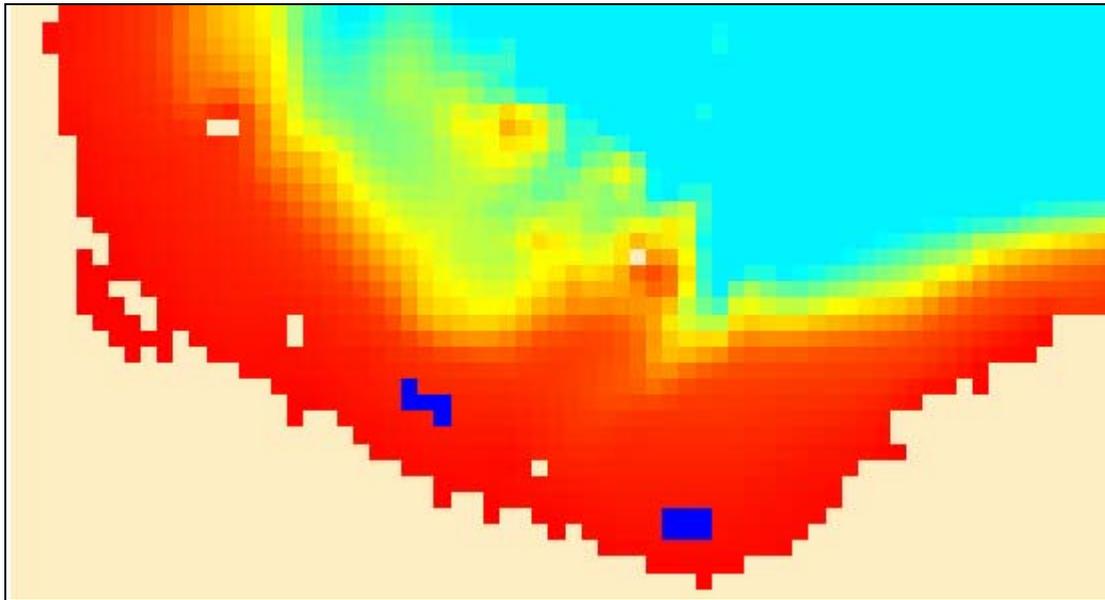


Bay of Plenty Primary Production Modelling: Influence of climatic variation and change



For



Environment Bay of Plenty



October 2006

Bay of Plenty Primary Production Modelling: Influence of climatic variation and change

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Bay of Plenty Primary Production Modelling: Influence of climatic variation and change

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Report prepared for Bay of Plenty Regional Council

EXECUTIVE SUMMARY

Altered wind patterns have consequences for up/downwelling of ocean bottom waters that provide an important source of nutrients for phytoplankton and zooplankton. In addition, the dispersal of land-sourced nutrients from the rivers throughout the Bay of Plenty will vary as the weather patterns change.

The present report deals with the effects of climate on primary production in the Bay of Plenty. The numerical modelling examined changes to phytoplankton productivity during La Nina, El Nino and a more extreme westerly wind pattern (described here as “Diablo” El Nino). The latter is predicted to occur in the Bay of Plenty in response to global climate change.

Phytoplankton levels in the Bay were considerably higher during El Nino than La Nina with typical values of 4-7 mg/m³ and 2-3 mg/m³ respectively. These bounded the values in the “normal” year (2003/04) which experienced levels of 4-5 mg/m³. The Diablo El Nino, with the stronger westerlies, shows no similar increase in average levels. In fact, the levels are between the El Nino and La Nina cases. However, the phytoplankton distribution pattern was very different; the stronger westerlies moved the location of the phytoplankton maxima to the east, more towards East Cape and the south-east corner of the Bay of Plenty. As such, it appears that climate change will increase productivity of the Bay relative to the existing conditions, but different regions of the Bay will be most productive.

Supporting information

The numerical model results were in good general agreement with measurements of Chlorophyll *a* off Goat Island Bay, Leigh, in north-eastern New Zealand.

Other supporting evidence comes from satellite Chlorophyll *a* images of the Bay. These show the Coromandel coast having lower phytoplankton abundance than the central coast of the Bay of Plenty. The satellite Chlorophyll *a* measurements (from Longdill et al. (2005)) were highly correlated with the patterns predicted by the modelling in the La Nina year.

Consideration of the phytoplankton patterns in the Bay of Plenty

In this report, terrestrial sources were found to play a very important role. The lowest phytoplankton abundances occur along the Coromandel coast, with considerably higher abundances in the central Bay. This is counter intuitive because the expectation is for strongest upwelling along the Coromandel coast under prevailing westerlies, and indeed results from the model confirm this (excluding local effects of the rivers). Further confirmation occurs on the tip of East Cape where upwelling is strong, but phytoplankton numbers are low (both in the model and satellite images).

Of relevance is a predicted halo of low phytoplankton abundances around the river entrances. The rivers deliver no phytoplankton and so the halo arises because the phytoplankton takes time to grow. Similarly, bottom waters reaching the surface off Coromandel and East Cape may temporarily remain depleted of phytoplankton.

The river flows have a profound affect on phytoplankton growth, due both to mixing-induced upwelling of bottom waters and the direct input of nutrients. Ocean upwelling effects were clearly still in evidence. For example, phytoplankton levels in the south-east of the Bay (adjacent to East Cape) are lower than off Whakatane and the upwelling in this area is predicted to be less intense. In general, it would appear that the ocean bottom waters are responsible for sustaining base levels, while the rivers substantially supplement this base.

Further sensitivity modelling would distinguish these mechanisms more fully and provide insights into the importance of terrestrial sources on the ecology, fisheries and sustainable health of the Bay of Plenty.

Mussel farming

Potential effects of two large aquaculture farms within the Bay of Plenty on chlorophyll *a* levels for both El Nino and La Nina climatic periods were simulated. As discussed above, compared to “normal” years, phytoplankton levels (Chlorophyll *a*) in surface waters in the Bay of Plenty (averaged over an entire year) were 1-2.5

mg/m³ greater in El Nino periods ~ 6 mg/m³ and 1.25-2 lower ~ 3 mg/m³ during La Nina periods. Similar differences were evident between 15-25 m depth.

When averaged over a year, the proposed farms (Opotiki and Pukehina) reduce the phytoplankton in a region some 40 km by 20 km by approximately 1% in the surface waters of the Bay (0-5 m depth). This depletion represents a decrease of ~ 0.08 mg/m³ chlorophyll-*a* from a typical average value of ~ 6 mg/m³ in El Nino years and 0.02 mg/m³ from a typical average value of ~ 3 mg/m³ in La Nina.

Larger impacts are evident at the depth layer in the water column where the mussels are located (15-25 m), with phytoplankton abundance reductions of 2-4 % at Pukehina and 5% at Opotiki during El Nino and reductions of 4-5 % at Pukehina and 6% at Opotiki during La Nina periods (averaged over the full year). These impacts are similar in spatial extent to those in surface waters.

Due to on average higher levels of coastal chlorophyll *a* on the shelf off Pukehina, (also see Longdill et al. 2006) and greater Chlorophyll *a* depletion rates at Opotiki, Pukehina, is possibly the optimal area for farm productivity.

It is unlikely that the production carrying capacity of the Bay of Plenty system will be adversely affected by the level of aquaculture modelled in this study for El-Nino and La Nina climatic periods, given that maximum depletion rates resulted in chlorophyll-*a* levels above published threshold production carrying capacity levels identified for mussel farming in other parts of New Zealand, e.g., ~ 1 µg L⁻¹.

Further assessments of production and ecosystem carrying capacity can be achieved by additional modelling and investigating present knowledge gaps, particularly the variation in phytoplankton species composition within the Bay of Plenty in relation to the magnitude of El-Nino and La Nina events.

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1 INTRODUCTION

1.1 BACKGROUND – THE PROJECT

New Zealand has been experiencing a rapid growth in the aquaculture industry in recent years. This growth, coupled with outdated legislation has prompted the government to reform the aquaculture legislation. The reforms took effect on 1 January 2005, amending five different Acts:

- Resource Management Amendment Act (No 2) 2004
- Fisheries Amendment Act (No 3) 2004
- Conservation Amendment Act 2004
- Biosecurity Amendment Act 2004
- Te Ture Whenua Maori Amendment Act (No 3) 2004

It also created two new Acts:

- Maori Commercial Aquaculture Claims Settlement Act 2004
- Aquaculture Reform (Repeals and Transitional Provisions) Act 2004

Under the new laws, new marine farms can now only be established within zones called Aquaculture Management Areas (AMAs). An AMA must be a defined area, mapped and described in the regional coastal plan. In considering AMAs, councils must consider the effects of aquaculture on the environment, fisheries resources, fishing interests and other uses of the coastal marine area. One of the central considerations in establishing AMA's is sustainability of the natural resources. This creates a need for a scientifically defensible understanding of the physical interactions in the offshore environment and the likely effects of any proposal.

Recent advances in technology coupled with pressure for space within the coast has seen proposals for large offshore farms. A single mussel farm of 4,750 ha has interim approval (Mfish Interim decision 2006) offshore from Opotiki (Figure 1.1). A further pre-moratorium mussel farm application for 3,800 ha near Pukehina/Otamarakau, in the central Bay of Plenty is yet to be heard (Figure 1.1).

While there are many uncertainties with the expansion of aquaculture in the Bay of Plenty, there are many opportunities for both filter feeders and other species. As the Regional Council are in the “driving” seat for planning for aquaculture, a robust and defensible understanding of the offshore Bay of Plenty is needed. This work provides a basis for decisions for the understanding of how marine farming is likely to affect the physical dynamics and biological values of the Bay of Plenty.

If aquaculture is to be advanced in the Bay of Plenty the council needs to:

- Ensure the current proposals are monitored and are sustainable; and
- Make decisions about other sites suitable for aquaculture, which sustain the environment and lead to an effective aquaculture industry.

Mussels and other filter feeders are known to extract both phytoplankton and zooplankton from the water column. Moreover, most nutrients arriving at the coast come from deeper water in the bottom mixed layer (Park, 1998) (Fig. 1.1). To reach the coast, this nutrient-rich seawater must pass through the AMAs and so impacts on the inshore wider environment need to be understood.

The goals of this project were to provide focused information over-viewing the Bay of Plenty for planning of AMAs. The aims were achieved by establishing data collection programmes coupled with sophisticated numerical models. Thus, any scenario can be modelled to provide information on the likely effects.

Regional councils are also obliged to monitor cumulative effects of activities. This work also can be readily absorbed into the regional monitoring programs or for particular farms.

This information provides significant potential benefits to the aquaculture industry by providing background information on the nature of the offshore environment and providing the tools by which effects of any proposal can be assessed.

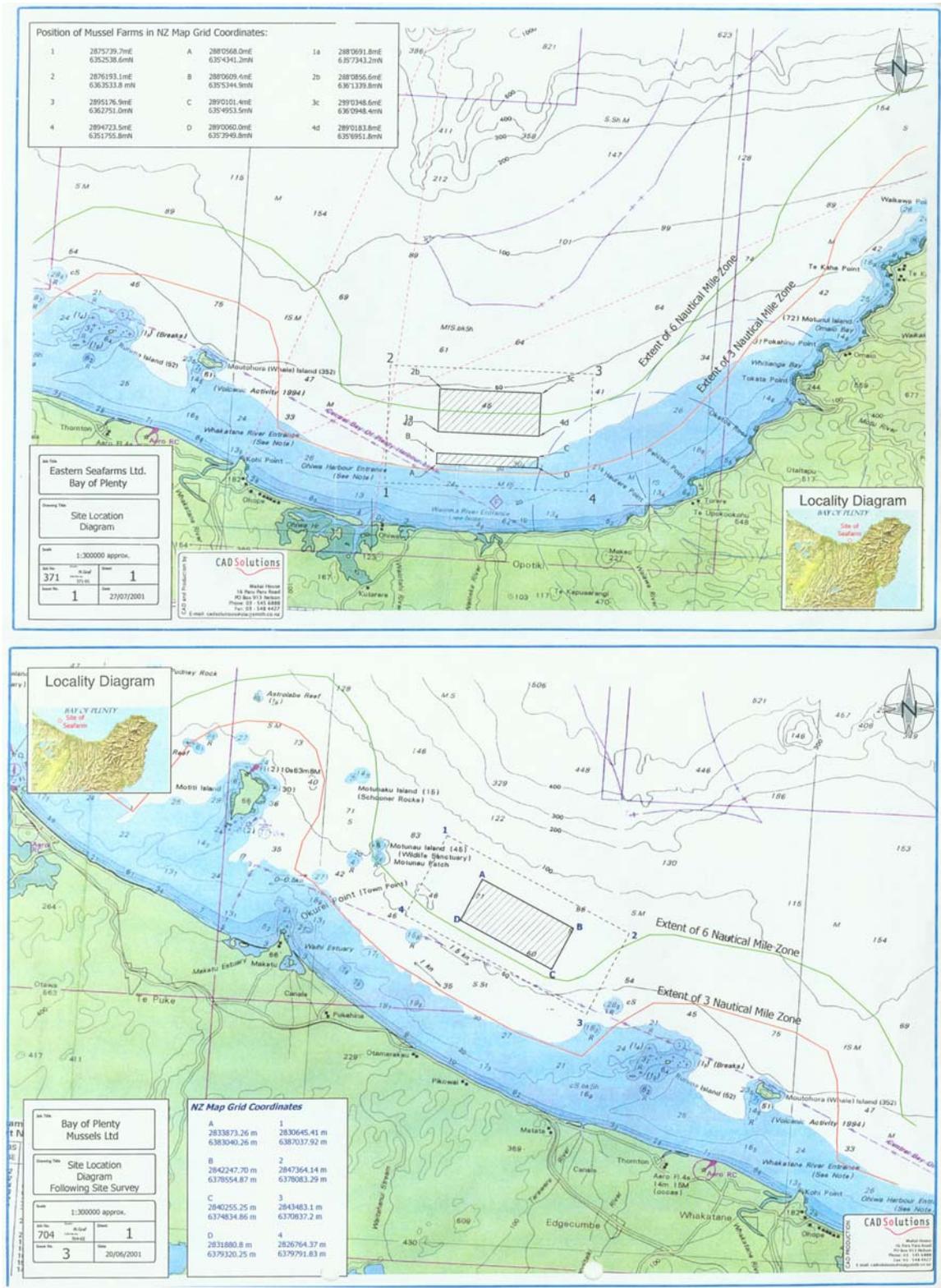


Figure 1.1 - Proposed offshore aquaculture sites in the Bay of Plenty

1.1.1 STUDIES UNDERTAKEN

To redress the lack for data and understanding of the system, EBoP commissioned ASR Ltd as follows:

- To be informed about offshore oceanographic and ecological systems when choosing open coast AMA sites, for a sustainable environment, kaimoana and aquaculture industry in the Bay of Plenty

The goals were achieved by:

- Establishing monitoring stations and undertaking regular surveys of water properties, currents and waves
- Undertaking numerical modelling of circulation and physical dynamics
- Undertaking numerical modelling of the food chain (food dynamics modelling), with particular focus on green mussels
- Developing recommendations about the carrying capacity of sites around the Bay of Plenty

1.2 PURPOSE OF THIS REPORT

The present report deals with the numerical modelling of the effects of climate on primary production. The modelling examined changes to phytoplankton productivity during La Nina, El Nino and a more extreme westerly wind pattern. The latter is predicted to occur in the Bay of Plenty in response to global climate change. During these periods, the wind patterns are different with consequences for up/downwelling of ocean nutrients that provide the primary source of nutrients for phytoplankton and zooplankton, which are sustaining the coastal eco-system. In addition, the spatial spread of land-sourced nutrients from the rivers throughout the Bay of Plenty varies with the different wind patterns.

Previous modelling examined “normal” conditions, during 2003/04. The years modelled in this report were 1997/98 for El Nino and 1998/99 for La Nina. For the extreme wind case modelled here, the westerly wind components of the El Nino year were strengthened and the easterlies were weakened. We also examine the impacts of large scale green-lipped mussel farming within the Bay of Plenty during the El Nino year.

While AMA designation within the Bay of Plenty system could be used for a variety of different aquaculture types e.g., sponge, scallop, fin-fish and mussel aquaculture, this study has used mussel aquaculture to examine likely effects on primary production and carrying capacity. This is predominantly due to large mussel farms representing the present applications, and the fact that mussel culture has received the most attention with respect to effects on primary production and carrying capacity and as such, useful benchmarks using chlorophyll *a* levels have been derived for determining likely impacts and effects (e.g., Inglis *et al.* 2005). Mussels feed on phytoplankton, zooplankton, detritus and other organic particles in the size-range 3-200 μm . which they filter from the water column, and large mussels can filter up to 350 liters of water per day.

1.3 BACKGROUND-REPORT STRUCTURE

This report describes numerical modelling of the effects of climate on primary production within the Bay of Plenty. The list of reports that are relevant to the study are listed below:

- Black, K.P., Beamsley, B., Longdill, P., Moores, A., 2005 *Current and Temperature Measurements: Aquaculture Management Area*. Report prepared by ASR Consultants for Bay of Plenty Regional Council, March 2005.
- Longdill, P.C., Black, K.P., Park, S. and Healy, T.R., 2005. *Bay of Plenty Shelf Physical and Chemical Properties 2003-2004 : Choosing open coast AMAs to sustain the environment, kaimoana and aquaculture industry*.

Report for Environment Bay of Plenty, ASR Ltd, P.O. Box 67, Raglan, NZ, and the University of Waikato. 35p

- Longdill, P. C., and Black, K. P., and Healy, T.R. 2005. *Locating aquaculture management areas – an integrated approach*. Report for Environment Bay of Plenty, ASR Ltd, P.O. Box 67, Raglan, NZ, and the University of Waikato. 53p.
- Longdill, P.C., Black, K.P. 2006. *Numerical Hydrodynamic Modelling: Aquaculture Management Areas*. Report for Environment Bay of Plenty, ASR Ltd, PO Box 67, Raglan, New Zealand. 67p.
- Longdill, P.C., Black, K.P., Haggitt, T. and Mead, S.T., 2006. *Primary Production Modelling, and Assessment of Large Scale Impacts of Aquaculture Management Areas on the Productivity within the Bay of Plenty*. Report for Environment Bay of Plenty, ASR Ltd, PO Box 67, Raglan, New Zealand. 51p
- Mead, S.T., Longdill, P.C., Moores, A., Beamsley, B., and Black, K.P. *Underwater Video, Grab Samples and Dredge Tows of the Bay of Plenty Sub-Tidal Area (10- 100 m depth)*. Report for Environment Bay of Plenty, ASR Ltd, PO Box 67, Raglan, New Zealand. 34p
- Park, S.G. and Longdill, P.C. 2006. Synopsis of SST and Chl-a in Bay of Plenty waters by remote sensing. *Environment BOP Environmental Publication 2006/13. Environment Bay of Plenty, PO Box 364, Whakatane*.

Longdill and Black (2006) and Longdill et al. (2006) describe the numerical hydrodynamic modelling and productivity modelling respectively in detail. This report primarily considers the results of the global climate simulations.

The structure of the report is as follows:

- Section 1** Introduction and background to the project.
- Section 2** Model background – 3DDLIFE.
- Section 3** Yearly averages of phytoplankton growth
- Section 4** Mussel farming aquaculture scenarios
- Section 5** Summary of results.

2 MODEL BACKGROUND

2.1 3DDLIFE – MODEL FORMULATION

2.1.1 BACKGROUND

The model 3DDLIFE is a Eulerian-based, fixed stoichiometry coastal marine ecosystem productivity model. The model solves multiple interactive equations for the state variables in a forward explicit time-stepping scheme, with the variables represented on a regular grid. The model describes nutrient cycling (nitrogen and phosphorus), phytoplankton and zooplankton growth and decay along with the dissolved oxygen conditions within the coastal marine environment, though its primary concern is phytoplankton and zooplankton dynamics.

The model 3DDLIFE is coupled to the 3DD hydrodynamic model from the commercial 3DD Suite (© Black, 2001) in order to simulate the concurrent processes of advection, dispersion, ecology and biology. Information from the hydrodynamic model used by 3DDLIFE includes the 3-dimensional water velocities to determine the advection and dispersion of variables, while the water temperature and salinities are used to determine reaction rates which are sensitive to these parameters. Details relating to the hydrodynamic model methods, calibration and validation are included in an accompanying report (Longdill and Black, 2006).

Required inputs for 3DDLIFE include solar radiation and wind velocities at 10 m above Mean Sea Level (MSL), along with boundary conditions at all open boundaries within the grid detailing the concentration of all 8 state variables throughout the simulation (Table 2.1).

Table 2.1 State variables, abbreviations and units used in 3DDLIFE.

State Variable	Abbreviation	Units
Phytoplankton (dry weight biomass)	P	g/m ³
Zooplankton (dry weight biomass)	Z	g/m ³
Nitrate + Nitrite	NO _x	g/m ³
Ammonia	NH ₃	g/m ³

Detrital Nitrogen	DN	g/m^3
Inorganic Phosphorus	PO4	g/m^3
Detrital Phosphorus	DP	g/m^3
Dissolved Oxygen	DO	g/m^3

The processes simulated by the model include (Figure 2.1):

- phytoplankton production,
- phytoplankton sedimentation,
- non-predatory phytoplankton death,
- grazing by zooplankton,
- zooplankton excretion,
- zooplankton respiration,
- non-predatory zooplankton death,
- mineralization of suspended detritus,
- sedimentation of detritus,
- mineralization of detritus on the bed,
- nitrification of ammonia,
- re-aeration at the air-water interface, and
- green-lipped mussel grazing.

Details of these various functions and the empirical constants applied within 3DDLIFE are the same as those adopted by Longdill et al. (2006) and are not repeated here.

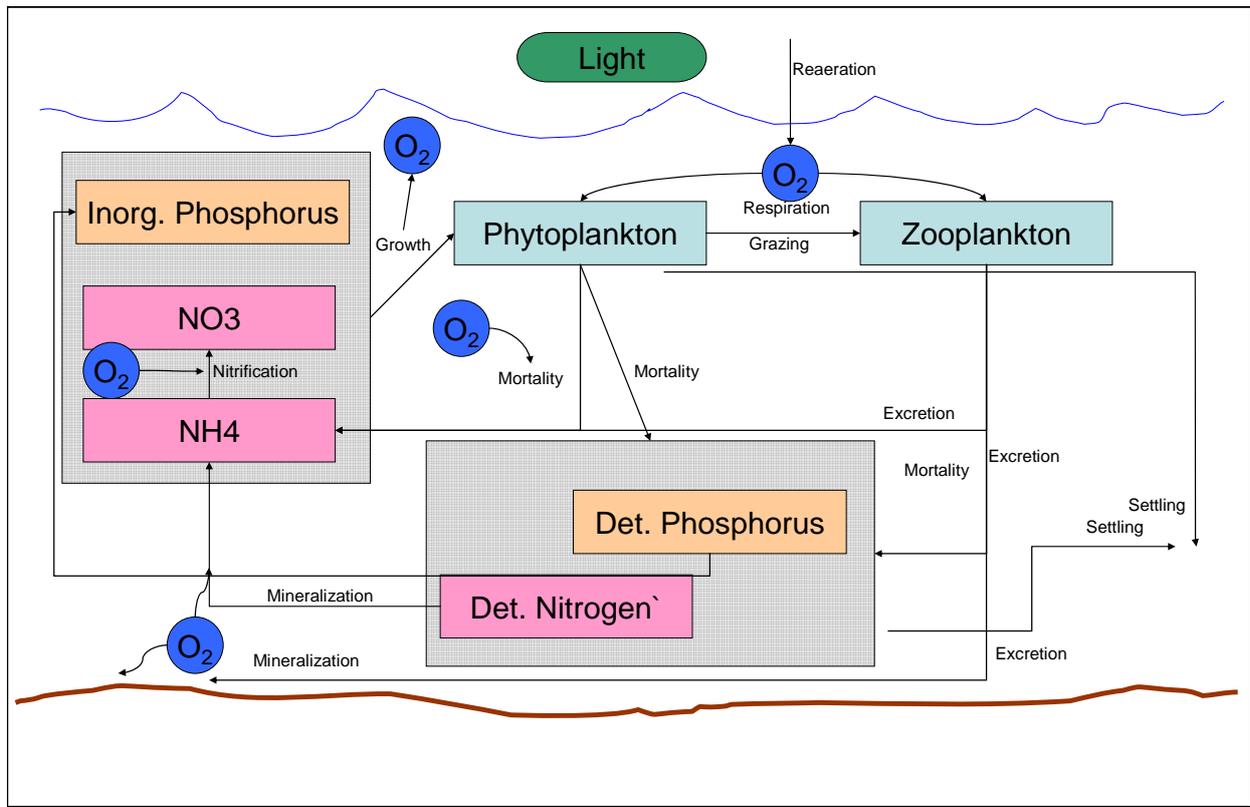


Figure 2.1 – Simplified flow diagram of fluxes of nitrogen and phosphorus within the model 3DDLIFE.

2.2 EL NINO / LA NINA

The El Nino-Southern Oscillation (ENSO) (Figure 2.2) is a tropical Pacific-wide air pressure difference that affects wind, sea-surface temperature (SST) and rainfall. During the El Nino phase, the easterly trade winds weaken and SSTs in the eastern tropical Pacific can become several degrees warmer than normal. New Zealand experiences stronger than normal south-westerly airflow, which results in lower seasonal temperatures and drier conditions in north-eastern parts of the country, such as the Bay of Plenty (NIWA, 2003). In winter, the wind tends to be more from the south, bringing colder conditions to both the land and the surrounding ocean. In spring and autumn, south-westerly winds are more common (NIWA, 2003; www.niwascience.co.nz, ENSO website). During La Nina events, New Zealand

experiences more northeasterly flow, higher temperatures and wetter conditions in the Bay of Plenty. During the El Nino period, over much of the Bay of Plenty region seasonal rainfall is typically at least 15 % below normal, while rainfall in La Nina increases by up to 10-15%.

NIWA report that although ENSO events have an important influence on New Zealand climate, it accounts for less than 25 percent of the year to year variance in seasonal rainfall and temperature at most New Zealand measurement sites.

The ENSO cycle varies between about 3 and 7 years in length, and there is large variability in the intensity of individual events. The SOI showing the El Nino and La Nina years is presented in Figure 2.2, where a negative index signifies El Nino and a positive index is La Nina.

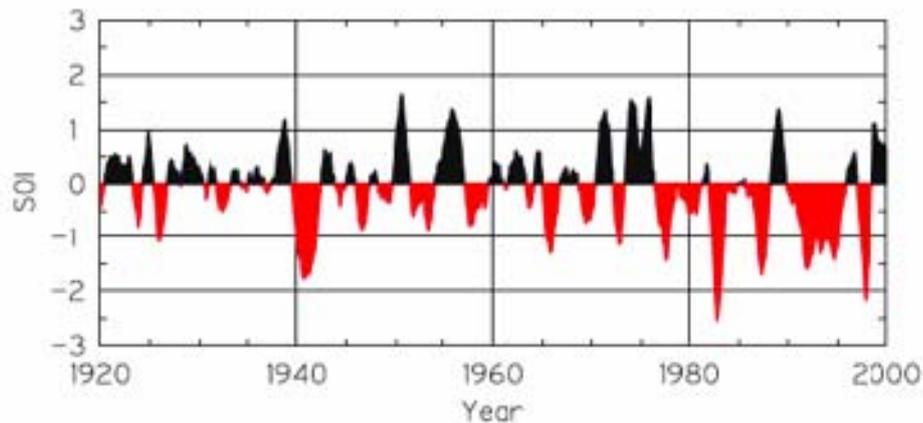


Figure 2.2 - Southern Oscillation Index, derived from Tahiti minus Darwin pressure different anomalies, and normalised by the standard deviation of the monthly differences. Monthly values have been smoothed by taking a 12-month running mean, in order to highly El Nino events (SOI below about -1) and La Nina events (SOI above about +1) (From Taylor and Park, 2001). (see also www.meteora.ucsd.edu/~pierce/el_nino/en97/en97/html and the website www.pmel.noaa.gov/toga-toa/el-nino-story).

2.3 MODELLED PERIODS

We chose the period 1997-1998 for the El Nino year and 1998-1999 for the La Nina year (Figure 2.2). Climate change predictions for the Bay of Plenty suggest that the westerly wind component will strengthen. For this case, the El Nino winds were separated into N/S and E/W components. The west components were increased by

10% and the east components were decreased by 10%. All other inputs (solar radiation, river flows, model settings etc. were left unchanged). The case was dubbed “Diablo El Nino”.

The hydrodynamic and primary production models were run for the 3 entire years, with an initial start date of 1 August for each case. This was chosen because the water column was free of thermal stratification at this time, which makes the initial conditions in the model more easily defined and accurate.

Current patterns came from a 1-year hydrodynamic simulation with Model 3DD. The model has 10 vertical layers and a 3000 x 3000 m horizontal grid size. Vertical layer thicknesses were 5, 10, 10, 10, 15, 20, 80, 100, 250, 500 m respectively from the sea surface to the seabed.

To make direct comparisons between the years, the physical inputs were changed, but none of the constants or methods (other than the elimination of thermal stratification in the hydrodynamic model, see below) were changed between the runs. For the numerical modelling we used:

- River flows provided for each year by EBoP;
- Wind data (14 stations within the Bay of Plenty) derived from ASR’s Metocean Data Interface (MDI) based on Quikscat satellite wind observations at 10 m above the sea surface (3 hourly datasets); and
- Measured solar radiation from Tauranga airport.

Parameters adopted as in Longdill et al. (2006) were:

- Riverine nutrient inputs from typical concentrations detailed in Taylor and Park (2001)
- Deep ocean nutrient boundary conditions and initial conditions

Unfortunately, the satellite sea surface temperature (SST) data were not available for this study. (Notably, it has since become available through a CSIRO web site). As

such, we modelled the hydrodynamics without the ocean atmosphere temperature (thermal stratification) simulation included. This meant that the hydrodynamics were run in 3-dimensional mode, including the salinity-stratified gravitational circulation due to the fresh water coming from the rivers, but without water temperature. To obtain the water temperatures for the primary production model, we extracted the predicted water temperatures from the Longdill et al (2006) simulations. While this may introduce some error, the primary production model is not very sensitive to small variations in water temperature. The model calibration of the hydrodynamic model indicated that only small changes to the currents occur between barotropic and baroclinic simulations and so it is assumed that the current pattern is a good approximation. Notably, the driving force on the up/downwelling is associated with wind, and actual winds from the chosen years were used. Moreover, solar radiation plays an important role in phytoplankton growth and actual measurements of that variable were used for the modelled years.

For the measurements, the yearly-averaged values of the solar radiation were 167.46 Watt/m² for El Nino and 172.93 Watt/m² for La Nina (including the zero radiation overnight), which indicates a very small difference in phytoplankton growth during the two years, due to solar radiation alone.

The wind roses for the 3 years are shown in Figures 2.3a, b, and c respectively, and it is seen that much stronger westerly wind blows during the El Nino year, in accordance with expectations. This would be expected to lead to much increased coastal upwelling and a greater spread throughout the Bay of the nutrient-rich freshwater coming from the river sources. Both induce higher nutrient levels during El Nino. During La Nina, the wind has a wider directional spread, with more easterlies. The different wind patterns may be expected to cause higher phytoplankton abundance during El Nino.

The average river flows for the two modelled years are given in Table 2.2 and it is evident that the rainfall was marginally higher during La Nina.

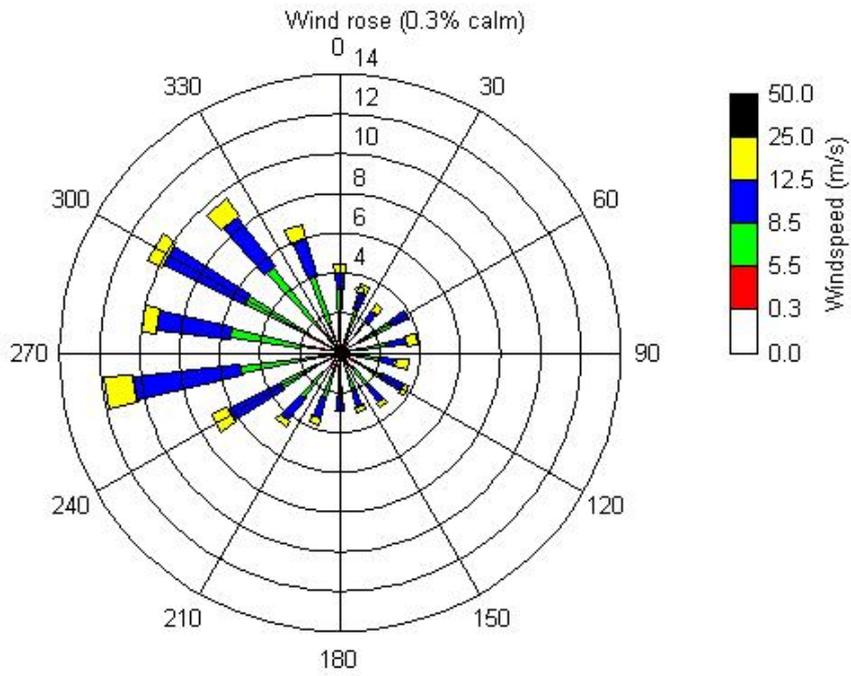


Figure 2.3a - Wind rose for the El Niño year, from August 1, 1997.

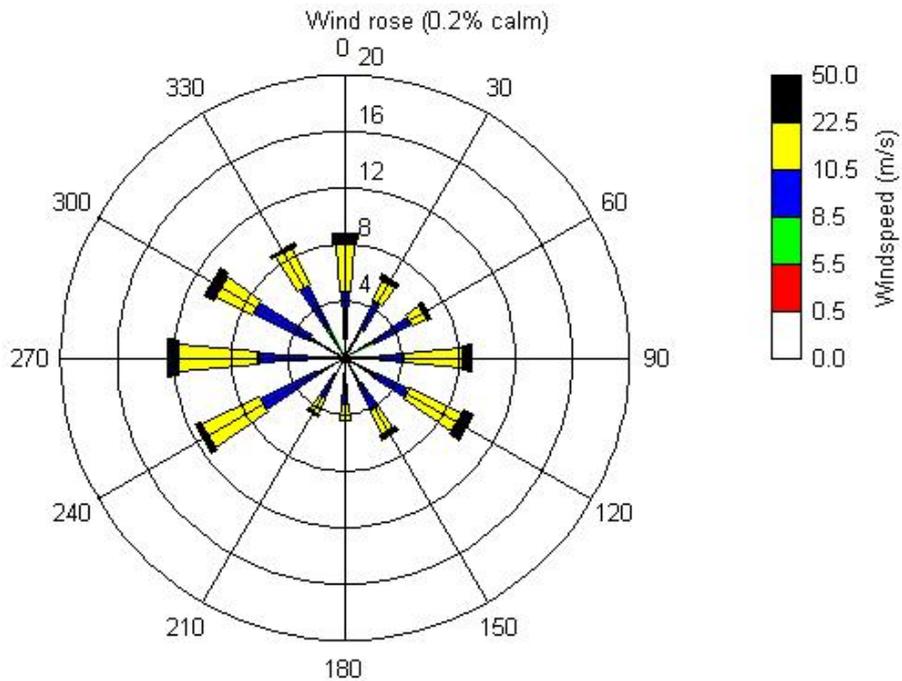


Figure 2.3b - Wind rose for the La Niña year, from August 1, 1998

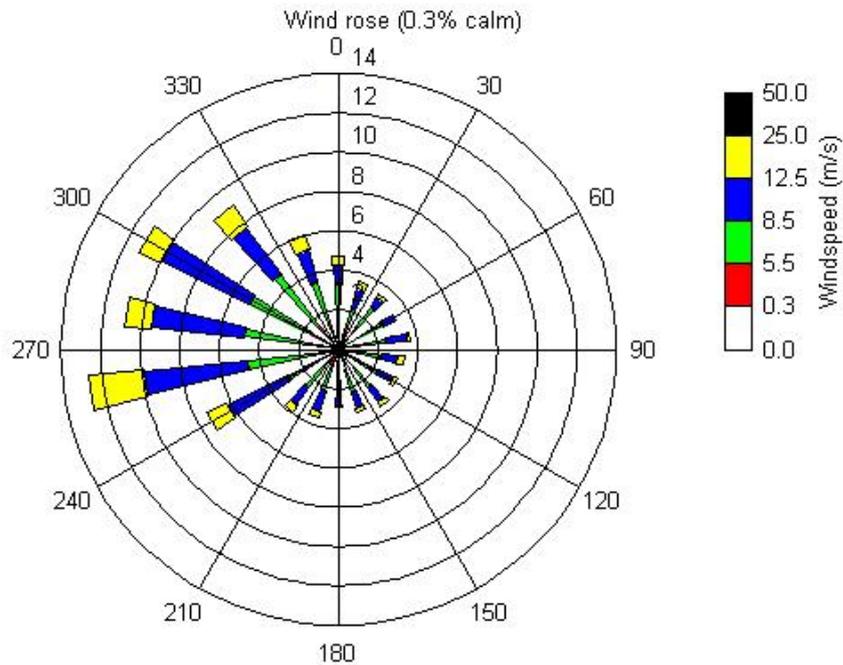


Figure 2.3c - Wind rose for the “Diablo” El Nino year, from August 1, 1997, with strengthened westerlies and weakened easterlies.

Table 2. 2 Average river flows.

River name	El Nino yearly averaged flow (m ³ /s)	La Nina yearly averaged flow (m ³ /s)
Kaituna	20.27	23.43
Rangitaiki	65.29	69.99
Raukokere	33.92	33.78
Waioeka	32.98	34.65
Whakatane	60.20	58.45
Tarawera	27.30	30.23
Wairoa	16.92	16.03
Average of all rivers	256.88	266.56

2.4 AQUACULTURE SCENARIOS

Various aquaculture scenarios were modelled by Longdill et al. (2006) and the differences between the ‘no-aquaculture model runs’ and the ‘with aquaculture model runs’ was calculated. Here, the size of the farms and simulated stocking density of the green-lipped mussels was kept the same, as adopted by Longdill et al. (2006).

They considered three different farm scenarios:

- Two farms at Opotiki and Pukehina (similar to the proposed farms)
- Four farms spread along the coast
- Four farms placed on a cross-shore transect

In this report, we modelled the first scenario only, as the trends identified by Longdill et al. (2006) adequately explain the anticipated outcomes for the scenarios with 4 farms (Table 2.2).

Longdill et al. (2006) found for the 2003/4 years that Chlorophyll *a* within the Bay of Plenty is spatially and temporally variable, being highest in coastal waters between August and January (Austral spring-summer) at all depths examined (Figure 2.4).

The chlorophyll-*a* averaged over the year 2003/04 in the surface layer (0-5 m) is shown in Figure 2.4 (from Longdill et al., 2006) and there are some large spatial variations in the levels. Typically phytoplankton concentrations are predicted to be greater near the coast. The nutrients used by the phytoplankton are provided by both the river inputs and nutrient-rich deep water upwelling to the coast. The circulation creates a tongue of phytoplankton that extends along East Cape. Highest levels are predicted to be on the shelf, near the coast in the Central Bay of Plenty, off the Pukehina/Otarmarakau/Matata area. There is a reduction in levels to the east of Opotiki at the base of East Cape. Chlorophyll *a* was typically higher in the Pukehina region than Opotiki. (refer to Table 2.3).

Overall results showing the impacts of the farms are presented in Table 2.3.

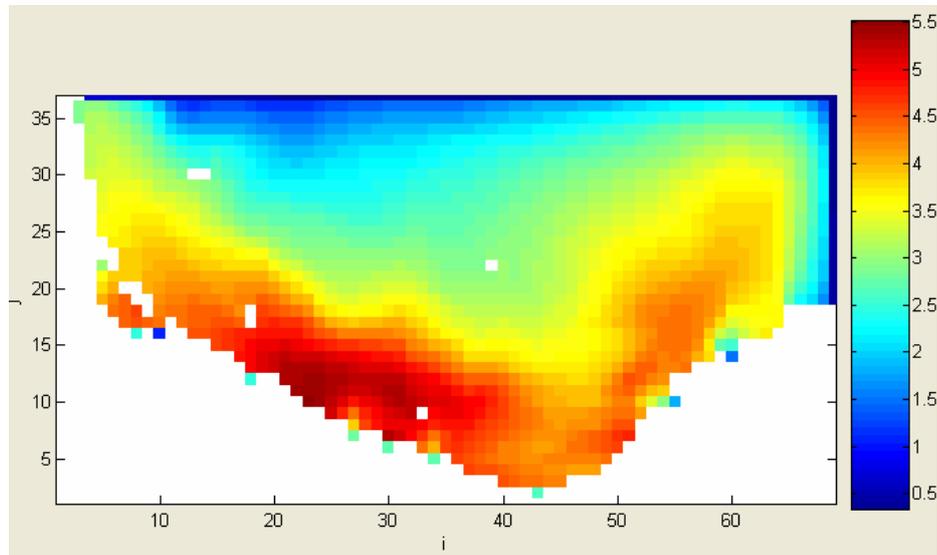


Figure 2.4 – Modelled yearly averaged phytoplankton chlorophyll-*a* (mg/m³) in the surface layer within the Bay of Plenty.

Table 2.3 – Results from modelling scenarios by Longdill et al. (2006) for three depth ranges examined for each farm scenario. Farm scenario 1 – Two farms at Opotiki and Pukehina; Farm scenario 2 – Four farms long-shore; Farm scenario 3 – Four farms cross-shore. Table denotes ambient seasonal range of chlorophyll *a* (μL^{-1}) and corresponding percent decrease relative to each farming scenario for each time period. Yearly averages are also presented.

Farm Scenario 1	Time	Pukehina		Opotiki	
		Range μL^{-1}	% decrease	Range μL^{-1}	% decrease
Surface waters	Aug-Oct	4.5-7.0	0.2-0.45	4.5-6.0	0.3-0.6
	Nov-Jan	5.5-8.25	0.2-0.6	5.5-6.5	0.1-0.6
	Feb-Apr	2.5-3.25	1.0-2.25	2.5-3.25	1.5-2.5
	May-Jul	2.5-4.5	0.6-1.2	2.5-3.5	0.8-1.2
	Yearly Average		0.4-1.0		0.6-1.2
15 m	Aug-Oct	3.5-7.0	0.2-0.55	4.0-6.0	0.45-0.8
	Nov-Jan	4.0-8.0	0-0.8	4.0-8.0	0-3.0
	Feb-Apr	2.75-3.5	0.5-2.0	2.75-3.75	0-3.0
	May-Jul	3.0-5.0	0.5-1.6	0-4.75	1.0-1.6
	Yearly Average		0.6-1.4		0.4-1.5
25m	Aug-Oct	3.0-6.0	0.5-4.5	4.0-5.5	0.5-4.5
	Nov-Jan	2.5-7.0	0-7.0	4.0-9.5	0-7.0
	Feb-Apr	2.25-3.75	1.5-6.0	2.5-3.75	0-9.0
	May-Jul	2.5-4.5	1.0-5.5	2.5-4.0	1.0-5.5
	Yearly Average		0-2.25		0-3.5.0

Farm Scenario 2	Time	Pukehina		Opotiki	
		Range μL^{-1}	% decrease	Range μL^{-1}	% decrease
Surface waters	Period				
	Aug-Oct	4.5-7.0	0.4-1.0	4.5-6.0	0.6-1.0
	Nov-Jan	5.5-8.25	0.4-1.4	5.5-6.5	0.2-1.4
	Feb-Apr	2.5-3.25	2.25-4.0	2.5-3.25	3.0-4.5
	May-Jul	2.5-4.5	1.5-2.5	2.5-3.5	1.75-2.5
	Yearly Average		1.25-2.0		0.6-1.2
		Range μL^{-1}	% decrease	Range μL^{-1}	% decrease
15 m	Aug-Oct	3.5-7.0	0.25-1.5	4.0-6.0	0.25-1.6
	Nov-Jan	4.0-8.0	0.5-1.5	4.0-8.0	2.0-5.0
	Feb-Apr	2.75-3.5	2.0-4.25	2.75-3.75	2.0-5.0
	May-Jul	3.0-5.0	1.25-2.75	0-4.75	2.0-3.0
		Yearly Average		1.0-3.0	
		Range μL^{-1}	% decrease	Range μL^{-1}	% decrease
25m	Aug-Oct	3.0-6.0	0.75-6.0	4.0-5.5	0.75-5.0
	Nov-Jan	2.5-7.0	0.5-0.70	4.0-9.5	0.5-7.0
	Feb-Apr	2.25-3.75	2.0-7.0	2.5-3.75	3.0-10.5
	May-Jul	2.5-4.5	2.0-6.0	2.5-4.0	2.0-6.5
		Yearly Average		0.5-2.5	

Farm Scenario 3	Time	Pukehina		Opotiki	
		Range μL^{-1}	% decrease	Range μL^{-1}	% decrease
Surface waters	Period				
	Aug-Oct	4.5-7.0	0.4-1.0	4.5-6.0	0.5-0.5
	Nov-Jan	5.5-8.25	0.25-0.2	5.5-6.5	0-0.75
	Feb-Apr	2.5-3.25	2.5-4.0	2.5-3.25	1.5-3.0
	May-Jul	2.5-4.5	1.0-2.0	2.5-3.5	0.75-1.25
	Yearly Average		5.0-8.0		4.0-5.5
		Range μL^{-1}	% decrease	Range μL^{-1}	% decrease
15 m	Aug-Oct	3.5-7.0	0.6-1.5	4.0-6.0	0.2-0.5
	Nov-Jan	4.0-8.0	0.25-2.5	4.0-8.0	2.0-4.0
	Feb-Apr	2.75-3.5	2.5-5.5	2.75-3.75	2.0-4.0
	May-Jul	3.0-5.0	1.25-2.75	0-4.75	0.75-1.0
		Yearly Average		1.0-2.75	
		Range μL^{-1}	% decrease	Range μL^{-1}	% decrease
25m	Aug-Oct	3.0-6.0	0.5-5	4.0-5.5	0.25-5.0
	Nov-Jan	2.5-7.0	0-8.0	4.0-9.5	0-1.0
	Feb-Apr	2.25-3.75	2.0-10.0	2.5-3.75	1.5-3.0
	May-Jul	2.5-4.5	2.0-6.5	2.5-4.0	1.0-1.5
		Yearly Average		0.5-4.0	

3 YEARLY-AVERAGED PHYTOPLANKTON ABUNDANCES

Several outputs can be taken from the simulations, including averages. In this report we present the yearly-averaged Chlorophyll *a* in the surface layer (0-5 m depth) and the farm layer (15-25 m depth) for El Nino and La Nina and Diablo cases (with and without the mussel farms), and the differences between the cases.

3.1 EL NINO AND LA NINA YEARLY AVERAGES

3.1.1 Comparisons With Data and Expectations

The yearly-averaged phytoplankton levels in the surface layer for El Nino and La Nina are shown in Figures 3.1a, b respectively, and the patterns are very different with higher abundances of phytoplankton in El Nino.

When compared with the modelling of 2003/04 (Figure 2.4), the chlorophyll *a* coastal values of around 4-5 mg/m³ lie between El Nino and La Nina, as expected.

The results are in good general agreement with measurements of Chlorophyll *a* off Goat Island Bay, Leigh, in north-eastern New Zealand (Figure 3.2). These showed

- Typical values at Leigh in El Nino years of 4-6 mg/m³ (including a peak of 4 mg/m³ at Leigh in December 1997) compared to the model values of 4-7 mg/m³.
- Typical values at Leigh in La Nina of 1-2 mg/m³ (with a measured peak of 2 mg/m³ in December 1998) compared to the model values of 2-3 mg/m³.
- Goat Island is closest to and has the same orientation as the Coromandel. Along the Coromandel coast, the model predicts 4.5 and 1.5 mg/m³ for El Nino and La Nina, while measurements at Goat Island were 4-6 and 1-2 mg/m³ respectively.

Other supporting evidence comes from satellite Chlorophyll *a* images of the Bay. These show the same tendency for the Coromandel coast to have lower

phytoplankton abundance than the central coast of the Bay of Plenty. For example, the satellite Chlorophyll *a* measurements shown in Figures 3.3 (from Longdill et al. (2005)) are highly correlated with the patterns predicted by the modelling in the La Nina year (Figure 3.1b).

In summary, the results are in accordance with expectations.

3.2 DIABLO EL NINO CASE

The El Nino phytoplankton levels are much higher than those in La Nina, as discussed above. However, the Diablo El Nino with the stronger westerlies shows no similar increase in average levels above El Nino, but the model predicts a large region of the Bay with levels higher than 5 mg/m³ (Figure 3.1c). In fact, the levels are between the “normal” and El Nino cases. In addition, the pattern is very different. The stronger westerlies have moved the location of the maxima to the east, more towards East Cape and the south-east corner of the Bay of Plenty. As such, it appears that climate change will increase productivity of the Bay relative to the normal and La Nina years, and it could lead to different regions of the Bay being the most productive.

3.3 CONSIDERATION OF THE PHYTOPLANKTON PATTERNS IN THE BAY OF PLENTY

One important result helps to explain the differences between the cases. For the Bay of Plenty, the lowest phytoplankton abundances occur along the Coromandel, with considerably higher abundances in the central Bay. This outcome is also evident in the satellite measurements. Under prevailing westerlies, the expectation is that the strongest upwelling would occur along the Coromandel coast and indeed Figure 3.5a from the model confirms that the upwelling there is higher than along the central coast of the Bay, excluding the effects of the rivers. The rivers, however, also induce strong upwelling and the largest rivers are in the central Bay. The upwelling in the rivers relates to upward mixing of bottom waters into the buoyant plumes as they dilute after entering Bay waters. In addition, the rivers bring land-sourced nutrients into the Bay directly. In combination, the highest levels of phytoplankton occur around the Central Bay, particularly near the largest rivers, rather than on the

Coromandel coast. In general, the results of this study show that the river flows have a profound effect on phytoplankton abundances. Further confirmation occurs on the tip of Cape Runaway along East Cape where upwelling is strong, but phytoplankton numbers are low (both in the model and satellite images).

However, the ocean upwelling effects are still in evidence. For example, the relatively low phytoplankton levels in the south-east of the Bay are lower than off Whakatane. Similarly, the upwelling in this area is predicted to be less (Figure 3.5a,b). In general, both the ocean bottom waters and the rivers are responsible for sustaining phytoplankton levels in the Bay.

In accordance with this mechanism, the patterns of mean salinity in the model's surface layer for the 3 cases modelled (Figure 3.6a,b,c) show some coincidence with the patterns of phytoplankton in the surface layer (Figures 3.1a,b,c), particularly in the "Diablo" El Nino modelling.

Another phenomenon in the model is the halo around the river entrances. The rivers deliver no phytoplankton and so the halo arises because the phytoplankton takes time to grow. A similar outcome can occur in upwelling areas where phytoplankton numbers in the bottom waters are small and so a halo can occur around a strongly upwelling area if the upward velocity is fast enough to outstrip the growth rates. Then, the bottom waters reaching the surface temporarily remain depleted of phytoplankton.

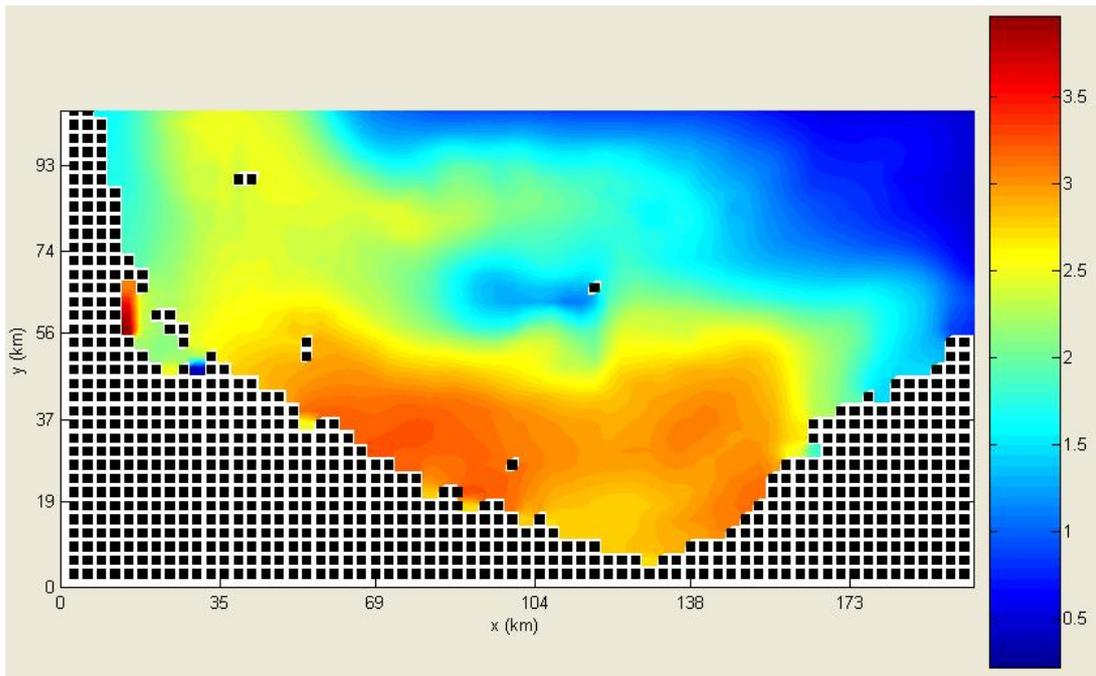


Figure 3.1a – Modelled yearly averaged phytoplankton (chlorophyll-*a* mg/m³) in the surface layer for La Nina within the Bay of Plenty.

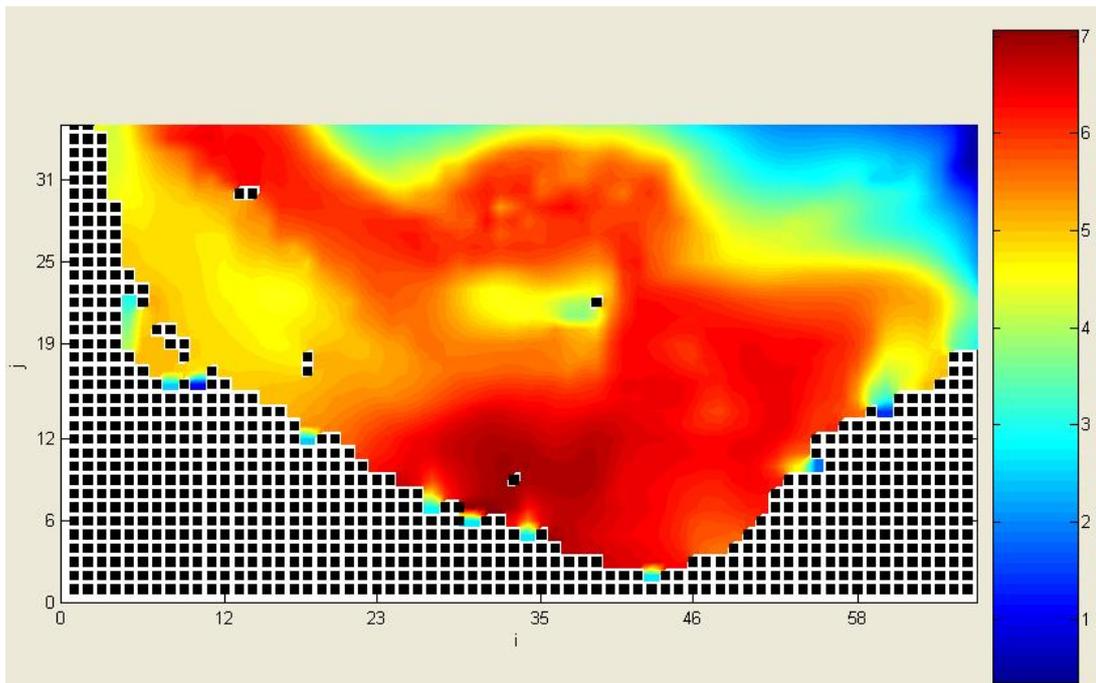


Figure 3.1b – Modelled yearly averaged phytoplankton (chlorophyll-*a* mg/m³) in the surface layer for El Nino within the Bay of Plenty.

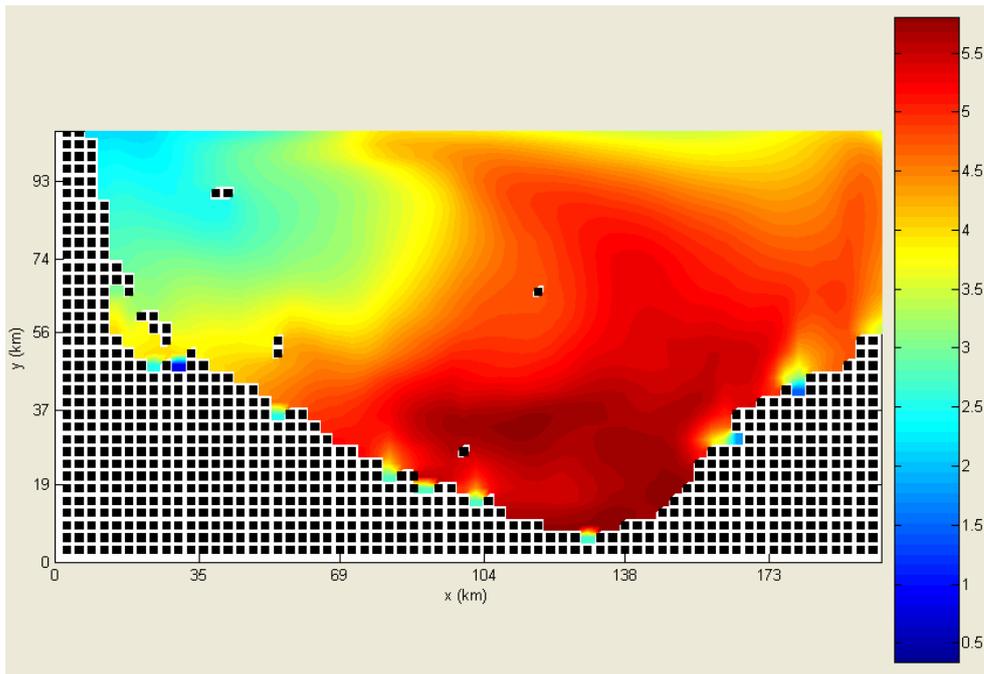


Figure 3.1c – Modelled yearly averaged phytoplankton (chlorophyll-*a* mg/m³) in the surface layer for the “Diablo” El Nino year within the Bay of Plenty.

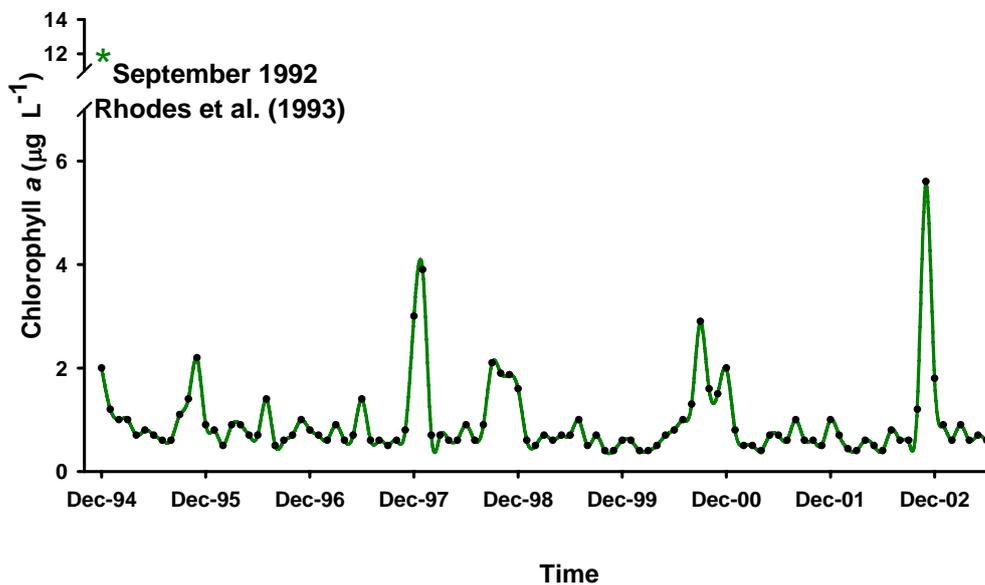


Figure 3.2 - Seawater Chlorophyll *a* at Goat Island Bay, Leigh, north-eastern New Zealand from December 1994 to July 2002. Asterisk on graph denotes values from within the Bay recorded by Rhodes et al. (1993). Note: values are somewhat conservative, due to the high water column mixing that occurs at the sampling location

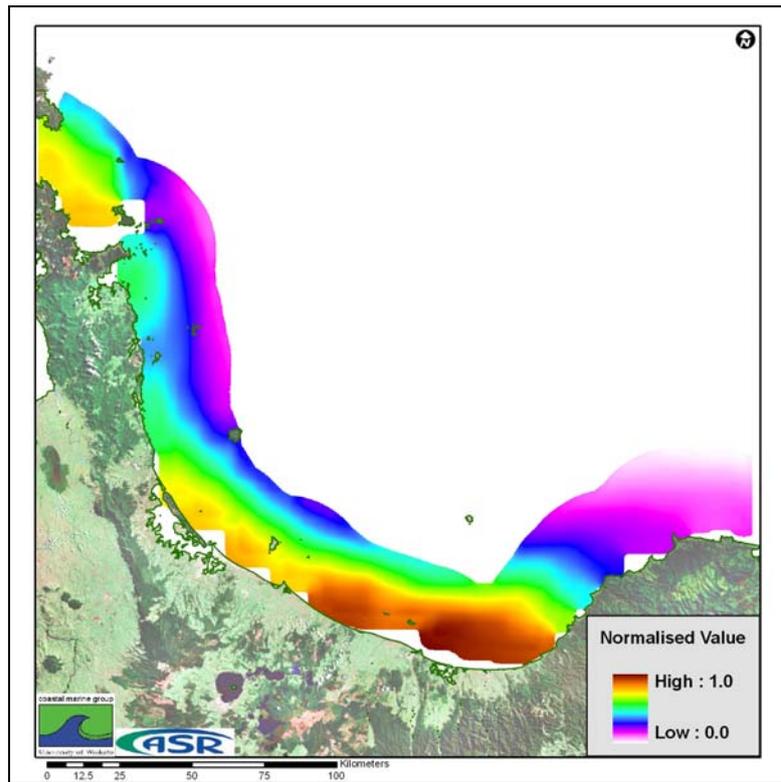


Figure 3.3 - Chlorophyll-*a* (Case 2 algorithm) anomaly within the Bay of Plenty and Coromandel areas over the period 1997 - 2004. High values represent higher than typical (relative to the coastal segment) chlorophyll-*a* concentrations, while low values represent lower than typical concentrations. Original satellite data provided by NIWA.

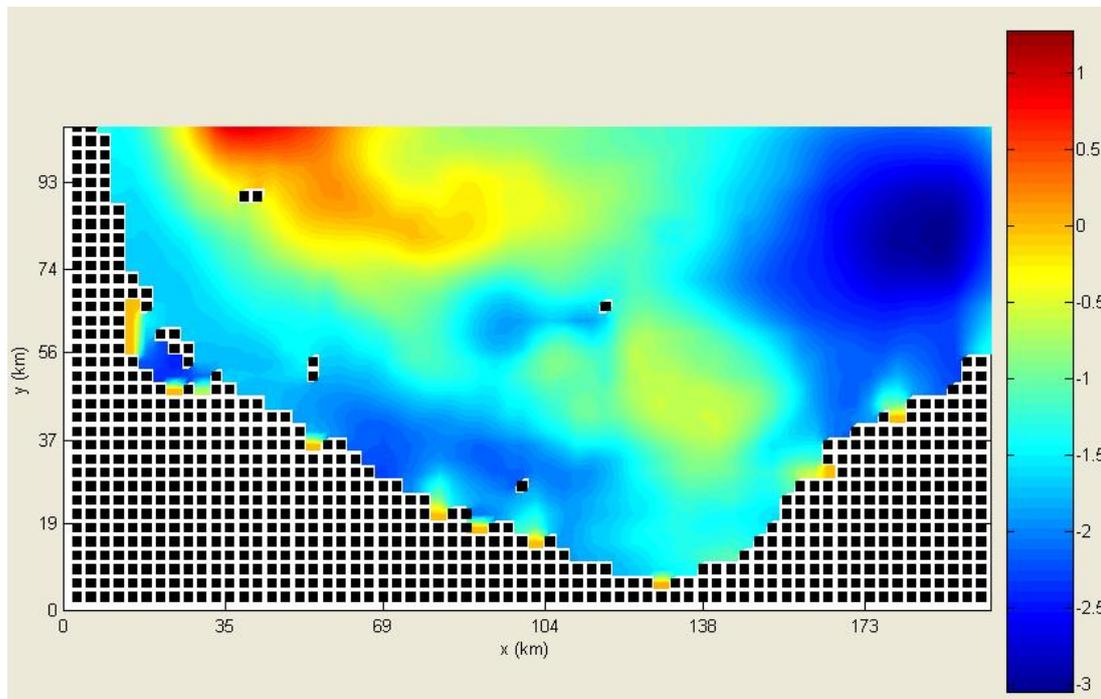


Figure 3.4a - Difference in Chlorophyll-*a* (mg/m³) between the “normal” year of 2003/04 and the La Nina simulation.

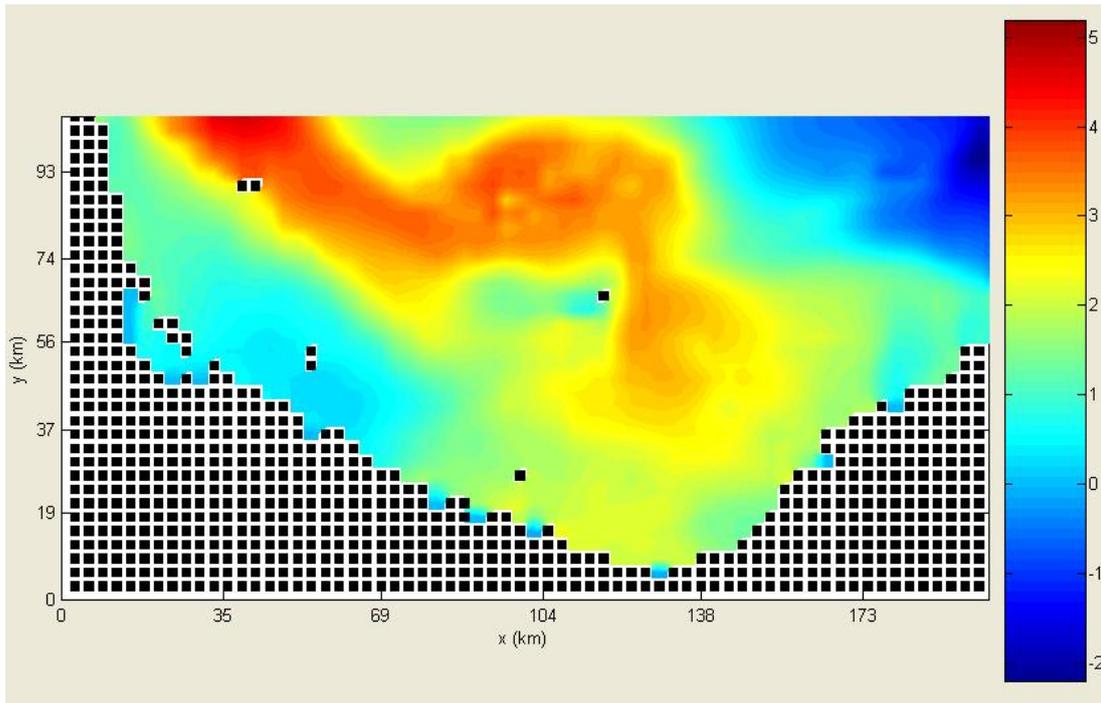


Figure 3.4b - Difference in Chlorophyll a (mg/m³) between the “normal” year of 2003/04 and the El Nino simulation.

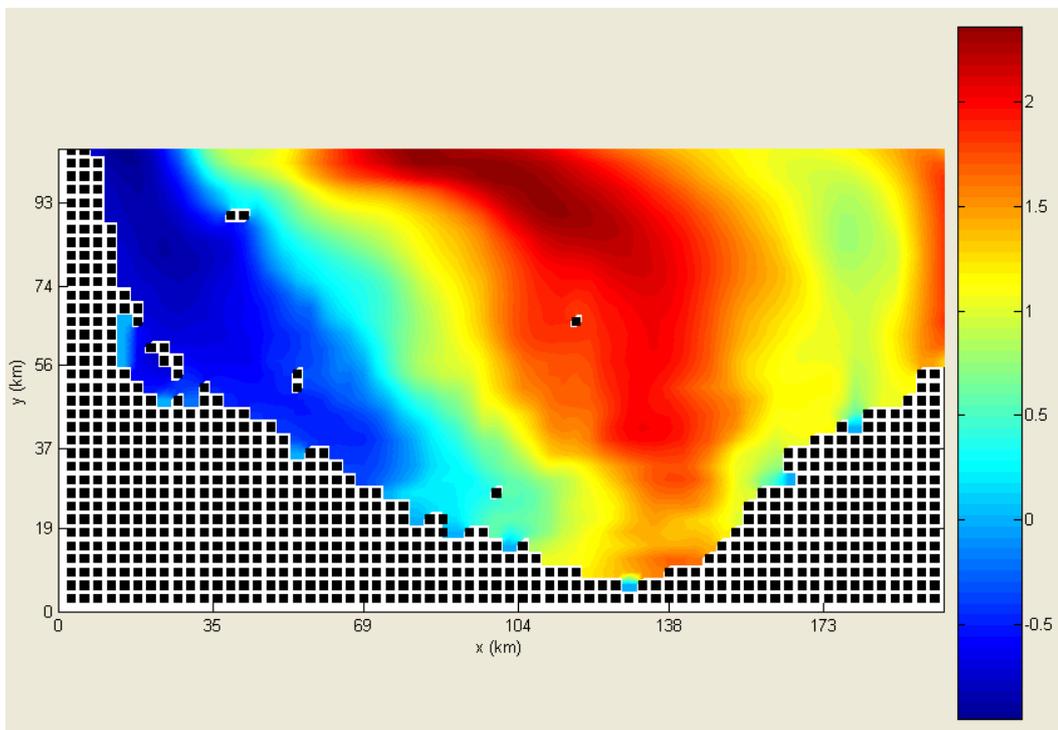


Figure 3.4c - Difference in Chlorophyll a (mg/m³) between the “normal” year of 2003/04 and the “Diablo” El Nino simulation.

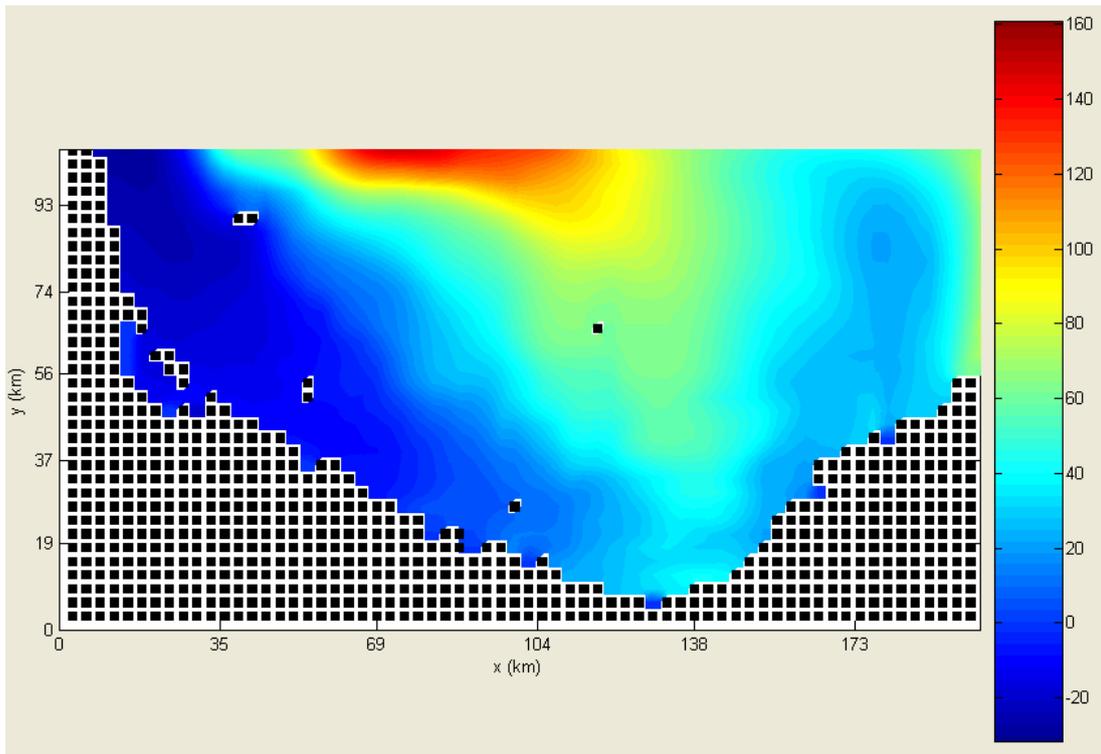


Figure 3.4d - Percentage difference in Chlorophyll a (mg/m³) between the “normal” year of 2003/04 and the El Niño simulation.

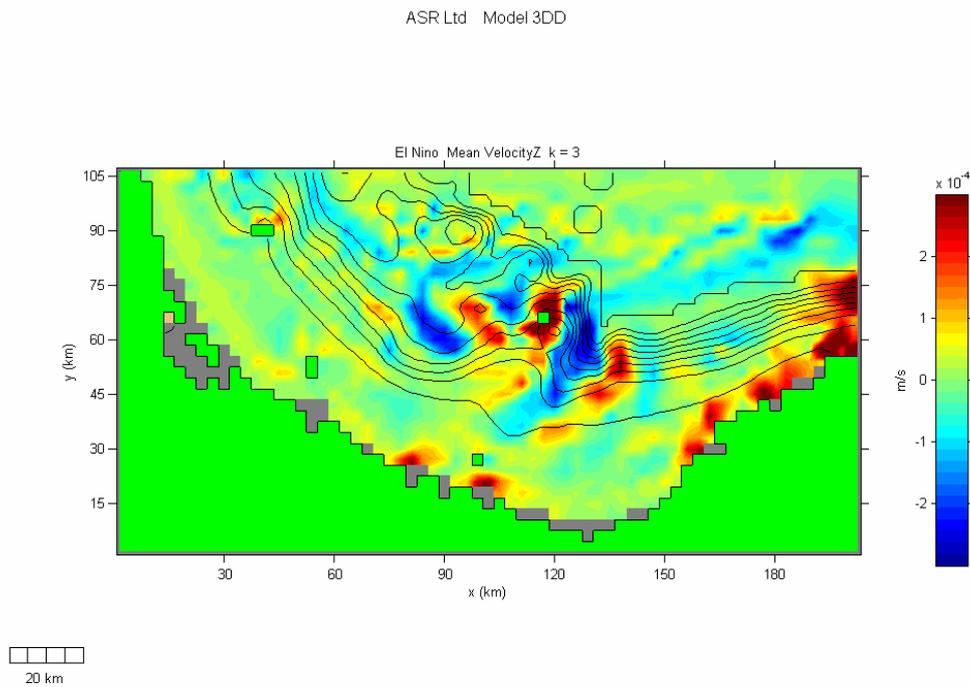


Figure 3.5a – Modelled up/downwelling patterns in the Bay of Plenty averaged over the El Niño yearly simulation. The red and yellow tones show upwelling and the blue tones show downwelling.

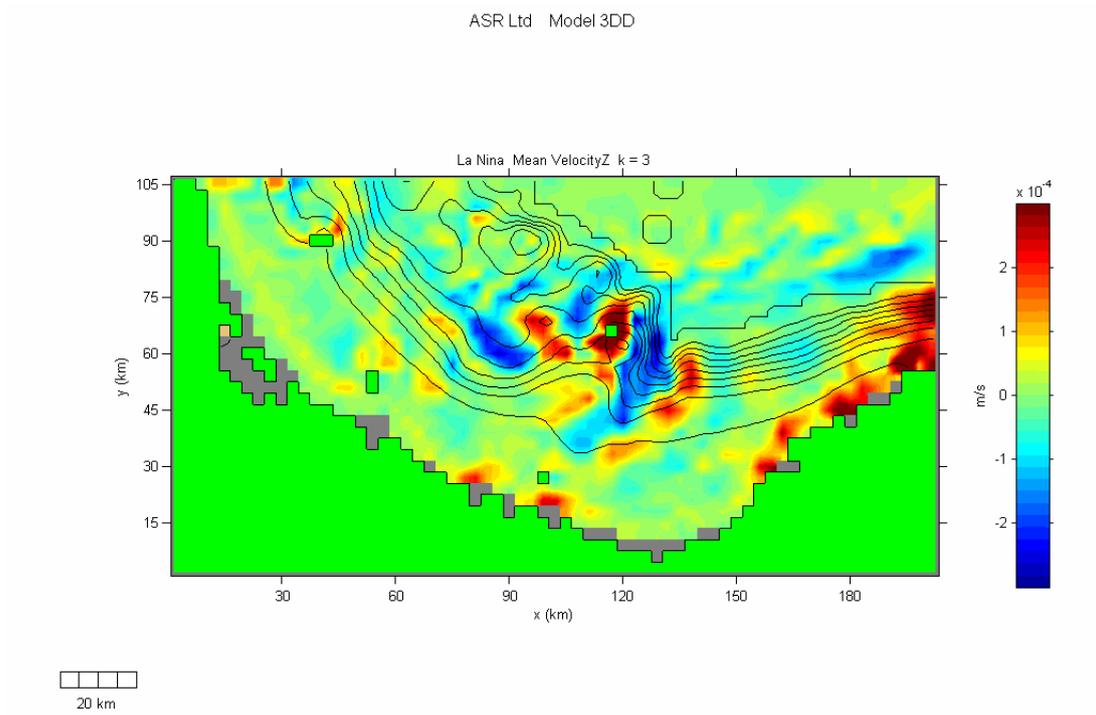


Figure 3.5b – Modelled up/downwelling patterns in the Bay of Plenty averaged over the La Nina yearly simulation. The red and yellow tones show upwelling and the blue tones show downwelling.

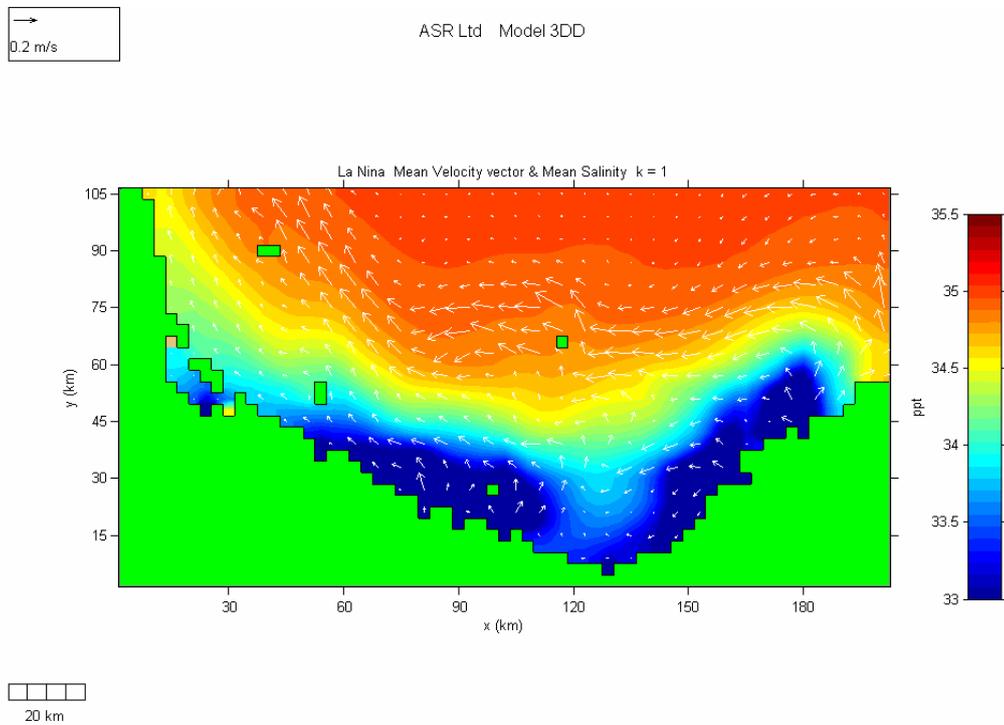


Figure 3.6a – Modelled mean salinity (pseudo colours) and vector averaged velocity during La Nina in the surface layer of the model.

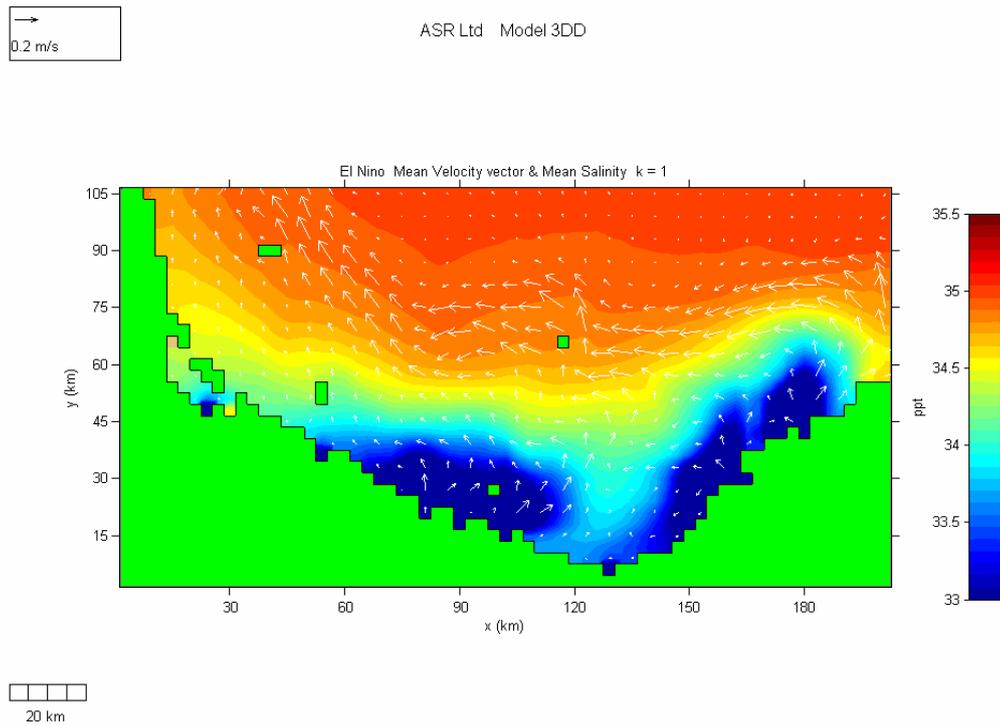


Figure 3.6b – Modelled mean salinity (pseudo colours) and vector averaged velocity during El Nino in the surface layer of the model.

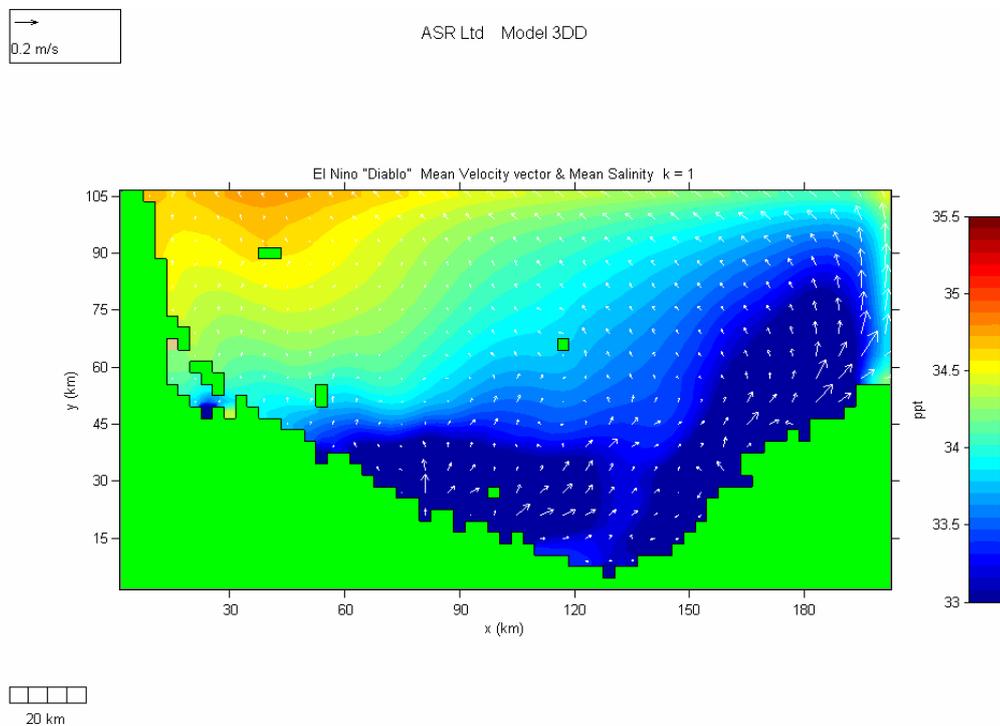


Figure 3.6c – Modelled mean salinity (pseudo colours) and vector averaged velocity during “Diablo” El Nino in the surface layer of the model. Note the tendency for the stronger westerlies to push the plumes to the east.

4 MUSSEL FARM MODELLING

4.1 FARMS SCENARIO

Two mussel farms were modelled together: a 5400Ha farm in a rectangular block offshore from Opotiki and a slightly smaller 4500Ha farm offshore from Pukehina (Figure 3.2)

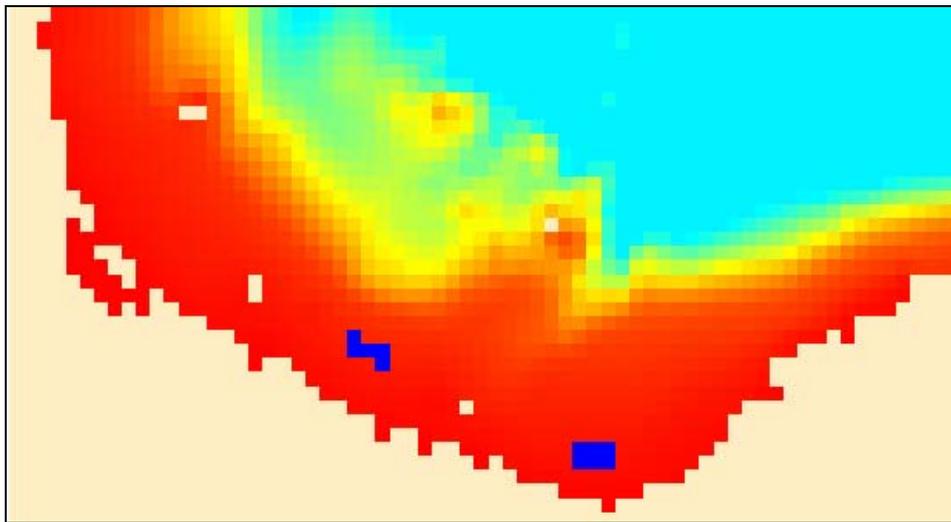


Figure 4.1 – Mussel farm locations offshore from Opotiki and Pukehina, 5400Ha and 4500Ha respectively. Farms shown in dark blue.

The model was run for the entire year (identical to the ‘no farm’ simulation) and the differences between the two runs calculated and averaged (Figures 4.2 to 4.6). Only selected plots are presented, i.e. at the surface or at the depth range of 15-25 m (which is where the mussels are located in the model and where effects are likely to be greatest).

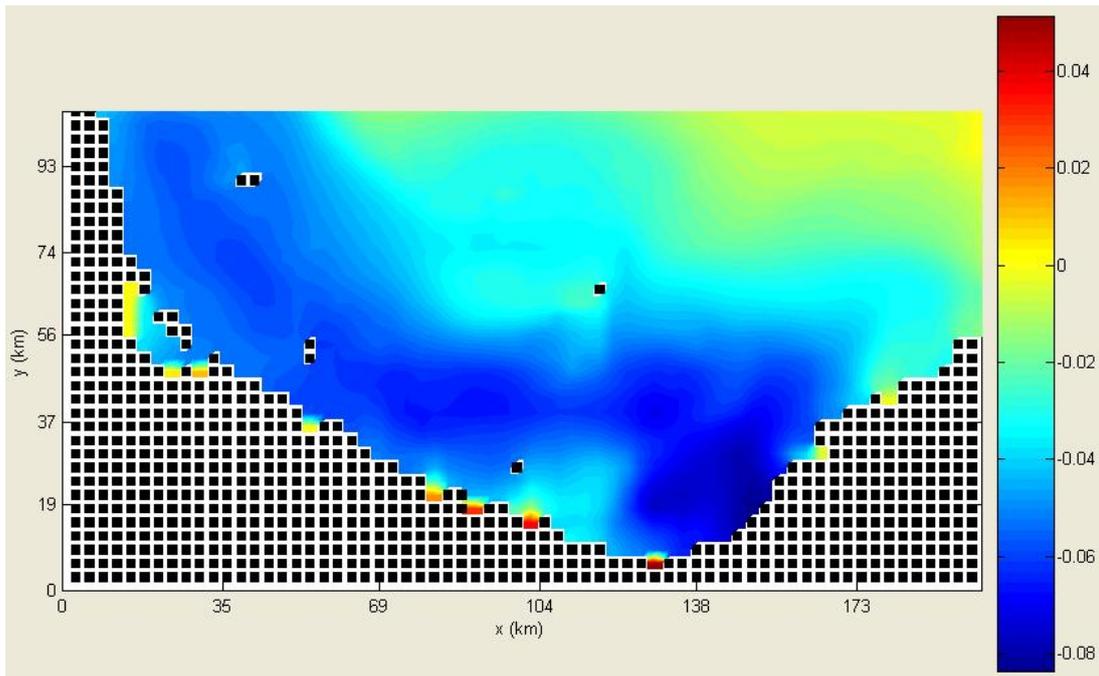


Figure 4.2a –Year long difference in the surface layer chlorophyll-*a* concentration (mg/m^3) between the ‘no farm’ and the ‘2 mussel farm’ scenario for El Nino.

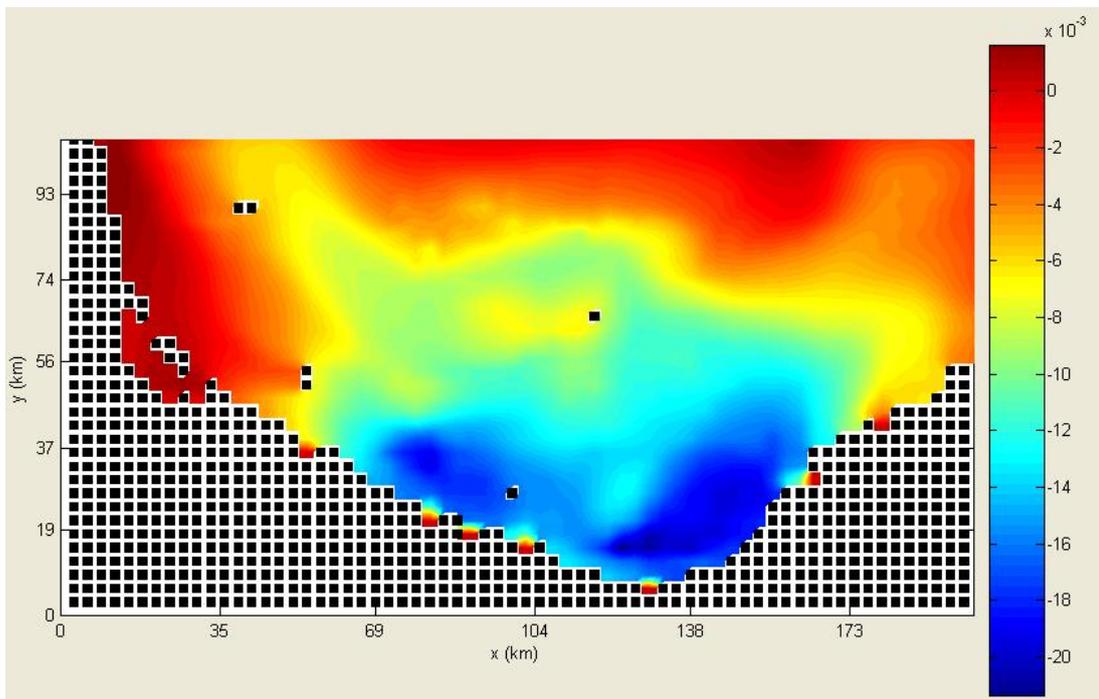


Figure 4.2b–Year long difference in the surface layer chlorophyll-*a* concentration (mg/m^3) between the ‘no farm’ and the ‘2 mussel farm’ scenario for La Nina.

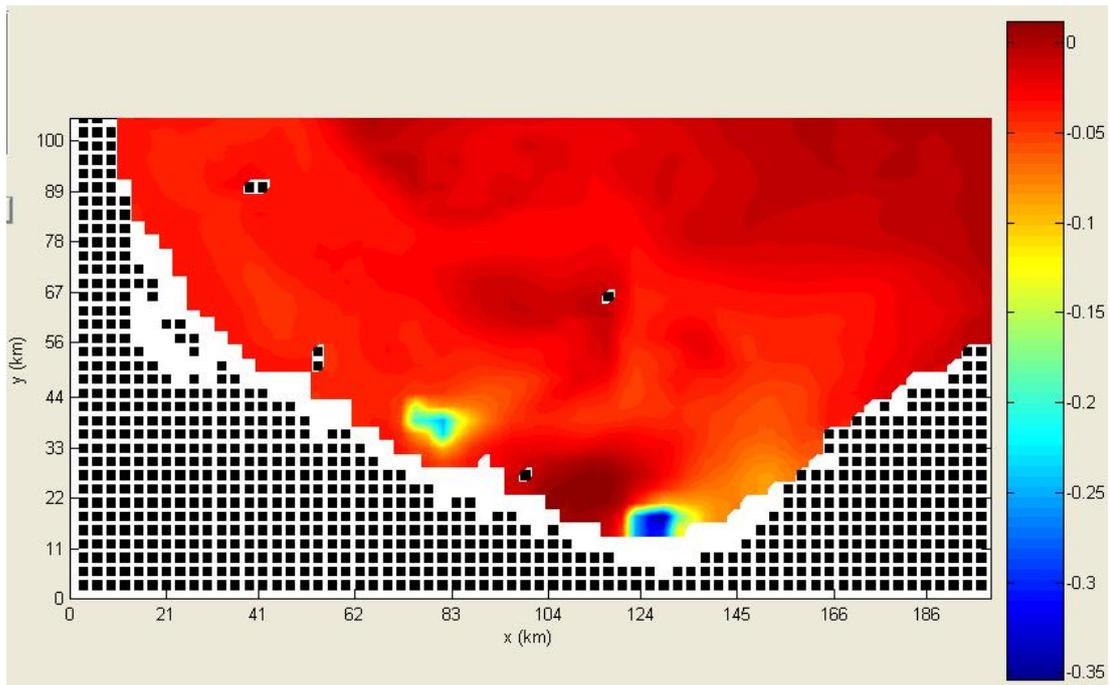


Figure 4.3a –Year long difference in 15-25 m water depths of chlorophyll-*a* concentration (mg/m^3) between the ‘no farm’ and the ‘2 mussel farm’ scenarios for El Niño.

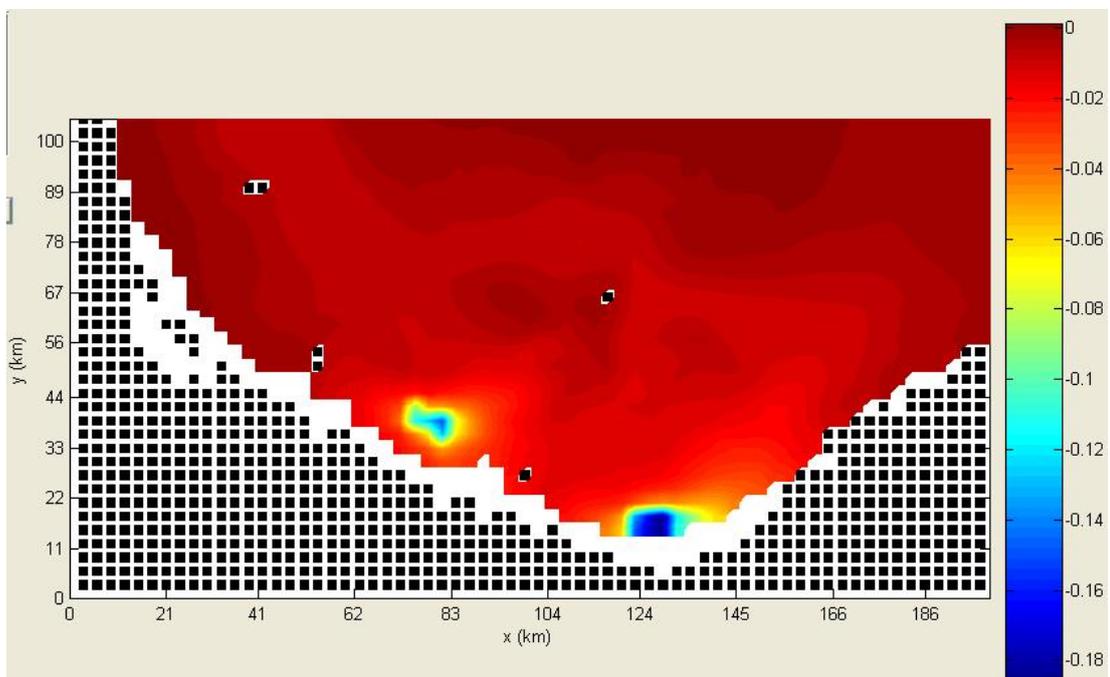


Figure 4.3b –Year long difference in 15-25 m water depths of chlorophyll-*a* concentration (mg/m^3) between the ‘no farm’ and the ‘2 mussel farm’ scenarios for La Niña.

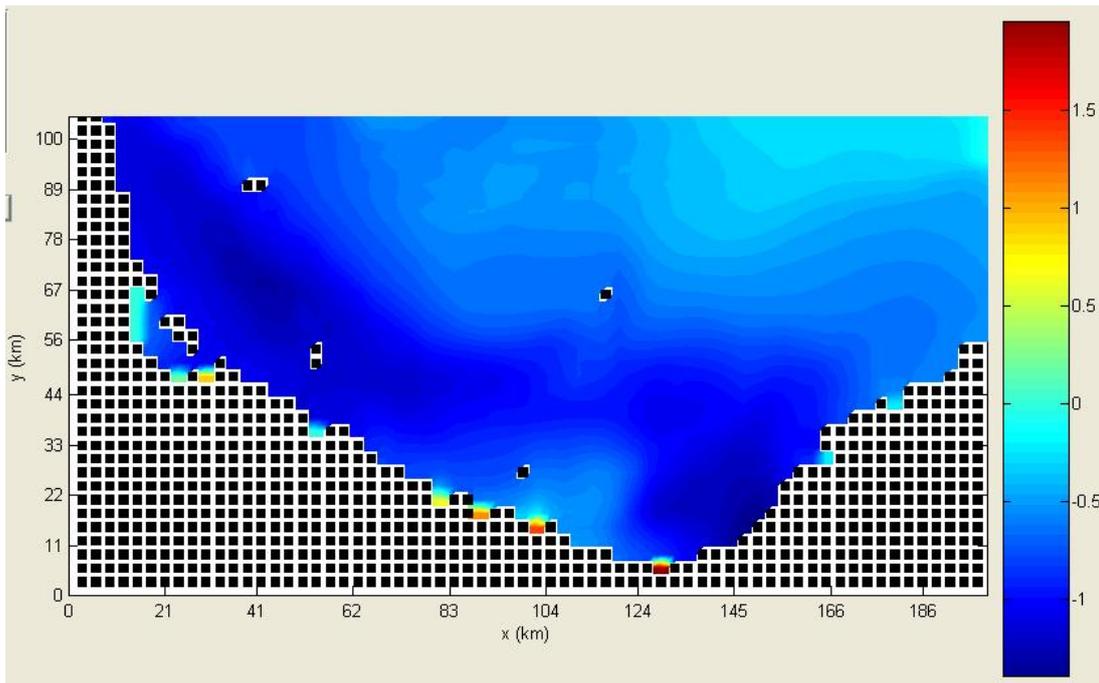


Figure 4.4a –Year long percentage difference in the surface layer chlorophyll-*a* concentration (mg/m^3) between the ‘no farm’ and the ‘2 mussel farm’ scenario for El Nino.

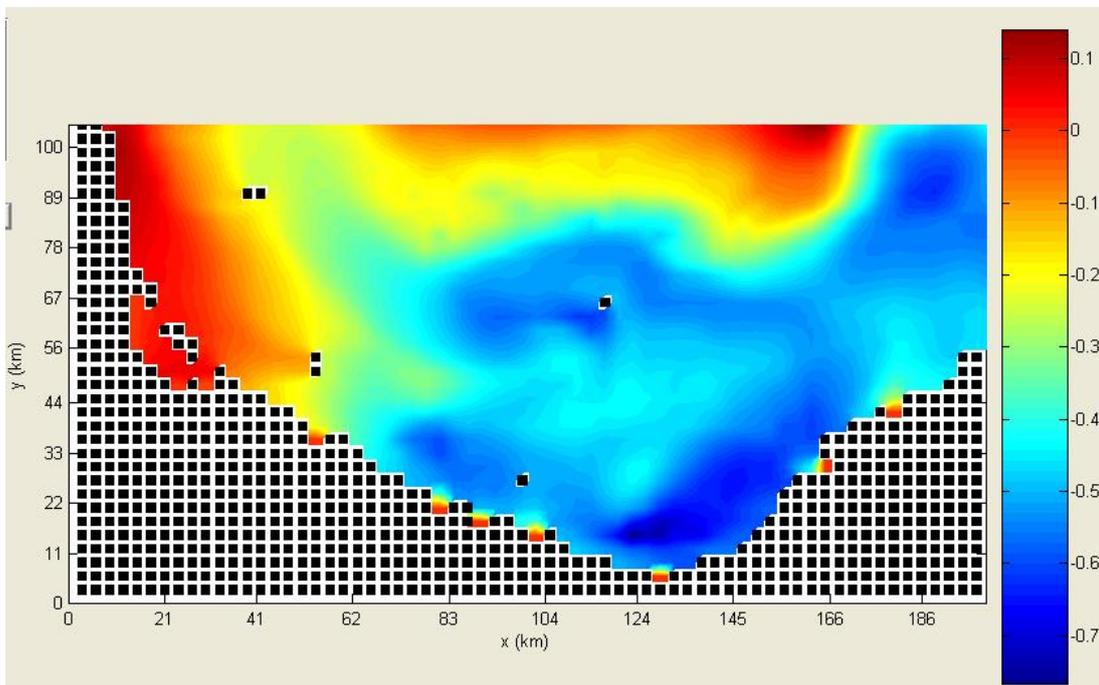


Figure 4.4b –Year long percentage difference in the surface layer chlorophyll-*a* concentration (mg/m^3) between the ‘no farm’ and the ‘2 mussel farm’ scenario for La Niña.

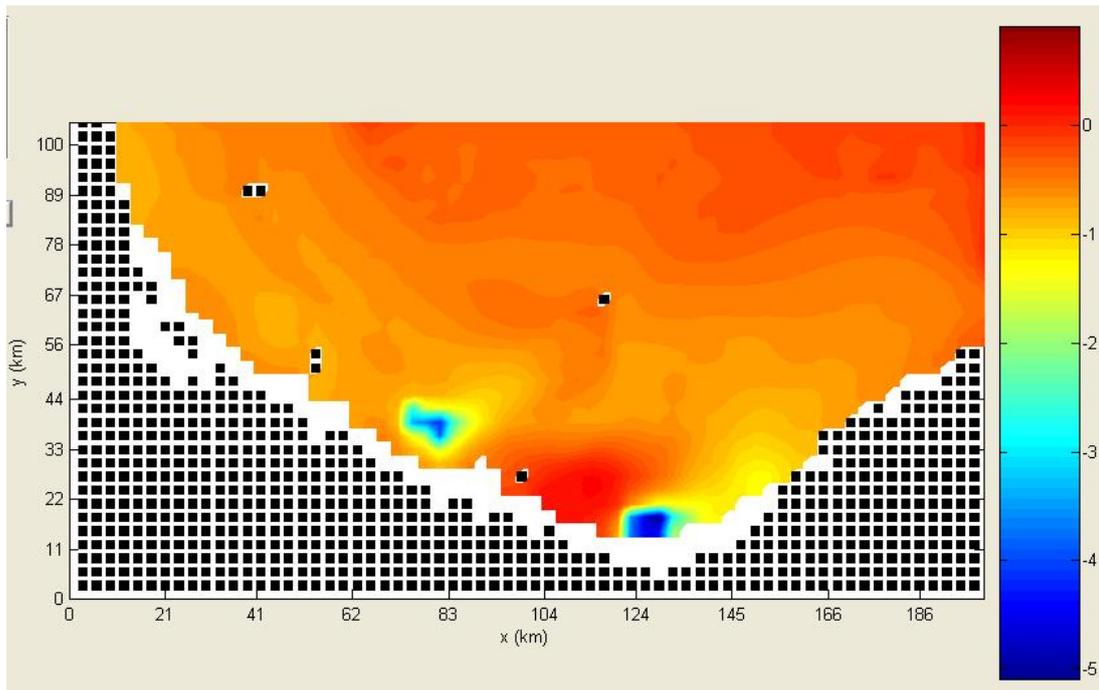


Figure 4.5a –Year long percentage difference in 15-25 m water depths of chlorophyll-*a* concentration (mg/m^3) between the ‘no farm’ and the ‘2 mussel farm’ scenarios for El Niño.

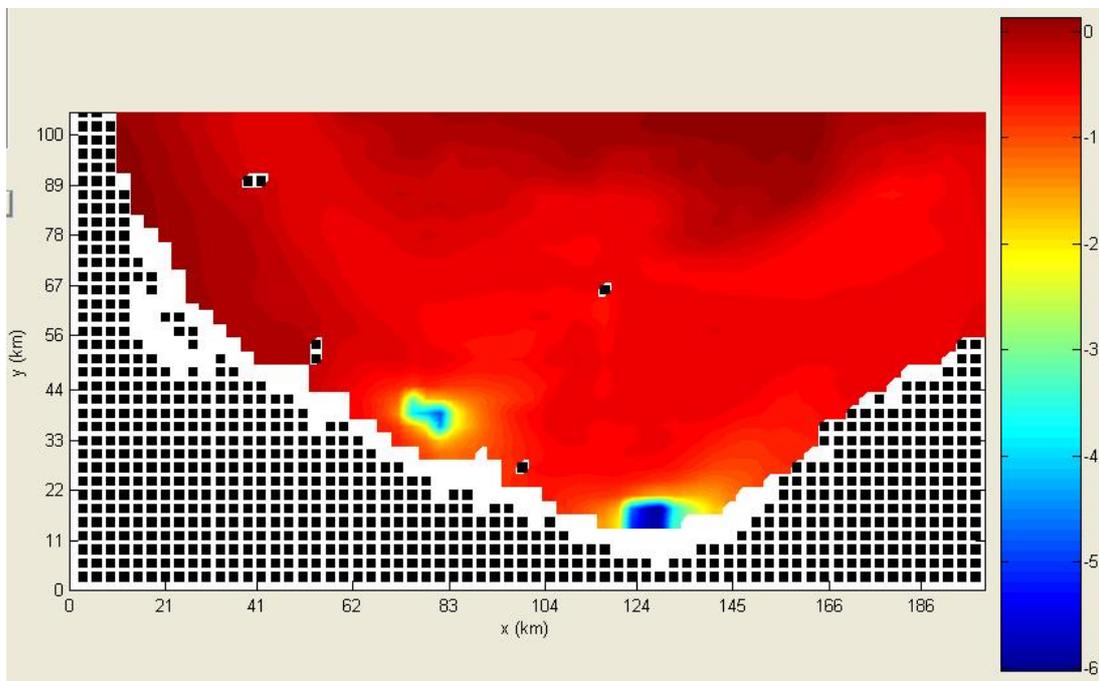


Figure 4.5b –Year long percentage difference in 15-25 m water depths of chlorophyll-*a* concentration (mg/m^3) between the ‘no farm’ and the ‘2 mussel farm’ scenarios for La Niña.

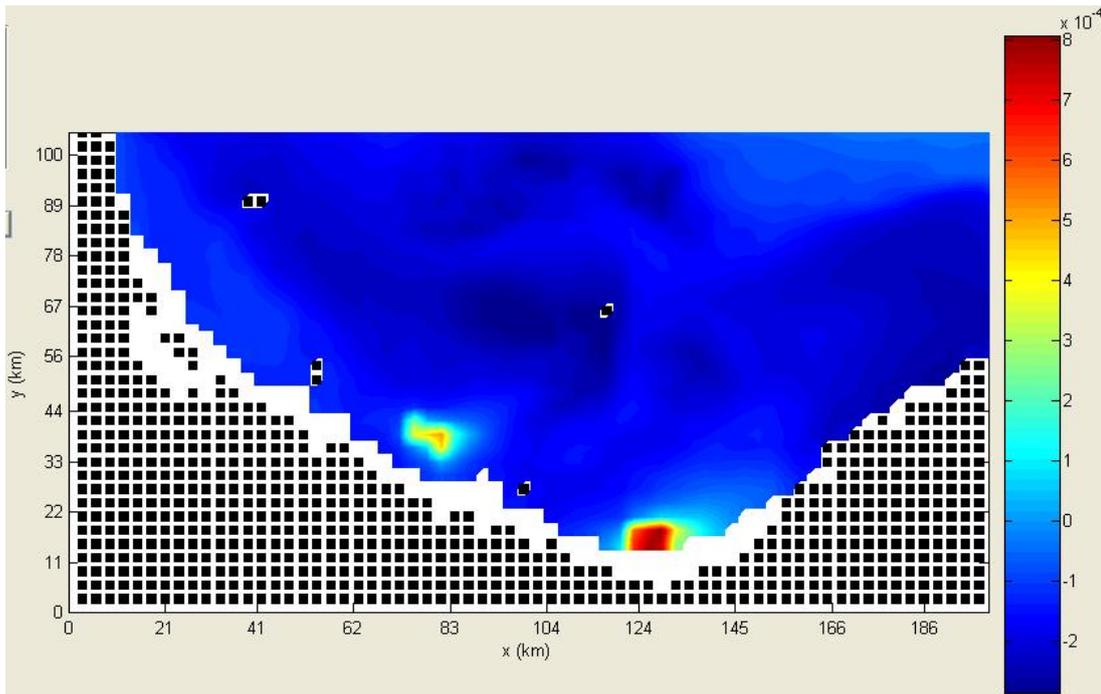


Figure 4.6a - Year long difference in 15-25m water depths of ammonia concentration (g/m^3) between the 'no farm' model run and the '2 mussel farm scenario' for El Niño. Note the local increase in ammonia as a result of excretion by the mussels.

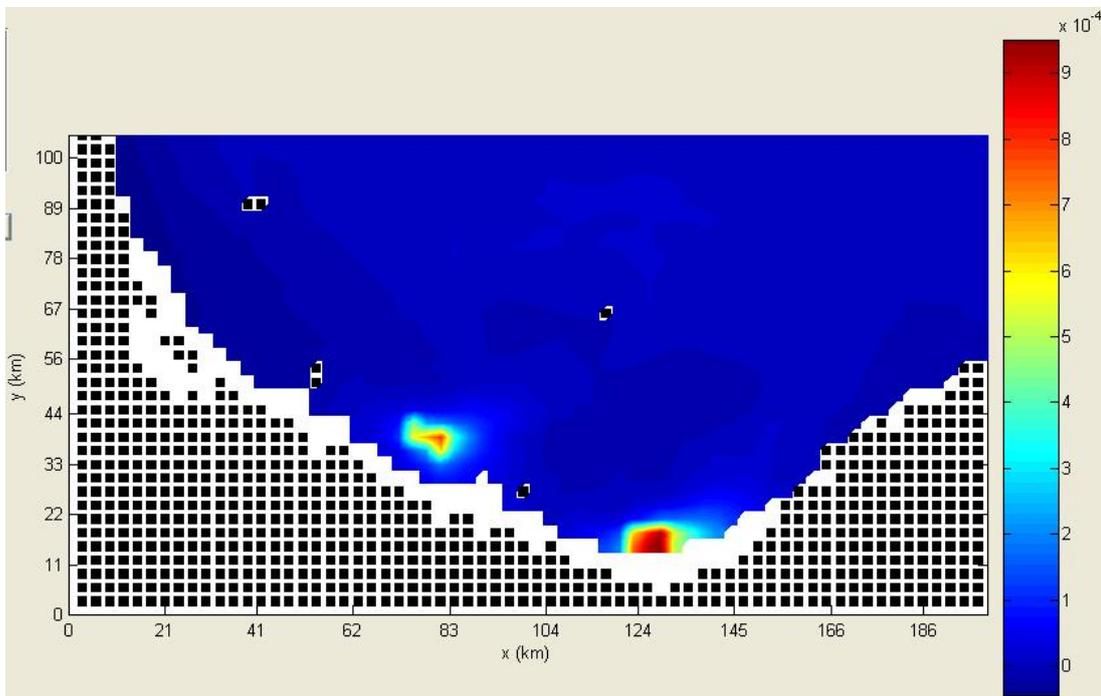


Figure 4.6b - Year long difference in 15-25m water depths of ammonia concentration (g/m^3) between the 'no farm' model run and the '2 mussel farm scenario' for La Niña. Note the local increase in ammonia as a result of excretion by the mussels.

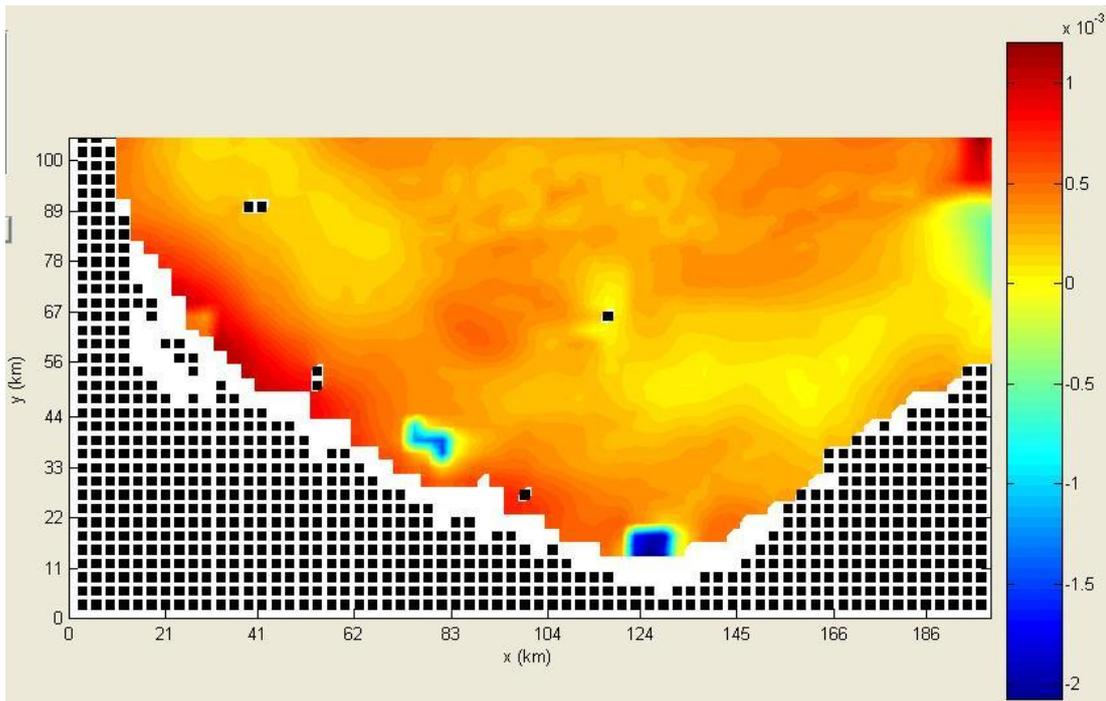


Figure 4.7a - Year long difference in 15-25m water depths of dissolved oxygen concentration (g/m^3) between the 'no farm' model run and the '2 mussel farm scenario' for El Niño.

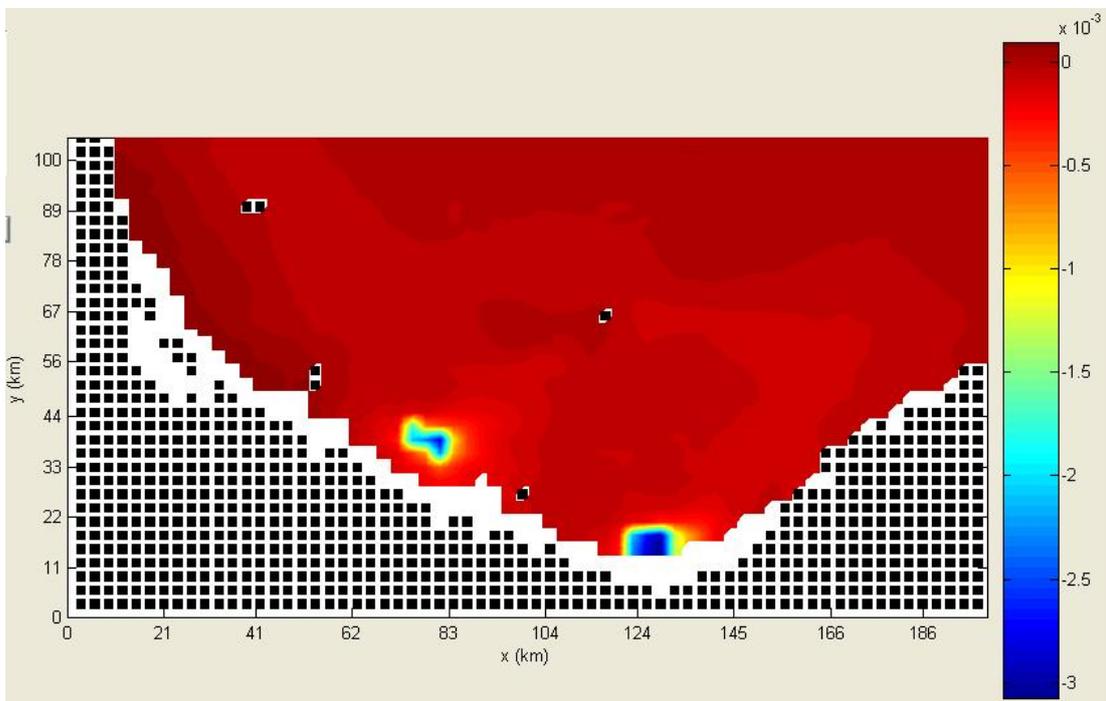


Figure 4.7b - Year long difference in 15-25m water depths of dissolved oxygen concentration (g/m^3) between the 'no farm' model run and the '2 mussel farm scenario' for La Niña.

It is apparent from the model runs that the two mussel farms are extracting phytoplankton, contributing ammonia, and extracting oxygen from the water column,

as would be expected. The effects are greatest at the depth at which the farms are located and close to the farms themselves (Figures 4.2 to 4.6). Figure 4.2, showing the year long average difference in phytoplankton chlorophyll concentrations between the 'no farm' and '2 farm' scenarios indicates that the effects of phytoplankton depletion may be apparent at a considerable distance from the farms as a result of the residual water currents transporting the 'filtered' water around the Bay.

The scale of this depletion however, must be considered. Figure 3.1a indicates the year long average phytoplankton chlorophyll *a* value at the same location is ~6 mg/m³ for El Nino and 2.5 mg/m³ for La Nina.

Surface water depletion (year long) rates in El-Nino years at both Pukehina and Opotiki are relatively small, equating to a reduction of 0.06 to 0.08 mg/ m³ in both areas (Figure 4.2a; also refer to Table 3.1). Despite lower ambient chlorophyll *a* in surface waters during La-Nina periods, even smaller depletions are apparent at Pukehina and Opotiki (Figure. 4.2b) over this period.

Average depletion rates in El-Nino years at 15-25 m depth at Pukehina range from 0.2-0.25 mg/ m³ with higher depletion shadows in nearshore areas at Opotiki ranging from 0.3-0.35 mg/ m³ (Figure 4.3a). In La-Nina years average depletions at Pukehina range from 0.08-0.15 mg/ m³ and at Opotiki depletions of ~ 0.18 are evident (Figure 4.4b).

Thus, the depletion of phytoplankton at the water surface near the coast of Opotiki is approximately -1%. The year long differences in the water layer from 15 – 25 m (Figures 4.3 and 4.5) indicate changes of a larger magnitude, with reductions of approximately -3% in a zone that extends around the farms and to the coast inshore of the farms.

Considering El Nino seasonal effects, the largest decline of chlorophyll *a* in surface waters equates to a value of ~-0.08 mg/m³ (0.08 µg L⁻¹) near the coast at Opotiki and at Pukehina between February and April. Effects are also greatest during this time period at 15 m depth where there is a reduction of -0.11 mg/m³ at Opotiki and -0.08

mg/m^3 at Pukehina. Similarly, larger effects are evident at 25 m depth between February and April with a reduction of -0.35 mg/m^3 at Opotiki and -0.25 mg/m^3 at Pukehina, during El Nino. The period between August and October, corresponds to the period of least impact, where Chlorophyll *a* is highest, which is a trend consistent among all depths at both Opotiki and Pukehina. Some depletion is compensated for by the increased ammonia inputs to the water column by mussel excretion (Figure 4.6a) providing additional nutrient for phytoplankton growth – though the beneficial effect may vary with phytoplankton species. Depletion shadows of dissolved oxygen at 15-25 m are also evident, with effects being slightly higher at Opotiki, but generally effects are restricted to the footprint of the farms (Figure 4.7a)

During La Nina, seasonal chlorophyll *a* is at its minimum between February and April and greatest between August and October. Taking into account that La Nina climatic periods correspond to a $\sim 2.0 \text{ } \mu\text{g/m}^3$ reduction in chlorophyll *a* for all depths, farming-related decreases are not predicted to reduce chlorophyll *a* levels to $< 2 \text{ mg/m}^3$ – even in summer months. As for El Nino periods, some depletion is compensated for by increased ammonia inputs to the water column by mussel excretion, which is similar at 15-25 m for both El Nino and La Nina periods (Figure 4.6b). Dissolved oxygen depletion shadows are slightly higher in La Nina periods, due to different oceanographic processes, although as for El Nino, effects are generally restricted to the footprint of the farms (Figure 4.7b).

Due to on average higher levels of coastal chlorophyll *a* on the shelf off Pukehina, during across all climatic periods modelled (also see Longdill et al. 2006) this location is possibly the optimal area for farm productivity.

Table 3. 1– Results from modelling scenarios of chlorophyll *a* for surface waters and 15-25 m. for Pukehina and Opotiki. Values are yearly averages.

Farm Scenario 1	Period	Ambient μgL^{-1}	Pukehina		Opotiki	
			Range μgL^{-1}	% decrease	Range μgL^{-1}	% decrease
Surface waters	El Nino	~ 6	0.04-0.08	$\sim 1\%$	0.08	$\sim 1\%$
	La Nina	~ 3	$12-18 \times 10^{-3}$	$\sim 0.4-0.6\%$	$18-20 \times 10^{-3}$	0.7%
15-25 m	El Nino	~ 6	0.13-0.20	$\sim 2-4\%$	0.25-0.30	$\sim 5\%$
	La Nina	~ 3	0.07-0.12	$\sim 4-5\%$	0.12-0.18	$\sim 6\%$

5 ECOLOGICAL IMPLICATIONS

Ecological implications with regard to aquaculture are generally defined in terms of production carrying capacity and ecosystem carrying capacity (see Longdill et al. 2006). Briefly, maximum production carrying capacity has been described as the maximum level of bivalve culture, which replaces the ecological role of zooplankton, whereby the ecosystem is reduced to a nutrient–phytoplankton–culture–detritus system with the absence of zooplankton (Jiang and Gibbs 2004). In the absence of zooplankton, higher trophic levels dependent on zooplankton are not present. On the other hand, ecological carrying capacity has been defined as the stocking or farm density which causes unacceptable ecological impacts (Inglis *et al.* 2005).

Using the generic guidelines for phytoplankton abundance of Inglis et al. (2005), it is unlikely that phytoplankton abundance in coastal waters during El-Nino or La-Nina periods will be detrimental to production carrying capacity within the Bay of Plenty System. This is because modelled depletion rates suggest that even in times of lowest phytoplankton abundance (February-April) levels in surface waters and at 15-25 m should be well above $> 1 \mu\text{g L}^{-1}$; considered the lower critical chlorophyll concentration for mussel growth (Box 1).

Box 1: Guidelines for levels of phytoplankton abundance and water velocity for sustainable mussel culture defined by Inglis *et al.* (2005)

Food levels

- *Chlorophyll* $<0.5 \mu\text{g/l}$ – very poor growing conditions, very slow growth and loss of condition if for a prolonged period
- *Chlorophyll in range* $0.5-1 \mu\text{g/l}$ – generally poor growing conditions. Mussels grow slowly and may not lose condition, but recovery following spawning is slow, and it takes a long time to reach harvestable size.
- *Chlorophyll in range* $1-2 \mu\text{g/l}$. Moderate growing conditions, mussels of reasonable condition if interspersed with periods of higher chlorophyll concentration.
- *Chlorophyll in range* $2-4 \mu\text{g/l}$. Good growing, likely to achieve harvestable size in

10-12 months. Mussels should achieve good condition with rapid recovery from spawning.

- *Chlorophyll in range 4-8 µg/l.* Ideal growing conditions. Likely to be rare, fast growth.
- *Chlorophyll > 8 µg/l.* Little known, could be good growing but food handling difficulties.

While detailed empirical evaluation of the ecosystem carrying capacity of the Bay of Plenty System requires further examination, and was outside of the general scope of this study, based on the existing information obtained from the first-order ecological study (Mead *et al.* 2005), detailed analysis of hydrology (Black *et al.* 2005) and the results of the productivity modelling (this report) it is unlikely that the present ecological carrying capacity, in terms of altering the major energy fluxes or structure of the food web would be adversely affected by the proposed marine farming.

As for normal oceanographic conditions (Longdill *et al.* 2006), two aspects unknown for both El-Nino and La-Nina scenarios important for determining production and ecosystem carrying capacity effects are: 1) how the modelled aquaculture activities will affect phytoplankton species composition through space and time, given mussels are selective feeders; and 2) how the magnitude of El-Nino/La Nina events may affect species composition (see Rhoades *et al.* 1992, Chang *et al.* 1996). This information can then be used to address issues concerning food web dynamics.

Other factors that also impact on ecosystem health and warrant investigation are the significance of zooplankton mortality due to marine farms with respect to recruitment of other water-borne marine organisms and the potential impacts of mussel spat colonisation to new locations outside the marine farms (resulting to a decreased of marine biodiversity and/or community change).

6 SUMMARY

Potential effects of two large aquaculture farms within the Bay of Plenty on chlorophyll *a* levels in El Nino and La Nina climatic periods were simulated with a calibrated ecological model. El Nino periods are typically characterised by stronger offshore winds (winds) and greater coastal upwelling, whereas La Nina climatic periods are associated with more frequent on-shore winds (easterlies) and less upwelling of ocean nutrients.

Modelled scenarios conformed to expectation and compared to “normal” years phytoplankton abundance (Chlorophyll *a*) in surface waters in the Bay of Plenty (averaged over an entire year) was 1-2.5 mg/m³ greater in El Nino periods and 1.25-2 mg/m³ lower during La Nina periods. Similar differences were apparent between 15-25 m depth.

From the model runs, it was evident that the two mussel farms were extracting phytoplankton, contributing ammonia, and extracting oxygen from the water column, as would be expected. While effects were evident some distance from the farms, comparing depletion ranges depicted in this study with the published values of Inglis et al. (2005), it is unlikely that phytoplankton abundance will be limiting to production carrying capacity within the Bay of Plenty ecosystem during either El Nino or La Nina periods.

Further assessments of the ecosystem carrying capacity of the Bay of Plenty system would be of value and can be achieved by additional modelling as well as investigating present knowledge gaps, particularly the variation in phytoplankton species composition through space and time in relation to El Nino and La Nina periods.

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