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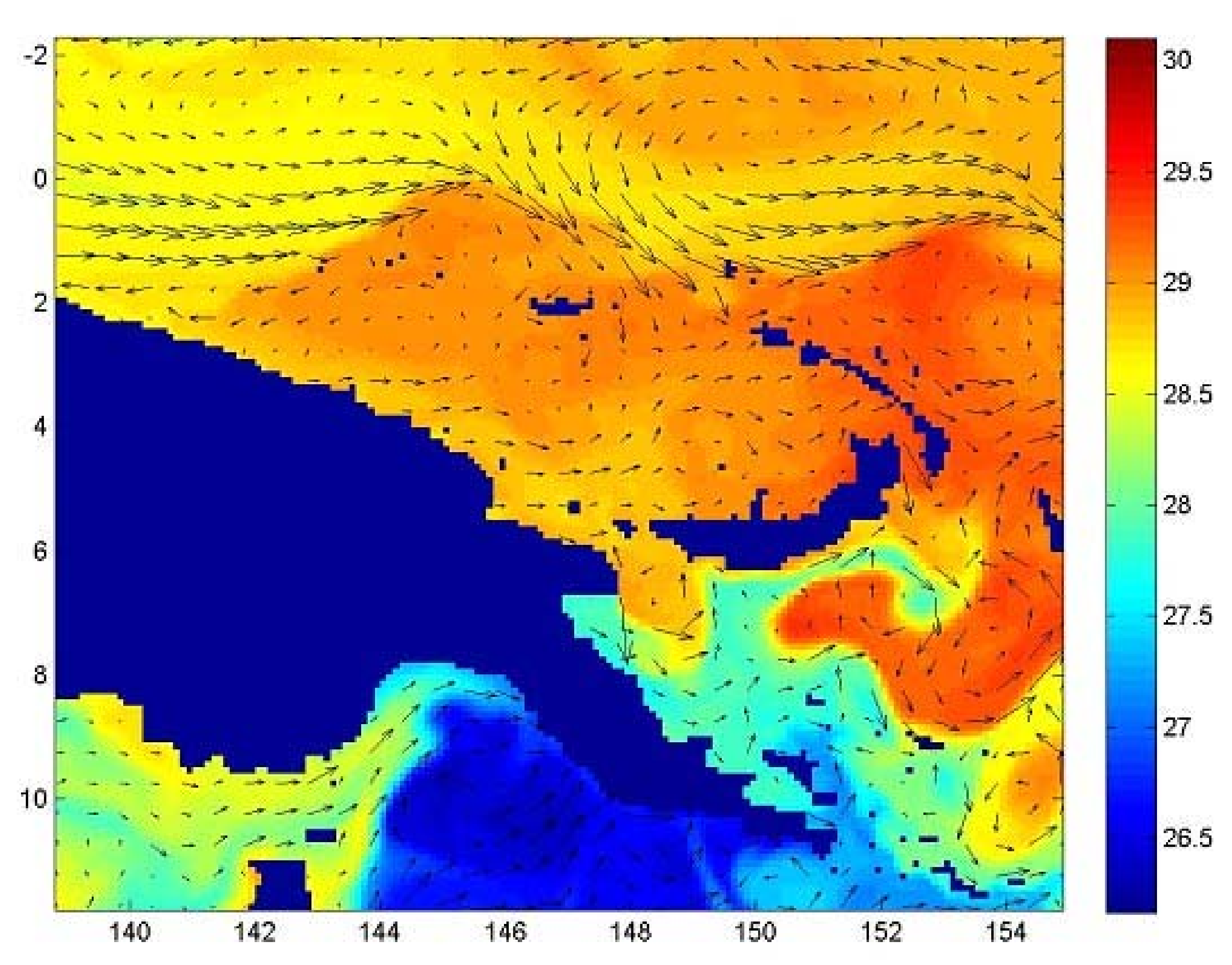
Australian Institute of Marine Science

December 2006
TNC Pacific Island Countries
Report No 6/06

Currents in the Bismarck Sea and Kimbe Bay



Papua New Guinea

Prepared for The Nature Conservancy by:
C.R. Steinberg, S.M. Choukroun, M.M. Slivkoff,
M.V. Mahoney & R.M. Brinkman
Australian Institute of Marine Science

Supported by:

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DISCLAIMER

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CONTENTS

LIST OF FIGURES

LIST OF TABLES

1. INTRODUCTION

The Nature Conservancy (TNC) is in the process of conducting an Eco-regional assessment of the Bismarck Sea, to use as the basis for expanding its conservation efforts in this important area. The goal is to develop a network of coral reef Marine Protected Areas (MPAs) for the Bismarck Sea with Kimbe Bay as a platform site.

Physical oceanographic data can be used more effectively in the design of MPAs. This is often difficult to achieve in many remote regions that yield few actual direct observations.

The Australian Institute of Marine Science (AIMS) has a unique archive of daily 1km satellite imagery to the north and east of Australia that had not been analysed prior to this project. It is contributed to a global archive managed by Goddard Space Flight Center, NASA. In 2005 access to CSIRO's global model BlueLINK> reanalysis (BRAN) was made available to the wider research community. It has a ~10km resolution, 12 year hind-cast and includes the assimilation of wind and satellite altimetry.

The combination of these model and satellite observations are analysed in order to reveal the major characteristics of the Bismarck Sea circulation. Once the large scale circulation is known, connectivity studies within the Bismarck Sea can then be made and provide the basis for oceanic boundary conditions for any higher resolution model of Kimbe Bay.

This report summarises the following data sets.

Large-scale circulation model:

BRAN model output was subset of the global data set at its 10km resolution and visualised to discern surface currents and temperatures. Data was downloaded for the period January 1997 to August 2002, inclusive. This represents a total of 4,414 daily images of circulation in the region.

Satellite data:

Satellite data obtained from the AIMS remote sensing archive was processed to produce chlorophyll-A concentration maps for case 1 waters (oceanic not coastal) and sea surface temperatures. Processing included cloud masking and geo-correction to map coordinates. Ocean Colour (~3 day frequency) was analysed from late 1997 when the satellite was launched, until the end of 2004. A total of 2,632 daily images were produced. Daily 1 km sea surface temperatures (SST) were processed for the period of July 1998 to June 2001 inclusive. The total number of images is 1,245.

1.1 DATA USAGE AND CARE IN INTERPRETATION

Users of this data should be aware that it is experimental and significant errors may exist. It is being made available for educational and research purposes particularly by The Nature Conservancy.

The BRAN model data is supplied for research purposes only and remains an experimental product. Until more rigorous validation of the product is made the results should only be used qualitatively rather than quantitative. For further information see http://www.marine.csiro.au/bluelink/exproducts/index.htm.

The satellite data used to validate oceanographic features were received at AIMS using the local HRPT direct broadcast receiving station.

The SST data is derived from the AVHRR/2 or AVHRR/3 sensor on board the NOAA series of satellites. The NOAA satellites are operated by the US National Oceanic and Atmospheric Administration. The data from these platforms is freely available to anyone with a receiving system and there is no limitation on data distribution.

The Chl a product is derived from the SeaWiFS sensor on board the Seastar or Orbview 2 satellite. The Seastar satellite is operated by GeoEye (formerly Orbimage Inc.) and the distribution of data from this platform is restricted by a research agreement with that company. NOTE: All SeaWiFS images and data presented on this website are for research and educational use only. All commercial use of SeaWiFS data must be coordinated with GeoEye, http://www.geoeye.com/.

The location of the Bismarck Sea does not lend itself well to visible and infra-red remote sensing. This is due to high incidence of cloud and high humidity (Barr-Kumarakulasinghe et al, 1995). The occurrence of patchy cloud can also make it difficult to distinguish between atmospheric and oceanic phenomena. This was evident when Coastal Zone Color Scanner data was first analysed in the region by Wolanski *et al.* (1987) and remains true today. Ocean surface signals were found only on days when clear atmospheric conditions prevailed, however the full processed data sets are provided for completeness on the accompanying DVD.

Some of the data may have errors due to undetected cloud and other aerosols. This may produce reductions in the apparent SST. The SST product measures only the skin layer (<1mm) of the ocean surface from the infra-red region of the electro-magnetic spectrum and is a spatial average of over 1km. Algorithms are dependant upon wind speed and the relationship with the so called “bulk water temperatures” that are usually referenced to be at 1m below the surface. So care needs to be taken if comparing with other in situ measurements that have significant differences in observing methodology and technique.

Ocean colour in shallow coastal regions can see the bottom and may not indicate true water column colour. Other carbon dissolved organic matter can also be present especially from riverine sources. The Chl-a algorithms are designed for open ocean waters only and so the values here should not be thought as purely from photosynthetic plants or algae. Nevertheless significant features shown in the data allow the oceanographic complexity of coastal and ocean waters to be revealed. For example river plumes have a high level of “greenness” from a variety of sources such as sediment and coloured dissolved organic matter and will show up clearly in the imagery.

1.2 COMPANION ATLAS DVD

This report summarises existing knowledge and describes the new data sets.

A companion Atlas has been provided on the DVD to allow the quick viewing and animation of the data. Simply place the DVD in your computer’s reader and move to the Atlas subdirectory and then choose “Bismarck Sea Atlas.html” to begin viewing the data sets. Various animations can be located in the “Animations” subdirectory. Alternatively, a link from the website, http://www.aims.gov.au/remote-sensing, has been set up to access the atlas and animations.

2. REVIEW OF EXISTING KNOWLEDGE

2.1 LOCATION

The Bismarck Sea is located between Latitude 2 and 5 degrees South of the Equator, 146-152 degrees East in the Western Equatorial Pacific Ocean. It is located in one of the world's most diverse and significant tropical marine environments. It is also located in one of the warmest parts of the ocean: the Western Pacific Warm Pool. It is highly correlated with El Nino Southern Oscillation (ENSO) events (Lindstrom, 1987) and is warmest during the La Nina phase.

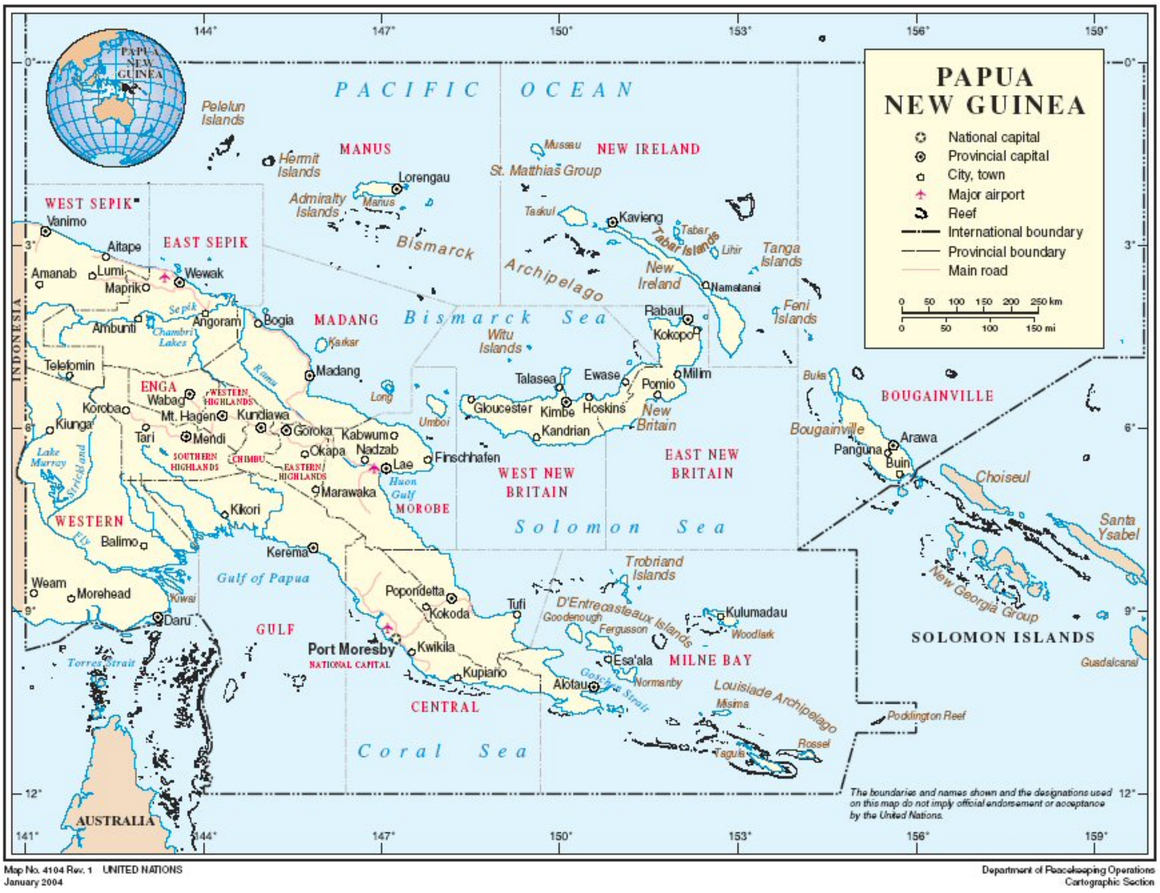

Figure 1. Location of the Bismarck Sea and Kimbe Bay, Papua New Guinea. Map courtesy of the United Nations (http://www.un.org/Depts/Cartographic/map/profile/papua.pdf).

There are 4 main pathways that water can enter the semi-enclosed Bismarck Sea:

1. Vitiaz Strait, between Papua New Guinea and Umboi island, west of New Britain
2. St George's Channel between New Britain and New Ireland
3. Ysabel Channel between Manus and New Ireland
4. The open sea to the west between the Admiralty Islands and Papua New Guinea

Kimbe Bay is located on the northern side of New Britain. It has high mountain ranges (~11000 metres) and active volcanos (Mt Pago, Mt Gabuna and Mt Uluwan). Kimbe is approximately 140km x 70km and is bounded by the Willaumez Peninsula to the west and Cape Tokoro to the east (Green and Lokani, 2004). The bay has a narrow shelf and drops to ~2000m on the eastern side but remains about 500m deep, inshore of Kimbe Island in the western portion of the bay.

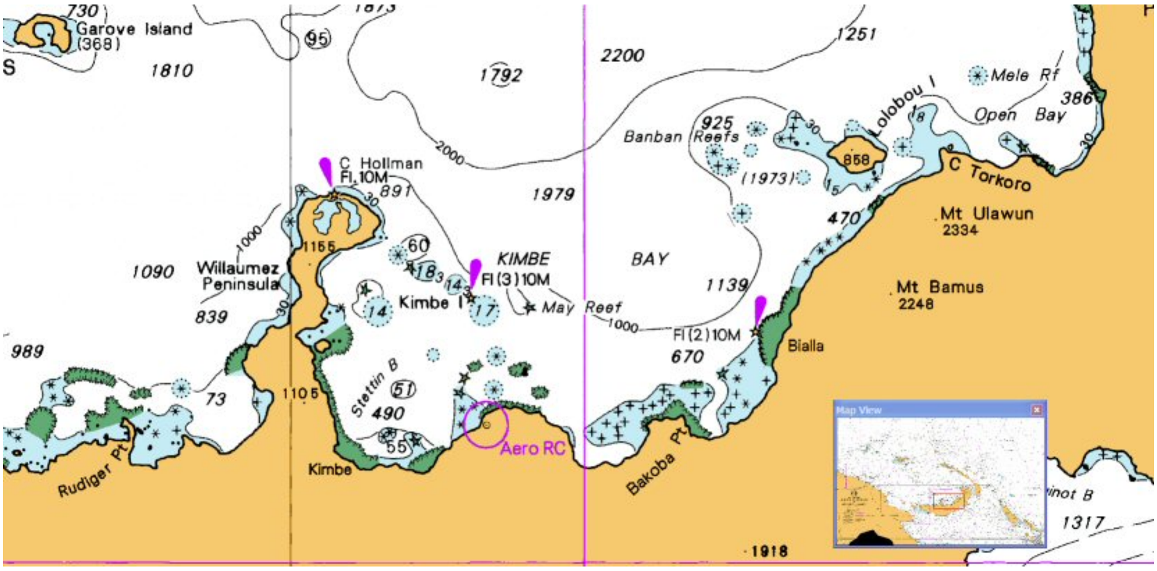

Figure 2. Kimbe Bay, New Britain (adapted from chart AUS4622)

2.2 BATHYMETRY

The Bismarck Sea comprises a semi-enclosed body of water bounded by Papua New Guinea to the Southwest, New Britain to the southeast, and New Ireland to the northeast and the Admiralty Islands to the north.

Figure 3. The bathymetry of the Bismarck Sea and region.

The islands of the Bismarck Archipelago have been created by the active tectonics of the region. The New Britain Trench to the south of New Britain has been formed by the subduction of the Solomon Plate under the South Bismarck Plate (Hall and Spakman, 2003). Depths here can reach 8,600m. New Ireland sits on the North Bismarck Plate and there is a trench that delineates the North and South Bismarck Plates to the south of the Admiralty Islands. The Manus Basin reaches depths of ~2,500m as does the New Guinea Trench just off the northern coast.

Volcanic activity (http://www.bom.gov.au/info/vaac/images.shtml) is regular and tsunamis have recently occurred, emanating from the northern coast of Papua New Guinea (PNG) from earthquakes causing slumping on the continental slope.

2.3 WINDS

The Bismarck Sea experiences two very distinct seasons associated with the Southeast Asian/Australian monsoon system. The northwest monsoon season usually extends from November to March and the southeast monsoon from May to October.

The Equatorial Madden Julian Oscillation or Intra-seasonal Oscillation (ISO) is a 30 to 60 day cycle that can affect the onset and break of the monsoon (Madden and Julian, 1971) and lead to cyclone genesis in higher latitudes (Godfrey et al, 1998).

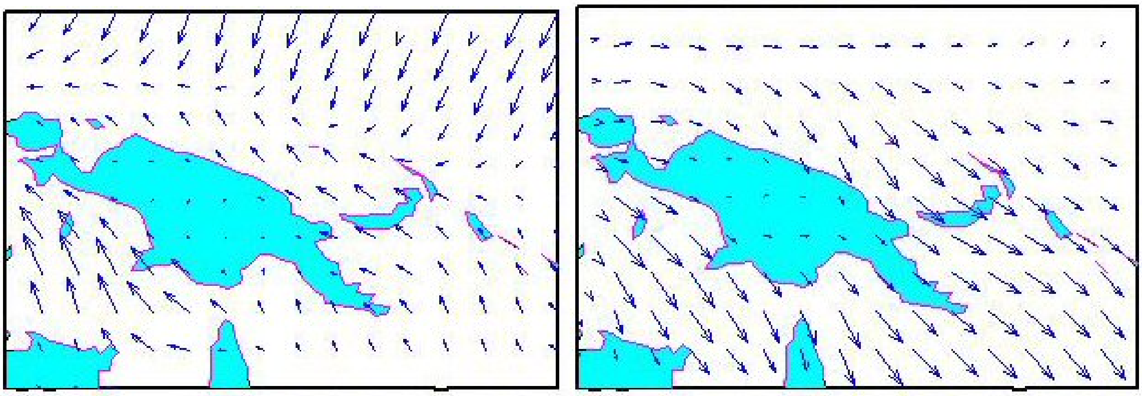

Figure 4. Monthly average winds in Papua New Guinea for February 2001 (left) and August 2001 (right). N.B. Winds are in meteorological convention showing where wind is coming from.

Rainfall in Kimbe Bay is quite high (3,180 mm per annum) with most of it falling during the NW monsoon and a dryer season prevails during the SE trades (May-August). The Inter-tropical South Pacific Convergence Zone (ISPCZ) also extends over the region and causes the air to rise, creating and thereby forming, extensive cloud. The high mountain ranges provide additional uplift for the humid monsoonal winds and so orographic rainfall is also a contributing factor.

A major river is the Sepik River located on the northern coast of PNG at the western end of the sea. The Sepik River plume is shallow (5-10 m) and its fate is controlled by the local winds and currents. During the SE monsoon it tracks northwest along the coast of PNG however it will move to the SE during the NW monsoon with the reversal of the New Guinea Coastal Current (Cresswell, 2000). It has recently been the subject of a large international research project: TROPICS (http://www.aims.gov.au/pages/research/projects/project05/tropics/tropics.html).

2.4 SEA LEVEL

The Tides in the Bismarck Sea are reasonably small as they only have a range of 1m at spring tides. Figure 5 shows a 30 day time series of predicted sea levels for selected stations in the Bismarck Sea and Port Moresby for comparison. They show principally diurnal tides (one high and one low per day) for all stations in the Bismarck Sea, whereas Port Moresby has two highs and lows per day giving it a semi-diurnal character. Port Moresby also has twice the range (note change of scale on the x axis).

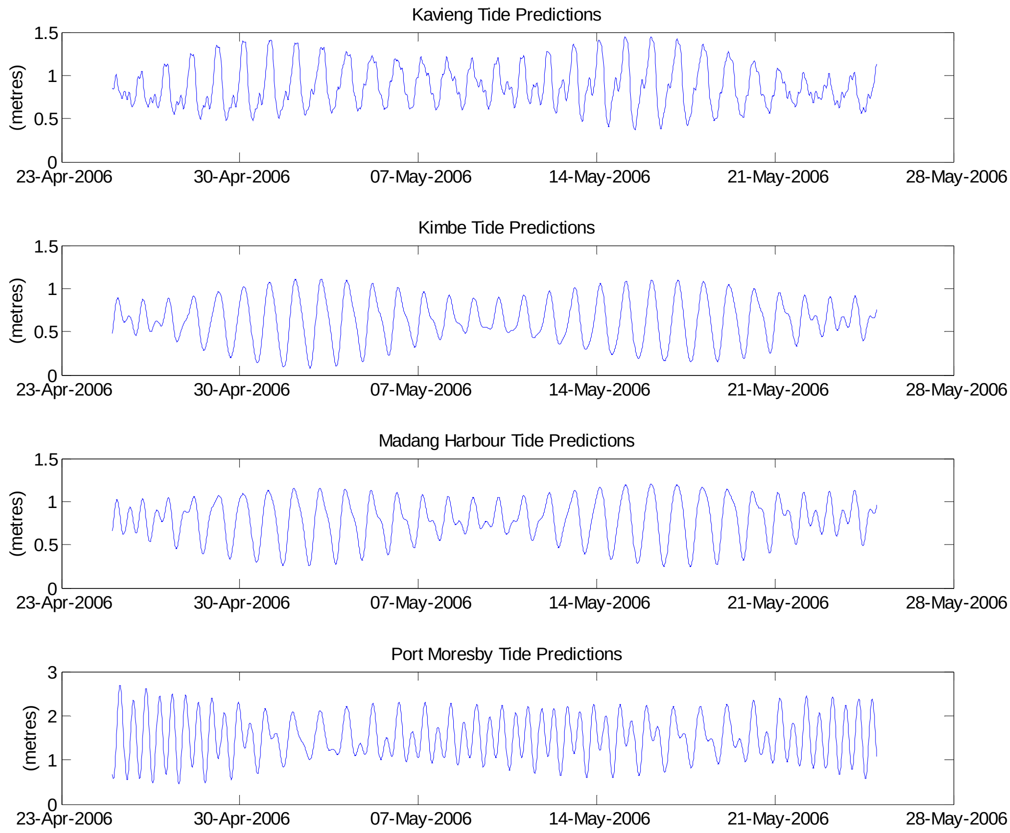

Figure 5. Tide Predictions for Kavieng, Kimbe, Madang and Port Moresby for 30 days.

Tides can be classified according to a form factor which is the ratio of the sum of the amplitudes of the two major diurnal constituents to the sum of the two major semi-diurnal constituents. Kimbe Bay yields a form factor of 2.959 (see Table 1), which indicates a diurnal tide. Madang to the south and Kavieng to the north show lower form factors of 1.764 and 2.487, respectively. This reveals the increasing influence of the semidiurnal constituents and so they still exhibit dominant daily peaks in range but with some secondary highs and lows. The dominance of the Diurnal constituents is due to the suppression of the semi-diurnal constituents in this region and not to any amplification of them. Port Moresby (Table 1) shows it has similar O1 and slightly larger K1 amplitude.

Tidal currents will therefore be much slower and less vigorous than what can be expected in other semi-diurnal dominated areas. They however have flood and ebbs over 12 hours which means the tidal excursion can still be quite large. This will have implications for any connectivity studies.

Table 1. Bismarck Sea major tidal harmonic constants and form factor.

	Kavieng	Kimbe	Madang	Port Moresby
Amplitudes in metres				
M2	0.081	0.047	0.096	0.491
S2	0.122	0.076	0.060	0.290
K1	0.221	0.221	0.244	0.280
O1	0.137	0.143	0.144	0.141
Form Factor, F = (M2+S2)/(K1+O1)				
F	1.764	2.959	2.487	0.539
Phases (degrees) -10 UTC				
M2	85.3	222.6	209.7	279.4
S2	96.2	123.1	116.5	249.5
K1	210.7	217.6	209.7	193.8
O1	182.6	189.8	185.3	152.9

Sea level anomalies (tides, seasonal cycles and trend removed) for the region are highly correlated with the Southern Oscillation index (SOI) as the Bismarck Sea is located in the Western Pacific warm pool. Local trade wind changes associated with ENSO therefore directly affect the local sea levels. Figure 6 clearly shows the 1997/1998 and 2002 El Nino's.

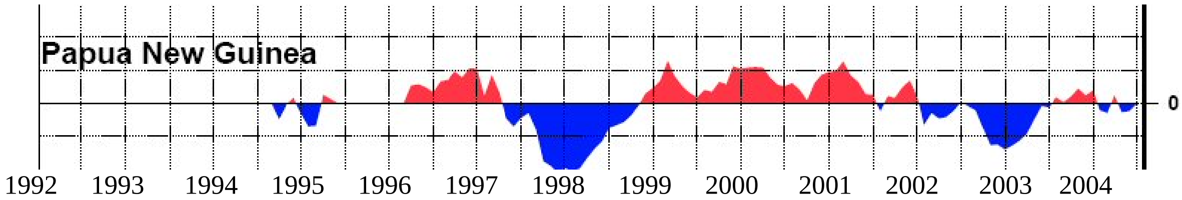

Figure 6. Sea level anomaly observed by the Manus Island sea level gauge. (Adapted from Pacific Country Report, Sea Level & Climate: Their present state, Papua New Guinea, June 2004. http://www.bom.gov.au/oceanography/projects/spslcmp/spslcmp.shtml). Each square on the y axis represents 10 cm height change.

2.5 LARGE-SCALE CIRCULATION

Due to the location of the Bismarck Sea in the Western Equatorial Warm Pool there has been much international interest in studying the air-sea interactions given the global effects of ENSO. In the 1980s The Western Equatorial Pacific Ocean Study (Lindstrom et al, 1987) described the major ocean currents and upper ocean structure. This was followed by the Coupled Ocean-Atmosphere Response Experiment (COARE) Godfrey et al, 1998.

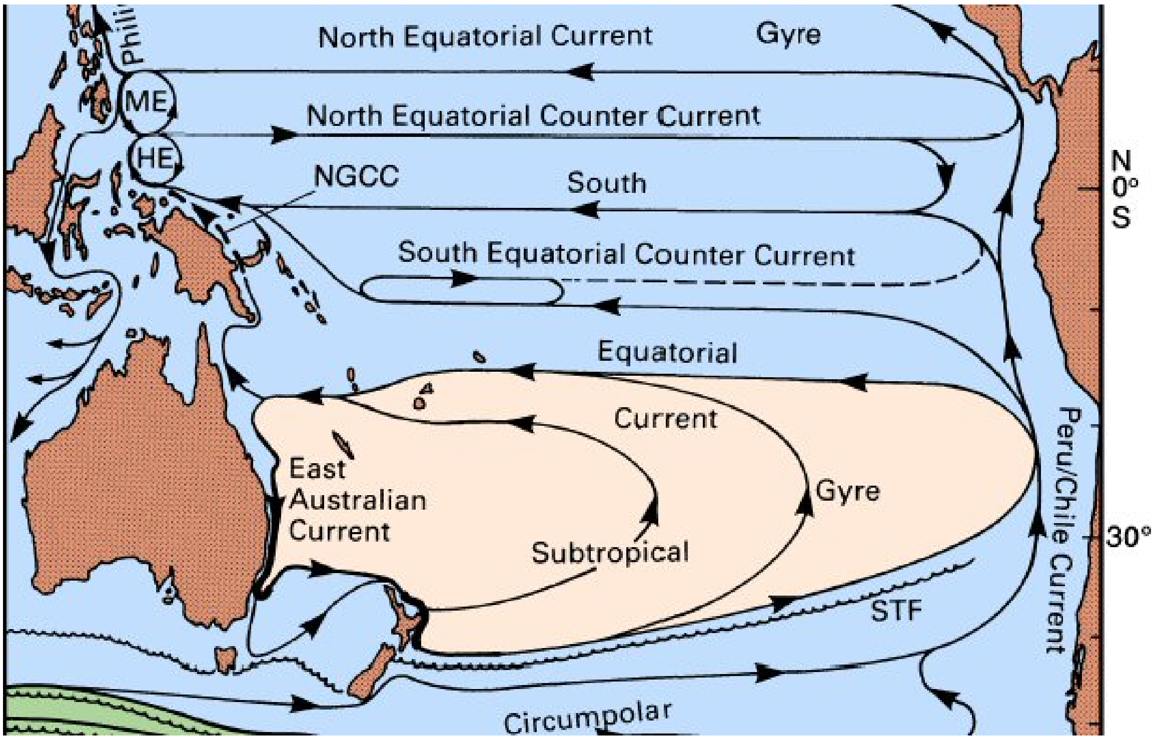

Figure 7. Surface currents of the Pacific Ocean, adapted from Figure 8.6 Tomczak and Godfrey, 1994.

Figure 7 shows the major surface current systems of the Pacific Ocean during the SE monsoon (April to November). The broad westward flow of water on the northern arm of the South Pacific Gyre is called the Southern Equatorial Current (SEC). SEC water that traverses the Coral Sea can form a northern branch when it meets northeastern Australia and forms the New Guinea Coastal Current (NGCC). This flows around and through the Louisiade Archipelago to the southwest of Papua New Guinea and resumes its flow toward the Bismarck Sea through Vitiaz Strait. The more northern SEC tends to flow past the Solomons and can either enter the Bismarck Sea through St Georges Channel or Ysabel Channel from the North.

During the NW monsoon the NGCC and northern arm of the East Australian Current can reverse and flow southeast through Vitiaz Strait along the northern coast of Papua New Guinea.

The above studies focused on the major regional circulation systems and pathways however the circulation within the Bismarck Sea still remains relatively poorly known. The navigational chart (AUS 4622) mentions an anti-clockwise eddy may form. Discerning circulation features through remote sensing has been limited in part due to the region being very cloudy and high in humidity. The Bismarck Archipelago acts as a barrier to the main SEC flow and so any circulation outside the major current pathways is likely to be characterised by complex flows and recirculations in the lee of the island arcs, especially during the prevailing southeast trades.

3. OCEAN COLOUR

Ocean colour imagery from polar-orbiting satellites provides a near-daily synoptic view of ocean constituents including phytoplankton, suspended minerals and dissolved organics. The spatial distribution of these optically active constituents can be studied over time to gauge the effect of oceanographic forcing on particular surface water masses, and the extent of terrestrial influence in coastal waters.

In order to study these features, Sea-viewing Wide Field of View Sensor (SeaWiFS) Ocean colour satellite imagery was received by the AIMS/NOAA High Resolution Picture Transmission station between October 1997 and December 2004.

3.1 PROCESSING

Data in the region [2.3N, 11.7S, 139W, 155E] was processed using the default standard operational chlorophyll-a product (OC4v4) incorporated into msl12 from SeaDAS 4.8.2 (http://oceancolor.gsfc.nasa.gov/seadas/), using NCEP Meteorological data and TOVS or EPTOMS Ozone measurements for the level-2 processing. The level-2 quality flags were generated with the SeaDAS default settings.

To maintain high quality data, level-2 quality flag masks were applied to the imagery to exclude pixels with high sensor viewing angles, probable cloud or ice contamination, chlorophyll algorithm failure, stray light, shallow water, cloud shadows, absorbing aerosols and suspect atmospheric correction. More details about the OC4v4 algorithm and masking flags can be found at http://oceancolor.gsfc.nasa.gov/VALIDATION/.

Depending on data availability, daily images were projected to a cylindrical equidistant mapping, and IDL's high resolution coastline was overlaid on the region of interest, along with major rivers and a coarse gridline. Weekly average imagery was calculated by averaging every seven days worth of valid, masked data to suppress clouds in the output imagery.

The colour table applied to the data for chlorophyll-a image output for Papua New Guinea was IDL's colour table 40, a Rainbow scale where violet is the minimum data value and red is the maximum data value. The minimum (violet) was set to 0.02 ug/L (micrograms per litre of chlorophyll) and the maximum (red) was set to 8.0 ug/L to enhance the image contrast for the particular region.

Finally, for the Bismarck Sea imagery, a sub-set of the initial region of interest was selected to co-incide with an oceanographic model, which was defined by the region [1.05N, -6.65S, 146.05W, 154.75E], and png images were written, with a colour rescaling so that violet was attributed to 0.04 ug/L and Red was attributed to 4 ug/L.

For further details about the data please go to http://oceancolor.gsfc.nasa.gov/SeaWiFS.

3.2 SELECTED IMAGERY

A selection of imagery is presented here that highlight characteristic oceanographic features of interest. The full data set is provided on the accompanying DVD.

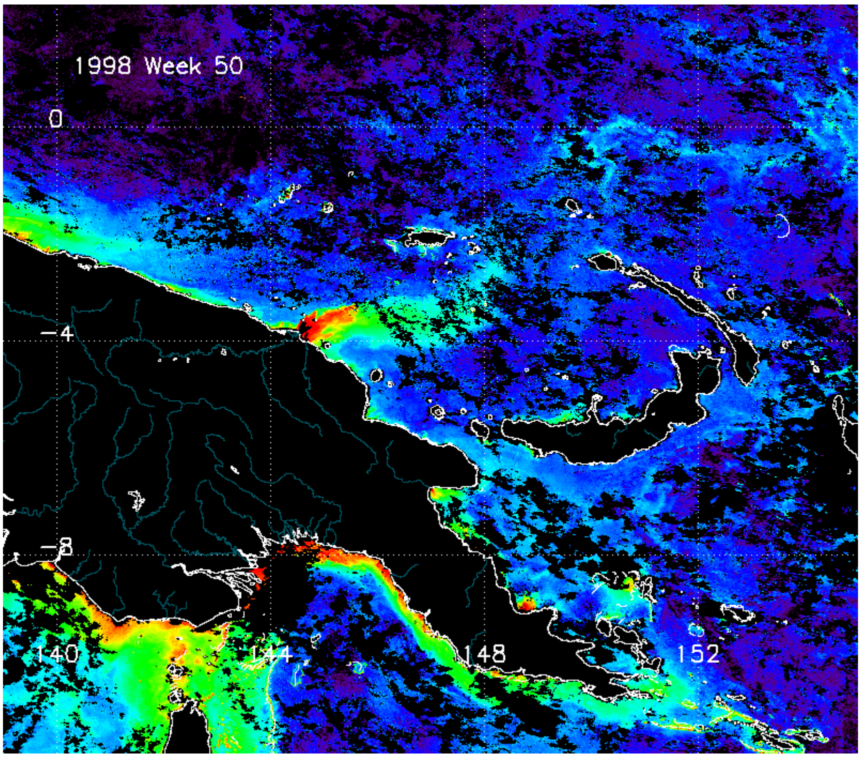

Figure 8. SeaWiFS 1998 Week 50.

Sepik River plume moving northeast into central Bismarck Sea.

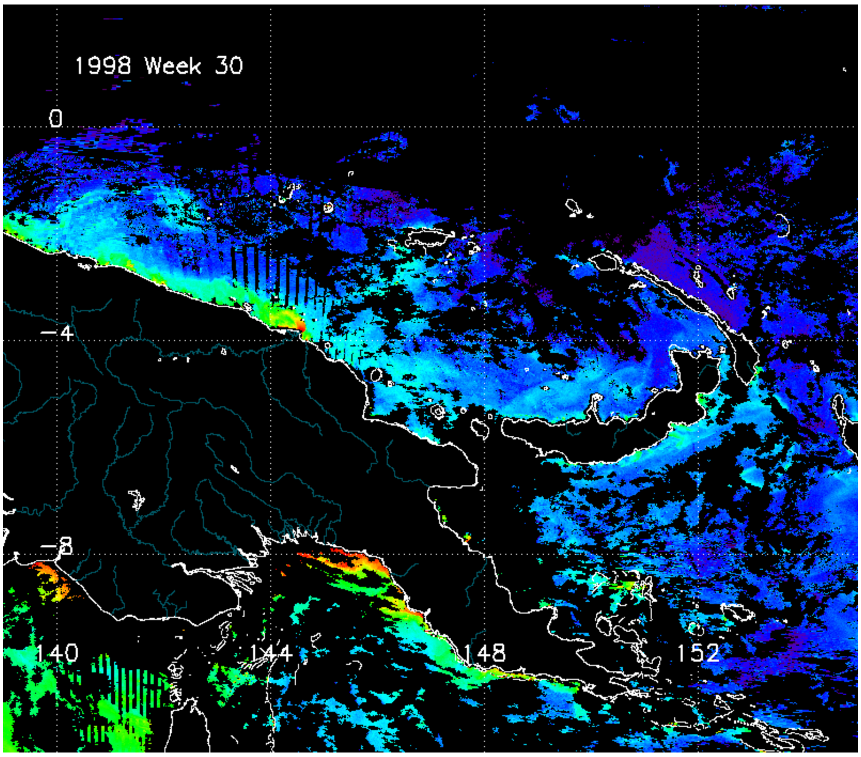

Figure 9. SeaWiFS 1998 Week 30.

Sepik River Plume entrained in the New Guinea Coastal Current moving along the PNG coast.

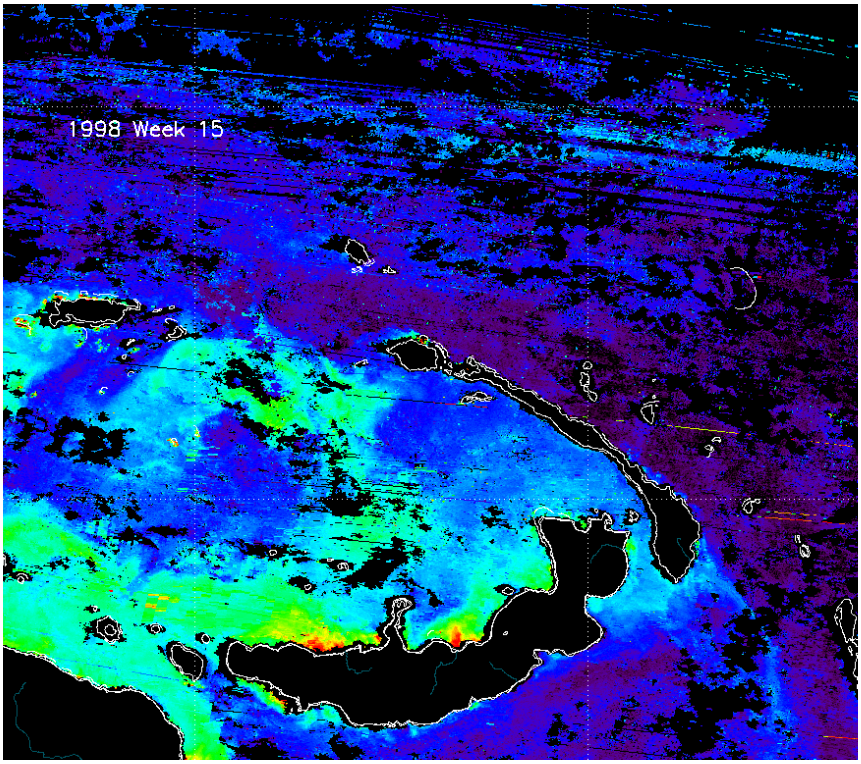

Figure 10. SeaWiFs 1998 Week 15.

Coastal Bismarck Sea – Coastal River Plumes in Kimbe Bay and. Higher Chl a in the lee of Manus Island. A swirl of green water in central Bismarck Sea indicating a large eddy on the Western side.

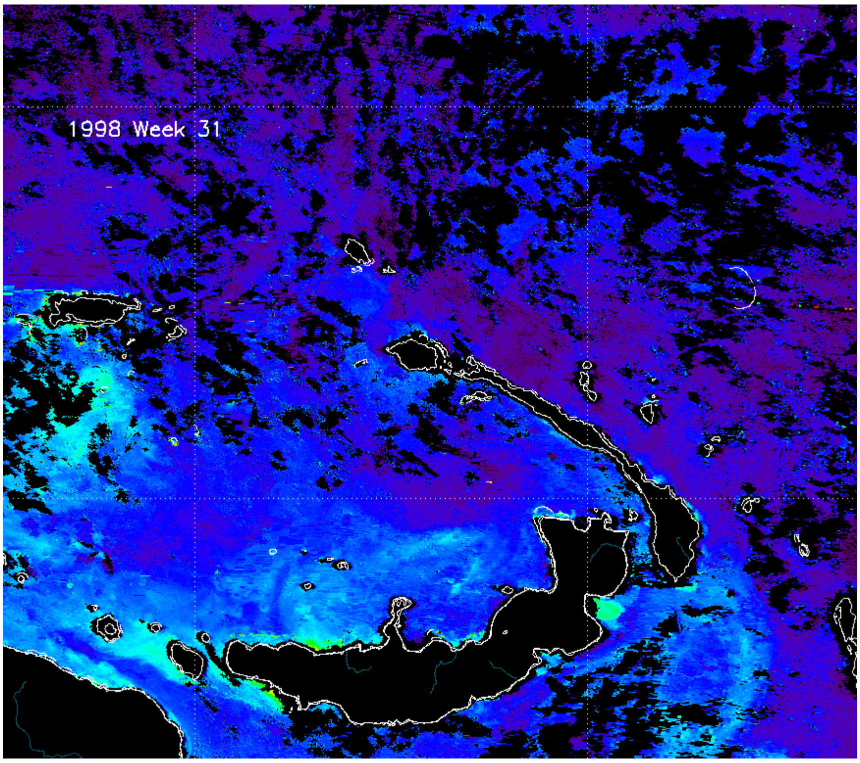

Figure 11. SeaWiFS 1998 Week 31.

Clear NW flow through Vitiaz Strait and higher Chl a flow past Vitu Islands and recirculating in outer Kimbe Bay.

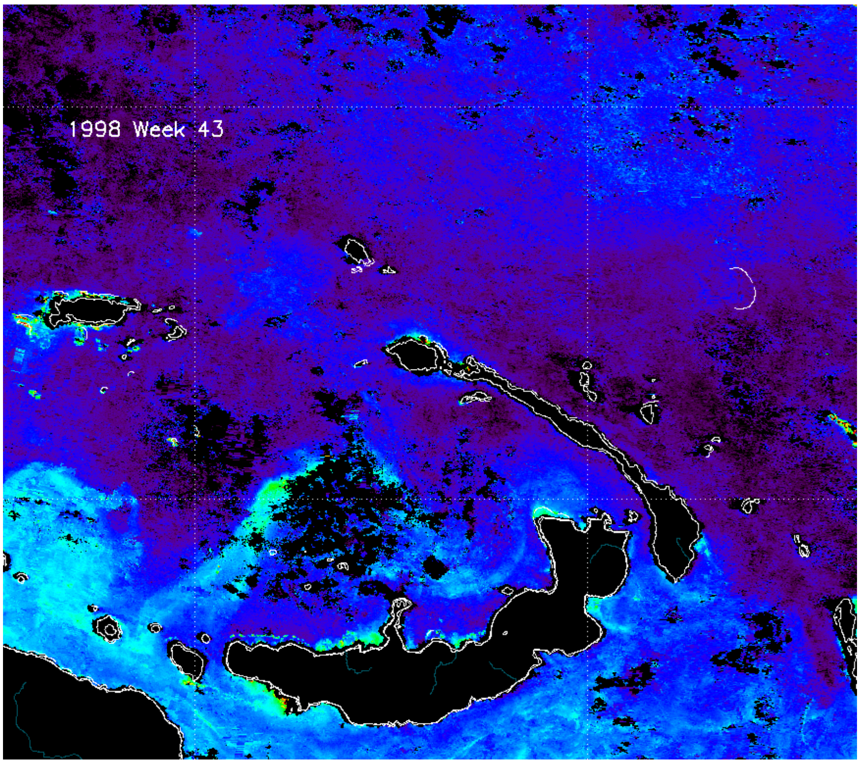

Figure 12. SeaWiFS 1998 Week 43.

Meandering Chl a from Long Island through central Bismarck Sea and outer Kimbe Bay.

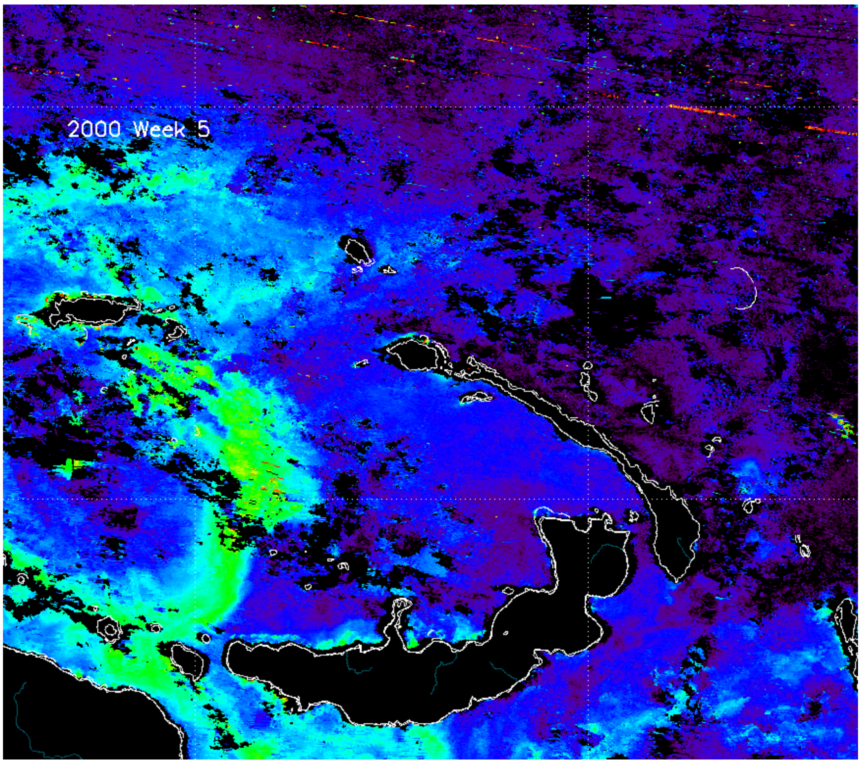

Figure 13. SeaWiFS 2000 Week 5.

Arc of high Chl a water from Vitiaz strait toward Manus Island. Coastal signatures Kimbe Bay.

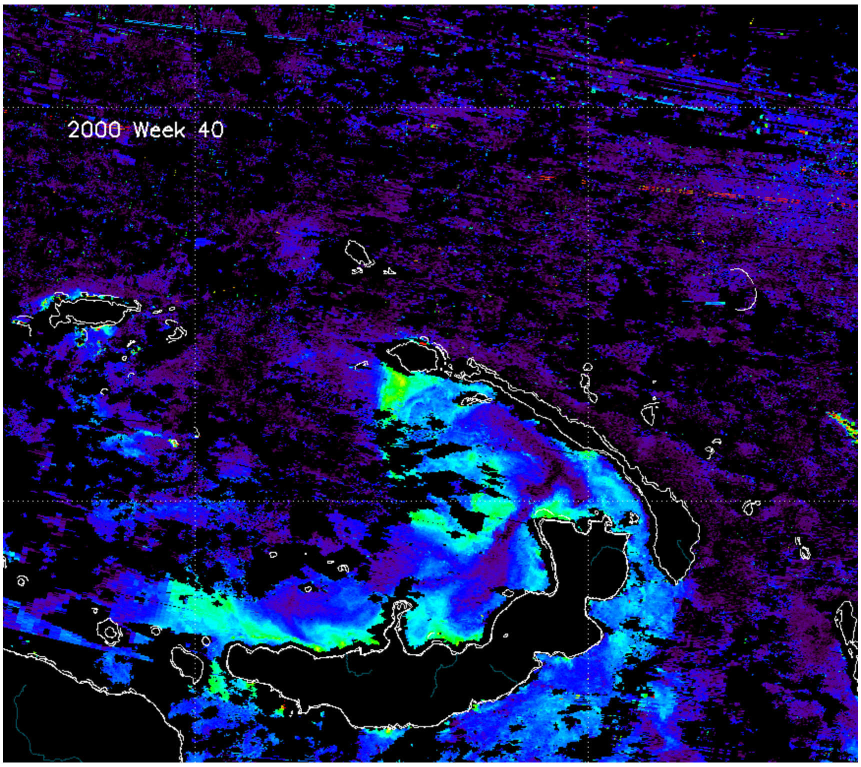

Figure 14. SeaWiFS 2000Week 40.

Oceanic water in East Kimbe Bay, Eddy extending from New Hanover to the Gazelle Peninsula (East New Britain, Peninsula where Rabaul is found).

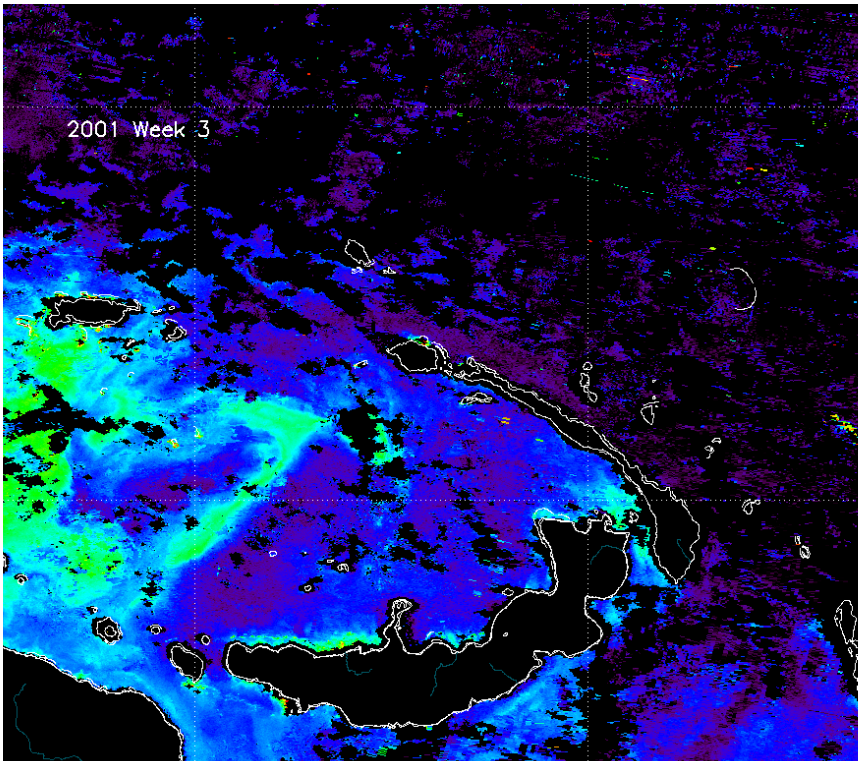

Figure 15. SeaWiFS 2001 Week 3.

High Chl a water in central Bismarck Sea and South of Manus Island.

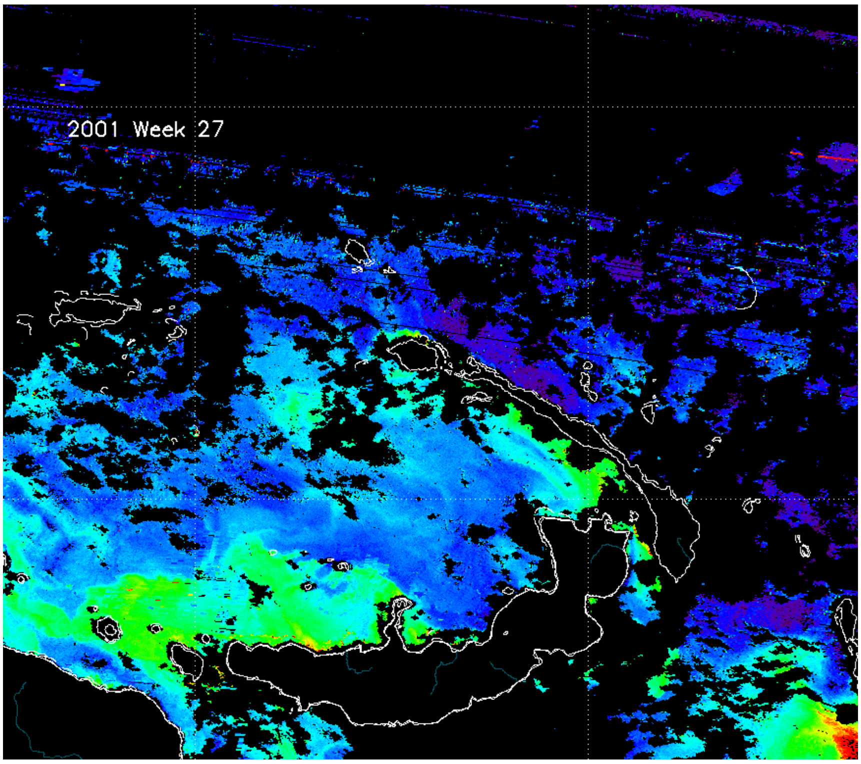

Figure 16. SeaWiFS 2001 Week 27.

Oceanic (low Chl a) waters in east Kimbe Bay, High Chl a West of Willaumez Peninsula.

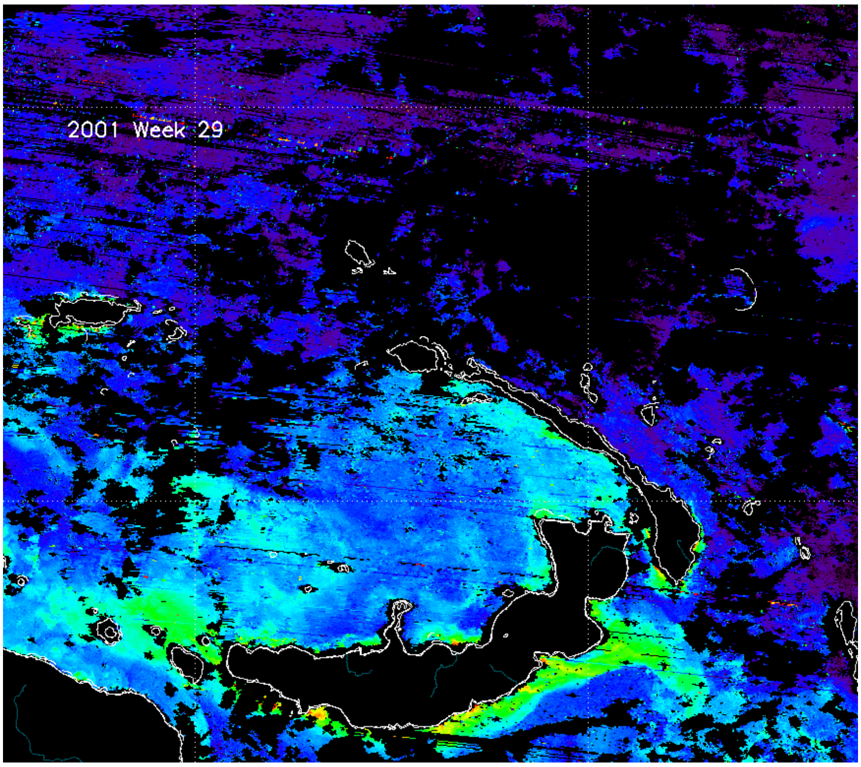

Figure 17. SeaWiFS 2001 Week 29.

Lee eddy formed from an eastward current past Willaumez Peninsula into outer Kimbe Bay. Strong bloom from upwelling along the southern coast of New Britain.

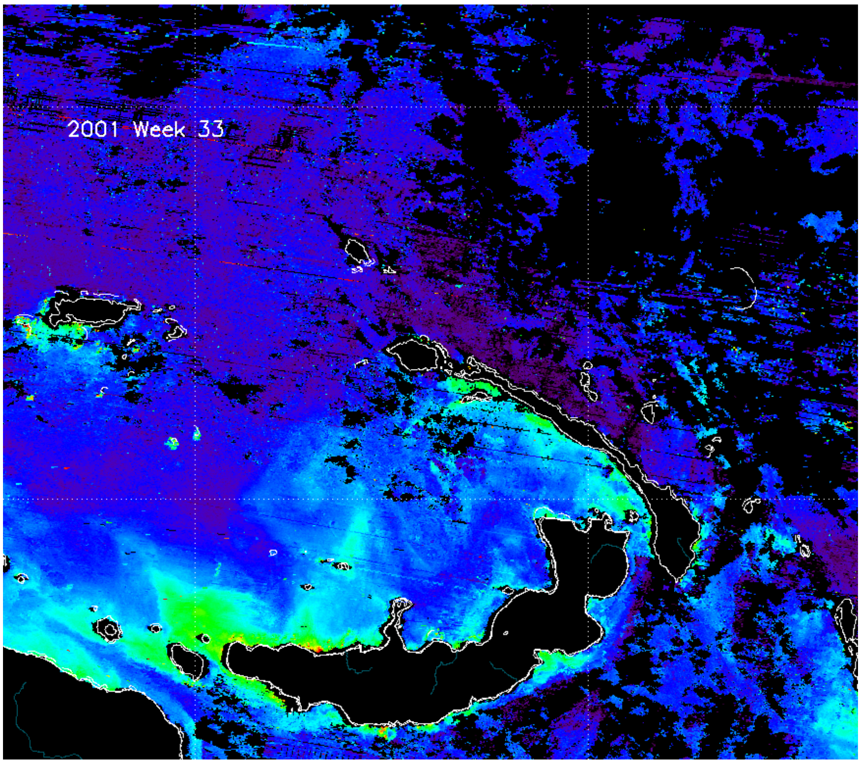

Figure 18. SeaWiFS 2001 Week 33.

Strong Chl a signal north of Dampier Strait and Chl a signature in central Bismarck Sea indicating northerly flow and an eddy forming.

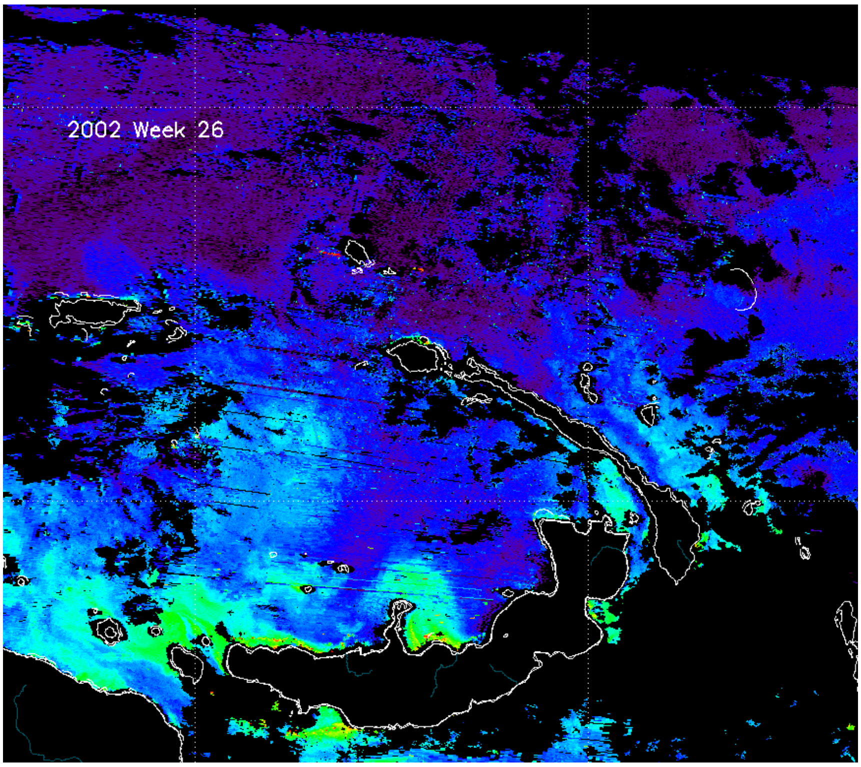

Figure 19 SeaWiFS 2002 Week 26.

High Chl a in western Kimbe Bay, St Georges channel and Dampier Strait.

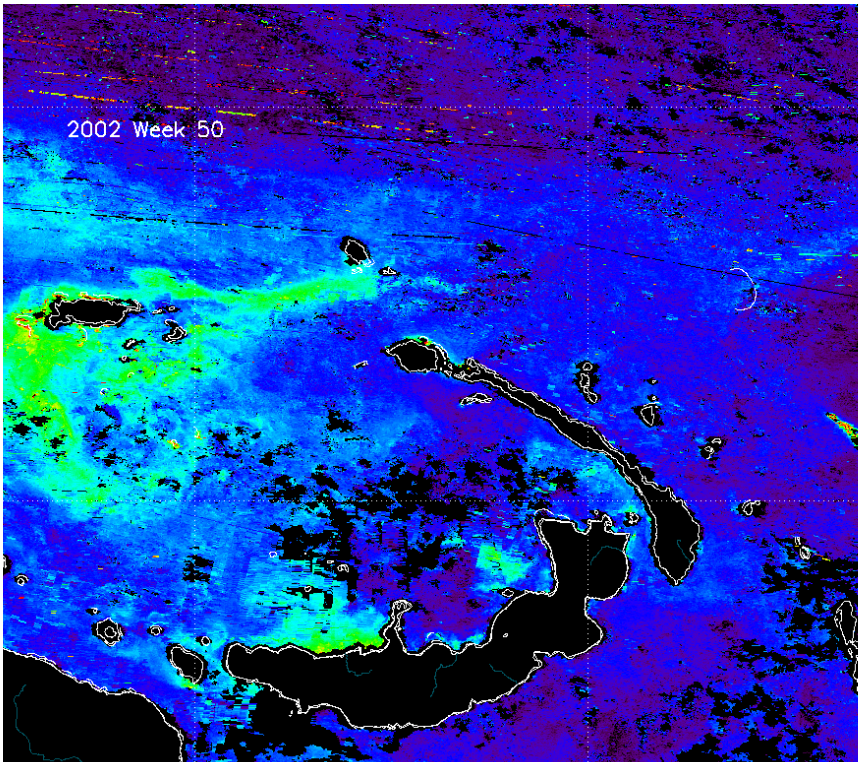

Figure 20. SeaWiFS 2002 Week 50.

High Chl a trailing from Mussau Island past Manus Island and eddying south of Manus.

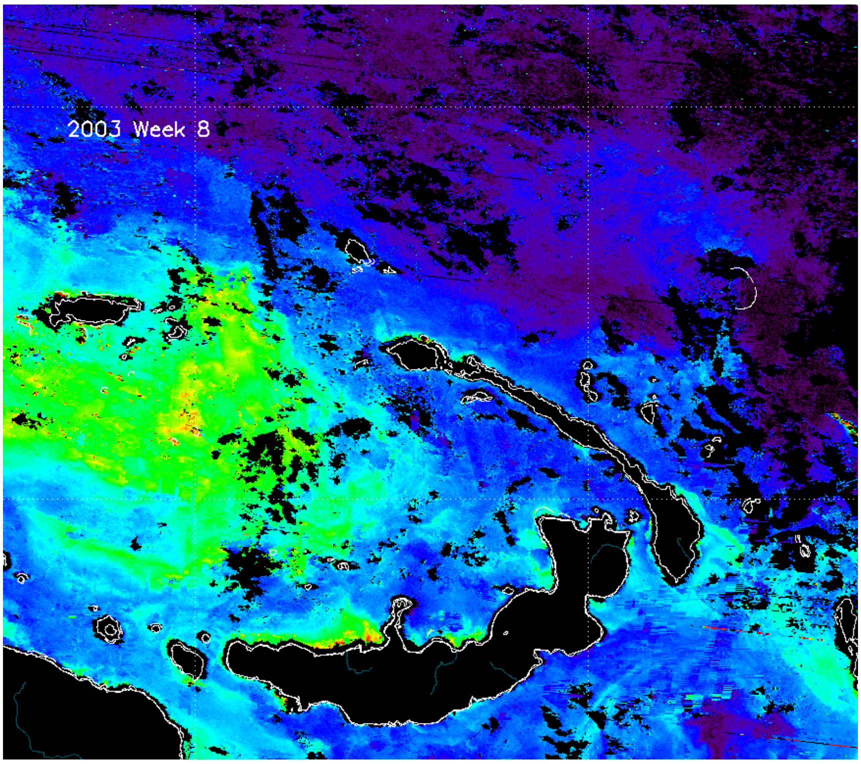

Figure 21. SeaWiFS 2003 Week 8.

High Chl a in Western Bismarck Sea. Strong coastal signatures on northern coastal New Britain.

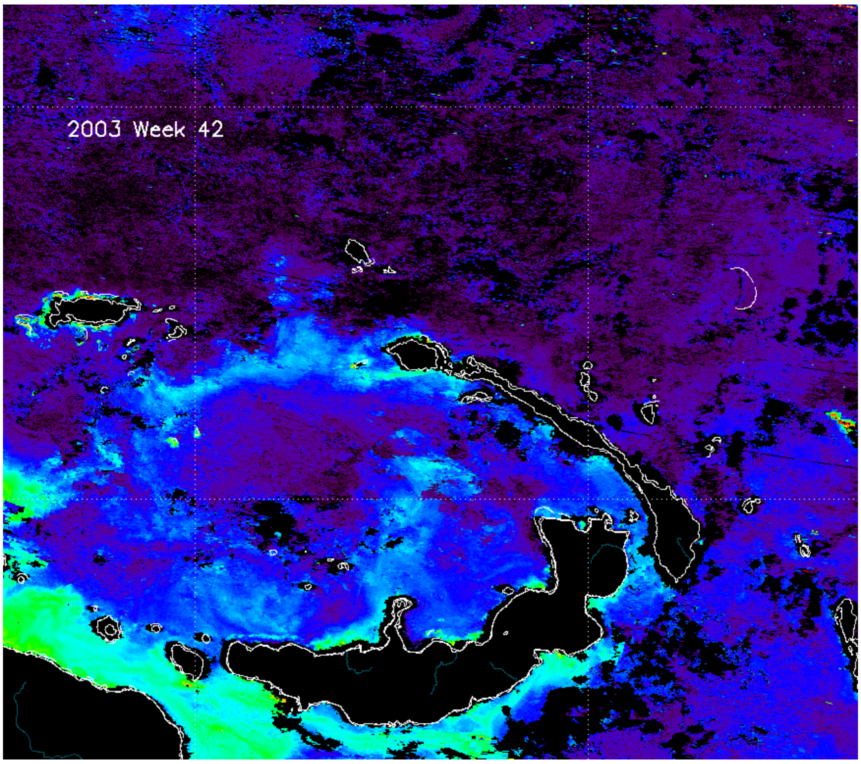

Figure 22. SeaWiFS 2003 Week 42.

Strong Chl a through Vitiaz Strait, Northern projection from Willaumez Peninsula and arcing from New Hanover toward PNG coast

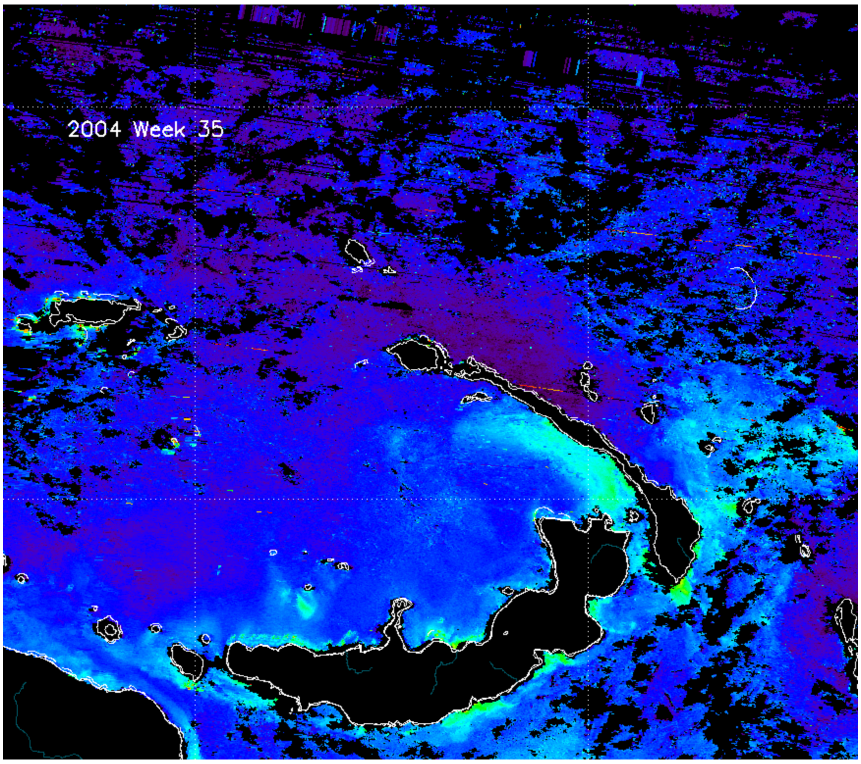

Figure 23. SeaWiFS 2004 Week 35. 2004 Week 35.

Strong Chl a signal out of St Georges Channel and along the coast of New Ireland

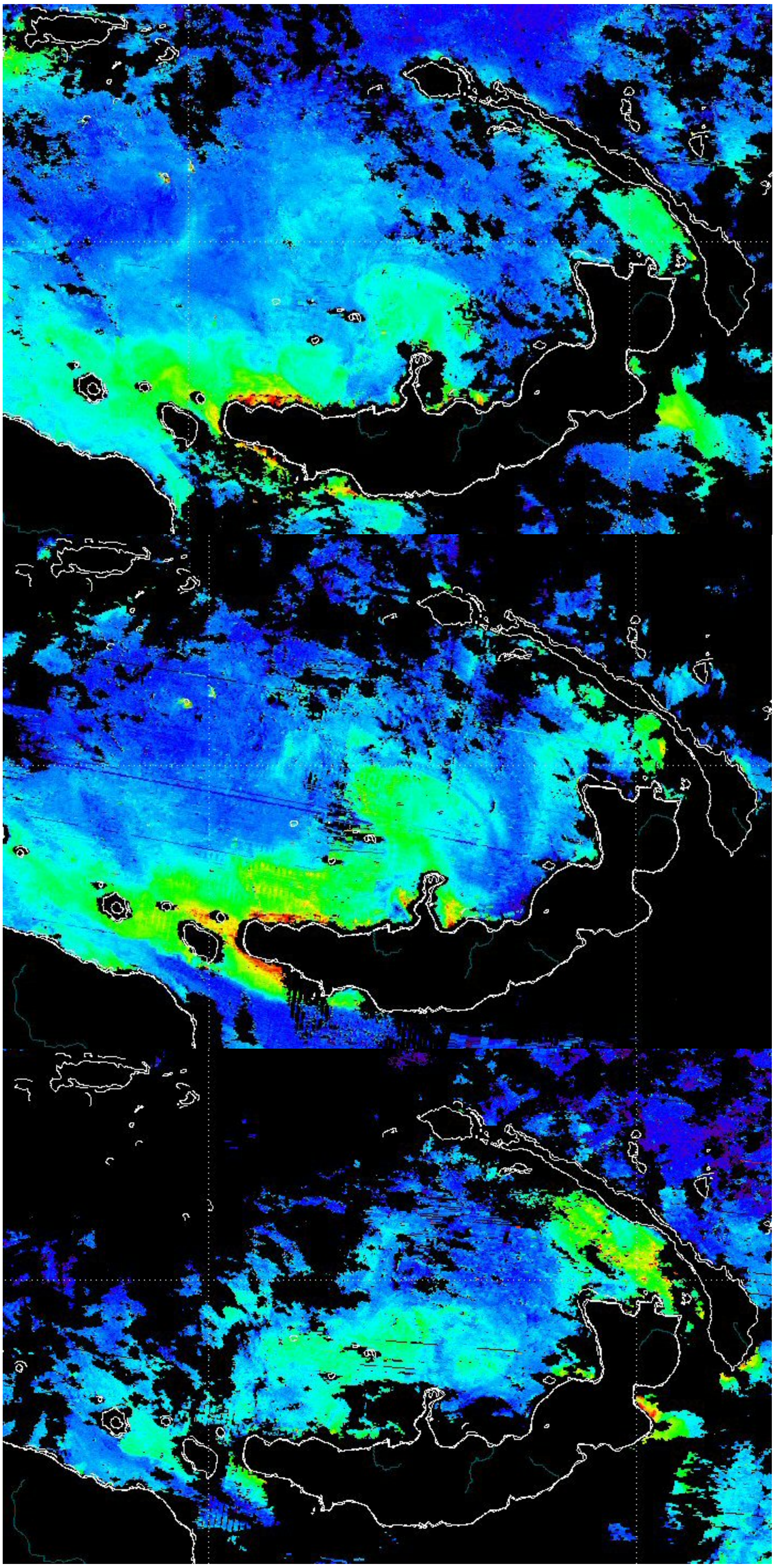

Figure 24. SeaWifs 2004 Week 28 (top) Week 29 (middle) Week 30 (bottom).

Sequence shows the development of an eddy of Chl a rich watermoving north from Willaumez Peninsula and a southerly flow oceanic (low Chl a) water into Kimbe Bay.

4. SEA SURFACE TEMPERATURE

4.1 PROCESSING

The AIMS NOAA data archive consists of over seventeen years of HRPT data from the NOAA TIROS-N series oceanographic/atmospheric satellites. Between 1989 and 1996 the Northeast Australian Satellite Imagery System (NASIS) consortium collected the NOAA AVHRR data with its HRPT satellite receiving station located at James Cook University in Townsville, Queensland, Australia. From 1996 to the present, the data have been collected at the AIMS HRPT satellite receiving station located at its Cape Ferguson facility near Townsville. AIMS continues to collect, archive and process in near real time data from the operational NOAA satellites.

The AVHRR sensor package was designed with the intention that the thermal infrared channels would be used to measure surface temperatures, and hence SST. The largest error source in the computation of satellite SST from infrared satellite imagery is the correction for signal attenuation by atmospheric water vapour (Emery *et. al*. 1999). As a result, all SST retrieval algorithms are principally concerned with the removal of atmospheric effects from the earth-atmosphere signal sensed by the satellite.

The Advanced Very High Resolution Radiometer (AVHRR) is currently in its third version. AVHRR/1 had four spectral channels, one visible (580-680 nm), one near infrared (725-1100 nm), one middle infrared (3.55-3.93 mm) and one thermal infrared (10.5-11.3 mm). AVHRR/2 was first brought into use during August, 1981, when NOAA-7 became operational. Since then it has flown on board NOAAs 9, 11, 12, 14. In addition to the four spectral channels of AVHRR/1, AVHRR/2 had an additional thermal channel (11.5-12.5 mm). AVHRR/3 first became operational in June 1998. It is currently flown on board NOAA-15 and will be the sensor used on NOAAs 16, 17 and 18. The upgrade from AVHRR/2 to 3 included the addition of a second near infrared channel (1.58-1.64mm). For the purpose of sensing SST, there is no functional difference between AVHRR/2 and 3.

The Papua New Guinea SST Atlas is constructed with the NOAA 14 and 16 satellites and consists of 1245 daily images for the period July 1998 to June 2001 inclusive.

4.2 SELECTED SST IMAGERY

A selection of imagery is presented here that highlight discernable oceanographic features of interest. The full data set is provided on the accompanying DVD. Due to the high prevalence of cloud, and humidity it is often difficult to be sure that we are actually seeing the actual SST. N.b.The cloud and land masking algortithm maps to black.

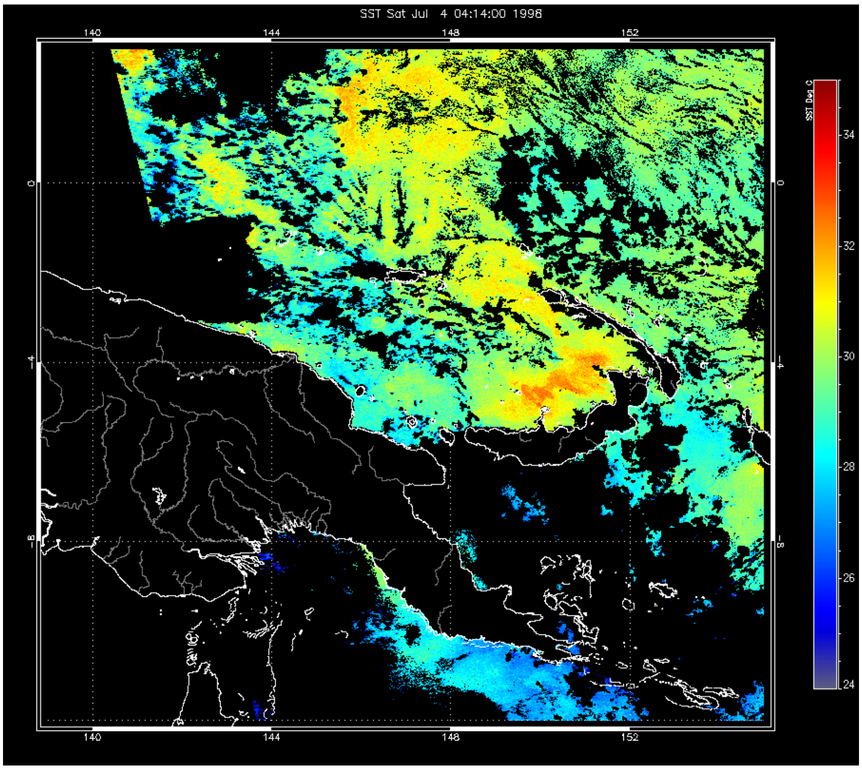

Figure 25 SST July 4 1998.

Warm eastern Bismarck Sea past Willaumez Peninsula toward Cape Lambert on the Gazelle Peninsula (East New Britain, Western Point of Peninsula where Rabaul is found).

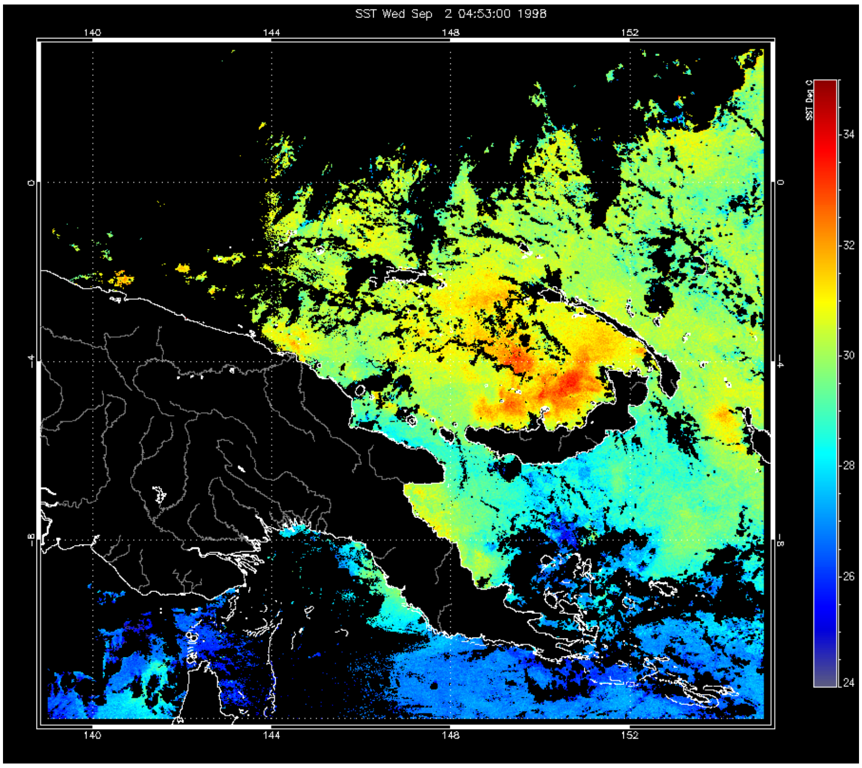

Figure 26. SST September 2 1998.

Cooler Vitiaz Strait inflow and warmer eastern Bismarck Sea

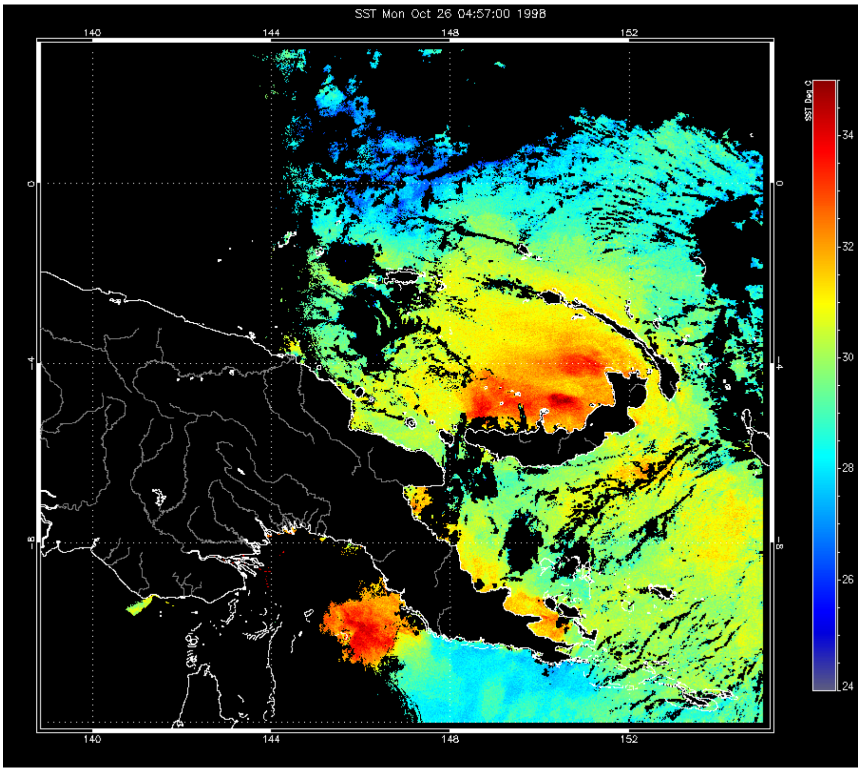

Figure 27. SST October 26 1998.

Warm eastern Bismarck Sea

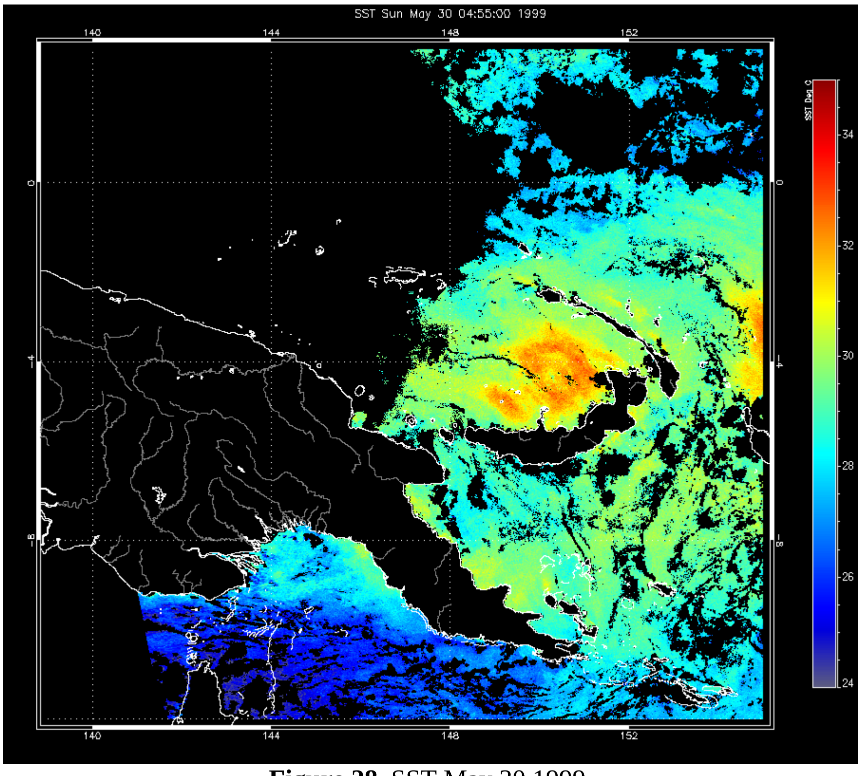

Figure 28. SST May 30 1999.

Warm Bismarck Sea north of New Britain. Cooler eastern Kimbe Bay

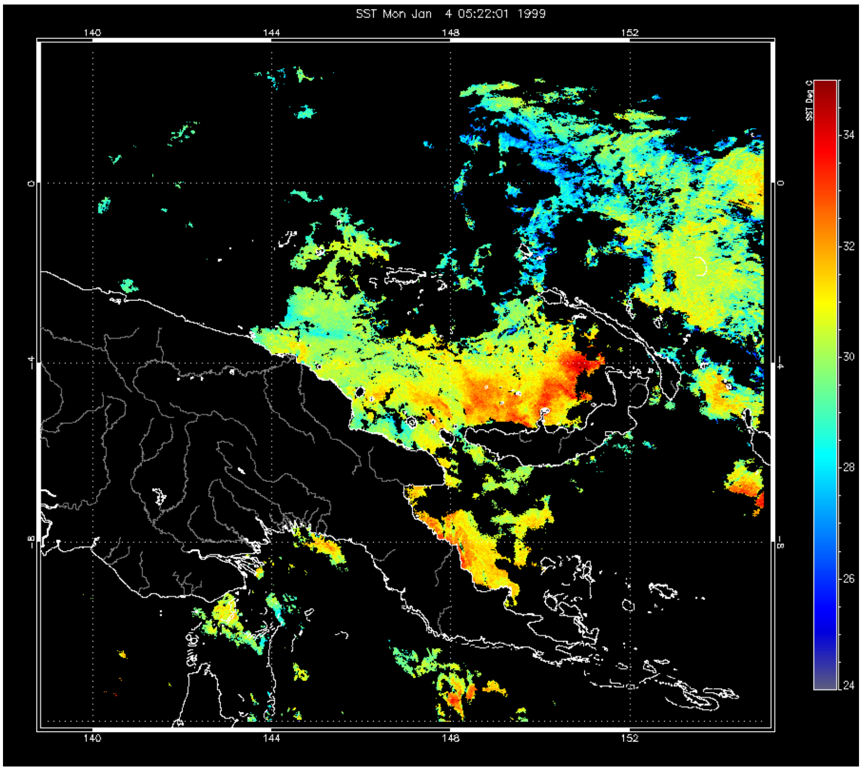

Figure 29. SST January 4 1999.

Significant thermal structure from Willaumez Peninsula meandering toward New Ireland

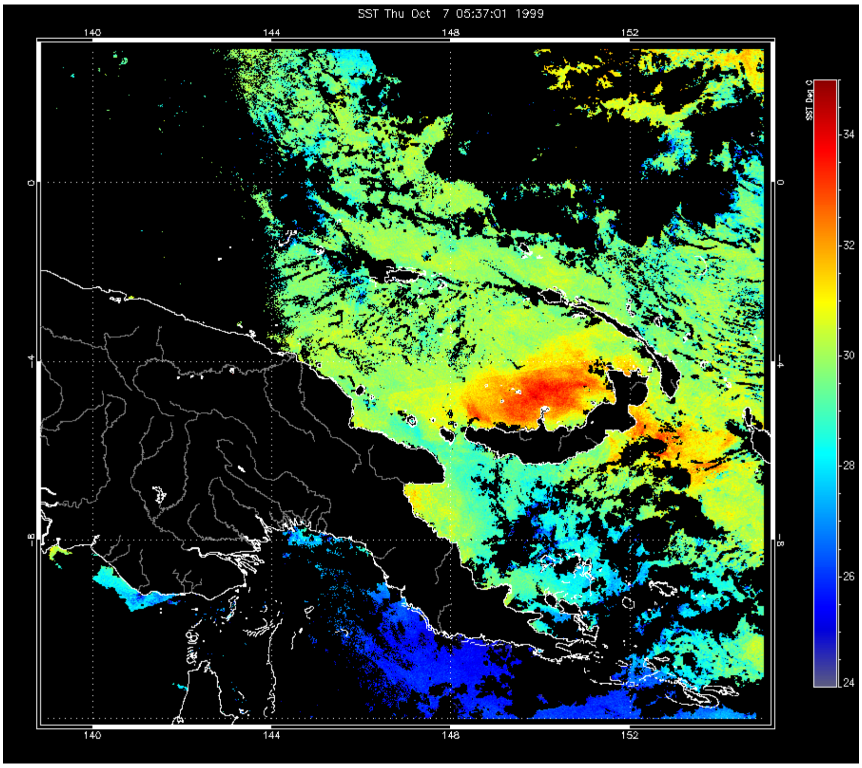

Figure 30. SST October 7 1999.

Warm north of Kimbe Bay with cooler coastal waters

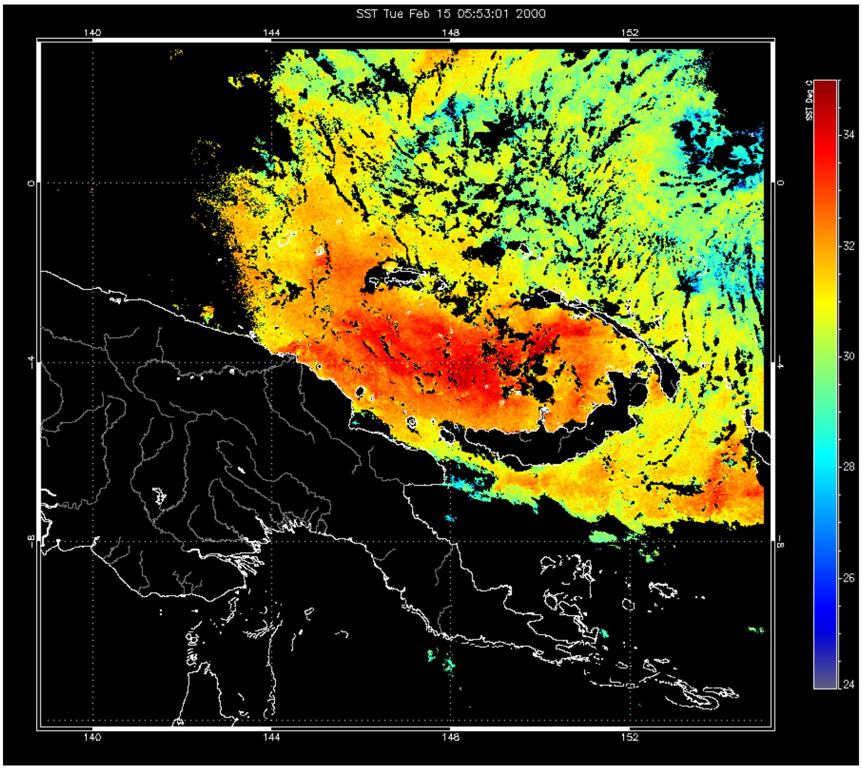

Figure 31. SST February 15 2000.

Warm Bismarck Sea

5. CURRENTS

5.1 DESCRIPTION OF THE MODEL

CSIRO MAR has led the development of an Ocean General Circulation Model for the Asian-Australian region in partnership with the BoM and RAN in a project named BLUElink> Ocean Forecasting Australia. The Ocean Forecast Australia Model (OFAM) is based on MOM4 (Modular Ocean Model version 4) developed by NOAA's Geophysical Fluid Dynamics Laboratory. The grid has $1/10^{O}$ x $1/10^{O}$ horizontal resolution in the Asian-Australian region (90E-180E, 75S-16N) that is suitable for oceanic eddy-resolving. The vertical grid has 47 levels with uniform resolution of 10m over the surface 200m and gradually coarsens to a maximum depth of 5000m (Brassington et al, 2005).

We have chosen to use the "spinup4" run that is non-data assimilating. It is forced from ECMWF fluxes (Weller and Anderson, 1996) and uses CARS. A fuller description of the model is expected to be published soon (Schiller et al, 2007) and the following web site should be consulted for any updates: http://www.cmar.csiro.au/bluelink/exproducts/index.htm

A 13 year hindcast (1992-2004) at daily temporal resolution of ocean circulation has been made available for non-commercial research. The full data set is ~10 terabytes and so as part of this project we chose to subset the global model for the years 1997- August 2002 inclusive.

The model has a number of limitations, not in the least due to the lack of detailed observations for forcing and the spatial and temporal resolution of the model. The performance of the model in the Bismarck Sea needs to be validated before being used quantitavely, however this is outside the scope of this project. It does give a much better indication of what the circulation is likely to be and can therefore be used in a suggestive way. This will allow the testing or assist in planning observations of oceanic phenomena in the future.

The model data is displayed with the background colour being temperature and the arrows represent the surface (0-10m) current speed and direction. The size of each arrow is indicative of current strength and the oceanographic convention means the arrows point in the direction of flow.

5.2 SELECTED MODEL PLOTS

Daily snapshots of the model are provided below. Full yearly animations are provided on the accompanying DVD. The animations give the viewer a better appreciation of the dynamics and complex responses of the Bismarck Sea circulation.

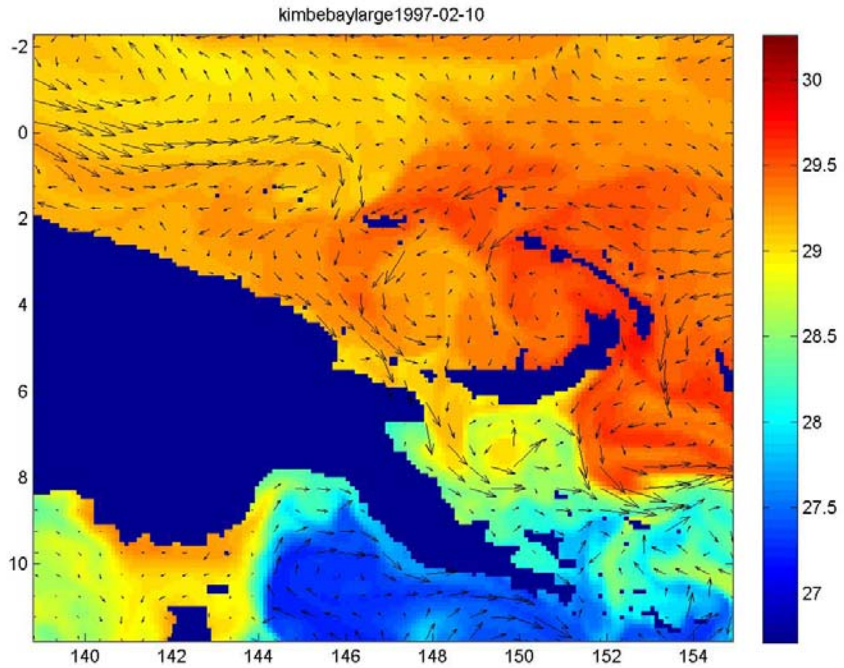

Figure 32. Model 1997-02-10.

Typical NE monsoonal circulation with currents moving eastwards and reversing the NGCC along the coast of PNG. Two counter rotating gyres are set up in the Bismarck Sea one Anti-cyclonic in the west and the other cyclonic in the East influencing outer Kimbe Bay.

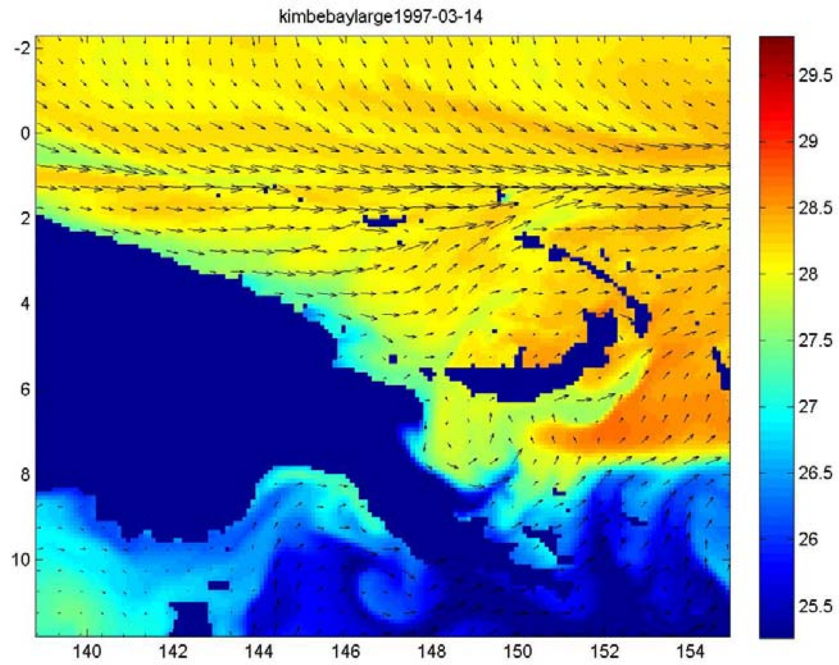

Figure 33. Model 1997-03-14.

Strong easterly winds reverse the SEC to form the Southern Equatorial Counter Current (SECC).Flow into the Bismarck Sea is from the West and exits through Ysabel, St Georges and Vitiaz Strait.

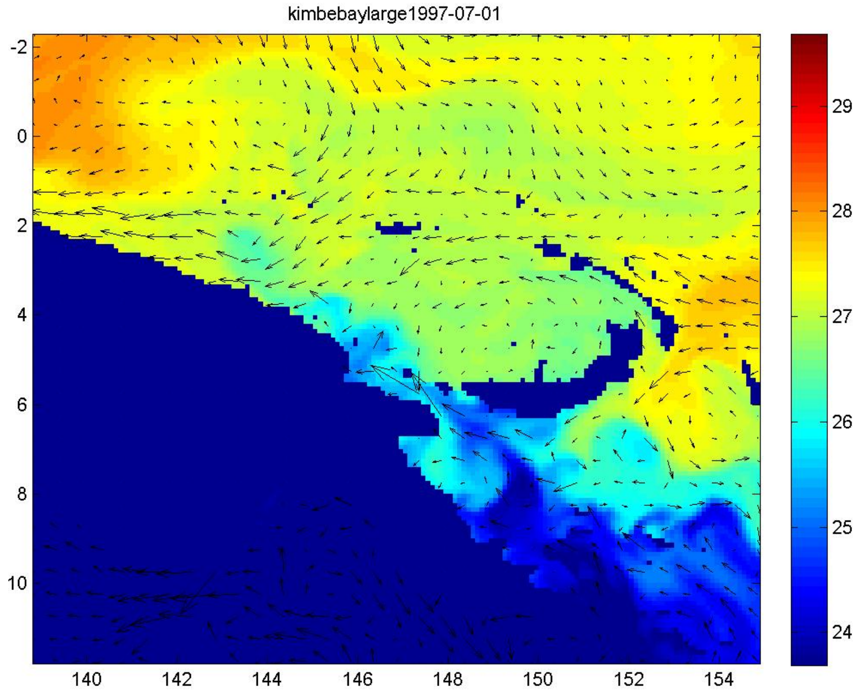

Figure 34. Model 1997-07-01.

A representative southeast monsoon with the NGCC flowing strongly through Vitiaz Strait along the PNG coast. The SEC flows around New Ireland and enters the Bismarck Sea through Ysabel Channel and some is deflected southwards into the Solomon Sea causing a number of gyres to form. This flow can eventually makes its way through Vitiaz Strait and St Georges Channel.

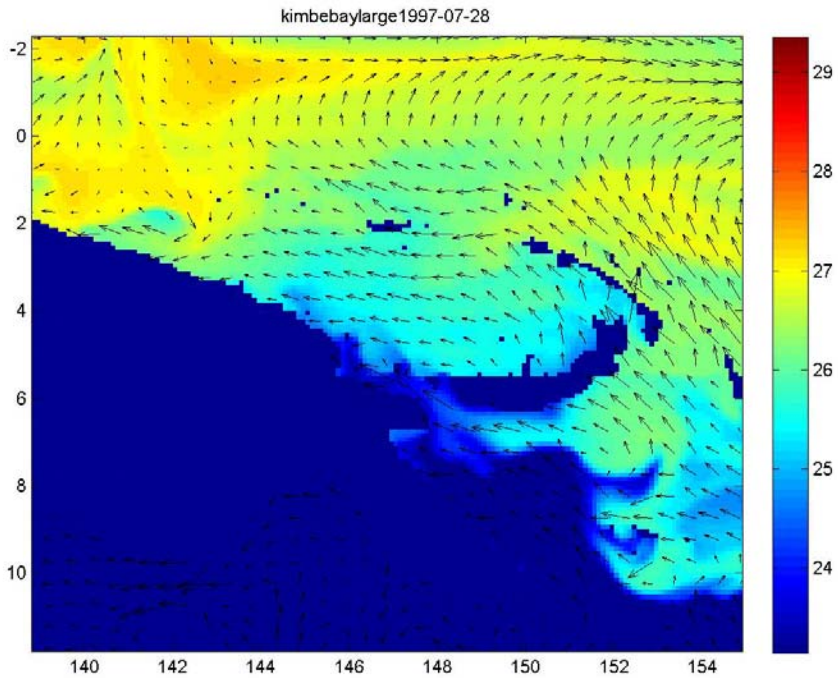

Figure 35. Model 1997-07-28.

Typical currents under a strong southeasterly. Surface flow moves toward the northeast and some evidence of upwelling is seen along Kimbe Bay.

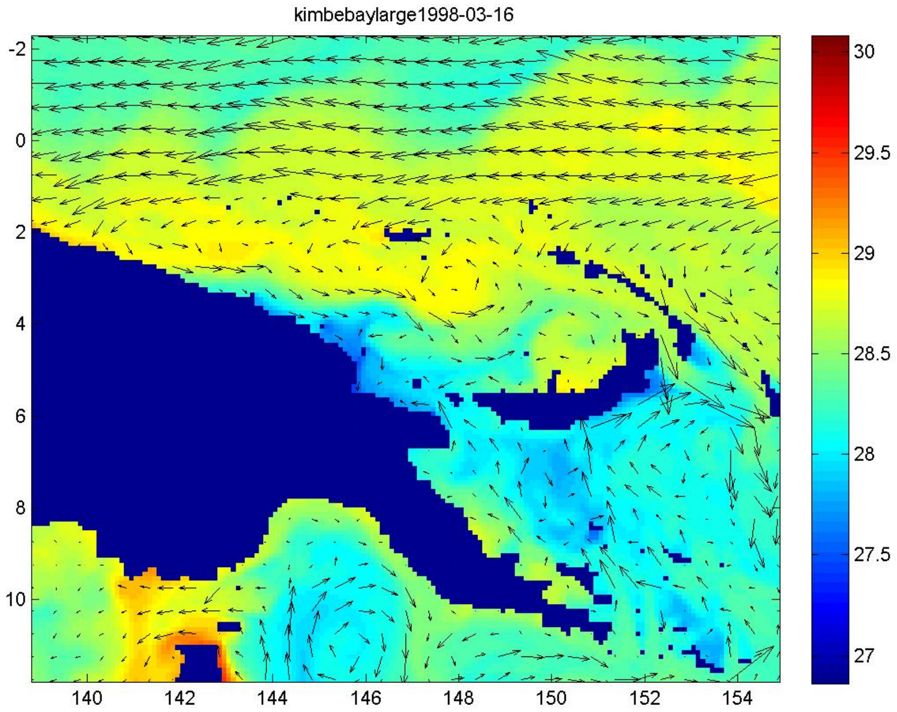

Figure 36. Model 1998-03-16.

Strong Equatorial flow to the West and a counter current into the Bismarck Sea south of Manus Island. This forms an anticyclonic eddy in western Bismarck Sea and cyclonic one off Kimbe Bay.

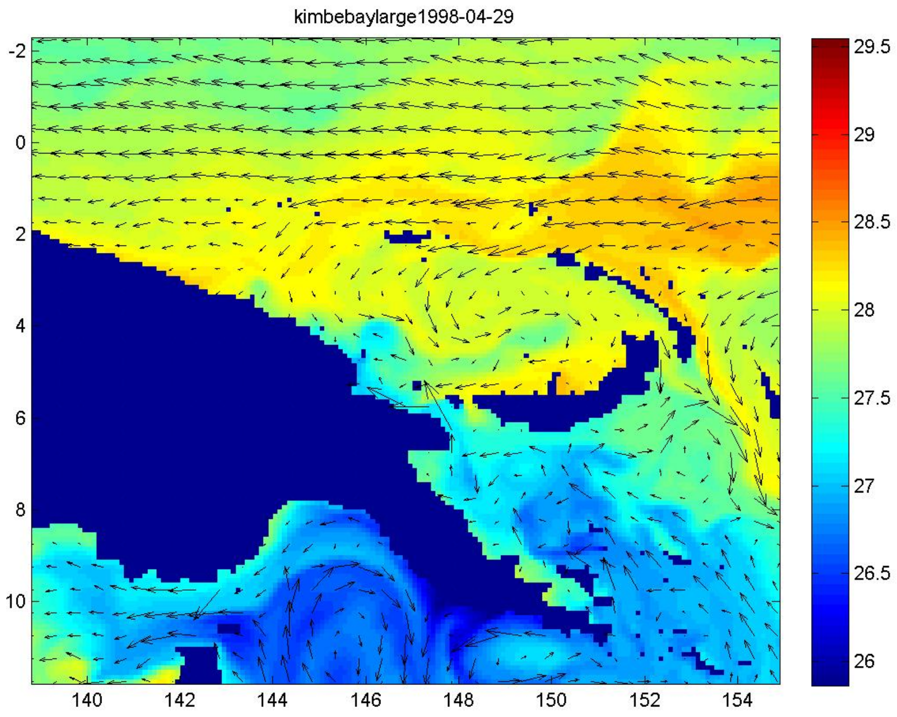

Figure 37. Model 1998-04-29.

A tongue of cooler waterfromVitiaz Strait meanders east and recirculates in a cyclonic eddy off Kimbe Bay. Significant inflow through Ysabel Channel with some evidence of cooling in the Lee of Manus Island due upwelling.

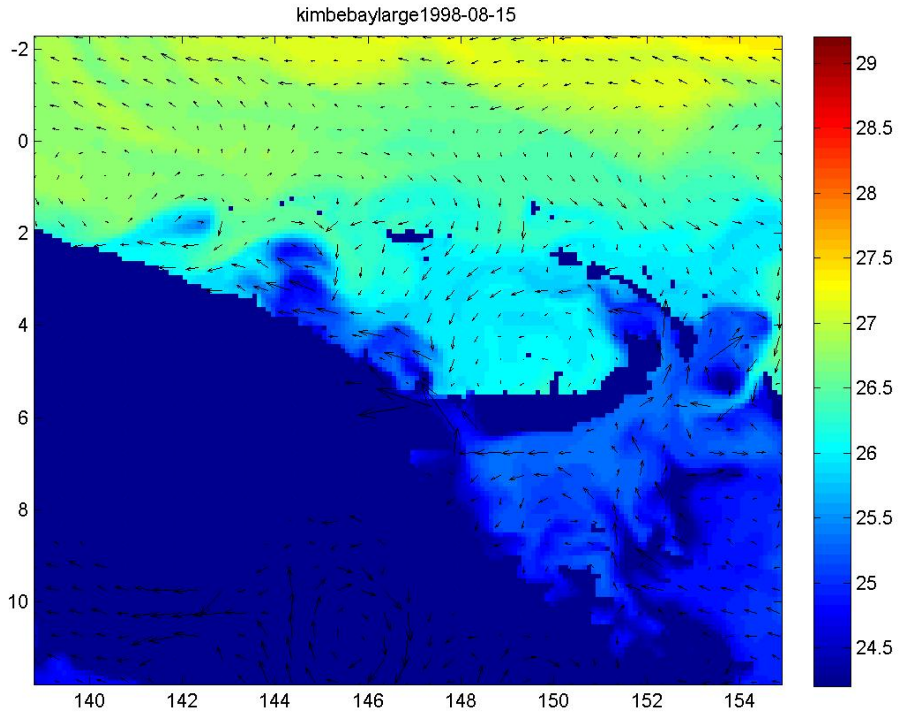

Figure 38. Model 1998-08-15.

The NGCC flows strongly through Vitiaz Strait. St Georges Channel also has inflow creating an antcyclonic eddy north of New Britain.

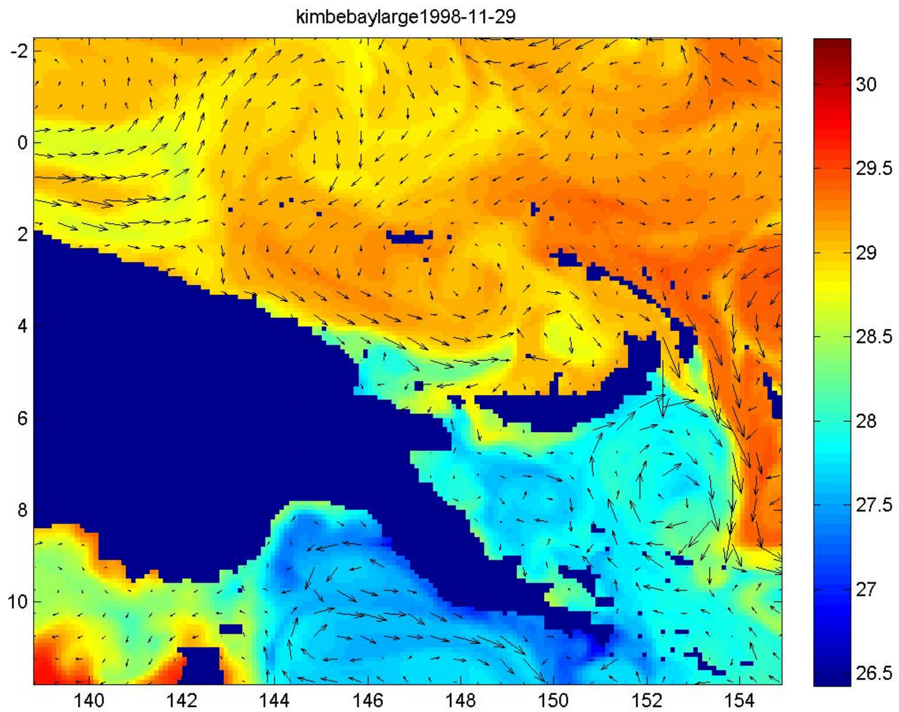

Figure 39. Model 1998-11-29.

Evidence of a mushroom vortex in the Bismarck Sea caused by a strong inflow of water from the Admiralty Islands moving east and being deflected north into two counter rotating eddies. Cooler water from the Vitiaz Strait are being entrained in the flow.

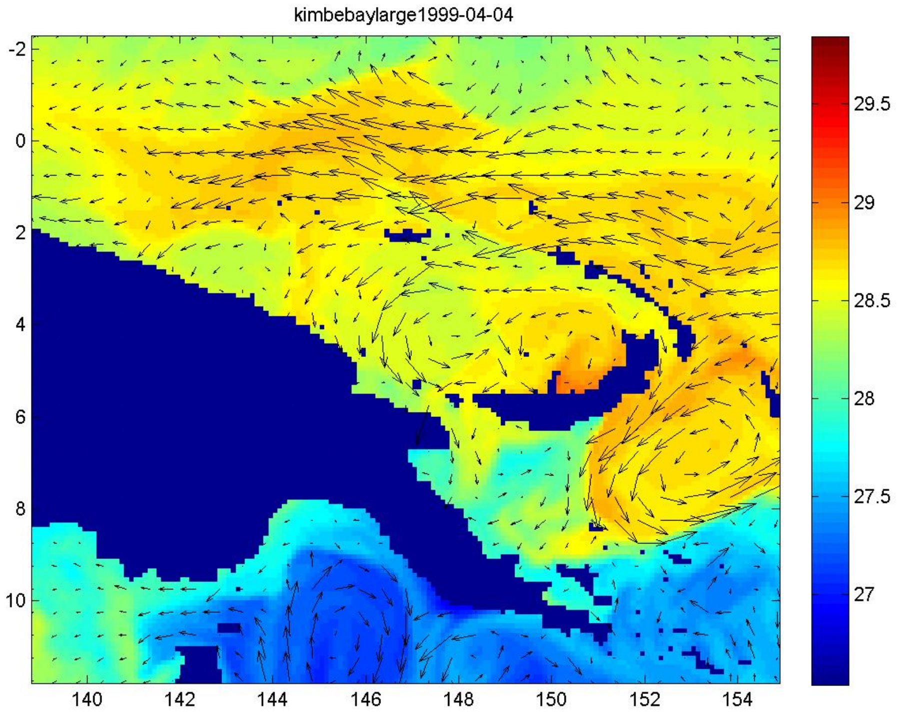

Figure 40 Model 1999-04-04.

Warming Kimbe Bay with a recirculation in the lee of Willaumez Peninsula

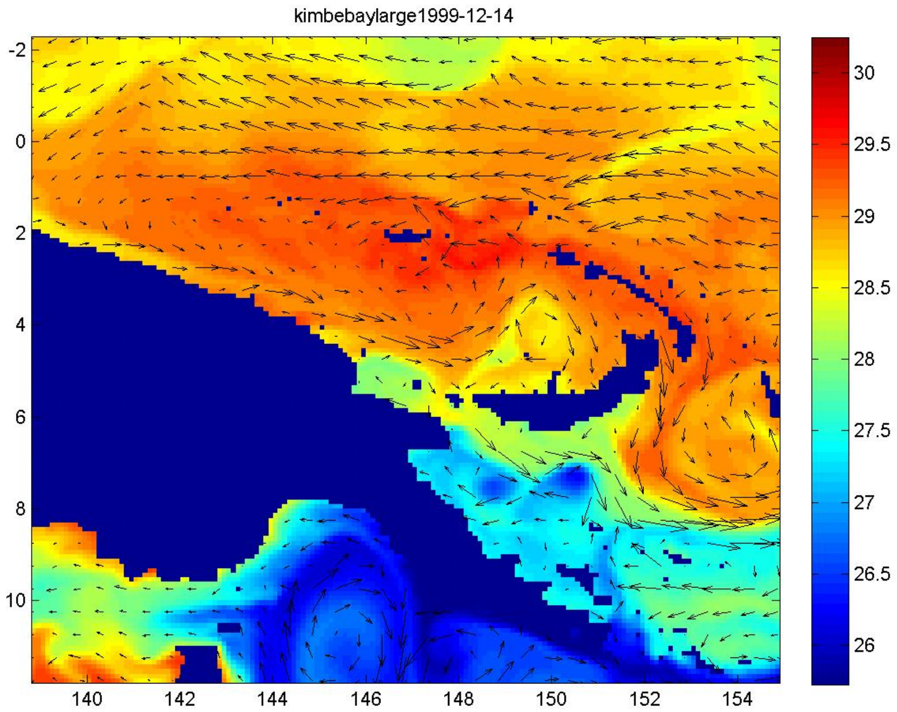

Figure 41 Model 1999-12-14.

Cooler water from Dampier Strait being entrained in a northeast flow toward New Hanover and forming an eddy.

6. CONNECTIVITY

There is limited information on local scale oceanographic processes and features that may be relevant to the management of Kimbe Bay and the Bismarck Sea. To address this gap in knowledge, preliminary numerical modelling studies have been undertaken to investigate local circulation, transport and flushing of water borne material.

The transport and dispersion of waterborne material in the vicinity of the Bismarck Sea was investigated via the application of an advection-diffusion model (Spagnol et al., 2002) forced by the predicted hydrodynamic circulation. The dispersion model was applied to investigate possible trajectories of inert, buoyant material and to determine synoptic patterns of transport and flushing. The predicted dispersal of a plume of neutrally buoyant particles released from a number of locations around the Bismarck is supplied on the accompanying DVD in the form of animations.

Neutrally buoyant particles were released from a number of key sites: Kimbe Bay, Manus Island, Rabaul and Madang. The initial date was chosen to be April 1 2001 and they were then tracked for 90 days to determine their fate and to reveal pathways.

Dispersion patterns predicted by the model serve to identify a number of noteworthy features of the hydrodynamics. At this time of year there is significant connectivity between sites within the Bismarck Archipelago due to a number of recirculations. The fate of the particles was eventually revealed by them eventually being entrained in the northwestward flowing NGCC and leaving the Bismarck Sea.

Releases from West and East Kimbe show the eastern side of the bay is more open to the influence of the larger scale circulation and the particles leave the bay much sooner than those in the west. Figure 42 shows a sequence of snapshots from a Kimbe Bay release of passive particles. Particles originating from west Kimbe Bay are coloured yellow and those from the east, pink. The depth of colour indicates particle concentration. Whilst some of the particles leave the western side of the bay toward the east, over half remain suggesting high retention. Some of the particles do return from the east and are retained in the western part of the bay until day 45 where they are then swept to the north. By this time particles that originated from the eastern side of the bay have reached as far as Manus Island, and also around the Witu Islands. Due to the delayed release from the western part of the bay, these particles have reached as far as the southern coast of New Ireland and are moving past New Hanover toward Manus. At the end of the 90 day simulation some remnant particles are trapped in the Bismarck Sea eddy however the vast majority have been entrained in the NGCC and move along the northern PNG/Papua coast toward the equator.

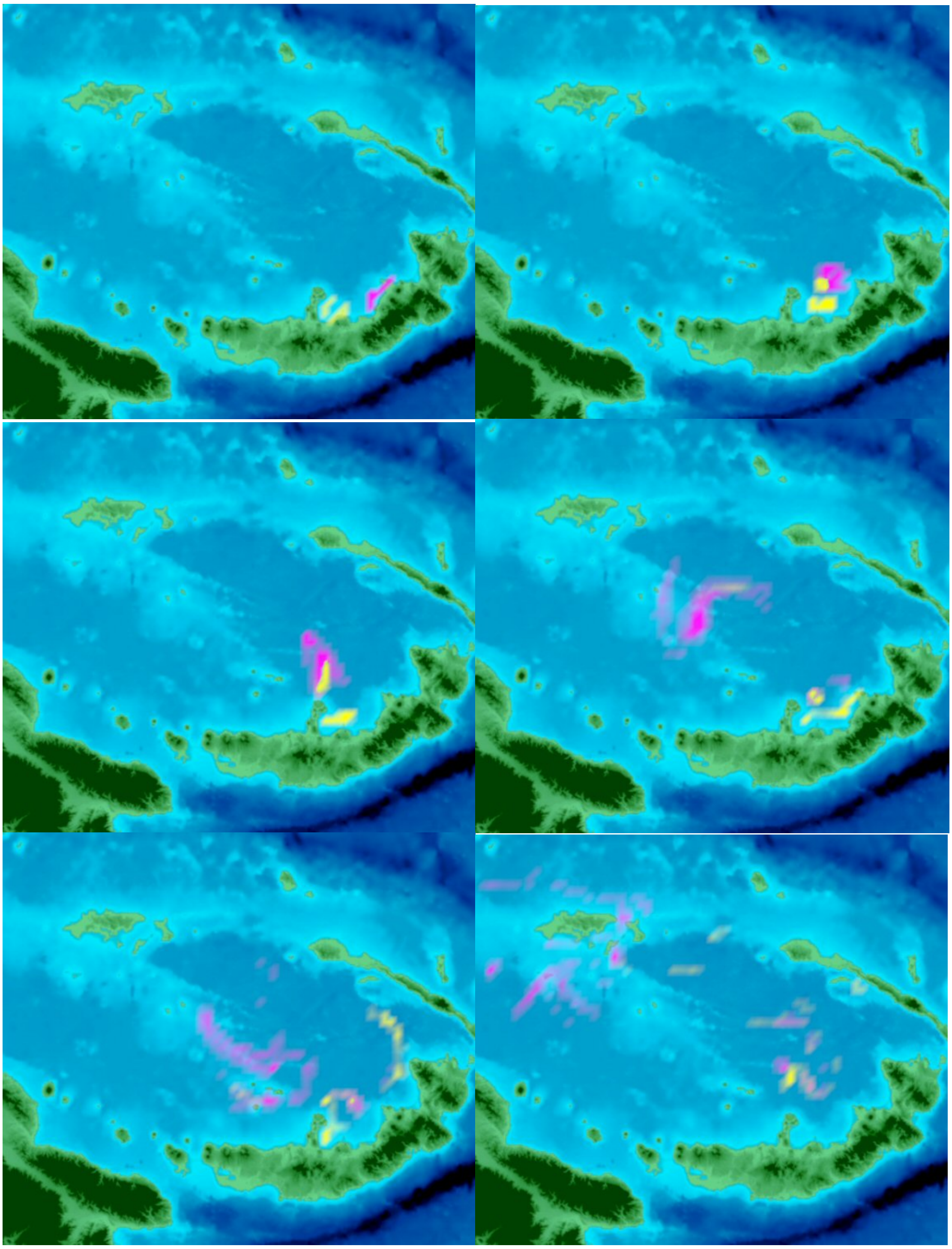

Figure 42. Bismarck Sea connectivity snapshots for days 0, 11, 20, 30, 40 and 50 since release from Kimbe Bay April 1 2001.

7. DISCUSSION

The following section discusses the currents at various scales that can be seen in the combined model, ocean colour and SST data sets. References are made to supporting publications and figures in this report where possible.

7.1 REGIONAL CURRENTS

The model shows that the Bismarck Sea circulation is largely driven by the Southern Equatorial Current (SEC) for most of the year. The man entry point is through Ysabel channel to the North, and Vitiaz Strait in the South. The SEC is obstructed by the Solomons upstream and guides the flow northwards past Bougainville Island. The flow then moves towards Ysabel Channel, around New Ireland. The SEC can also enter the Solomon Sea and recirculate, or to contribute to the Vitiaz Strait and/or St Georges Channel inflows. The main source of water though Vitiaz Strait is via the New Guinea Coastal Current (NGCC) and undercurrent (NGCUC). Coral Sea waters are a significant contributor, in turn sourced from more southerly branches of the SEC, south of the Solomons. As the water approaches the east coast of Australia it bifurcates as a poleward flowing East Australian Current and an equatorward current, which has been named the Hiri current or the North Queensland Current (NQC). This current skirts the continental shelf and is redirected toward the east in the Gulf of Papua and continues along the Louisiade Archipelago, southwest PNG. The flow then enters the Solomon Sea and follows the northern coast of PNG to Vitiaz Strait, Lindstrom et al (1987), Sokolov & Rintoul (2000).

During the northwest monsoon the NGCC reverses and flows along the coast and out of Vitiaz Strait into the Solomon Sea. The model reveals that there can be strong westerly wind bursts that force significant inflow to the Bismarck Sea between PNG and Manus Island. Selected imagery shows that this can continue as far as Kimbe Bay, however for the most part, there tends to be a number of eddies formed in the Bismarck Sea. At these times the South Equatorial Counter Current (SECC) also forms reversing the flow past the Solomon Islands (figure 33).

7.2 BISMARCK SEA CURRENTS

The circulation within the Bismarck Sea can be complex and very dynamic. It is determined principally by inflow through the 3 major straits/channels during the southeast trade wind season and during the northwest monsoon by the inflow between Manus Island and the PNG coast.

During the southeast trades the NGCC tends to hug the northern PNG coastline. Instabilities do form along this current and eddies can be advected northwest with the general flow. The rest of the circulation is driven by what comes in through Ysabel channel with a lesser, but reinforcing, contribution from St Georges channel (figure 38). This usually forms a large anticlockwise recirculation in western and central Bismarck Sea (figure 40).

An interesting feature is captured during the onset of the northwest monsoon. The southeastward flow and the opposing remnant NGCC through Vitiaz Strait meet and cause the convergent waters to deflect out into the central Bismarck Sea. Figure 41 shows cooler Vitiaz Strait sourced waters being entrained and moving offshore. This may be the mechanism causing ocean colour features in the central Bismarck Sea (Figure 22). A double vortex is also captured in the model (Figure) and possibly in the ocean colour imagery (Figure 18).

The Sepik River plumes provide an interesting tracer when it is in flood. Its fate is primarily determined by local winds and currents. When the NGCC is well developed it tends to hug the coastline (Figure 9). However, when this current wanes in strength the plume can be observed to meander out into the central Bismarck Sea (Figure 8).

Manus Island is located in the path of the SEC being deflected around New Ireland. The modelled flows and evidence from ocean colour indicates there is significant upwelling in the Lee of the Admiralty Islands (Figure 20). During the northwest monsoon the flow can reverse forming the SECC (Figure 33).

7.3 KIMBE BAY CURRENTS

Interpreting the currents here are testing the limits of the resolution of the model however some general indication of net currents and variability can be made. Circulation within the bay is driven by larger eddies in the eastern Bismarck Sea that can reverse. Eastward flow past Willaumez Peninsula from can result in eddying in the lee efand upwelling in West Kimbe Bay.

The connectivity sequence (Figure 42) and animations on the DVD do show that there is evidence for higher retention in the western side of the bay with more flushing occurring to the east. Due to the grid coarseness of the model not resolving the reef system the retention is likely to be higher than presented here.

Upwelling can occur along the coast of New Britain and Kimbe Bay during the southeast trades (Figure 35) when the wind is oriented off-shore and during the northwest monsoon along the northern PNG coast (Cresswell, 2000).

8. CONCLUSIONS AND RECOMMENDATIONS

The analysis of remotely sensed data and visualisation of the hydrodynamic model undertaken in this study represents only an initial investigation of the oceanography of this region. Satellite data was provided at a higher level of spatial and temporal resolution than has been available before (1km, daily), but the benefits of this analysis (i.e. the degree to which we can use this information to ground truth the model) are limited due to the high degree of cloud cover in the area. When there is good satellite imagery the features observed do show agreement with those being modelled.

The relative coarseness of the model computational grid in comparison to the local geographic features will result in a loss of accuracy in the predicted circulation close to the coast and in the vicinity of coral reefs that are sub-grid scale.

In order to address these limitations, further research is recommended to increase the certainty and understanding of key physical oceanographic processes relevant to the design and management of marine protected areas in the region through the characterisation of the local environment and connectivity studies.

Nevertheless, the model provides a promising understanding of large scale circulation in the Bismarck Sea, and provides an excellent basis for finer scale modelling of the currents at key sites in future (e.g. Kimbe Bay, Tigak Islands, Manus, Madang etc).

The development and application of a finer computation grid to the Bismarck Sea would allow the following:

- Resolve complex topography associated with coral reefs in Kimbe Bay
- Allow tidal dynamics, local winds and river outflows to also be included.
- Perform multiple simulations spanning the natural range of relevant meteorological and oceanographic conditions at coral reef to Bismarck Sea scales.
- Connectivity studies of particles such as fish and coral larvae.

Biological characteristics of the larvae will also need to be considered in future connectivity modelling for the area as we have only introduced buoyant and passive particles here. However, this study will provide an excellent basis for fine scale circulation (and connectivity) models to be developed for key sites in the Bismarck Sea in the future

ACKNOWLEDGEMENTS

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BLUElink> ReANalysis (BRAN) data access and advice from Andreas Schiller and David Griffin, CSIRO MAR. Orbimage SeaWiFS and NOAA AVHRR data sourced from the AIMS receiving station. NCEP-NCAR Reanalysis 1 data was provided by the NOAA-CIRES Climate Diagnostics Center, Boulder, Colorado, USA, from their Web site at http://www.cdc.noaa.gov/. Thanks to Alison Green, Jeanine Almany, Maria Beger and Glenn Almany for providing guidance and input into throughout this process. Thanks also to Simon Spagnol for imagery display advice and Joanna Ruxton for proofing. Maya Srinivasan provided expert advice on local bleaching responses and general conditions.

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GLOSSARY

AIMS	Australian Institute of Marine Science
AVHRR	Advanced Very High Resolution Radiometer
BoM	Bureau of Meteorology
BRAN	BLUElink> ReANalysis
CSIRO	Commonwealth Scientific and Industrial Research Organisation Marine and Atmospheric Research
DVD	Digital Video Disc
EAC	East Australian Current
ECMWF	European Centre for Medium-Range Weather Forecasts
ENSO	El Nino Southern Oscillation
ENVI	Environment for Visualising Images
EPTOMS	Earth Probe TOMS
IDL	Interactive Data Language
ISO	Intra-seasonal Oscillation
ISPCZ	Inter-tropical South Pacific Convergence Zone
NCEP-NCAR	National Centers for Environmental Prediction – National Center for Atmospheric Research
NGCC	New Guinea Coastal Current
NOAA	National Oceanic and Atmospheric Administration
PNG	Papua New Guinea
RAN	Royal Australian Navy
SeaDAS	SEAWIFS Data Analysis System
SeaWiFS	Sea-viewing Wide Field-of-view Sensor
SEC	South Equatorial Current
SECC	South Equatorial Counter Current
SST	Sea Surface Temperature
TIROS	Television Infrared Observation Satellite
TNC	The Nature Conservancy
TOVS	TIROS Operational Vertical Sounder
TOMS	Total Ozone Mapping Spectrometer
TROPICS	Tropical River-Ocean Processes In Coastal Settings

The mission of The Nature Conservancy is to preserve the plants, animals and natural communities that represent the diversity of life on Earth by protecting the lands and waters they need to survive.

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