A hydrographic study on the effect of Rumble III on the thermohaline structure and circulation

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Non-technical Summary

Rumble III is an active submarine volcano located on the Kermadec Arc, north of New Zealand at -35.75°N, 178.5°E. During March 2009 a hydrographic survey was conducted to measure temperature, salinity and density changes with water depth near the volcano. Water samples were collected to measure nutrient and oxygen concentrations. The speed and direction of the currents were measured using a 75kHz Acoustic Doppler Current Profiler (ADCP). Using this data, evidence of upwelling and downwelling was found. Upwelling occurs when water from deeper in the water column is pushed up towards the surface. Downwelling is the opposite of this. By plotting temperature, salinity and density changes with depth the uplift of isotherms, isohaline and isopycnals (levels of the same temperature, salinity and density) was seen throughout the water column up to 75 meters below the surface. The distribution of nutrient and oxygen concentrations agreed with this pattern with higher nutrient concentrations seen where the isotherms, isohalines and isopycnals were uplifted and lower concentrations seen where they dipped down. The distribution of oxygen was the inverse of this because oxygen concentrations decrease with depth whereas nutrient concentrations increase with depth. From the ADCP data, internal tides were found. Internal tides are waves within the water column that repeat over the same time period as the normal tide. These are generated when the normal tide passes over a topographical feature such as a ridge, seamount or volcano, vertically displacing the water. This provides a mechanism by which the upwelling of water can occur on short timescales. Another mechanism that would result in upwelling is the formation of an eddy; a circular flow pattern that is tens of kilometers wide. An eddy above the volcano would result in water being pulled down over the summit and then spread out horizontally. This then causes water to be upwelled further out from the volcano to replace the water being downwelled. Evidence for this type of circulation was found at Rumble III. Nutrient rich water is upwelled to 75 meters depth

above Rumble III which is in the zone where light penetrates. This may increase primary productivity in the surface waters by providing a nutrient source. Photosynthetic organisms will use these nutrients to grow by taking carbon dioxide out of the atmosphere and turning it into organic matter. When the organisms die this organic matter sinks to the sea floor where it may be buried. A high rate of carbon export to the sea floor means a high rate of carbon dioxide removal from the atmosphere. This has global climate implications as it is a means by which levels of atmospheric carbon dioxide can be decreased.

Abstract

A hydrographic survey was conducted during March 2009 at Rumble III, an active volcano on the Kermadec Arc, North of New Zealand at -35.75°N, 178.5° E. A mixture of vertical CTD, tow-yo and XBT casts was used along two perpendicular transect lines of 24.14 km and 14.27 km length. Current velocity data was collected using a 75 kHz ADCP and nitrate, silicate and oxygen concentrations were also measured. Fluctuations in the depths of the isotherms, isopycnals and isohalines were seen around the volcano with the vertical displacement ranging from 10 to 33m for an individual isotherm. The fluctuations extended from the summit at 310m depth to the thermocline at approximately 75m depth. Oxygen concentrations were seen to be relatively lower at depths where isotherms were uplifted and relatively higher where isotherms were drawn downwards. The distributions of nutrient concentrations were the inverse of this. Upwelling was more dominant over the flanks with downwelling occurring over the summit of Rumble III. From this pattern it is determined that an anticyclonic eddy present over the volcano is drawing water down over the summit resulting in upwelling over the flanks to replace this water. Though primary production may be increased by the upwelling of nutrient rich water into the euphotic zone over the flanks, overall there is no net upwelling. However, the circulation cell does provide a mechanism for retention of larvae and for an increased flux of detritus to benthic communities.

Rumble III is an active submarine volcano located on the southern Kermadec Arc, north of New Zealand in the southwest Pacific and is a topographical feature that could cause upwelling. This volcano has the shallowest summit of all the volcanoes in the Arc and is also extremely hydrothermically active. How water flows around Rumble III will be affected by the major currents in the area, primarily the East Auckland Current (EAUC) and the East

Cape Eddy (ECE). The centre of the ECE, as found by Roemmich and Sutton (1998), is very near the location of Rumble III at approximately 35.5°S, 178.5°E. This warm core eddy is quasistationary and its position varies over time about a preferred position. Roemmich and Sutton (1998) found that the surface currents can reach a maximum of 25 cm s^{-1} which flow in an anticlockwise direction and that the eddy is detectable to 1500m. The location, size and depth of this eddy mean that it will heavily influence the flow around Rumble III.

In previous studies the summit of Rumble III was reported to be approximately 200 meters below the sea surface (de Ronde et al. 2001) and so this volcano could cause water to be upwelled into the euphotic zone and possibly entrain hydrothermal fluids from the volcano's vent plume. However, it is now believed to be 310m below the sea surface (Dodge 2009) though upwelled water may still reach the euphotic zone. If upwelling does occur then it will have an impact on productivity in the surface waters, as it will bring up water with high nutrient concentrations. This increase in nutrients will lead to an increase in primary production, as photosynthetic organisms will be less limited by the amount of nutrients in the water. Factors that increase productivity in surface waters have a global relevance as regions of high productivity are likely to be areas of high carbon export. This has huge implications for global climate as high carbon export leads to large amounts of carbon being removed from the atmosphere and sequestered in deep sea sediments. Comeau et al. (1995) found that phytoplankton abundances were greater over Cobb Seamount in the northeast Pacific than in the surrounding water column. The summit of Cobb Seamount penetrates into the euphotic zone and although the nutricline was seen to dome upwards Comeau et al. (1995) concluded that the increased biomass was due more to the stability the seamount gave to the water column than the increase in nutrient concentrations.

The relationship between topography and flow is also important when looking at the transport of heat and chemical species, especially when considering this extremely hydrothermal environment. The transport of hydrothermal fluids into the euphotic zone by the upwelling of water can enhance productivity as it provides essential macro and micro nutrients, such as iron, to photosynthetic organisms which utilize these nutrients during photosynthesis. Tarasov et al. (1999) found that primary production was significantly influenced by the shallow water hydrothermal system in Matupi Harbour, Papua New Guinea. The semi isolation of this harbor from the open ocean allowed this influence to be more pronounced.

The flow around seamounts has been intensively studied especially for the Fieberling Seamount Group located off the Californian coast. Roden (1991) conducted a survey to determine the flow and thermohaline structure around the individual seamounts and also as a group. Upwelling caused by the Fieberling Seamount was detected through the uplift of isopycnals around the summit. Nutrient data also showed the presence of low oxygen and high nutrient water, indicating that water was being upwelled from deeper in the water column.

Variability in the flow around seamounts will cause different patterns in the hydrography. Lavelle (2006) used a primitive equation model to examine flow around the Fieberling Seamount. This model showed anticyclonic flow features around the summit which were approximately 24 km in diameter. It was also seen that a reversal in the tidal flow caused the isotherm displacement to switch sides. This same anticyclonic flow feature was discussed by Mullineaux and Mills (1997) where downwelling was caused to replace water flowing horizontally outwards from the summit of Fieberling Seamount in a circulation cell. This also caused upwelling of water over the flanks to replace the water being downwelled over the summit. From the observations Mullineaux and Mills (1997) conclude that the circulation was generated from non linear interactions of the tide with the topography.

Further work on a model of the Fieberling Seamount by Roden (1994) found that for isolated seamounts the strength of the upwelling could be enhanced by certain flow configurations. The scenario is described as having cyclonic flow in the top part of the water column caused by wind, with a pair of meandering jets flowing in opposite directions below. This configuration will generate vertical velocity, through vorticity being generated by differences in the flow velocities through the water column. Upwelling was enhanced when sources of positive vorticity, which create vertical velocity flowing upwards, and the circulation in the mixed layer were aligned vertically with the vorticity sources created by the presence of the seamount. Such flow configurations may occur at Rumble III and enhance any upwelling caused by the volcano, and as the summit is so shallow, could cause this water to reach the euphotic zone. Upwelling cones 120 to 240 meters high were observed above the summit of Fieberling (Roden 1994) though the degree of displacement of the isopycnals due to upwelling depended on the height of the seamount and the current speed as found through a series of model experiments conducted by Smith (1992).

Another mechanism that could cause upwelling of water is internal waves. In their investigation of the generation of internal tides at different topographical features, Holloway and Merrifield (1999) discuss the role of the slope of the topography, α, compared to the slope of the characteristic the internal wave travels along, s. Internal tides were more likely to be generated when α/s is greater than 1, though if the topography is very large and creates too much of a barrier then the current may just flow around the barrier. Topographic features which are elongated were seen to generate internal tides more frequently than symmetrical seamounts, causing vertical displacement of the water. The vertical displacement of water over the Kermadec Ridge was found to be 5m by Chiswell and Moore (1999) and 12-20m over the Mendocino Escarpment (Althaus et al. 2003). This is small when compared to the

40m vertical displacement of isopycnals over the summit of Fieberling Seamount (Roden 1991).

This is the first study of the flow patterns around Rumble III. As Rumble III and the Fieberling Seamount are located at the same latitude, flow patterns around the seamounts will be similar. This is because the forces generating the flow will be comparable, due to the coriolis parameter being of the same magnitude. Upwelling observed at the Fieberling Seamount Group reached a height of 120 to 240 meters above the summits of the Seamounts. Based on a calculation using the Rossby radius of deformation, $L = NH/f$, where L is the length, N is the Brunt-Vaisala frequency, H is depth and f is the Coriolis parameter, the height the isopycnals perturbations are expected to reach is 177m above the summit when using the diameter of Rumble III at its base as L. As the summit of Rumble III is only 310 meters deep, it is likely that upwelling will bring nutrient rich waters into the euphotic zone. This study finds that the flow around Rumble III is complex and that upwelling does occur and the evidence for different mechanisms that result in upwelling is discussed.

Methods

Between8-12 March 2009 the R/V Thomas G Thompson made hydrographic measurements using a mixture of conductivity temperature and depth system (CTD), tow-yo and expendable bathythermograph (XBT) casts around Rumble III (Figure 1). Rumble III is located at 35°44.377' S, 178°29.839' E and the sampling area covered was approximately 280 km^2. Four CTD casts and two tow-yo casts were used to collect temperature, salinity, density and dissolved oxygen data (Table 1). The XBT casts collected additional temperature data. All casts were conducted along two transect lines which were perpendicular to each other and that intersected over the summit of Rumble III. The spacing of the stations was closer together nearer the summit, approximately 2 km apart, whilst stations located further away were approximately 4 km apart. The stations nearer the summit also coincided with the tow-yo lines to give an even higher spatial resolution.

The XBT data were merged with the CTD data after correcting the raw data using the new fall rate equation described by Hanawa et al. (1995). By comparing the data from a tow-yo line and XBT cast conducted at the same time between 448.2 and 488.6 meters an offset in the temperature reading between the CTD and the XBT of 0.37°C was found. This was accounted for before joining the two data sets.

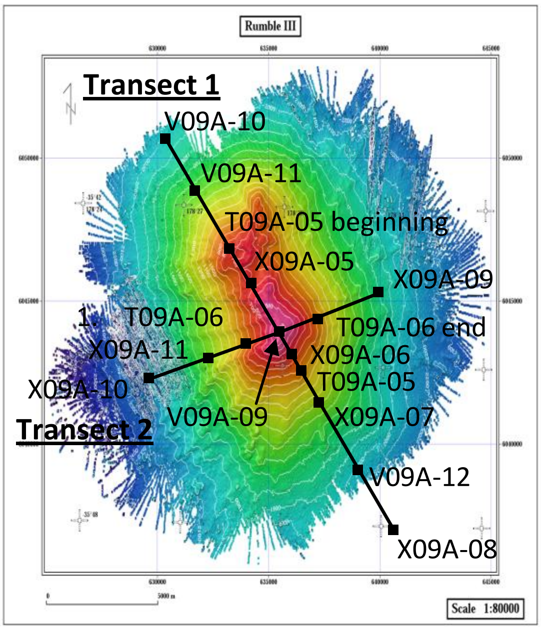


Figure 1: Map showing the location of the stations. Station names beginning with V indicate a vertical CTD cast, T indicates a tow-yo cast and X indicated an XBT cast. Bathymetry data is from Dodge (2009). For exact station positions see Table 1.

Using a 24 Niskin bottle rosette on the CTD, water samples were taken at 3 depths, 0, 200, 350m at each of the CTD casts and at the beginning and end of the tow-yo casts. These samples were analyzed by Kathy Krogslund, University of Washington for nitrate and silicate concentrations using the methods as described by Hager et al. (1972). Salinity samples were also taken to calibrate the CTD sensor. After the cruise the salinity samples were analyzed by Aaron Morello, University of Washington using a Guildline Autosal 8400B Laboratory Salinometer. An offset of 0.003 was found between the CTD sensor and the salinometer and the CTD data was corrected for this.

Current velocity data was also collected throughout the cruise using the onboard 75 kHz RD instruments Acoustic Doppler Current Profiler (ADCP). Using the UHDAS system the data were averaged over 5 minute intervals and into 8 meter depth bins processed using Common Oceanographic Data Access System (CODAS) to remove bad profiles (Firing et al.

1995) and gaps in the data were vertically interpolated over using MATLAB. The depth-mean current velocity was removed from each profile to remove the barotropic tide to leave just the baroclinic velocities.

Satellite altimetry data was also collected from the AVISO Live Access Server to show sea surface height. This gives an indication of the location of major eddies in the region and puts the localized circulation at Rumble III into a wider perspective. The data is merged from all altimeter missions (*Jason*-1&2, *T/P*, Envisat, *GFO*, *ERS*-1 & 2 and *Geosat*) and shows absolute geostrophic velocities on the 10 March 2009.

Station Name	Latitude (decimal degrees N)	Longitude (decimal degrees E)	Maximum depth
V09A-09	-35.7376	178.4935	450
V09A-10	-35.6375	178.4284	450
V09A-11	-35.6635	178.4460	450
V09A-12	-35.8000	178.5403	450
T09A-05 beginning	-35.6991	178.4697	1200
T09A-05 end	-35.7651	178.5095	-
T09A-06 beginning	-35.7443	178.4693	1000
T09A-06 end	-35.7322	178.5228	-
X09A-05	-35.7197	178.4831	200
X09A-06	-35.7551	178.5090	1000
X09A-07	-35.7810	178.5275	1000
X09A-08	-35.8348	178.5627	1000
X09A-09	-35.7173	178.5684	1000
X09A-10	-35.7588	178.4182	1000
X09A-11	-35.7491	178.4462	1000

Table 1: Position and maximum depth of the CTD, XBT and tow-yo casts. Vertical CTD casts are denoted by V, tow-yo casts with a T and XBT casts with a X.

Results

Hydrography

The depth of the isotherms fluctuate more over the summit of the volcano than over its flanks though this is probably a function of the higher spatial resolution of sampling over the summit compared to over the flanks (Figure 2). Over a larger spatial scale across the whole of both transects the isotherms dip down over the summit and trend upwards either side over the flanks. This is seen especially well in the isotherms between 12°C and 16°C. The depth of the isopycnals and isohalines along both transects show the same pattern. Fluctuations in

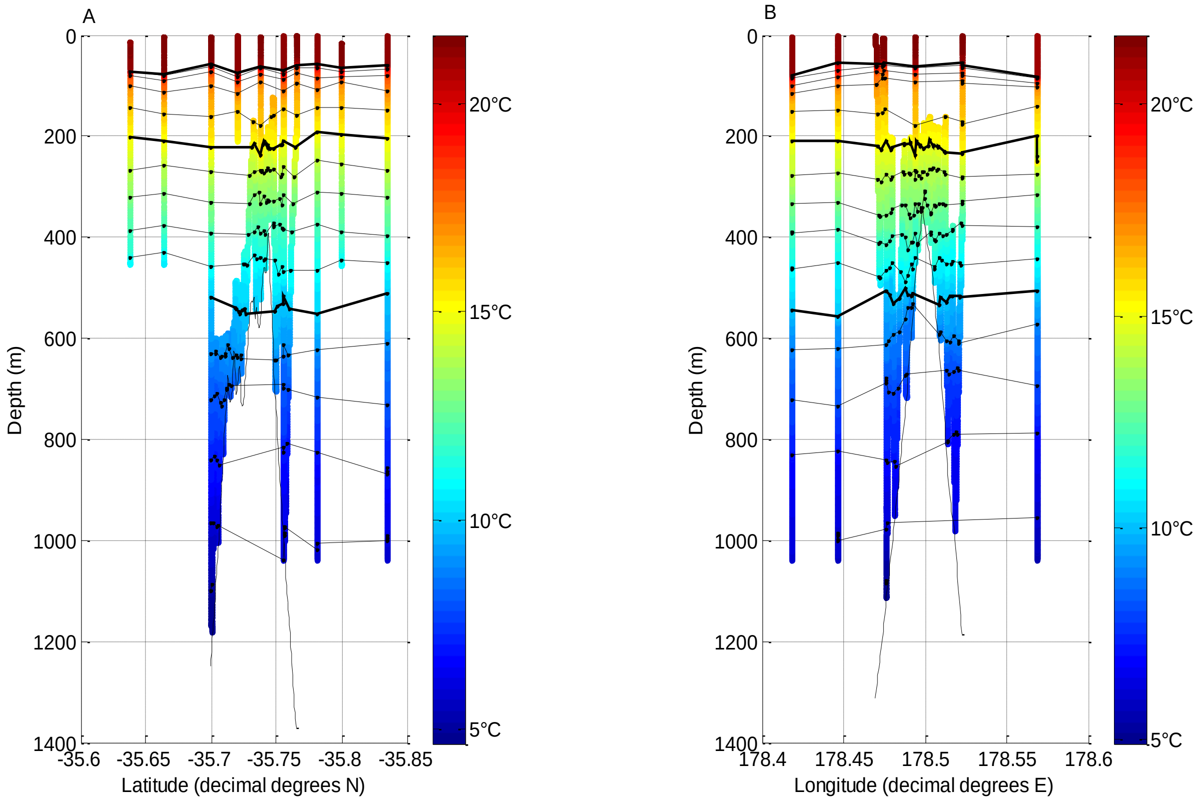


Figure 2: Depth of isotherms along (A) Transect 1 and (B) Transect 2. Contour intervals are 1°C and range from 6°C to 20°C. Isotherms highlighted in bold are 20°C 15°C and 10°C.

the isotherms appear throughout the water column and range from approximately 10-33m in height. A sharp spike in the depth of the isotherms is seen at -35.76°N along Transect 1 where a tow-yo and a XBT cast were conducted at different times and record different temperatures at the same point in space. The size of this spike ranges from approximately 9-21m in height and this height changes with depth.

Nutrients and Oxygen

The range of nutrient concentrations increased with depth with the silicate concentration ranging from 3.37 to 6.07 µmol L^{-1} at the surface and 6.53 to 9.96 µmol L^{-1} at 350m depth. The general spatial distribution of silicate is similar at all 3 depth sampled with relatively lower concentrations over the summit of the volcano and relatively higher concentrations over

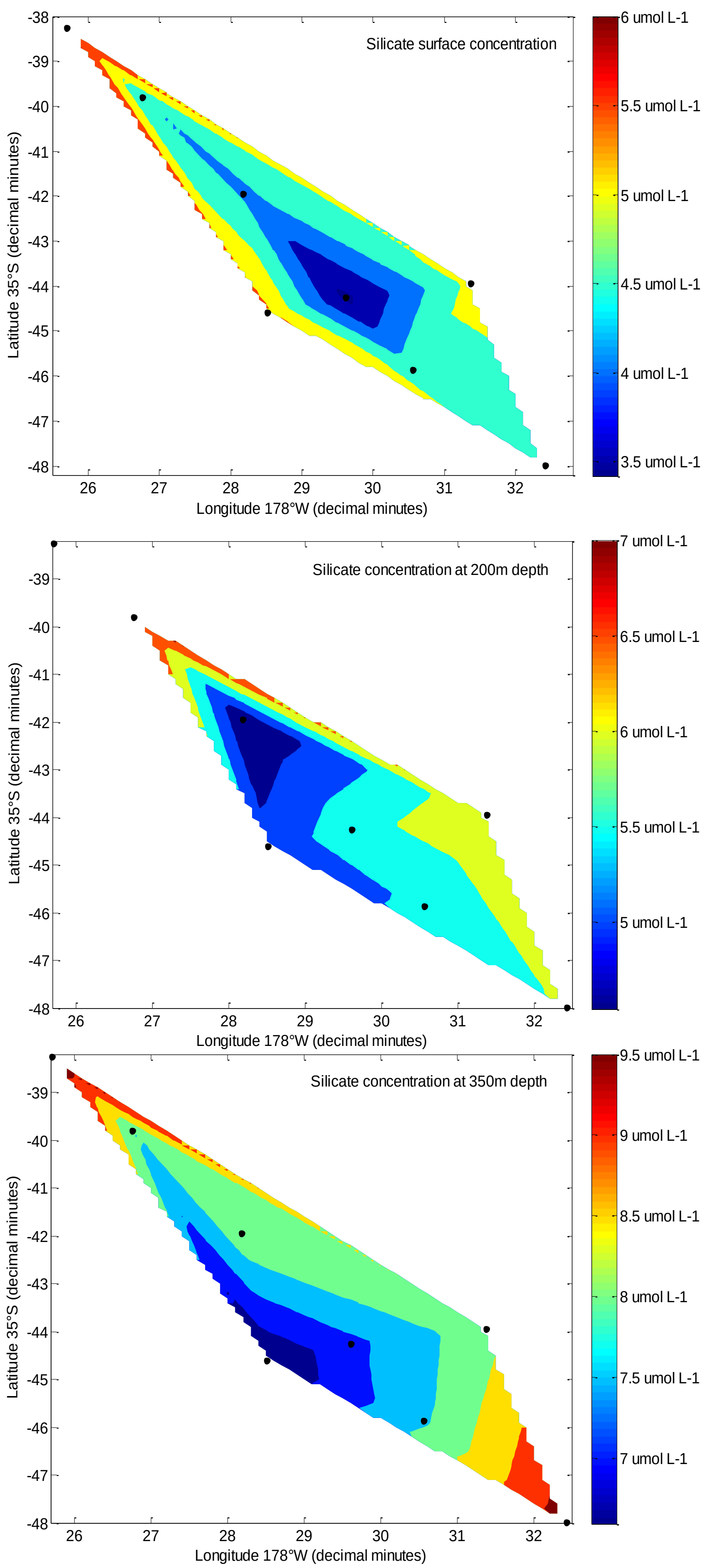


Figure 3: Distribution of silicate concentration at the surface, 200m and 350m depth. Black circles mark where samples were taken along the two transects. The summit of Rumble III is situated at the intersection of the two transects.

the flanks (Figure 3). Nitrate concentrations had the same relationship with depth as silicate (Figure 4) and a similar spatial distribution. Oxygen concentrations had an inverse relationship with depth when compared to silicate concentrations (Figure 4) and an inverse spatial distribution with relatively higher concentrations occurring over the summit and relatively lower concentrations over the flanks.

When tracing the depth of the 13°C isotherm and the corresponding oxygen concentration a relationship is found (Figure 5). When the 13°C isotherm is shallower/deeper the oxygen concentration is lower/higher. As nitrate and silicate concentrations are seen to be inversely related to oxygen concentrations it is reasonable to assume that higher nutrients concentrations will be found when the 13°C isotherm is shallower.

Changes in the oxygen concentrations can also be found along Transect 1 and T09A-06 with a general decrease in

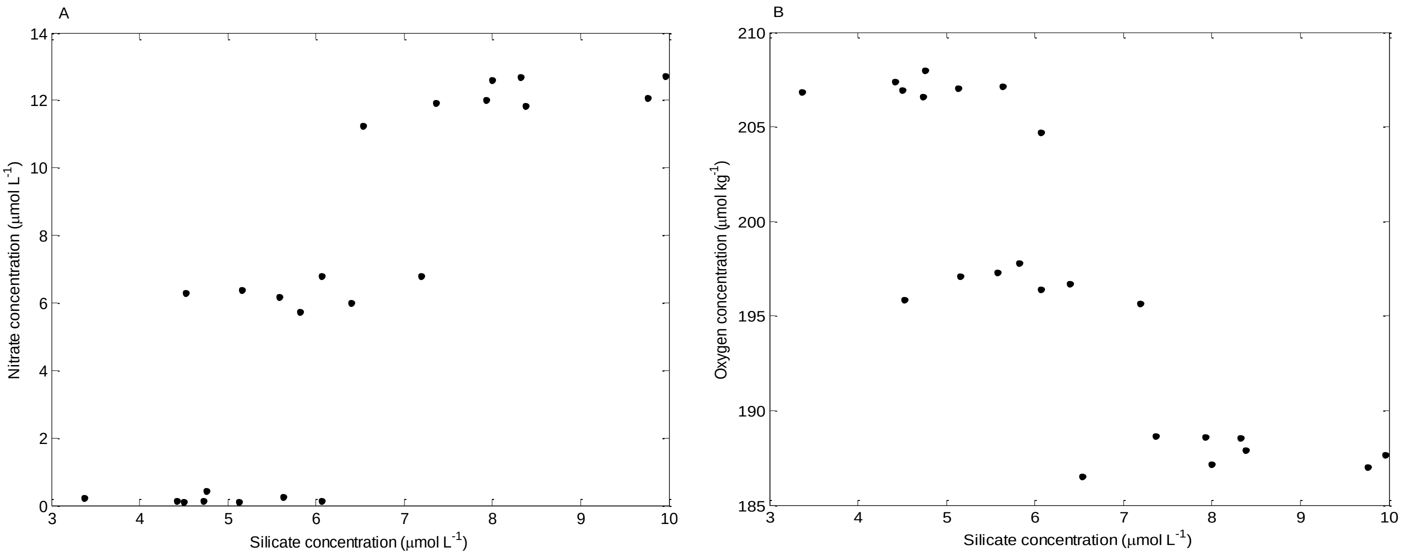


Figure 4: Relationship of (A) silicate and nitrate concentrations and (B) silicate and oxygen concentrations. Samples were taken at the surface, 200m and 350m along Transect 1 and T09A-06.

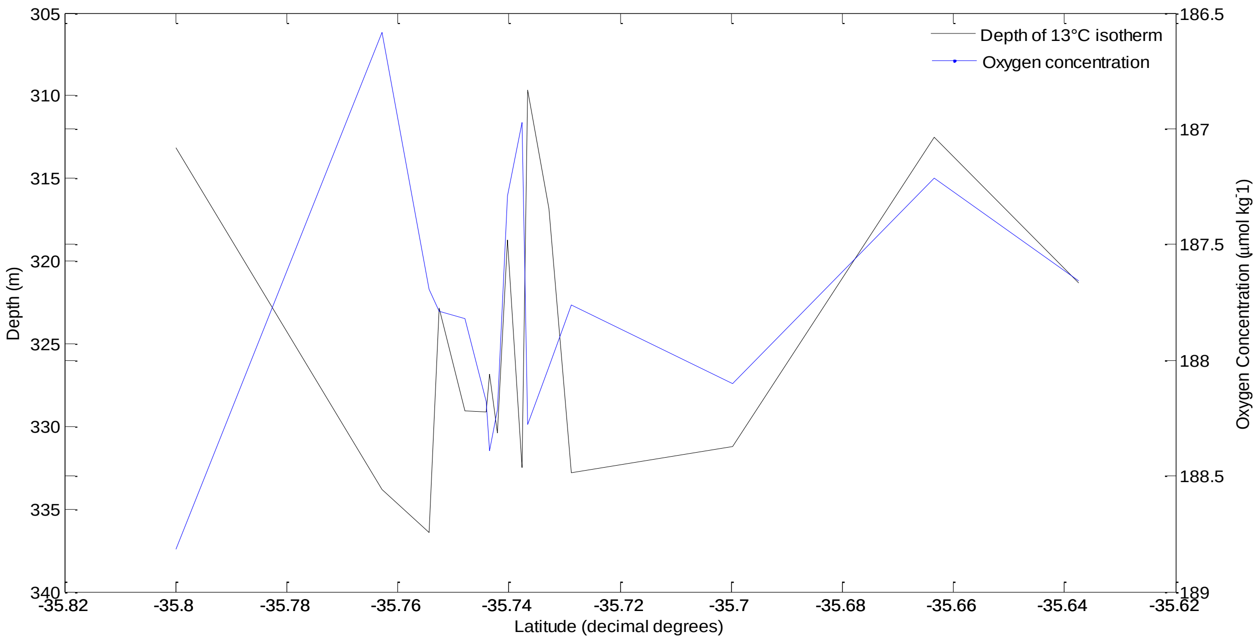


Figure 5: Relationship of the depth of the 13°C isotherm and the oxygen concentration at that depth.

concentration with depth (Figure 6). However anomalies can be seen at 100m depth in the thermocline, at 250m depth over the summit and between approximately 750m and 900m depth.

Currents

The satellite altimetry image shows that at the location of Rumble III the major current is flowing northwest (Figure 7). This is part of the permanent East Cape Eddy (Roemmich and

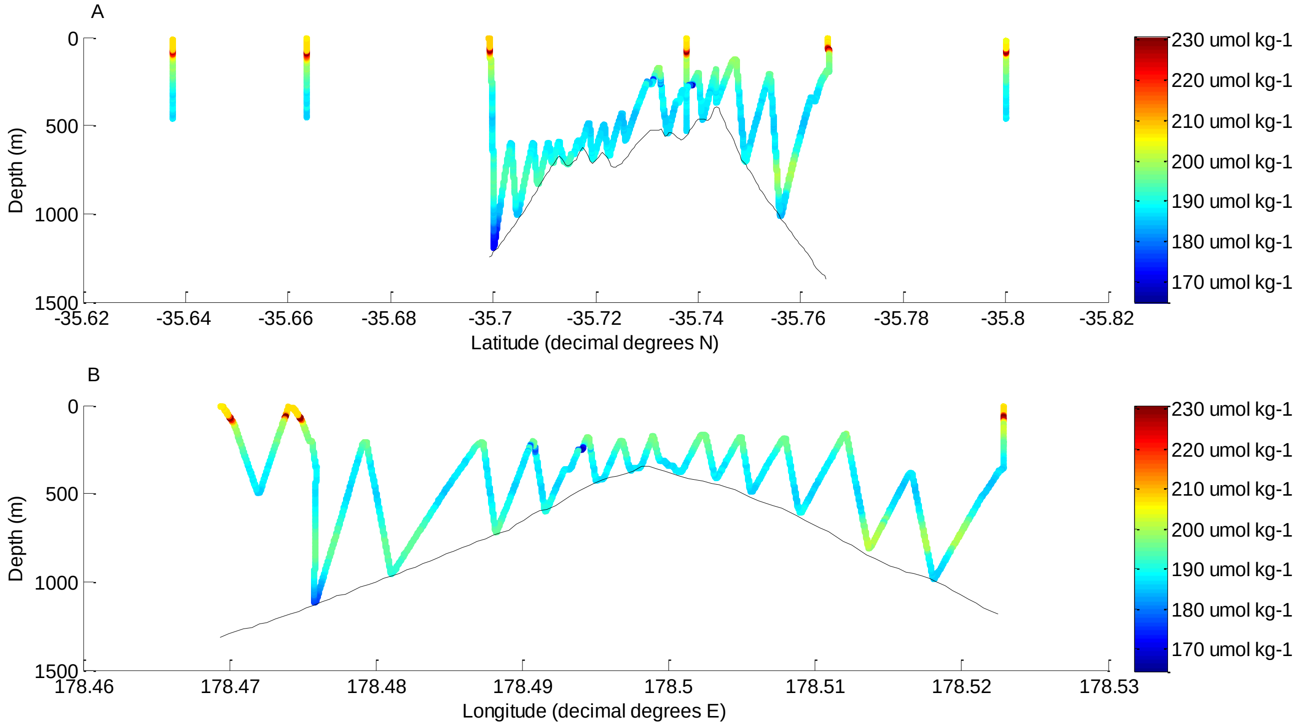
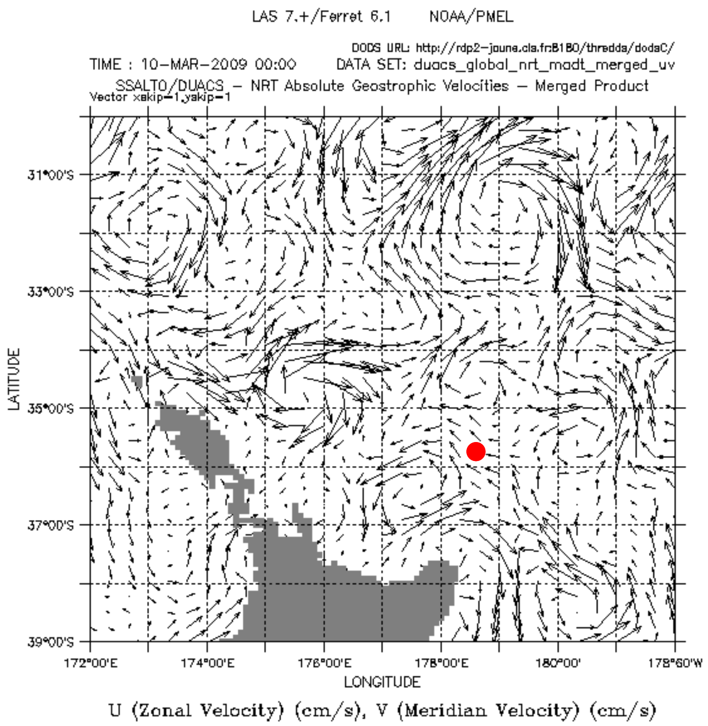


Figure 6: Distribution of oxygen concentration with depth along (A) Transect 1 and (B) T09A-06.

Sutton 1998) and its presence over time will allow features in the flow around Rumble III to occur.

Maximums in the baroclinic meridonal and zonal velocities are seen every 12 hours throughout the time series at Rumble III (Figure 8). Focusing on the baroclinic velocities along Transect 1 flow is generally to the northwest above 200m and to the southeast below (Figure 9). The velocities recorded during T09A-06 show a similar pattern (Figure 10).



Several isolated areas of very strong flow are seen to the southeast at -35.72°N and 600m depth (Figure 9) and to the northeast at 178.485°E and 550m (Figure 10) though this is only seen in one profile. Fast flows are also seen

Figure 7: Satellite altimetry data of absolute geostrophic velocities north of New Zealand on the 10th March 2009. The red circle shows the location of Rumble III.

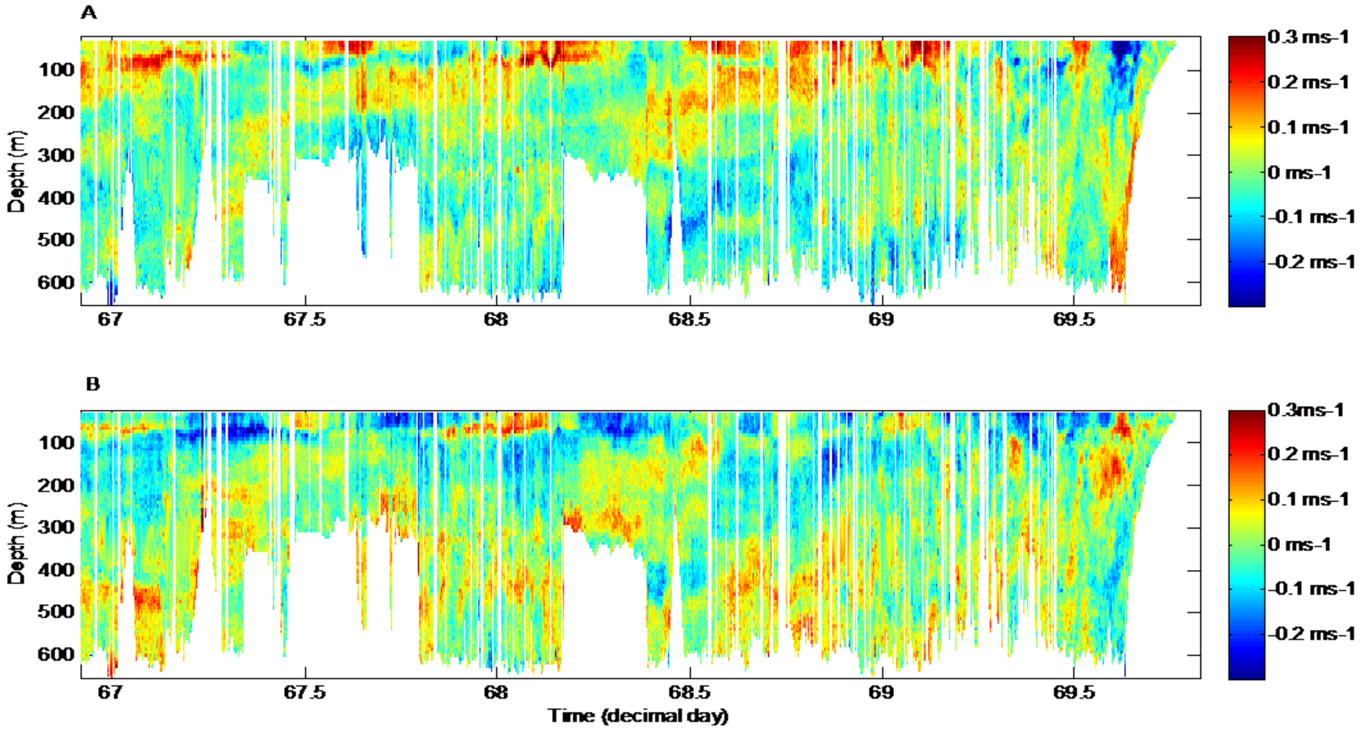


Figure 8: ADCP plot of the (A) meridonal and (B) zonal baroclinic velocities for the Rumble III time series. Velocities are averaged over 32m.

over the summit and western flanks of Rumble III (Figure 9 and 10).

Between 350m and 400m depth the currents appear to change direction either side of the volcano (Figure 9 and 10). Moving from the northwest to the southeast along Transect 1, the direction of flow changes from southeast to southwest (Figure 11). The direction of flow is mostly to the east, east of the summit and more southeast, west of the summit along T09A-06 (Figure 11). Overall these changes suggest a cyclonic pattern to the flow which is detectable between 330m and 470m depth and increases in speed with depth.

Discussion

Upwelling and downwelling

The fluctuations in the isotherms, isopycnals and isohalines around Rumble III suggest that the upwelling of colder, denser water and the downwelling of warmer, less dense water does occur in the region. The general pattern seen is upwelling over the flanks of the volcano with downwelling happening over the summit. The fluctuations are more frequent over the summit though this is probably due to increased spatial resolution of sampling from the tow-

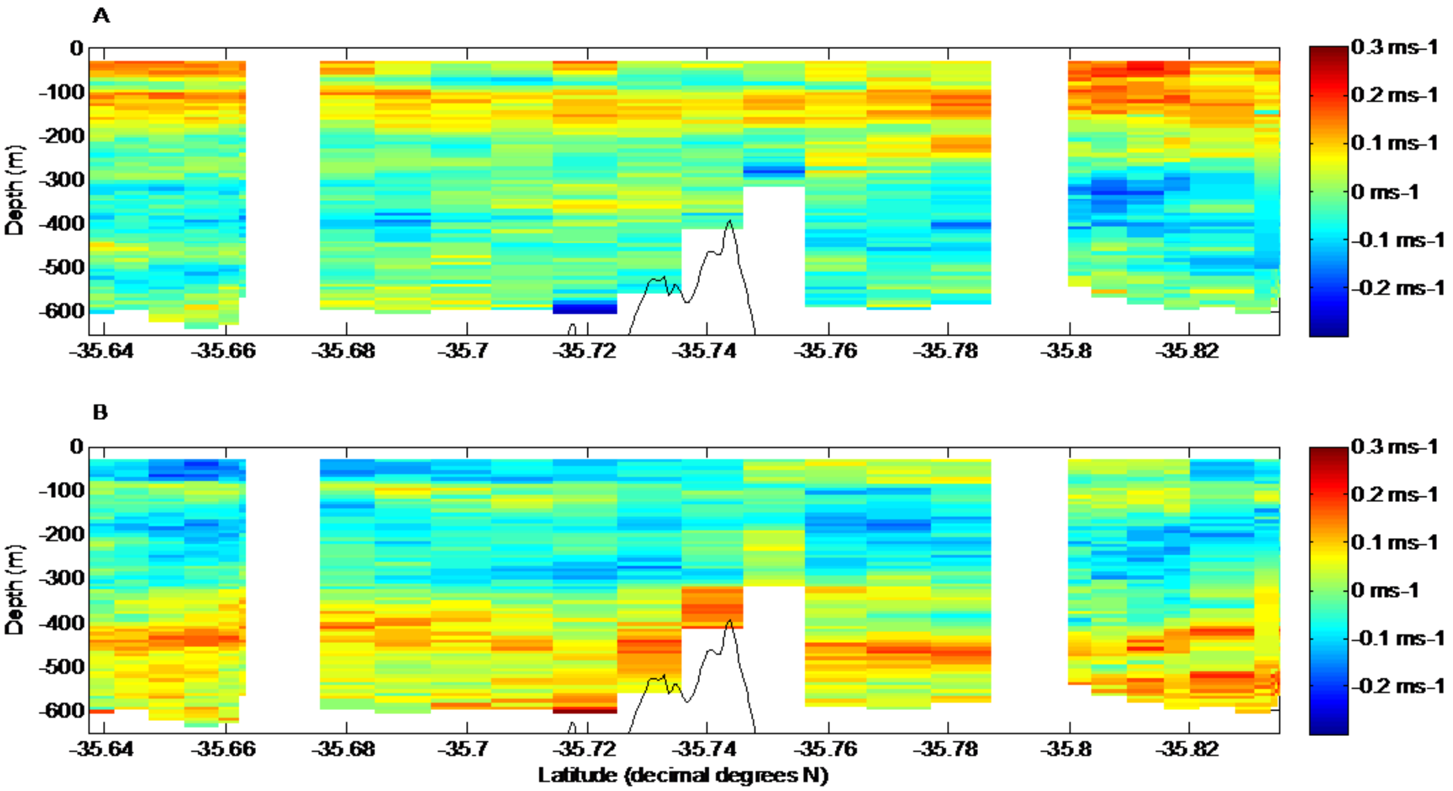


Figure 9: ADCP plot of the (A) meridonal and (B) zonal baroclinic current velocities recorded along Transect 1. Velocities are averaged over 32m.

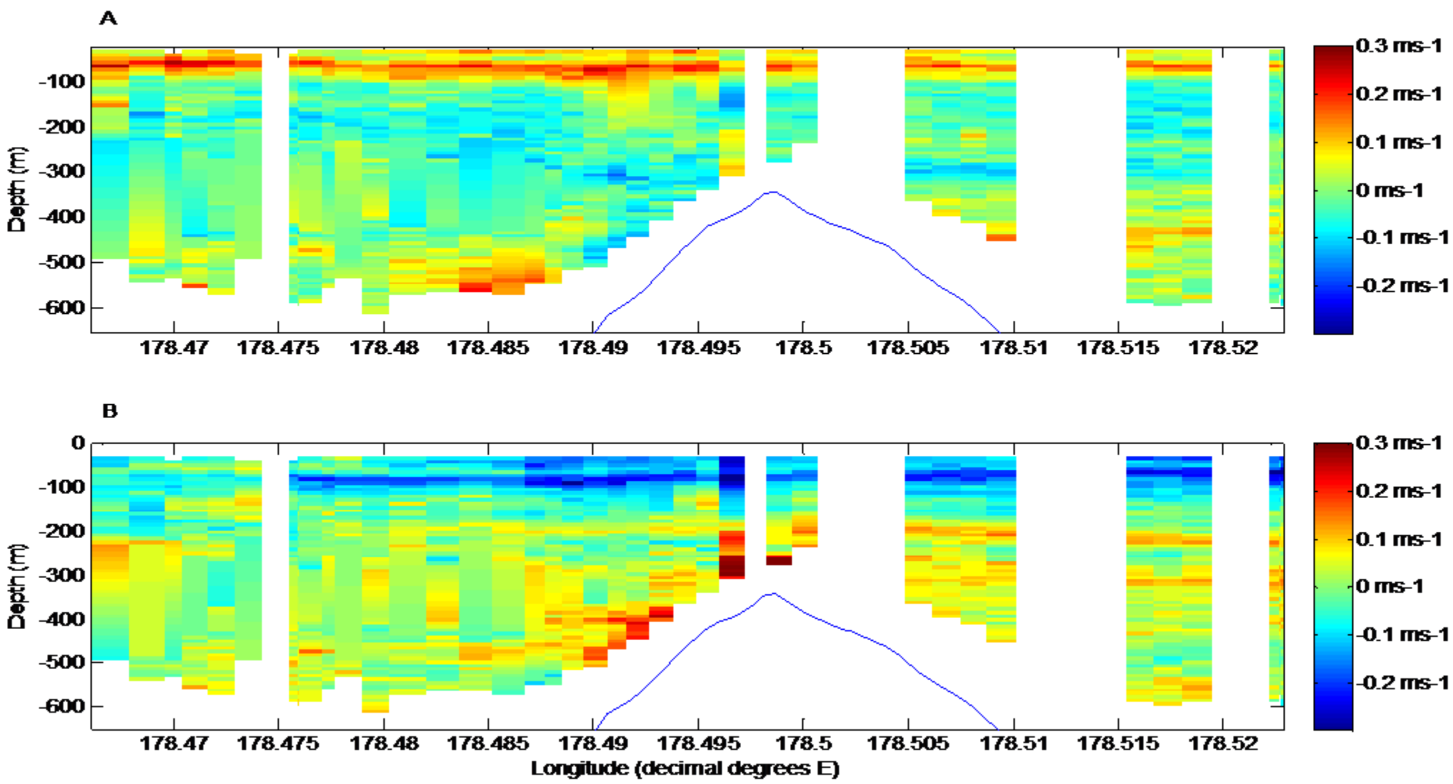


Figure 10: ADCP plot of the (A) meridonal and (B) zonal baroclinic current velocities recorded during T09A-06. Velocities are averaged over 32m.

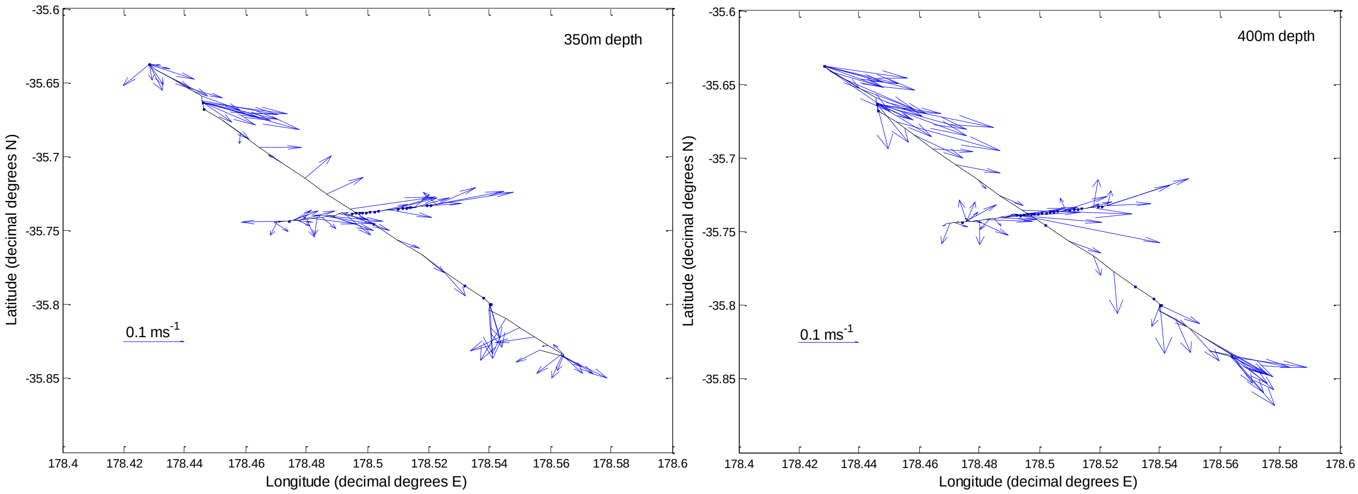


Figure 11: Vector plots of baroclinic velocities recorded along Transect 1 and T09A-06 at 350m and 400m depth. The location of the summit of Rumble III is located where the two transects intersect.

yo casts. The scales of the fluctuations over the summit are smaller than those found over the flanks.

Fieberling Seamount is a good seamount to use as a comparison to Rumble III as both the seamounts lie at the same latitude though the summit of Rumble III is 128m shallower than the summit of Fieberling Seamount. The width of the uplift of isotherms over the flanks of Rumble III are similar to those found at Fieberling Seamount (Lavelle 2006; Roden 1991) being 18 km and 20 km respectively. The height of the vertical displacement of the isotherms is much smaller at Rumble III. At Fieberling Seamount Roden (1991) found the vertical displacement of isotherms to be 40m whereas at Rumble III isotherms are displaced by 10-20m. However, the scales found at Rumble III may have been found to be larger with a larger survey area. The degree of stratification of the water column will influence the degree of uplift of isotherms with stronger stratification inhibiting the size of the vertical displacement. The difference in the scales of the uplift of isotherms between the seamounts may be explained by a difference in the stratification of the water column at the different depths of their summits. Roden (1991) found the upwelling cones above Fieberling summit extended up 120-240m. Fluctuations in the isotherms extend upwards from the summit of Rumble III to approximately 75m depth giving an upwelling cone height of 235m which is comparable to those at Fieberling Seamount. The model run by Lavelle (2006) found upwelling cones of 140m in height and a vertical displacement of 20m. The Brunt-Vaisala frequency (N) used by Lavelle (2006) was $5 \times 10^{-3}\ s^{-1}$ which is similar to N at Rumble III which was calculated to be $4.7 \times 10^{-3}\ s^{-1}$. Both these values are for the upper 1000m of the water column. The similar N values suggest that the stratification of the water column is similar in the model by Lavelle (2006) and at Rumble III. Thus the size of the displacement of isotherms will be similar or slightly larger at Rumble III as described above.

Further evidence of upwelling and downwelling is found in the relationship of nutrients and oxygen concentrations with fluctuations in the depth of the isotherms. Upwelling over the flanks brings higher nutrients and lower oxygen up to shallower depths and downwelling over the summit brings lower nutrients and higher oxygen to deeper depths. Similar spatial patterns were seen at Fieberling Seamount (Roden 1991, 1994). However, the circulation is not the only factor that influences the distribution of nutrients and oxygen. Relatively lower nutrients and higher oxygen concentrations may occur through relatively higher primary productivity. From the distribution of oxygen with depth the highest oxygen concentrations are in the thermocline and not at the surface so the relatively nutrient and higher oxygen concentrations at the surface are more likely to be caused by the circulation. This observation coupled with the uplift of isotherms in the thermocline suggests that upwelled water may act as a nutrient source for photosynthetic organisms. Primary production may also be increased by the presence of the volcano increasing the stability of the water column as discussed by Comeau et al. (1995).

Another factor is the difference in concentrations of nutrients and oxygen between water masses. The deep oxygen maximum seen along Transect 1 and T09A-06 is found at the same depth as a deep oxygen maximum seen on section P14 of the World Ocean Circulation Experiment (WOCE). This is an intrusion of the low salinity, high oxygen Antarctica

Intermediate Water (AAIW) mass which is detectable at low and mid latitudes throughout the Southwest Pacific at intermediate depths (Qu and Lindstrom 2004).

Mechanisms for upwelling

The time series of baroclinic velocities show the presence of internal tides as a maximum in current velocities occur every 12 hours. These internal tides may be generated by the Kermadec Ridge or by the volcanoes located along the Kermadec Arc. A vertical displacement of 4-5m was found to be caused by internal tides generated by the Kermadec Ridge (Chiswell and Moore 1999). This amplitude is too small to have caused the 10-26 m isothermal displacement seen at Rumble III though the internal waves in question were recorded below 2000m. Althaus et al. (2003) reported isopycnal displacements of 12-20m at internal tides generated by Mendocino Ridge at a much shallower depth than along the Kermadec Ridge. The cast X09-09 was cast 15 hours after T09A-05 but was cast at a location

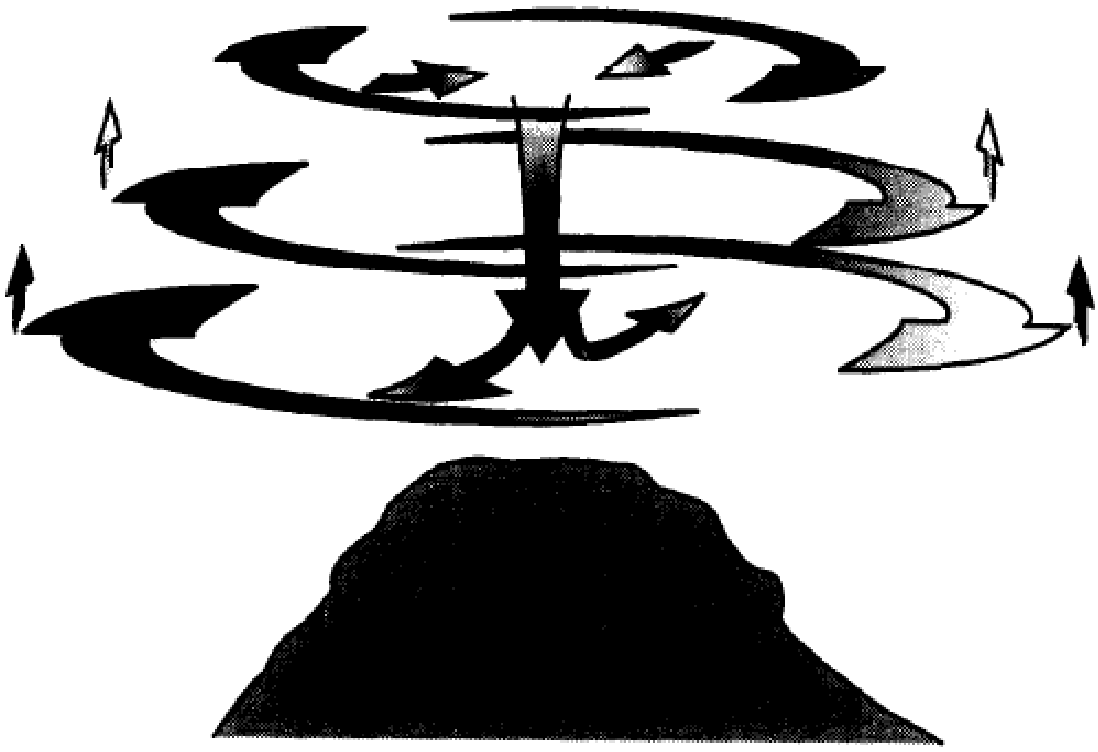


Figure 12: A schematic of the tidally rectified circulation cell over a seamount. Downwelling occurs over the summit with upwelling occurring over the flanks. Taken from Fig. 3 Mullineaux and Mills (1997). Diagram is not to scale.

that the tow-yo T09A-05 passed through. The difference in the temperatures recorded by the two casts causes a vertical displacement of the isotherms ranging from 9-22m. Though these casts were conducted at different times in the tidal cycle and the displacement could be a result of internal tides the majority of the spatial patterns at Rumble III are probably caused by a different mechanism.

From the pattern of uplift and dipping of isotherms a different mechanism for upwelling and downwelling is more probable. From data gathered by Roden (1991), Mullineaux and Mills (1997) discuss the presence of a tidally rectified circulation cell above Fieberling Seamount (Figure 12). This model shows upwelling over the flanks of the seamount and downwelling over the summit with lateral flow outwards from the summit and an increase in speed of the clockwise currents with depth. The uplift and dipping of isotherms and the accompanying spatial distribution of nutrient and oxygen concentrations are consistent with this mechanism. Also, cyclonic flow that increases in speed with depth is seen especially well along Transect 1. This is not so obvious along T09A-06 but as Mullineaux and Mills (1997) discuss the circulation cell is shed from the seamount and a new one set up in a different position as the impinging currents change over time. This may explain why circular flow is seem in one transect but not the other. Though cyclonic flow is seen above Rumble III and anticyclonic flow is described in the model (Lavelle 2006; Mullineaux and Mills 1997) Roden (1994) found many occurrences of paired cyclonic and anticyclonic eddies over the seamounts in the Fieberling Group.

The circulation cell was also found by Lavelle (2006) and Smith (1992) in a numerical model of Fieberling Seamount. This circulation cell is approximately 200m thick in the model which is comparable to the clockwise flow found at Rumble III which is 140m thick. The horizontal scales are also similar. In the model the cell is approximately 24 km wide and is approximately 20 km wide at Rumble III.

Though this circulation cell does result in upwelling Mullineaux and Mills (1997) state that over the whole region there is no net upwelling of nutrients and so primary productivity is not likely to be increased relative to areas further away from the influence of the volcano. However, the cell is likely to cause aggregation of larvae and provide a greater flux of detritus to benthic communities through the downwelling at the center of the cell (Mullineaux and Mills (1997).

Conclusion

The presence of Rumble III causes fluctuations in the depths of the isotherms and changes in the circulation structure. Upwelling occurs over the flanks of the volcano with downwelling occurring over the summit. The spatial distribution of nitrate, silicate and oxygen concentrations supports this upwelling and downwelling pattern with higher nutrient and lower oxygen concentrations occurring where there is upwelling and the inverse occurring where there is downwelling. As the fluctuations are seen in the thermocline it is highly likely that relatively higher nutrient water is brought into the euphotic zone possibly acting as a nutrient source.

Although internal tides are present in the region the pattern of upwelling and downwelling with the cyclonic flow in the region of the summit of the volcano is suggestive of a tidally rectified circulation cell. This circulation does not result in the net upwelling of water but the localize upwelling over the flanks may increase primary production by increasing nutrient concentrations over the flanks. Also the circulation cell does have retentive characteristics which are important for larvae distributions and the flux of detritus to benthic communities may be increased by the downwelling in the center of the cell. Over time the presence and location of this cell will change as the impinging flows on the volcano change. Changes in this circulation cell between seasons may be significant as the degree of stratification of the water column affects the magnitude of vertical displacement of water. Also the larger scale circulation around Rumble III and any possible interactions with the other volcanoes on the Kermadec Arc remains to be investigated.

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