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Dynamical oceanographic processes impact on reef manta ray behaviour: Extreme Indian Ocean Dipole influence on local internal wave dynamics at a remote tropical atoll.

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Phil Hosegood: Conceptualization; Methodology; Investigation; Resources; Data Curation; Writing – Draft, Review, Editing; Supervision; Project Administration; Funding acquisition

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Abstract

1 Physical oceanographic observations were made with subsurface, taut-line moorings at Egmont
2 Island, a tropical atoll within the Chagos Archipelago in the central Indian Ocean, to elucidate the
3 dynamics of near-bed cold-water intrusions implicated in driving local aggregations of reef manta rays
4 (*M. Alfrede*). Manta have been previously shown to aggregate within ‘Manta Alley’, a lipped gully at 65
5 m depth along the north coast, at times when the surface to bottom temperature difference was
6 highest. We here identify the dynamical processes driving these temperature differences and shaping
7 the foraging landscape at Egmont, and equivalent small-scale atolls, improving our understanding of
8 manta behavior at hotspots where they are most vulnerable to exploitation.

9 The thermal regime within Manta Alley is shown to be governed at several spatiotemporal scales. The
10 extreme 2019 Indian Ocean Dipole event drove a depression of the 26 °C isotherm to a depth of 115
11 m precluding the observation of cooling within the alley. As the thermocline shoaled with the change
12 in phase of the IOD, near bed cold water flushing was seen with tidal periodicity within the gully. The
13 internal tide is accompanied by high frequency internal waves with periods of $O(5)$ minutes which are
14 shown to promote mixing through shear instability, evidenced by subcritical Richardson numbers, with
15 surface-seabed temperature differences ~ 4 °C observed throughout a tidal period.

16 Our results highlight a level of heterogeneity in oceanographic dynamics at sub-atoll spatial scales
17 within an environment in which these processes are rarely resolved. Whilst the physical mechanisms
18 through which these dynamics drive foraging within the resident manta population remain unclear,
19 the generation of turbulence by high frequency internal wave events as shown here may influence
20 zooplankton distributions, improving feeding efficiency at discrete locations within atolls. Our results
21 thus highlight the need to account for fine scale changes in oceanographic conditions when
22 attempting to explain habitat utilization by mobile species.

23 1 - Introduction

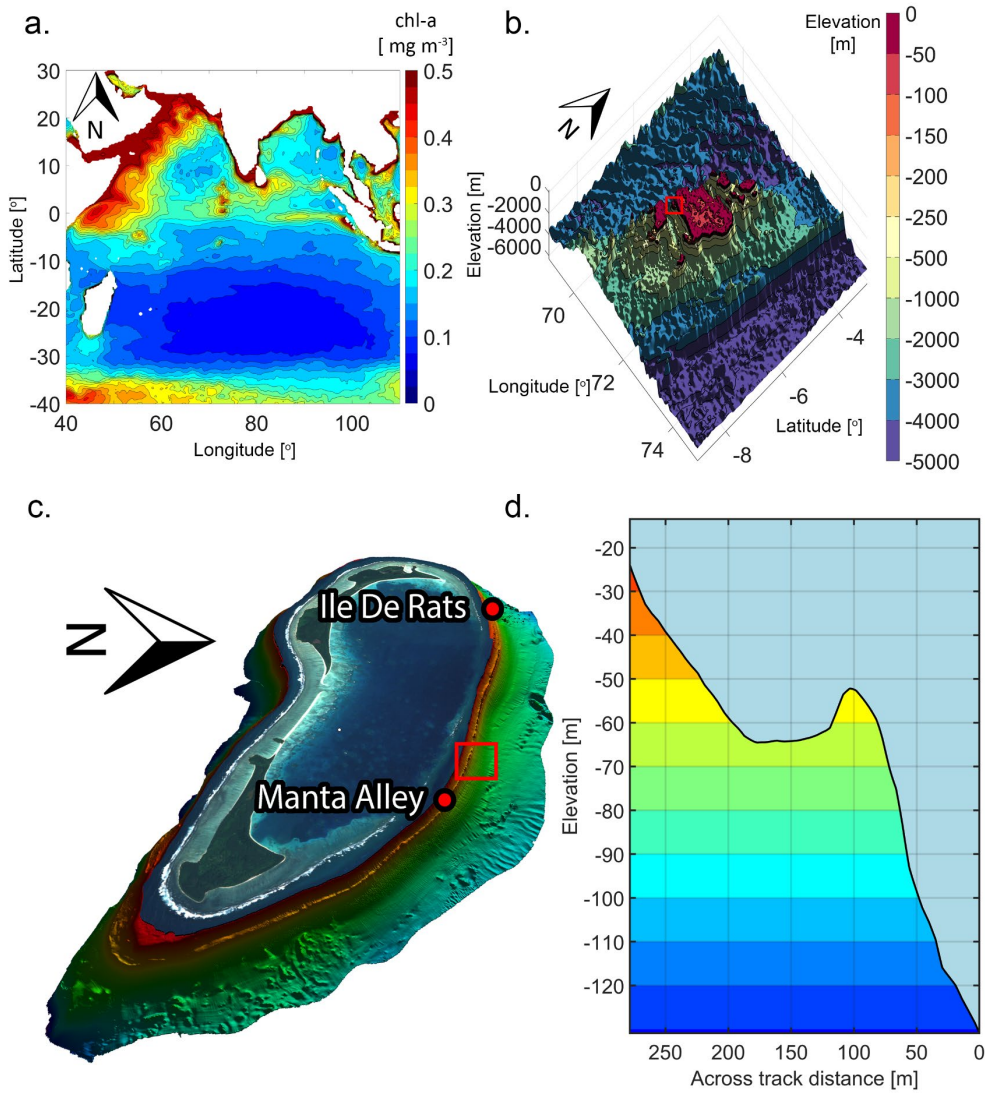
24 Within tropical regions, manta rays are a highly visible, but threatened species for which various
25 protection measures have been implemented regionally. Such measures rarely, if ever, account for
26 the physical drivers that govern their distribution and behaviour; as oceanographic conditions change,
27 manta move into different biophysical habitats at both inter, and sub-atoll scales, raising the likelihood
28 that current location specific protection measures are deficient. At regional scales, manta ray
29 populations have been observed to track elevated levels of primary productivity (Jaine *et al.*, 2014;
30 Weeks *et al.*, 2015; Armstrong *et al.*, 2016, 2019) and coastal populations have been observed to
31 respond to changes in food availability and physical properties of the water column, including
32 temperature, tidal timing, and local current regime (e.g. Rohner *et al.*, 2013; Armstrong *et al.*, 2021).

33 Recent studies have shown that manta exhibit strong site fidelity at local (i.e. single island) scales (Peel
34 *et al.*, 2019; Andrzejaczek *et al.*, 2020) but with variability at sub-tidal timescales (Harris *et al.*, 2021).
35 The mid-ocean atolls inhabited by these populations are characterised by steep slopes (Velmurugan,
36 2015), and are known to promote energetic internal processes, such as internal waves and elevated
37 mixing through turbulent dissipation (Wolanski and Delesalle, 1995; Fu *et al.*, 2016; Rayson *et al.*,
38 2018). Internal waves are capable of advecting cold water upslope over large horizontal and vertical
39 distances (Klymak *et al.*, 2012; Hosegood *et al.*, 2019; Reid *et al.*, 2019), thereby impacting nutrient
40 supply into the photic zone. These dynamics are driven by a range of forcing processes, generally tidal
41 and, in some limited capacity, through wind and atmospheric forcing (Farmer and Armi, 1999;
42 Holloway and Merrifield, 1999; Balmforth and Peacock, 2009; Nikurashin and Ferrari, 2010). The
43 timescale for bottom-up support via nutrient injection is on the order of days, and so the fine scale
44 dynamical variability at these oceanic island habitats, and the comparatively short temporal scales
45 over which a community response is observed (Harris *et al.*, 2021), implies that localised processes
46 generate sites of improved foraging efficiency of zooplankton which the manta exploit at discrete
47 times.

48 Whilst suggestions have been made as to which processes drive aggregation events, there have been
49 limited physical in-situ observations to provide insight into the oceanographic regime over fine scales,
50 with observations typically limited to single point temperature and tidal timings (Armstrong *et al.*,
51 2016; Peel *et al.*, 2019). Prior research efforts have also typically taken a relatively isolated approach
52 to understanding the influence of physical dynamics on the ecosystem, often focusing on a single
53 physical parameter (e.g. tide) without further insight into the resultant fine scale dynamical variability
54 (e.g. Armstrong *et al.*, 2021). This approach results in the inability to identify fine-scale dynamical
55 processes that may act as drivers for manta behaviour, hindering the development of adequate
56 conservation strategies that are typically derived from coarse scale models and remote observations
57 that are unable to account for sub grid scale dynamics occurring locally within atolls. Improving our
58 ability to understand fine scale dynamics will enable the focusing of protection efforts on specific
59 locations which are disproportionately important to host species in terms of residence time and
60 abundance, allowing for more efficient use of monitoring and enforcement resources.

61 In this paper we identify localised hydrodynamics responsible for the differences between the surface
62 and near bed temperatures that have been identified as a dominant indicator of manta aggregation
63 at an atoll in the tropical Indian Ocean (Harris *et al.*, 2021) using moored, high resolution, in-situ
64 observations. Egmont Atoll is a steep sloped atoll within the Chagos Archipelago located within the
65 central Indian Ocean and is the site of the world's second largest no-take Marine Protected Area (Fig.
66 1). Long term remotely sensed observations of chlorophyll-a (Chl-a) highlight a sustained increase in
67 local primary production throughout the archipelago (Fig. 1a). However, the complete picture of
68 primary production is obscured by the concentration of phytoplankton within the deep chlorophyll

69 maximum (DCM) at a typical depth of >50 m corresponding to the base of the surface mixed layer,
 70 rendering it usually invisible to satellite-based sensors. Here we demonstrate that physical processes
 71 at a wide range of spatiotemporal scales act to govern the biophysical regime at Egmont atoll and are
 72 responsible for generating the site preferentiality for resident manta rays shown in Harris et al. (2021)



73 *Fig. 1. a) January 2019 – January 2021 Chl-a mean in the Indian Ocean with the location of the Chagos*
 74 *Archipelago highlighted. Data from CMEMS Biogeochemical hindcast (10.48670/moi-00019) at*
 75 *monthly timesteps. b) GEBCO bathymetry of the wider archipelago with the location of Egmont Atoll*
 76 *annotated c) High resolution multibeam bathymetry of Egmont atoll showing the steep slopes which*
 77 *are greatly underrepresented within the GEBO bathymetry, and d) a representative cross-section of*
 78 *Manta Alley. Inset Landsat image courtesy of the U.S. Geological Survey. GEBCO 2023 Grid*
 79 *(doi:10.5285/f98b053b-0cbc-6c23-e053-6c86abc0af7b) courtesy of GEBCO Compilation Group (2023)*

80 Here we show that the cold water, near-bed intrusions at Egmont are localised and intermittent,
 81 occurring predominantly at tidal periods but with higher frequency waves accompanying the tidal
 82 carrier wave as observed elsewhere (e.g. Hosegood and Van Haren, 2004). We further observe
 83 significant variability in internal wave behaviour and characteristics at different sites separated by
 84 short horizontal distances. Finally, we demonstrate that the depth to which cooling extends is dictated

85 by the prevailing regional conditions where the IOD is responsible for migration of the thermocline at
86 interseasonal time scales.

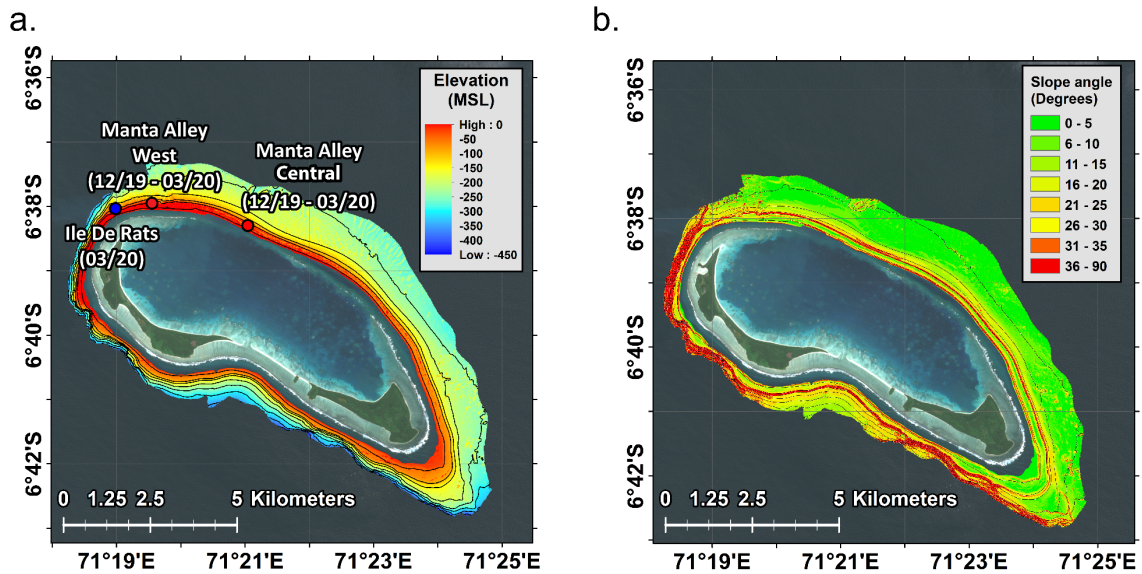
87 This paper is structured as follows; firstly the methodology is presented, including moored in-situ
88 observations, and supporting remotely sensed data and numerical model output. We then briefly
89 explore the characteristics of the dynamical mechanisms that are implicated in driving the
90 temperature differences at both local and basin scales. Results are then presented, beginning with
91 the basin-scale evolution of stratification in response to the extreme 2019 IOD event which coincided
92 with the first research cruise, followed by characterisation of the background tidal environment, and
93 its evolution over the course of the observation period. The impact of the stratification, specifically
94 the evolution of thermocline depth, is considered in relation to local thermal variability at tidal and
95 higher frequencies, as well as the role of high-frequency internal waves in promoting overturning and
96 mixing. The implications of the dynamics in driving the local thermal changes are then discussed, with
97 emphasis on the biophysical impacts likely to be responsible for the aggregations seen in Harris et al.
98 (2021) and their applicability to alternative sites of similar scale which may also be oversimplified by
99 use of remote observations and coarse-scale numerical model output.

100 **2 - Methodology**

101 ***2.1 - Study region and cruise timings***

102 Data were obtained from two research cruises to the Chagos Archipelago conducted during the
103 transition period between the south-east and north-west monsoon. The first cruise spanned the
104 period 13/11/2019 – 03/12/2019 (hereafter referred to as ‘November’) and the second,
105 approximately 4 months later, the period 07/03/2020 – 18/03/2020 (hereafter referred to as ‘March’).
106 Whilst both cruises fell between the monsoon seasons when winds were expected to be light, the
107 prevailing meteorological conditions nonetheless varied; wind direction during November was north-
108 easterly (rather than the expected south-easterly) and predominantly north-westerly during March;
109 below we identify the role played by the especially strong IOD influence during November in
110 generating the unusual wind direction. Air temperature in November averaged 28.5 °C, whilst March
111 was warmer on average at 29 °C.

112 The specific geographic focus of this paper is constrained to Egmont (Fig. 2), an atoll on the
113 southwestern flank of the archipelago, approximately 9 km south of Great Chagos Bank (GCB). The
114 channel between Egmont and Great Chagos Bank on the north-eastern flank of Egmont is 200-300 m
115 deep, with the drop-off to the south being considerably deeper, extending to over 1000 m depth. The
116 steep slopes, which routinely exceed 30° at depths <150 m, surrounding Egmont (Fig. 2b) are
117 characteristic of similar volcanic islands (Velmurugan, 2015) and present a challenge to the
118 deployment of subsurface moorings that may slip down the slope. Additionally, vessel-based acoustic
119 Doppler current meter (ADCP) measurements are challenging due to the obstruction of one or more
120 beams by the seabed when sampling close to the atoll flanks.



121 *Fig. 2. a) Top-down view of Egmont with bathymetry overlaid on Landsat true colour imagery, indicated*
 122 *are the locations of mooring deployments with long-term moorings marked in red, and short-term*
 123 *moorings marked in blue. b) Local slope map of Egmont atoll calculated at 1 m cell size from multibeam*
 124 *bathymetry. Note the steep slopes which fringe the atoll and the comparatively flat slope within the*
 125 *gully of Manta Alley on the northeast flank. Landsat imagery courtesy of the U.S. Geological Survey.*

126 The atoll is elliptical and approximately 11.0 km along the major axis and 4.3 km along the minor, with
 127 the major axis-oriented west-northwest to east-southeast. Most of the internal area of the island is a
 128 lagoon (8.5 km x 3.2 km) with the primary inlet along the north face of the island. The atoll consists of
 129 shallow reef until approximately 20 m depth, after which the slope steepens, exceeding 40° to depths
 130 of ~200 m to the north and >1000 m on all other slopes. The north face of the atoll is lined with a
 131 lipped gully at approximately 65 m depth, referred to as ‘Manta Alley’ due to regular sightings of
 132 manta along that specific bathymetric feature. Note that Egmont is a spatially distinct atoll separated
 133 from surrounding bathymetric features by deep water; however, the relative proximity of Great
 134 Chagos Bank raises the potential for remotely generated processes to propagate into the area
 135 surrounding Egmont and onto its submarine flanks.

136 **2.2 - Oceanographic Instrumentation**

137 The primary oceanographic measurements presented in this paper were obtained from three sets of
 138 moorings deployed along the north face of Egmont Atoll. The first site consisted of a pair of moorings
 139 deployed in central Manta Alley (Manta Alley – Central); the second site (Manta Alley – West) featured
 140 a mooring located to the northwest at the boundary of Manta Alley and Ile De Rats, and the third site
 141 was further west again at the point where flow exits into deeper water off Ile De Rats (Ile De Rats)
 142 (Fig. 2a).

143 At the central Manta Alley site, one mooring contained a near-bed mounted Nortek Signature (5
 144 beam) 500 kHz acoustic Doppler current profiler (ADCP) housed in an elliptical buoy 2 m above the
 145 seabed. To acquire data relating to changes in temperature throughout the water column,
 146 temperature sensors were mounted on a second mooring located within 200 m of the ADCP. Since
 147 the two moorings are separated by a minimal distance, we consider them as a single entity for the
 148 purpose of our results. The mooring locations were selected due to the proximity to the primary

149 lagoon entrance but fortuitously coincided with the location at which manta presence was highest
150 during the period between cruises.

151 Average currents were monitored during the period between cruises (November 2019 – March 2020,
152 corresponding to 102 days) and estimated from 2 minutes of sampling at 1 Hz every 10 minutes with
153 a 2 m vertical resolution. Additionally, higher resolution burst data (velocity and echosounder) were
154 acquired in 1 m bins at 1 Hz for the first 23 mins of each hour. During March, the ADCP deployed in
155 Manta Alley provided the same average sampling every 10 minutes but also sampled continuously at
156 1 Hz with a 1 m vertical resolution for 7.4 days.

157 RBR Solo³T temperature sensors were spaced at various vertical intervals on the nearby taut-line
158 mooring, with the highest vertical resolution at the thermocline to maximise the ability to resolve
159 small-scale overturns associated with internal wave perturbations. Conductivity-temperature-depth
160 (CTD) sensors were located at the top and bottom of the mooring, enabling the calculation of both
161 final resting depth and checking for any significant knock-down of the mooring, in addition to
162 monitoring changes in water properties due to outflow from the lagoon. Temperature sensors logged
163 at 1 Hz resolution, while each CTD sampled at 0.2 Hz.

164 The Manta Alley – West mooring was approximately 2 km to the northwest of the Manta Alley –
165 Central mooring and comprised a Nortek 400 kHz Aquadopd ADCP sampling in 2 m vertical bins and
166 providing 10-minute velocity averages. Vertical profiles of temperature were obtained from 19
167 Seabird SBE56 sensors sampling at 1 Hz and spaced at various vertical intervals.

168 During March, the Ile De Rats mooring was deployed on the northern edge of Ile de Rats in 65 m water
169 depth (Fig. 2) housing an RDI 600 kHz ADCP and 13 temperature sensors.

170 **2.3 - Quality control & Processing**

171 Thermistor (T) data from the subsurface taut line moorings were merged to create a time series of
172 temperature variability over depth. Moorings with variable thermistor spacing were vertically
173 interpolated to common 2 m vertical intervals for any comparative analysis, and data from the slower
174 sampling CTD sensors and the 19 SBE56 sensors were linearly interpolated to 1 Hz to match the sample
175 rate of the RBR SoloT sensors. Data were cleaned using a 2σ median window filter and a 5-point
176 running average.

177 Data from Nortek Signature series ADCP's was processed using OceanContour for coordinate
178 transformation, cleaning, and quality control on the data. Data correlation threshold was set at 40%
179 due to the challenging nature of the sampling conditions caused by bodies of water with few scatterers
180 as well as a high dynamic range in return signal though the water column. Data from the RDI ADCPs at
181 Ile de Rats were filtered by both signal quality and cut off at a maximum sampling distance. Velocity
182 data were filtered using a running mean window in both dimensions. Data were averaged into 10
183 second ensembles to reduce susceptibility to random noise.

184 **2.4 - Frequency domain analysis**

185 Tidal analysis of currents at the central Manta Alley mooring are based on continuous 10-minute
186 average velocities calculated over 2 m vertical bins. Tidal decomposition was performed using the U-
187 Tide toolbox (Codiga, 2011) and tidal constituents selected as defined in Foreman (1977). Tidal
188 velocity reconstructions were calculated for each ADCP depth bin, excluding any constituent with a
189 signal-to-noise ratio < 2. These predictions were then used to remove the periodic velocity signal,
190 associated here with the barotropic tide, to isolate any non-periodic signals which may be associated
191 with baroclinic motions.

192 To characterise the variance in the observed currents due to periodic, deterministic signals, power
193 density spectra were computed for each ADCP depth bin. The temporal variability in power spectra
194 was further evaluated by use of wavelet analysis using a continuous Morse wavelet transform.

195 **2.5 - Vertical current shear and water column instability**

196 Assessment of the susceptibility of the water column to overturning and mixing by shear instability,
197 which is frequently invoked as a dynamical impact driving a biological response throughout the ocean
198 (Mahadevan, 2016; Hosegood *et al.*, 2019), was estimated by the Richardson number, $Ri = N^2/S^2$
199 where $N^2 = g/\rho_0 \delta\rho/\delta z$, ρ_0 is a reference density taken as the depth mean density from a CTD profile
200 taken in Manta Alley, and $S^2 = (\delta u/\delta z)^2 + (\delta v/\delta z)^2$ where u and v are eastward and northward
201 velocities, respectively. Instability is expected for periods where $Ri < 0.25$, theoretically leading to the
202 development of Kelvin-Helmholtz billows within which vertical overturns are generated and that
203 manifest themselves as temperature inversions. Density estimates for N^2 were calculated for the
204 moorings by assuming a constant T-S relationship; a mean salinity profile was calculated from two
205 CTDs on the mooring (top and bottom) that demonstrated a minimal variation in salinity (<0.05 PSU
206 standard deviation over the calculated period at each CTD). Temperature was measured through
207 throughout the water column by the thermistor string, and density estimated using the TEOS-10
208 expression for in-situ density (Roquet *et al.*, 2015). Due to the dominance of temperature in driving
209 density gradients in the water column at this site with little freshwater input, the use of a static salinity
210 for time series Ri calculations is expected to result in only a small underestimate of the density
211 variability (Leichter *et al.*, 2012). CTD profiles were vertically binned at 0.5 m for temperature, salinity,
212 and pressure to compute density.

213 **2.6 - Remote sensing & numerical model output.**

214 The IOD index used in this work is provided by the Ocean Observations Panel for Climate (OOPC)
215 Dipole Mode Index data series, which in turn is calculated from the monthly sea surface temperature
216 difference between the tropical western Indian Ocean, and tropical eastern Indian Ocean as defined in
217 Saji *et al.* (1999) using the Reynolds Olv2 SST analysis. A shorter timescale of variability (1-2 months)
218 arises through the influence of the Madden-Julian Oscillation, for which the daily index values at 70°
219 E are taken from the Climate Prediction Centre (Xue, Higgins and Kousky, 2002). The MJO is
220 responsible for the enhancement of westerly winds that may potentially promote nutrient
221 entrainment into the euphotic zone and increased rainfall that may increase upper ocean stability but
222 also elevate run-off of nutrients from atolls host to bird populations (Graham *et al.*, 2020)

223 Local wind data is taken from the ERA5 delayed ECMWF reanalysis (10.24381/cds.adbb2d47), which
224 was cross compared to in-situ met station observations for validation. To evaluate the wider scale
225 influence of the IOD on the thermocline within the central Indian Ocean, the numerical model output
226 from the Copernicus Global Ocean reanalysis (10.48670/moi-00021) and forecast (10.48670/moi-
227 00016) were taken at 1/12° resolution with interpolated depth bins at 5 m increments for improved
228 resolution of the thermocline depth. Remote Chl-a data are taken from the Copernicus global
229 biogeochemistry hindcast at 1/4° with a monthly time step (10.48670/moi-00019).

230

231 **3 – Dynamical oceanographic drivers of temperature heterogeneity**

232 Given the local topography, candidate mechanisms for the generation of near bed cooling implicated
233 in manta foraging include internal (tidal) waves (Thorpe and Lemmin, 1999; Williams *et al.*, 2018; Reid
234 *et al.*, 2019) as well as the generation of cold water fronts by flow topography interaction (Lü *et al.*,
235 2010). Internal waves propagate within the ocean interior within the frequency range $f < \sigma < N$,
236 where $f = 2\omega \sin \theta$ is the local Coriolis frequency determined by earth's rotation rate ω at latitude
237 θ (herein taken as 6.55° S). Upon interaction with topography, the evolution characteristics of internal
238 waves are primarily governed by the relationship between the slope of the internal wave, and the
239 slope of the topography. The slope of an internal wave is given by:

$$240 \quad s = \sqrt{\frac{\sigma^2 - f^2}{N^2 - \sigma^2}} \quad [1]$$

241 where σ is the forcing frequency of the internal wave. When the bed slope is shallower than the wave
242 slope, the bed is deemed subcritical, and slopes steeper than the wave face are deemed supercritical.
243 By this classification most slopes in the region are supercritical with respect to the internal tide,
244 meaning that the majority of energy in the internal tide is reflected into deeper water (Müller and Liu,
245 2000) rather than, in the subcritical case, reflected further up the slope. The propagation of waves
246 obliquely to the slope, however, can reduce the effective angle of the slope, allowing for the upslope
247 propagation of internal waves in cases where the steepness is prohibitive of perpendicular
248 propagation (e.g. Hosegood and Van Haren, 2004).

249 Local generation of internal tides by topography is governed by the body force function where the
250 baroclinic internal tide is generated by the vertical motion induced by the interaction of the barotropic
251 tide with sloping topography (Baines, 1973):

$$252 \quad w(x, z, t) = -Qz \left(\frac{1}{h}\right)_x \cos \omega t \quad [2]$$

253 Where the mass flux (Q) is determined by changes of bed height (h) in the cross-slope direction (x),
254 and where ω is the tidal forcing frequency and $w(x, z, t)$ is the vertical velocity. This means that, in
255 the case of Egmont, a cross-shore velocity component is necessary for local internal wave generation
256 given the small depth gradients in the along-slope direction in Manta Alley (Fig. 1). Prior studies (e.g.
257 Haury *et al.*, 1979; Lamb, 2004) have identified the role of tides in generating these cross-slope
258 currents which in turn may generate internal waves and vertical excursions of the thermocline which
259 manifest as near bed reductions in temperature.

260 In the presence of strong and continuous stratification and steep bottom slopes, the predominantly
261 mode-1 internal wave response from (tidal) flow-topography may become more complicated by the
262 generation of a mode-2 response (Vlasenko and Alpers, 2005; Liang *et al.*, 2018; Liu, Grimshaw and
263 Johnson, 2019). Mode-2 internal waves have received significantly less attention than mode-1 internal
264 waves that are dominant in (approximately) two-layer systems in which two weakly stratified layers
265 are separated by a discrete pycnocline of finite thickness. Mode-2 waves are characterised by a
266 divergence in isotherms and strong vertical shear across distinct layers that alternatively drive water
267 upslope and downslope. Mode-2 waves have recently gathered traction as a mechanism for inducing
268 mixing across the pycnocline due to their potential for promoting instability, and thus turbulence (Carr
269 *et al.*, 2019).

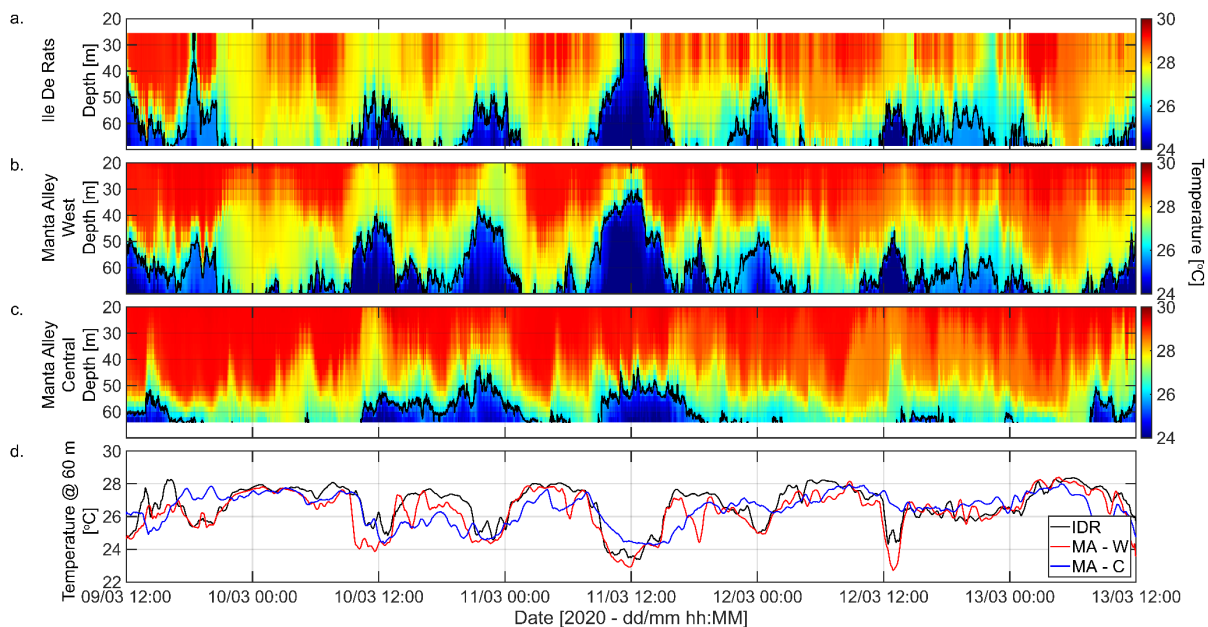
270 The depth at which internal wave effects are pronounced depends on the regional stratification.
271 Strong positive IOD events result in a deeper thermocline within the archipelago and negative events

272 cause shoaling of the thermocline (Liu *et al.*, 2022); the timescale and strength of the IOD varies,
 273 although recent years have shown an increased in bias towards positive events (Abram *et al.*, 2008;
 274 Du *et al.*, 2020). The modulation of the thermocline by these processes will in turn determine the
 275 depth band which any internal wave activity within the region impacts.

276 **4 - Results**

277 **4.1 – Near bed cooling on the north face of Egmont Atoll: An overview**

278 As previously described, the north face of Egmont Atoll features a lipped gully referred to as Manta
 279 Alley that runs along-slope and, under certain conditions, is inundated at the bed with cold water.
 280 While cooling is observed at all three sites (two within MA and one at IDR), the vertical extent of
 281 cooling at the Manta Alley – Central mooring is reduced relative to the other two sites. For example,
 282 at 11/03/2020 when 26 °C water is seen to extend to ~30 m depth at Ile De Rats, the same cooling
 283 does not extend shallower than ~40 m within central Manta Alley (Fig. 3). Additionally, over extended
 284 time periods the variation in thermocline depth plays a central role in governing the depth range over
 285 which cooling events are observed.



286 *Fig. 3. Temperature at the three moorings located along the north face of Manta Alley in West-East*
 287 *order: a) Ile De Rats: March 2020 mooring (IDR) b) Manta Alley – West: long term mooring to the east*
 288 *of the Ile De Rats 2020 mooring (MA – W) and c) Manta Alley – Central: long-term mooring close to*
 289 *the primary entrance to the lagoon (MA – C). Panel d) shows the temperature at 60 m for each of the*
 290 *moorings to aid in highlighting the variability between sites. Thermistor data overlaid with 26 °C*
 291 *contour.*

292 With the aim of exploring how the differences in these cold-water intrusions may be responsible for
 293 the spatial variability in manta residence, the following sections each explore a specific periodicity to
 294 examine in further detail how these cooling events are influenced by the local and regional dynamics
 295 at three temporal scales:

296 S 1—Regional stratification (controlled by the IOD) determines the absolute vertical limit to
 297 which cooling can extend by varying the depth of the thermocline which support the

298 propagation of processes such as internal waves; the regional impact of the IOD further
299 implies an influence over a significantly wider region than Egmont or the Chagos Archipelago
300

301 S 2 – Local tidal period cold water intrusions are regularly seen near the bed at both Ile de
302 Rats and Manta Alley; the similar timings of the events at both locations are suggestive of
303 cooling which propagates up-slope despite the along-slope alignment of the barotropic tide.
304

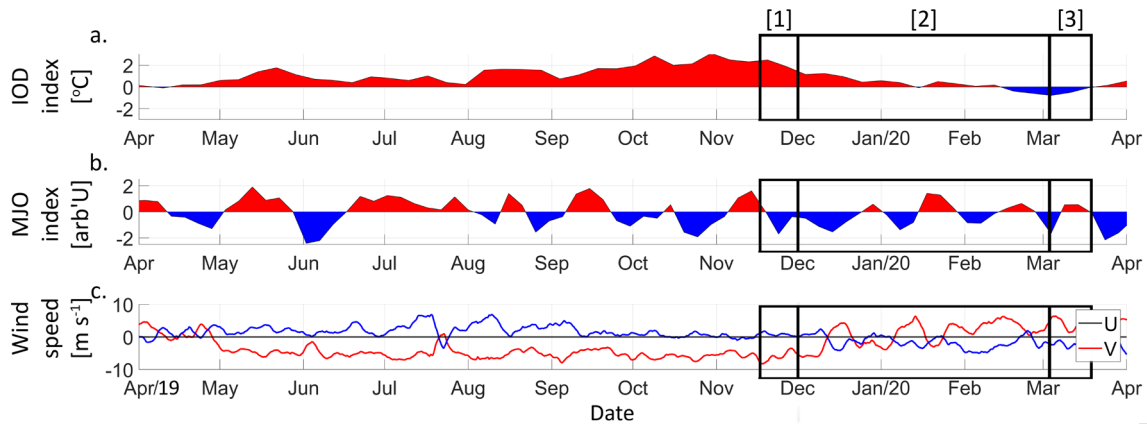
305 S 3 – Baroclinic currents introduce further variability to the local cooling events; observations
306 of high frequency ($T < 30$ mins) internal waves coincide with rapid cooling at the bed in
307 addition to the tidal period cooling, as well as introducing elevated levels of shear near the
308 bed.
309

310 **4.2 – Seasonal modulation of background stratification & currents**

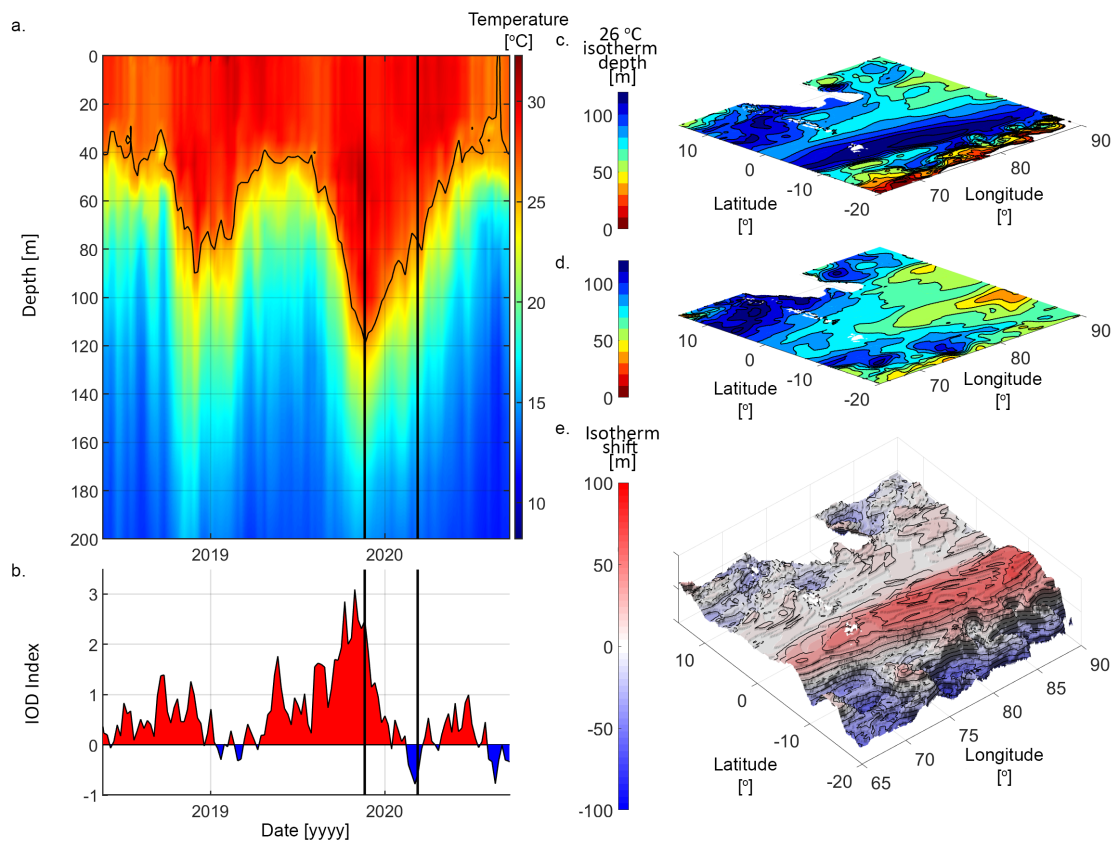
311 November 2019 saw an historic peak in the strength of the positive phase IOD (Fig. 4), driving a
312 sustained intensification of the easterly wind fields in the western Indian Ocean and a deepening of
313 the thermocline to > 100 m throughout the archipelago (Lu and Ren, 2020). Modelled results indicate
314 a suppression of the local wind field (Fig 4.) and a depression of the $26\text{ }^{\circ}\text{C}$ isotherm to 120 m in deep
315 water to the east of the archipelago in 2019 compared to 85 m at the same time in 2018 (Fig. 5).

316 The MJO has a shorter period than the IOD, varying over timescales of $30 - 60$ days. Both cruises
317 captured a transition in the MJO, from positive to negative in November, and negative to positive in
318 March. Locally observed wind was not clearly impacted by these transitions, but the stability of the
319 wind field over this period may be in part due to the relative strength of the IOD suppressing the
320 impacts of the MJO (Fig. 4).

321 The relaxing of the IOD between November 2019 and March 2020 into a neutral phase materialises in
322 the water column as a shoaling of > 35 m of the $26\text{ }^{\circ}\text{C}$ isotherm (a proxy for the top of the thermocline)
323 (Fig. 5). In situ observations corroborate this change with CTD profiles taken in November 2019 and
324 March 2020 showing the $26\text{ }^{\circ}\text{C}$ isotherm migrating from 104 m to 63 m. This initially results in limited
325 opportunity for cooling events during November 2019 within Manta Alley as any internal waves in the
326 region are limited to depths inundated by the thermocline. As the IOD relaxes throughout the end of
327 2019 and into early 2020, the shoaling of the thermocline facilitates the introduction of cold water at
328 shallower depth bands and, specifically, into Manta Alley (Fig. 6). Data collection in March 2020 took
329 place in comparatively neutral phases of the IOD with shallower accompanying thermoclines at ~ 60 m
330 and increased observations of near bed cold-water incursions into Manta Alley.



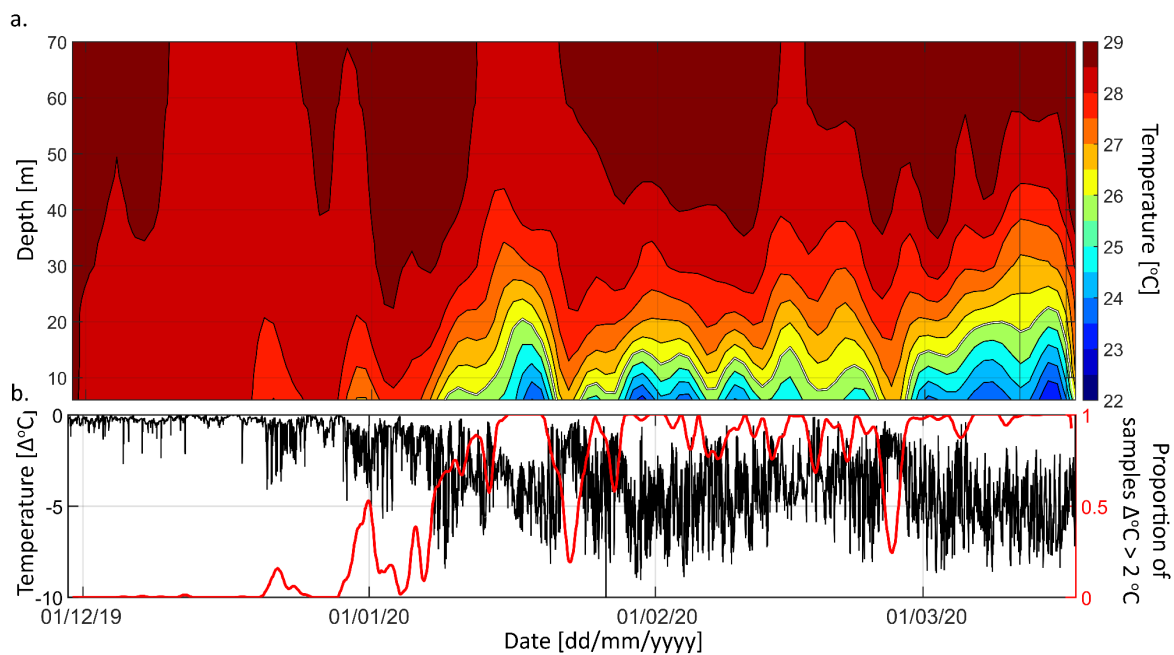
331 *Fig. 4. a) Evolution of the IOD (via. DMI) and b) MJO (via. MJO index at 70E) between September 2019*
 332 *and March 2020 showing the occurrence of an extreme positive IOD event. c) ERA5 Wind data at 6.75°*
 333 *S 71.25° W showing the suppression of wind variability during the strong positive IOD phase. Indicated*
 334 *are the three observational periods in Nov 2019 [1], over the long-term period [2], and in Mar 2020 [3]*



335 *Fig. 5. (a) Modelled (Copernicus) time series of temperature at -8.125 N 73.875 E with cruise timing*
 336 *marked. (b) IOD index provided by OOPC. Spatial position of the 26 °C isotherm is shown over the*
 337 *archipelago between (c) November and (d) March to generate (e) a difference map [November 2019 –*
 338 *March 2020] with positive values indicating a shoaling of the thermocline over the period. Over the*
 339 *region encompassing the Chagos Archipelago, the 26 °C isotherm is 40-50 m shallower during March*
 340 *than in November.*

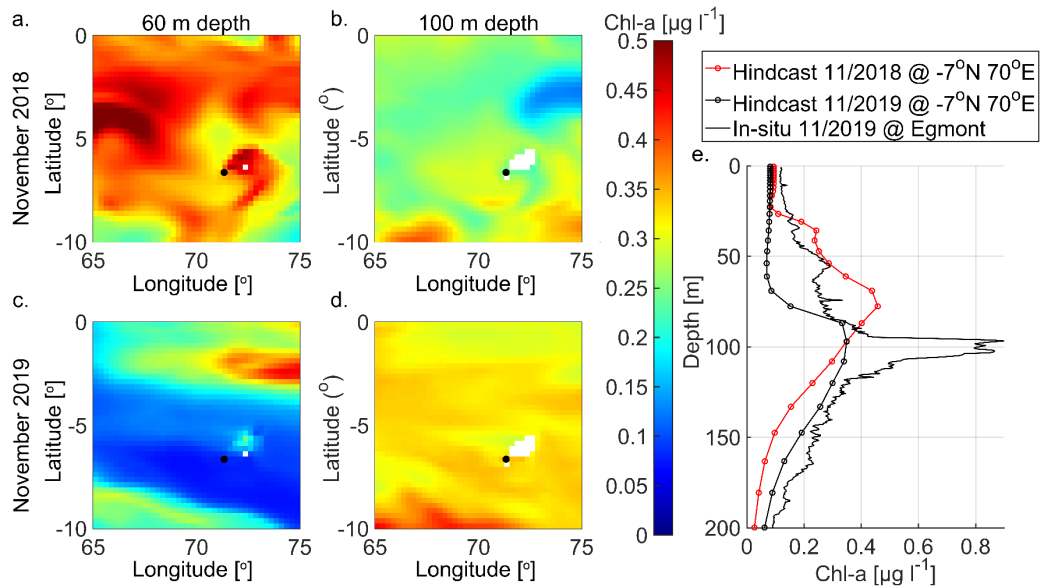
341

342 At the Manta Alley – West mooring (which was deployed for an extended duration and features the
 343 deepest observations out of the three sites) the gradual shallowing of the thermocline can be seen
 344 between December 2019 and March 2020 in response to both the relaxing of the IOD and the standard
 345 seasonal evolution, which corresponds well with the remotely sensed / modelled data seen in Figure
 346 5a. Initially, in November the mixed layer base was deep enough (at ~100 m) to exclude monitoring of
 347 the thermocline by the moorings, which had maximum depths 65 m (MA) and 75 m (IDR). As the IOD
 348 relaxed, the thermocline shoaled and moved into the observable range of the instrumentation (Fig.
 349 6). The date of initial observation for cold water at the bed, defined here as a 2 °C difference across
 350 the mooring range, ΔT , on the Ile De Rats mooring was 05/12/2019, and by 31/12/2019 > 25 % of
 351 profiles in any given 24 h window exhibited a $\Delta T > 2$ °C over the vertical extent of the mooring.



352 *Fig. 6. a) Long-term thermistor data from Ile De Rats showing the evolution of the thermocline depth.*
 353 *0.5 °C interval isotherms overlaid with 26 °C isotherm shown in white. b) Surface (10 m depth) and*
 354 *near bed (77 m depth) temperature difference [black] and proportion of 5 min samples with a*
 355 *difference greater than 2 °C [red, 201 point running average] over the course of the long-term mooring*
 356 *deployment at Ile De Rats.*

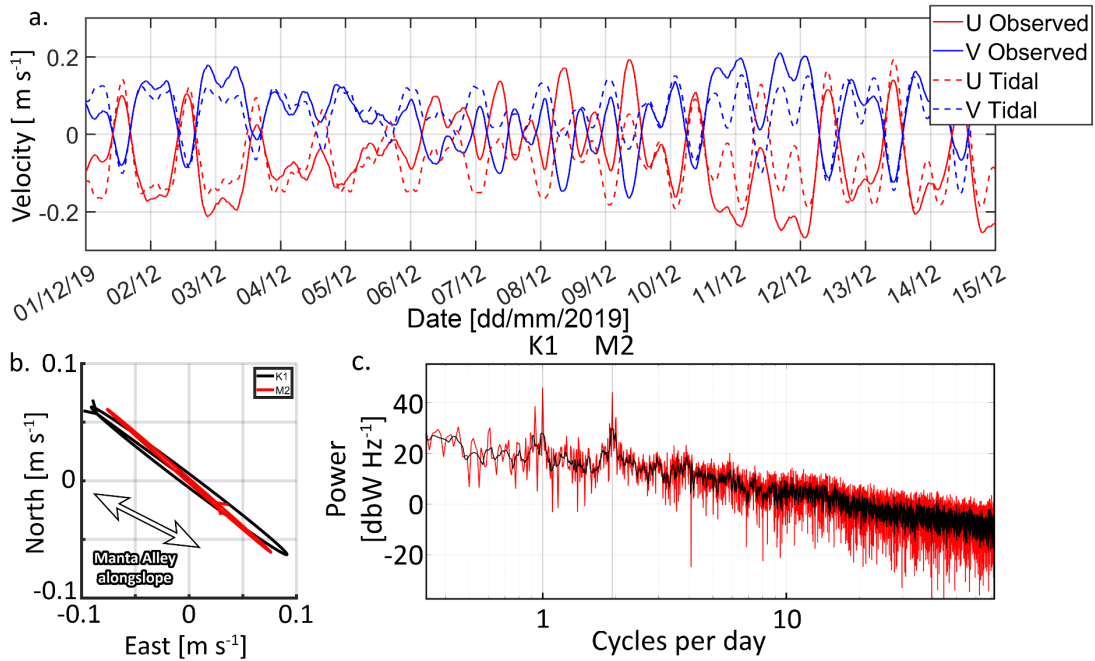
357 Due to the presence of a DCM within the Indian Ocean, the seasonal migration of the thermocline also
 358 resulted in vertical migration of the DCM. Comparing the hindcast data for Chl-a in November 2018
 359 and 2019 (Fig. 7), it is apparent that the 60 m depth band (the depth at which the majority of Manta
 360 Alley lies) was comparatively depleted of Chl-a in 2019 compared to a more historically representative
 361 year in 2018. Comparatively, at 100 m during 2019 there were higher Chl-a concentrations suggestive
 362 of a DCM migrating with the thermocline which was a consistent feature from in-situ CTD profiles
 363 taken during this period. These profiles show Chl-a concentrations at the thermocline of $0.82 \mu\text{g L}^{-1}$
 364 compared to $< 0.2 \mu\text{g L}^{-1}$ in the top 20 m of the water column (Fig. 7). This coupling of the thermocline
 365 with the DCM is a key element of the biophysical coupling that allows for physical oceanographic
 366 processes to influence local ecosystems, particularly via internal waves propagating along the
 367 thermocline.



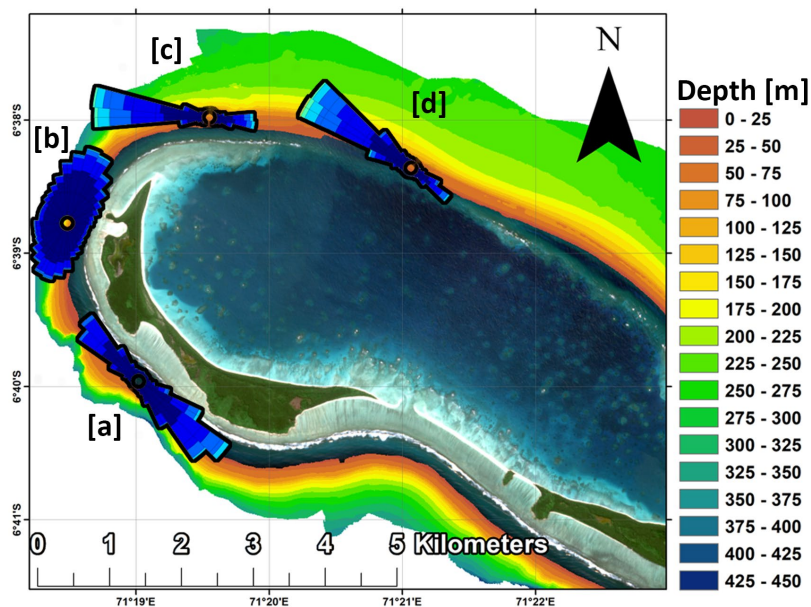
368 *Fig. 7. Chl-a concentrations at 60 m and 100 m depth from the global ocean biogeochemistry hindcast*
 369 *in 2018 (a, b) representative of a standard depth thermocline and 2019, (c, d) with the thermocline*
 370 *deepened by the IOD. Egmont is marked by the black dot, visible is the comparatively depleted Chl-a*
 371 *at the depth of Manta Alley in 2019. e) Profiles of Chl-a from both scenarios in deep water to the south-*
 372 *west of Egmont, along with an in-situ profile taken in deep water off Egmont in November 2019.*

373 **4.3 – Local Tidal Forcing**

374 The tide is mixed and asymmetric within Manta Alley; the magnitude of the solar diurnal (K_1)
 375 component is equal to that of the lunar semi-diurnal (M_2) component (Fig. 8). Semi-major axes
 376 amplitudes are 0.111 m s^{-1} (95 % confidence interval [CI95] 0.006) and 0.097 m s^{-1} (CI95 0.007) for K_1
 377 and M_2 , respectively, with a similar ratio of M_2/K_1 currents to that reported previously at the nearby
 378 more exposed Sandes seamount by Hosegood *et al.* (2019). Currents are forced to align locally along-
 379 slope, resulting in rectilinear current ellipses (Fig. 8a) both within Manta Alley and around the wider
 380 atoll following the underlying isobaths (Fig. 9). Within Manta Alley the flood tide runs eastwards, and
 381 the ebb tide runs westwards. The minimal local cross-shore current implies a low likelihood of local
 382 internal tide generation due to the requirement of flow over slopes for IW generation in the body
 383 force function as shown in eq. 2.



384 Fig. 8. a) One month of observed currents in Manta Alley overlain with predicted tidal velocities from
 385 tidal decomposition analysis. b) Depth-mean tidal ellipses for the K_1 and M_2 components over the
 386 period of long-term observations taken from within Manta Alley. Within Manta Alley the magnitude
 387 of the K_1 component matches that of the M_2 , not visible within the ellipse is the asymmetry in the
 388 strength of the tidal currents. c) FFT of depth averaged eastwards velocity showing equal powers for
 389 the K_1 & M_2 components

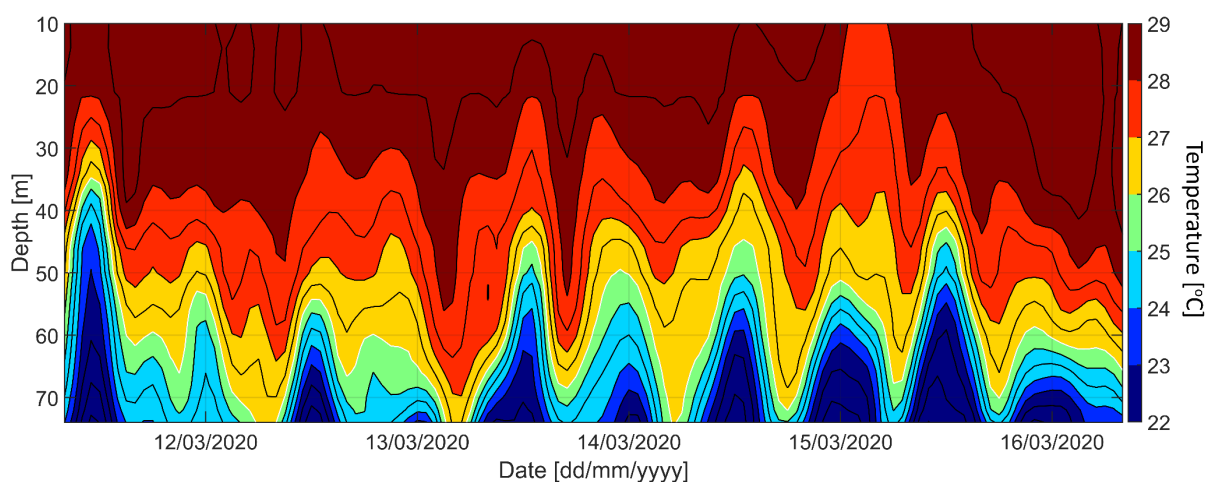


390 Fig. 9. Current roses inset into bathymetry at Egmont, showing the modulation of current direction by
 391 the local bathymetry. Instrumentation was as follows [a] Ile Sepille 1000 kHz ADCP (Nov 19) [b] Ile De
 392 Rats (W) 600 kHz ADCP (Nov 19) [c] Ile De Rats 400 kHz ADCP (Nov 19 – Mar 20) [d] Manta Alley 500
 393 kHz ADCP (Nov 19 – Mar 20). Background imagery from Copernicus Sentinel-2B [2022] / Sentinel Hub

394

395 **4.4 – Barotropic tidal forcing of near bed thermocline incursions**

396 To assess the baroclinic response to tidal forcing over the slopes surrounding Egmont, a subset of data
397 is presented in the presence of the shallower thermocline (March 2020) from Ile De Rats with a 6-hour
398 low pass filter applied to isolate variability at the M_2 periods and above (Fig. 10). Cold water incursions,
399 evident as cold water at the seabed and extending vertically towards the surface, are visible at tidal
400 periods with vertical amplitudes of up to 40 m; these events generate $\Delta T > 8^\circ\text{C}$ between the bed and
401 10 m depth over a short period (≈ 5 mins), and 4°C over the course of a tidal period, compared to a
402 baseline ΔT of $\sim 2^\circ\text{C}$ (Fig. 10). The cooling evident over tidal periods is a persistent feature at diurnal
403 and semi-diurnal frequencies when the thermocline intersects the slope within the observational
404 range. This cooling is likely to be a persistent feature, including in the presence of a deeper
405 thermocline due to the consistency of any tidal forcing, despite being beyond the depth range of our
406 observations that are constrained by the steep slopes offshore of Manta Alley.

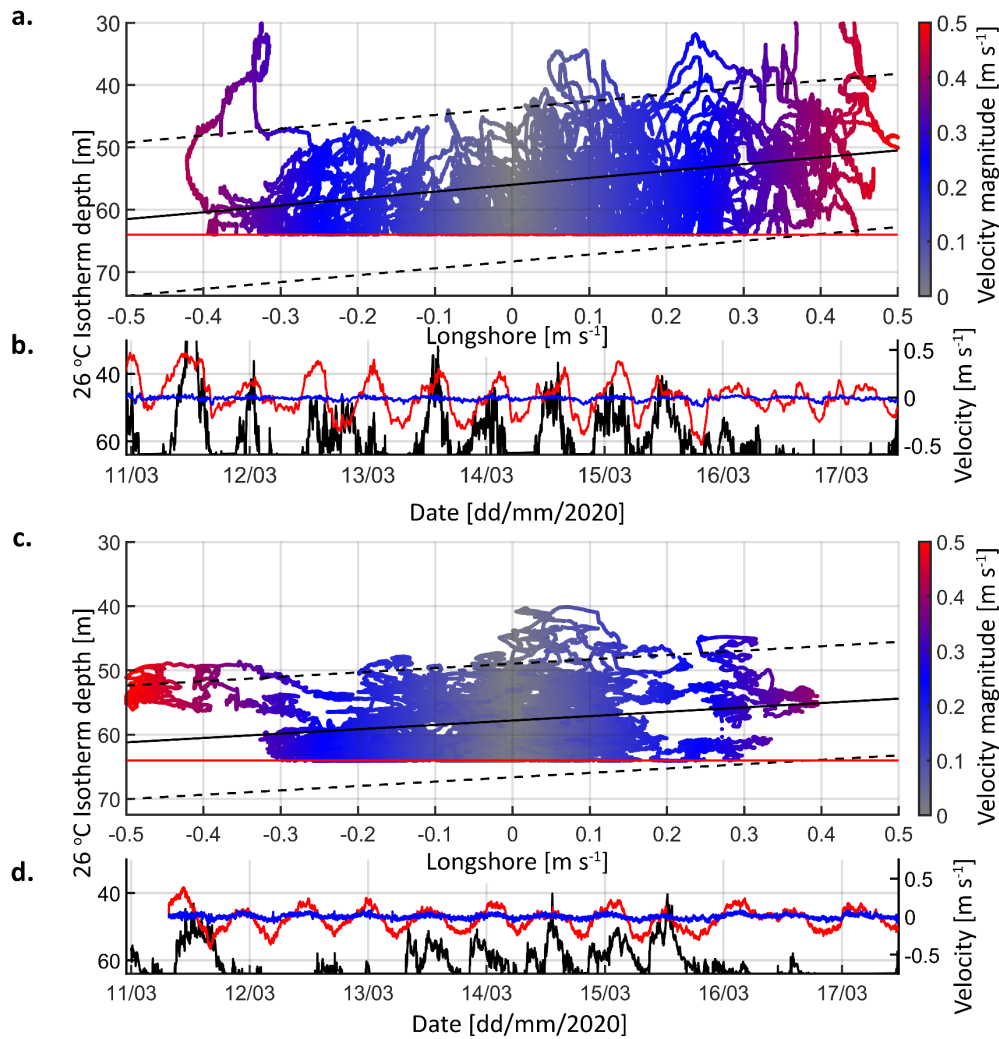


407 *Fig. 10. Long-term thermistor data from Ile De Rats. low passed at 6 hours to remove high-frequency*
408 *oscillations and isolate the temperature change at the timescales associated with tidal (M_2 , K_1)*
409 *processes. Seabed at 77 m depth. 0.5°C interval isotherms overlaid with 26°C isotherm shown in white.*

410 Despite the tidal currents being aligned predominantly along-slope, the temperature differences that
411 are the subject of this paper appear to be only weakly linked to currents orientated in this direction.
412 At Ile De Rats, along-slope velocity, and the depth of the 26°C isotherm (chosen as a marker for the
413 base of the surface mixed layer) have a weak linear relationship. Positive along-slope flows (flood tide,
414 eastwards) are associated with shallower isotherms and cooler near bed temperatures. This
415 relationship is weaker at Manta Alley – Central, with the gradient of the linear fit at Ile de Rats being -
416 11, compared to -6.1 at Manta Alley over the same period. This can be seen in figure 11a where the
417 distribution at Ile De Rats shows that the shallowest elevations of the isotherm are predominately
418 associated with strong positive along-slope flows. Manta alley shows a comparatively normal
419 distribution with the shallowest isotherms found during periods of relatively minimal ($<0.1\text{ m s}^{-1}$)
420 velocity as shown by the central distribution in figure 11c.

421 At Ile De Rats, the measured velocity range was 0.37 m s^{-1} (2σ) and the depth of the 26°C isotherm
422 varied between $>64\text{ m}$ to as shallow as 31 m depth, a range of over 33 m with the shallowest isotherm
423 seen on 13/03/2020, on the flood phase of a spring tide. Velocities at Manta Alley were smaller with
424 a range of 0.28 m s^{-1} (2σ) with the thermocline not reaching depths shallower than 40 m during this
425 period, this is again demonstrated by the reduced vertical and horizontal spread in figure 11c.

426 The limited correlation between the along-slope velocity, which is primarily driven by the barotropic
 427 tide, and the shoaling of the isotherm suggests that a freely propagating internal tide in the along-
 428 slope direction is relatively unlikely to be the driver of the observed cooling within Manta Alley. This
 429 is further corroborated by cross-correlation between temperature at a depth of 60 m at each site; no
 430 time delay is observed between the two signals over the period of observation, despite a horizontal
 431 separation distance > 1 km.



432 *Fig. 11. Depth of the 26 °C isotherm between 2020/03/10 23:00 and 2020/03/17 11:30 at (a, b) Ile De*
 433 *Rats and (c, d) Manta Alley – Central related to depth mean longshore velocity between 31 & 61 m*
 434 *depth (overlapping observational range). Visible at Ile De Rats is the trend of raised isotherms during*
 435 *eastwards flow and depressed isotherms during westwards flow fitted with the linear regression $y = -$*
 436 *$11.0x + 56.0 \pm 12.3$ CI95, R 0.11. Longshore [red] and cross-shore [blue] velocities shown with isotherm*
 437 *depth [black] with clear correlation between the peaks in cross-shore velocity and shallow isotherm.*
 438 *At Manta Alley longshore velocity has limited impact on the depth of the isotherm when fitted with the*
 439 *linear regression $y = -6.1x + 57.08 \pm 8.8$ CI95, R 0.05. While normally there are weak positive LS velocities*
 440 *with shallow isotherms, the event on 11/03 is out of phase with the background velocity resulting in*
 441 *the block visible to the left of panel c.*

442

443 **4.5 Internal wave generation and propagation**

444 To assess the role of a cross-slope propagating internal tide in generating bed temperature
445 fluctuations at Egmont, the ability of nearby slopes to generate internal tides was calculated. The
446 background stratification is strong, with temperature gradients up to $1.4\text{ }^{\circ}\text{C m}^{-1}$ observed in November
447 2019 and $0.5\text{ }^{\circ}\text{C m}^{-1}$ in March 2020 and peak N^2 values exceeding $4 \times 10^{-3}\text{ s}^{-2}$ in 2019. The range of
448 observed N^2 values (Fig. 12) indicate that internal waves forced by the M_2 tide in the vicinity of Egmont
449 would have a peak slope of approx. 3.5° in the strong stratification found in November 2019. The local
450 slope at Egmont regularly exceeds 30° (Fig. 2) and is therefore supercritical to the slope of semi-diurnal
451 tide forced internal waves within the region (Balmforth and Peacock, 2009).

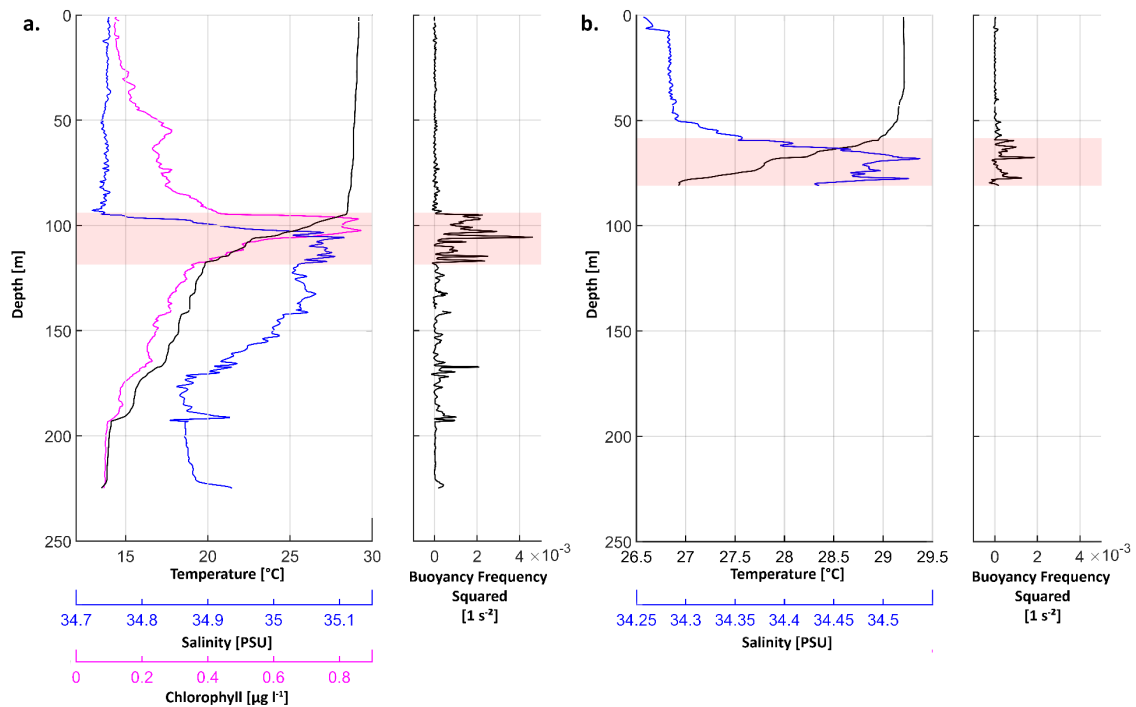


Fig. 12. In-situ Temperature, Salinity, Chlorophyll profiles at Egmont from a) November 2019 and b) March 2020 showing the shift in stratification along with accompanying N^2 values for the profiles showing increased buoyancy frequency at the thermocline. Note differing horizontal scales due to vastly different prevailing conditions. The region of peak stratification (associated here with the thermocline) has been shaded.

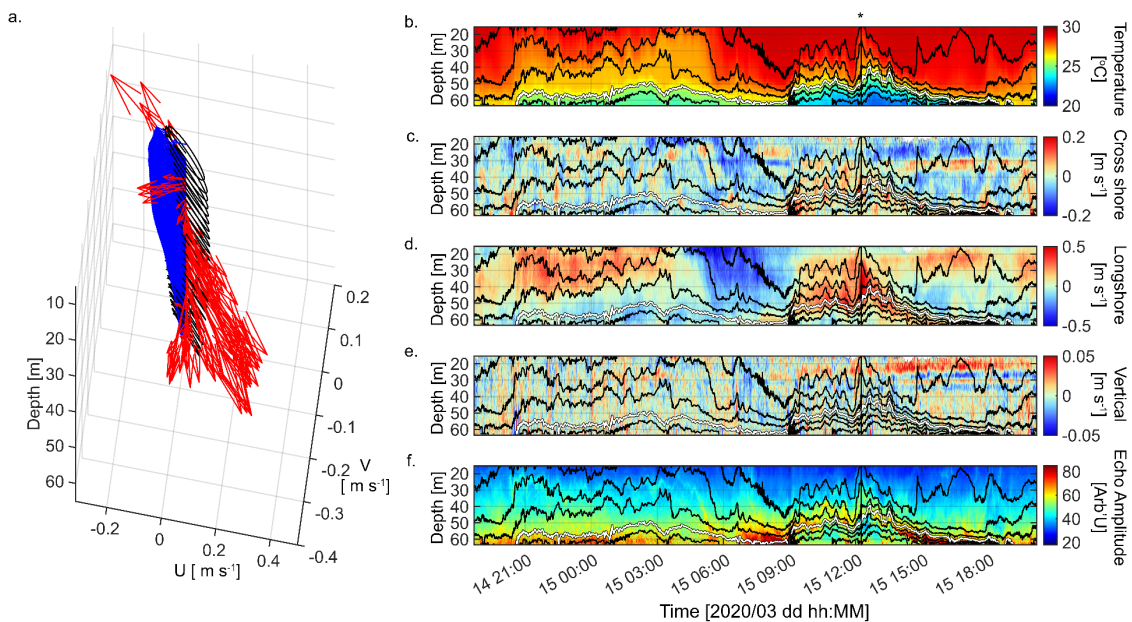
452 **4.6 — Baroclinic dynamics: High frequency internal waves and cooling events outside the barotropic**
453 **tidal regime**

454 Cooling events at Egmont are not exclusively phase-locked to barotropic tidal forcing but appear, on
455 occasions, at irregular intervals resulting in variations of the cooling signature between each
456 occurrence (Fig. 11, 13). To elucidate the dynamics controlling these apparently non-tidal events, and
457 to demonstrate their turbulent nature, an example case is shown with two tidal periods exhibiting
458 vastly different characteristics; the first period commencing on 14/03/2020 20:00 shows weaker
459 stratification with a 5-15 m vertical separation of isotherms at $1\text{ }^{\circ}\text{C}$ intervals, whilst the second on
460 15/03/2020 09:00, shows strong stratification and the presence of colder $20\text{ }^{\circ}\text{C}$ water at the bed. Data
461 are presented with the barotropic tidal velocity from the tidal analysis removed to better highlight the
462 local baroclinic forcing.

463 During the first event a residual along-slope current amplitude of 0.5 m s^{-1} was observed between 10
 464 and 30 m above the seabed, with an associated decrease in temperature of $4.2 \text{ }^\circ\text{C}$, from $26.3 \text{ }^\circ\text{C}$ to
 465 $22.1 \text{ }^\circ\text{C}$, measured 2 m above the seabed with a peak rate of $0.28 \text{ }^\circ\text{C}$ per minute (measured over a 5-
 466 min window). The barotropic velocity of $\sim 0.5 \text{ m s}^{-1}$ was opposed by the baroclinic component
 467 responsible for the cooling, resulting in an observed current of effectively 0 m s^{-1} . This cooling
 468 persisted for a duration of 4.5 h before the thermocline returned to depths below the mooring (Fig.
 469 13.).

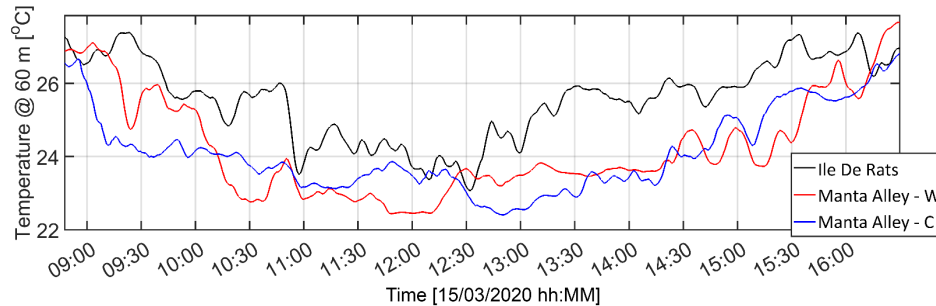
470 The baroclinic component exhibited significant vertical shear (Fig. 13a.), as well as an enhanced cross-
 471 shore component with velocities up to 0.2 m s^{-1} . The cross-shore component is oscillatory at short
 472 time scales (15-30 mins) associated with the presence of high frequency variability in isotherm depth
 473 accompanying the tidal carrier wave (Fig. 13 b,c). Vertical velocities are generally below 0.05 m s^{-1} with
 474 the strongest vertical velocities found at the bed on the leading edge of the 09:00 event. The near bed
 475 cold water incursion is constrained to the vertical layer in which the residual current is strong and
 476 aligned along-slope, with an increased residual cross-shore component compared to the warmer
 477 surface water.

478 A high concentration of scatterers within the upper edge of the thermocline can be seen for the
 479 duration of the cooling event, with a separate body of highly clear water below this scattering layer
 480 (Fig. 13f). Without ground truthing it is not possible to definitively establish the cause of these
 481 scatterers, with potential sources being sedimentary, biological, or turbulence based (Muchowski *et*
 482 *al.*, 2022). The presence of cold clear water below this high intensity band is, however, suggestive of
 483 either a plankton layer which has been vertically advected into the alley or reflections of stratified
 484 turbulence generated by the shear across the interface.



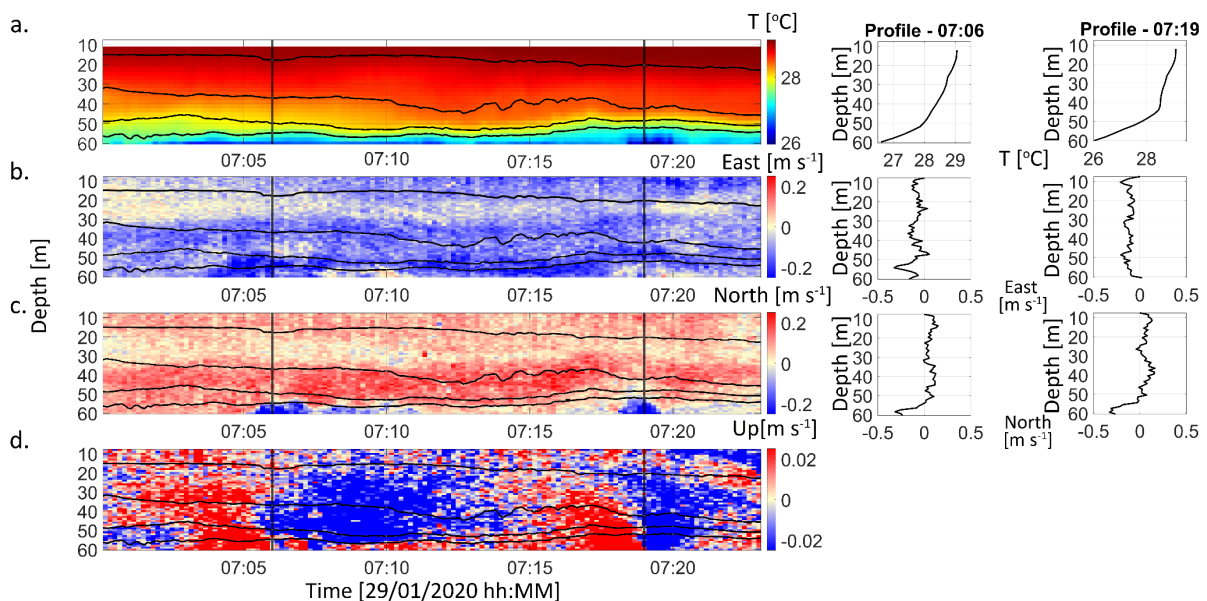
485 *Fig. 13. a) K1 Tidal ellipses (Black) with instantaneous predicted tide quivers (Blue) and residual current*
 486 *quivers (Red) overlain and showing a cross-shore component near the bed. b) Temperature, c)*
 487 *baroclinic cross-shore velocity, d) baroclinic longshore velocity, e) vertical velocity, and f) echo*
 488 *amplitude from the Manta Alley – Central mooring showing two consecutive tidal periods which*
 489 *display different cooling characteristics. Seabed at 66 m. Panels b-f are overlaid with temperature*
 490 *contours at $1 \text{ }^\circ\text{C}$ intervals ($29 - 23 \text{ }^\circ\text{C}$) with the $26 \text{ }^\circ\text{C}$ shown in white.*

491 During this event, cooling is also observed at the other two moorings to the west; in this case at 60 m
 492 depth the cooling appears first at central Manta Alley at approximately 08:57 followed by western
 493 Manta Alley at approximately 09:15, 18 minutes later, suggesting that this event may be propagating
 494 obliquely to the slope. A further delay can be seen before a weakened cooling signal is seen at the Ile
 495 De Rats mooring, further to the west (Fig. 14)



496 *Fig. 14. 60 m temperature at three moorings on 15/03/2020 (Ile De Rats, Manta Alley - West, and*
 497 *Manta Alley – Central) showing a short delay in the appearance of cooling at the three sites, as well as*
 498 *generally weaker cooling at the westmost (Ile De Rats) mooring.*

499 Whilst most observations of subtidal frequency internal waves at Egmont were in the presence of a
 500 larger, tidal, carrier wave, there were limited examples seen of isolated trains of high frequency
 501 internal waves near the bed, one of which is presented below. In this case there is an associated
 502 temperature drop of 3 °C observed at the mooring, with the level of cooling subsiding rapidly after the
 503 passing of the wave. These high-frequency waves have short periods between 5 & 10 mins (where
 504 local N in the region limits the lower period to approx. 4 mins) and exhibit the elevation-depression
 505 vertical velocity pattern characteristic of nonlinear internal waves. This vertical velocity signal peaks
 506 at 0.1 m s⁻¹ during the first wave at 07:05 and 0.2 m s⁻¹. The lack of corresponding drop in temperature
 507 at Ile De Rats, and the strongly cross-shore direction of the flow within the wave, which flows south-
 508 westwards with shear at the wave interface between 0.4 and 0.5 m s⁻¹ (Fig. 15) both suggest that this
 509 may be an upslope propagating wave.

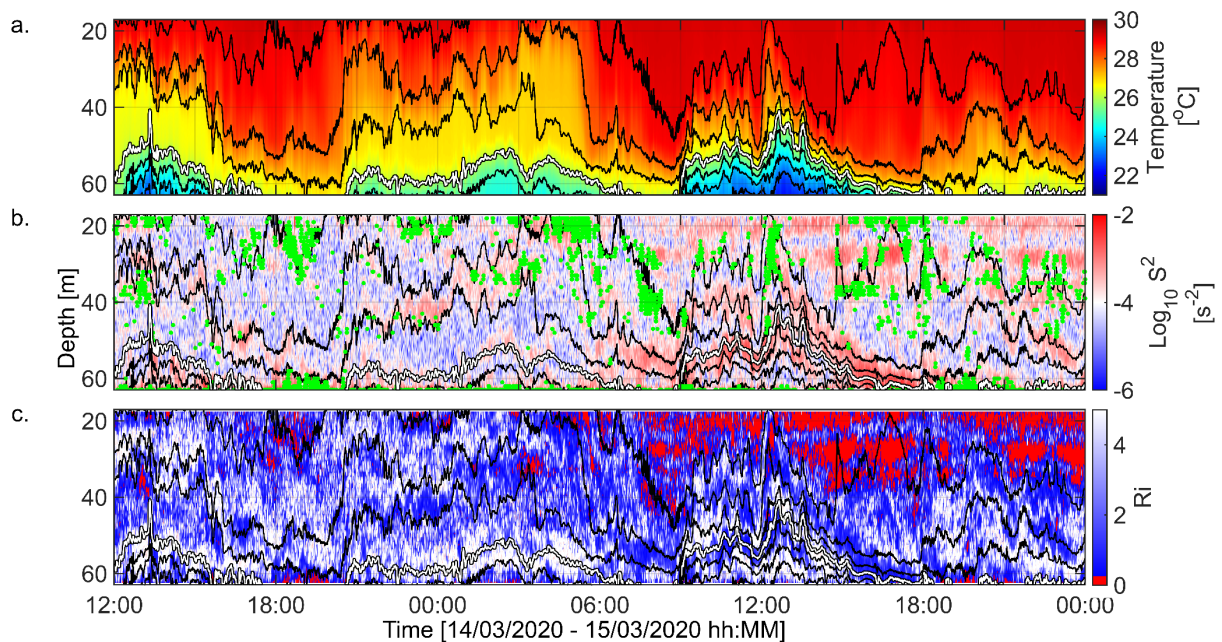


510 *Fig. 15. Spilling of an upslope propagating internal wave into Manta Alley, bringing a cooling of 3 °C*
 511 *and resulting in turbulent mixing across the thermocline from high levels of shear at the interface a)*
 512 *Temperature + (b) East / (c) North / (d) Up Velocity Panels with isotherms overlaid at 1 °C intervals.*

513 **4.7 Enhanced mixing through internal wave activity generated shear instability.**

514 The shear associated with the near bed propagation of the internal waves shown in section 4.6 is likely
515 to enhance turbulent mixing through shear instability, a metric which can be quantified by Ri. In the
516 example presented in figure 16 (covering the same period shown in fig. 13) two tidal periods were
517 observed with near bed cooling signatures that generate mixing through shear instability. The first
518 period on 14/03/2020 shows weaker stratification, however over the zone of peak stratification
519 enhanced shear was observed. On the trailing edge of the cooling at ~ 15/03/2022 05:00 in the
520 presence of high frequency internal waves the observed Ri values are subcritical ($Ri < 0.25$), likely due
521 to the stabilising influence of the strong stratification ($N^2 > 1 \times 10^{-5} \text{ s}^{-2}$) (Fig. 16b).

522 During the second event, vertically banded shear is visible within the core of the wave, with the
523 interface of the tidal period wave exhibiting S^2 values orders of magnitude larger than the background
524 water column, with values of 1×10^{-5} - $1 \times 10^{-4} \text{ s}^{-2}$ in the background water column, and values in excess of
525 $1 \times 10^{-3} \text{ s}^{-2}$ at the interface of the wave. These waves are associated with reductions in Ri but not always
526 to the point of instability. Shear instability is primarily visible on the leading and tail edges of the short
527 period waves, suggesting that these features enhance mixing across the boundary of the tidal period
528 cooling. During the wave at 12:00 internal instability is also apparent within the lower stratification at
529 42 m depth.

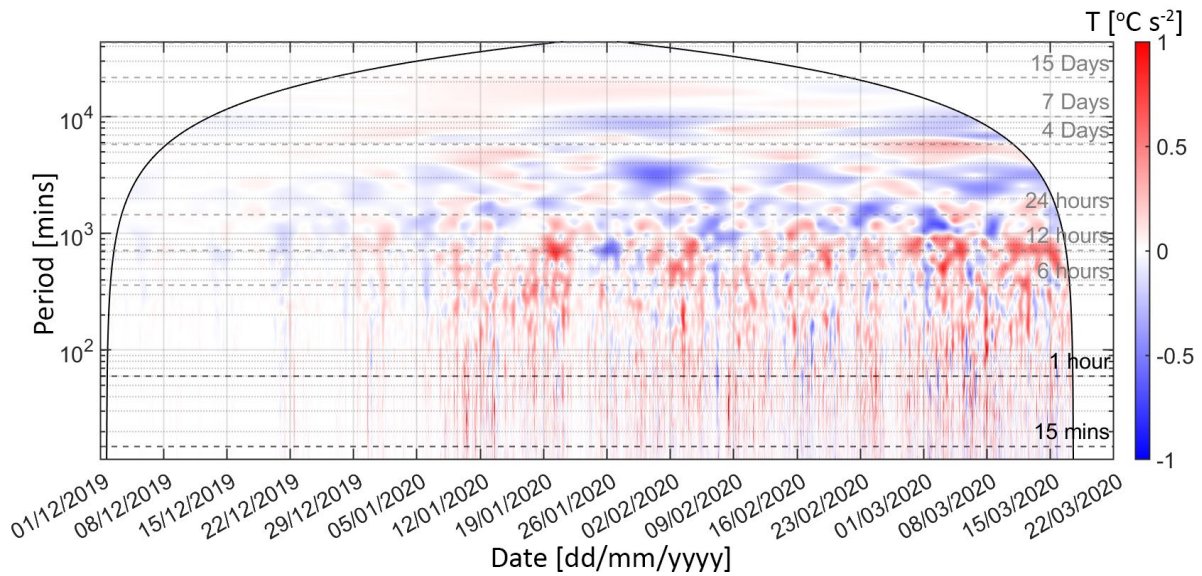


530 *Fig. 16. a) Temperature at the Manta Alley – Central Mooring on 14/03/2020 - 15/03/2020 showing*
531 *tidal period cooling carrying higher frequency internal waves. b) 2-Dimensional vertical shear overlaid*
532 *with temperature contours, and areas where $Ri < 0.25$ & $N^2 > 1 \times 10^{-5}$ marked in green. c) Ri with highly*
533 *stable areas marked in white, and zones of subcritical Ri marked in red. Panels are overlaid with*
534 *temperature contours at 1 °C intervals (29 – 23 °C) with the 26 °C shown in white.*

535 **4.8 – Site specific variability in internal wave activity**

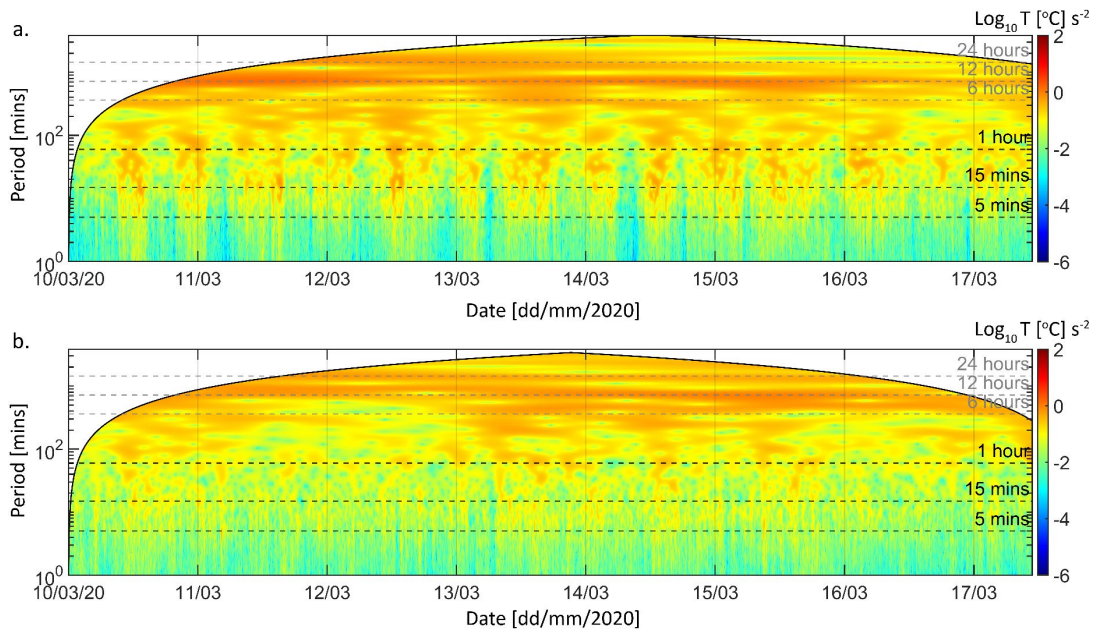
536 The form of the observed cold-water intrusions varies on a case-by-case basis, with the tidal intrusions
537 being the most consistent and high frequency internal wave driven cooling being more site specific.
538 To demonstrate that the cooling observed at both sites, driven by both tidal, and high-frequency
539 internal processes, wavelet analysis was used to highlight the frequencies driving the cooling at a
540 depth of 60 m.

541 In the initial period spanning 12/2019 – 01/2020, less than 0.3 °C temperature variability was
 542 observed, particularly above tidal frequencies (<6h period). The shoaling of the thermocline results in
 543 more frequent cold-water incursions, and as such greater thermal variability at each site. In the
 544 presence of a shallow thermocline at periods shorter than 12 h, Ile De Rats demonstrates a greater
 545 variability of >0.5 °C s⁻², indicating that high-frequency fluctuations in temperature are more prevalent
 546 at this site (Fig. 17).



547 *Fig. 17. Wavelet comparison between the long-term moorings in Central & West Manta Alley between*
 548 *December 2019 and March 2020. Areas in red represent periods of higher variance at western Manta*
 549 *Alley, whereas blue areas exhibit higher variance at central Manta Alley. Note the higher energies at*
 550 *high frequencies in the western extent of manta alley (>12h).*

551 A subset of data from March 2020 (Fig. 18.) demonstrates the differences in thermal variability
 552 between Ile De Rats and Manta Alley. Both sites are highly active at tidal periods and show a high
 553 frequency internal wave signal which is clearly coincident with tidal forcing. This signal is more
 554 prevalent at Ile De Rats, with poorer definition within Manta Alley, but the magnitude of thermal
 555 variance at shorter periods ($T < 1$ h) is comparable between the two sites.



556 *Fig. 18. Wavelet analysis of temperature at 60 m depth at a) Ile De Rats and b) Manta Alley – Central*
 557 *demonstrating the difference in temperature variability between sites over a shorter period but at*
 558 *higher frequencies. Both sites show tidal extension of energy into higher frequencies associated with*
 559 *short period internal waves, however the effect is less pronounced at western Manta Alley.*

560 **5 - Discussion**

561 Expanding on the results of Harris (2021) which focused on the impact of temperature on reef manta
 562 ray presence/absence at several sites around Egmont atoll, these results show that over short spatial
 563 scales Egmont exhibits differences in the thermal regime driven by highly localised physical processes.
 564 The temperature changes in Manta Alley are a result of periodic changes to the thermocline depth
 565 driven by several mechanisms. At interseasonal time scales the IOD modulates the depth of
 566 background stratification; at tidal periods rapid thermal variation is seen, potentially due to an internal
 567 tide, and high frequency internal waves drive both shorter period (5 – 15 mins) highly localised cooling
 568 events and promote mixing through shear instability in the presence of a tidal carrier wave.

569 The extreme positive IOD event (Lu and Ren, 2020) resulted in one of the deepest thermoclines, at a
 570 depth of ~100 m, seen within the available record. This deep thermocline caused the inundation of
 571 features in the 60-70 m range with warm water characteristic of the surface layer, pushing the
 572 thermocline too deep for cooling events to be observed in Manta Alley. Previous work examining mass
 573 aggregations of manta species have typically suggested that food plays a key role in promoting
 574 aggregative behaviour (Armstrong *et al.*, 2016). Manta feed on zooplankton which are in turn
 575 dependent on phytoplankton and so to a degree the presence of zooplankton can be inferred by proxy
 576 using Chl-a with manta presence previously linked to increased Chl-a levels (Harris *et al.*, 2020). During
 577 historic positive IOD events the 40-70 depth band across the entire SCTR in which the archipelago
 578 resides showed a decrease in chlorophyll concentrations (Dilmahamad, Hermes and Reason, 2016),
 579 and hindcast observations from 2018 and 2019 suggest that the same decrease occurred in 2019.

580 Due to the large scale of the IOD, impacting on the wider eastern Indian Ocean, many other reefs,
 581 atoll, and seamount ecosystems within the 50 -100 m depth band were likely impacted by inundation
 582 with warm surface waters at depths typically associated with the cooler thermocline. With climate
 583 change driving intensification of the IOD (Abram *et al.*, 2008) the depth range impacted by this

584 variation, as well as the duration for which depth bands may be excluded from cooling is likely to
585 become more extreme.

586 At local scales, the flow dynamics at Egmont are strongly influenced by the underlying bathymetry,
587 with differences in near bed temperature seen over small distances. The predominant frequency
588 associated with the cooling is semi-diurnal on the flood tide, although the cooling is not exclusively
589 phase locked with the local barotropic tide. The western extent of Manta Alley shows larger amplitude
590 incursions of the thermocline and more activity at the frequency bands associated with short period
591 internal waves. The constraint imposed by the channel to the north of Egmont may cause the
592 generation of accelerated tidal currents despite the small elevation of the tide but, regardless, the
593 changes in oceanographic conditions over small distances indicates the need to adopt approaches that
594 account for the bathymetric complexity at other sites.

595 Throughout the tidal cycle, cooling events are observed which are consistent with the downstream
596 evolution of mode-2 waves generated by interaction with steep topography in the presence of
597 continuous stratification beneath a weakly stratified surface layer. The generation and lifespans of
598 mode-2 waves is dependent on both the background stratification and shear environments (Chen *et al.*,
599 *et al.*, 2014; Deepwell and Stastna, 2016). Given the difference in stratification observed at Egmont over
600 tidal time scales, this accounts for part of the temporal variability seen. Existing insights into how these
601 waves develop is almost exclusively reliant on the use of nonlinear models (Cheng *et al.*, 2017; Liu,
602 Grimshaw and Johnson, 2019) and so there have been limited in-situ observations of how topography
603 impacts on their evolution.

604 Considering here that the cooling events are predominantly trapped at the bed due to the proximity
605 of the thermocline to the topography, we typically observe waveforms in which the waves of
606 depression have been potentially suppressed/destroyed (similar to Cheng *et al.*, 2017) or undergone
607 fission and converted to waves of elevation (e.g as in Deepwell *et al.*, 2019). As some of the
608 characteristics of these waves are like mode-1 waves differentiation of the two is challenging.
609 However, the presence of continuous stratification within Manta Alley, as opposed to a two-layer
610 system, and the strong banded shear observed in the waves increases the likelihood of these being
611 mode-2 waves. Additionally a previous study has shown that tidal flow in constrained channels, such
612 as the one between Egmont and Great Chagos Bank, can result in the generation of mode-2 internal
613 waves (Rayson *et al.*, 2018) that likely promote turbulence.

614 The similarity in timings of the tidal period cooling at both sites is indicative of events which propagate
615 perpendicular to the slope. Recent oceanographic modelling has suggested the presence of an
616 enhanced mode-2 internal tide near the Chagos-Laccadive Ridge relative to the wider Indian Ocean
617 (Zhao, 2018). However, this coarse scale oceanographic modelling ($1/10^\circ$) is unable to accurately
618 represent the fine-scale bathymetry of the region; at this resolution, Egmont atoll is represented by a
619 single grid point, and bottom slopes are significantly underestimated with GEBCO data showing a peak
620 slope angle of 8° compared to the high-resolution multibeam bathymetry which exceeds slope angles
621 of 40° . The steep bathymetry in the archipelago is widely capable of generating internal tides which
622 may then freely propagate to remote sites such as Egmont, and recent fine scale modelling at Egmont
623 has demonstrated the presence of an arrested mode-2 internal tide in the wider channel between
624 Egmont and Great Chagos Bank due to the local tide being sufficiently strong to arrest the slower,
625 higher mode, internal tide (Diaz *et al.*, submitted [unpublished data]).

626 Any remotely generated internal waves reaching Egmont and propagating perpendicularly to the
627 north face of the atolls are likely to have the majority of energy reflected due to the supercriticality of
628 the local slopes, however the oblique propagation of internal waves presents a mitigation to this factor

629 (Gemrich and van Haren, 2002; Hosegood et. al, 2004) meaning that the propagation of remote
630 waves towards Egmont remains a plausible. If these internal tides propagate perpendicular to the
631 north face as suggested by our observations the far side of the atoll is expected to experience reduced
632 cooling compared to the sites on the North & Western faces promoting further dynamical variability
633 over the atoll.

634 Based on our observations, Egmont displays large thermal variability over even the limited length of
635 Manta Alley. This supports the hypothesis of Harris *et al.* (2021) that fine scale dynamics can have
636 pronounced ecosystem effects which impact on fine scale preferentiality in mobile species. The
637 interaction between diel vertical migration of zooplankton to the DCM, local internal wave dynamics,
638 and topography may directly influence distribution of zooplankton within Manta Alley (Lennert-Cody
639 and Franks, 1999, 2002; A. Cordeiro *et al.*, 2013; Liccardo *et al.*, 2013). Whilst we are unable to directly
640 determine why manta exploit the internal wave-driven events shown here, we hypothesise that the
641 distribution of zooplankton is impacted by the turbulent nature of these dynamics, as seen in motile
642 phytoplankton (Durham *et al.*, 2013), or by fine scale flow fields, and that potentially zooplankton
643 distribution is modified in a manner that assists manta foraging.

644 Site preferential foraging in response to biophysical processes has already been shown in both manta
645 rays (Couturier *et al.*, 2011; Weeks *et al.*, 2015), and other highly mobile marine species (Jones *et al.*,
646 2014). As the events are most energetic in Manta Alley, it supports the hypothesis that manta rays are
647 exploiting these features to enhance their foraging efficiency and are detected more often at this
648 location. Further work to validate the relationship between these cold water events and chlorophyll
649 concentrations would provide observational support for the biochemical drivers which may be at play
650 given the lower residence time over the eastern end of Manta Alley (Harris *et al.*, 2021).

651 **6 - Summary**

652 Observations from sub-surface moorings, supplemented with regional remotely sensed data over the
653 period of November 2019 to March 2020 were used to evaluate the dynamical processes driving near
654 bed cooling at Egmont, a steep sloped atoll within the Chagos Archipelago and home to a large and
655 highly resident reef manta ray population. The basin-scale oceanographic regime, particularly the IOD,
656 exerted a controlling influence on the depth of the thermocline throughout the archipelago, driving a
657 historically deep thermocline during November 2019 and precluding the observation of cooling at 60-
658 70 m depth. A relaxing of the IOD coupled with standard seasonal evolution resulted in a shoaling of
659 the thermocline back into the 65-75 m depth range and the emergence of the temperature signals
660 associated with manta presence, driven at semi-diurnal frequencies.

661 At tidal, and subtidal frequencies differences in the thermal regime were seen between the central
662 Manta Alley mooring and the Western Manta Alley, and Ile De Rats moorings, despite a separation
663 distance of just 2.7 km. Simultaneous near-bed cooling was observed at tidal frequencies at both sites
664 with time synchronicity which precludes a freely propagating along-slope internal tide as the driver.
665 At both sites high frequency internal waves with periods, T , < 20 minutes were observed and
666 associated with subcritical Ri values, indicating the capacity of these waves to generate mixing through
667 shear instability that may influence zooplankton distributions and thereby manta foraging efficiency.

668 Some observed signals are consistent with the presence of mode-2 waves generated downstream of
669 interaction with steep topography. However, the complex local topography makes the differentiation
670 between mode-2 and mode-1 waves difficult. Wavelet analysis shows that the internal wave activity
671 varies in intensity, likely governed by the prevailing stratification and shear environments, and serves

672 as a reminder that these processes have extremely complex interactions that are challenging to
673 resolve either with in-situ observations or through numerical modelling.

674 The differences in tidal and sub-tidal cooling measured along Manta Alley demonstrates that, in highly
675 dynamical regimes, changes in the physical environment occur over short spatiotemporal scales. This
676 fine scale variability will generate changes in the underlying ecosystems, which may then play a role
677 in influencing the site preferentiality of highly mobile species such as reef manta rays. Overall, this
678 demonstrates the need to understand the fine scale dynamics when working at highly energetic sites
679 where reliance on coarse remote products, either satellite derived or modelled, produces an
680 erroneous perspective of physical processes at these sites where high frequency energetic dynamics
681 are underrepresented and local environmental gradients are occluded into single data points.

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References

- 687 A. Cordeiro, T. *et al.* (2013) 'Deep Chlorophyll Maximum in Western Equatorial Atlantic - How does it
688 Interact with Islands Slopes and Seamounts?', *Marine Science*, 3(1), pp. 30–37. Available at:
689 <https://doi.org/10.5923/j.ms.20130301.03>.
- 690 Abram, N.J. *et al.* (2008) 'Recent intensification of tropical climate variability in the Indian Ocean',
691 *Nature Geoscience*, 1(12), pp. 849–853. Available at: <https://doi.org/10.1038/ngeo357>.
- 692 Andrzejaczek, S. *et al.* (2020) 'Individual variation in residency and regional movements of reef
693 manta rays *Mobula alfredi* in a large marine protected area', *Marine Ecology Progress Series*, 639,
694 pp. 137–153. Available at: <https://doi.org/10.3354/meps13270>.
- 695 Armstrong, A.O. *et al.* (2016) 'Prey Density Threshold and Tidal Influence on Reef Manta Ray
696 Foraging at an Aggregation Site on the Great Barrier Reef', *PLOS ONE*. Edited by J.-S. Hwang, 11(5), p.
697 e0153393. Available at: <https://doi.org/10.1371/journal.pone.0153393>.
- 698 Armstrong, A.O. *et al.* (2019) 'Photographic identification and citizen science combine to reveal long
699 distance movements of individual reef manta rays *Mobula alfredi* along Australia's east coast',
700 *Marine Biodiversity Records*, 12(1), pp. 10–15. Available at: [https://doi.org/10.1186/s41200-019-](https://doi.org/10.1186/s41200-019-0173-6)
701 0173-6.
- 702 Armstrong, A.O. *et al.* (2021) 'Reef manta rays forage on tidally driven, high density zooplankton
703 patches in Hanifaru Bay, Maldives', *PeerJ*, 9, p. e11992. Available at:
704 <https://doi.org/10.7717/peerj.11992>.
- 705 Baines, P.G. (1973) 'The generation of internal tides by flat-bump topography', *Deep-Sea Research*
706 *and Oceanographic Abstracts*, 20(2), pp. 179–205. Available at: [https://doi.org/10.1016/0011-](https://doi.org/10.1016/0011-7471(73)90050-8)
707 7471(73)90050-8.
- 708 Balmforth, N.J. and Peacock, T. (2009) 'Tidal conversion by supercritical topography', *Journal of*
709 *Physical Oceanography*, 39(8), pp. 1965–1974. Available at: <https://doi.org/10.1175/2009JPO4057.1>.
- 710 Carr, M. *et al.* (2019) 'Shoaling mode-2 internal solitary-like waves', *Journal of Fluid Mechanics*, 879,
711 pp. 604–632. Available at: <https://doi.org/10.1017/jfm.2019.671>.
- 712 Chen, Z.-W. *et al.* (2014) 'Density stratification influences on generation of different modes internal
713 solitary waves', *Journal of Geophysical Research: Oceans*, 119(10), pp. 7029–7046. Available at:
714 <https://doi.org/10.1002/2014JC010069>.
- 715 Cheng, M.H. *et al.* (2017) 'Transformation of mode-2 internal solitary wave over a pseudo slope-
716 shelf', *AIP Advances*, 7(9). Available at: <https://doi.org/10.1063/1.5000972>.
- 717 Codiga, D.L. (2011) 'Unified Tidal Analysis and Prediction Using the UTide Matlab Functions',
718 (September), p. 59. Available at: <https://doi.org/10.13140/RG.2.1.3761.2008>.
- 719 Couturier, L.I.E. *et al.* (2011) 'Distribution, site affinity and regional movements of the manta ray,
720 *Manta alfredi* (Krefft, 1868), along the east coast of Australia', *Marine and Freshwater Research*,
721 62(6), p. 628. Available at: <https://doi.org/10.1071/MF10148>.
- 722 Deepwell, D. *et al.* (2019) 'Wave generation through the interaction of a mode-2 internal solitary
723 wave and a broad, isolated ridge', *Physical Review Fluids*, 4(9). Available at:
724 <https://doi.org/10.1103/PhysRevFluids.4.094802>.
- 725 Deepwell, D. and Stastna, M. (2016) 'Mass transport by mode-2 internal solitary-like waves', *Physics*
726 *of Fluids*, 28(5). Available at: <https://doi.org/10.1063/1.4948544>.
- 727 Dilmahamod, A.F., Hermes, J.C. and Reason, C.J.C. (2016) 'Chlorophyll-a variability in the Seychelles-

- 728 Chagos Thermocline Ridge: Analysis of a coupled biophysical model', *Journal of Marine Systems*, 154,
729 pp. 220–232. Available at: <https://doi.org/10.1016/j.jmarsys.2015.10.011>.
- 730 Du, Y. *et al.* (2020) 'Thermocline Warming Induced Extreme Indian Ocean Dipole in 2019',
731 *Geophysical Research Letters*, 47(18), pp. 1–10. Available at:
732 <https://doi.org/10.1029/2020GL090079>.
- 733 Durham, W.M. *et al.* (2013) 'Turbulence drives microscale patches of motile phytoplankton', *Nature*
734 *Communications*, 4, pp. 4–10. Available at: <https://doi.org/10.1038/ncomms3148>.
- 735 Farmer, D. and Armi, L. (1999) 'The generation and trapping of solitary waves over topography',
736 *Science*, 283(5399), pp. 188–190. Available at: <https://doi.org/10.1126/science.283.5399.188>.
- 737 Foreman, M.G. (1977) 'Manual for tidal heights analysis and prediction, Institute of Ocean Sciences,
738 Sidney', *Tech. Rep. Pac. Mar. Sci.* [Preprint], (January 1977). Available at:
739 [http://champs.cecs.ucf.edu/Library/Journal_Articles/pdfs/Manual for tidal heights analysis and
740 prediction.pdf](http://champs.cecs.ucf.edu/Library/Journal_Articles/pdfs/Manual%20for%20tidal%20heights%20analysis%20and%20prediction.pdf).
- 741 Fu, K.H. *et al.* (2016) 'The Deformation of Shoaling Internal Waves Observed at the Dongsha Atoll in
742 the Northern South China Sea', *Coastal Engineering Journal*, 58(2), pp. 1–19. Available at:
743 <https://doi.org/10.1142/S0578563416500017>.
- 744 Gemrich, J.R. and van Haren, H. (2002) 'Internal wave band eddy fluxes above a continental slope',
745 *Journal of Marine Research*, 60(2), pp. 227–253. Available at:
746 <https://doi.org/10.1357/00222400260497471>.
- 747 Harris, J.L. *et al.* (2020) 'Gone with the wind: Seasonal distribution and habitat use by the reef manta
748 ray (*Mobula alfredi*) in the Maldives, implications for conservation', *Aquatic Conservation: Marine
749 and Freshwater Ecosystems*, 30(8), pp. 1649–1664. Available at: <https://doi.org/10.1002/aqc.3350>.
- 750 Harris, J.L. *et al.* (2021) 'Fine-scale oceanographic drivers of reef manta ray (*Mobula alfredi*)
751 visitation patterns at a feeding aggregation site', *Ecology and Evolution*, 11(9), pp. 4588–4604.
752 Available at: <https://doi.org/10.1002/ece3.7357>.
- 753 Haury, L.R., Briscoe, M.G. and Orr, M.H. (1979) 'Tidally generated internal wave packets in
754 Massachusetts Bay', *Nature*, 278(5702), pp. 312–317. Available at:
755 <https://doi.org/10.1038/278312a0>.
- 756 Holloway, P.E. and Merrifield, M.A. (1999) 'Internal tide generation by seamounts, ridges, and
757 islands', *Journal of Geophysical Research: Oceans*, 104(C11), pp. 25937–25951. Available at:
758 <https://doi.org/10.1029/1999jc900207>.
- 759 Hosegood, P., Bonnin, J. and van Haren, H. (2004) 'Solibore-induced sediment resuspension in the
760 Faeroe-Shetland channel', *Geophysical Research Letters*, 31(9), pp. 2–5. Available at:
761 <https://doi.org/10.1029/2004GL019544>.
- 762 Hosegood, P. and Van Haren, H. (2004) 'Near-bed solibores over the continental slope in the Faeroe-
763 Shetland Channel', *Deep-Sea Research Part II: Topical Studies in Oceanography*, 51(25-26 SPEC. ISS.),
764 pp. 2943–2971. Available at: <https://doi.org/10.1016/j.dsr2.2004.09.016>.
- 765 Hosegood, P.J. *et al.* (2019) 'Internal lee waves and baroclinic bores over a tropical seamount shark
766 "hot-spot"', *Progress in Oceanography*, 172(June 2018), pp. 34–50. Available at:
767 <https://doi.org/10.1016/j.pocean.2019.01.010>.
- 768 Jaine, F.R.A. *et al.* (2014) 'Movements and habitat use of reef manta rays off eastern Australia:
769 Offshore excursions, deep diving and eddy affinity revealed by satellite telemetry', *Marine Ecology
770 Progress Series*, 510, pp. 73–86. Available at: <https://doi.org/10.3354/meps10910>.

- 771 Jones, A.R. *et al.* (2014) 'Fine-scale hydrodynamics influence the spatio-temporal distribution of
772 harbour porpoises at a coastal hotspot', *Progress in Oceanography*, 128, pp. 30–48. Available at:
773 <https://doi.org/10.1016/j.pocean.2014.08.002>.
- 774 Klymak, J. *et al.* (2012) 'The Direct Breaking of Internal Waves at Steep Topography', *Oceanography*,
775 25(2), pp. 150–159. Available at: <https://doi.org/10.5670/oceanog.2012.50>.
- 776 Lamb, K.G. (2004) 'Nonlinear interaction among internal wave beams generated by tidal flow over
777 supercritical topography', *Geophysical Research Letters*, 31(9), pp. 1–4. Available at:
778 <https://doi.org/10.1029/2003GL019393>.
- 779 Leichter, J.J. *et al.* (2012) 'The island-scale internal wave climate of Moorea, French Polynesia',
780 *Journal of Geophysical Research: Oceans*, 117(6), pp. 1–16. Available at:
781 <https://doi.org/10.1029/2012JC007949>.
- 782 Lennert-Cody, C.E. and Franks, P.J.S. (1999) 'Plankton patchiness in high-frequency internal waves',
783 *Marine Ecology Progress Series*, 186, pp. 59–66. Available at: <https://doi.org/10.3354/meps186059>.
- 784 Lennert-Cody, C.E. and Franks, P.J.S. (2002) 'Fluorescence patches in high-frequency internal waves',
785 *Marine Ecology Progress Series*, 235(Baines 1986), pp. 29–42. Available at:
786 <https://doi.org/10.3354/meps235029>.
- 787 Liang, J. *et al.* (2018) 'Generation of mode-2 internal waves in a two-dimensional stratification by a
788 mode-1 internal wave', *Wave Motion*, 83, pp. 227–240. Available at:
789 <https://doi.org/10.1016/j.wavemoti.2018.09.014>.
- 790 Liccardo, A. *et al.* (2013) 'Response of the deep chlorophyll maximum to fluctuations in vertical
791 mixing intensity', *Progress in Oceanography*, 109, pp. 33–46. Available at:
792 <https://doi.org/10.1016/j.pocean.2012.09.004>.
- 793 Liu, H. *et al.* (2022) 'Interannual variability of the thermocline depth in the south-central Indian
794 Ocean: Respective influences of IOD and ENSO', *International Journal of Climatology*, 42(10), pp.
795 5111–5120. Available at: <https://doi.org/10.1002/joc.7522>.
- 796 Liu, Z., Grimshaw, R. and Johnson, E. (2019) 'Generation of mode 2 internal waves by the interaction
797 of mode 1 waves with topography', *Journal of Fluid Mechanics*, 880, pp. 799–830. Available at:
798 <https://doi.org/10.1017/jfm.2019.679>.
- 799 Lu, B. and Ren, H.L. (2020) 'What Caused the Extreme Indian Ocean Dipole Event in 2019?',
800 *Geophysical Research Letters*, 47(11), pp. 0–2. Available at: <https://doi.org/10.1029/2020GL087768>.
- 801 Lü, X. *et al.* (2010) 'Upwelling and surface cold patches in the Yellow Sea in summer: Effects of tidal
802 mixing on the vertical circulation', *Continental Shelf Research*, 30(6), pp. 620–632. Available at:
803 <https://doi.org/10.1016/j.csr.2009.09.002>.
- 804 Mahadevan, A. (2016) 'The Impact of Submesoscale Physics on Primary Productivity of Plankton',
805 *Annual Review of Marine Science*, 8, pp. 161–184. Available at: <https://doi.org/10.1146/annurev-marine-010814-015912>.
- 807 Muchowski, J. *et al.* (2022) 'Potential and Limitations of a Commercial Broadband Echosounder for
808 Remote Observations of Turbulent Mixing', *Journal of Atmospheric and Oceanic Technology*, pp.
809 1985–2003. Available at: <https://doi.org/10.1175/jtech-d-21-0169.1>.
- 810 Müller, P. and Liu, X. (2000) 'Scattering of internal waves at finite topography in two dimensions,
811 Part II: Spectral calculations and boundary mixing', *Journal of Physical Oceanography*, 30(3), pp. 550–
812 563. Available at: [https://doi.org/10.1175/1520-0485\(2000\)030<0550:SOIWAF>2.0.CO;2](https://doi.org/10.1175/1520-0485(2000)030<0550:SOIWAF>2.0.CO;2).
- 813 Nikurashin, M. and Ferrari, R. (2010) 'Radiation and dissipation of internal waves generated by

- 814 geostrophic motions impinging on small-scale topography: Theory', *Journal of Physical*
815 *Oceanography*, 40(5), pp. 1055–1074. Available at: <https://doi.org/10.1175/2009JPO4199.1>.
- 816 Peel, L.R. *et al.* (2019) 'Movement and residency patterns of reefmanta rays *Mobula alfredi* in the
817 Amirante Islands, Seychelles', *Marine Ecology Progress Series*, 621, pp. 169–184. Available at:
818 <https://doi.org/10.3354/meps12995>.
- 819 Rayson, M.D. *et al.* (2018) 'Resolving high-frequency internal waves generated at an isolated coral
820 atoll using an unstructured grid ocean model', *Ocean Modelling*, 122(June 2017), pp. 67–84.
821 Available at: <https://doi.org/10.1016/j.ocemod.2017.12.007>.
- 822 Reid, E.C. *et al.* (2019) 'Internal waves influence the thermal and nutrient environment on a shallow
823 coral reef', *Limnology and Oceanography*, 64(5), pp. 1949–1965. Available at:
824 <https://doi.org/10.1002/lno.11162>.
- 825 Rohner, C.A. *et al.* (2013) 'Trends in sightings and environmental influences on a coastal aggregation
826 of manta rays and whale sharks', *Marine Ecology Progress Series*, 482, pp. 153–168. Available at:
827 <https://doi.org/10.3354/meps10290>.
- 828 Roquet, F. *et al.* (2015) 'Accurate polynomial expressions for the density and specific volume of
829 seawater using the TEOS-10 standard', *Ocean Modelling*, 90, pp. 29–43. Available at:
830 <https://doi.org/10.1016/j.ocemod.2015.04.002>.
- 831 Saji, N.H. *et al.* (1999) 'A dipole mode in the tropical Indian Ocean', *Nature*, 401(6751), pp. 360–363.
832 Available at: <https://doi.org/10.1038/43854>.
- 833 Thorpe, S.A. and Lemmin, U. (1999) 'Internal waves and temperature fronts on slopes', *Annales*
834 *Geophysicae*, 17(9), pp. 1227–1234. Available at: <https://doi.org/10.1007/s00585-999-1227-6>.
- 835 Velmurugan, A. (2015) 'Tropical islands', pp. 1–41. Available at:
836 <https://doi.org/10.1090/gsm/161/01>.
- 837 Vlasenko, V. and Alpers, W. (2005) 'Generation of secondary internal waves by the interaction of an
838 internal solitary wave with an underwater bank', *Journal of Geophysical Research C: Oceans*, 110(2),
839 pp. 1–16. Available at: <https://doi.org/10.1029/2004JC002467>.
- 840 Weeks, S.J. *et al.* (2015) 'Unique sequence of events triggers manta ray feeding frenzy in the
841 Southern Great Barrier Reef, Australia', *Remote Sensing*, 7(3), pp. 3138–3152. Available at:
842 <https://doi.org/10.3390/rs70303138>.
- 843 Williams, G.J. *et al.* (2018) 'Biophysical drivers of coral trophic depth zonation', *Marine Biology*,
844 165(4). Available at: <https://doi.org/10.1007/s00227-018-3314-2>.
- 845 Wolanski, E. and Delesalle, B. (1995) 'Upwelling by internal waves, Tahiti, French Polynesia',
846 *Continental Shelf Research*, 15(2–3), pp. 357–368. Available at: [https://doi.org/10.1016/0278-4343\(93\)E0004-R](https://doi.org/10.1016/0278-4343(93)E0004-R).
- 848 Xue, Y., Higgins, W. and Kousky, V. (2002) 'Influences of the Madden Julian Oscillations on
849 temperature and precipitation in North America during ENSO-neutral and weak ENSO winters', *Proc.*
850 *Workshop on Prospects for Improved Forecasts of Weather and Short-Term Climate Variability on*
851 *Subseasonal (2 Week to 2 Month) Time Scales*, pp. 1–4. Available at:
852 https://www.cpc.ncep.noaa.gov/products/precip/CWlink/daily_mjo_index/CPCmjoindex.pdf.
- 853 Zhao, Z. (2018) 'The Global Mode-2 M2 Internal Tide', *Journal of Geophysical Research: Oceans*,
854 123(11), pp. 7725–7746. Available at: <https://doi.org/10.1029/2018JC014475>.