Remote sensing of river plumes in the Canterbury Bight.

Stage II: final report

NIWA Client Report: CHC2010-048
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Appendix A: MODIS true colour imagery during periods when Lake Ellesmere was open.

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Executive Summary

Ten rivers in the Canterbury Bight, as well as Lake Ellesmere, were studied using a core, cloud-free dataset of colour satellite imagery from the NASA MODIS-Aqua sensor. Freshwater extent was measured wherever neighbouring river plumes could be distinguished from one another based on gradients in light scattering derived from the satellite data. The processed images were used to answer four key questions raised by ECan as to the fate of freshwater in the Canterbury Bight. Additionally, a ten-year record of optical satellite data was used to derive a monthly climatology of phytoplankton and sea surface temperature dynamics in the Canterbury Bight.

Each of the questions raised by ECan was addressed using satellite data from the MODIS-Aqua sensor. The major findings were:

- River plumes are frequently visible in satellite imagery of the Canterbury Bight.

- The plume fronts were generally constrained to within 6 km of the coastline. Whether the Southland Current or tidal currents are responsible for limiting offshore excursion could not be explored in this study.

- The combined river plumes travelled a median distance of 62 ± 23 km northwards along the shoreline and eastwards around Banks Peninsula.

- Of the ten rivers studied here, the Waitaki, Ashburton and Pareora Rivers were seen to undertake the greatest northward excursions. However, there were many instances in the core dataset of 115 images where individual river plumes could not be distinguished from one another. In situ corroborating data is therefore required to support these satellite observations.

- Under high flow situations, the Rakaia River plume frequently merged with resuspended sediments and/or water from the Ashburton River and Lake Ellesmere and could, therefore, not be distinguished.

- Water flowing from Lake Ellesmere was more easily traced than river plume water because of its characteristic yellow/green colour, reflecting hyper-eutrophic conditions in this lake as well as high suspended sediment content. Lake water was observed up to 95 km northeast of the lake opening, up to 33 km off-shore and up to 27 km to the southwest. The dominant pattern of lake water dispersal was north-eastwards transport along the shoreline, around Banks Peninsula and into Pegasus Bay.

- Akaroa Harbour was potentially affected by river water from the Canterbury Bight on 55 % of the days in this analysis. Whether river plume water entered the harbour could not be

discerned using MODIS imagery. Indeed, the harbour itself acted as a source of suspended material on some occasions.

- Water from rivers in the Canterbury Bight could be detected as far north-east as Pegasus Bay in 40 % of the days included in this analysis.

- Phytoplankton blooms originating off-shore and/or in the Southland Current typically interfere with near-shore water during the spring- and summer (November to February). This makes the near-shore and off-shore waters difficult to distinguish.

Further work is desirable to improve and extend these results. Hydrodynamic modelling of the coastal region would be very useful in furthering our understanding of freshwater dispersal. Oceanographic measurements (e.g., salinity, mixing and chlorophyll fluorescence and turbidity) would improve validation of remotely-sensed optical signatures and modelled ocean dynamics. More detailed consideration of river flow history and watershed characteristics would enhance understanding of their relationships with river plume metrics and the impact of land run-off on ecologically sensitive coastal areas in the Canterbury Bight.

1. Introduction

Environment Canterbury is concerned that land-use intensification in the Canterbury region, especially from dairying, is increasing mass-load of nutrients, sediments and other contaminants to the Canterbury Bight, with unknown consequences on coastal water quality. ECan, therefore, sought information on coastal water circulation and mixing processes in the Bight that affect dispersion of river-borne materials, with particular reference to conditions under which ecologically sensitive areas, such as Akaroa Harbour and other sites around the Banks Peninsula, are likely to be adversely affected by river plumes.

The goal of this project is to use satellite imagery to map the extent and development in time of river plumes in the Canterbury Bight. This is the final project report, which builds upon the results given in Schwarz et al. (2008, 2009). The study is based on a core dataset of satellite imagery of the Canterbury Bight under minor cloud cover conditions. This dataset was analysed to address five specific questions raised by ECan.

1.1. Objectives of the project

Information required by Environment Canterbury

1. *Does the freshwater that flows into the Canterbury Bight from the rivers, streams, creeks and stockwater races/drains get trapped nearshore in the Bight by the Southland Current?*

2. *As much detail as possible on the mixing and dispersal (distances alongshore and offshore, directions of the plume) of the water that flows into the Canterbury Bight from the Rakaia and Ashburton Rivers and, if the budget allows, also the Rangitata, Orari and Opihi Rivers. Any information that could be provided on the plumes from the larger streams between the Ashburton River mouth and Lake Ellesmere would be useful.*

3. *As much detail as possible on the mixing and dispersal (distances alongshore and offshore, directions of the plume) of the water that flows out of Lakes Ellesmere and Forsyth when they are opened.*

4. *How often and under which conditions is the water quality of the southern bays of Banks Peninsula, Akaroa Harbour, northern Banks Peninsula and Pegasus Bay affected by the freshwater inputs to the Canterbury Bight?*

5. *Provide any available information on algal blooms in the Canterbury Bight, including size, frequency and time of year of these blooms.*

1.2. Structure of the final report

The datasets and methods used in this work are described briefly in Sections 2 and 3. Subsequent sections address each objective in turn: Section 4 addresses Objective 1; Section 5 addresses Objective 2 by describing the behaviour of plumes from the ten major rivers draining into the Canterbury Bight; in Section 6, all available satellite imagery from times when Lake Ellesmere was open are illustrated and analysed to address Objective 3; Section 7 summarises the interactions between river plumes and ecologically sensitive areas (Objective 4); and Section 8 gives an analysis of phytoplankton blooms and sea surface temperature in the Canterbury Bight over the past seven years (Objective 5). Satellite data for Objective 3 are illustrated in Appendix A. The core dataset (115) images and their derived products are given in Appendix B.

2. Datasets and methods

2.1. Satellite data

The two main sources of satellite imagery chosen for this study (Schwarz et al., 2008, 2009) were Landsat (Landsat satellites 1 to 7, administered by the United States Geological Survey, USGS) and MODIS (MOderate-resolution Imaging Spectrometer, on the Aqua satellite, operated by the National Aeronautics & Space Administration, NASA). Examples of Landsat scenes were chosen to coincide with times when Lake Ellesmere was open. The Landsat images were used to corroborate the features observed in MODIS imagery by visually comparing data from Landsat, which has excellent spatial resolution but low response from all but the brightest water bodies, with data from the MODIS, which is very responsive to the low signals from water, but has coarser spatial resolution. SeaWiFs 9km resolution data were used to compile a long time series of phytoplankton concentrations in Canterbury Bight waters.

True colour images were generated for the entire MODIS-Aqua dataset at 1 km resolution. These images were supplied to ECan as a useful resource illustrating near-shore sediment features. The true colour images were used to select cloud-free days for further data analysis.

Three processing steps were applied to the satellite-sensed radiance data:

a. Optical and biogeochemical products were derived using NASA algorithms, specifically calcite, chlorophyll, particulate backscatter at 555 nm, phytoplankton absorption at 488 nm, dissolved matter and detrital absorption at 412 nm, water-leaving radiance at 551 nm and daytime sea surface temperature. Upon closer examination, only the calcite and chlorophyll algorithms were found to function robustly near-shore, whereas the others suffered from invalid data points (pixels too bright for the algorithm) of water adjacent to the coast;

b. These satellite-derived variables (often referred to as products) were plotted onto a standard, 500 x 500 m grid (500 m avoids data loss where no direct downward-looking overpasses are available – if the sensor is looking slightly obliquely at the area of interest, then each ground pixel is larger than the best-possible 250 x 250 m);

c. Adjacent and consecutive overpasses were composited to give a single image per day with as many valid pixels as possible.

Data processing was carried out using NASA's freeware SeaDAS, with the standard processing flags for high radiance (HILT – very bright pixels which are likely to be land) and shallow water disabled.

A core dataset of all images that were mainly cloud-free across the entire Bight was compiled. The direction of transport was inferred from true colour, calcite and chlorophyll core images. Distances travelled were also calculated by manually tracing the plume path, using the SeaDAS software. Cases for which no clear river plume was observed, or for which neighbouring plumes could not be distinguished from one another, were excluded from further analysis.

Automated river plume tracking was attempted using the chlorophyll and calcite products for each of the ten major rivers – Rakaia, Ashburton, Rangitata, Orari, Opihi, Pareora, Otaio, Makikihi, Waihao and Waitaki. River flow data were available for all except the Makikihi River. River flow was taken as an indicator for the loading of terrigenous material in each river. Mass flow of sediments increases as a strong power-law function of flow, so that river plumes often correspond to hydrograph events. The chlorophyll product was taken as an indicator for both phytoplankton and absorbent dissolved substances, and the calcite product was chosen as a potential means of distinguishing recently arrived riverine sediments from re-suspended coastal sediments (Schwarz et al., 2009). Automated tracking was hindered by the tendency of the river plumes to merge along the coast (discussed further in section 9.2). Plume metrics reported here were, therefore, measured subjectively, case by case,, as described in Section 3.

Chlorophyll, calcite and sea surface temperature products from MODIS were used to examine the plumes occasionally dispersed from Lake Ellesmere. The absence of direct, daily measures of river flow associated with the lake plume meant that there was no means to identify a threshold value of, for example, chlorophyll concentration, which could be used to automatically define the lake plume. Thus, individual satellite images were examined to determine a range of thresholds for which temperature, true colour, chlorophyll and calcite images were in broad visual agreement. Plume statistics were then calculated to yield minimum, maximum, median and standard deviations of plume area (and associated extent off-shore) for each cloud-free MODIS image. That is, if the plume appeared realistic and in agreement with a visual assessment of the true colour image on three of the four different products, then the plume metrics were computed for all products.

A third satellite dataset was chosen to augment the analysis of long-term variability of chlorophyll concentrations in the Canterbury Bight (Objective 5 Section 8.2). NASA's Sea-viewing, WIde Field-of-view Sensor (SeaWiFS) provides the longest time series of good quality chlorophyll concentrations, at a maximum spatial resolution of 1 km. The data shown here span the period August 1997 to February 2009, and comprise weekly composites of chlorophyll concentration at 9 km resolution, obtained directly from NASA (*http://reason.gsfc.nasa.gov/OPS/Giovanni/ocean.swf8D.2.shtml).*

Future work could include the estimation of outflow rates using lake and tidal levels, together with river hydraulic equations. Such calculations were beyond the scope of this report.

2.2. Corroboration of MODIS data using Landsat

The Landsat satellite series has been operated for over 30 years by the National Ocean & Atmosphere Administration (NOAA) and the United States Geological Survey (USGS). These data were made free to the public in late 2008 / early 2009. The Enhanced Thematic Mapper (ETM) sensors employ very broad spectral channels, but with very high spatial resolution of up to 30 m. These sensors were designed for observations of land and, hence, lack the sensitivity required for measuring water-leaving radiance over open water. However, the high concentrations of suspended sediments found in the Canterbury Bight river plumes or re-suspended from shallow coastal beds are visible to the ETM because they increase backscatter of water-reflected light. Landsat data are used here to verify that features identified as river plumes in the coarser resolution MODIS imagery are, indeed, river plumes. During the MODIS mission period, the current Landsat sensor developed a problem with its scan-line corrector onboard the satellite. This means that some overlapping of adjacent scan-lines, or gaps between scan-lines, is found in all images since 2003. An additional problem with comparing the MODIS and ETM sensors is the great spectral breadth of the ETM channels, with only two channels covering the visible spectral range and one in the near infra-red. This makes it impossible to develop generic algorithms for deriving concentrations of suspended particulates in the water. The ETM data are, therefore, used here for a visual comparison with the MODIS data. Landsat-7 ETM data coincided with cloud-free MODIS images on 7 dates during 2006/7: 26th January 2006, 11th February 2006, 18th May 2006, 25th October 2006, 10th November 2006, 18th March 2007 and 19th April 2007. The imagery for each date is discussed separately below.

2.2.1. 26th January, 2006

Figure 1 shows true colour images from MODIS-Aqua and Landsat-7 ETM on 26th January, 2006. The main features in the near-shore zone are visible in both images:

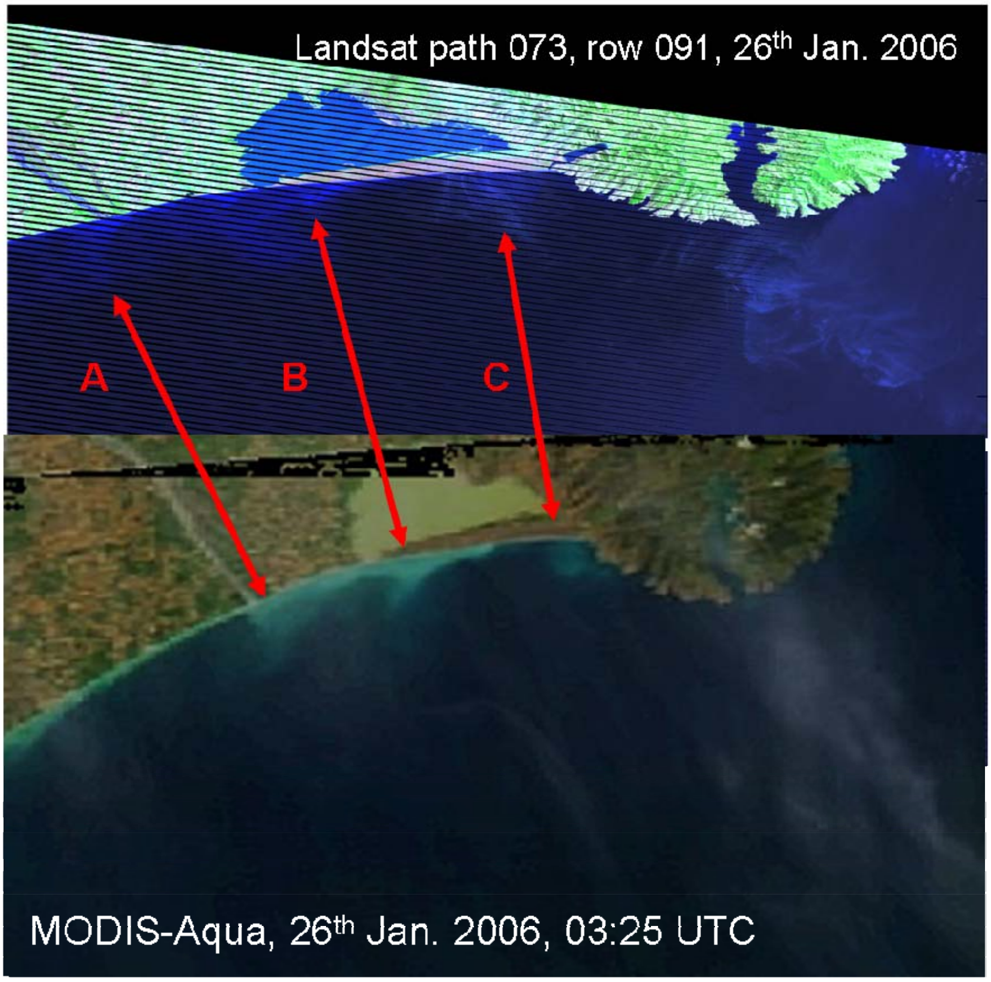

Figure 1: Comparison of MODIS and Landsat ETM true colour images from 26th January, 2006.

Feature A: Rakaia River plume. The ETM data resolve the breadth of the braided river mouth, with two clear blue river sections proceeding from land to sea. In the MODIS data, the river is barely identifiable, and the plume appears as a single bright patch.

Feature B: Along-shore sediment transport adjacent to Lake Ellesmere. 26th January 2006 is not recorded as an open period for Lake Ellesmere, hence we conclude that this bright feature in the MODIS data simply represents resuspension and transport of sediments by wave and/or tidal action. In both images, a bright patch is visible close to the shore, sweeping off-shore. In the ETM image, it is clear that the sediments are swept eastwards as they proceed off-shore.

Feature C : Narrow plumes of sediment proceeding directly off-shore from the eastern end of Lake Ellesmere. As for Feature B, it must be assumed that these plumes represent re-suspension, since they do not appear connected to nearby Lake Forsyth.

2.2.2. 11th February, 2006

On 11th February 2006 (Figure 2), notable features were visible to different degrees in the Landsat and MODIS imagery. Features D, E and F are all swirls of high sediment loading with fine detail clear in the Landsat image, but a single, blurred feature in the MODIS image.

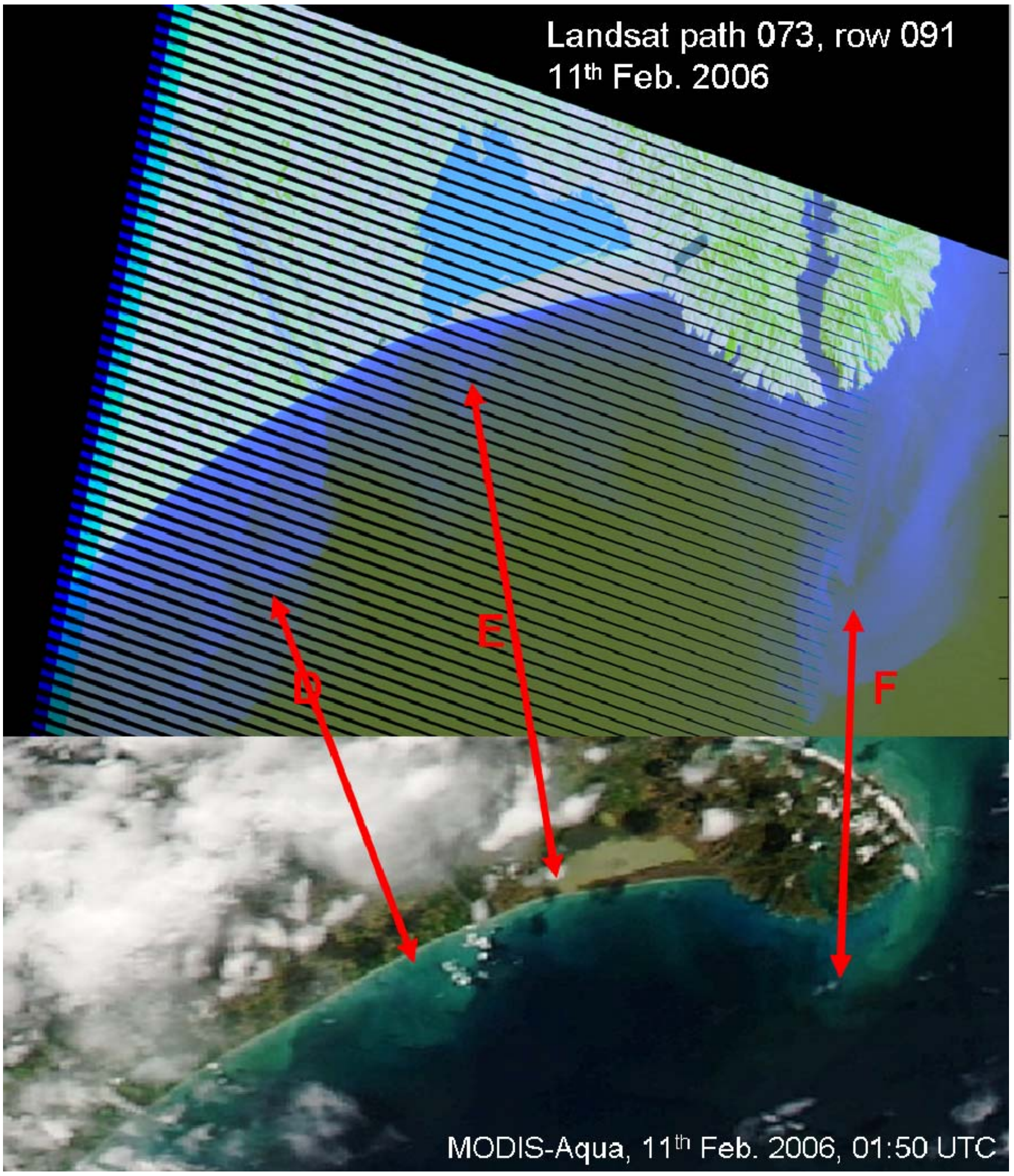

Figure 2: Comparison of MODIS and Landsat ETM true colour images from 11th February, 2006.

2.2.3. 25th October, 2006

On 25th October 2006 (Figure 3), the Landsat sensor picks up a small plume proceeding from the Rakaia River which is not distinctive in the MODIS image (Feature G). This may reflect rapid variability in the near-shore sediment dynamics, since the Landsat image was taken several hours before the MODIS image. In contrast, Feature H - a loop of sediment off-shore from Lake Ellesmere - is visible in both images. Note that Lake Forsyth is clearly visible in the Landsat imagery, but too blurred to be made out in the MODIS images.

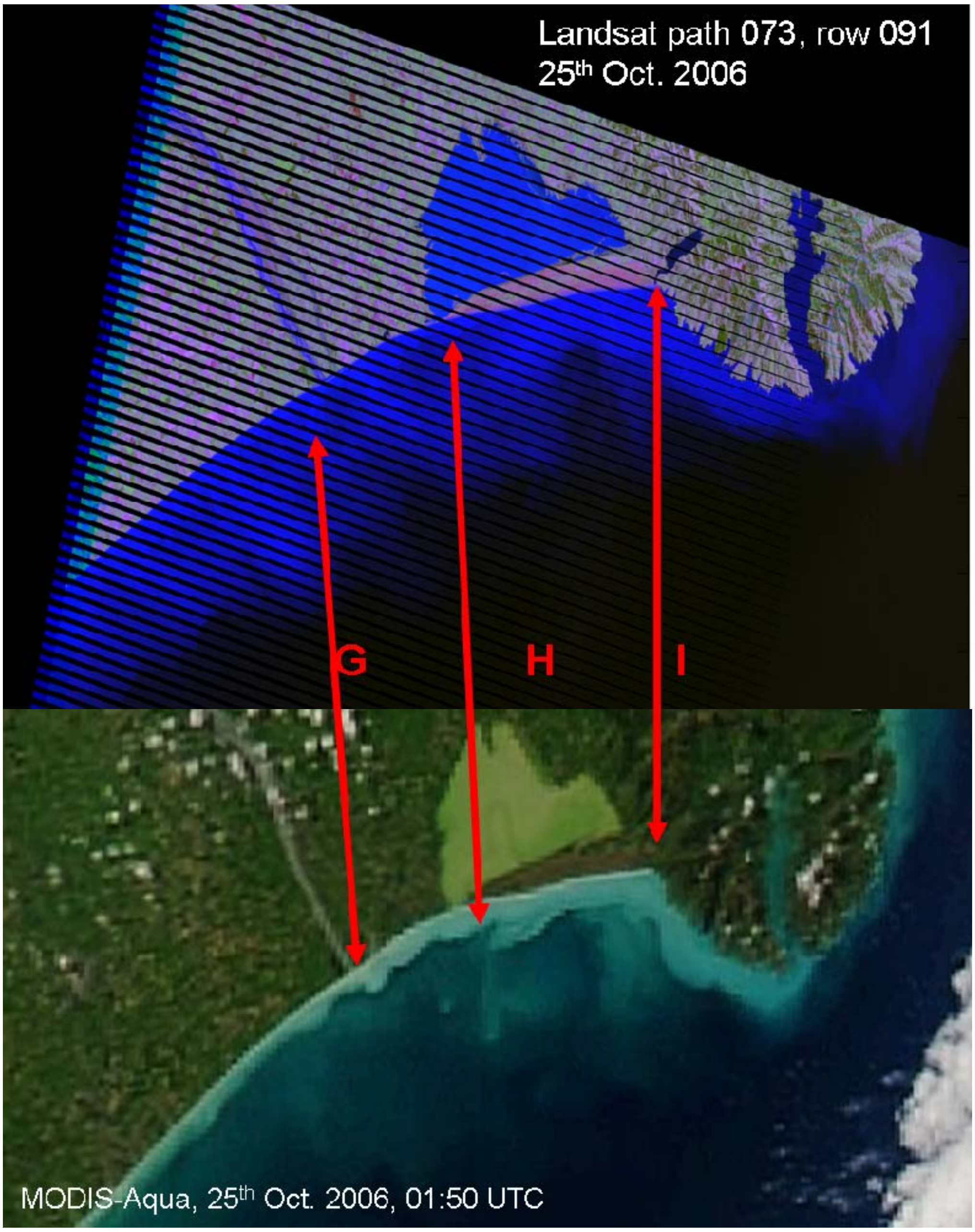

Figure 3: **Comparison of MODIS and Landsat ETM true colour images from 25th October, 2006.**

2.2.4. 10th November, 2006

On 10th November 2006 (Figure 4), the mouth of Lake Ellesmere was open. Feature J is the plume of green-brown water proceeding from the lake. Feature J is distinct in the MODIS image, but barely detectable in the LandSat image. This pair of images highlights dramatically the different radiometric performance of the two satellite sensors and their suitability for detecting near-shore features: Landsat has coarse, insensitive bands which are well-suited to mapping features on the bright, strongly reflecting land surfaces, but do not detect colour changes within the water effectively. In contrast, the water from Lake Ellesmere was generally a distinctive, bright yellow/green colour in the MODIS imagery.

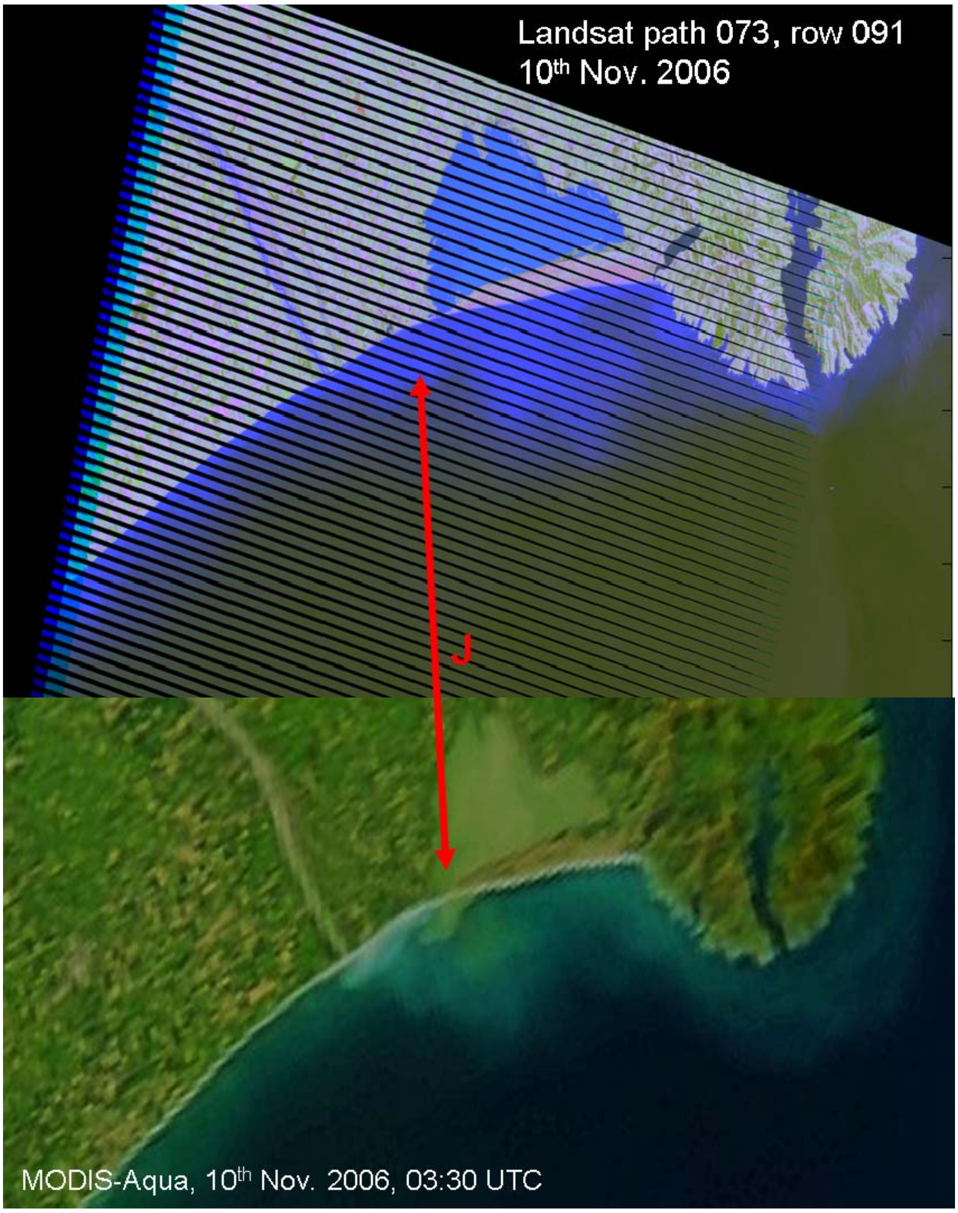

Figure 4: **Comparison of MODIS and Landsat ETM true colour images from 10th November, 2006.**

2.2.5. 18th March, 2007

On 18th March 2007 (Figure 5), the advantage of Landsat's morning overpass time is again clear – by the time the Aqua satellite reached New Zealand, the Bight was clouding over. Feature K shows a loop of sediment which is again well-resolved in the Landsat image, and present but blurred in the MODIS image. The more diffuse Feature L is, however, equally distinctive for both sensors.

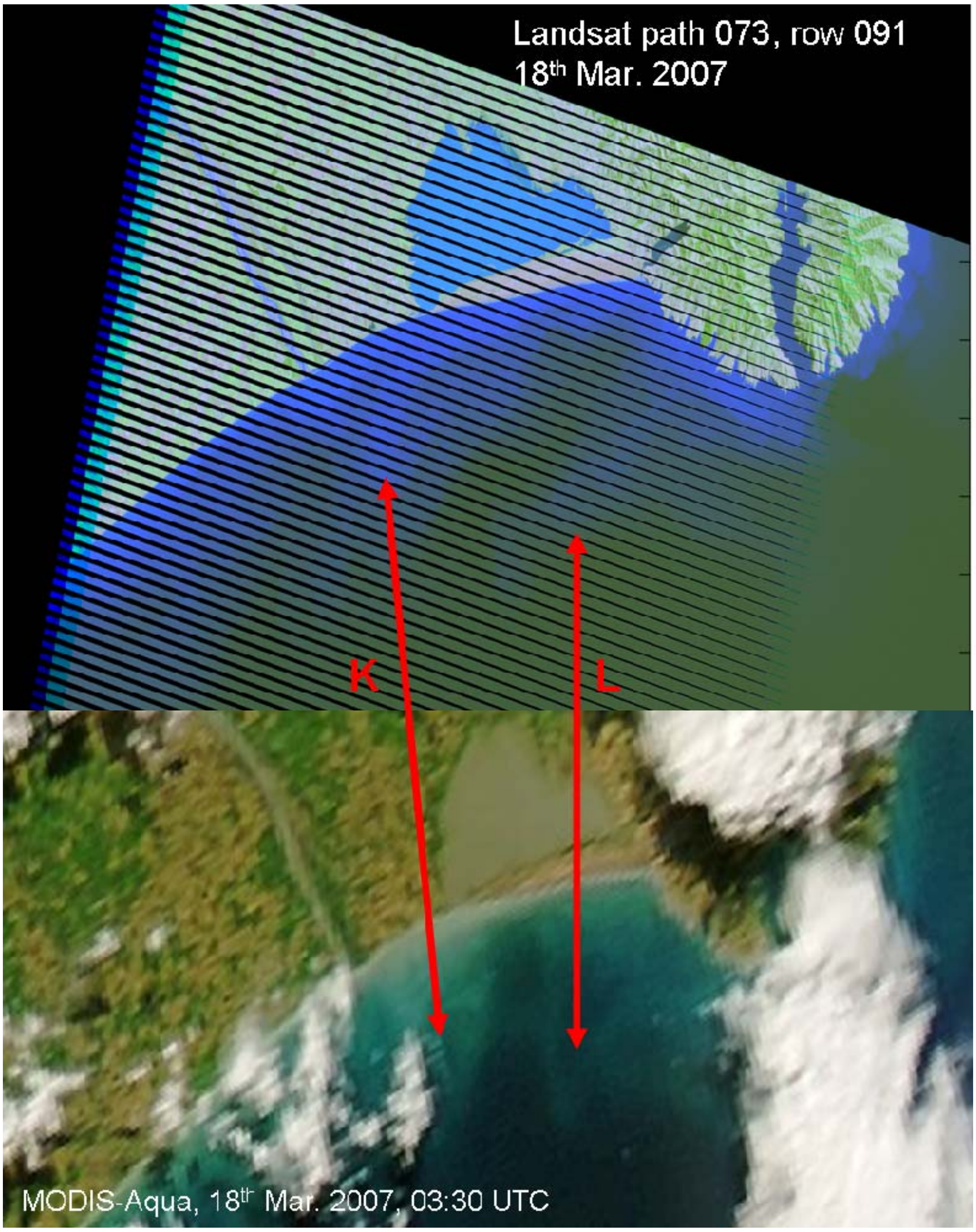

Figure 5: Comparison of MODIS and Landsat ETM true colour images from 18th March, 2007.

2.2.6. 19th April, 2007

In the final pair of Landsat:MODIS images, from 19th April 2007 (Figure 6), a change in brightness detected off-shore from Akaroa Harbour in the Landsat image is well-resolved in the MODIS image, with greater spatial detail apparent in the MODIS data, presumably owing to its superior radiometric sensitivity.

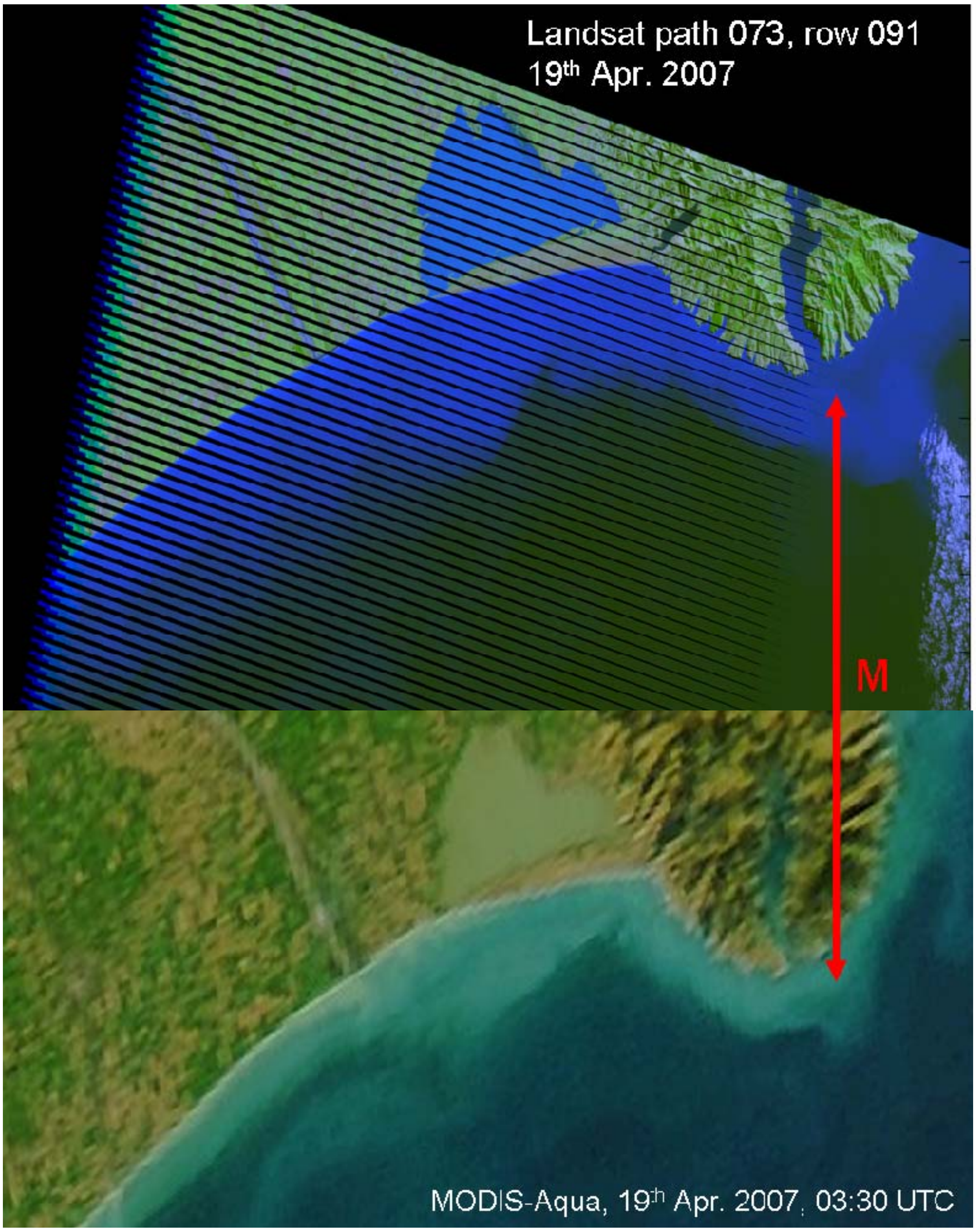

Figure 6: **Comparison of MODIS and Landsat ETM true colour images from 19th April, 2007.**

2.3. Summary of MODIS:Landsat comparison

With a spatial resolution of 30 – 80 m, the Landsat sensors are clearly capable of detecting much finer detail in bright waters than the MODIS sensors. On the other hand, the increased spectral resolution and radiometric sensitivity of the MODIS sensor provides more information on water quality – distinguishing between chlorophyll- and sediment- laden waters, for example (e.g. Figure 4). The majority of features appear blurred but detectable in the MODIS imagery, and it is assumed for the remainder of the study that MODIS successfully detects coastal water features at the spatial scales relevant to river plumes in the Canterbury Bight.

3. Core Dataset

The core dataset of MODIS-Aqua images was selected based on < 10 % cloud cover for the whole Canterbury Bight area. This enabled cases where adjacent river plumes merged together to be recognised, as well as preventing the plume metrics of partially glimpsed river features from biasing results. Coverage statistics for this dataset are summarised in Table 1. October was the clearest month for satellite imagery, spring the best season and 2007/2008 the clearest years.

Table 1: Coverage statistics (< 10 % cloud) for the core MODIS-Aqua dataset.

Monthly coverage		**Seasonal coverage**		**Yearly coverage**	
December	8	Summer	25	2002	7
January	4			2003	15
February	13			2004	13
March	14	Autumn	34	2005	15
April	13			2006	14
May	7			2007	22
June	2	Winter	12	2008	22
July	1			2009	7
August	9				
September	14	Spring	44		
October	22				
November	8				

River plume metrics were measured, where possible, in each of the core images for each of the ten rivers draining into the Bight, from the Rakaia in the north, to the Waitaki in the south. The rivers are shown in Figure 7, together with their calcite product signatures (most of the rivers had a clear calcite signal) as an example of their plume extents. In Figure 7, land and low calcite values are masked in black. The yellow meandering band of elevated calcite values off-shore between the Opihi and Rakaia Rivers is interpreted here as re-suspended coastal sediments, and this type of signal was classified as not belonging to any of the river plumes.

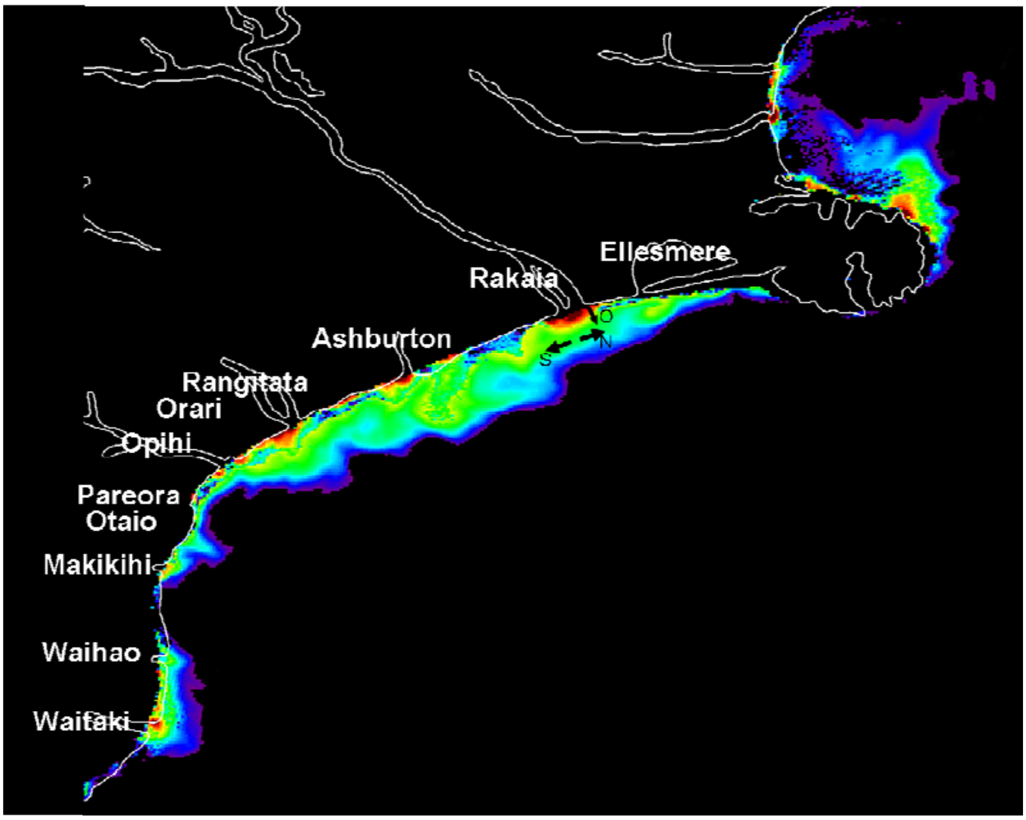

Figure 7: Demonstration of the measurement of river plume extent using the calcite algorithm.

Plume metrics were recorded only when calcite values enabled neighbouring river plumes to be distinguished from one another. The automated tracking algorithm failed to identify useful thresholds, so this step was completed subjectively, one image at a time. The metrics recorded were northward (N) and southward (S) extent parallel to the shore, and distance off-shore (O) measured perpendicular to the shore at the broadest part of the plume.

4. Objective 1: Trapping of freshwater near-shore in the Canterbury Bight

Objective 1: *Does the freshwater that flows into the Canterbury Bight from the rivers, streams, creeks and stockwater race/drains get trapped nearshore in the Bight by the Southland Current?*

River plumes in the Canterbury Bight are clearly visible for at least some rivers in each of the core dataset based on MODIS true colour images. The plumes form coherent elongated or pooled structures adjacent to the river mouths. Plume dispersal tendencies are summarised in Table 2.

Table 2: River plume northward (N), southward (S) and off-shore (O) extent, measured using the calcite product, subjectively, with a varying plume cut-off threshold of between 0.01 and 0.06 (arbitrary units, mol Calcite per litre). Plume extent was only recorded where neighbouring plumes could be distinguished from one another. The number of plume metrics recorded in each case is denoted by 'n'.

River	Minimum plume extent (km)	Maximum plume extent (km)	Northward extent (median ± standard dev.) (km)	Southward extent (median ± standard dev.) (km)	Off-shore extent (median ± standard dev.) (km)
Rakaia	N: 1.7 S: 1.6 O: 1.5	N: 62 S: 23 O: 23	9.7 ± 12.5 n = 47	10.6 ± 6.4 n = 44	6.4 ± 5.0 n = 71
Ashburton	N: 2.1 S: 2.6 O: 1.6	N: 29 S: 22 O: 16	13.1 ± 7.1 n = 48	7.0 ± 4.9 n = 44	4.4 ± 3.1 n=63
Rangitata	N: 1.8 S: 1.9 O: 1.3	N: 24 S: 25 O: 48	9.1 ± 6.1 n = 41	6.1 ± 4.9 n = 32	4.4 ± 6.2 n = 62
Orari	N: 1.8 S: 1.1 O: 1.0	N: 11 S: 10 O: 7.0	4.3 ± 2.9 n = 16	3.4 ± 2.9 n = 17	3.0 ± 1.5 n = 18
Opihi	N: 2.6 S: 3.2 O: 1.0	N: 28 S: 14 O: 10	5.2 ± 4.9 n = 24	6.8 ± 2 n = 17	5.6 ± 2.4 n = 32
Pareora	N: 2.2 S: 2.7 O: 0.8	N: 20 S: 7.0 O: 6.0	10.1 ± 5.5 n = 25	5.1 ± 2.0 n = 4	3.5 ± 3.6 n = 30
Otaio	N: 3.5 S: 6.3 O: 1.9	N: 8.0 S: 7.0 O: 6.0	4.9 ± 1.4 n = 9	6.7 ± 0. n = 3	2.7 ± 1.2 n = 12
Makikihi	N: 3. O: 0.8	N: 15 S: 18 O: 17	5.9 ± 3.5 n = 14	6.8 ± 4.4 n = 11	2.8 ± 4.5 n= 19
Waihao	N: 2.1 S: 2.5 O: 1.9	N: 1 S: 18 O: 19	9.3 ± 3 n = 22	7.9 ± 4.7 n = 13	4.1 ± 4.2 n = 26
Waitaki	N: 2.5 S: 1.8 O: 1.4	N: 51 S: 20 O: 38	12.9 ± 7. n = 71	9.0 ± 5.7 n = 17	5.0 ± 5.8 n = 77

The median offshore extent of the plumes was below 10 km for each of the ten major rivers studied. Maximal values of between 6 km (Otaio and Pareora) and 48 km (Rangitata) were recorded, but the standard deviation for all rivers was low at < 6.5 km. From the core dataset, it is clear that the river plumes are, indeed, constrained to within 10 km of the coastline.

Offshore plume extent was found to be significantly correlated with river flow for the Waitaki River, with a correlation coefficient of 0.263 ($p = 0.02$, $N = 77$). That is, plumes from the Waitaki tend to extend further offshore at higher flow. No significant correlations were found for the other rivers.

5. Objective 2: Behaviour of plumes from the ten major rivers draining into the Canterbury Bight

Objective 2: *As much detail as possible on the mixing and dispersal (distances alongshore and offshore, directions of the plume) of the water that flows into the Canterbury Bight from the Rakaia and Ashburton Rivers and, if the budget allows, also the Rangitata, Orari and Opihi Rivers. Any information that could be provided on the plumes from the larger streams between the Ashburton River mouth and Lake Ellesmere would be useful.*

5.1. Northward and southward long-shore plume extent

The distances travelled along-shore by plumes from each of the ten major rivers are reported in Table 2. Note that under extremely turbid conditions, the river plumes merged together and could not be distinguished from one another. This applied particularly to the Rakaia River, which often could not be distinguished from the Ashburton River plume travelling northwards, from sediments flowing from Lake Ellesmere or from resuspended sediments at the north end of the Bight. These distances are, therefore, conservative estimates of the dispersal paths of river water, with a potential bias to shorter plume paths.

The dominant direction of flow at the river mouths, for the core dataset, was northwards (39 out of 115 images). Maximal northwards travel was recorded for the Rakaia (62 km) and Waitaki (51 km) rivers. Only the Otaio River had a maximum extent of less than 10 km. Median northward values ranged from 4.3 km (Orari) to 13.1 km (Ashburton). The standard deviation about the median was greater than 50 % for most of the rivers, indicating strong variability. Maximum southerly flow was greatest for the Rakaia (34 km) and Rangitata (25 km) rivers. Median southerly extents ranged from 3.4 km (Orari) to 10.6 km (Rakaia), again with strong variability (standard deviation exceeds 50 % for all rivers except the Otaio).

To mitigate the problem of plumes merging together under high flow or turbid conditions, the 'bulk signature' of merged river water was tracked northwards and its maximum extent recorded separately, regardless of whether individual plumes could be distinguished. This bulk signature probably comprises river water and coastal water, with resuspended sediments and dissolved organic material. The minimum and maximum extents of this signature were 24 and 141 km northwards, with a median value of 62 ± 23 km. The strongest predictor of the northerly extent of this bulk signature was the Rakaia River flow (multiple regression), however this relationship between the northerly extent of the signature and the daily flow from all rivers not statistically significant.

To put these distances into context, the distance between mouths of each of the ten rivers studied are listed in Table 3, together with the median northerly plume extent of the southern river in each pair (from Table 2). The median plume extents are typically less than the distance between river mouths. This implies that our difficulty in distinguishing adjacent river plumes was due to signals from wave-resuspended sediments, from streams plumes not studied here, and/or from the lack of an algorithm specifically adapted to the optical properties of sediments found in the Canterbury Bight.

Table 3: Distances between adjacent rivers compared to the median northward plume extents for the core dataset.

River names	Distance between rivers (km)	Median northerly plume extent of the southernmost of these two rivers (km)
Waitaki to Waihao	20	12.9 ± 7.8
Waihao to Makikihi	23	9.3 ± 3.9
Makikihi to Otaio	10	5.9 ± 3.5
Otaio to Pareora	5	4.9 ± 1.4
Pareora to Opihi	18	10.1 ± 5.5
Opihi to Orari	8	5.2 ± 4.9
Orari to Rangitata	10	4.3 ± 2.9
Rangitata to Ashburton	26	9.1 ± 6.1
Ashburton to Rakaia	36	13.1 ± 7.1
Rakaia to Lake Ellesmere	15	9.7 ± 12.5
Lake Ellesmere to Akaroa Harbour	47	See Section 7.

5.2. Relationship between plume extent and river flow

Statistically significant relationships between plume extent and river flow were found in only two cases: the northerly extent of the Opihi River was moderately correlated with the Opihi flow rate ($r = 0.41$, $p = 0.045$, $N = 24$); and the northerly extent of the Ashburton River was weakly correlated with the Ashburton flow rate ($r = 0.228$, $p = 0.0476$, $N = 76$).

6. Objective 3: Lakes Forsyth and Ellesmere

Objective 3: *As much detail as possible on the mixing and dispersal (distances alongshore and offshore, directions of the plume) of the water that flows out of Lakes Ellesmere and Forsyth when they are opened.*

Lake Forsyth plumes could not be studied because there were no cloud-free images when this lake mouth was open.

Cloud-free MODIS imagery was available on 22 occasions when Lake Ellesmere was open. The Lake Ellesmere outflow was generally bright green compared to surrounding waters, which were either pale blue/brown (sediments) or blue (clearer coastal waters). On three occasions, no clear plume was detected, either because the plume was overwhelmed (optically) by northward-flowing river sediments (25th July, 2007, JD 206), or because the plume was restricted too closely to the shoreline, and was masked out by the satellite's atmospheric correction algorithm, which is sensitive to very bright pixels and to coastal aerosols (10th November, 2003, JD 314); in this case, the plume dispersal pattern was discernable in the true colour image, but no area statistics could be derived. For one MODIS image, a phytoplankton bloom originating along Banks Peninsula appeared to interfere with any signal from Lake Ellesmere (2nd December, 2002, JD 336). For all other MODIS images, the Lake Ellesmere plumes were larger than the Rakaia and Ashburton river plumes.

Lake plume statistics are summarised in Table 4, which lists, for each MODIS image, the lake opening dates, the date of the MODIS overpass, the satellite product (chlorophyll, chl, or calcite, cal) that best displayed the plume, plume areal statistics, direction of flow and the maximum distances at which the plume was detected off-shore and along-shore. Three plume patterns were observed, listed in order of frequency:

1. The plume pools directly in front of the lake opening, with a long tail peeling north-eastward along the shore, around Banks Peninsula (11 cases).

Table 4: **Lake Ellesmere outflow summary. Plume direction: northeast (N), flow hugging the shoreline towards Banks Peninsula; south (O), pooling of the plume water just outside the lake opening; southwest (S), flow hugging the shoreline southwards.**

Lake open dates	Season	MODIS image date	Best MODIS product	Plume statistics			Plume is Warm/Cool relative to coastal waters	Plume direction	Distance off-shore	Distance along-shore
				Min. Area (km^2)	Median. Area (km^2)	Max. Area (km^2)				
30/11 14/12 2002	Su	2/12	Direction SW; plume only visible in true colour image							
	Su	9/12	chl	159	216 ± 200	530	C	O,N	4	26
13 – 29/7 2003	W	21/7	chl	-	289	-	C	N	4	54
	W	25/7	chl	371	443 ± 161	586	C	O,N	17	28
16 – 29/9 2003	Sp	18/9	chl	47	57 ± 25	94	C	O	8	13
	Sp	21/9	chl	78	123 ± 46	181	W	S,N	7	25
	Sp	25/9	chl	177	400 ± 257	962	W	O,S	18	27
31/10 – 17/11 2003	Sp	8/11	chl	-	168	-	W	O,S	14	10
	Sp	10/11	No plume detected							
29/8 – 18/9 2004	W	6/9	chl	302	357 ± 118	528	W	N	5	63
	W	7/9	cal	727	793 ± 64	855	W	O,N	11	95
8/1 – 8/2 2005	Su	27/1	cal	-	479	-	W	O	33	24
10 – 26/8 2005	W	15/8	chl	270	288 ± 62	385	C	O	6	33
	W	18/8	chl	157	163 ± 16	188	W	O	10	8
	W	20/8	chl	185	194 ± 43	263	W	O	9	10
10 - 26/8 2005	W	29/8	cal	136	273 ± 92	311	-	O	5	30
	W	1/9	No plume detected							
15/6 – 3/7 2006	W	3/7	chl	331	355 ± 62	448	C	N	7	46
16 – 30/8 2006	W	27/8	chl	-	316	-	W	N	2	64
	W	29/8	chl	81	215 ± 117	314	W	N	5	20
8 – 24/7 2007	W	25/7	No plume detected							
31/8 – 1/10 2008	Sp	31/8	chl	-	318	-	-	O, N	20	30
	Sp	17/9	Cal	197	258 ± 127	567	W	S, O	8	17
	Sp	26/9	Chl	-	46	-	C	S	7	4

2. The plume pools directly in front of the lake opening with no marked northward or southward dispersal (5 cases).

3. The plume travels southwest, sometimes close to the shore, sometimes with a change in direction to the southward (4 cases).

In Pattern 1 and 2 events, the plume water reached between 2 and 20 km off-shore at the lake opening point. In Pattern 1 events, the plume typically proceeded around Banks Peninsula, and was detected at distances of 25 to 95 km along-shore from the lake opening. Pattern 3 events were characterised by short, narrow plumes, reaching up to 27 km southwest and 33 km directly off-shore.

The daytime temperature of the lake plume water relative to the coastal water varied over time scales of days, with no clear seasonal pattern. Near-shore daytime water surface temperature appeared to be strongly affected by diurnal warming and associated wind-sheltering by Banks Peninsula, and possibly by upwelling of cool subsurface water induced by off-shore winds.

Figures 8 to 12 summarise the satellite imagery used to address this objective. For each cloud-free MODIS image, the true colour, calcite, chlorophyll and sea surface temperature are shown, along with the best-guess lake plume pattern. All dates are given in UTC. Full-page versions of the true colour images are given in Appendix B.

From this analysis, it is clear that water flowing out of Lake Ellesmere is most commonly transported north-eastwards along the shoreline, towards and around Banks Peninsula, and that the spread of water to the south is restricted to within 33 km of the coast.

7. Objective 4: Ecologically sensitive areas

Objective 4: *How often and under which conditions is the water quality of the southern bays of Banks Peninsula, Akaroa Harbour, northern Banks Peninsula and Pegasus Bay affected by the freshwater inputs to the Canterbury Bight?*

In the core dataset of 115 images, the optical signals from Canterbury Bight river plumes were detected at the ecologically sensitive areas highlighted by ECan as follows:

- Southern bays of Banks Peninsula: 92 encounters (80 %)
- Akaroa Harbour: 64 encounters (55 %)
- Northern Banks Peninsula 47 encounters (40 %)

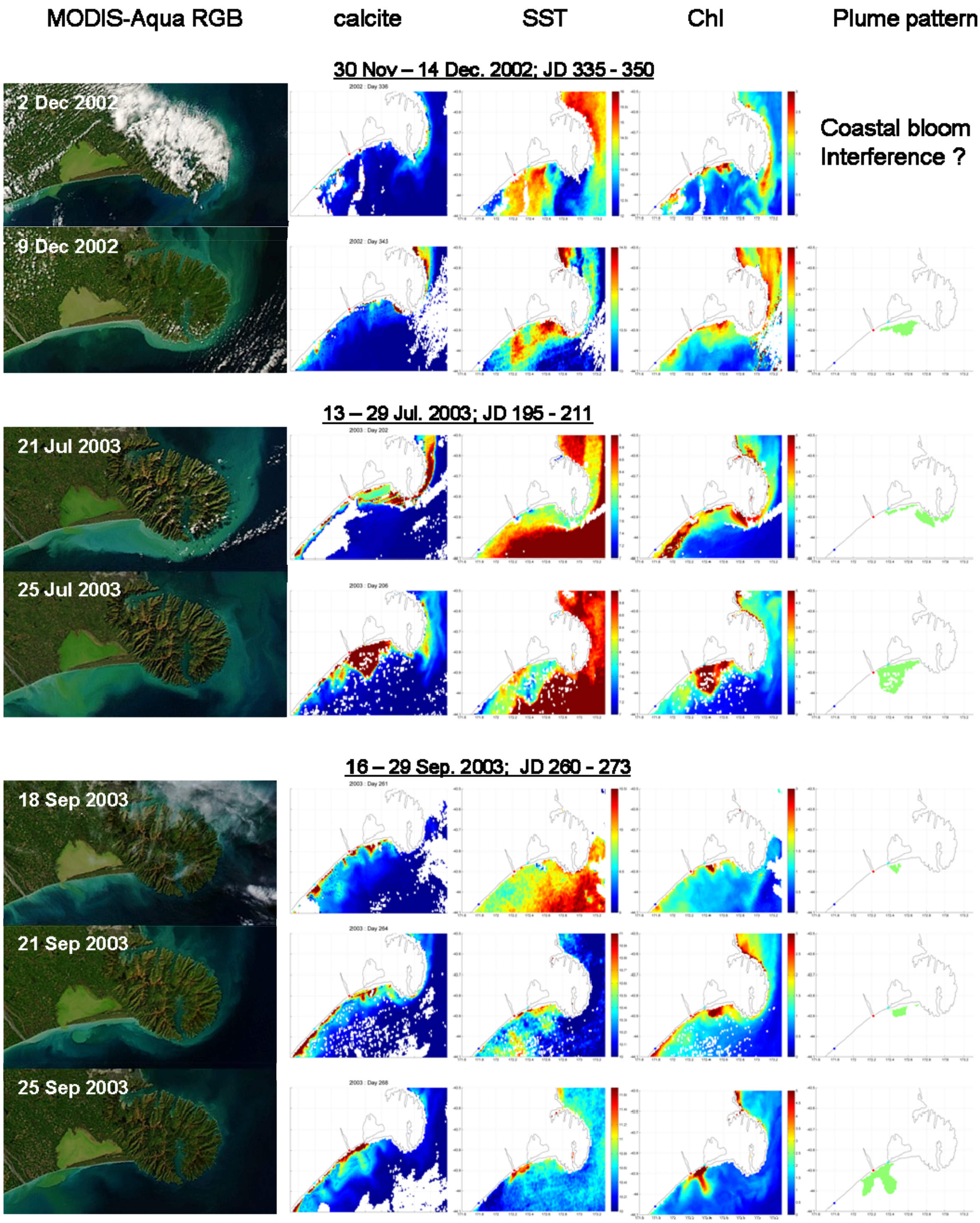

Figure 8: **MODIS imagery for Lake Ellesmere openings from 30 November – 14 December, 2002; 13 – 29 July, 2003 and 16 – 29 September, 2003.**

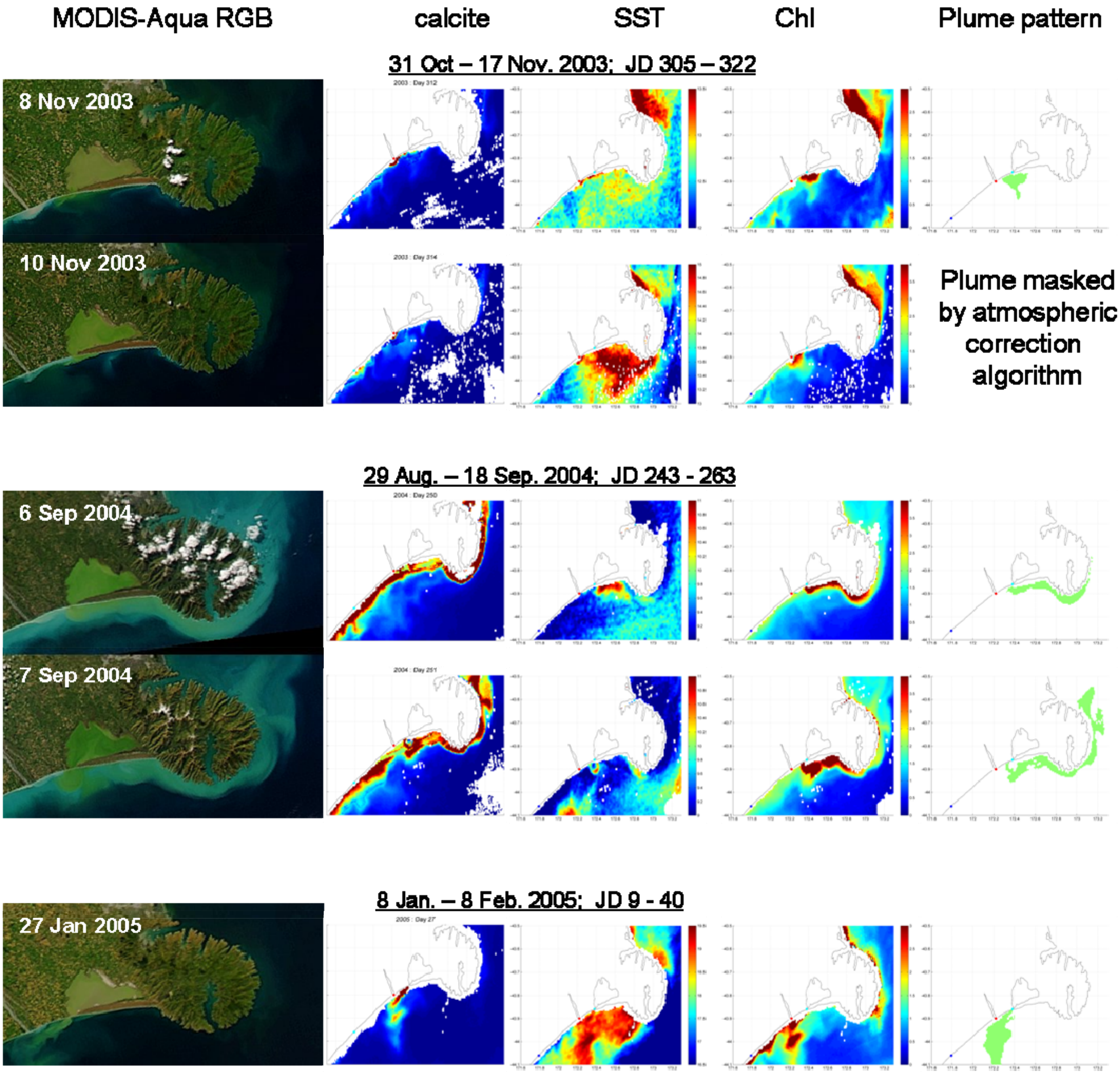

Figure 9: **MODIS imagery for Lake Ellesmere openings from 31 October – 17 November, 20003; 29 August – 18 September, 2004 and 8 January – 8 February 2005.**

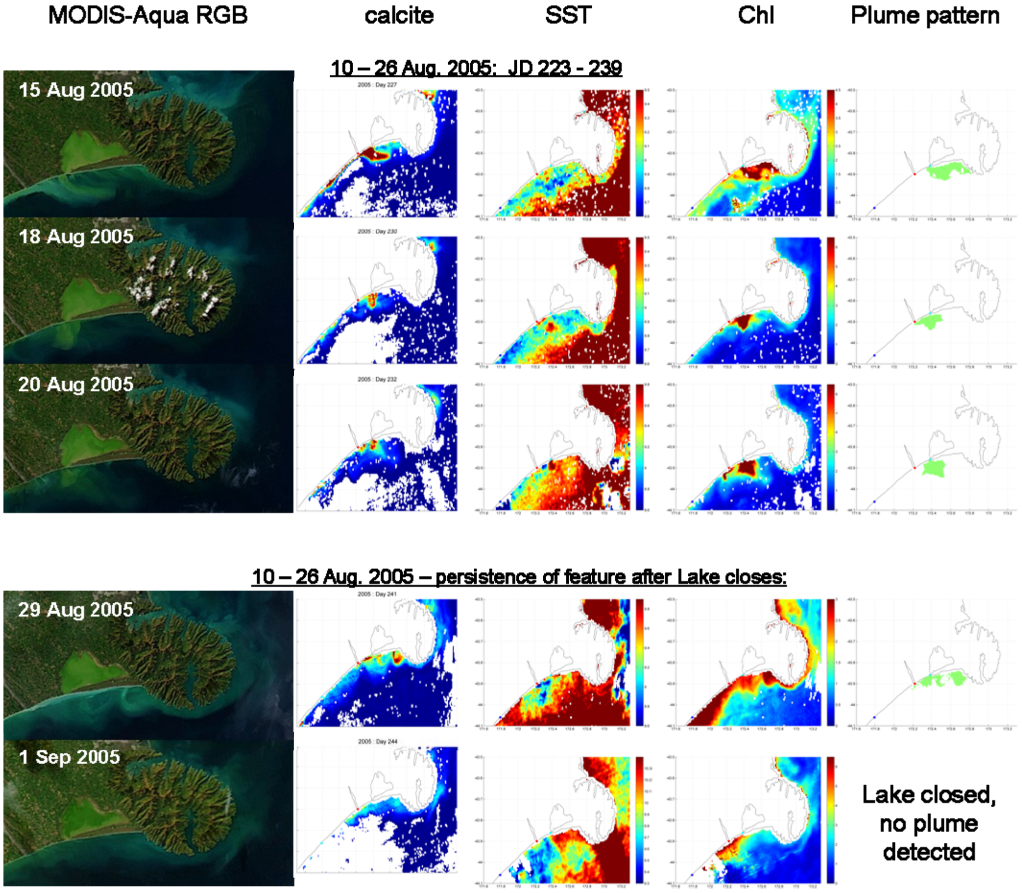

Figure 10: **MODIS imagery for Lake Ellesmere opening from 10 – 26 August, 2005, and for two images just after the lake closed. Note that no plume was detected three days after the lake closed.**

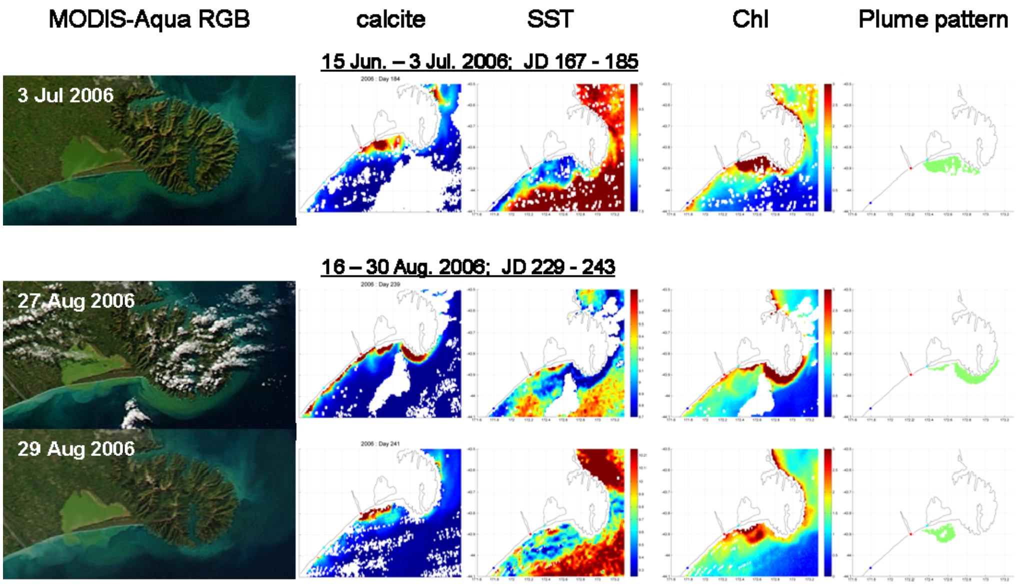

Figure 11: **MODIS imagery for Lake Ellesmere openings from 15 June – 3 July, 2006 and 16 – 30 August, 2006.**

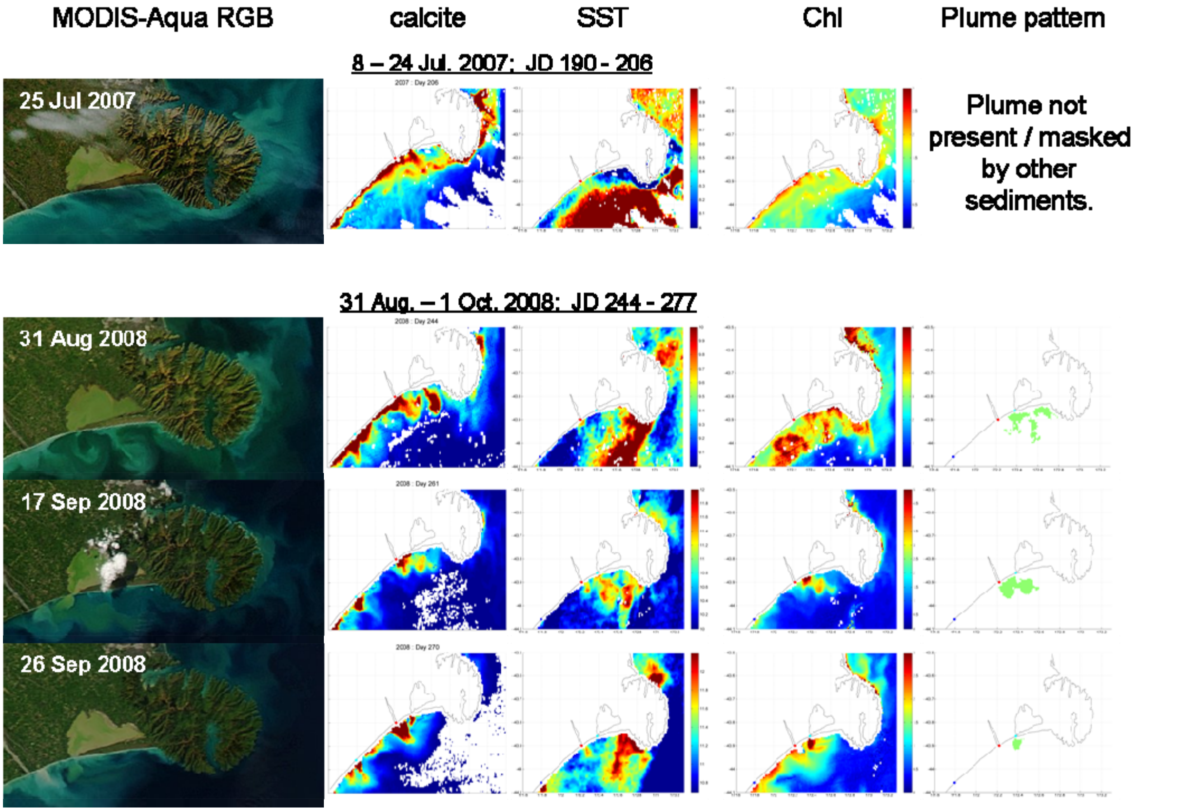

Figure 12: **MODIS imagery for Lake Ellesmere openings from 8 – 24 July, 2007 and 31 August – 1 October, 2008.**

Water which reached the north coast of Banks Peninsula always flowed on into Pegasus Bay. Of the three closest freshwater sources to the peninsula, the Rakaia River was the most frequent to contribute sediments directly to the plume of water travelling eastwards around the coast (see Section 4.1).

Akaroa Harbour itself presented a source of suspended matter into the flow of water around the Peninsula towards Pegasus Bay, for example on JD 293 2007, and JD 50 2006. Another source of strongly scattering material was observed on the north-eastern edge of the peninsula, possibly indicating a large freshwater outflow, or coastal upwelling.

The Rakaia River flow rates on days when the Rakaia plume travelled at least as far as Akaroa Harbour were significantly higher than on dates when no Bight water proceeded east along Banks Pensinsula ($p = 0.0967$, $n = 115$); 7474 ± 4500 l/s compared to 6177 ± 3900 l/s.

8. Objective 5: Statistical analysis of chlorophyll distributions in the Canterbury Bight

Objective 5: *Provide any available information on algal blooms in the Canterbury Bight. Including size, frequency and time of year of these blooms.*

8.1. Spatial distribution of phytoplankton blooms in the Canterbury Bight

Over 2000 MODIS images were remapped at 600 x 600 m resolution for the Canterbury Bight area, yielding more manageable image sizes for a large statistical analysis. Images with more than 90 % cloud cover were discarded. At each pixel, the minimum, maximum, median and root mean square variability (of log-transformed chlorophyll) chlorophyll values through the time period, together with the number of valid data points, were recorded. These statistics were calculated for each month to produce a monthly chlorophyll climatology at high spatial resolution for the period September 2002 to April 2009 (Figures 13-14).

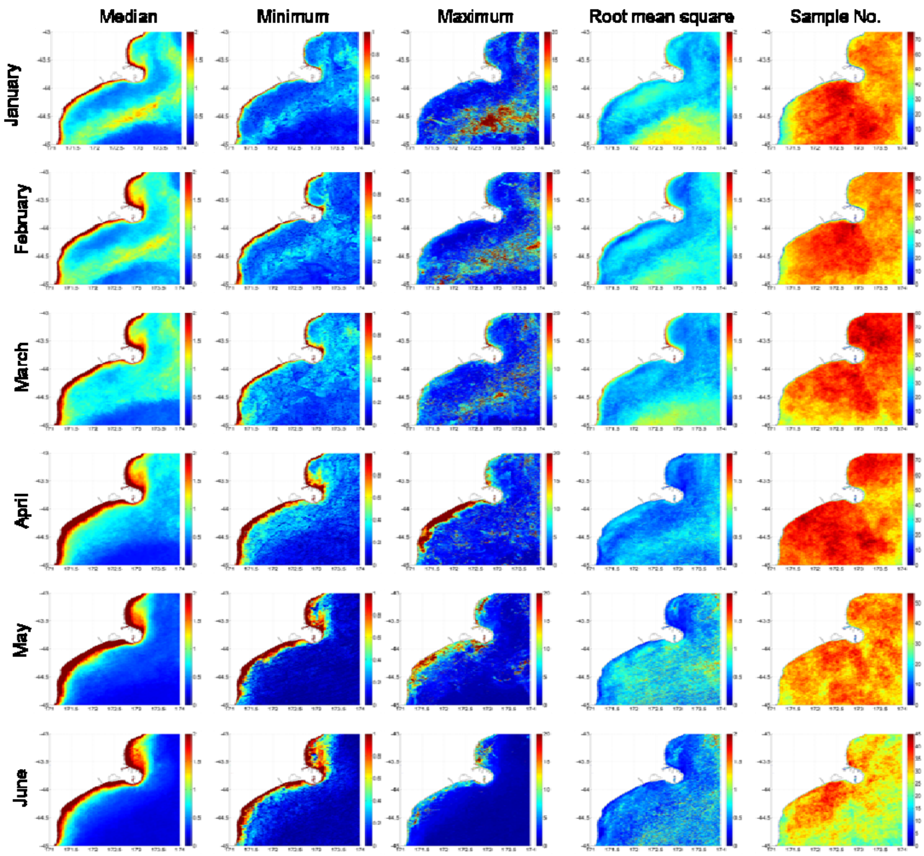

Figure 13: Monthly chlorophyll climatology for the Canterbury Bight, January to June, from September 2002 to April 2009, showing the median, minimum and maximum chlorophyll concentrations, and root mean square variability of log-transformed chlorophyll concentrations, and number of datapoints used, for each month, respectively.

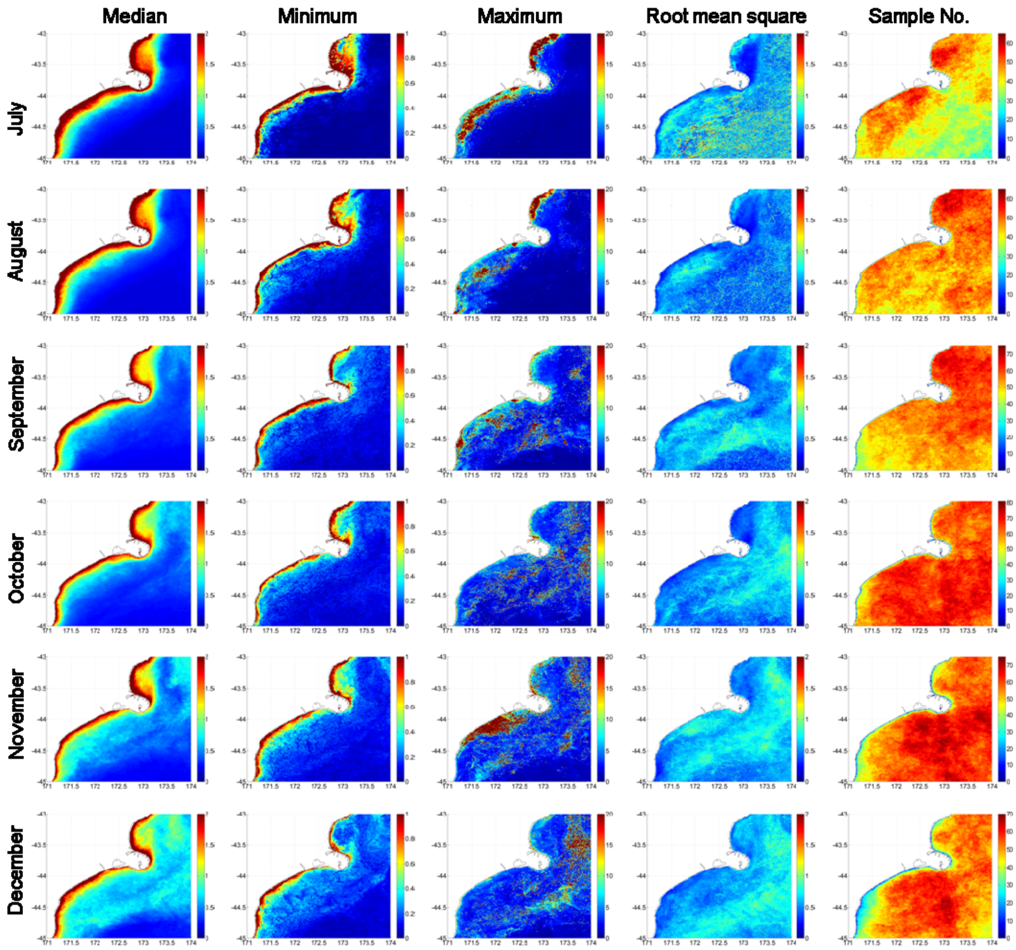

Figure 14: Monthly chlorophyll climatology for the Canterbury Bight, July to December, from September 2002 to April 2009, showing the median, minimum and maximum chlorophyll concentrations, and root mean square variability of log-transformed chlorophyll concentrations, and number of datapoints used, for each month, respectively.

Near-shore (0-10 km) chlorophyll values are seriously compromised by high mineral loadings associated with river plumes and re-suspension, and by shallow water. However, off-shore (beyond the variable inshore riverine signature) the major uncertainty is simply the lack of in situ calibration of the chlorophyll algorithm in these waters. Pinkerton et al. (2006) reported that errors in satellite-derived chlorophyll can range from -50 % to +22 % in waters around New Zealand. It is, therefore, safe to assume that relative changes in the magnitude of chlorophyll for the off-shore Canterbury Bight area are reliable, but that absolute values will be unreliable. Thus, the spatial patterns of relative chlorophyll concentrations discerned are reliable, but actual concentrations are questionable.

Off-shore chlorophyll values peak in a southwest to northeast aligned band which is deflected across the Bight from the latitude of the Waitaki River mouth. This band represents the Southland Current, travelling northeast. Maximum values are reached in

January, minimum values in July – consistent with a seasonal trend associated more strongly with light than temperature (which fluctuates seasonally lagged well behind light). Note that the colour scales are identical for all months for each parameter in Figures 13 and 14. Sample numbers (i.e., clear-skies) were highest for February and lowest for June and July. Chlorophyll variability (standard deviations of log-transformed chlorophyll concentrations; Figures 13-14) is typically highest where chlorophyll values are lowest. Chlorophyll variability was particularly low near-shore because the consistently high suspended mineral particles within this nearshore riverine plume resulted in positive biasing of chlorophyll values for this zone.

8.2. Timing of phytoplankton blooms in the Canterbury Bight

The timing of phytoplankton blooms can best be observed using chlorophyll concentrations averaged over one week periods. This represents a compromise between avoiding missing values due to cloud cover and retaining sufficient temporal resolution to avoid smearing out any blooms which last less than a month.

Weekly chlorophyll concentrations from the 9 km SeaWiFS record had over 11 years of data, compared to the seven years available from MODIS. Based on the results of the spatial analysis (Section 8.1), SeaWiFS chlorophyll concentrations were extracted at three points along a north-south transect (Figure 15); 44.2◦S, between the mean Southland Current path and the coast; 44.6◦S to the south of the mean Southland Current path (Figure 16). A 14-month subset of this time series, from 1st May 2005 to 31t July 2006, reveals the intra-annual variability in mean weekly chlorophyll concentrations over this period (Figure 17).

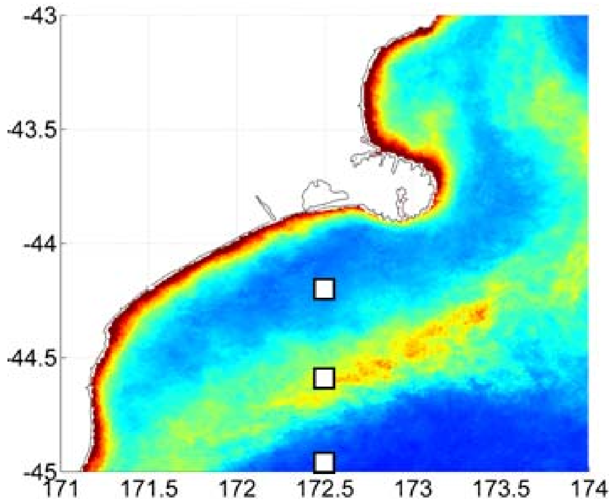

Figure 15: Locations at which chlorophyll time-series were extracted for Figure 16, overlaid on the median January chlorophyll field.

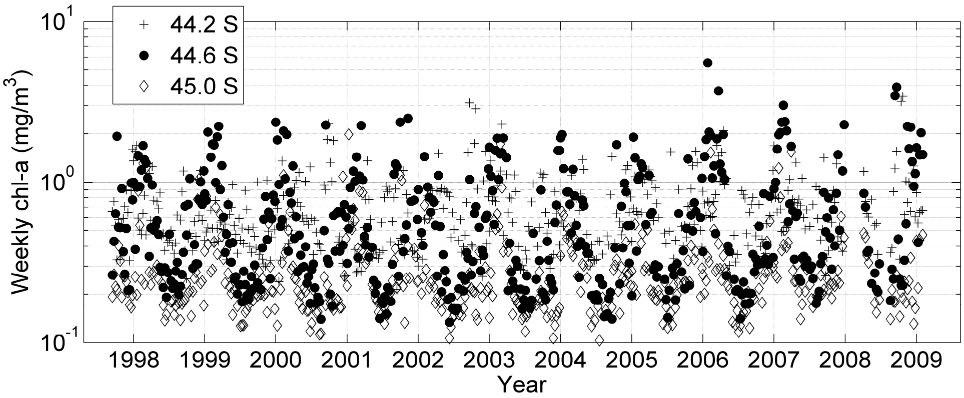

Figure 16: **Weekly averaged chlorophyll concentrations at three latitudes within the Canterbury Bight along longitude 172.5 °E: 44.2 °S, between the mean Southland Current path and the coast (+ signs); 44.6 °S, within the mean Southland Current path (filled circles); and 45.0 °S, to the south of the mean Southland Current path (diamonds).**

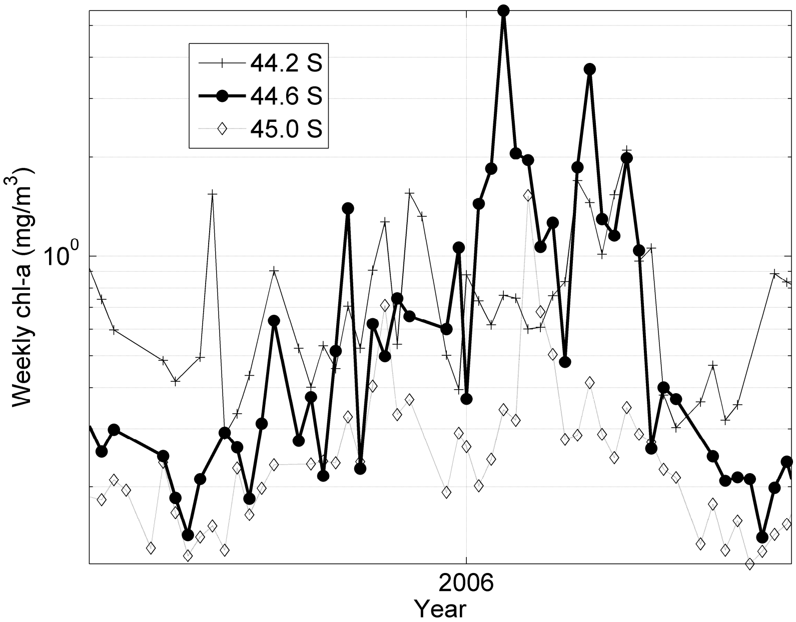

Figure 17: **Detail of weekly variability in chlorophyll concentrations north of, within (44.6 °S) and south of the mean Southland Current path, 1st May, 2005 to 31st July, 2006.**

Both Figures 16 and 17 highlight the extreme patchiness of the chlorophyll distributions, even when averaged over a 9 x 9 km grid-cell and across a week. Cloudiness (i.e., inconsistent temporal coverage, see the sample number plots in Figures 13 and 14) and, for the northernmost site, shallow water and mineral particles, probably contaminate this chlorophyll record. At each location, a late spring/early summer bloom is evident. This is followed by a late summer/early autumn bloom of equal or higher intensity. The range of chlorophyll values is wider in the open water to the south (as seen in column 4 of Figures 13 and 14). Within the Southland Current, any decline which may occur in chlorophyll values during the summer is not resolved at the monthly scale. In contrast, a decline is evident at sites to the north and south of the current (Figure 17). This suggests a continual replenishment of nutrients within the current.

9. Conclusions, limitations and recommendations

9.1. Conclusions

Each of the questions raised by ECan was addressed, at least in part, using satellite data from the MODIS-Aqua sensor, Landsat and SeaWiFs. The major findings were:

River plumes are frequently visible in satellite imagery of the Canterbury Bight.

The plumes were generally constrained to within 6 km of the coastline. Whether the Southland Current or tidal currents are responsible for this flow pattern could not be explored in this study.

The combined river plume waters travelled a median distance of 62 ± 23 km northwards along the shoreline and eastwards around Banks Peninsula.

Of the ten rivers studied here, the Waitaki, Ashburton and Pareora Rivers had the greatest distinguishable northward extent.

The Rakaia River plume's northward flow frequently merged with resuspended sediments and/or water from the Ashburton River and Lake Ellesmere, and could, therefore, not be measured during flood events in these rivers.

Water flowing from Lake Ellesmere was more easily detectable than river plume water because of its characteristic yellow/green colour. Lake water was observed up to 95 km northeast of the lake opening, up to 33 km off-shore and up to 27 km to the southwest. The dominant pattern of lake water dispersal was north-eastwards along the shore of Kaitorete Spit and around Banks Peninsula to its north-eastern margin and then into Pegasus Bay.

Akaroa Harbour was potentially affected by river water from the Canterbury Bight in 55 % of the days in this analysis. Whether river plume water proceeded into the harbour could not be discerned using MODIS imagery. Conversely, it was clear that the harbour itself acted as a source of suspended material to the coast on some occasions.

Water from rivers in the Canterbury Bight travelled as far as Pegasus Bay in 40 % of the days included in this analysis.

Phytoplankton blooms originating off-shore and/or in the Southland Current typically cross paths with near-shore water during the spring- and summertime (November to February).

9.2. Limitations of this study

In derived variables or products, such as chlorophyll concentrations from MODIS images, the atmospheric correction required prior to calculating chlorophyll concentrations does not distinguish well between land and very bright coastal waters along the shoreline. For this reason, determining the precise origin of a given plume feature is often more difficult with the derived products than with the true colour images.

Insufficient optical data are available at present to robustly characterise the river plumes of the Canterbury Bight. It is not known whether the plume waters are sufficiently distinctive to enable them to be identified using MODIS imagery. Attempts to apply automatic plume tracking algorithms eventually failed in this study, and no truly objective means of identifying the signature of each river was found. For example, as reported by Schwarz et al. (2009), calcite was the satellite product best suited to tracking the Rakaia River plume. The tracking algorithm (Schwarz et al., 2009) was applied to all images with clear sky and there were no algorithm failures between the Ashburton River and south Pegasus Bay, using a range of 20 threshold values for plume designation: 0.006 > calcite > 0.025 (the units are arbitrary here, since we are using the calcite algorithm outside of its intended purpose). Pixels adjacent to the known river mouth were designated 'plume' or 'non plume' according to the calcite threshold value, and successive iterations were applied to expand the plume area until no more pixels adjacent to the plume exceeded the threshold values. The resulting plume areas were regressed against the corresponding daily river flows, using both linear (Pearson) and rank (Spearman) correlations. None of the correlations was significant. Limiting the regression to plume areas greater than 100 km^2 (i.e., a moderate plume was visible) yielded a maximum correlation coefficient at a threshold value of 0.02 ($r_s = 0.188$, $p = 0.1682$, $N = 55$). The Canterbury Bight was, therefore, not amenable to the more simplistic, but objective, methods for river plume tracking reported in the literature (Dzwonkowski & Yan, 2005; Lihan et al., 2008; Nezlin & DiGiacomo, 2005; Nezlin et al., 2005; Nezlin et al., 2008).

9.3. Recommendations for future study

Given the paucity of optical and geophysical data required to robustly characterise the river plumes of the Canterbury Bight, we recommend that future work aimed at understanding the fate of terrigenous material in the Bight be focussed in three areas:

1. Hydrodynamic modelling of the coastal region including its river outflows (assuming sufficient information about the coastal morphology is available) would be very useful in furthering our understanding of freshwater dispersal.

2. *In situ* oceanographic measurements, at high spatial and temporal resolution and including salinity, mixing, chlorophyll fluorescence, turbidity, light attenuation and CDOM absorption would improve validation of remotely-sensed optical signatures and modelled ocean dynamics.

3. More detailed consideration of the recent river flow history and watershed characteristics would enhance understanding of catchment process relationships with river plume metrics.

10. Acknowledgements

We are grateful to visiting student Felix Baumann for acquiring Landsat data over the Canterbury Bight. MODIS data were kindly provided by the NASA MODIS Science Team.

11. References

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Schwarz, J.N.; Pinkerton, M.H.; Wood, S.; Zeldis, J. (2009). Remote sensing of river plumes in the Canterbury Bight: Stage IIA Progress Report. NIWA Client Report June 2009 CHC2009-207 (Client: Environment Canterbury).

Appendix A: MODIS true colour imagery during periods when Lake Ellesmere was open.

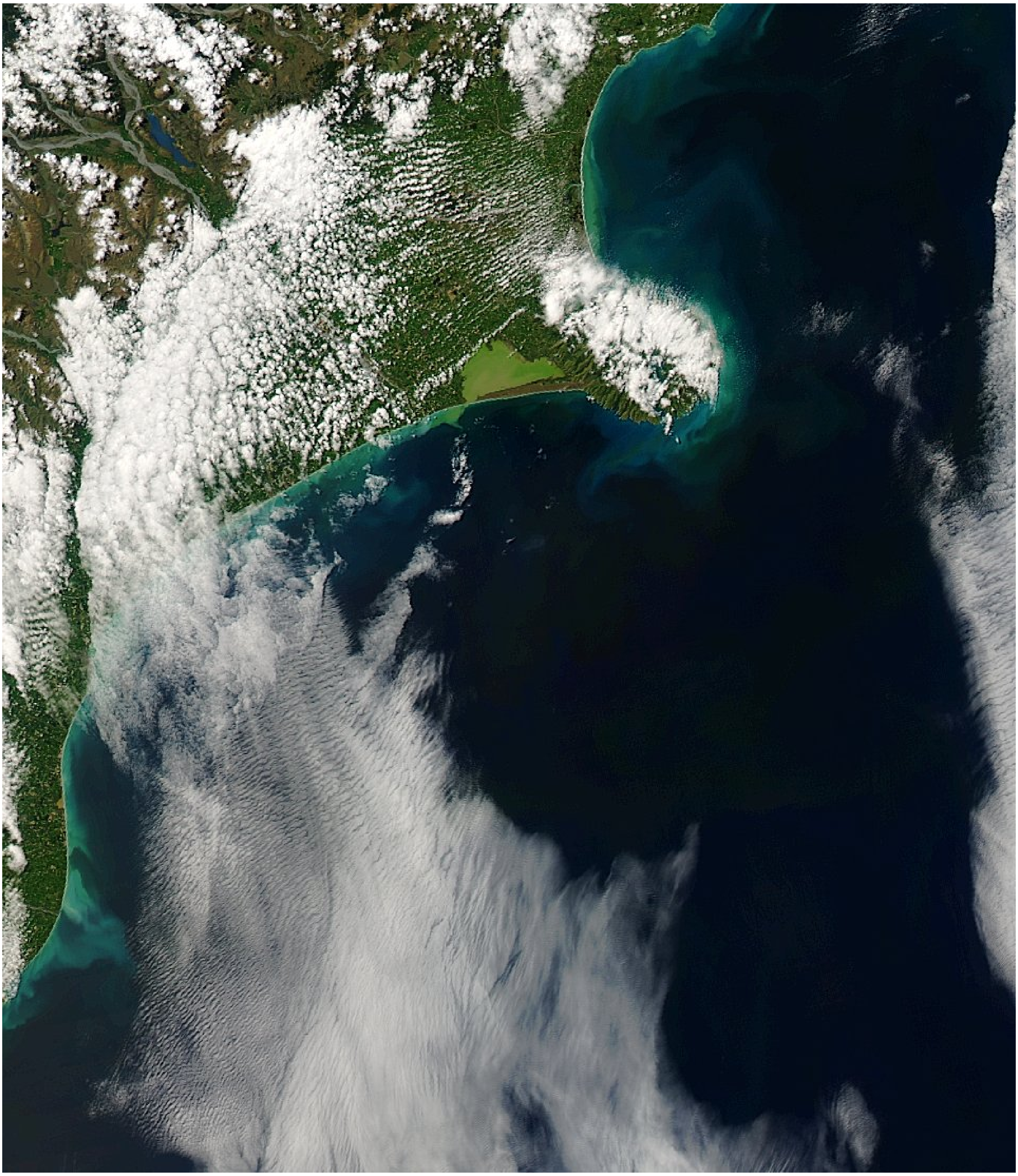

Figure A1: **2nd December, 2002.**

Figure A2: 9th December, 2002

Figure A3: 21st July, 2003

Figure A4: **25th July, 2003**

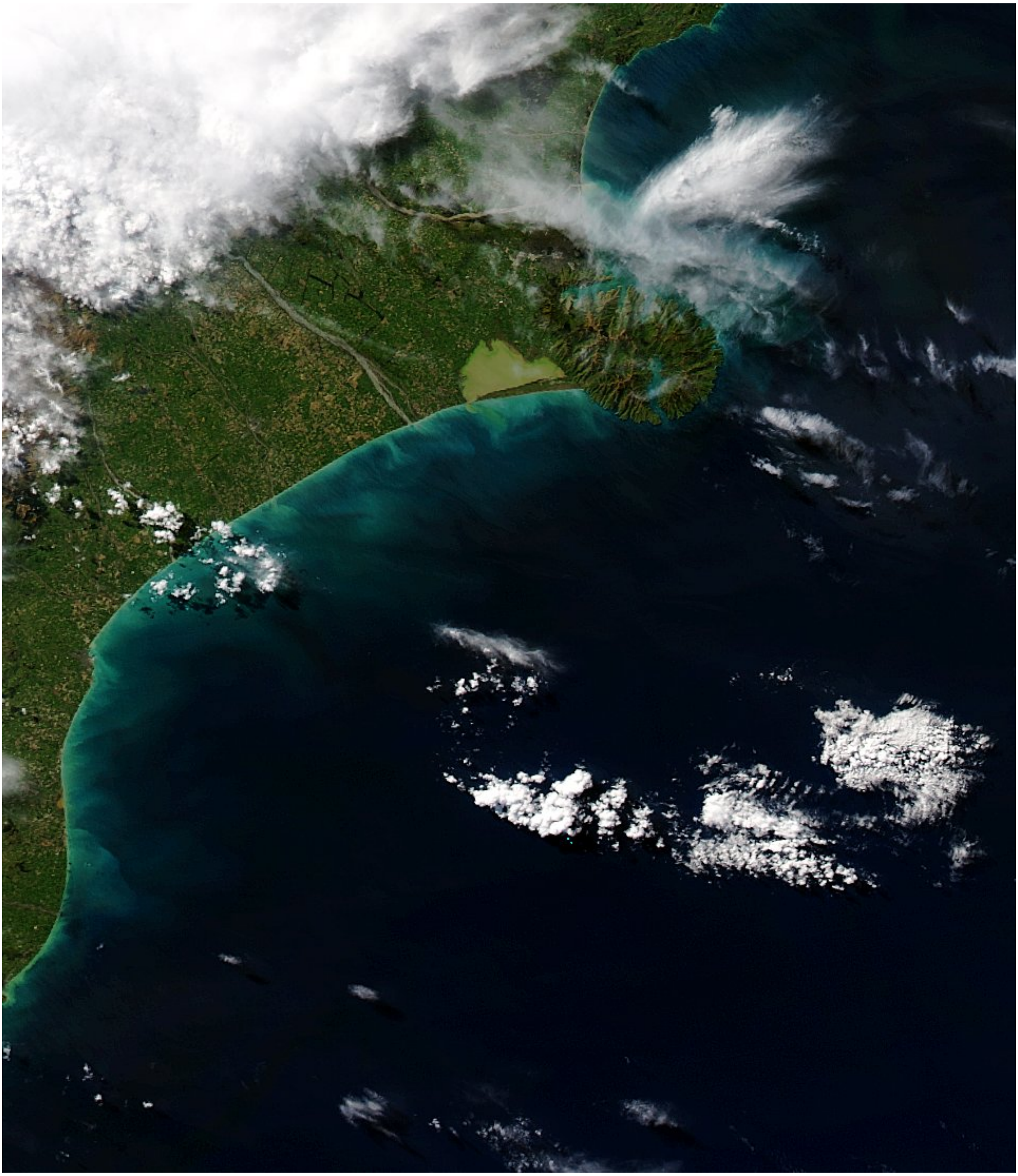

Figure A5: **18th September, 2003**

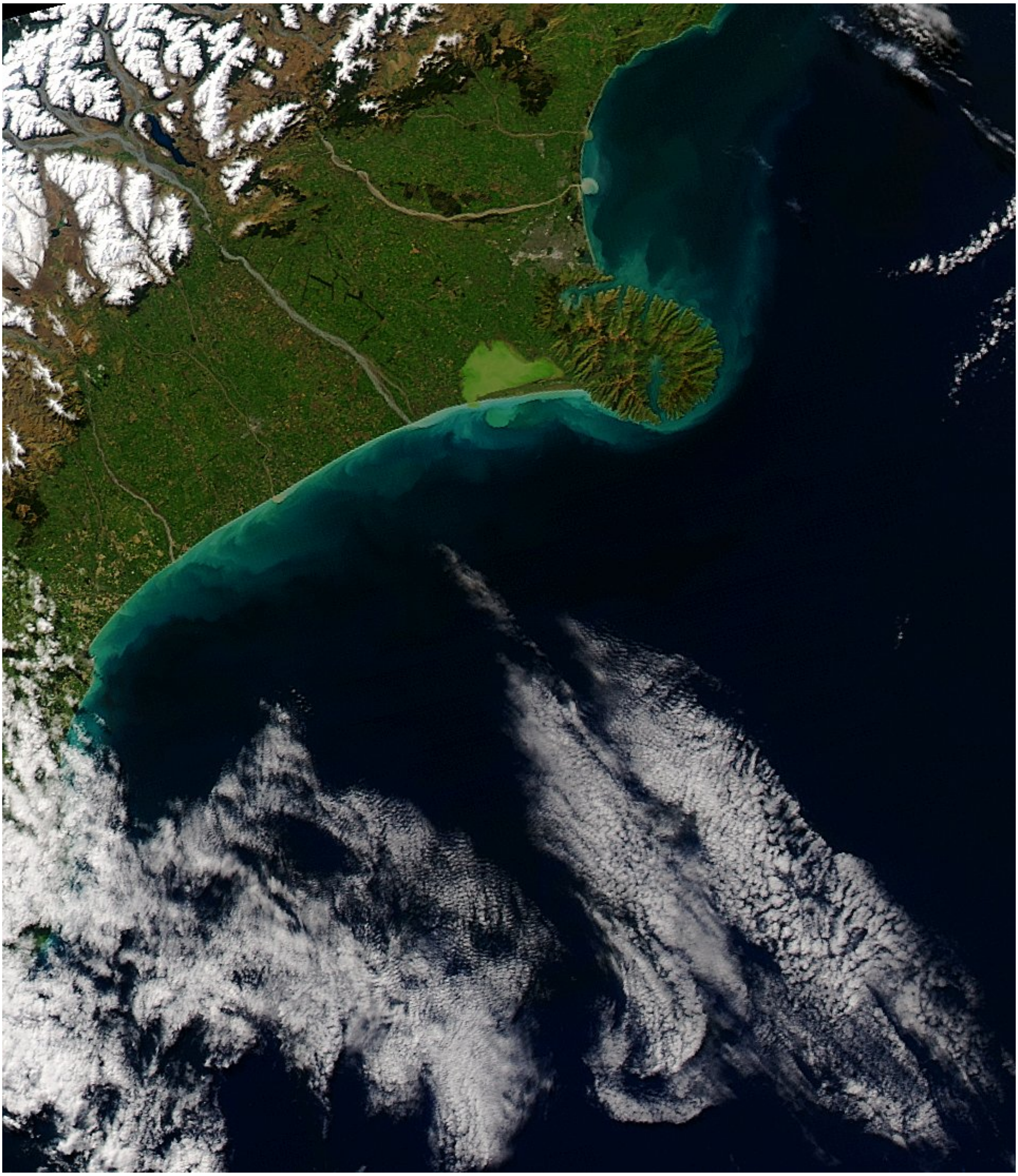

Figure A6: **21st September, 2003**

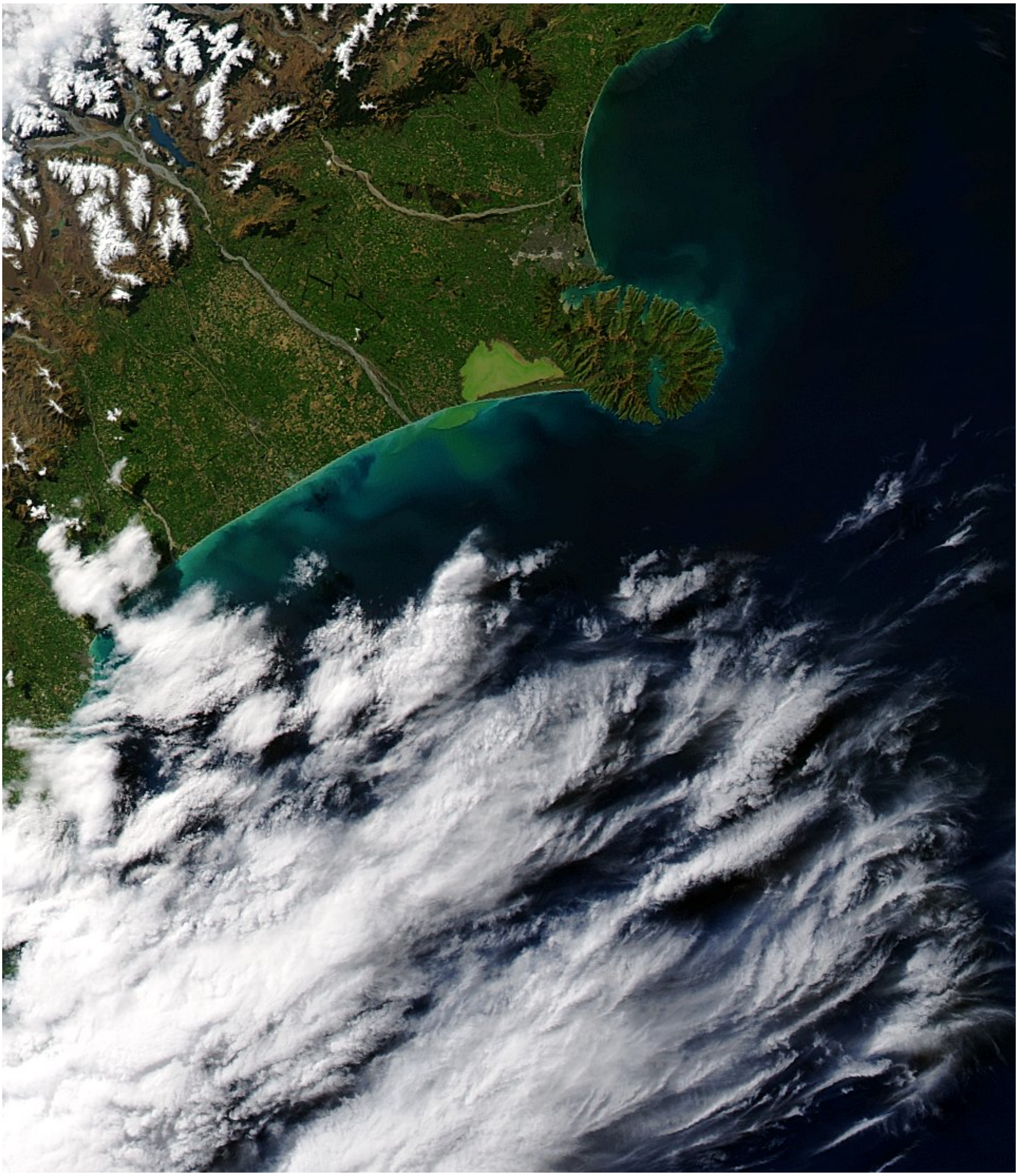

Figure A7: **25th September, 2003**

Figure A8: 8th November, 2003

Figure A9: **10th November, 2003**

Figure A10: 6th September, 2004

Figure A11: 7th September, 2004

Figure A12: **27th January, 2005**

Figure A13: 15th August, 2005

Figure A14: 18th August, 2005

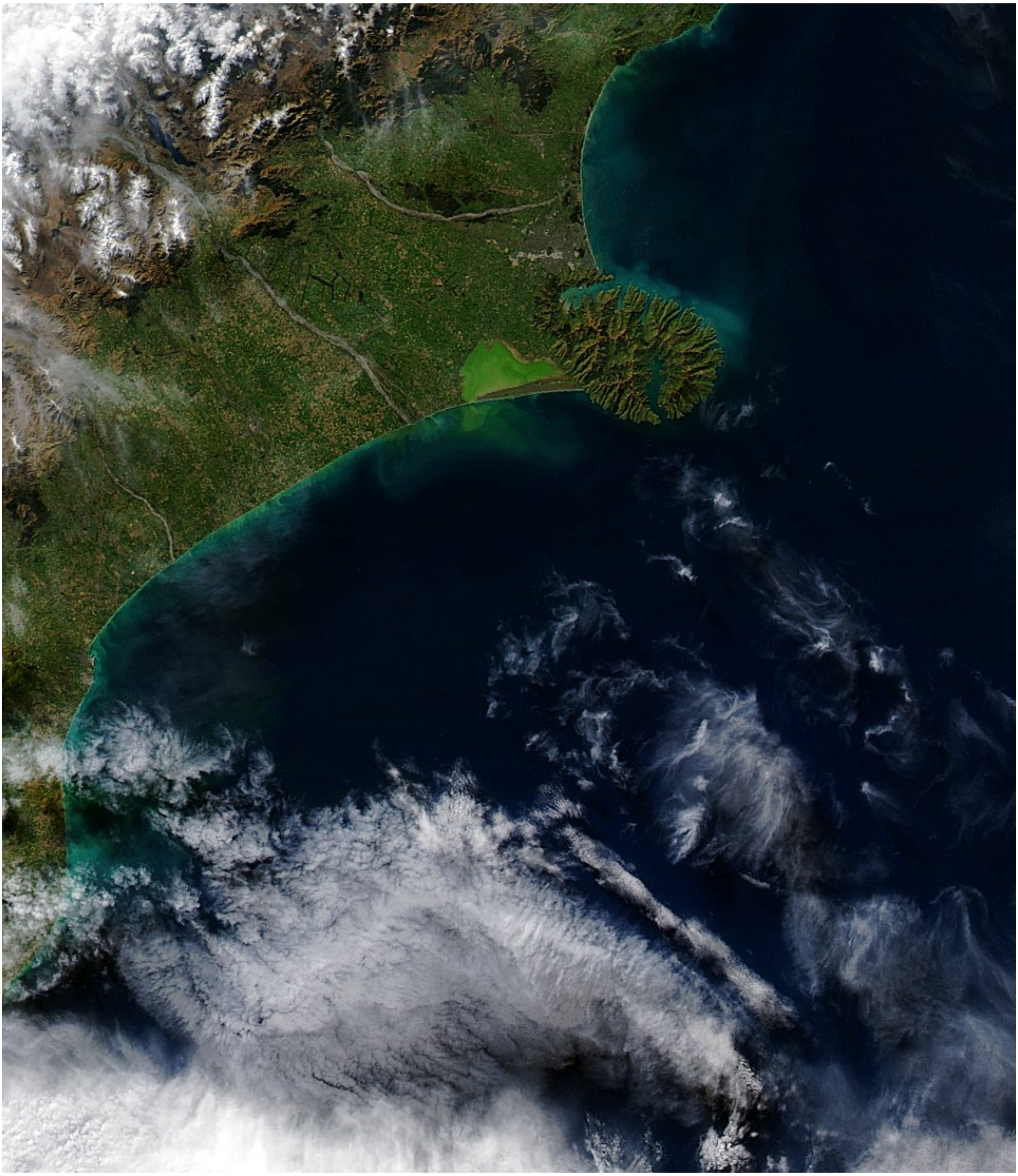

Figure A15: 20th August, 2005

Figure A16: **29th August, 2005**

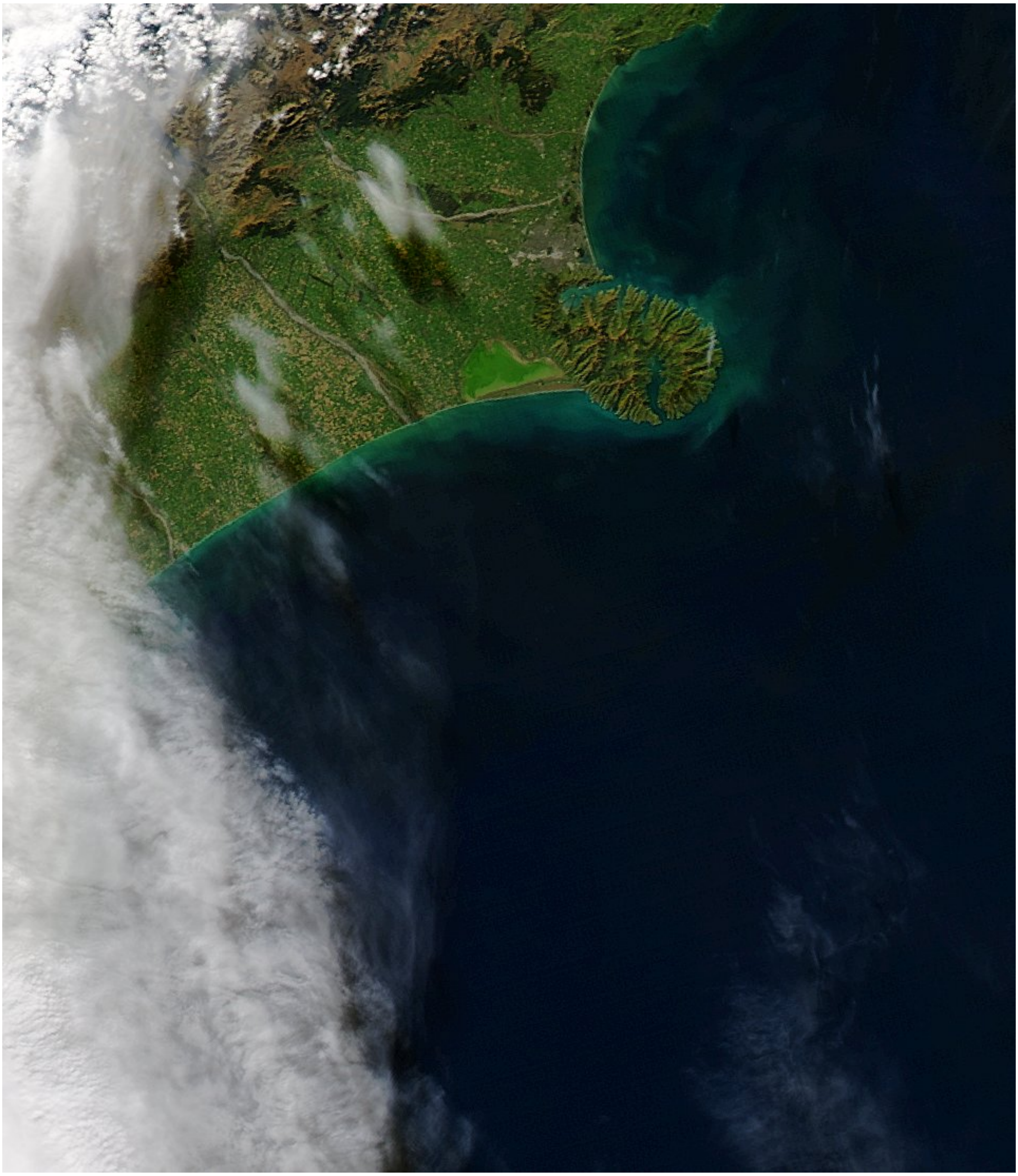

Figure A17: 1st September, 2005

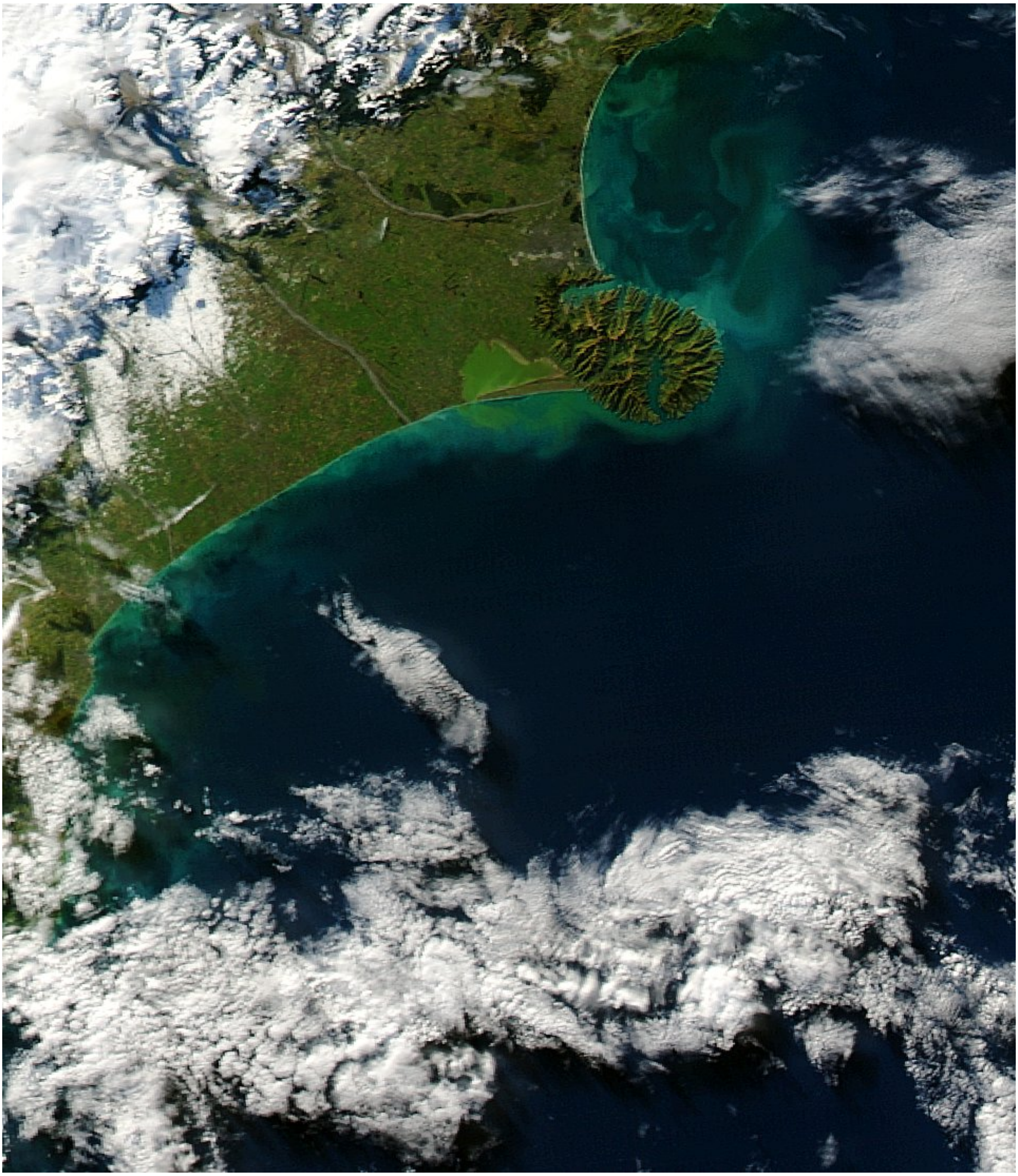

Figure A18: 3rd July, 2006

Figure A19: 27th August, 2006

Figure A20: 29th August, 2006

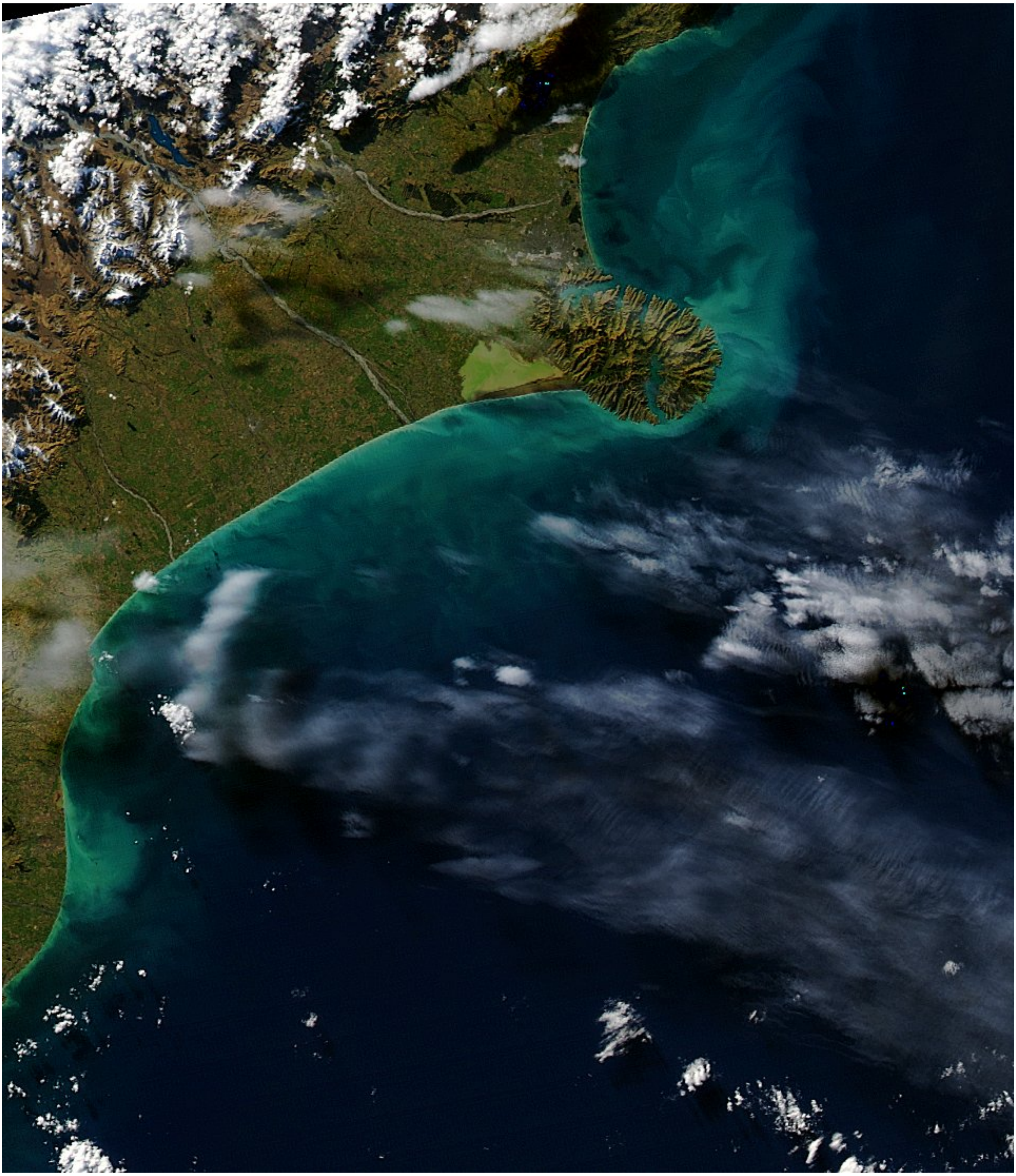

Figure A21: 25th July, 2007

Figure A22: **31st August, 2008**

Figure A23: **17th September, 2008**

Figure A24: **26th September, 2008**