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An introduction to the physical oceanography of six seamounts in the southwest Indian Ocean

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ABSTRACT

Exploratory surveys of six seamounts in the Southwest Indian Ocean provide a description of physical processes induced by seamounts along the Southwest Indian Ridge. Mean currents (15–25 cm s^{-1}) in the vicinity of each seamount were dominated by mesoscale eddies. The dominant seamount-driven process was the generation of internal tides by the barotropic tide interacting with the seamount crests. This led to enhanced shear in the vicinity of the crests resulting in mixing where stratification was weak, for example in the core of an anticyclonic mesoscale eddy or where there had been a winter mixed layer. Tidally driven up- and downwelling was observed at the seabed with associated variability in bottom temperature of up to 3 °C over a tidal cycle. Vertical displacement of isopycnals by internal tidal waves reached 200 m peak to trough. Fluorescence in the surface (eutrophic) layer could thus extend down to the seamount crest on each tidal cycle. Apparently spatial variations in short conductivity/temperature/depth sections across each seamount were probably aliased temporal variations from the strong tidal signal. Evidence for Taylor caps or other potential trapped circulations at the seamount crest was weak, most likely because currents associated with mesoscale eddies were too strong to allow their formation.

1. Introduction

Seamounts are isolated topographic features, rising relatively steeply from the deep-sea floor. Such features impact ocean circulation, interacting with large-scale flows, converting ocean tidal energy to smaller scales, and creating turbulence that affects local and global circulation as well as impacting on biological response. Seamounts have been hypothesised to be hotspots of biological biodiversity and productivity (Clark et al., 2010; Rogers, 1994; Rowden et al., 2010) and the physical processes associated with seamounts are thought to impact the local fauna and flora in several different ways. Many of the paradigms have been questioned (Genin and Dower, 2007; Rowden et al., 2010) and the evidence is mixed (White et al., 2007), but there is little doubt that physical oceanography can play an important role in the distribution of fauna and flora (Genin, 2004; Shank, 2010). Therefore, when a first investigation took place into the deep-sea biology of selected seamounts of the Southwest Indian Ocean, physical observations were made as well. Acoustic studies of fish and zooplankton distribution and bathymetric swath mapping were made alongside measurements of upper ocean currents and full depth profiling of physical parameters. Because of the constraints imposed by multi-disciplinary collaborative work, the physical oceanography measurements were sufficient to provide a description of some of the likely processes operating but were inadequate to fully quantify them.

Physical processes induced by seamounts and their biological consequences have been recently reviewed (Lavelle and Mohn, 2010; White et al., 2007), so need be only briefly introduced here. The passage of a steady current over a seamount can induce a Taylor column or cap, an isolated region of water trapped above the topography (Hogg, 1973) which has been hypothesised to influence the distribution of biota by retention of plankton over the summit (White et al., 2007). If currents are too large, a Taylor cap will not form. Seamounts are also impacted by periodic flows, with semidiurnal tidal oscillations dominating the Nansen observations. Because these tides have a shorter period than the local inertial period (18–23 h at the seamounts observed during Nansen, Table 1), they can exist as free internal waves. Thus the barotropic (depth independent) semidiurnal tidal flow, impinging on the seamount topography, generates internal tides, leading to vertical motions and possibly mixing in the vicinity of the seamount.

Substantial internal tides can be generated over rough topography such as ridges and seamounts. These internal tides play an important role in deep ocean mixing. The global thermohaline circulation results from the balance between sinking cold water in polar regions and the mixing upwards of cold water at lower latitudes. The global energy requirement for this mixing is about 2 terawatts (1

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Table 1
Surveyed seamounts.

Seamount		Atlantis	Sapmer	Middle of What	Coral	Melville	Walter
Latitude	°S	32.6–23.9	36.7–37.0	37.8–38.1	41.3–41.6	38.3–38.6	31.5–31.8
Longitude	°E	57.1–57.5	51.9–52.3	50.2–50.6	42.7–43.1	46.5–46.9	42.6–43.1
Mean latitude		32° 42' S	36° 51' S		41° 25' S	38° 28' S	31° 37' S
Mean longitude		57° 16'E	52° 9' E		42° 51' E	42° 49' E	42° 49' E
Minimum Depth	m	750	350	1100	200	100	1250
Date occupied	2009	17–19 Nov	22–24 Nov	25–27 Nov	2–4 Dev	7–10 Dec	12–13 Dec
Day of year	2009	321–323	326–328	329–331	336–338	341–344	346–347
Speed	cm/s	12.9	21.4	25.2	17.4	10.8	20.3
Direction	degrees	60	90	74	84	61	80
Height of seamount (h_0)	m	1650	1650	900	1800	2000	750
Depth of water column (H)	m	2400	2000	2000	2000	2100	2000
Alpha (α)	h_0/H	0.69	0.82	0.45	0.90	0.95	0.37
Seamount width (L)	km	27.8	27.8	27.8	27.8	15.0	33.4
Flow speed (U)	m/s	0.13	0.21	0.25	0.17	0.11	0.2
f ($2\omega\sin(\text{lat})$)	10^{-5} rad/s	7.9	8.8	9.0	9.7	9.1	7.6
Inertial period	h	22.1	19.8	19.4	18.0	19.2	23.0
Rossby number (Ro)	U/(fL)	0.059	0.088	0.101	0.065	0.079	0.080
Blocking factor (Bl)	α/Ro	11.7	9.4	4.5	13.8	12.0	4.7
Brünt-Väisäla frequency (N)	rad/s	0.0044	0.0014	0.0028	0.0035	0.0030	0.0057
Decay height (Hd)	fL/N	498	1737	891	767	458	446
Rossby radius of deformation (Lr)	(NH)/f	133.9	32.0	62.4	72.5	694.1	149.6
Burger number (B)	(NH)/(fL)	4.82	1.15	2.25	2.61	4.63	4.49

terawatt $=10^{12}$ W) (Garrett, 2003). Analysis of altimetric sea surface height shows the western Indian Ocean to be a region of enhanced dissipation, in particular the Mascerene and Southwest Indian Ridges and the Madagascar Plateau are major source regions (Egbert and Ray, 2001). Therefore it is important to understand the role seamounts play in interacting with tides and the generation of internal waves that dissipate tidal energy through the mixing and vertical redistribution of heat in the water column.

In this paper, we overview the circulation of the Southwest Indian Ocean then examine the physical behaviour at each seamount. Finally, we summarise the evidence for several processes: Taylor columns; rectified flow; generation of internal tides and mixing. We begin by introducing the data collected.

2. Data

The data described here were collected during the RV *Dr Fridtjof Nansen* cruise 2009 410, between 12 November and 19 December 2009 (Rogers et al., 2009). The objectives of the cruise were to understand the pelagic biology and physical oceanographic setting of seamounts on the Southwest Indian Ocean Ridge as part of a larger project to investigate seamount benthic communities, coral diversity and the impact of deep-sea fishing activities (Rogers et al., 2014). Six seamounts were investigated (Fig. 1). Five were along the Southwest Indian Ridge, from north to south these were Atlantis Bank, Sapmer Seamount, Middle of What Seamount, Melville Bank and Coral Seamount. The final seamount was an unnamed feature on the Madagascar Ridge, north west of a large submarine plateau, Walter's Shoals. In this paper we refer to the seamount as Walter Seamount for convenience, but it should be noted that the feature is separate from the plateau and is not officially named.

Physical processes at seamounts are driven by both steady state and periodic flows. To investigate these different flows requires different approaches. In the limited time available, conductivity, temperature and pressure (CTD) sampling consisted of (i) a 24-h CTD yoyo at or close to the seamount summit (with the ship held stationary relative to the seamount) to quantify the periodic flows resulting primarily from tides and (ii) a short, closely spaced, CTD transect across each seamount. Station spacing varied from <1 km to ~ 4 km and was designed around the topography, but transect orientation followed the alignment of acoustic mapping of currents using an acoustic Doppler current profiler (ADCP), zooplankton (with a Simrad EK60 multiple transducer array) and bathymetry (using a Simrad EM710 multibeam echosounder) at the same time (Rogers et al., 2014). Survey alignment was designed to optimise acoustic performance allowing for the prevailing weather conditions at the time of each survey. With the multitude of acoustic instruments, data from the ADCP were occasionally compromised. The CTD transects provided information about water masses, cross seamount gradients and steady or slowly varying flows. Two longer CTD transects, across the major current systems south of Melville and Middle of What Seamounts (Fig. 1) were also undertaken. When combined with satellite altimetry, these provided information about the larger scale circulation (Pollard and Read, 2015).

The CTD data were collected with a SeaBird Electronics SBE 9/11+ CTD and deck unit. All profiles were worked to within a few metres of the seabed. Conductivity was calibrated using samples drawn from twelve 5-litre Niskin bottles and analysed on a Guildline Portasal model 8410 using standard seawater batch number P144. Problems were encountered with the calibration (Rogers et al., 2009), but following post cruise re-processing and calibration, salinity is believed to be good to 0.0003 ± 0.005. A total of 423 stations were worked, the majority during CTD yoyos.

Upper ocean currents were measured throughout the cruise using an RDI Ocean Surveyor 150 kHz ADCP mounted in the ship's hull. The instrument was configured with 100 8-metre bins, of which the top 50 were meaningful. Individual pings were corrected internally for ship's heading using the 1-second NMEA input from the Seatex Seapath 200. Data were averaged internally over 3 min and 20 min. No calibration for misalignment angle was attempted during the cruise. However, the first acoustic survey provided coherent data (with neither convergence nor divergence of a steady, unidirectional, flow) over a grid indicating that any misalignment angle must be small. Current data gathered during the 24-h CTD yoyo period were decomposed into barotropic and baroclinic components. The depth-averaged current formed the barotropic component and the baroclinic component consisted of the deviation from this (Park et al., 2008).

Maps of sea surface height (mean absolute dynamic topography, MADT) were obtained from the Segment Sol multimissions d'ALTimétrie, d'Orbitographie et de localisation precise/Developing Use of Altimetry for Climate Studies (SSALTO/DUACS) multimission altimeter

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