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Centre for Marine Studies

Development of an Operational Capacity for Real-time Observation and Forecasting of Harmful Algal Blooms in the Benguela Current Large Marine Ecosystem Region:

Utility of Models in Forecasting Harmful Algal Bloom Events

BCLME Project number:
EV/HAB/02/06

Prepared for:
Benguela Current Large Marine Ecosystem Programme

Prepared by:
Centre for Marine Studies
University of Cape Town
South Africa

Date:
December 2004

CSIR
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Benguela Current Large Marine Ecosystem Programme

CSIR REPORT ENV-S-C 2004-066

DEVELOPMENT OF AN OPERATIONAL CAPACITY FOR REAL-TIME OBSERVATION AND FORECASTING OF HARMFUL ALGAL BLOOMS IN THE BENGUELA CURRENT LARGE MARINE ECOSYSTEM REGION:

UTILITY OF MODELS IN FORECASTING HARMFUL ALGAL BLOOM EVENTS

December 2004

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Issued and printed by, also obtainable from:

Centre for Marine Studies
University of Cape Town
Rondebosch
South Africa

Executive Summary

Harmful algal blooms (HABs), which are endemic to the inner shelf near shore environments over the whole BCLME region, give rise to concerns about public health related to shell fish contamination as well as ecological or ecosystem impacts related to oxygen depletion following the collapse of large blooms. In both cases, the variability of these impacts varies not only interannually but seasonally and at the event scale as well.

In view of the socio-economic significance of the impacts of algal toxins on wild and farmed species and the subsequent oxygen depletion problems it has become desirable to develop an early warning capability to help off set some of those costs.

The objective of this study was to use a demonstration project approach to assess the feasibility of using numerical models in conjunction with other real time observations such as remote sensing to develop a generic capacity to anticipate the onset, development and fate of HAB events.

There are two complementary processes, which may govern the development of the very intense blooms in the Benguela. The first is the hydrodynamics-controlled transport and concentration of HAB cells along the near shore environment and thought to be closely linked to the upwelling cycle in the late summer period. The second suggests that the shift from diatoms to dinoflagellates is linked to a low, turbulence controlled, rate of nutrient supply, which favours the success of species that can most effectively overcome the need for vertical migration such as dinoflagellates.

This study focussed primarily on the mechanisms behind the first hypothesis and only provides an assessment of the feasibility for the second. It has delivered the basis on which the HAB thrust of the BCLME can advance towards an early warning system. The model outputs show that they can simulate the temporal and spatial characteristics of physical variability in the St Helena Bay – Namaqua system with uncertainties of approximately 20%.

The model was calibrated with a month long high resolution (2m vertical resolution and hourly records) temperature data set from January 2002 and verified against the

data for February – April 2002. The model was run freely with forcing from atmospheric heat fluxes, tides and temperature sections at the boundaries.

The model results reflected the main circulation characteristics of the system over the upwelling cycles (event scales) and the seasonal scale. The event scale features that were specifically addressed and which are particularly important for the early warning system include:

- Upwelling at Cape Columbine and the behaviour of the plume
- The barotropic jet on the seaward side of the plume
- Narrow upwelling belt along the eastern margin of the system
- The dynamics of frontal features associated with the interaction of upwelling plumes and retention driven warming
- The warming of surface waters in the St Helena Bay retention zone
- The development of the narrow inshore poleward flow during the relaxation phase of the upwelling cycle
- The variability of stratification as a result of the interactive effects of buoyancy forcing by upwelling, wind driven entrainment and mixing and solar heat flux.
- Inertial circulation

The stability of the model set up for the St Helena Bay – Namaqua system was also verified by undertaking runs that had initial conditions (temperature) throughout the domain that were very different to those in reality. In all cases the model was able to recover back to reflecting the expected variability. This behaviour is an essential feature for a forecasting system as it shows that all key processes are correctly set up and that with realistic forcing the model produces realistic rather than chaotic behaviour.

This feasibility study showed that the dynamical characteristics of the circulation and stratification of St Helena Bay are more complex than was initially understood. This caused the emphasis of the study to shift towards elucidating the underlying processes and their scales rather than on the operationalisation of a modelling set up.

An additional study was undertaken in parallel to provide a mechanistic understanding of the event scale narrow poleward.

The improved understanding of the stratification variability and how it related to the scales of forcing will contribute significantly to further investigation and modelling of the biogeochemical aspects of both diatom and HAB productivity and their role on the ecosystem.

In conclusion, the use of hydrodynamic models as part of a HAB early warning system is feasible and realistic. The uncertainty levels will be improved to below 20% with the following recommended actions:

- Implementation of space varying winds through MM5
- Improvement on temperature boundary conditions either through data or through nesting with a more regional model.
- Better understanding of the dynamical considerations behind the poleward flow.

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List of Acronyms

CODE	Coastal Ocean Dynamics Experiment
GMT	Greenwich Mean Time
HAB	Harmful Algal Bloom
MCM	Marine and Coastal Management
MM5	Meteorological Model 5
MSL	Mean Sea Level
QuickScat	Quick Scattermeter
SAN	South African Navy
SST	Sea Surface Temperature

List of Symbols

u, v	=	velocity in the x- and y-directions, respectively
d	=	variable water depth
t	=	time
x,y	=	horizontal Cartesian rectangular co-ordinates
η	=	water level elevation
U	=	magnitude of total current velocity
$F_{x,y}$	=	x- and y- components of the wind forcing
f	=	Coriolis parameter $2\Omega \sin\phi$, where Ω is the earth's angular velocity and ϕ is the geographic latitude
g	=	acceleration due to gravity
ρ	=	water density
C	=	Chézy coefficient

1. INTRODUCTION

Harmful Algal Blooms (HABs) are endemic to the Benguela system (Shannon, 1985), particularly during late summer, in periods of relaxation following an upwelling event. There are mainly two types of HABs: Those that form by a dominant (dense) population of particular species of harmful alga (typically a group of phytoplankton known as dinoflagellates), which often leads to a red discolouration of the water, or those that contain toxins within themselves.

The development of HABs is closely related to the prevailing winds of the southern Benguela, which govern most hydrodynamic processes on the continental shelf. The broad shelf of this region promotes stratification, which is intensified by surface warming and advection of very cold water over the bottom shelf. HABs occur mostly from January to May, during the later part of the upwelling season, when changes in the synoptic weather patterns result in diminished upwelling activity and increased thermal stratification. The complex physical processes and scales that drive the incidence and persistance of HABs are as yet not fully understood.

Pitcher and Boyd (1996) have investigated the across-shelf and alongshore phytoplankton distributions in the regions of upwelling fronts, where they found surface dinoflagellate accumulation. Following relaxation of upwelling, red tide forms and impacts the coast. Cross-shelf currents become weak and directed onshore, causing the dinoflagellate blooms to accumulate inshore. A net poleward surface current then propagates these blooms southward. Probyn *et al* (2000) suggests that this poleward flow (often occurring as a “flood” event) could possibly be caused by coastal-trapped waves or wind stress on the surface friction layer.

At the time this report was produced, this poleward current was being investigated in detail in an MSc thesis[1]. This report will thus only touch on the subject (see Results in Chapter 4) and illustrate the occurrence of the current at certain times during the simulation period.

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More information is required on the oceanography of harmful algal blooms, which will contribute to the ultimate goal of determining their principal causes. This will lead the way to improved skills at forecasting their occurrence. The numerical modelling of the dynamics of the upwelling front in this region will allow prediction of the timing, location, magnitude and duration of these coastal accumulations of frontal blooms.

The focus of this study is on the St Helena Bay area along the West Coast of South Africa. Figure 1-1 shows an illustration of this area. A numerical hydrodynamic model was set up for the St Helena Bay area in such a way to include the months that HABs occur most often.

File: Area-0.png

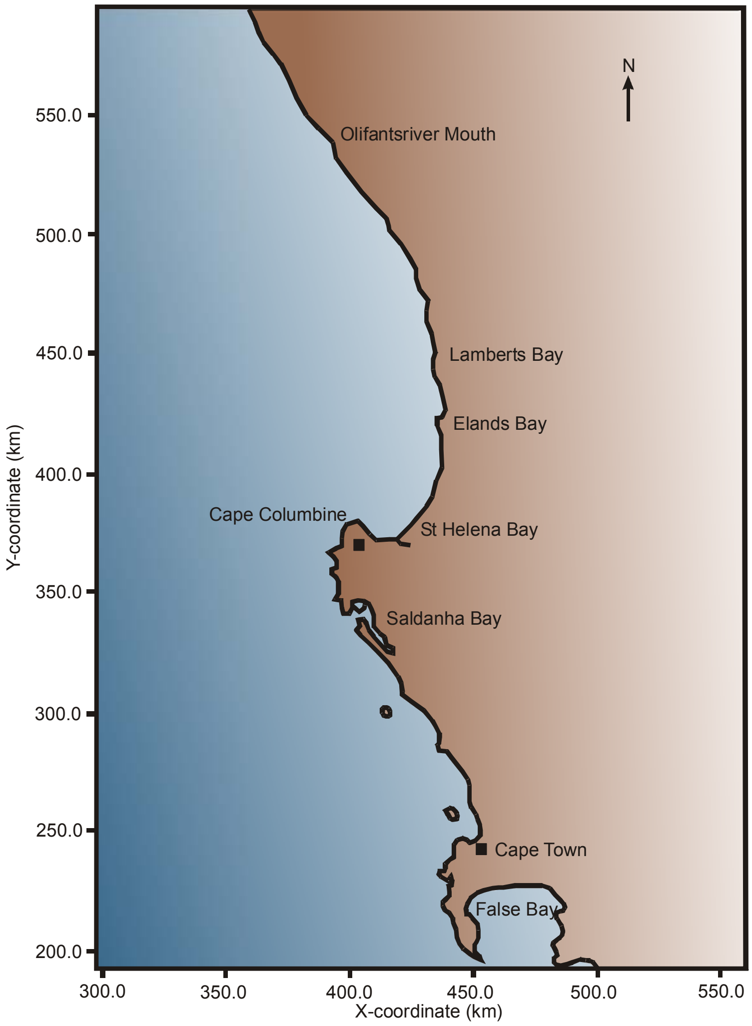

Figure 1-1: Illustration of the West Coast of South Africa.

This report is structured in the following way. Chapter 2 gives a description of the modelling methodology, which include a description of the numerical model Delft3D-FLOW, a description of the data that was used, the model setup, as well as a sensitivity test to illustrate the stability of the model. Chapter 3 discusses the calibration of the model for the period January 2002, while Chapter 4 shows the model results for the full simulation period (January – April 2002). These results include temperature time series in the vertical, as well as a comparison between remotely sensed temperatures and modelled temperatures on the horizontal scale. This chapter also address the poleward surface jet as seen in the model results. A discussion follows in Chapter 5, and Chapter 6 provides a summary and conclusions.

Throughout this report the following conventions were used: Time is in South African Standard Time (GMT + 2 hours). Current direction is the direction *to which* the current is flowing. Wind and wave directions are the direction *from which* the wind or wave is travelling. All directions are relative to True North. All depths and tidal levels are referenced to Mean Sea Level (MSL).

2. MODELLING METHODOLOGY

2.1 Description of the numerical model DELFT3D-FLOW

The modelling of the hydrodynamics of the St Helena / Lambert's Bay area has been undertaken using the DELFT3D-FLOW model (WL|Delft Hydraulics, 2003a). The hydrodynamic model is designed to simulate multi-dimensional hydrodynamic flows and transport phenomena, including sediments, in shallow seas, coastal areas, estuaries, rivers and lakes. The model is capable of solving the time-dependent shallow water equations in three dimensions, on a rectilinear or a curvilinear, boundary fitted grid. In the vertical, a sigma co-ordinate approach is applied.

The model's standard features include:

- tidal forcing
- the effect of the earth's rotation (Coriolis force)
- density driven flows (pressure gradients terms in the momentum equations)
- space and time varying wind and atmospheric pressure
- bed shear stress at the seabed
- turbulence induced mass and momentum fluxes (k-ε turbulence closure model).

The system of equations in Delft3D-FLOW comprise the horizontal momentum equations and the continuity equation, the equation of state and the advection-diffusion equation for heat, salt and other conservative tracers which are solved using the Alternating Direct Implicit scheme.

The equations and their numerical implementation are described in detail in the DELFT3D-FLOW user manual (WL|Delft Hydraulics, 2003a); simplified versions are provided below:

Conservation of momentum in x-direction:

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} + g\frac{\partial \eta}{\partial x} - f.v + \frac{g.u\,|U|}{C^2(d+\eta)} - \frac{F_x}{\rho(d+\eta)} - \left(\frac{\partial^2 u}{\partial^2 x} + \frac{\partial^2 u}{\partial^2 y}\right) = 0$$

Conservation of momentum in y-direction:

$$\frac{\partial v}{\partial t} + u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y} + g\frac{\partial \eta}{\partial y} + f.u + \frac{g.v\,|U\,|}{C^2(d+\eta)} - \frac{F_y}{\rho\,(d+\eta)} - \left(\frac{\partial^2 v}{\partial^2 x} + \frac{\partial^2 v}{\partial^2 y}\right) = 0$$

Conservation of mass, continuity equation:

$$\frac{\partial \eta}{\partial t} + \frac{\partial[(d+\eta)u]}{\partial x} + \frac{\partial[(d+\eta)v]}{\partial y} = 0$$

Advection-diffusion equation:

$$\frac{\partial C}{\partial t} - \frac{\partial}{\partial x}\left(Dx\frac{\partial C}{\partial x} - uC\right) - \frac{\partial}{\partial x}\left(Dy\frac{\partial C}{\partial y} - vC\right) - \frac{\partial}{\partial z}\left(Dz\frac{\partial C}{\partial z} - wC\right) = 0$$

where

u, v	=	velocity in the x- and y-directions, respectively
d	=	variable water depth
t	=	time
x,y	=	horizontal Cartesian rectangular co-ordinates
η	=	water level elevation
U	=	magnitude of total current velocity
$F_{x,y}$	=	x- and y- components of the wind forcing
f	=	Coriolis parameter $2\Omega\sin\phi$, where Ω is the earth's angular velocity and ϕ is the geographic latitude
g	=	acceleration due to gravity
ρ	=	water density
C	=	Chézy coefficient

The magnitude of the wind shear stress is determined by the following widely used quadratic expression:

$$\tau = \rho_a \, . C_d \, . |U_{10}| . U_{10}$$

where:

ρ_a	=	air density (kg/m3)
U_{10}	=	wind speed (m/s) 10 m above the free surface
C_d	=	wind drag coefficient, which is a linear function of wind speed (-).

2.2 Data

2.2.1 Bathymetry

A detailed bathymetry of the model domain was compiled by combining the following data sets:

- S A Navy hydrographic chart of Olifantsrivier to Cape Columbine (SAN 117);
- S A Navy hydrographic chart of Cape Columbine to Table Bay (SAN 118);
- S A Navy hydrographic chart of St Helena Bay – Eastern part (SAN 1008) and
- S A Navy hydrographic chart of St Helena Bay – Western part (SAN 1009).

2.2.2 Temperature

Time series of temperature data was collected by the CSIR by deploying a thermistor chain in 25 m depth in St Helena Bay. Figure 2-1 indicates the position of the thermistor chain. The data was collected for the period July 2001 to June 2002, with hourly intervals.

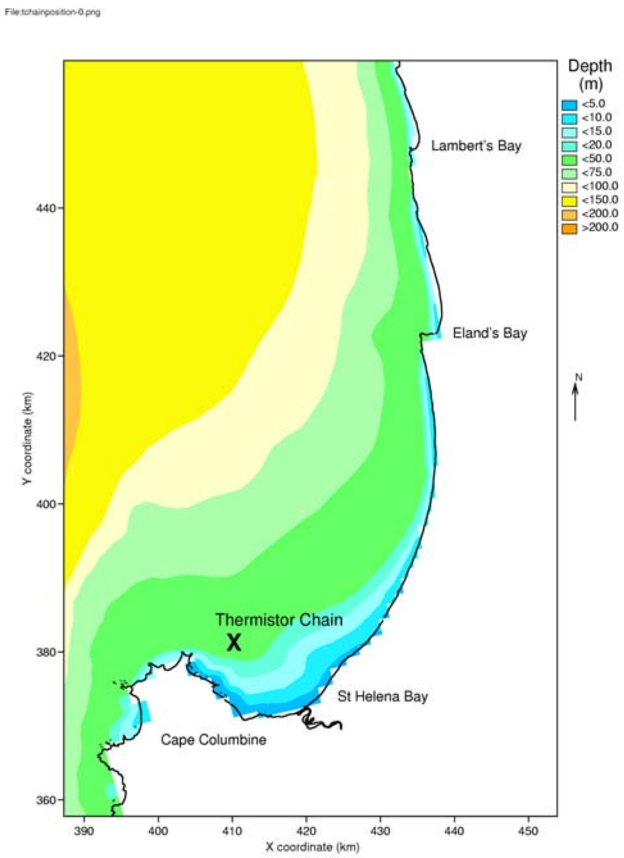

Figure 2-1: Position of the thermistor chain in St Helena Bay.

Figure 2-2 indicates temperature time series, measured by the thermistor chain, for the period 20 January – 15 February 2002, at depths of 0 m (surface), 10 m, 16 m and 25 m (bottom).

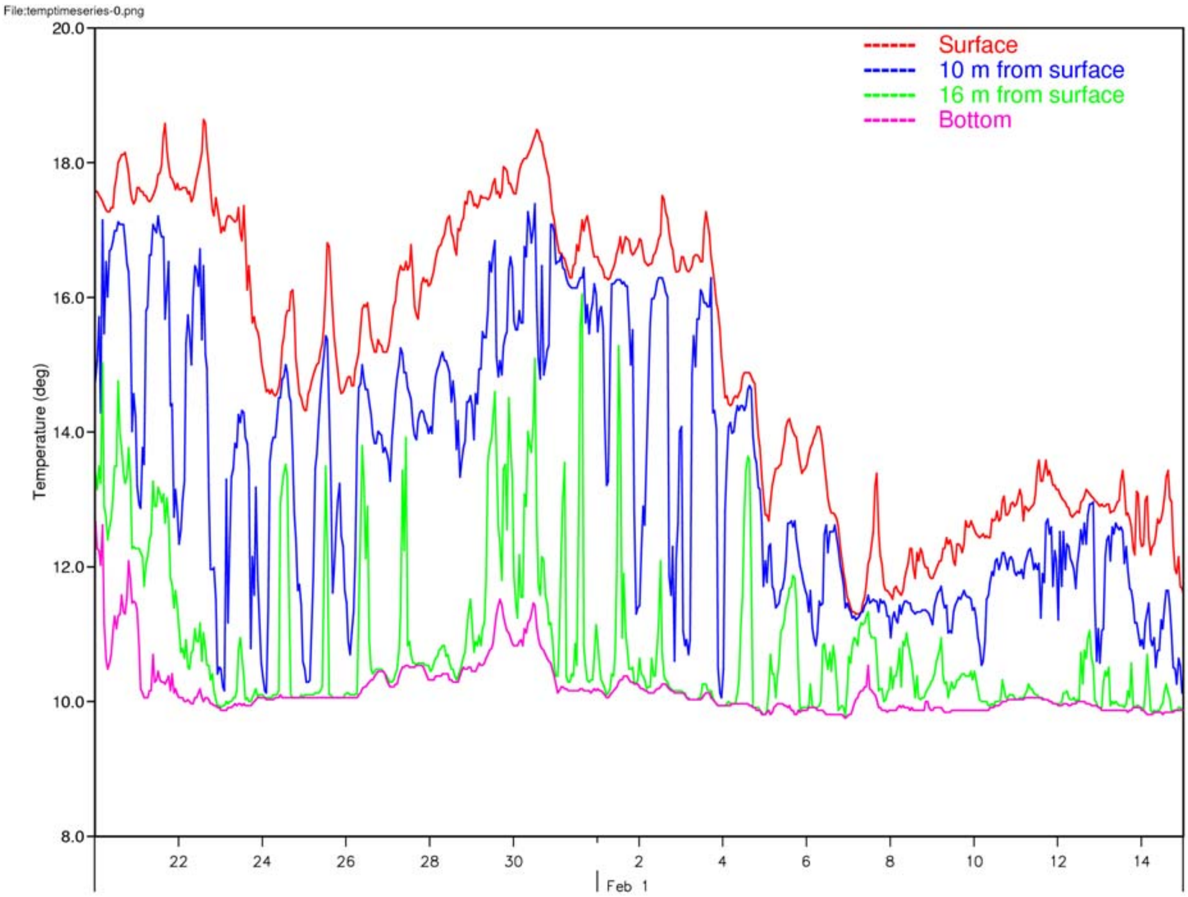

Figure 2-2: Temperature time series in St Helena Bay at four different depths, for 20 January – 15 February 2002.

The above time series shows an upwelling event (around the 24th – 26th of January) during which southwesterly winds persist and cold bottom water is entrained into the surface layers, leading to a collapse of stratification and a cooling of surface water. Following the period of upwelling, the wind relaxes, leading to a relaxation event and a subsequent warming of the surface water. During this time, the water becomes stratified again. In early February, a strong southwesterly wind blows, leading to another upwelling event and another collapse in stratification.

Temperature data obtained from Hondeklip Bay was applied at the model's northern and southern open boundaries (Monteiro, 1997). This data set was chosen because it was the best continuous data set available at the time.

2.2.3 Wind

The wind data applied in the model runs are those measured with hourly intervals at the St Helena Bay weather station, situated at Cape St Martin (north of Cape Columbine). The measured wind speed and direction for January and February 2002 are shown in Figures 2-3(a) and 2-3(b). Wind time series for March and April 2002 can be seen in Figures A-1(a) and A-1(b) in Appendix A.

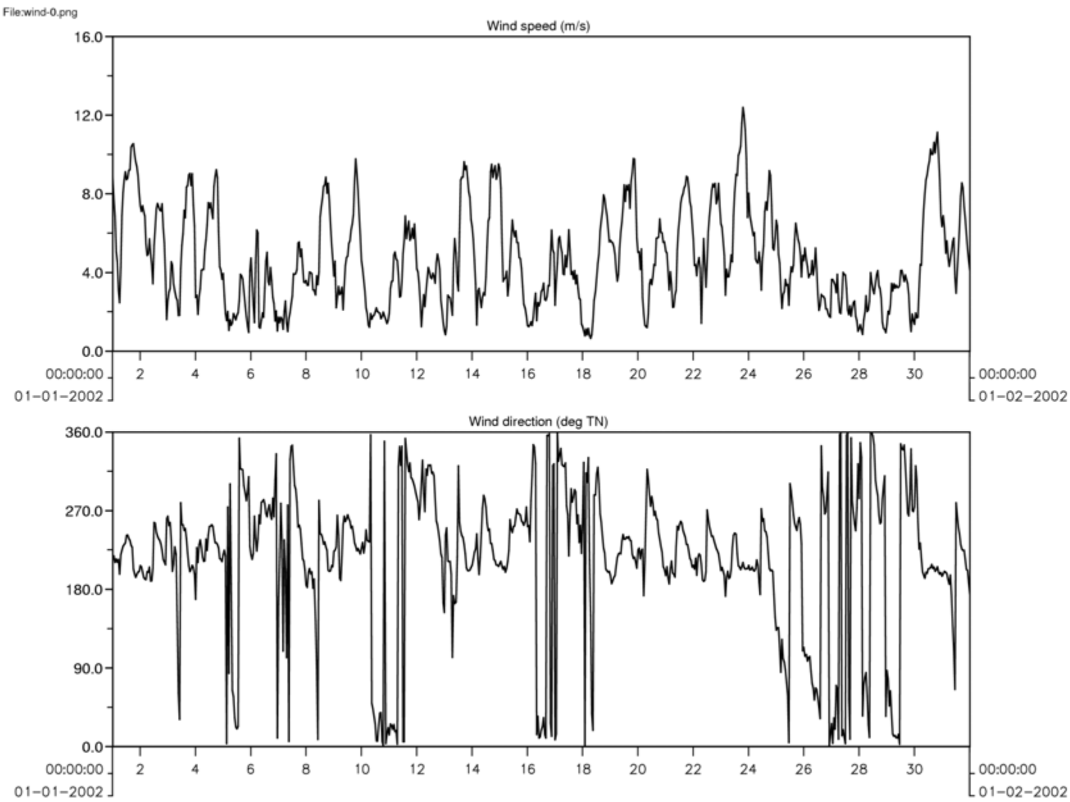

Figure 2-3(a): Measured wind speed and direction at the St Helena Bay weather station for January 2002, indicating long periods of upwelling favourable southwesterly winds, followed by periods of relaxation. Upwelling leads to the entrainment of cold bottom water into the surface layers, leading to cooling of surface water. Relaxation of the wind leads to warming of surface water (see Figure 2-2).

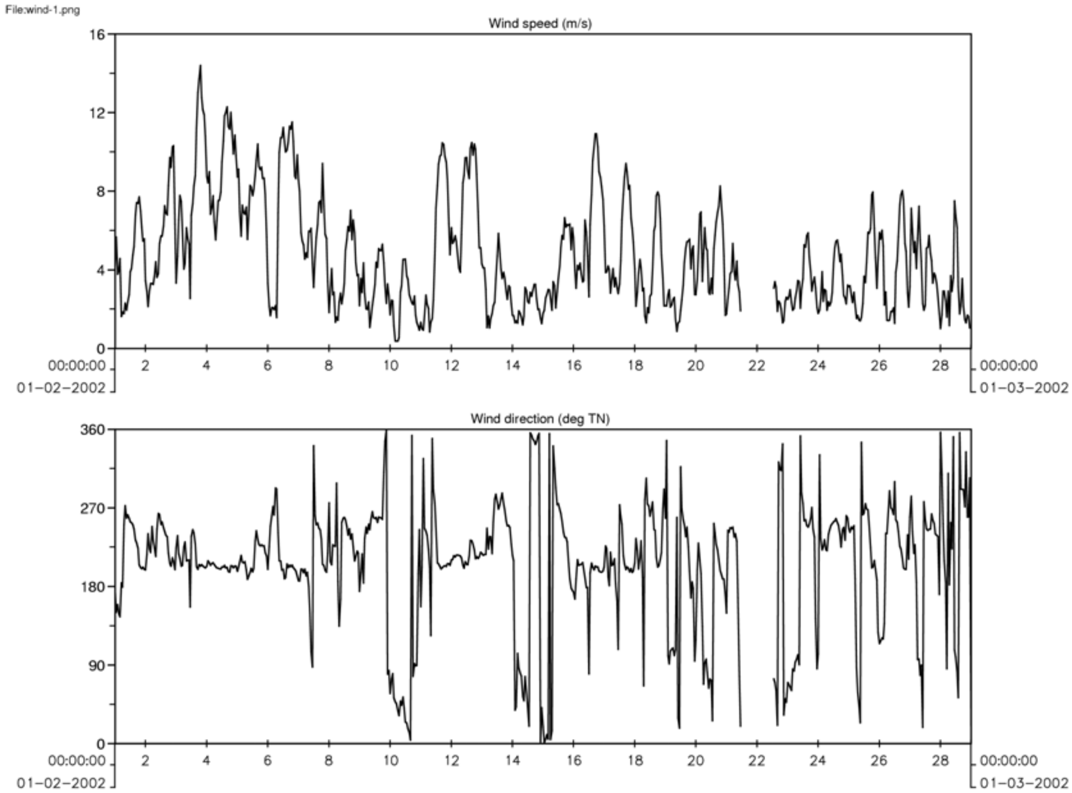

Figure 2-3(b): Measured wind speed and direction at the St Helena Bay weather station for February 2002, indicating a strong upwelling event at the beginning of the month. Upwelling leads to the entrainment of cold bottom water into the surface layers, leading to cooling of surface water. Relaxation of the wind leads to warming of surface water (see Figure 2-2).

2.2.4 Atmospherics

Hourly atmospheric data (air temperature, humidity, net solar radiation), measured at the St Helena Bay Weather Station, was obtained from the South African Weather Service.

2.3 Set-up of the hydrodynamic model

2.3.1 Processes included

Tides

Tides were included in the modelling via water level variations applied to the model boundary. This is the main driving force in the model.

Winds

Winds were included in the model calibration runs as well as in subsequent runs to simulate the hydrodynamic characteristics of St Helena Bay and the surrounding areas. Wind set up and Coriolis tilt effects on the water levels at the model boundaries were also taken into account during the predictions.

Temperature

Salinity was not modelled (a constant salinity was specified), but temperature was indeed one of the important processes included in the model. Consequently, the thermocline dynamics are explicitly included in the simulations.

Air sea interactions

Strong stratification is maintained by atmospheric heat fluxes into the surface waters and the inflow of cold bottom waters from upwelling on the adjacent open shelf. These processes control the thermocline dynamics and vertical mixing of the water column which, together with wind-and tidally-driven currents, ultimately determine the behaviour of biogeochemical parameters within the region. Heat fluxes were thus explicitly included in the modelling.

Note: Two major estuaries run into the ocean within the study area – The Great Berg Estuary and the Olifants Estuary. Compared to the large-scale marine processes that are being modelled and investigated, and because of the model period (summer), the freshwater run-off from these rivers is deemed insignificant. Therefore it was safe to assume that the river run-off in the vicinity of St Helena Bay and Olifants River mouth could be ignored for the purpose of this study. It should be noted that the run-off could become significant if a winter period is modelled. Waves were also not modelled, but this is a process that could possibly be tested in future.

2.3.2 Details of model setup

To enable an accurate simulation of the circulation patterns in the St Helena Bay area, it is necessary to include in the model a sufficiently large model domain. Such a large domain will ensure that the internal processes in the St Helena Bay model are not influenced in a significant way by the specified boundary conditions. The hydrodynamic grid is irregularly spaced, orthogonal and curvilinear, and is shown in Figure 2-4. As far as possible, the curvilinear grid is designed to follow the shoreline of the ocean, thus promoting a smooth flow pattern in these areas. It has a cross-shore length scale of 120 km on average, and a alongshore length scale of 280 km, stretching from south of Saldanha Bay to north of Olifants River mouth.

The hydrodynamic grid has 80 x 57 lines and is designed so that the grid size at the offshore boundary is as large as 9 km x 12 km, but is refined to a small size of approximately 1.8 km x 1km in the vicinity of St Helena Bay and along the coast, where a fine resolution in the results is required. The model grid has 3078 active cells. In the vertical, 10 layers were used with the thickness of the vertical layers (from surface to bottom) being 10 %, 10 %, 10 %, 9 %, 7 %, 7 %, 7 %, 15 %, 15 % and 10 % of the local water depth. The layers were concentrated around the thermocline in order to resolve this area accurately.

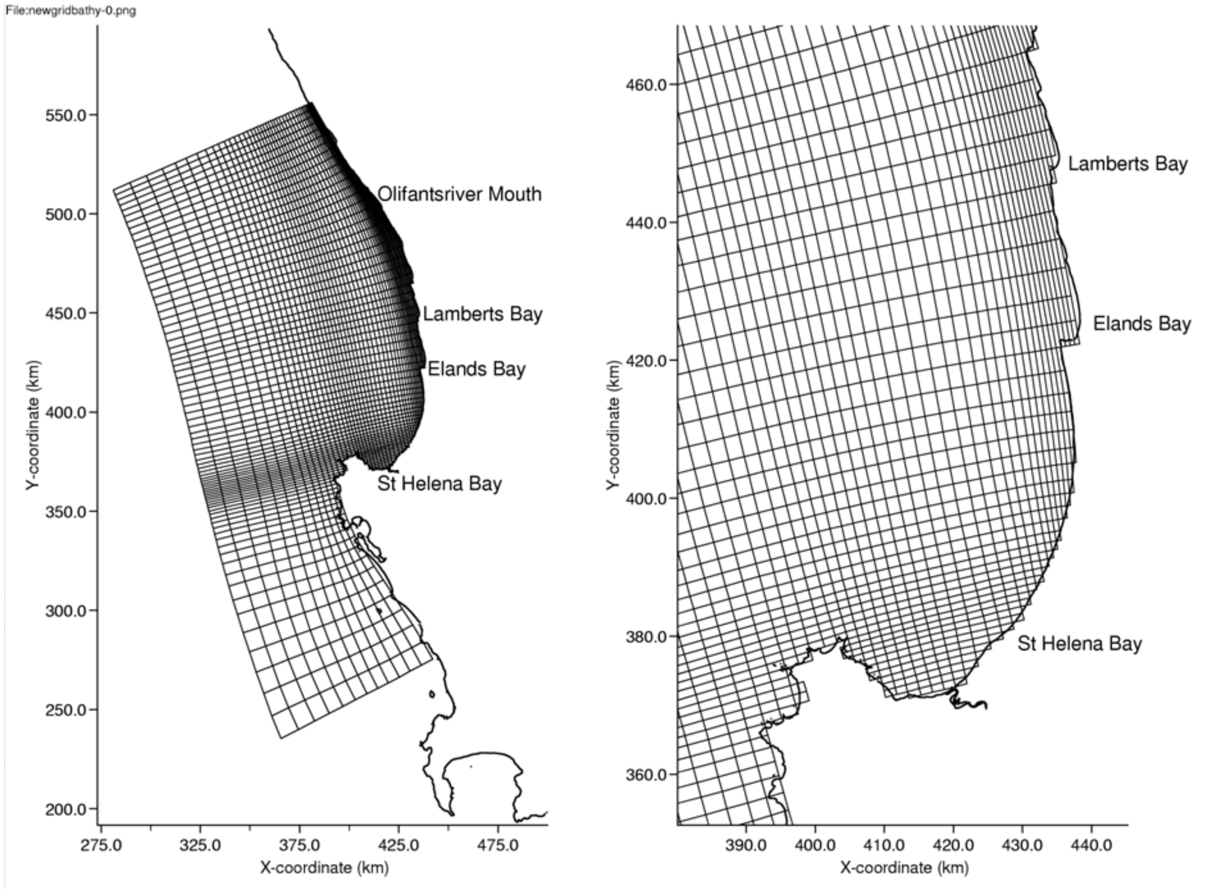

Figure 2-4: Hydrodynamic model grid: Full domain (left) and zoomed into the St Helena Bay area (right).

The x-y coordinate system used in the model is based on the Lo 19 coordinate system. A linear transformation is applied to the digitised SA Navy Chart depths (Section 2.3.1) to provide model coordinates (x_{model}, y_{model}) that are positive and increase from South to North and from West to East. The transformation used is:

$$x_{model} = 500\,000 - y_{lo19}$$
$$y_{model} = 4\,000\,000 - x_{lo19}.$$

These depths are mapped onto the computational grid by using triangular interpolation as well as grid cell averaging. The resulting bathymetry for the model is shown in Figure 2-5.

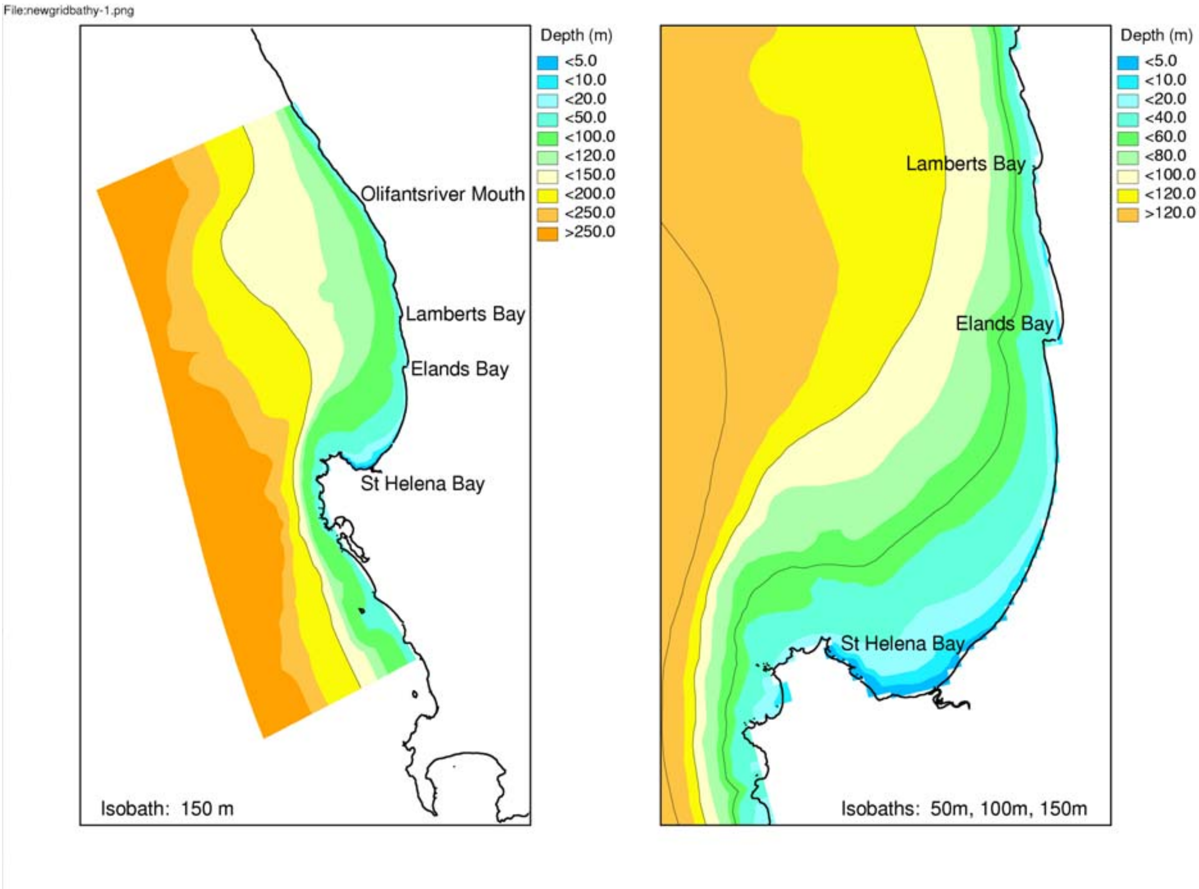

Figure 2-5: Hydrodynamic model bathymetry: Full domain (left) and zoomed into the St Helena Bay area (right).

The open boundaries in the sea are located along the three offshore edges of the model, which are the Southern, Western and Northern boundaries (Figure 2-5). For the simulations, water level time-series, which are based on the predicted tide, are specified at the open boundaries. The 8 largest amplitude tidal constituents along the West Coast (Saldanha Bay) were applied to predict the tide, namely those listed in Table 2-1 (Rozenthal and Grant, 1989). The tide is specified in the model at 10 minute time intervals.

Table 2-1: Tidal constituents to predict tidal sea levels at the open boundaries.

Tidal constituent	Amplitude (m)	Phase (degrees)
M2	0.4893	90.61
S2	0.2129	111.98
N2	0.1315	78.76
K2	0.0703	112.23
K1	0.0555	134.79
MU2	0.0209	64.44
O1	0.0154	260.06
P1	0.0144	131.00

Figure 2-6 shows a time series of the predicted tide at the open ocean boundaries of the model for the period January 2002. The spring-neap cycles can clearly be seen.

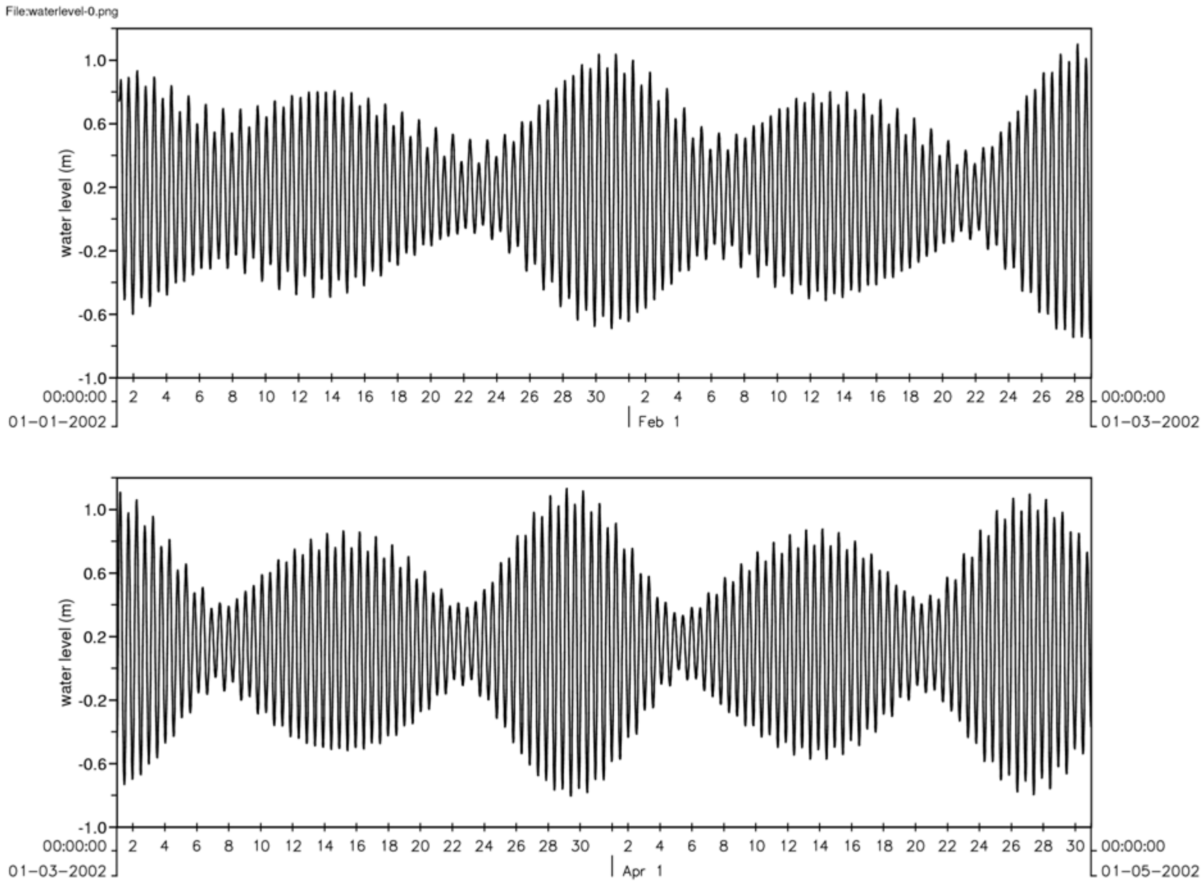

Figure 2-6: Predicted tide specified at the open boundaries for the period January 2002 – April 2002, indicating spring and neap tidal cycles.

All model runs used a “cold start” with the flow velocity being zero everywhere. The initial sea level was set to a constant according to the initial tidal sea level specified at the open boundaries.

2.4 Sensitivity test – Initial Conditions

Two model simulations were carried out in order to test the stability of the model with regards to the initial conditions specified at the start of each simulation. For the purpose of the sensitivity test, both simulations were undertaken for January 2002. The model setup in each case was exactly the same, except for the initial conditions. The difference in initial conditions was especially great in the top half of the water column.

Time series of the results from the two model simulations, compared to the measured temperatures at different depths in St Helena Bay are shown in Figure 2-7. The red line represents the measured temperatures from the thermistor chain in St Helena Bay, the blue line represents temperatures from the first test simulation, and the green line represents temperatures from the second test simulation.

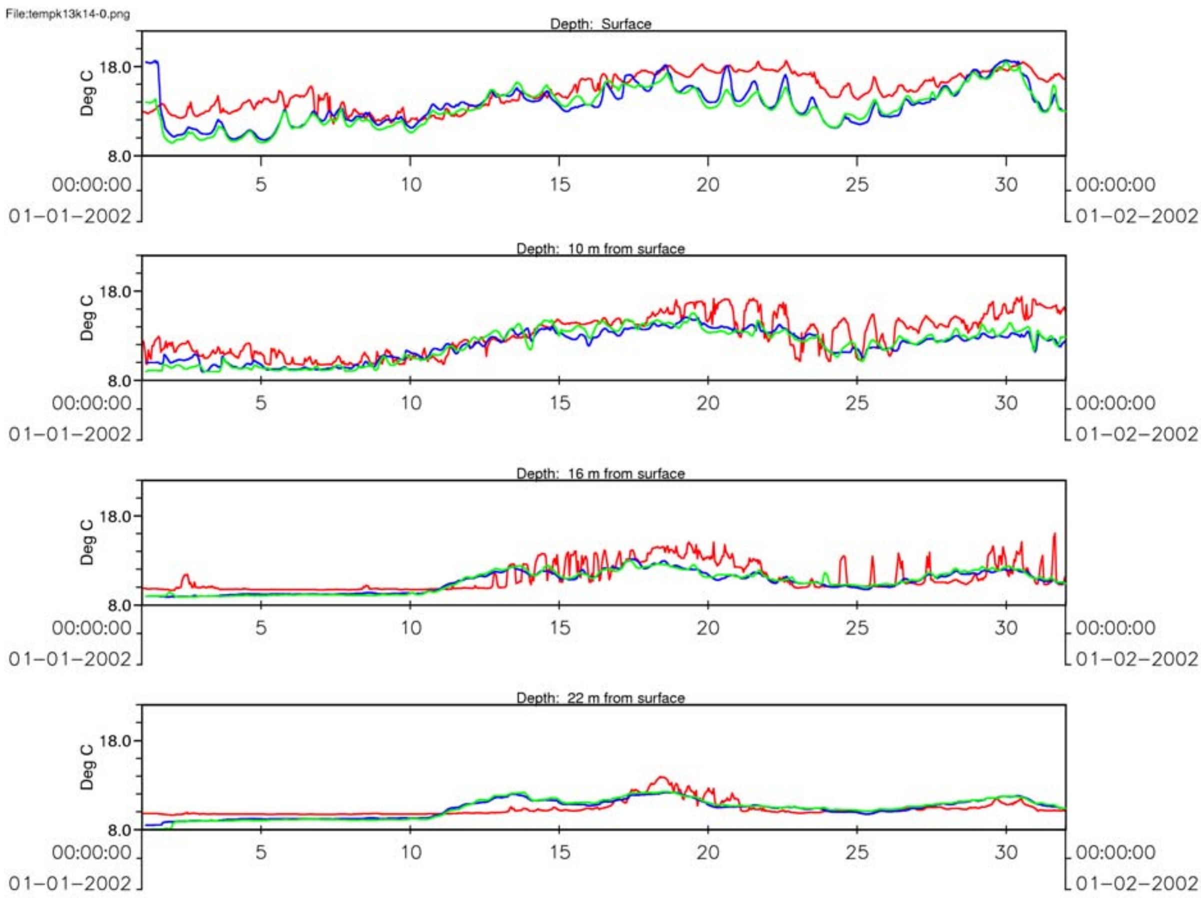

Figure 2-7: Sensitivity test: Comparison between measured temperatures (red) and modelled temperatures from two test simulations (blue and green) at different depths in St Helena Bay for January 2002.

Within a very short time (approximately three days) the effect of the different initial conditions were in essence eliminated. This finding is very useful when studying the predictive usage of this numerical model, as it shows that given a major perturbation, the system reverts back to its natural “attractor”, which indicates the stability of the model.

3. THE MODEL

3.1 Calibration

The first step in the modelling was to ensure that the model simulates the hydrodynamics of the system correctly. The calibration procedure was undertaken by modelling the hydrodynamics for the period January 2002. As mentioned in Section 2.2.2, high quality temperature data was obtained from a thermistor chain located in St Helena Bay. The model was calibrated by adjusting the static boundary conditions within acceptable limits, until acceptable agreement was obtained between the model results and the thermistor chain measurements.

The relevant model parameters applied in the model are shown in Table 3-1.

Table 3-1: Hydrodynamic model parameters.

Parameter	Value
Timestep	2 minutes
Horizontal eddy viscosity (*V*)	1 m^2/s
Bed friction formulation	Chezy
Roughness	55
Extra drying/flooding procedure	Max
Threshold depth for drying/flooding	1 m
Wind drag coefficient (C_d)	$0.0011 + 0.0065 \times U_{10}$

In the vertical, a comparison of the modelled and measured temperatures at the thermistor chain's location for January 2002 is shown in Figure 3-1.

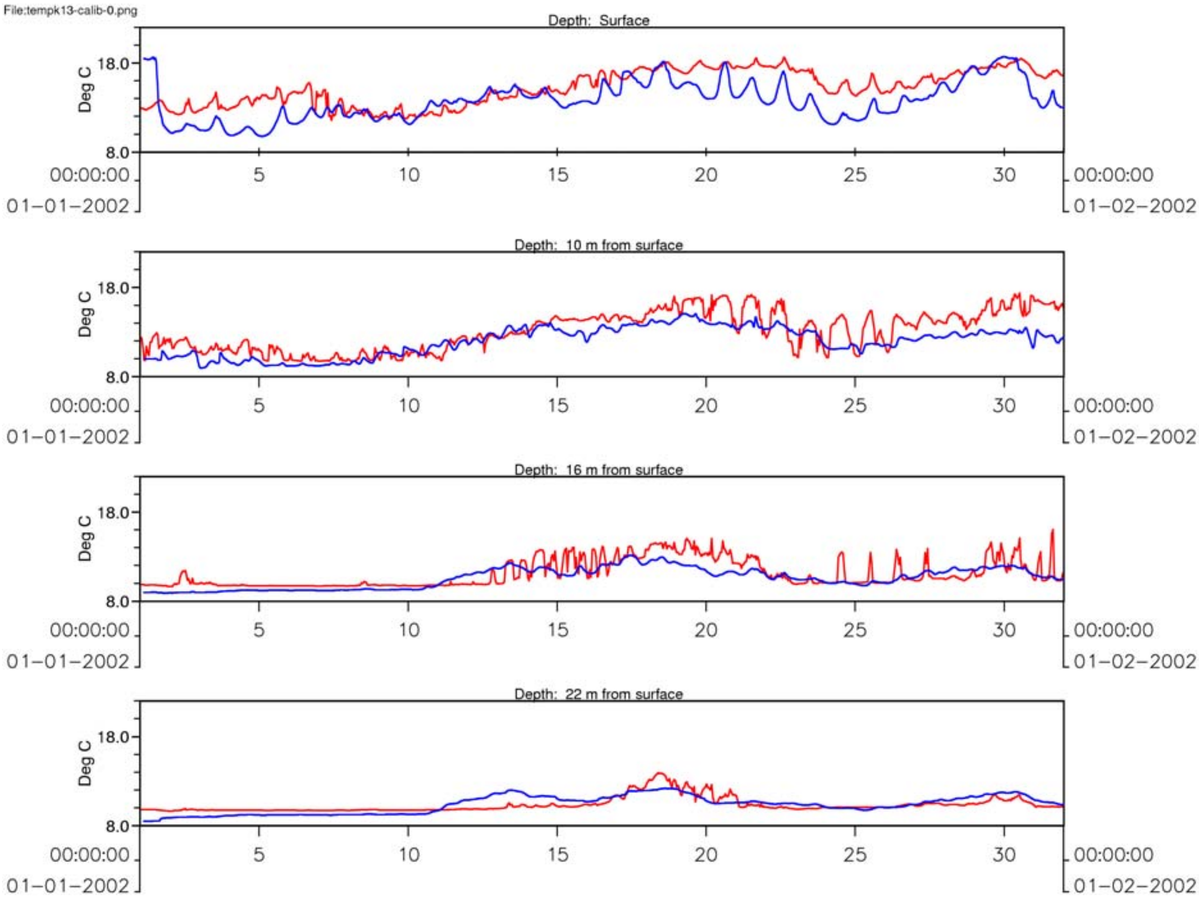

Figure 3-1: Comparison between measured (red) and modelled (blue) temperatures at different depths in St Helena Bay for January 2002.

Immediately evident is that the initial temperatures specified in the top layers of the model are approximately 4°C warmer than the measured temperatures. However, the modelled temperature cools down and stabilizes quickly (for a sensitivity test on the initial conditions of the model). Overall, the model represents the 6 - 8 day event scale warming and cooling well, although the modelled temperatures seem to be colder than the measured temperatures throughout the water column for most of the simulation time. The modelled temperatures also show less diurnal variability than the measured temperatures.

In general, the modelled temperatures in St Helena Bay are within 2°C - 3°C of the measured values, which were considered sufficiently accurate for the present application.

3.2 Calibrated model – Simulation

After calibration for January 2002, the same model setup was used to undertake a 4 month simulation. The simulation period was January to April 2002, long enough to include the major upwelling events and to include the months that red tide occur most often. The results from the 4 month simulation are presented in Chapter 4, and these results are verified relative to remote sensing imagery.

4. RESULTS

In this section, the model results from the 4 month simulation are being presented, as well as a verification of the results relative to remote sensing imagery.

In order to look at the seasonal behaviour of the model, a comparison of the modelled and measured temperatures at the thermistor chain's location for the period January – April 2002 is shown in Figure 4-1(a). The temperatures are given at four different depths (Surface, 10 m from the surface, 16 m from the surface, and bottom) in order to illustrate the temperature variations throughout the water column. In this figure, the red line represents the measured temperatures and the blue line represents the modelled temperatures.

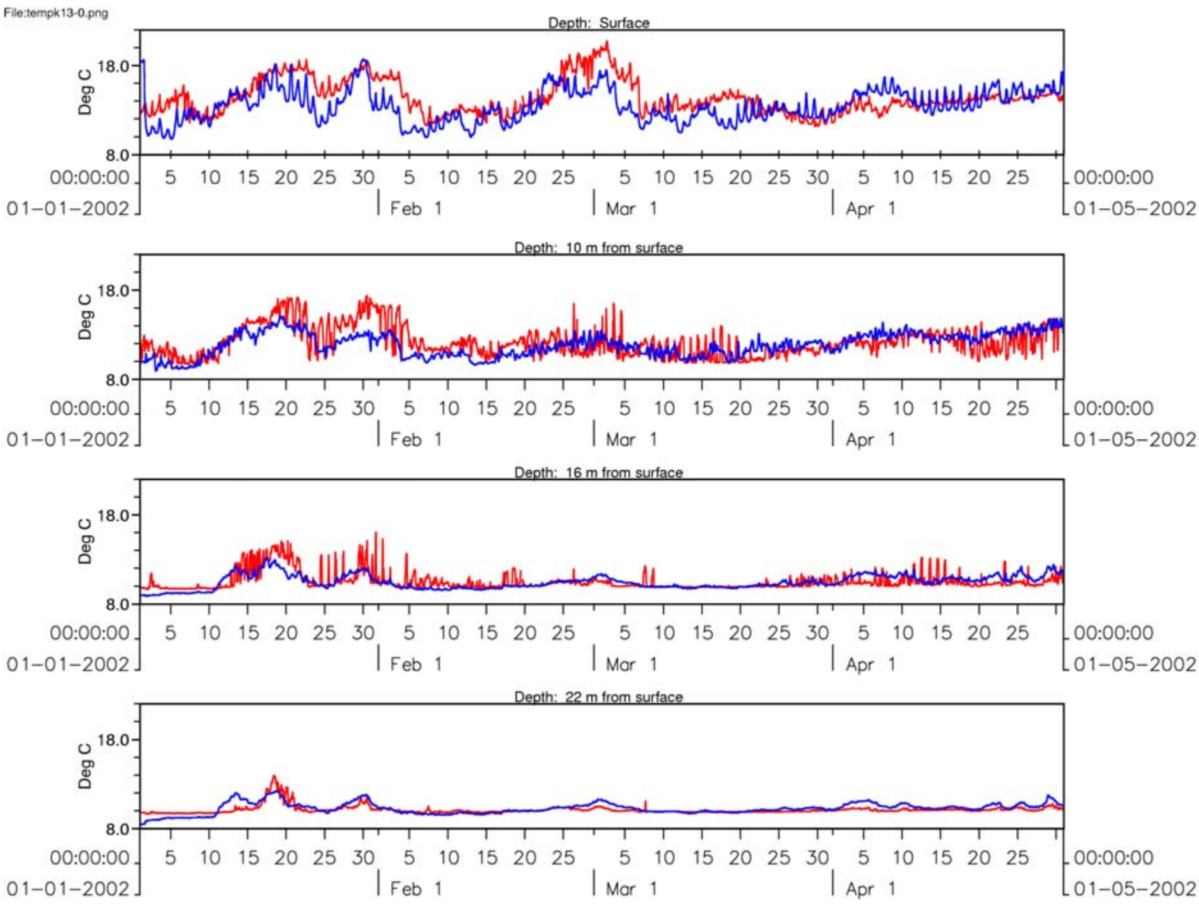

Figure 4-1(a) Comparison between measured (red) and modelled (blue) temperatures at different depths in St Helena Bay for January – April 2002.

The behaviour of the model for January 2002 was discussed in Section 3.1. For the period February – April 2002, the modelled temperatures still mostly display cooler values than the measured temperatures, especially in the surface layer, except for the period from late March to end April 2002. Here the modelled temperatures are warmer than the measured temperatures throughout the water column. In the deeper layers, the model gives a good representation of the event scale variations in temperature. The diurnal variations in temperature are, however, not well represented in the model results throughout the whole water column. Figure 4-1(b) shows the anomalies for temperature at different depths for the period mid February to end April 2002. The anomalies were obtained by calculating the percentage difference between the modelled and measured temperatures. Here a positive anomaly indicates that the modelled temperature was higher than the measured temperature, and a negative anomaly indicates the converse.

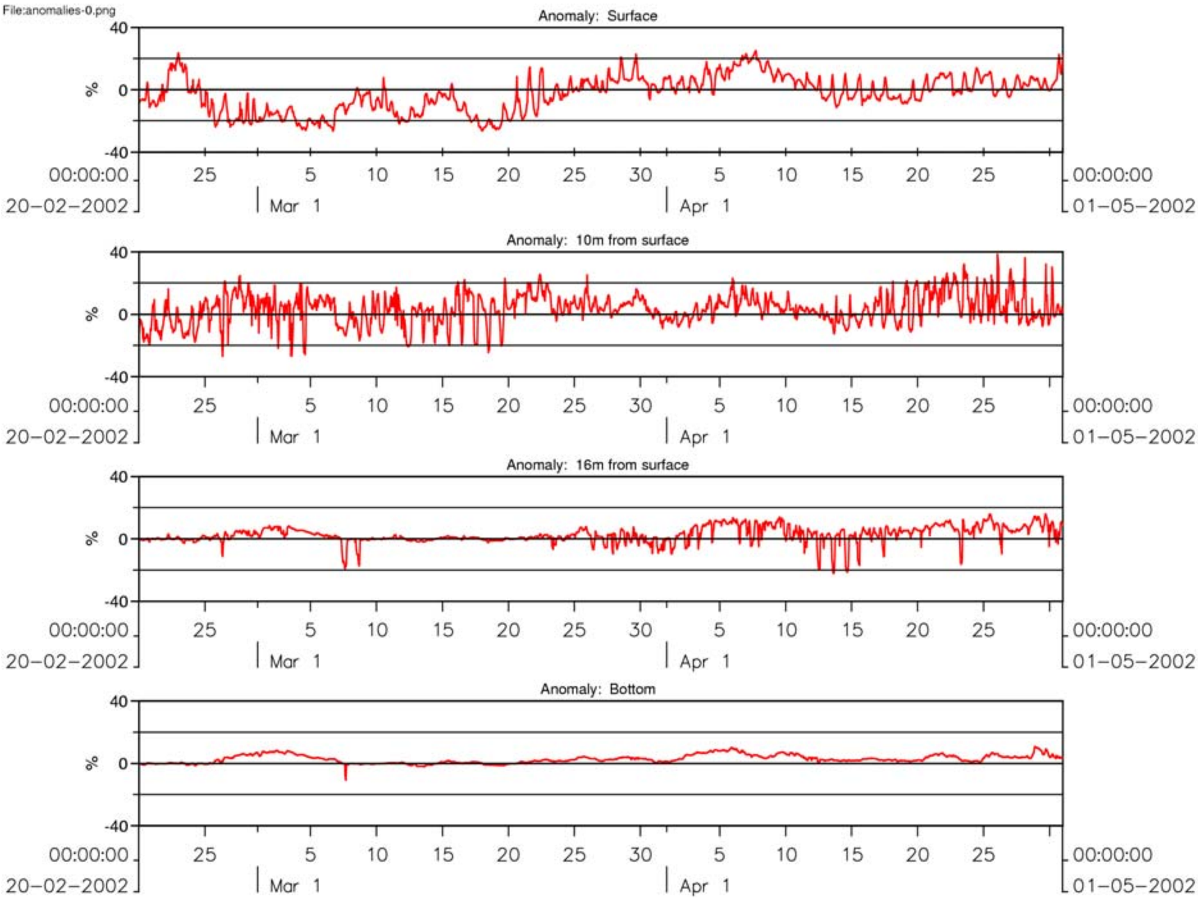

Figure 4-1(b): Anomalies for temperature for the period mid February to end April 2002, at different depths. Here a positive anomaly indicates that the measured temperature was higher than the modelled temperature.

At the surface, the above figure shows a negative anomaly ranging between 0% and 20% for most of March 2002, and a positive anomaly mostly ranging between 0% and 10% for April 2002.

At 10 m from the surface, the above figure shows highly variable anomalies, ranging between -20% and 20% for most March and April 2002. Towards the end of April, the anomalies show increasing instances of stronger positive anomalies, indicating that the modelled temperatures are between 0% and 40% higher than the measured temperatures. When focussing on the lower frequency values, thus the event scale rather than the diurnal/inertial scale, there is very good agreement between the measured and modelled temperatures.

At 16 m from the surface and at the bottom, the above figure shows relatively weak anomalies, ranging between -10% and 10% for most of March and April 2002. Towards the end of April, the anomalies become stronger positive with some instances of negative values, indicating that the modelled temperatures are on average between 0% and 20% higher than the measured temperatures.

Overall, Figure 4-1(b) indicates that there is a relatively good concordance between measured and modelled temperatures, especially in the deeper layers of the water column.

On a spatial scale, Figures 4-2(a) – (g) show a comparison between SST (sea surface temperature) obtained from remote sensing imagery, on different days towards the end of January and the beginning of February 2002, and the modelled surface temperatures at closely the same times. This period starts off during the onset of relaxation following an upwelling event. This relaxation event is followed by an extended period of upwelling.

The arrows on the model outputs indicate current speed and direction.

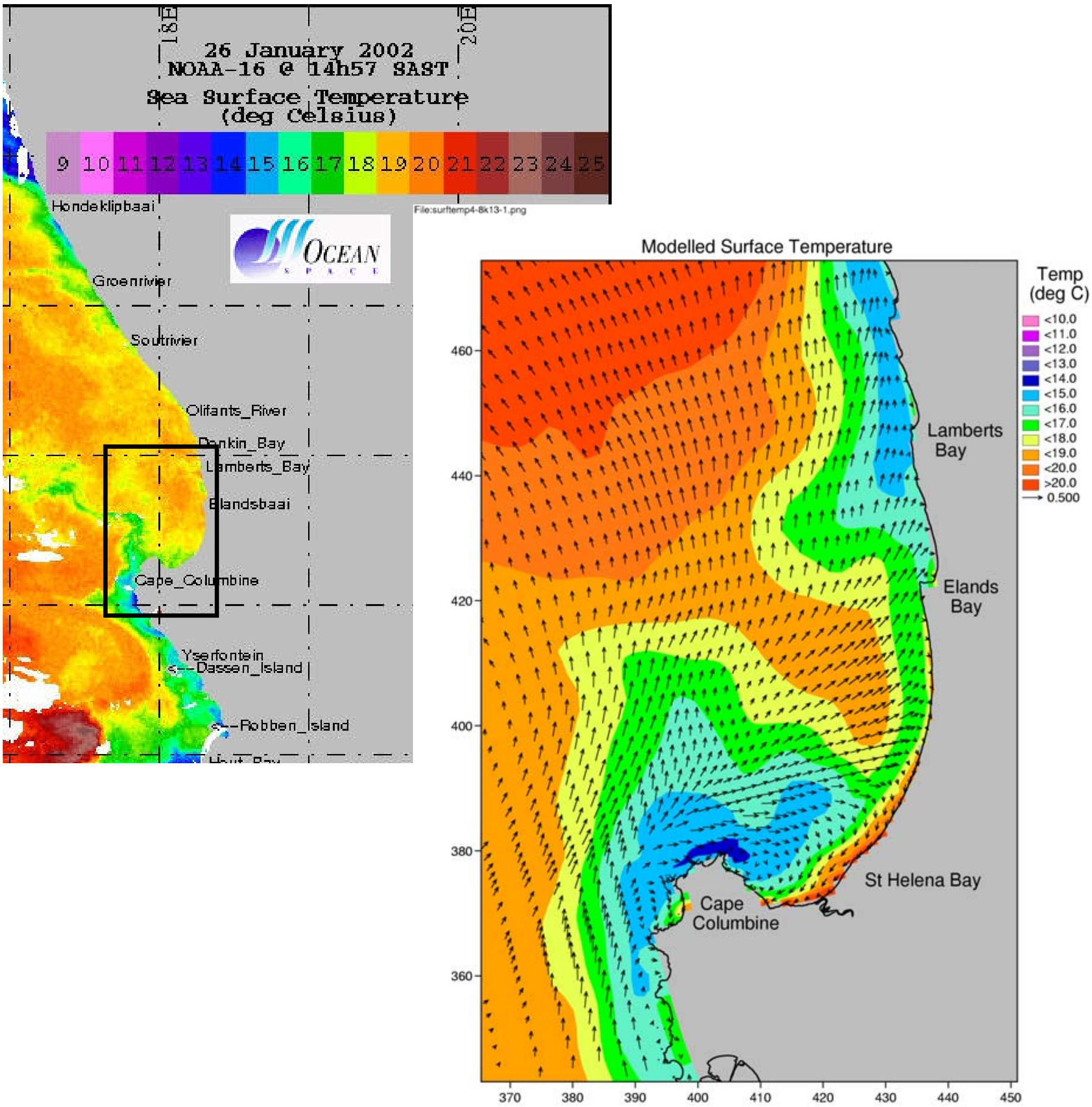

Figure 4-2(a): Comparison between the remote sensing image (top left) and modelled surface temperatures (bottom left) on 26 January 2002, showing the onset of relaxation following an upwelling event.

In Figure 4-2(a), the remote sensing image shows cold upwelled water at Cape Columbine and along the coast between Lamberts Bay and Elands Bay (as a result of the preceding upwelling event), with the water displaying temperatures of 14°C -17°C on average. It is clear that relaxation has started to take place. The rest of the area of interest has water temperatures ranging from 19°C to 20°C. Between Elands Bay and Lamberts Bay, a small patch of water with a temperature of 17°C is visible.

The modelled surface temperatures show similar trends, although the water along the coast from the eastern part of St Helena Bay northwards is too cold.

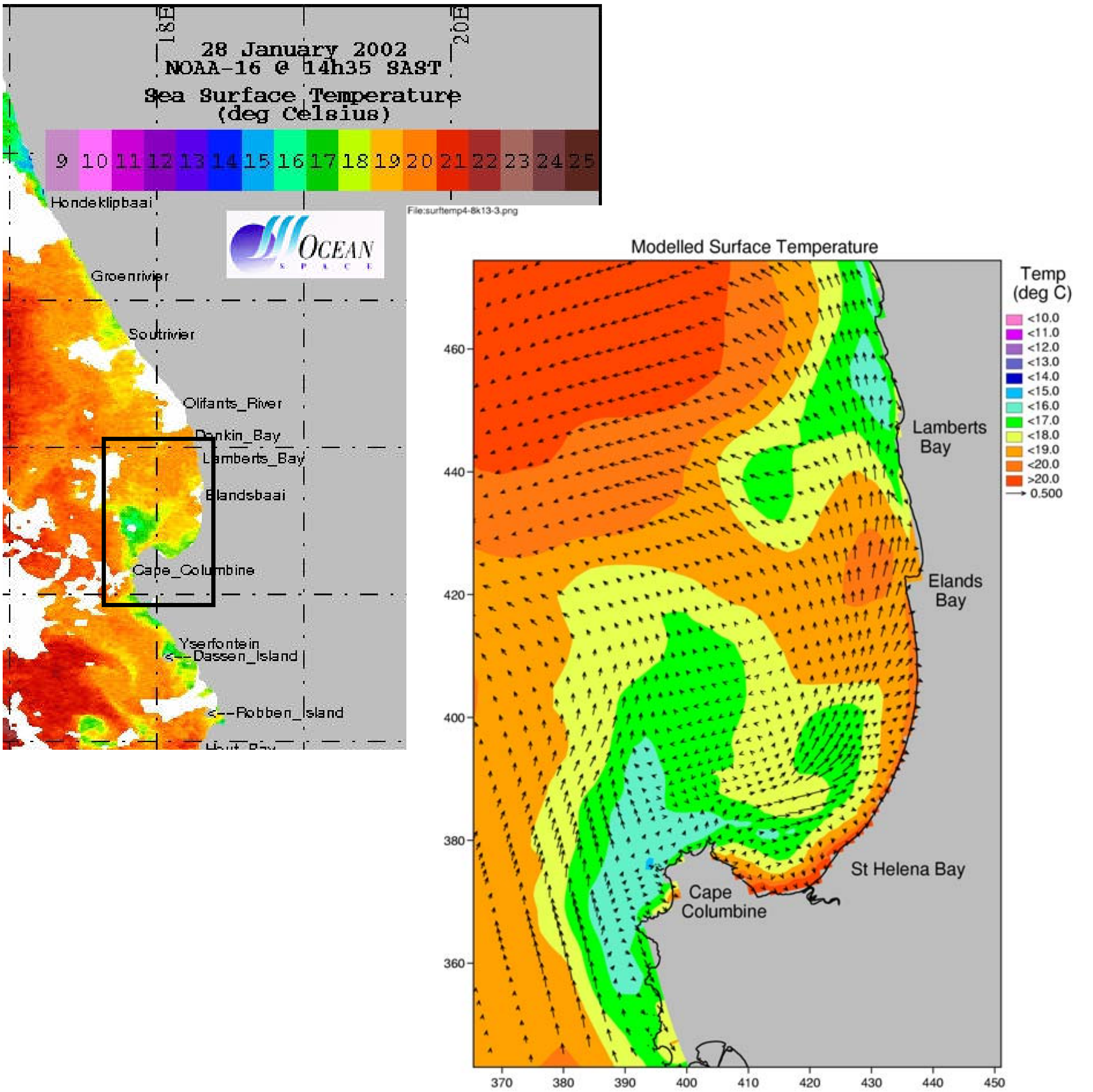

Figure 4-2(b): Comparison between the remote sensing image (top left) and modelled surface temperatures (bottom left) on 28 January 2002, showing the system in a relaxed state with warm temperatures throughout the area of interest.

In Figure 4-2(b), the remote sensing image shows the system in a relaxed state, with water temperatures ranging between 17°C and 20°C throughout the area of interest. The coolest water can be seen north of Cape Columbine and in St Helena Bay.

Throughout most of the area, the modelled temperatures range between 16°C and 20°C.

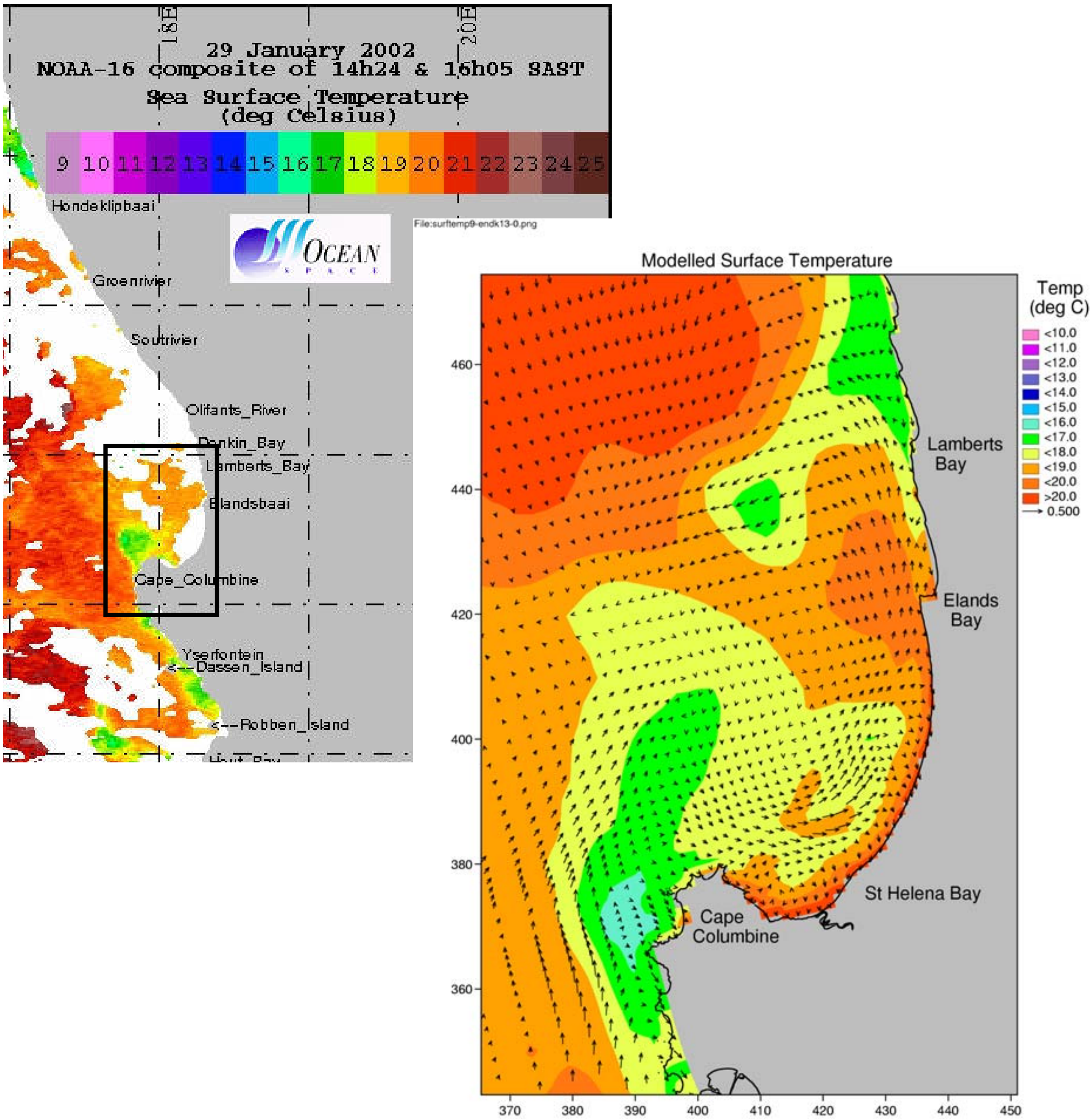

Figure 4-2(c): Comparison between the remote sensing image (top left) and modelled surface temperatures (bottom left) on 29 January 2002, showing the system in a relaxed state with warm temperatures throughout the area of interest.

In Figure 4-2(c), the remote sensing image still shows the system in a relaxed state, water temperatures ranging between 17°C and 18°C north of Cape Columbine. Due to the cloudiness, some of the detail is not clearly visible.

The model still indicates surface temperatures ranging between 16°C and 20°C.

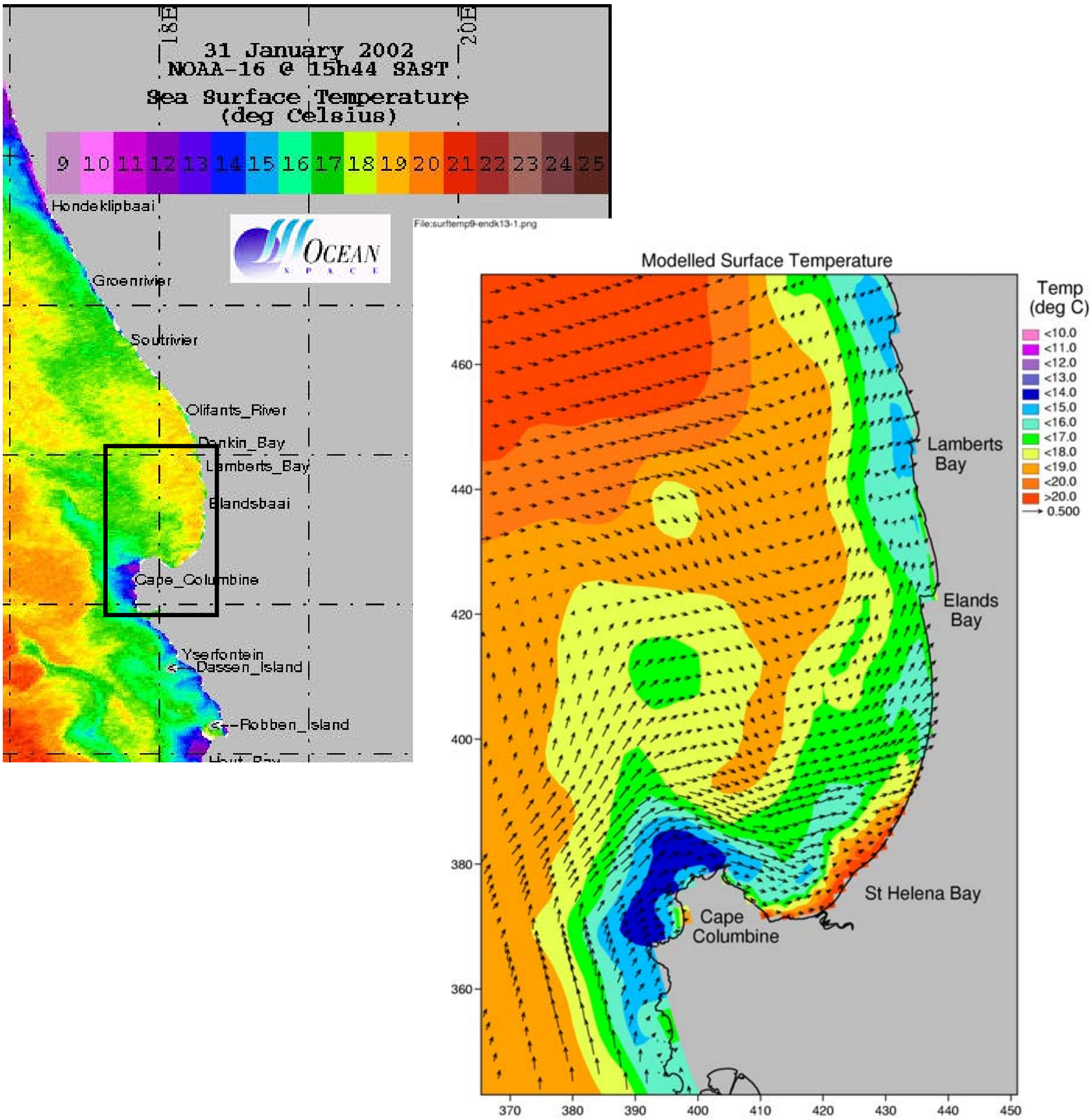

Figure 4-2(d): Comparison between the remote sensing image (top left) and modelled surface temperatures (bottom left) on 31 January 2002, showing upwelling at Cape Columbine and along the coast at Lamberts Bay and Elands Bay.

In Figure 4-2(d), the remote sensing image shows the start of an upwelling event at Cape Columbine. Temperatures to the west of Cape Columbine range between 12°C and 15°C. The water north of Cape Columbine is approximately 17°C, while the water closer inshore and in St Helena Bay is warmer at approximately 19°C. An upwelling event is also evident in the modelled temperatures, with the temperatures at Cape Columbine being approximately 14°C. The model also indicates a colder strip of water (approximately 15°C - 16°C) closely inshore.

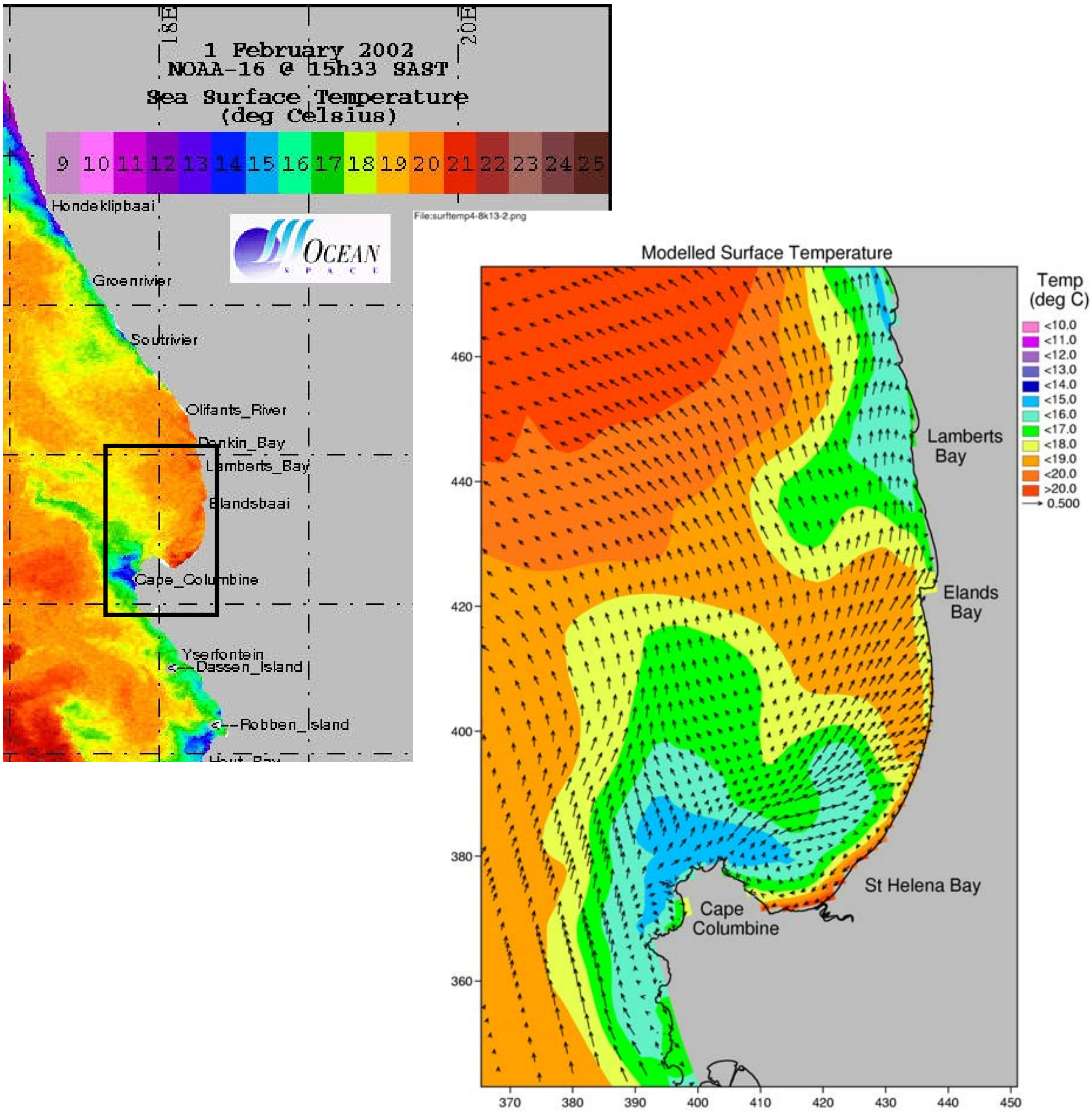

Figure 4-2(e): Comparison between the remote sensing image (top left) and modelled surface temperatures (bottom left) on 1 February 2002, showing upwelling at Cape Columbine and along the coast at Lamberts Bay and Elands Bay.

The remote sensing image in Figure 4-2(e) shows the beginning of an upwelling event. Cold water (between 14°C and 17°C) can be seen around Cape Columbine. The water on the shelf is approximately 20°C, while the water in St Helena Bay is as warm as 21°C. The model shows water ranging between 14°C and 17°C at Cape Columbine as well as along the coast. The water in St Helena Bay is warmer than 19°C.

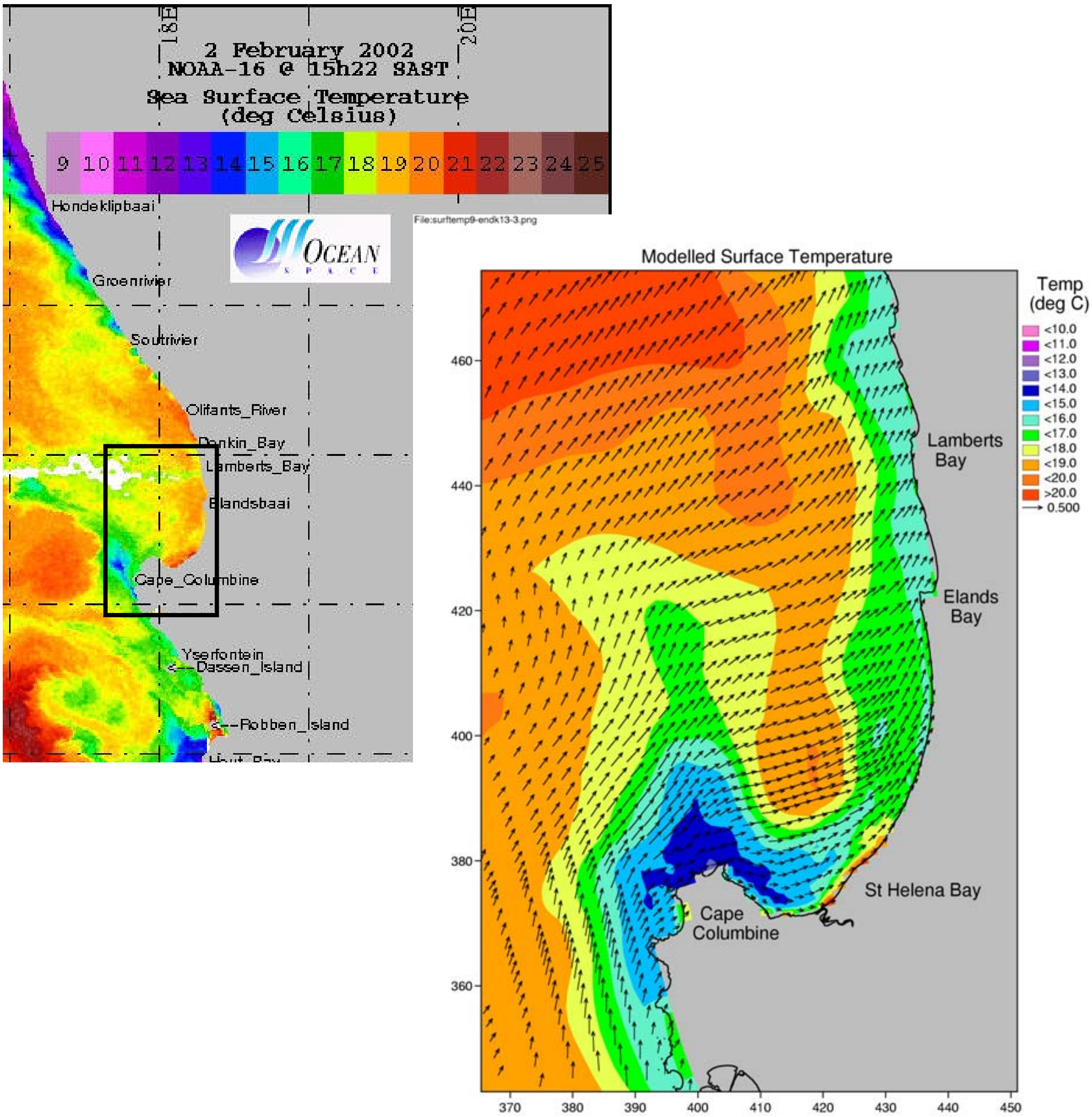

Figure 4-2(f): Comparison between the remote sensing image (top left) and modelled surface temperatures (bottom left) on 2 February 2002, showing strengthened upwelling at Cape Columbine and along the coast at Lamberts Bay and Elands Bay.

In Figure 4-2(f), the remote sensing image as well as the model results still show an upwelling event.

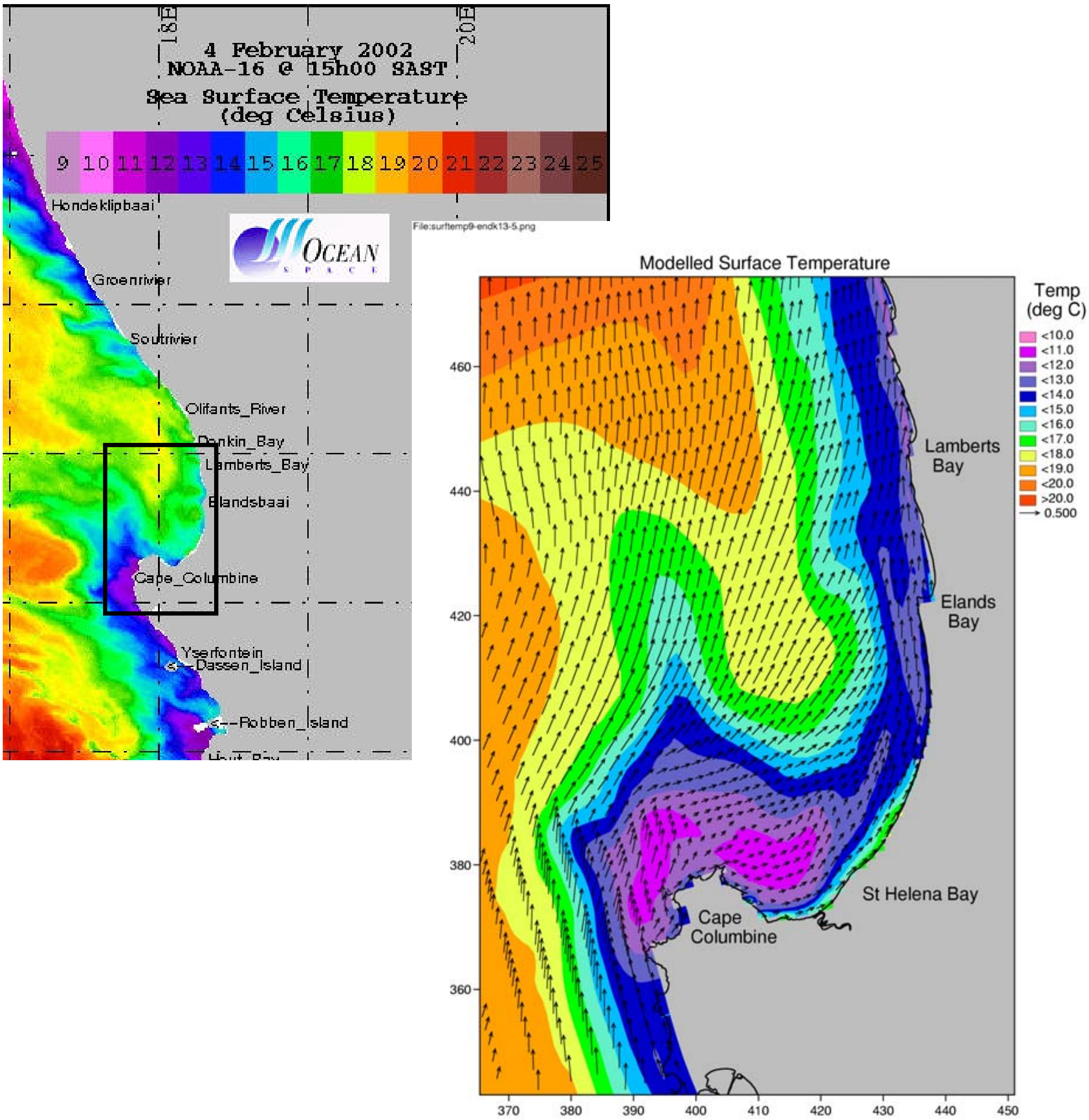

Figure 4-2(g): Comparison between the remote sensing image (top left) and modelled surface temperatures (bottom left) on 4 February 2002, showing strong upwelling at Cape Columbine, in St Helena Bay and along the coast at Lamberts Bay and Elands Bay.

In Figure 4-2(g), the remote sensing image as well as the model results indicate even stronger upwelling, with the temperature at Cape Columbine reaching minimum values of approximately 12°C.

In addition to the above figures, Figures A-2(a) – (d) in Appendix A show a series of modelled surface temperatures in the horizontal plane (at 15:00 daily for the whole of January 2002) in the study area. Figures A-3(a) – (d) in Appendix A show a series of vertical sections at Lamberts Bay at the same times. The vertical sections stretch 20 km offshore (up to a maximum depth of approximately 90 m).

Throughout the time series shown in these figures, the upwelling-relaxation events can clearly be seen.

A vertical temperature section was taken at the St Helena Bay measuring line during a CTD cruise undertaken by MCM (Marine and Coastal Management) from 16 - 17 January 2002 (Figure 4-3(a)).

The data consists of vertical temperature profiles at 10 locations along the measuring line. The plot was created by interpolating between values; therefore a smooth vertical profile could be drawn up.

Figure 4-3(b) shows the modelled vertical temperature section at closely the same location as the St Helena Bay measuring line. The date of this section is 17 January 2002.

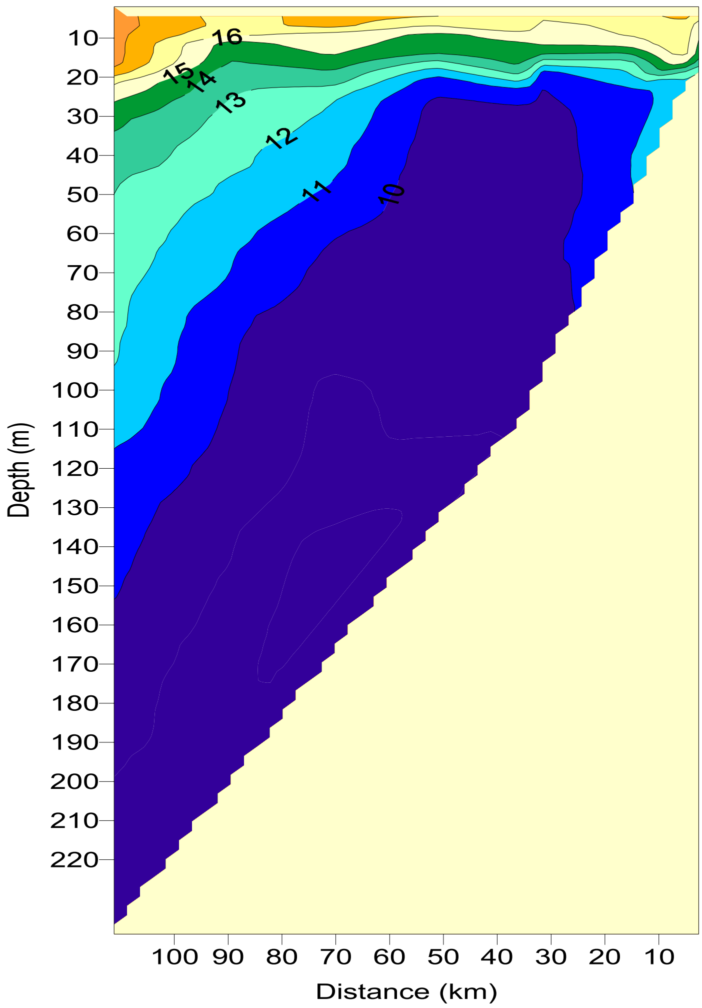

Figure 4-3(a): Vertical transect of measured temperature at the St Helena Bay measuring line: 16 - 17 January 2002.

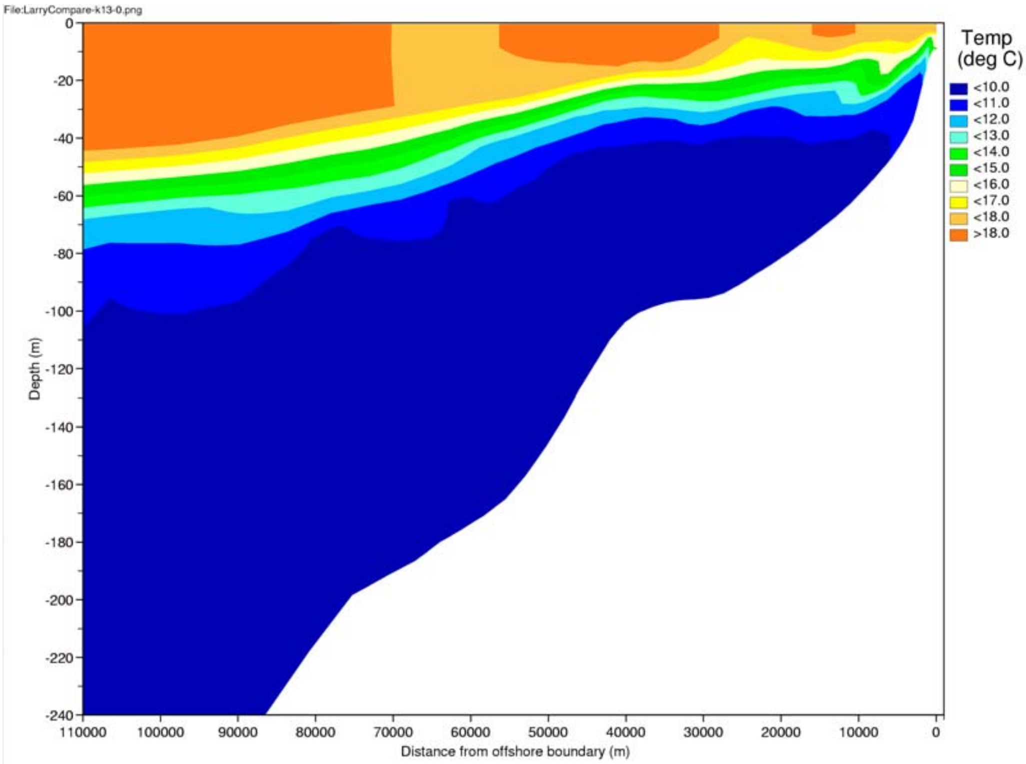

Figure 4-3(b): Vertical transect of modelled temperature at the St Helena Bay measuring line: 17 January 2002, 00:00.

Overall, a comparison between Figures 4-3(a) and (b) reveals a relatively good agreement between the measured and the modelled temperatures when looking at the overall pattern of temperature distribution. Three warm patches of water are noted in the surface waters of both of the sections. The modelled surface waters, however, are warmer and occurs in a thicker layer than indicated by the measured temperatures. Offshore, cold water of 10˚C is seen deeper than 150 m in Figure 4-3(a), and deeper than 110 m in Figure 4-3(b).

It should be noted that a perfect concordance between these sections would have been pure coincidence, as the measurements were taken over a period of time, and the model results are at one specific time during the simulation.

Poleward jet

The results from the numerical modelling shows several instances of the poleward surface jet developing along the coast. One of these occurances are shown in Figure 4-4. The “(a)” part of the figure indicates surface temperatures and currents in the horizontal plane during an upwelling and a subsequent relaxation event (dates and times are indicated on the figures). This part of the figure is zoomed in on the Lamberts Bay area.

The “(b)” part of the figure shows the temperatures and currents at the same times as the “(a)” part, except that this part shows the occurrence of the current over a larger area - all the way from Lamberts Bay to south of Cape Columbine.

The “(c)” part of the figure shows a vertical section at Lamberts Bay taken from the model at the same times.

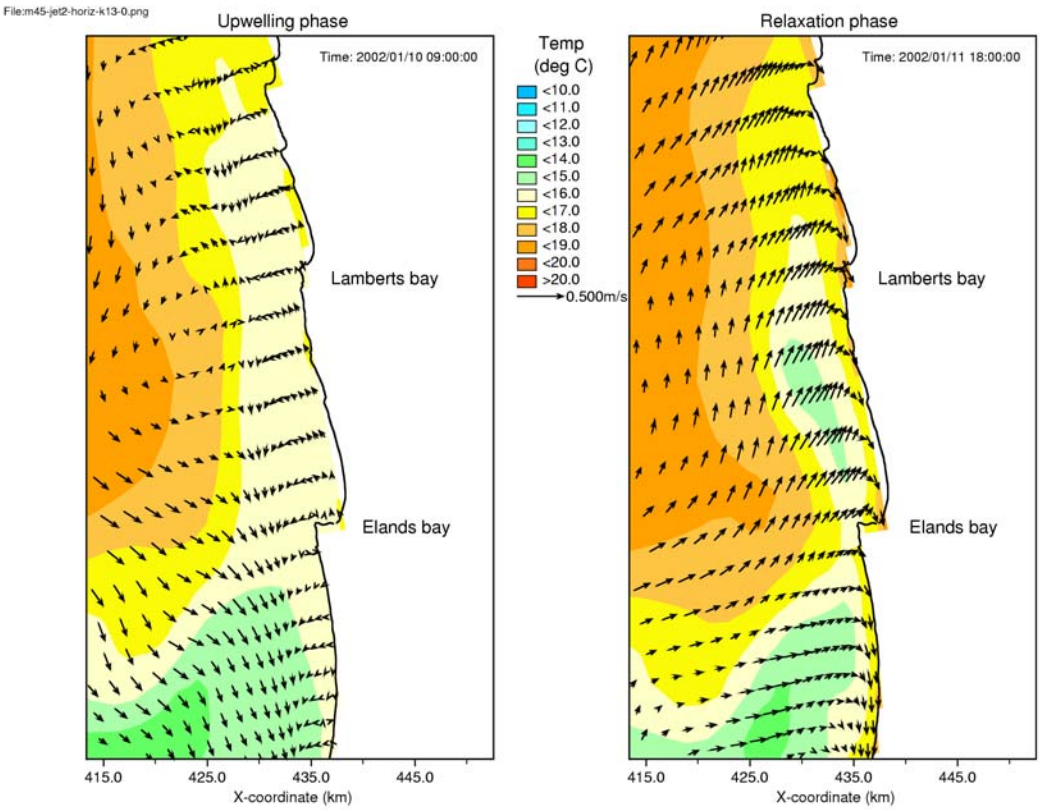

Figure 4-4(a): Modelled surface temperature and currents along the West Coast during an upwelling (2002/01/10) and consecutive relaxation (2002/01/11) event, zoomed in on Lamberts Bay.

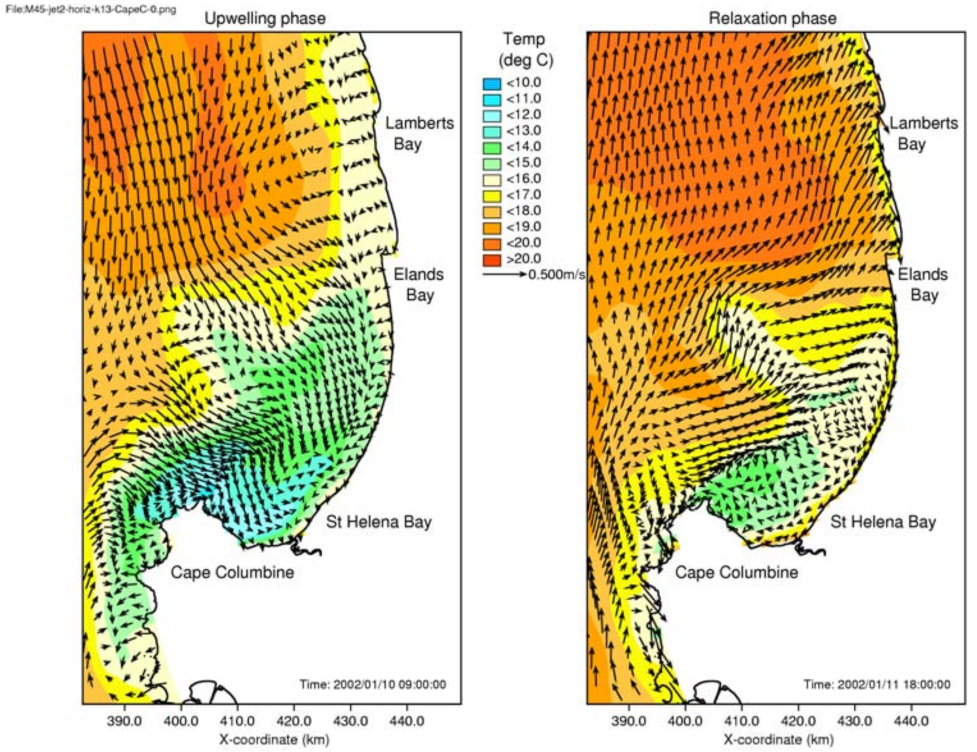

Figure 4-4(b): Modelled surface temperature and currents along the West Coast during an upwelling (2002/01/10) and consecutive relaxation (2002/01/11) event, showing the poleward jet in a narrow band along the coastline, from Lamberts Bay towards St Helena Bay and around Cape Columbine.

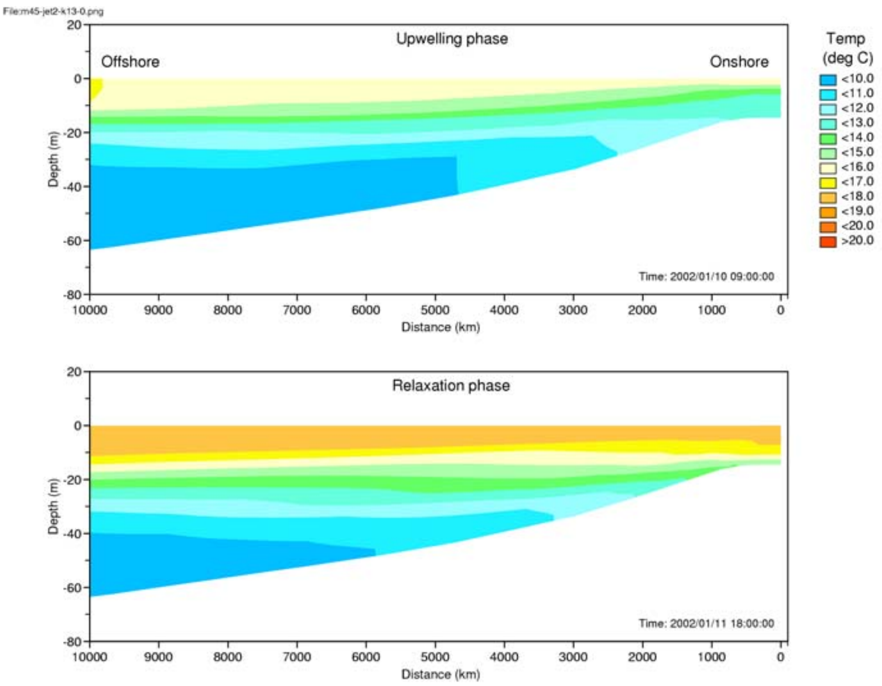

Figure 4-4(c): Modelled vertical temperature section at Lamberts Bay during an upwelling (2002/01/10) and consecutive relaxation (2002/01/11) event.

In each of the above illustrations the upwelling event (in this case in mid January 2002) is clearly visible in the horizontal and the vertical plane (for instance the cold water along the coastline, and the warm water offshore). As soon as the southwesterly wind relaxes, the cold inshore water that was situated in the surface layers pulls back into the deeper layers, and consequently the warmer, offshore water moves onshore. It is during this event that the poleward jet develops in a narrow band along the coastline. This jet is visible all along the coastline, from north of Lamberts Bay, into St Helena Bay, and all around Cape Columbine towards the south.

Figures A-4 and A-5 in Appendix A show two more instances of the poleward jet that developed during the simulation period.

5. DISCUSSION

Setting up a numerical model requires several data sets. Regarding the wind data applied during the model simulation, Figures 2-3(a) – (b) gave a representation of the wind time series during the months of January – February 2002 (the simulation period) measured at Cape Columbine. (Wind time series for March and April 2002 are given in the Appendix). The wind speed and direction play a key role in the development of upwelling events in the St Helena Bay region. Persistent southwesterly winds are upwelling favourable, while a reversal of the wind direction and lower wind speeds lead to relaxation conditions. During January 2002 the predominant wind direction was southwesterly, with speeds ranging between 2m/s and 10m/s (Figure 2-3(a)). A strong upwelling event was evident around the 24th of January, with a wind speed that reached 12m/s. The winds measured in February 2002 indicated more or less the same trends in wind speed and direction, with a strong upwelling event that stretched from the 3rd of February to the 7th of February (Figure 2-3(b)).

The possibility of using spatially-varying winds in the model simulations must be investigated, but in order to apply such winds in the model, good quality high resolution wind data is thought to be important. Wind data obtained from QuickScat is inadequate because of the large pixel size (25 km squares), as well as the location of the data. This data will not be reliable enough to apply as spatially varying winds in the model. There is thus a need for better wind data, and the solution would be to use output from an atmospheric model, such as MM5. This is planned as part of BCLME activities in the near future.

Another data set that is important for the model simulations are accurate boundary conditions. For the purpose of this study, data measured at Hondeklip Bay was applied at the boundaries, due to a lack of any better data. Very few good quality boundary conditions are obtainable from data sources, and the model requires measurements from specific areas at specific time scales, than do not exist. For this purpose, a measurement programme is underway to obtain good quality temperature data that can be applied as boundary conditions in a numerical model.

The calibration of the numerical model for the month of January 2002 was discussed in Section 3.1. It was noted that the model represents the 6-8 day event scale variations in temperature remarkably well. The stratification and mixing as strong wind events (and subsequent relaxation of the wind) take place are also reproduced well.

The most noticeable discrepancy between the measured and modelled temperature time series is that there are instances when the modelled temperatures are often colder than the measured temperatures. This discrepancy between the measured and modelled values can most probably be attributed to the fact that constant wind speed and direction is applied throughout the model domain for the purpose of this simulation; spatially-varying winds are thus not used. As a result, the model does not take account of the wind shadow that exists in the St Helena Bay area due to the presence of Cape Columbine. Larger wind speeds than the actual is thus being applied in the St Helena Bay area, leading to stronger entrainment of cold water into the surface layer, and thus colder temperatures in the model results.

Model results for the whole simulation period (January – April 2002) in Chapter 4 point to a number of key aspects that need to be investigated.

In the vertical (on a seasonal scale), it is important that the model represents the overall behaviour in the vertical temperature structure (i.e. stratification and mixing processes) sufficiently well over the simulation period. The warming and cooling of the water as upwelling-relaxation events take place must be evident.

In Chapter 4, a time series of temperature at different depths in the water column for the four month simulation period, as well as temperature anomalies for the period mid February to end April 2002, reveal that the model results compare well with the measured results in terms of overall behaviour of the temperature structure. The model performs well in reproducing the seasonal variability in temperature, as well as the event scale variability. The model, however, did not reproduce the diurnal variability in the temperature in the surface layer as clearly as it appears in the measurements. A likely reason for this could be the fact that the modelled temperatures are average values per model layer, and not values at a specific point in depth.

The most possible reason for this discrepancy between the measured and modelled temperatures in the surface layers could once again be attributed to the fact that spatially-varying winds were not applied in the model. An additional cause for the discrepancies could also be the static boundary conditions that are being applied in the model. Boundary values taken from data for January 2002 are being applied for the duration of the four month model simulation. The anomalies in Figure 4-1(b) show that the model data is already simulating at least 80% of the system correctly. Addressing these two factors (wind data and boundary conditions) will lead to a significant improvement in anomalies between measured and modelled data.

There were instances when the model results were colder than the measured results; at times, however, the model results were warmer than the measured temperatures. The temperatures in the deeper layers of the water column compared well to the measurements. The main differences are attributed to high frequency inertial period variability in the strong thermocline. The sigma layer model schematization does not resolve the sharpness of the thermocline in the same way as observations so the high frequency variability is weaker.

In order to study the model results on a spatial (horizontal) scale, a specific period stretching from end January to early February 2002 was chosen, due to the strong upwelling event that was evident during that time, as well as the availability of remote sensing imagery.

From the 18th of January to the 25th of January, a relatively strong southwesterly wind persisted (Figure 2-3(a)), leading to upwelling around Cape Columbine. This upwelling event can be clearly seen in the measured temperatures shown in Figure 2-2, as cold bottom water protrude into the surface layers, leading to mixing and the subsequent cooling of the surface waters. Stratification collapses and the water column becomes mixed. The surface temperature obtained from the remote sensing image in Figure 4-2(a) shows the end of this upwelling event, with cold water evident round Cape Columbine and in St Helena Bay. During this time, surface blooms of dinoflagellates accumulate inshore, north of Lamberts Bay.

The upwelling favourable wind dies down from the 26th to the 30th of January (Figure 2-3(a)), leading to a state of relaxation in the whole system. The system re-stratifies as the wind mixing ceases and as sun-warming takes place in the surface layers (Figure 2-2). The remote sensing image shows this relaxed state, with the surface waters staying relatively warm (Figures 4-2(b) and (c)). During a time of relaxation, currents become directed onshore, causing the dinoflagellate blooms to accumulate inshore. A narrow inshore poleward current then transports these blooms southward, towards St Helena Bay.

A persistent southwesterly wind develops on 30 January (Figure 2-3(a) – (b)), continuing for approximately 9 days, leading to a very strong upwelling event. This strong event is very clear in Figure 2-2, when stratification collapses almost completely through mixing/entrainment and the water throughout the water column becomes relatively cold. The remote sensing images also indicates this event (Figures 4-2(d) – (g)) as upwelling strengthens around Cape Columbine, leading to cold surface temperatures.

On a spatial scale the numerical model's surface temperatures represent the upwelling and relaxation events around Cape Columbine as it was observed on the days the remote sensing images were taken (Figures 4-2(a) – (g)). It also represents the upwelling inshore, along the coast towards the north of St Helena Bay. However, some discrepancies between the observed and the modelled surface temperatures do exist. At times the modelled temperatures in St Helena Bay did not become as warm as was observed at approximately the same times. Overall the model seems to show colder temperatures than what was observed. This is in accordance with the conclusion that was made previously when the vertical temperature structure in St Helena Bay was investigated via time series comparisons (Figure 4-1). Once again, these discrepancies between the measured and modelled surface temperatures are probably attributable to the constant wind speeds and directions that were applied throughout the model domain, as well as the use of static boundary conditions at all three boundaries of the model.

A feature that is not well represented in the model results is the residual cyclonic flow that has been observed in St Helena Bay (Penven *et al*, 2000). The model does not seem to indicate that such a flow exists. It may be that the cyclonic circulation inside the bay is not resolved in the context of the strong inertial flows.

As mentioned earlier, it is believed that a net poleward nearshore jet propagates dinoflagellate blooms southward during times leading up to a red tide event. Thus far, the origin of this current has not been clearly understood. It is believed, however, that this current transports the harmful algal blooms southward into St Helena Bay, leading to lobster walkouts. Understanding the origin and dynamics of this current, that propagates the harmful algal blooms southward, can ultimately be used to further improve the efficiency of forecasting programs, as it will help us to predict when this would occur.

A poleward jet is evident in the model simulations. This poleward jet is seen confined to a narrow nearshore band (approximately 5 km wide), from north of Lamberts Bay all the way south past Cape Columbine. Close investigation of the occurrence of the nearshore poleward jet in the model demonstrates that the current always appears after periods of upwelling, during relaxation events. These are the only instances of net poleward movement closely inshore.

A relevant study from a different part of the world is the modelling study undertaken by Gan & Allen (2002a and 2002b) on the continental shelf off northern California. A characteristic response observed during the CODE (Coastal Ocean Dynamics Experiment) is the time-dependant development of poleward currents over the inner shelf next to the coast, following the weakening, or relaxation, of equatorward upwelling favourable winds. An important observation was that the presence of poleward winds is not necessary for this response. Gan & Allen (2002a and 2002b) investigated the dynamics of the shelf flow response to upwelling wind relaxation events by setting up a numerical model and undertaking simulations, firstly under idealized conditions (Gan & Allen, 2002a), and thereafter by applying observed time varying winds (Gan & Allen, 2002b). After thorough investigation, they concluded that the poleward currents seem to be forced by a poleward pressure gradient force. Wind-forced flow interacts with alongshore variations in shelf topography to set up these poleward pressure gradients, and a relaxation of the wind then drives the current poleward.

As stated in the Introduction, the development of the poleward jet was investigated in an MSc thesis (Viljoen, 2006). From the idealized experiments that were undertaken during the study, it was found that the poleward flow seemed to be ‘driven from the surface’, and that the bottom topography had an important influence on the characteristics of the nearshore poleward current (a flatter inner shelf slope caused a narrower nearshore poleward current, and this current took longer to develop and longer to reach a steady state).

6. SUMMARY AND CONCLUSIONS

This study has delivered the basis on which the HAB thrust of the BCLME can advance towards an early warning system. The model outputs show that they can simulate the temporal and spatial characteristics of physical variability in the St Helena Bay – Namaqua system with uncertainties of approximately 20%.

The model was calibrated with a month long high resolution (2m vertical resolution and hourly records) temperature data set from January 2002 and verified against the data for February – April 2002. The model was run freely with forcing from atmospheric heat fluxes, tides and temperature sections at the boundaries.

The model results reflected the main circulation characteristics of the system over the upwelling cycles (event scales) and the seasonal scale. The event scale features that were specifically addressed and which are particularly important for the early warning system include:

- Upwelling at Cape Columbine and the behaviour of the plume
- The barotropic jet on the seaward side of the plume
- Narrow upwelling belt along the eastern margin of the system
- The dynamics of frontal features associated with the interaction of upwelling plumes and retention driven warming
- The warming of surface waters in the St Helena Bay retention zone
- The development of the narrow inshore poleward flow during the relaxation phase of the upwelling cycle
- The variability of stratification as a result of the interactive effects of buoyancy forcing by upwelling, wind driven entrainment and mixing and solar heat flux.
- Inertial circulation

The stability of the model set up for the St Helena Bay – Namaqua system was also verified by undertaking runs that had initial conditions (temperature) throughout the domain that were very different to those in reality. In all cases the model was able to recover back to reflecting the expected variability. This behaviour is an essential feature for a forecasting system as it shows that all key processes are correctly set up and that with realistic forcing the model produces realistic rather than chaotic behaviour.

This feasibility study showed that the dynamical characteristics of the circulation and stratification of St Helena Bay are more complex that was initially understood. This caused the emphasis of the study to shift towards elucidating the underlying processes and their scales rather than on the operationalisation of a modelling set up.

An additional study (Viljoen, 2006) was undertaken in parallel to provide a mechanistic understanding of the event scale narrow poleward flow. From the idealized experiments that were undertaken during the study, it was found that the poleward flow seemed to be ‘driven from the surface’, and that the bottom topography had an important influence on the characteristics of the nearshore poleward current (a flatter inner shelf slope caused a narrower nearshore poleward current, and this current took longer to develop and longer to reach a steady state).

The improved understanding of the stratification variability and how it related to the scales of forcing will contribute significantly to further investigation and modelling of the biogeochemical aspects of both diatom and HAB productivity and their role on the ecosystem.

In conclusion, the use of hydrodynamic models as part of a HAB early warning system is feasible and realistic. The uncertainty levels will be improved to below 20% with the following recommended actions:

- Implementation of space varying winds through MM5
- Improvement on temperature boundary conditions either through data or through nesting with a more regional model.
- Better understanding of the dynamical considerations behind the poleward flow.

7. RECOMMENDATIONS

It is recommended that the main sources of uncertainty identified in this study be addressed and that the processes implemented in this study be transferred to the ROMS platform with the required resolution achieved through nesting.

The physics and biogeochemistry of HABS in this system should be integrated with the low oxygen forecasting system.

A second phase in the operationalisation of an early warning system should proceed to a system scale way of understanding, forecasting and monitoring rather than a specific sector approach as is the case here. This system approach will reflect the linkages in a more explicit way and result in a more costs effective investment of resources in both forecasting and measurements.

8. ACKNOWLEDGEMENTS

The authors acknowledge with thanks the constructive critical comments from Prof. Geoff Brundrit, University of Cape Town, Dr Grant Pitcher from Marine and Coastal Management, Stephen Luger, CSIR, for modelling support, Chris Duncombe Rae for boundary data sets, and the partner institutions CSIR for financial support of Anél Viljoen's MSc research needs and MCM for general support.

Capacity Building

Ms Anél Viljoen has completed an MSc in March 2006 with a focus on this work and with registration at the University of Cape Town.

Ms Anél Viljoen also participated in the GEOHAB workshop in Lisbon, Portugal in November 2003

In kind contributions

CSIR: R200,000-00 for AV thesis studies (HR time)
St Helena Bay Water Quality Forum: The Data that was used to set up, calibrate and run the model for St Helena Bay
MCM: Remote sensing imagery acquired from OceanSpace and oceanographic data

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APPENDIX A : MODEL RESULTS

1.	Wind time series for March and April 2002
2.	Daily surface temperatures (spatial scale) for January 2002
3.	Daily vertical Sections at Lamberts Bay for January 2002
4.	Poleward jet

1. WIND TIME SERIES FOR MARCH AND APRIL 2002.

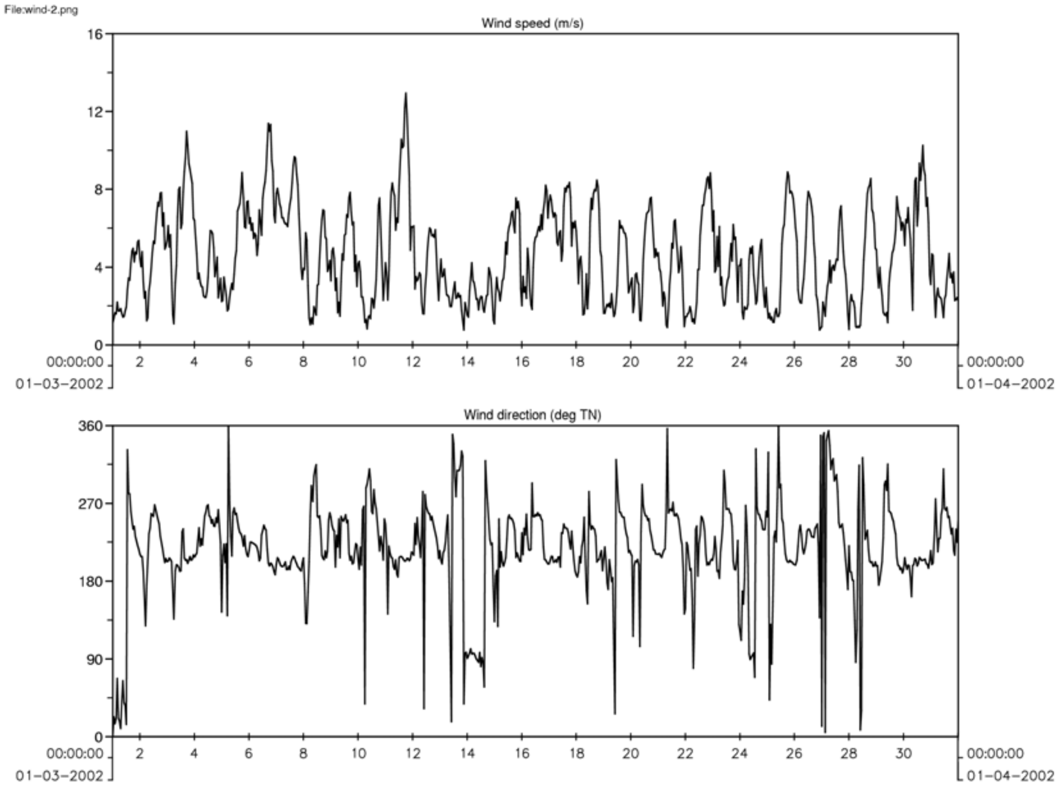

Figure A-1(a) Measured wind speed and direction at the St Helena Bay weather station for March 2002, indicating long periods of upwelling favourable southwesterly winds, followed by periods of relaxation.

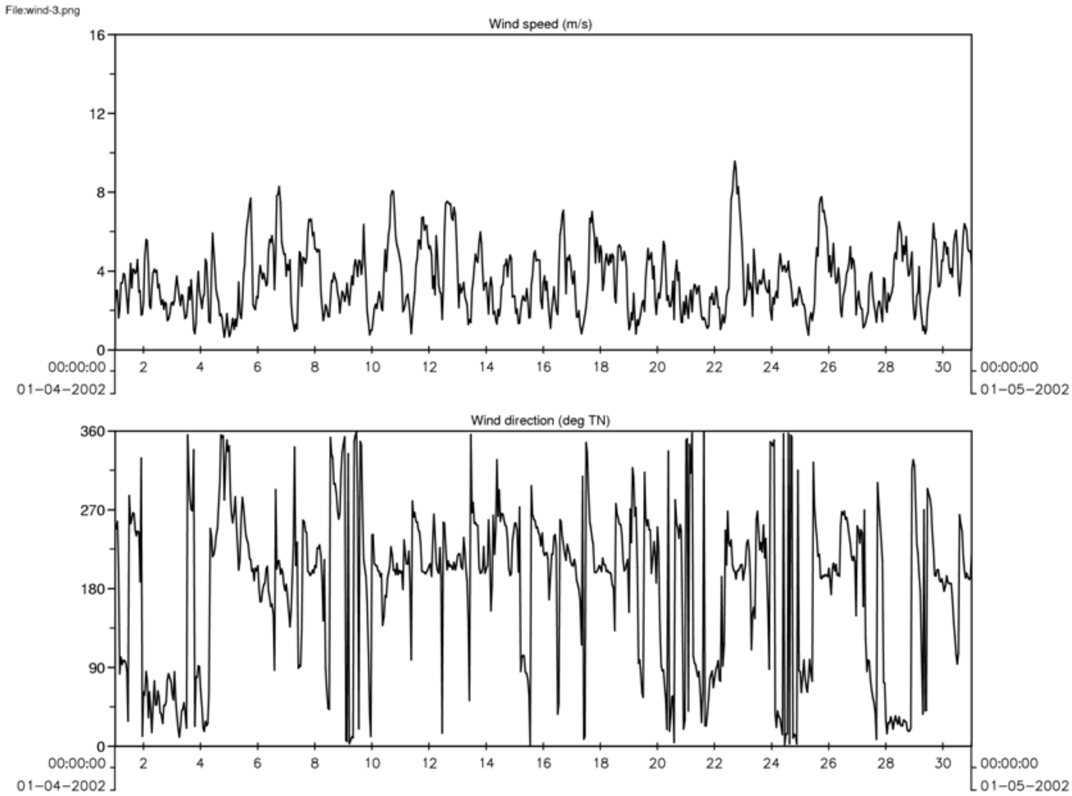

Figure A-1(b) Measured wind speed and direction at the St Helena Bay weather station for April 2002, indicating less persistant upwelling favourable southwesterly winds, and much lower wind speeds than the previous months.

2. DAILY SURFACE TEMPERATURES (SPATIAL SCALE) FOR JANUARY 2002

These spatial scale figures (Figures A-2(a) – (d)) indicate upwelling and relaxation events during January 2002. During periods when a southwesterly wind blows, upwelling conditions develop around Cape Columbine and in St Helena Bay. At times the wind event is so strong that cold, upwelled water is even noticed in the surface waters all along the coast north of St Helena Bay.

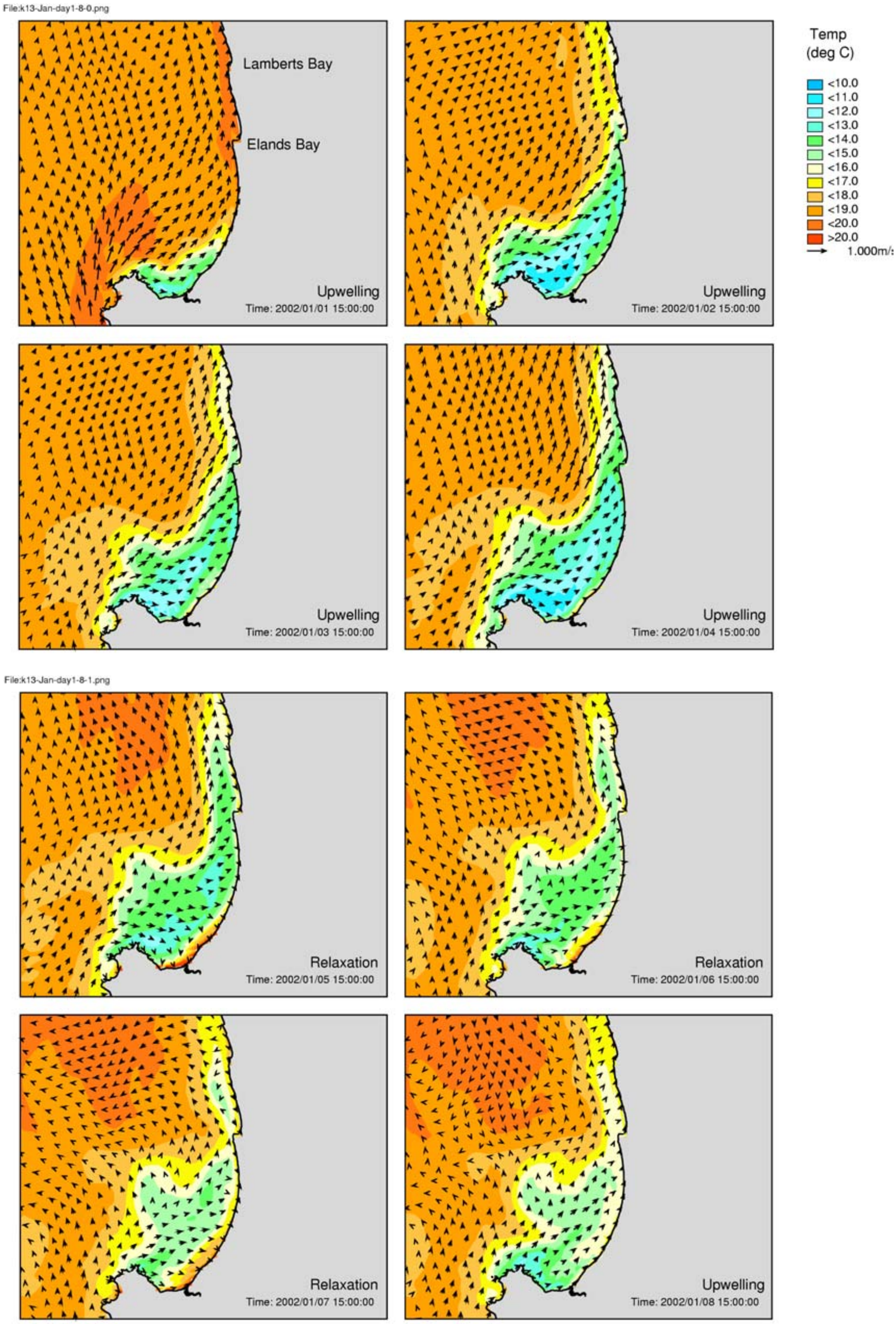

Figure A-2(a) Daily modelled surface temperatures and currents in the St Helena Bay area: 1 – 8 January 2002 (15:00).

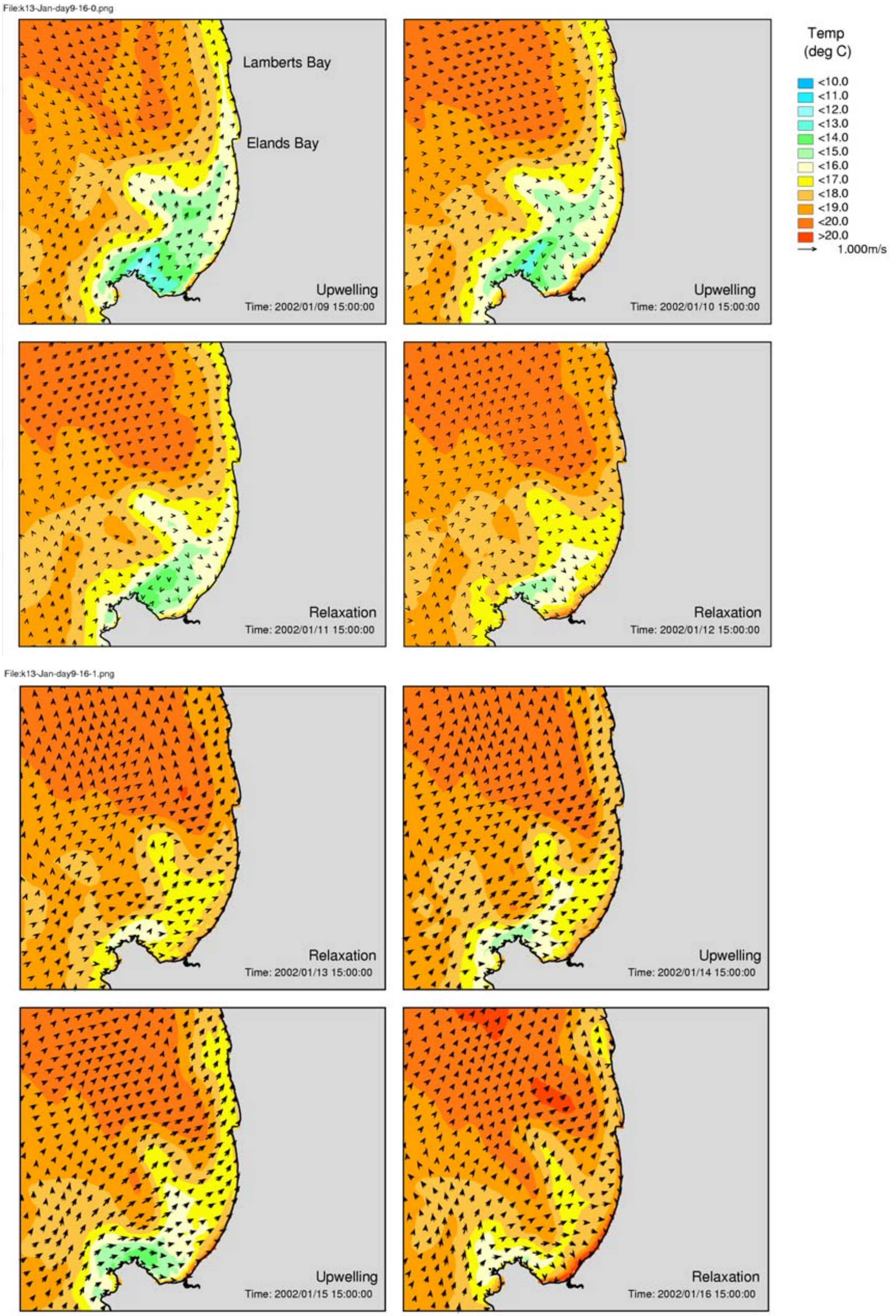

Figure A-2(b) Daily modelled surface temperatures and currents in the St Helena Bay area: 9 – 16 January 2002 (15:00).

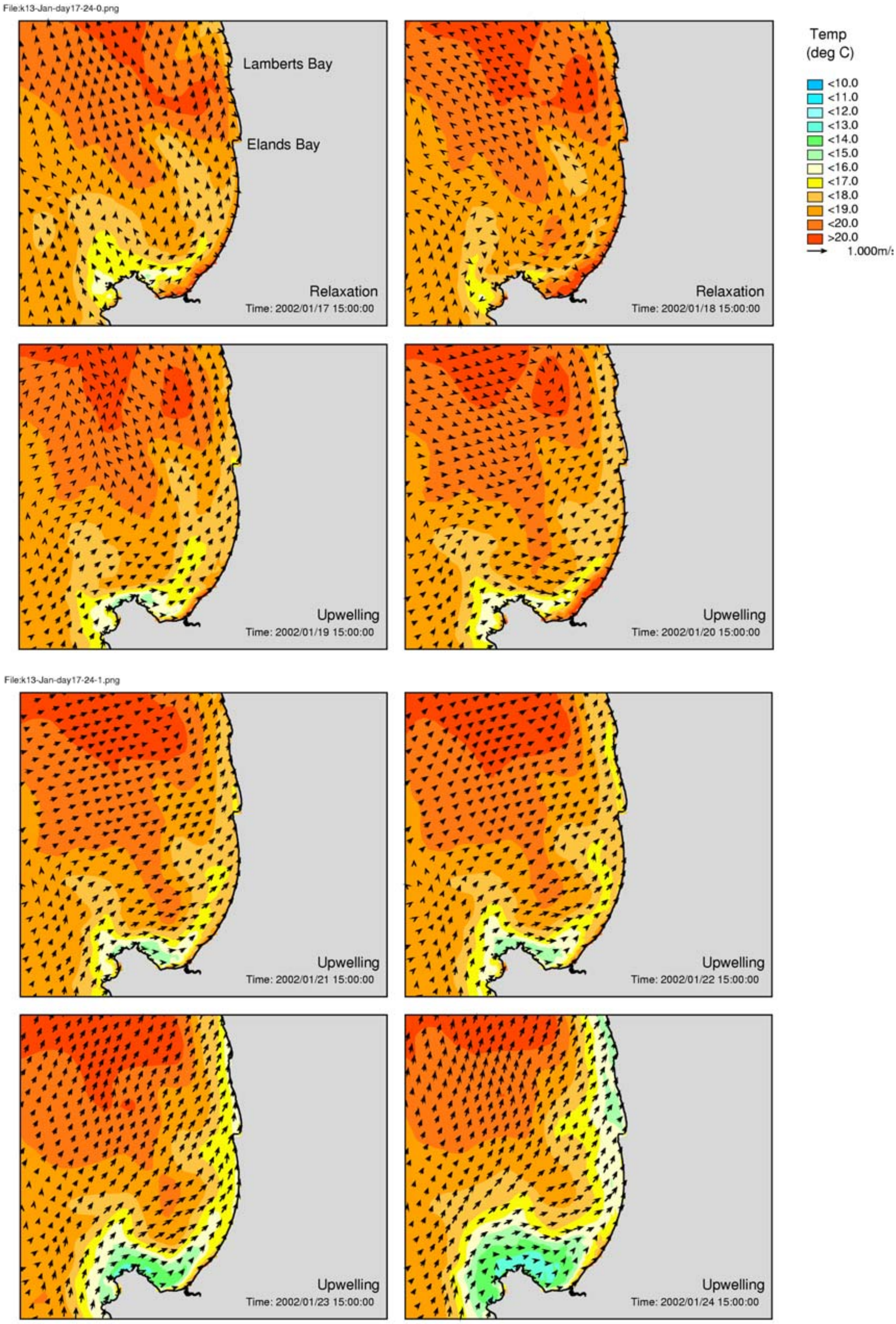

Figure A-2(c) Daily modelled surface temperatures and currents in the St Helena Bay area: 17 – 24 January 2002 (15:00).

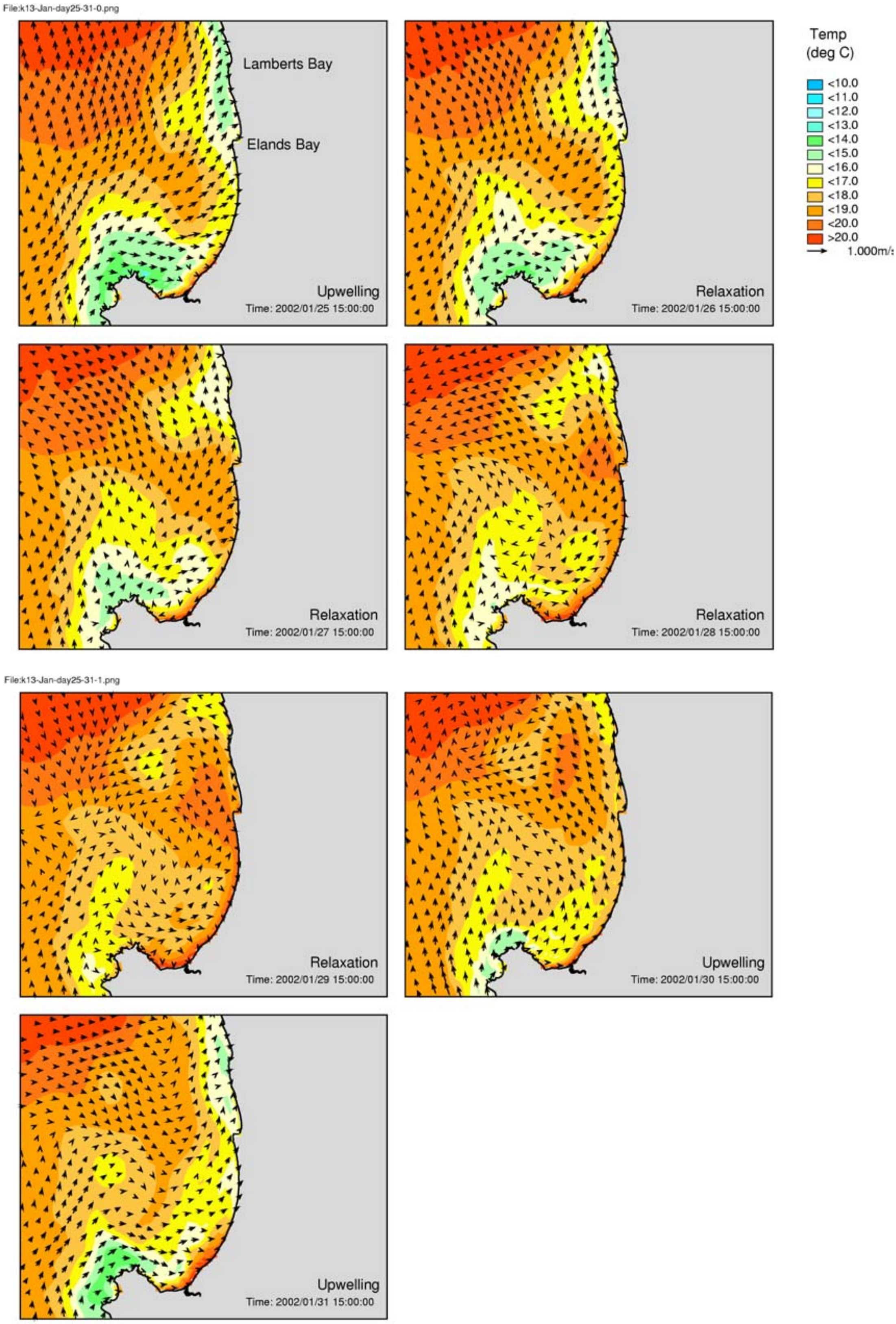

Figure A-2(d) Daily modelled surface temperatures and currents in the St Helena Bay area: 25 – 31 January 2002 (15:00).

3. DAILY VERTICAL SECTIONS AT LAMBERTS BAY FOR JANUARY 2002

The vertical sections in Figures A-3(a) – (d) at Lamberts Bay show cold bottom water moving inshore and entraining towards the surface layers during an upwelling event. During a subsequent relaxation event, the offshore warm water moves inshore, “capping” the colder water and this results in re-stratification of the system.

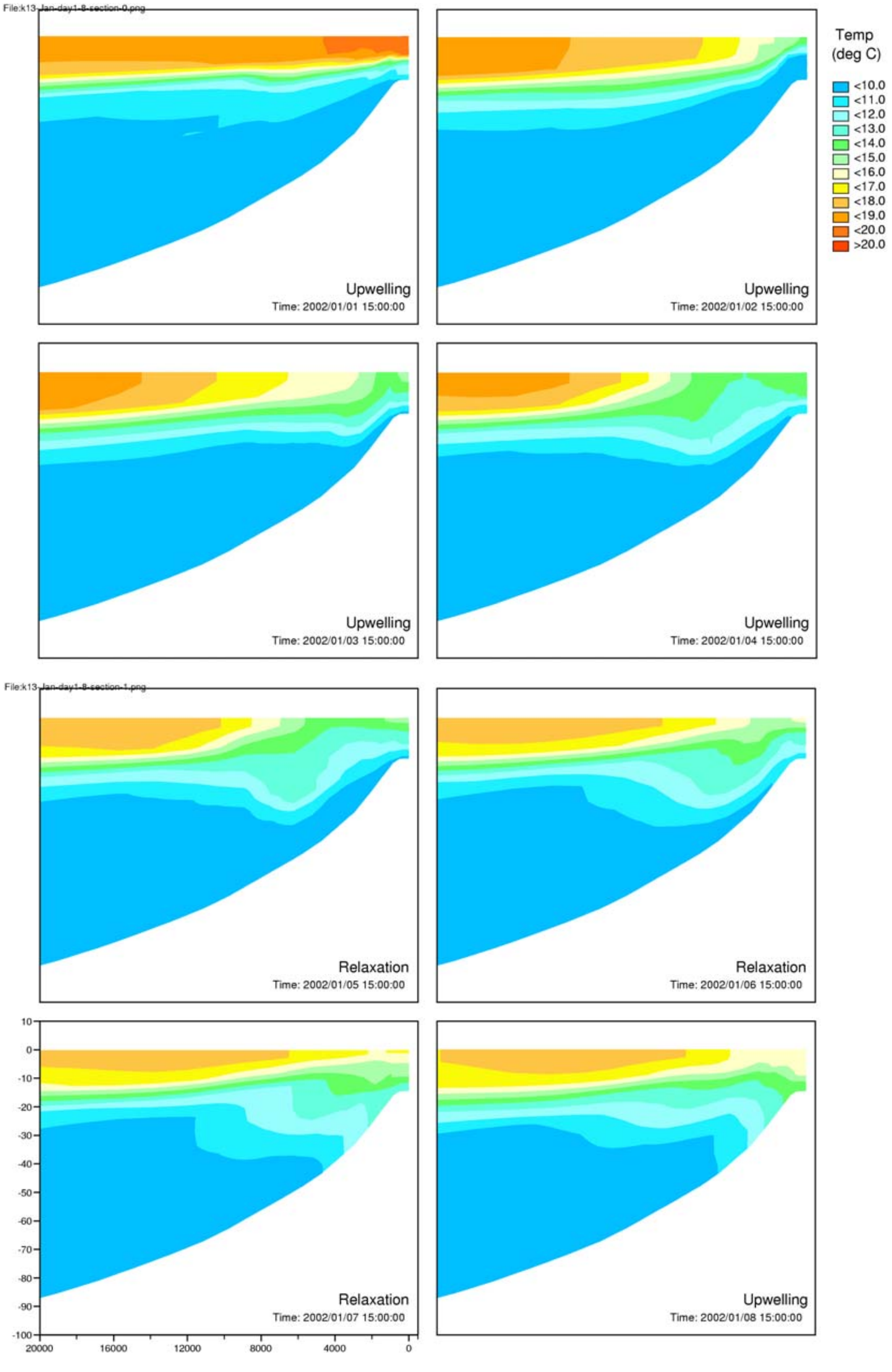

Figure A-3(a) Daily modelled temperature section at Lamberts Bay: 1 – 8 January 2002 (15:00).

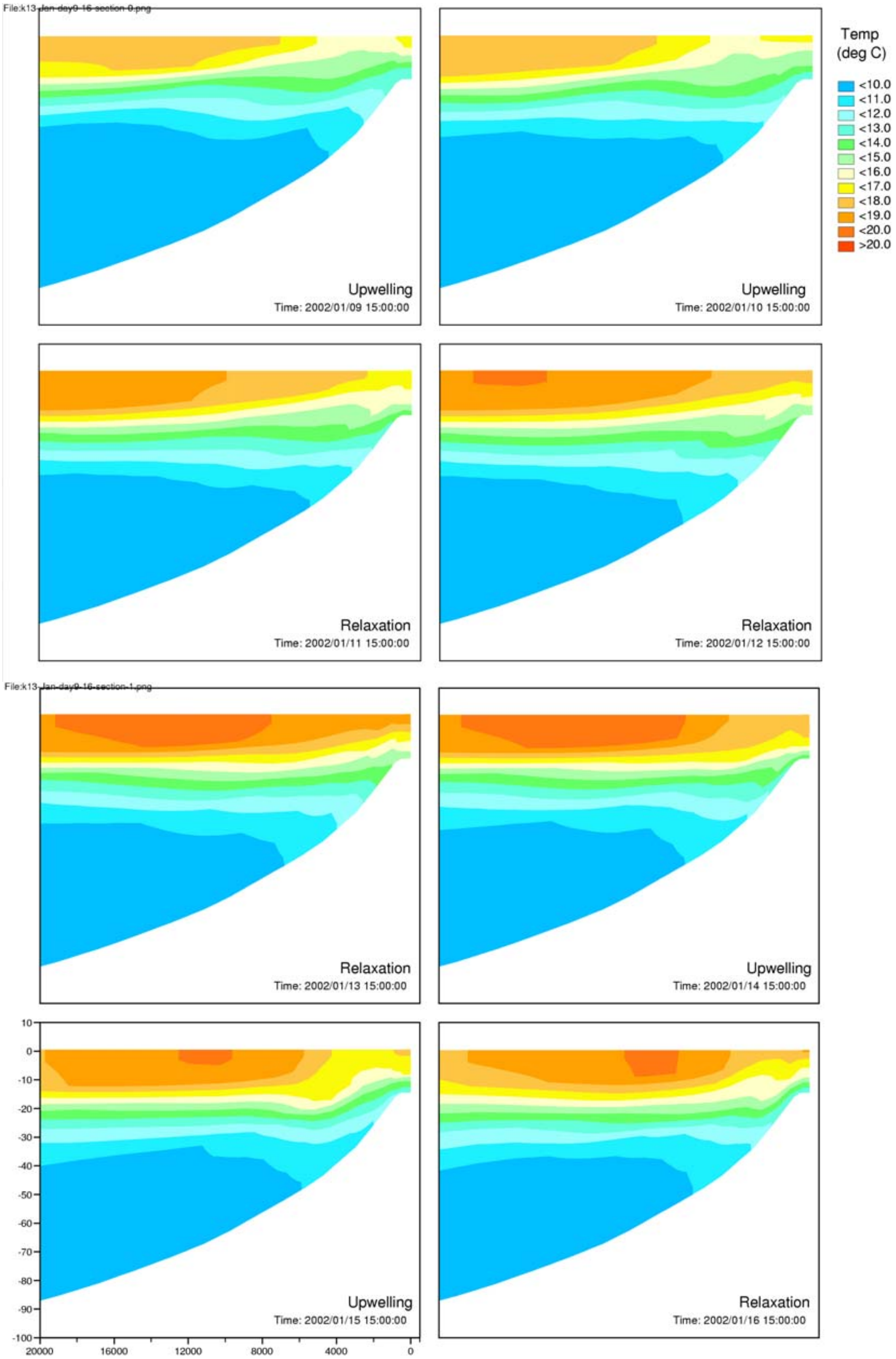

Figure A-3(b) Daily modelled temperature section at Lamberts Bay: 9 – 16 January 2002 (15:00).

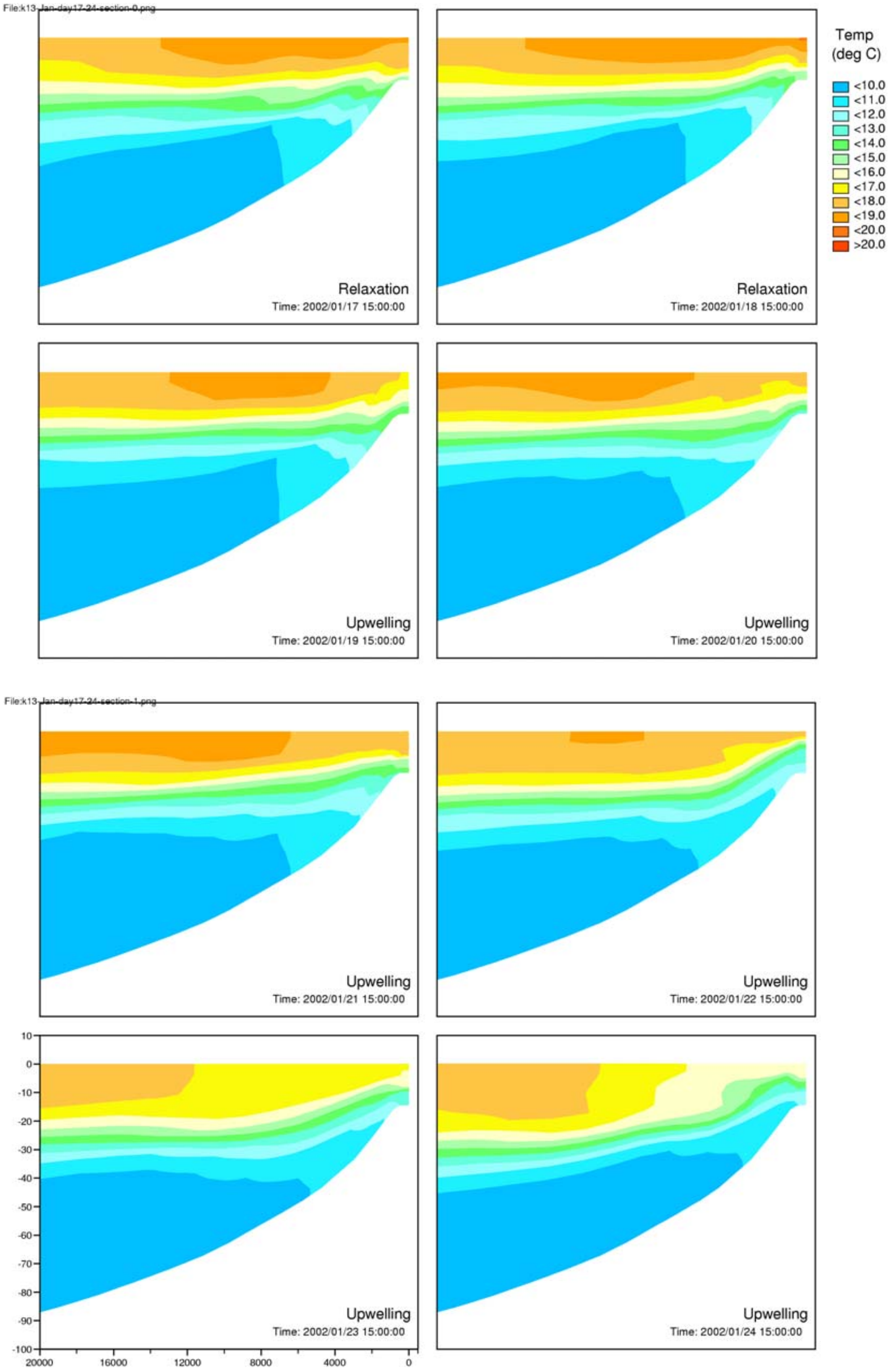

Figure A-3(c) Daily modelled temperature section at Lamberts Bay: 17 – 24 January 2002 (15:00).

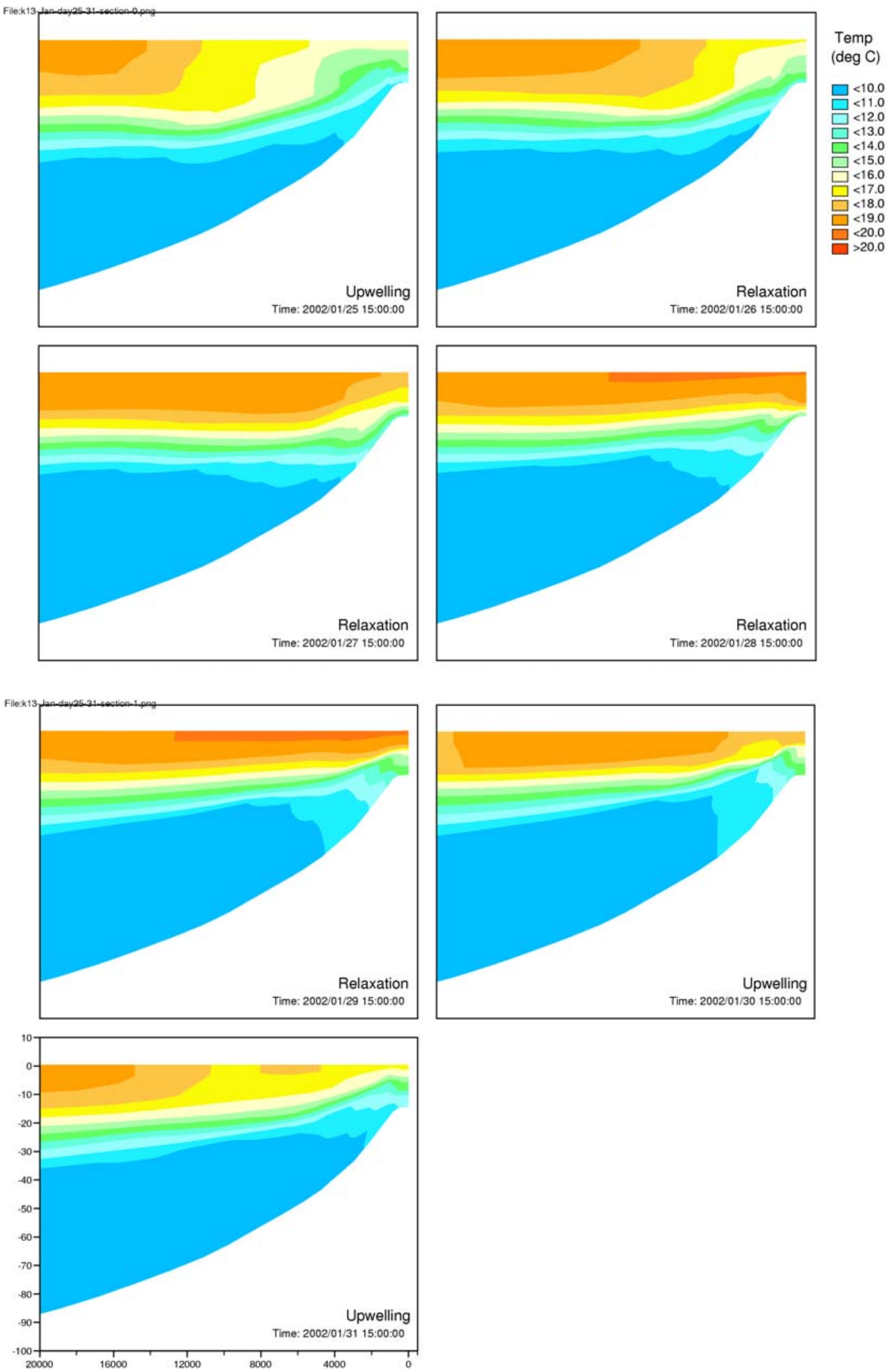

Figure A-3(d) Daily modelled temperature section at Lamberts Bay: 25 – 31 January 2002 (15:00).

3. POLEWARD SURFACE JET

In the figures below the upwelling event is clearly visible in the horizontal and the vertical plane. As soon as the southwesterly wind relaxes, the cold inshore water that was situated in the surface layers, pulls back into the deeper layers, and consequently the warmer, offshore water moves onshore. It is during this event that the poleward jet develops in a narrow band along the coastline. This jet is visible all along the coastline, from north of Lamberts Bay, into St Helena Bay, and all around Cape Columbine towards the south.

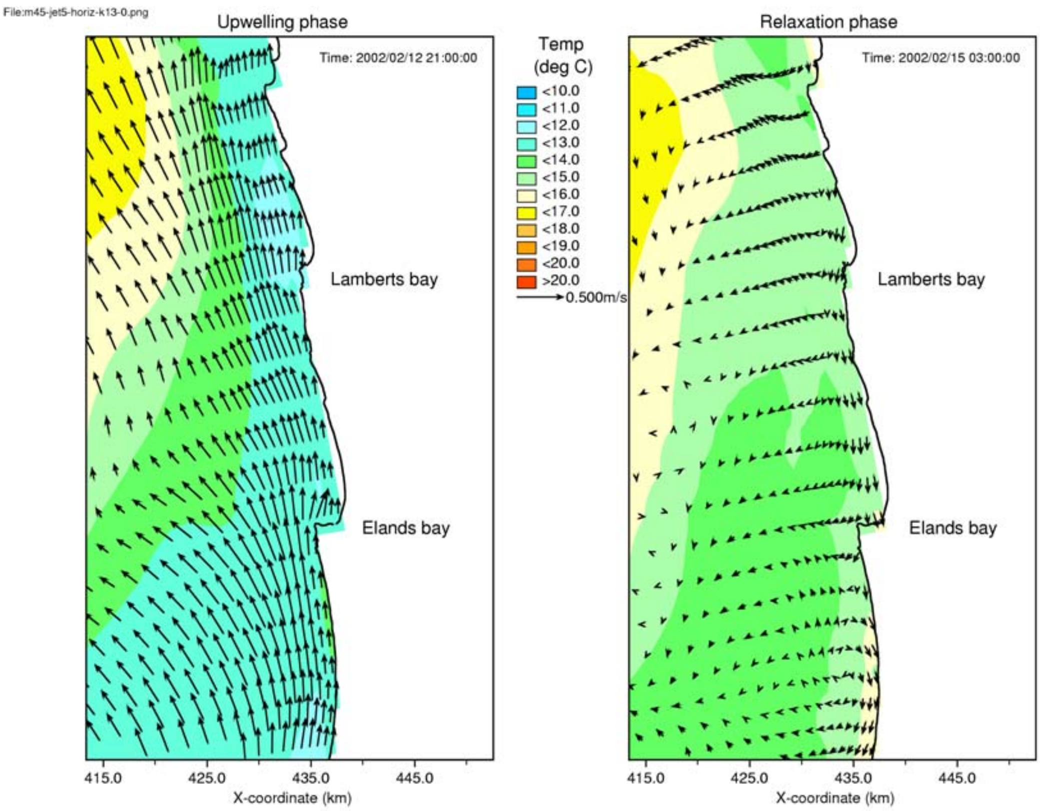

Figure A-4(a) Modelled surface temperature and currents along the West Coast during an upwelling (2002/02/12) and consecutive relaxation (2002/02/15) event, zoomed in on Lamberts Bay.

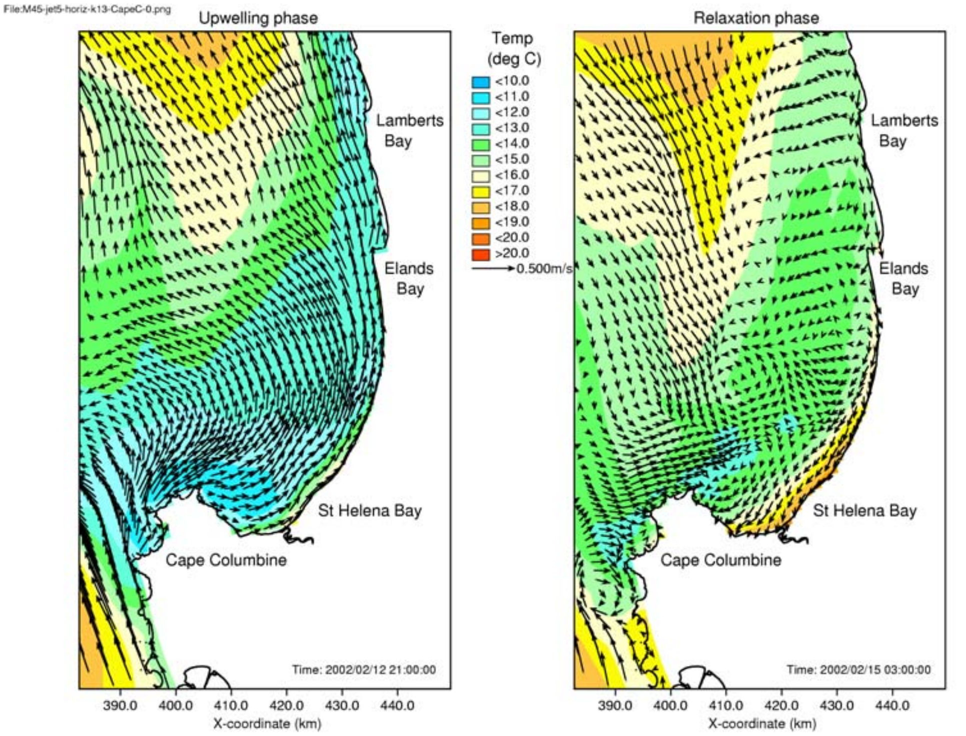

Figure A-4(b) Modelled surface temperature and currents along the West Coast during an upwelling (2002/02/12) and consecutive relaxation (2002/02/15) event, showing the poleward jet in a narrow band along the coastline, from Lamberts Bay towards St Helena Bay and around Cape Columbine.

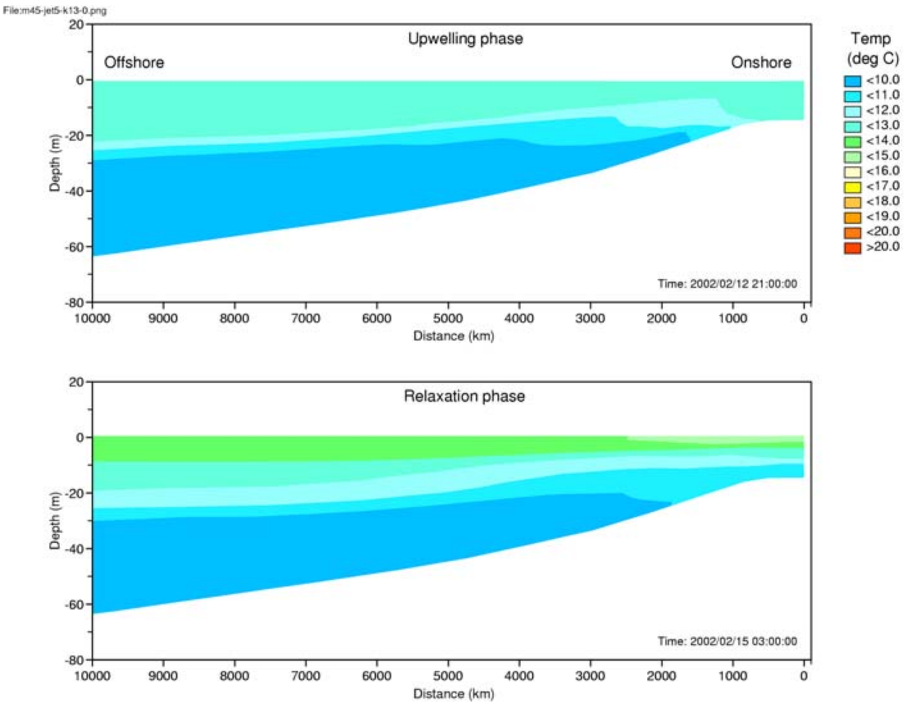

Figure A-4(c) Modelled vertical temperature section at Lamberts Bay during an upwelling (2002/02/12) and consecutive relaxation (2002/02/15) event.

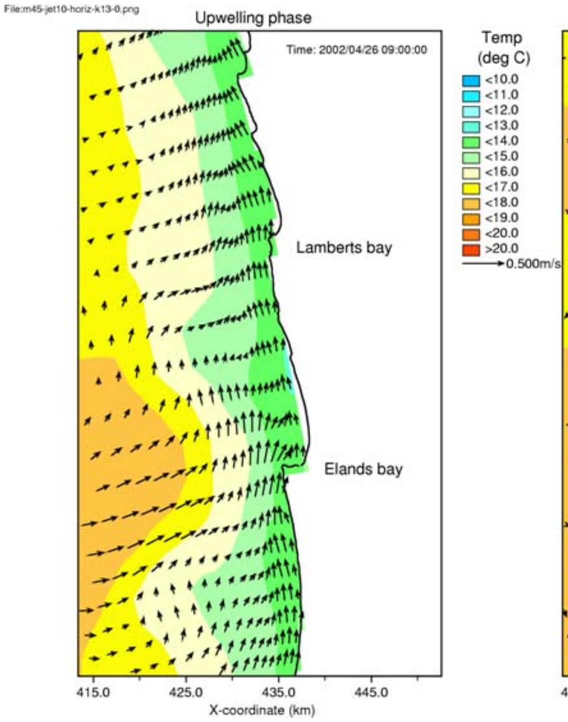

Figure A-5(a) Modelled surface temperature and currents along the West Coast during an upwelling (2002/04/26) and consecutive relaxation (2002/04/28) event, zoomed in on Lamberts Bay.

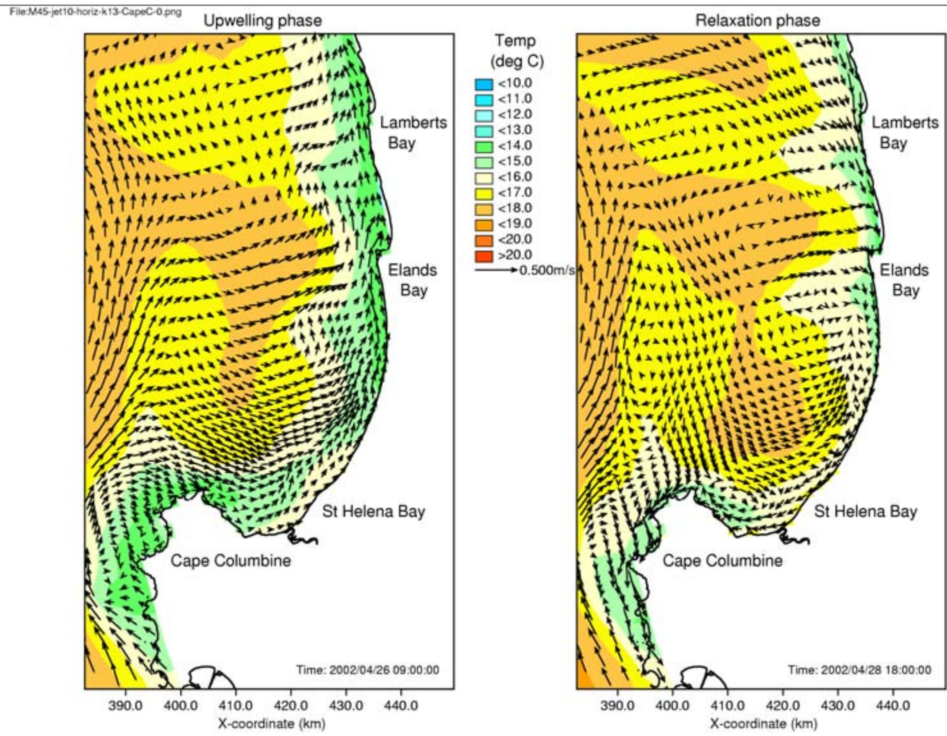

Figure A-5(b) Modelled surface temperature and currents along the West Coast during an upwelling (2002/04/26) and consecutive relaxation (2002/04/28) event, showing the poleward jet in a narrow band along the coastline, from Lamberts Bay towards St Helena Bay and around Cape Columbine.

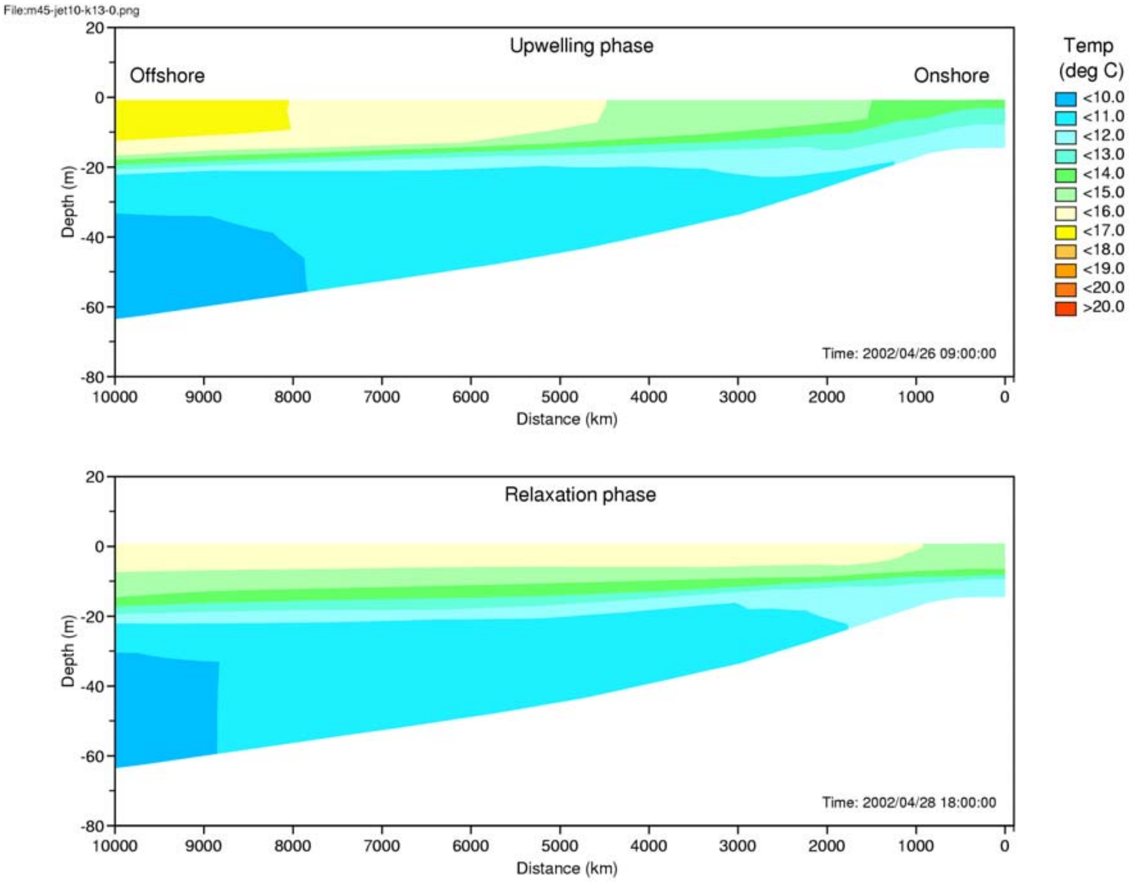

Figure A-5(c) Modelled vertical temperature section at Lamberts Bay during an upwelling (2002/04/26) and consecutive relaxation (2002/04/28) event.