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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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<u>Abstract</u>

- Physical oceanographic observations were made with subsurface, taut-line moorings at Egmont Island, a tropical atoll within the Chagos Archipelago in the central Indian Ocean, to elucidate the dynamics of near-bed cold-water intrusions implicated in driving local aggregations of reef manta rays (*M. Alfredi*). Manta have been previously shown to aggregate within 'Manta Alley', a lipped gully at 65 m depth along the north coast, at times when the surface to bottom temperature difference was highest. We here identify the dynamical processes driving these temperature differences and shaping 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 <u>1 - Introduction</u>

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; Weeks et al., 2015; Armstrong et al., 2016, 2019) and coastal populations have been observed to 30 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 though 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
- at a wide range of spatiotemporal scales act to govern the biophysical regime at Egmont atoll and are
- responsible for generating the site preferentiality for resident manta rays shown in Harris et al. (2021)



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

Here we show that the cold water, near-bed intrusions at Egmont are localised and intermittent, occurring predominantly at tidal periods but with higher frequency waves accompanying the tidal carrier wave as observed elsewhere (e.g. Hosegood and Van Haren, 2004). We further observe significant variability in internal wave behaviour and characteristics at different sites separated by short horizontal distances. Finally, we demonstrate that the depth to which cooling extends is dictated by the prevailing regional conditions where the IOD is responsible for migration of the thermocline atinterseasonal 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 <u>2 - Methodology</u>

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 period 13/11/2019 - 03/12/2019 (hereafter referred to as 'November') and the second, 104 105 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.

The specific geographic focus of this paper is constrained to Egmont (Fig. 2), an atoll on the 112 113 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 steep slopes, which routinely exceed 30° at depths <150 m, surrounding Egmont (Fig. 2b) are 116 117 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.



Fig. 2. a) Top-down view of Egmont with bathymetry overlaid on Landsat true colour imagery, indicated
 are the locations of mooring deployments with long-term moorings marked in red, and short-term
 moorings marked in blue. b) Local slope map of Egmont atoll calculated at 1 m cell size from multibeam
 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 manta along that specific bathymetric feature. Note that Egmont is a spatially distinct atoll separated 132 133 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**

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

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

- lagoon entrance but fortuitously coincided with the location at which manta presence was highestduring the period between cruises.
- Average currents were monitored during the period between cruises (November 2019 March 2020, corresponding to 102 days) and estimated from 2 minutes of sampling at 1 Hz every 10 minutes with a 2 m vertical resolution. Additionally, higher resolution burst data (velocity and echosounder) were acquired in 1 m bins at 1 Hz for the first 23 mins of each hour. During March, the ADCP deployed in 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.
- 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 Aquadopp 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.
- During March, the Ile De Rats mooring was deployed on the northern edge of Ile de Rats in 65 m water
 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 2 σ 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**

Tidal analysis of currents at the central Manta Alley mooring are based on continuous 10-minute average velocities calculated over 2 m vertical bins. Tidal decomposition was performed using the U-Tide toolbox (Codiga, 2011) and tidal constituents selected as defined in Foreman (1977). Tidal velocity reconstructions were calculated for each ADCP depth bin, excluding any constituent with a signal-to-noise ratio < 2. These predictions were then used to remove the periodic velocity signal, associated here with the barotropic tide, to isolate any non-periodic signals which may be associated 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 (Mahadevan, 2016; Hosegood et al., 2019), was estimated by the Richardson number, $Ri = N^2/S^2$ 198 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 199 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 200 velocities, respectively. Instability is expected for periods where Ri < 0.25, theoretically leading to the 201 202 development of Kelvin-Helmholtz billows within which vertical overturns are generated and that manifest themselves as temperature inversions. Density estimates for N² were calculated for the 203 204 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 topical eastern Indian Ocean as defined in 217 Saji *et al.* (1999) using the Reynolds OIv2 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)

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

230

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

Given the local topography, candidate mechanisms for the generation of near bed cooling implicated 232 233 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:

$$s = \sqrt{\frac{\sigma^2 - f^2}{N^2 - \sigma^2}}$$
[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. By this classification most slopes in the region are supercritical with respect to the internal tide, 243 244 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).

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

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

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

- cause shoaling of the thermocline (Liu *et al.*, 2022); the timescale and strength of the IOD varies,
 although recent years have shown an increased in bias towards positive events (Abram *et al.*, 2008;
 Du *et al.*, 2020). The modulation of the thermocline by these processes will in turn determine the
 depth band which any internal wave activity within the region impacts.
- 276 <u>4 Results</u>

277 <u>4.1 – Near bed cooling on the north face of Egmont Atoll: An overview</u>

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 cooling at the Manta Alley – Central mooring is reduced relative to the other two sites. For example, 281 282 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.



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

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



- 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

303

304

302

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

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 °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 °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 °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

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

are the three observational periods in Nov 2019 [1], over the long-term period [2], and in Mar 2020 [3]



Fig. 5. (a) Modelled (Copernicus) time series of temperature at -8.125 N 73.875 E with cruise timing 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. 6). The date of initial observation for cold water at the bed, defined here as a 2 °C difference across 349 350 the mooring range, Δ T, on the lle 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.





357 Due to the presence of a DCM within the Indian Ocean, the seasonal migration of the thermocline also resulted in vertical migration of the DCM. Comparing the hindcast data for Chl-a in November 2018 358 359 and 2019 (Fig. 7), it is apparent that the 60 m depth band (the depth at which the majority of Manta Alley lies) was comparatively depleted of Chl-a in 2019 compared to a more historically representative 360 year in 2018. Comparatively, at 100 m during 2019 there were higher Chl-a concentrations suggestive 361 of a DCM migrating with the thermocline which was a consistent feature from in-situ CTD profiles 362 363 taken during this period. These profiles show Chl-a concentrations at the thermocline of 0.82 μ g L⁻¹ compared to < 0.2 μ g L⁻¹ in the top 20 m of the water column (Fig. 7). This coupling of the thermocline 364 365 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

in 2018 (a, b) representative of a standard depth thermocline and 2019, (c, d) with the thermocline

deepened by the IOD. Egmont is marked by the black dot, visible is the comparatively depleted Chl-a
 at the depth of Manta Alley in 2019. e) Profiles of Chl-a from both scenarios in deep water to the south-

west of Eqmont, along with an in-situ profile taken in deep water off Eqmont 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) component is equal to that of the lunar semi-diurnal (M₂) component (Fig. 8). Semi-major axes 375 376 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.



Fig. 8. a) One month of observed currents in Manta Alley overlain with predicted tidal velocities from tidal decomposition analysis. b) Depth-mean tidal ellipses for the K₁ and M₂ components over the period of long-term observations taken from within Manta Alley. Within Manta Alley the magnitude of the K1 component matches that of the K2, not visible within the ellipse is the asymmetry in the strength of the tidal currents. c) FFT of depth averaged eastwards velocity showing equal powers for the K1 & M2 components



Fig. 9. Current roses inset into bathymetry at Egmont, showing the modulation of current direction by
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 <u>4.4 – Barotropic tidal forcing of near bed thermocline incursions</u>

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 M₂ periods and above (Fig. 10). Cold water incursions, evident as cold water at the seabed and extending vertically towards the surface, are visible at tidal 399 400 periods with vertical amplitudes of up to 40 m; these events generate Δ T >8 °C between the bed and 401 10 m depth over a short period (\approx 5 mins), and 4 °C over the course of a tidal period, compared to a 402 baseline Δ T of ~ 2 °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.



Fig. 10. Long-term thermistor data from Ile De Rats. low passed at 6 hours to remove high-frequency
oscillations and isolate the temperature change at the timescales associated with tidal (M2, K1)
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 lle 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 (2 σ) and the depth of the 26 °C isotherm 422 varied between > 64 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.

The limited corelation between the along-slope velocity, which is primarily driven by the barotropic tide, and the shoaling of the isotherm suggests that a freely propagating internal tide in the alongslope direction is relatively unlikely to be the driver of the observed cooling within Manta Alley. This is further corroborated by cross-correlation between temperature at a depth of 60 m at each site; no time delay is observed between the two signals over the period of observation, despite a horizontal 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 Rats and (c, d) Manta Alley – Central related to depth mean longshore velocity between 31 & 61 m 433 434 depth (overlapping observational range). Visible at Ile De Rats is the trend of raised isotherms during eastwards flow and depressed isotherms during westwards flow fitted with the linear regression y = -435 436 11.0x + 56.0 ± 12.3 CI95, R 0.11. Longshore [red] and cross-shore [blue] velocities shown with isotherm depth [black] with clear correlation between the peaks in cross-shore velocity and shallow isotherm. 437 438 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± 8.8 Cl95, 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

To assess the role of a cross-slope propagating internal tide in generating bed temperature 444 445 fluctuations at Egmont, the ability of nearby slopes to generate internal tides was calculated. The background stratification is strong, with temperature gradients up to 1.4 °C m⁻¹ observed in November 446 2019 and 0.5 °C m⁻¹ in March 2020 and peak N² values exceeding 4x10⁻³ s⁻² in 2019. The range of 447 observed N² values (Fig. 12) indicate that internal waves forced by the M₂ tide in the vicinity of Egmont 448 449 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 <u>4.6 — Baroclinic dynamics: High frequency internal waves and cooling events outside the barotropic</u> 453 <u>tidal regime</u>

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 °C intervals, whilst the second on 460 15/03/2020 09:00, shows strong stratification and the presence of colder 20 °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.

- During the first event a residual along-slope current amplitude of 0.5 m s⁻¹ was observed between 10 and 30 m above the seabed, with an associated decrease in temperature of 4.2 °C, from 26.3 °C to 22.1 °C, measured 2 m above the seabed with a peak rate of 0.28 °C per minute (measured over a 5min window). The barotropic velocity of ~ 0.5 m s⁻¹ was opposed by the baroclinic component responsible for the cooling, resulting in an observed current of effectively 0 m s⁻¹. This cooling persisted for a duration of 4.5 h before the thermocline returned to depths below the mooring (Fig. 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.
- A high concentration of scatterers within the upper edge of the thermocline can be seen for the duration of the cooling event, with a separate body of highly clear water below this scattering layer (Fig. 13f). Without ground truthing it is not possible to definitively establish the cause of these scatterers, with potential sources being sedimentary, biological, or turbulence based (Muchowski *et al.*, 2022). The presence of cold clear water below this high intensity band is, however, suggestive of either a plankton layer which has been vertically advected into the alley or reflections of stratified turbulence generated by the shear across the interface.



Fig. 13. a) K1 Tidal ellipses (Black) with instantaneous predicted tide quivers (Blue) and residual current quivers (Red) overlain and showing a cross-shore component near the bed. b) Temperature, c) baroclinic cross-shore velocity, d) baroclinic longshore velocity, e) vertical velocity, and f) echo amplitude from the Manta Alley – Central mooring showing two consecutive tidal periods which display different cooling characteristics. Seabed at 66 m. Panels b-f are overlaid with temperature contours at 1 °C intervals (29 – 23 °C) with the 26 °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
- 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 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 506 507 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.



Fig. 15. Spilling of an upslope propagating internal wave into Manta Alley, bringing a cooling of 3 °C
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.**

The shear associated with the near bed propagation of the internal waves shown in section 4.6 is likely 514 515 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 observed with near bed cooling signatures that generate mixing through shear instability. The first 517 518 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 ($N^2 > 1x10^{-5} s^{-2}$) (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 S² values orders of magnitude larger than the background water column, with values of 1×10^{-5} - 1×10^{-4} s⁻² in the background water column, and values in excess of 524 1×10^{-3} s⁻² at the interface of the wave. These waves are associated with reductions in Ri but not always 525 526 to the point of instability. Shear instability is primarily visible on the leading and tail edges of the short period waves, suggesting that these features enhance mixing across the boundary of the tidal period 527 528 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

tidal period cooling carrying higher frequency internal waves. b) 2-Dimensional vertical shear overlaid

532 with temperature contours, and areas where $Ri < 0.25 \& N^2 > 1x10^{-5}$ 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

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

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).



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

A subset of data from March 2020 (Fig. 18.) demonstrates the differences in thermal variability between IIe De Rats and Manta Alley. Both sites are highly active at tidal periods and show a high frequency internal wave signal which is clearly coincident with tidal forcing. This signal is more prevalent at IIe De Rats, with poorer definition within Manta Alley, but the magnitude of thermal 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

short period internal waves, however the effect is less pronounced at western Manta Alley.

560 <u>5 - Discussion</u>

561 Expanding on the results of Harris (2021) which focused on the impact of temperature on reef manta ray presence/absence at several sites around Egmont atoll, these results show that over short spatial 562 563 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 (Dilmahamod, 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

variation, as well as the duration for which depth bands may be excluded from cooling is likely tobecome 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 599 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 waves (Rayson et al., 2018) that likely promote turbulence. 613

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]).

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

629 (Gemmrich 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 pronounced ecosystem effects which impact on fine scale preferentiality in mobile species. The 636 637 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

rays (Couturier *et al.*, 2011; Weeks *et al.*, 2015), and other highly mobile marine species (Jones *et al.*,

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

location. Further work to validate the relationship between these cold water events and chlorophyllconcentrations 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 *<u>6 - Summary</u>*

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 highly resident reef manta ray population. The basin-scale oceanographic regime, particularly the IOD, 655 656 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.

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

- as a reminder that these processes have extremely complex interactions that are challenging toresolve either with in-situ observations or though numerical modelling.
- The differences in tidal and sub-tidal cooling measured along Manta Alley demonstrates that, in highly dynamical regimes, changes in the physical environment occur over short spatiotemporal scales. This fine scale variability will generate changes in the underlying ecosystems, which may then play a role in influencing the site preferentiality of highly mobile species such as reef manta rays. Overall, this demonstrates the need to understand the fine scale dynamics when working at highly energetic sites where reliance on coarse remote products, either satellite derived or modelled, produces an 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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