saddle and Chatham Rise, similar to the greater variability of the frontal position (Figure 3.3).
3.3.2 Seasonal distribution of phytoplankton productivity along the STF

The seasonal average of the Chl-a concentration was derived from the thirty monthly mean Chl-a concentrations over the ten-year study period: summer (December-February) (Figure 3.4a), autumn (March-May) (Figure 3.4b), winter (June-August) (Figure 3.4c), and spring (September-November) (Figure 3.4d). The results showed that the mean Chl-a concentrations within open ocean water (> 40 km from the shore) varied seasonally between 0.2 mg/m$^3$ and 1.5 mg/m$^3$. The permanently high estimates of Chl-a concentrations over the near-shore water along the east coast of the South Island were probably a result of elevated turbidity as explained earlier (Figure 3.4a-3.4d). The Chl-a concentration along the front differed between seasons yet the general spatial trend was similar.

Overall, the results showed the areas of higher Chl-a concentration were coincident with the front or close (< 20 km) to the front in all seasons (Figure 3.4a-3.4d). The seasonal mean Chl-a concentration varied between 0.25 mg/m$^3$ and 0.75 mg/m$^3$ across the front over the Snares Shelf, with the higher concentrations measured further inshore of the front during summer (Figure 3.4a). In the Southland Front region (box 16-28), the Chl-a concentration within 10 km inshore and offshore of the front was highest during summer (1.25-1.5 mg/m$^3$) (Figure 3.4a), and lowest during winter (0.25-0.5 mg/m$^3$) (Figure 3.4c). Throughout the season, the area of elevated concentration in the Mernoo Saddle consistently lay further offshore than in other regions, which was coincident with the mean position of the front. Nevertheless, the extent of this area varied among seasons. The area was greater in scale and
concentration level over the Mernoo Saddle during summer (Figure 3.4a) and autumn (Figure 3.4b). In contrast, spring had the highest Chl-a concentrations in the waters inshore of the front over the Chatham Rise (Figure 3.4d). The results showed small patches of high concentration varied seasonally in their locations, magnitude, and scale. These patches were normally found inshore of the front on the western side of the Mernoo Saddle during summer (1.25 mg/m$^3$) and autumn (1.25 mg/m$^3$) (Figure 3.4a & 3.4b), and over the Chatham Rise during winter (0.75 mg/m$^3$) and spring (1.25 mg/m$^3$) (Figure 3.4c & 3.4d). During summer, the patch was much greater in scale (> 30 km wide) and concentration (1.5 mg/m$^3$) across the front off Banks Peninsula (box 35-37) (Figure 3.4a).
Figure 3.4 The seasonal mean Chl-a concentration and position of the front in each box from 2003 to 2012, during (a) summer; (b) autumn; (c) winter; (d) spring. The mean position of the front (± SD) is shown by the red line and red dashed line, respectively. Positive and negative signs on the y-axis indicate the offshore and inshore water relative to the nominal STF, respectively. The masked bins are within the black dashed line. Note: the Chl-a concentrations within the masked bin were not used for the estimates of seasonal average maximum concentration.

The seasonal mean locations of the front and Chl-a maximum, including the 95% confidence intervals of these means, were estimated over the 10-year study period (Figure 3.5a-3.5d). The seasonal mean locations of the front and maximum concentration were
always significantly different (non-overlapping confidence intervals) off the east of coast of the South Island (box 20-32) and on the western flank of the Mernoo Saddle (box 40). The results showed that, irrespective of the seasonal variation in the frontal location, the maximum concentrations of Chl-a were consistently found inshore of the front in those regions. This finding was more obvious during winter (Figure 3.5c), when the front was located furthest offshore relative to the 500 m isobath, yet the maximum concentration of Chl-a remained inshore of the front.

The results showed that the mean location of the front and Chl-a maximum were significantly different over the Snares Shelf during winter and spring (Figure 3.5c & 3.5d). In this region, the location of maximum Chl-a concentrations varied seasonally, whereas the frontal location was relatively stable. Their locations were also significantly different along the Mernoo Saddle and Chatham Rise during spring, where the maximum concentrations were estimated further inshore relative to the position of the front (Figure 3.5d). The region of elevated productivity compared to the frontal location varied seasonally along the Chatham Rise. As the season changed from summer to spring, the maximum Chl-a concentration gradually shifted northward (inshore), while the frontal location moved southward (offshore). Apart from during spring, the region of elevated productivity was apparently associated with the frontal location along the Mernoo Saddle and Chatham Rise (Figure 3.5a-3.5c).
Figure 3.5 The seasonal means (± 95% confidence interval) of the position of the front and Chl-a maximum over the ten-year study period, during (a) summer; (b) autumn; (c) winter; (d) spring.
3.4 Discussion

3.4.1 Sensitivity of remote sensing Chl-a images

The measurement of Chl-a concentration over near-shore waters using remote-sensing can be problematic. Even though the general shoreward increase in the distribution of Chl-a concentrations presented in this study was consistent with the published studies, the estimated Chl-a concentrations over the near-shore waters were much higher than previous in-situ measurements (Vincent et al., 1991; Bradford-Grieve et al., 1997; Haywood, 2004; Jones et al., 2013). The shoreward increase in the surface Chl-a concentration was consistent with greater nutrient enrichment in coastal waters. Jones et al. (2013) found a persist excess of silicate and trace metals (e.g. iron, zinc, and copper) over near-shore waters, originating from the riverine outflows along the east coast of the South Island. This condition is likely to support phytoplankton growth, resulting in higher measurements of surface Chl-a concentration in near-shore compared to offshore waters (Boyd et al., 1999; Murphy et al., 2001; Jones et al., 2013).

In this study, the regions of persistently high Chl-a concentration (> 1.5 mg/m$^3$) were evident up to 30 km, and even further (> 40 km), from the shore during summer along the east coast of the South Island (Figure 3.2 & 3.4). Similar evidence was demonstrated by Murphy et al. (2001) in the annual variation of surface Chl-a concentration using monthly composite images from SeaWiFS between September 1997 and December 2000. They showed the monthly average Chl-a concentration was consistently greater than 1 mg/m$^3$ over the near-shore water off the east coast of the South Island. These findings contradict the spatial and seasonal structure in the surface Chl-a concentrations reported in Vincent et al. (1991), Bradford-Grieve et al. (1997), and Jones et al. (2013), who derived the Chl-a concentrations from in situ measurements. Jones et al. (2013) showed that seasonal Chl-a concentration in the near-shore water up to 20 km off Taiaroa Head varied between 0.1 mg/m$^3$ and 2 mg/m$^3$, with the peak concentration measured during summer. The autumn concentration measured by Vincent et al. (1991) near the Clutha River mouth was 0.6 mg/m$^3$, much lower than the concentration estimated at this site in this study at the same time of year (> 1.5 mg/m$^3$).

The overestimation of Chl-a concentrations in remote sensing algorithm retrievals over near-shore waters might be due to the presence of suspended sediment or inorganic particulate matter transported by several major rivers along the east coast of the South Island (Gibbs et al., 2006; Pinkerton et al., 2005). The consistent inshore estimates of maximum Chl-
a concentration may indicate that sediment contamination was always present along the east coast of the South Island (Figure 3.3 & 3.5). Pinkerton et al. (2005) classified the water shallower than 200 m off the east coast of the South Island as turbid water (Case 2 waters), and excluded this water from Chl-a measurements using SeaWiFS. Gibbs et al. (2006) estimated the seaward extent of New Zealand’s coastal zone using SeaWiFS images of combined Chl-a concentration and turbidity between September 1997 and September 2002. They found there was no strong relationship between the depth of the underlying water and the seaward extent of the coastal zone. They also found the mean offshore distance of the median edge of the coastal zone in the New Zealand region was between 67 km and 75 km. This finding suggests that Case 2 waters along the east coast of the South Island might be present much further offshore than the near-shore bin masking that was applied in this study. Remotely sensed data taken from Case 2 waters has issues due to the presence of suspended particulate matter (SPM) and coloured dissolved organic materials (CDOM), which are different from the phytoplankton pigment concentration (Joint & Groom, 2000). This condition is not ideal for the MODIS-Aqua Chl-a retrieval algorithm which is developed for open ocean waters (Case 1 waters) (Petrenko et al., 2013), thereby potentially overestimating Chl-a concentrations in near-shore waters.

Even though there might be overestimation in measuring the Chl-a concentrations within the near-shore water, remote sensing images should provide a robust picture of the spatial and temporal variability in Chl-a concentration over open-ocean water. This study found the Chl-a concentration along the STF generally increased towards the lower latitudes (e.g. Mernoo Saddle and Chatham Rise). This variation had been reported in Vincent et al. (1991), Murphy et al. (2001) and Pinkerton et al. (2005). Brewin et al. (2014) suggested that phytoplankton biomass at the lower latitudes (< 40 °S) was likely to be limited by nutrient availability, while at the higher latitudes (> 40 °S), where nutrients were more abundant, phytoplankton biomass was considered to be limited by light irradiance. Boyd (2002) and Jones et al. (2013) suggested the low seasonal Chl-a concentration off the southern South Island and in SAW offshore of the STF, was due to the limitation of silicate and iron. Pinkerton et al. (2005) compared in situ measurements and SeaWiFS Chl-a concentration estimates along a transect from 40 °S to 48 °S to evaluate the sensitivity of the Chl-a retrieval algorithm. They showed that the Chl-a concentrations were relatively lower (< 0.5 mg/m³) in the SAW beyond 45 °S, and from 0.3 mg/m³ to 1.1 mg/m³ between 40 °S and 45 °S, which were similar to this study. Their findings also indicated the in situ measurements of Chl-a were mostly representative of the conditions observed by the SeaWiFS images.
3.4.2 Phytoplankton productivity along the STF

A number of studies have reported the STF within the New Zealand region as a region of enhanced phytoplankton productivity (Butler et al., 1992; Bradford-Grieve et al., 1997; Chang & Gall, 1998; Murphy et al., 2001; Pinkerton et al., 2005; Jones et al., 2013). This study, however, found the enhanced phytoplankton productivity might not always be associated with the front. This disparity with previous findings may be due to the different approach for defining the front, and/or the sensitivity of the remote sensing images along the east coast of the South Island as explained in the earlier section. In support of Sokolov et al. (2006), higher Chl-a concentrations were mostly observed in the coastal and shelf waters, inshore of the front in this study. This is consistent with the greater silicate and iron concentrations which support the growth of large-celled phytoplankton (Hawke & Hunter, 1992; Boyd, 2002; Currie et al., 2011; Jones et al., 2013).

The enhanced phytoplankton productivity along the Snares Shelf in the ten-year and seasonal average were typically associated with the front during summer and autumn. During winter and spring, however, the enhanced phytoplankton productivity was observed further offshore (20 – 30 km) relative to the position of the front in this region. This seasonal variation in the location of enhanced phytoplankton productivity was probably not related to the variation in the frontal position since the front was relatively stable along the shelf break across all seasons on the Snares Shelf. This finding might indicate that the factors stimulating phytoplankton growth were not always found within the front. Sokolov & Rintoul (2007) suggested that the nutrient and iron enrichment in the open water of the Southern Ocean mixed layer were primarily driven by upwelling near the frontal systems caused by topographic interactions.

While the estimates of high productivity along the east coast of the South Island were suggested to be due to sediment contamination, this was not likely to be the case on the western side of the Mernoo Saddle since this water was distant from the shore. This high productivity was likely due to the presence of patches of high Chl-a concentration at this site (Figure 3.2 & 3.4). Over the Chatham Rise, enhanced phytoplankton productivity was consistently associated with the position of the STF, except during spring, when the maximum Chl-a concentrations lay 30-40 km inshore of the front (Figure 3.5d). Bradford-Grieve et al. (1997) and Murphy et al. (2001), found that the Chl-a concentrations tended to increase northward across the Chatham Rise during spring months. This study found that Chl-a concentrations were relatively higher over the Mernoo Saddle and Chatham Rise during
spring, whereas they were higher over Banks Peninsula during summer and autumn. Murphy et al. (2001) suggested that the region of enhanced phytoplankton productivity could extend across the Mernoo Saddle and Chatham Rise, projecting eastward as a tongue-like feature. As in the present study, they also found a narrow band of enhanced Chl-a concentration along the STF over the Chatham Rise during winter, which became broader and more variable stretching eastwards toward the Chatham Islands during the rest of the year.

This study suggests that enhanced phytoplankton productivity might be related to instabilities in the frontal position over the Mernoo Saddle and Chatham Rise. Instabilities in the frontal position can trigger greater horizontal mixing of the STW (inshore water) and SAW (offshore water), causing enrichment of nutrients in surface waters (Hadfield et al., 2007; Jones et al., 2013). The seasonal variation in the frontal position over the Mernoo Saddle and Chatham Rise is affected by the fluctuation of the Southland Current (SC) (Heath 1971, 1985; Vincent et al., 1991; Shaw & Vennell, 2000, 2001; Sutton, 2003; Hopkins et al., 2010). The combination of the northward flow of the SC, which potentially transports iron-rich near-shore waters, the horizontal advection of near-shore waters off Banks Peninsula (Uddstrom & Oien, 1999), and nitrate enrichment from the upwelling of subsurface SAW (Heath, 1985; Vincent et al., 1991; Reynolds-Fleming & Fleming, 2005), may stimulate the rapid growth of phytoplankton near the frontal system over the Mernoo Saddle.

3.5 Conclusions

- Enhanced phytoplankton productivity was not always associated with the STF to the south and east of New Zealand. The areas of highest phytoplankton productivity were consistently observed in the shelf regions, within the inshore water of the front or coincident with the front (e.g. off Banks Peninsula). Phytoplankton productivity typically increased heading northward and decreased with increasing distance from the coast. The location of enhanced Chl-a concentration relative to the position of the STF varied seasonally.

- High phytoplankton productivity might correlate with the instabilities of the STF caused by interactions with topographic features. The small patches of highest productivity were normally found across the regions where the front intensely meandered (e.g. Mernoo Saddle and Chatham Rise).
Measurements of Chl-a concentration by remote-sensing can be problematic in near-shore waters. The Chl-a retrieval algorithms might overestimate phytoplankton biomass due to the presence of high suspended sediment or inorganic particulates. However, remote sensing provided robust analysis of Chl-a concentrations within open-ocean water (approximately >40 km from the shore).
CHAPTER IV. SEASONAL VARIABILITY OF PHYTOPLANKTON BLOOMS OVER THE MERNOO SADDLE AND CHATHAM RISE

4.1 Introduction

A phytoplankton bloom is commonly defined as a rapid growth of phytoplankton in a short time that induces a significant increase in phytoplankton biomass (Diersing, 2009; Liu et al., 2014). The growth of planktonic organisms normally follows a regular annual cycle starting with a spring bloom of phytoplankton (Murphy et al., 2001; Bollmann et al., 2010). The increased wind mixing in autumn or winter generates a deep mixed layer during spring, driving the pycnocline below the euphotic zone and entraining nutrients from deep water (Longhurst, 1998). As the pycnocline becomes shallower than the euphotic zone due to the ocean warming during spring and summer, the availability of light and nutrients in the mixed layer stimulates phytoplankton growth (Murphy et al., 2001; Bollmann et al., 2010). These events are typically followed by a decrease in phytoplankton biomass, because of zooplankton feeding on the phytoplankton and the depletion of nutrients (Bollmann et al., 2010; Chiswell et al., 2013). Although Chl-a concentrations are generally low in the Southern Ocean, Sokolov & Rintoul (2007) found that phytoplankton blooms occurred in regions where oceanic fronts interact with large-scale topographic features.

The Chatham Rise, located east of New Zealand, is an underwater ridge acting as a partial barrier to the flow of subantarctic water (SAW) from the south and subtropical water (STW) from the north (Heath, 1981; Shaw & Vennell, 2000; Delizo et al., 2007). The Rise is separated from the South Island by a 40 km wide depression east of Banks Peninsula called the Mernoo Saddle. Previous studies have investigated the variability of the water mass properties (STW and SAW) in the region, along with the major oceanographic features, i.e. the Southland Current and STF (Heath, 1971, 1975, 1973, 1983; Uddstrom & Oien, 1999; Nelson, 2000; Shaw & Vennell, 2000; Nodder et al., 2003; Hadfield et al., 2007; Hopkins et al., 2010). Those studies showed the interaction between water masses across the Mernoo Saddle and Chatham Rise resulting in large gradients in physical properties, in turn influencing the biological properties (i.e. elevated phytoplankton biomass).

Murphy et al. (2001) computed the monthly average concentration of surface Chl-a around New Zealand using monthly-composite images taken from SeaWiFS during September
They found that Chl-a concentrations were highest in the Chatham Rise region. Other studies have shown that peak Chl-a concentrations occurred over the Chatham Rise during spring or autumn, while the lowest concentrations were during winter (Chang & Gall, 1998; Nodder & Northcote, 2001; Delizo et al., 2007; Chiswell et al., 2013). Murphy et al. (2001) found the evidence of phytoplankton blooms outside the spring bloom during summer or autumn, identified as secondary blooms. A climatology analysis of surface Chl-a concentration in the New Zealand region showed that in the STW, an autumn bloom was more likely to develop, whereas in the SAW, a spring bloom was more likely (Chiswell et al., 2013).

Previous studies have shown that the annual and inter-annual variations in Chl-a concentrations across the Chatham Rise were associated with nutrient availability (Bradford-Grieve et al., 1997; Chang & Gall, 1998), climate changes (Murphy et al., 2001), and dynamics of the mixed layer (Chiswell et al., 2013). Those studies, however, did not investigate the long-term seasonal variability of the Chl-a concentration and phytoplankton bloom with respect to the seasonal variations in the STF position east of the South Island.

The previous chapter examined the spatial and seasonal variability of phytoplankton productivity along the STF east of the South Island, whereas this chapter specifically examines the seasonal variability of phytoplankton blooms across the STF over the Mernoo Saddle and Chatham Rise. These regions were chosen since they are located further from the coast, thus are less likely to be affected by the presence of sediment transported by riverine outflows. This chapter aims to investigate if there are variations in the timing and strength of phytoplankton blooms within waters across the STF in these regions from 2003 to 2012. The location of the bloom will also be examined with respect to the position of the front. This information will help with understanding of how the phytoplankton bloom varies seasonally across the STF.

4.2 Methods

4.2.1 Box layout

A similar dataset of 120 monthly composite images of Chl-a concentration and SST from 2003 to 2012 used in previous chapters were used in this chapter. The same algorithm explained in sections 2.2.3 and 2.2.4 was applied to create boxes extending offshore and inshore relative to the nominal STF line. Each box spanned 160 km and was divided into 20 km
x 10 km bins. The layout of boxes is shown in Figure 4.1. In this chapter, the Mernoo Saddle and Chatham Rise regions were within box 39 to 42 and 43 to 60, respectively.

![Figure 4.1](image)

**Figure 4.1** The layout of boxes for extraction of Chl-a concentrations over the Mernoo Saddle and Chatham Rise. The width of each box was 320 km (160 km inshore and 160 km offshore relative to the nominal STF), divided into 20 km x 10 km bins.

### 4.2.2 Defining the phytoplankton blooms and frontal zone

In the previous studies of elevated primary productivity related to the STF, there is no consistent definition of what defines a phytoplankton bloom (Murphy et al., 2001; Sokolov & Rintoul, 2007; Chiswell et al., 2013; Jones et al., 2013). In this chapter, Chl-a concentrations were investigated in two regions: Mernoo Saddle and Chatham Rise. To do this, data from all four Mernoo Saddle boxes were pooled, and all 18 Chatham Rise boxes were pooled. For each bin distance relative to the nominal STF (i.e. 0-10 km, 10-20 km,...etc.), the Chl-a concentration image was averaged for each bin in that region.

This study used two thresholds to define the bloom. The first threshold was the average Chl-a concentration outside bloom events estimated in Murphy et al. (2001) across the STF east of New Zealand. They generally reported the presence of a bloom when the monthly average Chl-a concentration was above 0.5 mg/m³. The second threshold was derived from a specific percentile of the average monthly Chl-a concentration in each bin over the ten years for each region. This threshold was therefore different for each bin. The sensitivity to this threshold was examined by trialling the 70th, 80th, and 90th percentile value of the average
monthly Chl-a concentration in each bin over the ten years. For each bin, if the mean Chl-a concentration from one monthly image was greater than both thresholds, then a phytoplankton bloom was deemed to have occurred during this month. Phytoplankton blooms identified outside the spring period were referred to as secondary blooms.

In order to avoid possible biases in estimation of Chl-a concentrations due to sediment, the spatial and temporal variability of phytoplankton blooms were investigated within a zone 60 km north (inshore) to 60 km south (offshore) relative to the position of the front (note: this ensured that the zone would not overlap with the land, even if the front lay at its furthest inshore location as estimated in Chapter 2). Hereafter, this zone is referred to as the frontal zone. The phytoplankton blooms within this zone were discriminated into blooms inshore and offshore of the front. The bloom concentration was estimated within 30 km of the front and within 60 km of the front in both inshore and offshore. The mean Chl-a concentration in the blooms was estimated for each season and year from three monthly images of Chl-a concentration: summer (December-February), autumn (March-May), winter (June-August), and spring (September-November) between 2003 and 2012.

4.3 Results

4.3.1 Variation in Chl-a concentration over the Mernoo Saddle and Chatham Rise

The seasonal mean Chl-a concentration within the frontal zone was generally lowest during winter, rapidly elevated during spring, and continued to increase or be steady throughout summer and autumn in both regions (Figure 4.2a & 4.2b). There were small differences in the concentrations among summer, autumn, and spring periods, with median concentrations of ca. 1 mg/m³ over the Mernoo Saddle (Figure 4.2a) and ca. 0.7 mg/m³ on the Chatham Rise (Figure 4.2b). Over the Mernoo Saddle, the mean concentrations among those seasons were not significantly different (overlapping confidence intervals) to each other but the autumn concentration was normally higher and more variable, with the greatest variability occurring in 2007 and 2010 (Figure 4.3a). In contrast, the spring concentration was normally higher and more variable than the summer and autumn concentrations over the Chatham Rise (e.g. in 2005, 2009, and 2011) (Figure 4.3b).

The results showed that the mean Chl-a concentration during winter was typically significantly different from the mean concentrations during the other seasons over both the
Mernoo Saddle (Figure 4.3a) and Chatham Rise (Figure 4.3b). The exceptions were in 2005 for the Chatham Rise, and 2010 for both regions (Figure 4.3a & 4.3b). Unusually high concentrations were observed during spring 2011 over the Mernoo Saddle, and winter 2012 in both regions (Figure 4.2a & 4.2b). During winter 2012, the mean Chl-a concentration reached 2 mg/m³ over the Mernoo Saddle and 1.2 mg/m³ on the Chatham Rise.

**Figure 4.2** Box and whisker plots of the seasonal average Chl-a concentration within the frontal zone over 2003-2012 over (a) Mernoo Saddle; (b) Chatham Rise. On each box, the horizontal red line indicates the median, and the bottom and top edges of the box indicate the 25th and 75th percentiles, respectively. The whiskers indicate the maximum and minimum concentration. The ‘+’ symbol indicates outliers, which are concentrations greater than 1.5 times the maximum.
4.3.2 The seasonal variability of phytoplankton blooms within the frontal zone on the Mernoo Saddle and Chatham Rise

The phytoplankton bloom incidents over the Mernoo Saddle were derived from the 70th, 80th, and 90th percentiles of the ten-year average Chl-a concentration in each bin. Overall, the lower threshold resulted in more evidence of blooms with relatively low concentrations (≤ 1 mg/m³) within bins across the front in each season (Figure 4.4a). The higher threshold showed more evidence of phytoplankton blooms with high Chl-a concentrations (≥ 2 mg/m³) (Figure 4.4b). These findings suggest that the 70th percentile was not sensitive enough to correctly define bloom events as the relatively lower Chl-a concentration during winter was still characterized as a bloom. In contrast, the 90th percentile typically failed to identify blooms.
with concentrations between 1 mg/m$^3$ and 2 mg/m$^3$. In this case, the 80$^{th}$ percentile offered a good compromise, consistently identifying spring and summer blooms, but not identifying elevated Chl-a levels during winter as phytoplankton blooms (Figure 4.5a).

![Image](image_url)

(a)

![Image](image_url)

(b)

**Figure 4.4** Phytoplankton bloom incidents and mean Chl-a concentration over the Mernoo Saddle from 2003 to 2012. A bloom was identified if the monthly Chl-a concentration in each bin exceeded the (a) 70$^{th}$ percentile; (b) 90$^{th}$ percentile value, of the ten-year average Chl-a concentration in each bin, and exceeded 0.5 mg/m$^3$. Only bins with a bloom present are coloured. Seasons are indicated in: Sm (summer), A (autumn), W (winter), and Sp (spring).

The timing, magnitude, and location of phytoplankton blooms within the frontal zone over the Mernoo Saddle and Chatham Rise varied spatially and seasonally. The results showed that phytoplankton blooms were typically found during summer and autumn over the Mernoo
Saddle (Figure 4.5a), while they were mostly found during spring on the Chatham Rise (Figure 4.5b). Some evidence of phytoplankton blooms was still found during winter in both regions (e.g. 2005, 2010, and 2012). Overall, the mean concentrations of the summer, autumn, and spring blooms over the Mernoo Saddle were greater than the mean concentrations of the blooms on the Chatham Rise (Figure 4.5a). The results showed the spatial distribution of phytoplankton blooms was not always concentrated at the front. Patches of phytoplankton bloom were sometimes found further offshore relative to the mean position of the front (> 20 km) over the Mernoo Saddle, for example during spring 2005 and 2007.

Figure 4.5 Phytoplankton bloom incidents and mean Chl-a concentration over (a) Mernoo Saddle; (b) Chatham Rise from 2003 to 2012. A bloom was identified if the monthly Chl-a concentration in each bin exceeded the 80th percentile and exceeded 0.5 mg/m$^3$. Only bins with a bloom present are coloured. Seasons are indicated in: Sm (summer), A (autumn), W (winter), and Sp (spring).
The annual variation in the Chl-a concentration generally elevated during spring both inshore and offshore of the front over the Mernoo Saddle (Figure 4.6a) and Chatham Rise (Figure 4.6b). The results showed that phytoplankton blooms with higher Chl-a concentrations tended to occur during spring inshore of the front, whereas they typically occurred during summer offshore of the front (Figure 4.6a & 4.6b). The mean concentration of blooms during spring varied between 1.25 mg/m³ and 3 mg/m³ over the Mernoo Saddle and between 1 mg/m³ and 2.5 mg/m³ on the Chatham Rise. The spring bloom cycle was much clearer in the inshore waters compared to the offshore waters. The strongest inshore and offshore blooms (> 3 mg/m³) occurred during winter 2010 and 2012 over the Mernoo Saddle (Figure 4.6a). Secondary blooms were found inshore and offshore of the front during autumn or summer; for instances during summer 2005 over the Mernoo Saddle, and during autumn 2011 over the Chatham Rise. These secondary blooms were occasionally stronger than the spring blooms.

The phytoplankton bloom concentration typically decreased with increasing distance relative to the frontal location in both regions (Figure 4.6a & 4.6b). The mean concentrations within the 30 km of the front were consistently higher than the concentrations within 60 km of the front, although not always significantly. This finding suggests that the stronger phytoplankton blooms tended to occur near the front. Over the Mernoo Saddle, the mean concentration of the inshore bloom was typically higher and more variable than the offshore bloom (Figure 4.6a). On the other hand, the inshore bloom concentration on the Chatham Rise was not significantly different from the offshore bloom concentration (Figure 4.6b).
Figure 4.6 The mean Chl-a concentration (± 95% confidence interval) in phytoplankton blooms inshore and offshore of the front, over (a) Merno Saddle; (b) Chatham Rise, for each season and year from 2003 to 2012. The mean concentration was estimated within a zone 30 and 60 km inshore and offshore relative to the front.

4.4 Discussion

4.4.1 The characteristics of phytoplankton blooms across the STF

This study found that phytoplankton blooms were generally associated with the STF across the Merno Saddle and Chatham Rise. The phytoplankton bloom incidents identified in this study tended to be concentrated at the front, extending inshore (northward) and offshore (southward) relative to the position of the front in both regions (Figure 4.5). The localized bloom incidents within the frontal zone might be due to the variation in the position of the front across the Merno Saddle and Chatham Rise. This study suggested that the position of the front varied seasonally, potentially resulting in increased eddy mixing (Moore et al., 1999; Shaw & Vennell, 2001; Sokolov et al., 2006; Sokolov & Rintoul, 2007). Waite & Muete (2013) suggested the variability in the eddy over the Gulf of Alaska affected the spatial and temporal distribution of phytoplankton biomass. Within that eddy, nutrients are brought up to the surface water resulting in elevated phytoplankton biomass. Taylor & Ferrari (2011) also showed that frontal instabilities might lead to vertical restratification of the water.
column, which could trigger a localized bloom at the front once the vertical restratification overcomes the turbulent mixing.

The seasonal bloom was generally stronger over the Mernoo Saddle than the Chatham Rise. The observed concentrations of Chl-a were greater than those reported by Murphy et al. (2001) and Chiswell et al. (2013) for the same region. This could be explained by a number of factors. Firstly, the northward flow of the SC transports some of the macronutrients and iron-rich near-shore water to the Saddle, where it mixes with the macronutrient poor STW (Butler et al., 1992; Croot & Hunter, 1998). Bradford-Grieve et al. (1998) found there was a similarity in the mesozooplankton species found on the Chatham Rise and in the coastal water of the east coast of the South Island during summer and winter. This might indicate that near-shore water was entrained into the STF over the Mernoo Saddle and Chatham Rise. Secondly, the upwelling of the deep SC brings up the nutrients to the surface water of the Saddle (Roberts, 1980; Heath, 1985; Vincent et al., 1991; Fleming & Fleming, 2005). Heath (1985) suggested that the subsurface SAW along the continental slope was forced upwards as it flows through the Saddle. Alternatively, this discrepancy may be due to the different way of defining and estimating the bloom concentration in this study.

The magnitude of the bloom typically decreased with increasing distance from the front (Figure 4.5 & 4.6). The bloom concentrations inshore of the front were typically higher than the offshore concentrations over the Mernoo Saddle, while they were more variable on the Chatham Rise. This spatial trend was consistent with Bradford-Grieve et al. (1997), Chang & Gall (1998), Murphy et al. (2001) and Chiswell et al. (2003), who estimated higher surface Chl-a concentrations in the STW, and lower concentrations in the SAW east of New Zealand. The SAW of the STF region has been characterized as a HNLC region, with low phytoplankton biomass but a persistent excess of macronutrients. The low phytoplankton biomass was assumed to be due to the lack of iron, which generally decreases with increasing distance offshore (Croot & Hunter, 1998). Despite phytoplankton blooms most frequently occurring near the front, blooms were occasionally observed >20 km inshore or offshore of the front (Figure 4.5). Jones et al. (2013) estimated elevated Chl-a concentration up to 30 km offshore of the front across the east coast of Otago. These patches of elevated Chl-a concentration could be potentially triggered by the localized input of iron (Sokolov & Rintoul, 2007).

The seasonal cycle of phytoplankton blooms over the Mernoo Saddle and Chatham Rise was consistent with the spring bloom cycle reported in Probert & McKnight (1993), Murphy et al. (2001), Nodder & Northcote, (2001), Delizó et al. (2007), Taylor & Ferrari (2011) and Chiswell et al. (2013). The Chl-a concentration consistently increased during spring and
dropped during winter within the inshore and offshore waters of the front in both regions (Figure 4.2 & 4.3). The spring bloom cycle was very obvious inshore of the front, but weaker in the offshore water.

This study identified more bloom events within the frontal zone during summer and autumn over the Mernoo Saddle, while there were more blooms during spring on the Chatham Rise. Secondary bloom incidents were observed in both regions during summer or autumn, and were sometimes stronger than the spring bloom within the same year. Murphy et al. (2001) and Chiswell et al. (2013) also reported similar evidence of this secondary bloom during summer or early autumn. In contrast to the spring bloom, diatoms were only a minor component of the phytoplankton community in the secondary bloom events (Nodder & Northcote, 2001).

This study also suggested there was a difference in the timing of the stronger bloom within the frontal zone between the inshore and offshore waters. The bloom was typically stronger during spring inshore of the front, whereas during summer it was found in the water offshore of the front (Figure 4.6). A relatively stronger bloom during summer in both regions has been previously reported in Bradford-Grieve et al. (1997; 1998) and Murphy et al. (2001). A stronger bloom during spring over the SAW of the STF region east of New Zealand was suggested by Nodder & Northcote (2001), Nodder et al. (2003) and Chiswell et al. (2013). The timing of the bloom identified in this study was consistent, although the magnitude varied between years and regions. This indicates that phytoplankton may have the capacity to bloom in a particular season and year, but that favorable conditions are not always present.

Extremely strong winter blooms occurred during winter 2010 over the Mernoo Saddle, and in 2012 in both regions. These occurrences were assumed to be anomalies as phytoplankton growth is typically limited during winter due to low light availability. Taylor & Ferrari (2011) suggested that the front may enhance light exposure by restratifying the upper ocean and reducing the turbulent flux of phytoplankton out of the euphotic zone, thereby preserving the wintertime phytoplankton biomass. The spring bloom was weaker than the winter bloom in 2012. This may be due to phytoplankton growth during spring in this year being limited by the availability of nutrients that were depleted during the previous winter bloom (e.g. Delizo et al., 2007). They also suggested that the development of blooms might be inhibited by high rates of grazing. Other possible factors that may support a winter bloom over the shelf break are small-scale processes (e.g. storms; Chiswell et al., 2013) and episodic events (e.g. internal wave activity, and onshore impinging of warm-core rings; Zhang et al., 2013). These processes may have a large impact on the phytoplankton biomass in the shelf.
break region by altering the mixed layer depth and transporting nutrients through the advection of vertical motion.

4.5 Conclusions

- Phytoplankton blooms were associated with the STF across the Mernoo Saddle and Chatham Rise, and typically occurred near the front. The blooms were stronger and more variable over the Mernoo Saddle.
- Seasonal variation of phytoplankton biomass followed the spring bloom cycle, with the Chl-a concentration persistently increasing during spring and dropping during winter. The magnitude, timing and location of the blooms relative to the position of the front varied spatially and seasonally.
- Chl-a concentrations within blooms decreased with increasing distance from the front. An obvious spring bloom cycle was apparent inshore of the front, while the offshore water had a weak yet detectable spring bloom cycle. The strongest blooms were normally found during spring inshore of the front, and during summer offshore of the front. The inshore blooms were typically stronger than the offshore blooms.
- Secondary blooms were observed during summer or autumn, and were sometimes stronger than the spring bloom in that year.
CHAPTER V. SUMMARY AND RECOMMENDATIONS FOR FUTURE WORK

5.1 Summary

5.1.1 The position and characteristics of the STF off southeastern New Zealand

Remotely sensed images of sea surface temperature (SST) were analysed to estimate temperature gradients. The maximum gradient within cross frontal strips was taken as the location of the STF. The frontal location was examined on a range of time scales using a ten year mean (between 2003 and 2012), annual means, and seasonal means. The significant results found in this study were:

- The STF generally followed the shelf break (200 – 500 m isobaths) along the south and east of the South Island (Section 2.3.1-2.3.3). In contrast, over the Mernoo Saddle and Chatham Rise, the position of the STF was much more variable, intensely meandering between the inshore and offshore waters (Figure 2.9-2.11). In these locations, the continental shelf is less steep. This spatial variability has been reported in Uddstrom & Oien (1999), Shaw & Vennell (2001), Hopkins et al. (2010), and Smith et al. (2013).

- The mean positions of the STF were significantly different among years (Figure 2.10) and seasons (Figure 2.11). Similar to Shaw & Vennell (2001) and Hopkins et al. (2010), this study found the STF position was furthest offshore during winter and furthest inshore during summer off the south and east of the South Island. In these regions, the location of the STF found in this study was slightly inshore compared to previous findings (Figure 2.16). Over the Chatham Rise, the STF was located furthest inshore during autumn.

- The gradient of the front varied spatially, annually, and seasonally (section 2.3.4-2.3.6). The gradient of the front was consistently weakest (0.045 °C/km) south of the Clutha River and on the western side of the Mernoo Saddle in all time periods (Figure 2.12a, 2.13 & 2.15a). The strongest gradient (0.09-0.11 °C/km) of the front was estimated on the southern part of the Snares Shelf, being intensified by the steep bathymetry (Smith et al., 2013). Similar to Udsstrom & Oien (1999) and Hopkins at al. (2010), this study found the frontal strength off the east coast of the South Island was strongest during summer (0.07-0.09 °C/km), and the weakest during winter and spring (0.05-0.065 °C/km) (Figure 2.15a). In contrast, the strongest gradient of the front off
the southern South Island, over the Mernoo Saddle, and Chatham Rise, was typically found during winter (0.075-0.1 °C/km), while the weakest gradient was found during summer (0.055-0.06 °C/km) (Figure 2.15a). The observed differences in gradient magnitude compared to previous findings may be due to differences in resolution of remote sensing images.

- Temperature of the front generally increased northward and was relatively steady along the Chatham Rise in all time periods (section 2.3.4-2.3.6). The greatest seasonal difference in mean SST was approximately 3.5 °C between summer and winter. The temperature of the front consistently dropped on the western side of the Mernoo Saddle. The front was delineated by different isotherms in different regions and seasons, ranging from 12 - 13 °C during summer and autumn, to 9 - 10 °C during winter and spring (Figure 2.15b), similar to the levels reported in Heath (1972,1975,1981), Chiswell (1994,1996), Uddstrom & Oien (1999), Hopkins et al. (2010), and Currie et al. (2011).

5.1.2 Phytoplankton productivity along the STF

Surface Chl-a concentration images were used as a proxy for phytoplankton productivity. The mean Chl-a concentrations along the front were estimated for each season, and over ten years. The maximum Chl-a concentration within cross frontal strips was taken as the location of enhanced phytoplankton productivity relative to the position of the front. The significant results found in this study were:

- Unrealistically high estimates of Chl-a concentrations (> 1.5 mg/m³) were consistently found over the near-shore water off the east coast of the South Island (30-40 km off the coast) (section 3.3.1 & 3.32), consistent with Murphy et al. (2001). This was likely due to suspended sediment from riverine inputs in the neritic zone. Nevertheless, remote sensing was able to present a clear picture of spatial and seasonal variability in Chl-a concentrations over open-ocean water (> 40 km from the coast).

- Chl-a concentrations increased towards the lower latitudes and decreased further offshore (Figure 3.2 & 3.4). The Chl-a concentration rarely exceeded 0.5 mg/m³ over the Snares Shelf throughout the year. Areas of high Chl-a concentration (> 0.5 mg/m³) were generally found coincident with the frontal location, similar to Bradford-Grieve et al. (1997), Chang & Gall (1998), Murphy et al. (2001), and Jones et al. (2013). Peak
Chl-a concentrations were typically observed from Banks Peninsula to the Mernoo Saddle during summer and autumn, but during spring over the Chatham Rise.

- The location of enhanced phytoplankton productivity relative to the front varied spatially and seasonally (Figure 3.3 & 3.5). Similar to Bradford-Grieve et al. (1997) and Murphy et al. (2001), this study found that phytoplankton productivity was generally enhanced inshore of the front to the south of the Clutha River, off Banks Peninsula, and over the Chatham Rise during all seasons. Over the Chatham Rise, enhanced phytoplankton productivity was not associated with the front during spring.

- The enhanced phytoplankton productivity off the lower east coast of the South Island and on the western flank of the Mernoo Saddle was found much further inshore relative to the frontal location. This was possibly due to unrealistically high estimates because of suspended sediment in near-shore water.

- The locations of enhanced phytoplankton productivity were more variable over the Mernoo Saddle and Chatham Rise, similar to the greater variability in the frontal position (Figure 3.3 & 3.5). Small patches of high productivity were normally found across these regions where the front intensely meandered (Figure 3.2 & 3.4).

### 5.1.3 Phytoplankton blooms within the STF region over the Mernoo Saddle and Chatham Rise

The seasonal variability of phytoplankton blooms was examined over the Mernoo Saddle and Chatham Rise for each season and year, and over the ten year study period. A phytoplankton bloom was identified if the monthly mean concentration in each bin exceeded the 80\(^{th}\) percentile value of the ten year-average Chl-a concentration in each bin, and exceeded 0.5 mg/m\(^3\). The magnitude, timing, and location of the blooms were examined within a zone 60 km inshore to 60 km offshore relative to the position of the front. The significant results found in this study were:

- The phytoplankton blooms tended to occur at the front, extending inshore and offshore relative to the position of the front (section 4.3.2). The phytoplankton bloom concentration typically decreased with increasing distance relative to the frontal location (Figure 4.6). Similar evidence has been reported in the spatial distribution of Chl-a concentration across the STF east of New Zealand in Bradford-Grieve et al. (1997), Chang & Gall (1998), Murphy et al. (2001) and Chiswell et al. (2013).
This study found that phytoplankton biomass followed a spring bloom cycle, with the Chl-a concentration persistently elevated during spring and low during winter (Figure 4.2 & 4.6), which was similar to Murphy et al. (2001), Nodder & Northcote (2001), Delizo et al. (2007), and Chiswell et al. (2013). This study identified more bloom events within the frontal zone during summer and autumn over the Mernoo Saddle, while there were more blooms during spring on the Chatham Rise.

The phytoplankton blooms over the Mernoo Saddle were consistently stronger (1-5 mg/m³) compared to the phytoplankton blooms over the Chatham Rise (1-3 mg/m³) (Figure 4.5 & 4.6). Over the Mernoo Saddle, the mean concentration in the blooms was typically greater and more variable during autumn, while it was typically greater and more variable during spring on the Chatham Rise, similar to Bradford-Grieve (1997) and Murphy et al. (2001). Unusually high bloom concentrations (> 3 mg/m³) were estimated during winter 2010 over the Mernoo Saddle and in 2012 in both regions. This study found that secondary blooms occurring outside the spring bloom were sometimes stronger (Figure 4.6), as also reported in Murphy et al. (2001) and Chiswell et al. (2013).

The spring bloom cycle was much clearer in the inshore waters compared to the offshore waters (Figure 4.6). The phytoplankton blooms inshore of the front were typically stronger during spring, whereas offshore of the front they were typically stronger during summer in both regions, consistent with Bradford-Grieve et al. (1997,1998), Murphy et al. (2001), Nodder & Northcote (2001), Nodder et al. (2003) and Chiswell et al. (2013).

5.2 Recommendations for future work

This study examined the spatial, inter-annual, and seasonal variability of the position of the STF and Chl-a concentration using remote sensing images. It was recognized that the presence of suspended sediment could possibly bias concentration of Chl-a. A greater resolution in the remote sensing images may enable better discrimination of suspended sediment and Chl-a in near-shore waters. In future studies, it is recommended that a smaller bin resolution be used (<10 km), which may reveal finer structure in the Chl-a concentration and SST gradient across the shelf break.
In-situ measurements of surface Chl-a concentration and SST across the shelf-break would provide supporting data that could strengthen the remote sensing analysis. This study was not able to do this due to the time restriction. It is recommended to take samples from several locations for each season across the shelf break off the east coast of the South Island and Mernoo Saddle. These data may reveal if the elevated estimates of Chl-a concentration in these waters were actually caused by the presence of high phytoplankton biomass or suspended sediment, in particular on the western flank of the Mernoo Saddle.

It was noticed that the monthly composite satellite images used in this study may compromise the ability to detect short duration bloom events. Therefore, satellite Chl-a images with a finer time resolution (e.g. 8-day composites) could be used to reveal the more detailed structure in spatial and temporal distribution of phytoplankton blooms. Use of different bloom thresholds may also provide more robust analyses of the presence of phytoplankton blooms relative to the frontal location.

As the main focus of this study was to understand the spatial and temporal variability in phytoplankton productivity with respect to the variation in the frontal position, it is recommended to investigate whether the fluctuation in the strength of the front influences the Chl-a distribution along and across the front. A strong gradient may induce increased velocity of the Southland Current which could influence the water properties over the Mernoo Saddle and Chatham Rise (Chiswell, 1996; Hopkins et al., 2010). This water may contain high concentrations of micronutrients from the coastal and inshore waters of the front to support phytoplankton growth.

5.3 Conclusions

The Subtropical Front to the south and east of the South Island of New Zealand is characterized as an area of high phytoplankton productivity. This study proposed that the variation in the spatial and seasonal distribution of Chl-a concentration might follow the variation in the position of the front. The areas of higher Chl-a concentration were observed at the lower latitudes of the STF (< 45 °S), coinciding with intense meandering of the frontal position. This region is subject to greater mixing and nutrient transport between the two physically and chemically different water masses due to interaction with topographic features, potentially triggering the rapid growth of phytoplankton. The Chl-a concentration typically decreased with increasing distance from the front but it consistently increased shoreward off
the east coast of the South Island. This study found the near-shore waters along the east coast of the South Island may be referred to as Case 2 waters, which are highly affected by sediment contamination, and confirmed that analysis of remote sensing images provided a robust analysis of inter-annual and seasonal variation in phytoplankton distribution in open ocean water (> 40 km from the shore).
REFERENCES


