Observations of vertical turbulent nitrate flux during summer in the Great Australian Bight

M.J Doubell^{1*}, D. Spencer^{1, 2}, P.D van Ruth¹, C. Lemckert³ and J.F. Middleton¹

¹Aquatic Science Centre, South Australia Research and Development Institute, SA, 5024 Australia

²Cities Research Centre and School of Engineering, Griffith University, QLD, 4019, Australia

³School of Engineering, Mathematics and Statistics, Faculty of Science and Technology, University of Canberra, ACT 2617, Australia

*Corresponding author: mark.doubell@sa.gov.au

Abstract

To assist with developing an understanding of the nutrient supply dynamics in the Great Australian Bight (GAB) the vertical turbulent nitrate flux was calculated at stations along two cross-shelf transects using direct measurements of turbulence and nitrate concentrations. Coincident hydrographic profiling conducted at the onset of the summertime upwelling season revealed upwelling onto the shelf in the eastern GAB (eGAB) and downwelling at the shelf slope in the central GAB (cGAB). Under these conditions, examination of the strength of competing vertical temperature and salinity gradients using the Turner angle suggested a high potential for double diffusive convective mixing. However, corresponding estimates of the mixing efficiency derived from microstructure profiling indicated turbulence was the main mixing process driving vertical fluxes across the region. The average upward nitrate flux between the surface mixed layer depth (MLD) and the base of the euphotic layer (92 m depth) was $O(10^{-6}-10^{-5})$ mmol N m⁻² s⁻¹ in the cGAB, with the peak flux observed at the upper-slope station (~400 m total water depth). In the eGAB, the magnitude of flux estimates at the shelf-slope and offshore stations were similar to those measured in the cGAB. An enhanced nitrate flux $O(10^{-4})$ mmol N m⁻² s⁻¹ was observed on the shelf in the eGAB (~100 m total water depth) as the result of

enhanced turbulence and an increased vertical nitrate gradient. Application of Redfield stoichiometry suggests vertical turbulent nitrate fluxes play a significant role in supporting up to 50% of the primary production in the GAB. We hypothesize that mixing processes resulting from interactions between upwelled and downwelled water masses and new water masses formed on the shelf during summer play an important role in maintaining the bands of subsurface chlorophyll *a* maxima observed below the MLD at the nitricline during periods of strong stratification. The snapshot provided by this study, emphasizes the need to better understand the variability and influence of mixing processes on nutrient supply and productivity across the GAB marine ecosystem.

Keywords:

turbulence, microstructure, nutrients, upwelling, downwelling

1. Introduction

The Great Australian Bight (GAB) forms part of the world's longest zonal shelf (Fig. 1) and its temperate marine ecosystems support a variety of iconic and endangered marine species (Rogers et al., 2013, 2015; Goldsworthy et al., 2017; *Mackay et al. 2018) and valuable commercial fisheries (Ward et al., 2006; Eveson et al., 2015). The orientation and topography of the GAB includes a central region characterized by a wide, gently sloping shelf bordered by the narrow, steep shelf off Kangaroo Island to the east (Fig. 1a). Interactions between the shelf orientation and topography with summertime atmospheric forcing are expected to drive seasonal upwelling in the eastern GAB and year-round downwelling in the central and western GAB (Middleton and Bye 2007). Connected by the westward flowing Flinders Current (FC) along the continental slope (Bye, 2013; Middleton and Cirano, 2002), current speeds of 0.05 ms^{-1} between 300 to 600 m depth in the east (Cresswell and Petersen, 1993) suggest deep summertime connectivity across the GAB is weak. Hence, nutrient supply is likely to be influenced by mixing processes resulting from cross-shelf interactions between upwelling, downwelling and the formation of new waters on the shelf (Middleton and Bye, 2007; McClatchie et al., 2006; Richardson, 2015).

The eastern GAB (eGAB) is recognized as a region of episodic summertime upwelling; as prevailing south-easterly winds drive an offshore Ekman transport which draws cold, nutrient rich water (Kämpf et al., 2004; McClatchie et al., 2006) from depths as deep as 300 m (Kämpf, 2010) onto the shelf. Nutrient supply into the euphotic layer by upwelling is typically implied by lower sea surface temperatures (SST) and increased surface chlorophyll *a* (chl *a*) concentrations intermittently visible by satellite at upwelling hotspots centred off the Bonney coast and the southwestern tip of Kangaroo Island and the eastern Eyre Peninsula (Kämpf et al., 2004). Based on these observations, the occurrence of 2 to 3 major upwelling events per season, each with a duration of approximately 1 week, has been identified despite the persistence of long periods of upwelling favourable winds during summer (Kämpf et al., 2004). Subsequent observations have revealed the presence of subsurface chl *a* maxima (~ 50 m depth) associated with summertime stratification (McClatchie et al., 2006) may be a key source of elevated primary productivity measured in the eGAB during the summertime upwelling season (van Ruth et al., 2010). Over 500 km to the west in the central GAB (cGAB), the collision of the coastward Sverdrup transport with the seaward topographic transport is expected to drive year-round downwelling to depths greater than 200 m at the shelf-break (Middleton and Bye, 2007; Middleton et al., 2014). Hence, while the FC is likely to be important for deep upwelling along the slope to depths of 300 to 600 m (Middleton and Bye, 2007), downwelling at the shelf in the cGAB is expected to suppress nutrient supply and limit primary production.

Across the GAB, intense heating and evaporation experienced during summer months results in the formation of a warm-saline ocean surface layer overlying waters with a lower temperature and salinity (McClathie et al. 2006, Middleton and Bye, 2007). The resultant temperature and salinity profiles are expected to influence the stability of the density stratification and suggest double diffusive convection (hereafter double diffusion) may provide an additional mixing process alongside shear generated turbulence (hereafter turbulence) (Thorpe, 2007), provided the latter is relatively weak enough for double diffusion to be active (Gregg, 1988). Studies conducted in other oligotrophic (Lewis et al., 1986), upwelling (Hales et al., 2005, 2009) and frontal (Kaneko et al., 2013) systems have demonstrated vertical mixing due turbulence, and at times double diffusion (Oschlies et al., 2003; Nagai et al.,

2015), can be important mechanisms for the vertical supply of nutrients necessary for subsurface phytoplankton growth. In the GAB, analyses of summertime climatological nitrate data archived in the Commonwealth Scientific and Industrial Research Organization's Atlas of Regional Seas (CARS) has shown a large vertical nitrate gradient, with concentrations ranging from near zero at the surface to in excess of 5 mmol N m^{-3} at depths below 200 m across the GAB (Richardson, 2015). However, an understanding of the dominant mixing processes and quantification of the distribution of vertical nutrient fluxes across the GAB has not yet been described due to a lack of simultaneous observations of turbulence and nutrients.

In the following study, we investigate the mixing process in the GAB at the onset of the summertime upwelling season. With a focus on nitrate, an important fuel for primary production (Voss et al., 2013), the vertical turbulent nitrate flux is calculated along two cross-shelf transects located in the eastern and central GAB, respectively (Fig. 1). We discuss the significance of the observed vertical turbulent nitrate fluxes for supporting primary production in GAB. This study was undertaken as part of the multi-disciplinary Great Australian Bight Research Program (<http://www.misa.net.au/GAB>) with the objective of improving the understanding of the GAB ecosystems.

2. Data and Methods

Measurements of hydrographic structure, turbulence and nitrate concentrations were collected from the *RV Investigator* along two transects in the GAB. Sampling occurred at stations along the eastern GAB (eGAB) transect from November 30 to December 4 and the central GAB (cGAB) transect from December 10 to December 15, 2015 (Fig. 1).

To provide context to the regional-scale oceanographic conditions experienced in the GAB prior to and during the survey, remote sensed ocean surface data, wind and moored time-series of *in situ* water temperature were obtained. Remote sensed Level 3 OCM daily average surface chlorophyll *a* ($\text{chl } a$, $\mu\text{g l}^{-1}$) concentration, daily average sea surface temperature (SST, $^{\circ}\text{C}$) and daily sea surface height (SSH, m) for the period 20-November to 20-December were downloaded from the Australian Ocean Data Network (AODN; <https://portal.aodn.org.au/>). Hourly wind data was

obtained from the Bureau of Meteorology (BOM) Neptune Island automatic weather station. Wind data was standardized to 10 m height and the alongshore component of the wind stress (AWS) which drives coastal upwelling was determined by rotation of the principal axis relative to the orientation of the coastline, consistent with previous analyses for the eGAB (Kämpf et al., 2004; Middleton and Bye, 2007). Moored time-series of temperature at 35 m and 75 m depth measured at the Integrated Marine Observing System (<http://imos.org.au/>) Kangaroo Island National Reference Station (NRSKAI) were downloaded from the AODN.

2.1 Water Column Structure, Chlorophyll *a* and Nutrients

Hydrographic surveys were conducted at stations along cross-shelf transects in the eastern and central GAB (Fig. 1a). At each station, a rosette frame fitted with a Seabird9+ conductivity, temperature, depth (CTD) instrument, a Chelsea fluorometer and Niskin bottles were used to collect vertical profiles of temperature, salinity, chlorophyll *a* fluorescence and seawater samples. CTD profiles were made with a vertical resolution of about 1 m from the surface to (near) bottom in waters less than 800 m depth, or a maximum depth of 800 m in deeper waters.

Seawater samples were collected at approximately 10, 30, 65, 90, 120, 200, 300, 400 and 800 m depths and were analysed on-board for inorganic macro-nutrient concentrations using a Seal AA3HR segmented flow instrument. Here, we report on the distribution of nitrate, measured as oxides of nitrogen (i.e. nitrate + nitrite; NO_x), which is representative of the nitrogen source supporting new production (Voss et al., 2013). The detection limit for NO_x was $0.02 \text{ mmol N m}^{-3}$. Extracted chl *a* ($\mu\text{g l}^{-1}$) concentrations at each depth were determined by filtering 2 L seawater samples sequentially through $5 \mu\text{m}$ mesh and Whatman GF/F filters. Filters were stored on-board at -80°C prior to post cruise determination of pigment concentration using an Agilent 1200 series High-Performance-Liquid-Chromatography (HPLC) system. The size-fractionated chl *a* measures for each sample were summed to give a total chl *a* concentration and samples collected along the two transects were used to calibrate the fluorescence sensor ($r^2 = 0.79$, $p < 0.01$).

2.2 Turbulence, Mixing Processes and Flux Calculations

Vertical high-resolution profiles of temperature, salinity and velocity microstructure were collected at 4 stations along each transect (Fig. 1a) using a free-fall TurboMAP profiler (JFE Advantech Co., Ltd.). TurboMAP is equipped with two shear probes, a fast response thermistor (FP07) and sensors for the measurement of standard hydrographic parameters (CTD) (Wolk et al., 2002). Shear and FP07 data are sampled at 512 Hz and CTD sensors are sampled at 64 Hz. Typical profiling speeds were $0.5\text{--}0.6\text{ ms}^{-1}$ and profiling was limited to maximum depth of approximately 180 m or approximately 10–20 m from bottom in waters less than 200 m depth. Stations for turbulence measurements along each transect were commonly located at the shelf (sf), upper-slope (us) and mid-slope (ms) stations in 100 m, 400 m and 800 m water depths respectively. The shelf station in the eGAB coincided with the IMOS NRSKAI station. An offshore (off) station was located in water depths of 3000 m or greater. Following CTD profiling at each station, two consecutive microstructure profiles were made within approximately 20 minutes. In total 16 microstructure profiles were included in the analysis.

Measures of the turbulent kinetic energy dissipation rate (ε , W kg^{-1}) and temperature variance dissipation rate (χ , $^{\circ}\text{C}^2\text{ s}^{-1}$) at integrate levels of 2 m were processed using the TMTTools software (version 3.04A) (TMTTools, 2008) following standard methods (Ishizu et al., 2013; Doubell et al., 2009). Due to limited sensor resolution, unresolved variance in high wave number region of the shear and temperature gradient spectra were recovered by fitting the theoretical Nasmyth empirical spectrum (Nasmyth, 1970) and Batchelor spectrum (Batchelor, 1959), respectively (Oakey, 1982; Greg 1999). Estimates of ε were obtained by averaging across values from each of the two shear probes. Repeat profiles of ε and χ at each station were then averaged to provide a single value for each 2 m interval. Data from the surface to 10 m depth subjected to vessel-generated turbulence or profiler tilt, as well as and data below the sensor noise levels (Wolk et al., 2002), were discarded.

Considering the potential for double-diffusive mixing, measures of the Turner angle (Tu) and mixing efficiency (Γ_{obs}) were calculated to examine the relative dominance of mixing processes active across the GAB. Tu provides a useful measure to understand the strength of the competing temperature and salinity gradients

(Ruddick, 1983). Tu was computed using the TEOS 10 Gibbs-SeaWater Oceanographic Toolbox v3.06 (McDougall and Barker, 2011; <http://www.teos-10.org/>). When is Tu between -90° and -45° ‘diffusive’ double diffusion is possible. For Tu between 45° and 90° conditions are expected to be favourable for ‘salt fingering’ double diffusion. For Tu between -45° and 45° the water column is stably stratified with respect to both temperature and salinity. Estimates of the mixing efficiency were derived from microstructure profiles where $\Gamma_{obs} = (\chi N^2)/(2\varepsilon(\partial\bar{T}/\partial z)^2)$, and $N = -(g/\rho)(\partial\rho/\partial z)$ is the buoyancy frequency. Γ_{obs} provides a direct indication of active mixing processes (Oakey 1988). For Γ_{obs} less than 1 mechanical turbulent mixing dominates whereas for values greater than 1 more than half of the turbulent mechanical energy is expected to be converted to potential energy indicating active double diffusion.

The mean vertical eddy diffusivity of density, $\overline{K_\rho}$, was averaged over 10 m sections from 2 m scale estimates using the Osborn (1980) model where, $K_\rho = \Gamma \varepsilon / N^2$. The commonly used constant mixing efficiency (Γ) value of 0.2 is adopted (Thorpe, 2007). Several studies have shown Γ to be variable (see Ivey et al., 2018 and references within) with values greater than 0.2 typically occurring in areas of double diffusion (St. Laurent and Schmitt, 1999). While the precise value of Γ is the subject of continuing research, a recent examination of an extensive set of microstructure measurements demonstrated $\Gamma = 0.2$ to be generally constant for regions of the water column which are stably stratified (Monismith et al., 2018). Finally, the corresponding 10 m scale mean vertical turbulent flux of NO_x was then estimated as, $\overline{F_{NO_x}} = -\overline{K_z} \partial C / \partial z$, where C is the NO_x concentration and $-\partial C / \partial z$ is the vertical gradient of NO_x . Discrete measures of NO_x were linearly interpolated to provide values of $-\partial C / \partial z$ at the 10-m scale.

3. Results

3.1 Oceanographic Conditions

A synoptic view of remote sensed chl *a* concentrations (Fig. 1b) and SST (Fig. 1c) averaged over a 3 week period centred on the survey shows the presence of cooler surface waters (17°C or less) of the southwestern tip of Kangaroo Island and the southern tip of the Eyre peninsula in the eGAB. These cooler SST regions were

associated with increased chl *a* concentrations (approximately $0.5 \mu\text{g l}^{-1}$) relative to concentrations and temperatures measured in adjacent shelf waters to the south and west (Fig. 1b). Cooler SST's and increased chl *a* concentrations are also observed on the shelf to the south-east along the Bonney Coast. Collectively, the surface signatures of relatively cooler SST and higher chl *a* concentrations observed off the Eyre peninsula, Kangaroo Island and the Bonney Coast are indicative of large-scale upwelling (Kämpf et al., 2004) and are consistent previous observations of upwelling along Bonney Coast in November 2015 (Kämpf and Kavi, 2017). In the cGAB, surface water temperatures were warmer relative to the eGAB and decreased from approximately 20°C on the shelf to 18°C offshore. Chl *a* concentrations decreased from approximately $0.3 \mu\text{g l}^{-1}$ in shelf waters between the 100 and 200 m isobaths. At the slope and further offshore chl *a* levels were low and close to the limit of detection.

Analysis of the variability in wind strength and direction associated with the passing of atmospheric low and high pressure systems at Neptune Island showed the period leading up to (November), and during (December), the cruise was dominated by moderate to strong ($5\text{--}10 \text{ ms}^{-1}$) southerly winds (Fig. 2a). This resulted in a positive alongshore wind stress (AWS) and generally upwelling favourable conditions, with notable events occurring in early November and the latter part of sampling along the eGAB transect (Fig. 2b). Across this period, stronger periods of upwelling favourable Ekman transport were associated with the cooling of near bottom waters (75 m depth) relative to the general warming trend observed in the surface mixed layer (35 m depth) at the shelf station (NRSKAI) in the eGAB (Fig. 2c). This evidence of early season upwelling is expected to precondition the ocean thermohaline fields to have an upward tilt until downwelling and/or friction and diffusion act to oppose it. While relaxation of the upwelling occurred in the fortnight prior to sampling in the eGAB, a significant downwelling event and corresponding increase in near bottom waters did not occur until after the completion of the eGAB transect. Upwelling favourable winds returned during the cGAB transect. Thus upwelling favourable or neutral Ekman transport conditions pertained in the eGAB during the field survey.

Using CTD data to 800 m depth from the two transects, the temperature-salinity diagram (Fig. 3a) demonstrates connectivity of water masses between the eGAB and CGAB at depths below $\sim 200 \text{ m}$ ($\sigma_{\theta} > 26.7 \text{ kg m}^{-3}$, see Fig. 4). These deep water

masses, which include Tasmanian Intermediate Water (TIW), Tasmanian Subantarctic Mode Water (TSAMW) and South Australian Basin Central Water (SABCW), are predominantly formed off the west coast of Tasmania and are transported to the GAB by the Flinders Current (Richardson et al., 2009; Richardson, 2015). For depths shallower than ~200 m ($\sigma_\theta < 26.7 \text{ kg m}^{-3}$), the large scatter observed in temperature and salinity are associated with regional variations in heating and evaporation which result in mixing and the formation of local water masses on the shelf during summer (Richardson, 2015).

The NO_x -density relationship (Fig. 3b) shows NO_x concentrations increased with increasing density ($r^2 = 0.75$, $p > 0.01$). NO_x concentrations increased from low surface values near the limit of detection at densities less than $\sigma_\theta = 26.4 \text{ kg m}^{-3}$ to concentrations greater than 1 mmol N m^{-3} , indicative of the presence of the nitricline, at a density of $\sigma_\theta = 26.5 \text{ kg m}^{-3}$. Elevated NO_x concentrations, up to 30 mmol N m^{-3} , were observed at higher densities and corresponded with depths ranging between 600 to 800 m in the eastern and central GAB, respectively. These observations are consistent with the long-term climatological averages described in the CSIRO Atlas of Regional Seas (CARS) and demonstrate the presence of nutrient rich waters at depths below 200m along and offshore from the GAB continental slope.

Temperature, salinity and density cross-shelf structures along each transect to 200 m depth are presented in Figure 4. Surface temperatures along transects were in good agreement with remote sensed distributions (Fig. 1c). Both transects, showed strong vertical thermohaline contrasts across the upper 100 m of the water column and were characterised by a warm-saline surface layer overlying relatively cool-fresh waters of higher density. Strong stratification is shown by slanting and closely spaced isopycnals at the base of the surface mixed layer which was defined by a density of $\sigma_\theta = 26.3 \text{ kg m}^{-3}$ (Fig. 4). Mixed layer depths (MLD) for stations with turbulence observations had a mean and standard deviation of $60.2 \pm 3.3 \text{ m}$ in the cGAB and $40.3 \pm 15.2 \text{ m}$ in the eGAB. Short-term vertical variations in the depth distribution of high resolution temperature profiles between consecutive TurboMAP profiles (taken ~20 min apart) at each station were insignificant and no evidence for the modulation of the vertical distribution of the pycnocline, or nitricline, due to internal waves was observed within the resolution of our dataset.

Below the MLD, downwelling at the shelf slope in the cGAB was indicated by the downward displacement of the 26.5 and 26.6 kg m⁻³ σ_θ isopycnals to depths of approximately 150 to 230 m, respectively. This is consistent with previous studies which indicate downwelling is year-round feature at the slope in the cGAB (Middleton and Bye 2007; Middleton et al., 2014; Middleton et al., 2017). In comparison, the 26.5 to 26.7 kg m⁻³ isopycnals in the eastern GAB were shallower, with the 26.5 kg m⁻³ isopycnal located at a depth of approximately 80 m at the slope stations and 40 m on the shelf. Collectively, the NO_x-density relationship (Fig. 3) and temperature and salinity fields (Fig. 4) in the eGAB indicate the presence of cool-fresh, nutrient rich water on the shelf. This is consistent with the extended period of upwelling favourable winds (Fig. 2b) and subsurface temperature signals measured at the shelf (NRSKAI) station (Fig. 2c) in the weeks leading up to the survey (Fig. 2). The presence of a weak low pressure mesoscale eddy centred in deep water and between 36.8 and 37.2 °S (Fig. 1b) is a possible interpretation of the dome observed in the temperature salinity and density fields within and below the pycnocline offshore from the slope at the same latitude (Fig. 4a1, b1). In contrast, the distribution of the 26.5 to 26.6 kg m⁻³ isopycnals (Fig. 4) in the cGAB indicate nutrient rich offshore waters (Fig 3.) are downwelled to depths of 120 to 200m at the continental slope.

Chl *a* concentrations (Fig. 4 a3, b3) at the MLD were generally lower in the cGAB (< 0.3 µg l⁻¹) relative to the eGAB (~0.4 µg l⁻¹) and were in good agreement with the distribution low surface chl *a* levels overserved by remote-sensing (Fig. 1b). The slight increase in chl *a* concentrations observed offshore in the MLD of the eGAB (Fig. 4b3) may, in part, be associated with internal upwelling (Suthers et al. 2011) resulting from the presence of the low pressure eddy in this region (Fig. 1b).

Maximum chl *a* concentrations in the range 0.6 - 0.9 µg l⁻¹ were observed below the MLD in cross-shelf bands and aligned with the nitricline ($\sigma_\theta \sim 26.5$ kg m⁻³) across both transects. In the eGAB the subsurface chl *a* maximum (SCM) was narrower and located at higher in the water column (~40 to 80 m depth) relative to the cGAB (~70 to 130 m depth). Although limited, profiles of Photosynthetically Available Radiation (PAR) taken during the survey, the maximum depth of the euphotic layer to be approximately 92 m for both transects indicating the nitricline and associated SCM were located within the euphotic layer.

3.2 Mixing Processes and Turbulent Nitrate Fluxes

The Tu values calculated from high resolution profiles of temperature and salinity showed a high potential for double diffusion mixing processes across both transects (Fig. 5). Ocean conditions below the MLD were predominantly favourable to salt fingering ($45^\circ < Tu < 90^\circ$) at all stations in the eGAB and cGAB. Evidence for diffusive double diffusion ($-90^\circ < Tu < -45^\circ$) was observed near the base of the water column at the shelf stations and was most prominent in the eGAB where cooler-relatively fresh upwelled waters overlay warm, higher salinity waters originating from the shelf and Spencer Gulf. Comparison of 2-m scale Γ_{obs} and corresponding measures of Tu indicated that double diffusion was only likely to be active ($\Gamma_{obs} > 1$) in a very small fraction (approximately 1 %) of the regions where Tu suggested favourable conditions for double diffusion. Hence, despite the thermohaline structure being general favourable for double-diffusion at the time of the survey, turbulence was likely to be the major mixing process influencing vertical diapycnal fluxes.

The vertical distribution of NO_x over the upper 150 m of the water column for stations with corresponding 10 m scale estimates of the mean vertical eddy diffusivity for density, ($\overline{K_\rho}$) are shown in Figure 6. Since downwelling occurs in the cGAB (Fig. 4), NO_x concentrations of less than 3 mmol N m^{-3} were observed at depths above the base of the euphotic layer (92 m) at the shelf and slope stations (Fig 6). In contrast, for the eGAB, and as a consequence of upwelling (Fig. 4), NO_x concentrations greater than 3 mmol N m^{-3} were observed at depths above the base of the euphotic layer. For the offshore stations, similar NO_x concentrations of $\sim 3 \text{ mmol N m}^{-3}$ were observed at the euphotic depth in both transects. Maximum vertical NO_x gradients were associated with the depth of the nitricline and were located between approximately 40 m and 130 m depth across the GAB (Fig. 6a2, b2). Nitrate gradients were generally slightly higher at eGAB stations relative to corresponding cGAB stations; a likely consequence of upwelling and downwelling processes.

The vertical distribution of 10-m scale turbulent NO_x fluxes ($\overline{F_{NO_x}}$) (Fig 6. a4, b4) between the MLD and the base of the euphotic layer (Eu_z) ranged over 3 orders of magnitude from $O(10^{-7}-10^{-5}) \text{ mmol N m}^{-2} \text{ s}^{-1}$ and coincided with vertical fluctuations in $\overline{K_\rho}$ which spanned 4 orders of magnitude from $O(10^{-6}-10^{-3})$ (Fig 5. a3, b3).

Corresponding turbulent NO_x fluxes depth-averaged between the depth of the MLD and E_{u_z} were $O(10^{-5}-10^{-6}) \text{ mmol N m}^{-2} \text{ s}^{-1}$ in the cGAB and slope and offshore stations in the eGAB (Fig. 7). Increased depth-averaged fluxes of the $O(10^{-4}) \text{ mmol N m}^{-2} \text{ s}^{-1}$ were observed on the shelf in the eGAB (Fig. 7b). Differences in the vertical turbulent nitrate flux between sites in the central and eastern GAB (Fig. 7b) were the result of differences in $\overline{K_\rho}$ and the corresponding nitrate gradients (Fig. 6). For example, the importance of the nitrate gradient to the vertical flux is clearly demonstrated by comparison of the shelf station with the mid-slope and offshore stations in the cGAB (Fig. 7). Despite depth averaged $\overline{K_\rho}$ values up to an order of magnitude higher at the slope station, the corresponding low vertical NO_x gradient (Fig. 6a2) resulted in flux estimates of similar magnitude to those observed at the mid-slope and offshore stations (Fig. 7b). Additionally, comparison of the eGAB and cGAB shelf stations, clearly shows the elevated depth-averaged $\overline{K_\rho}$ values (Fig. 7a) and increased nitrate gradient observed at the eGAB shelf station (Fig. 6. a2, b2) resulted in the maximum observed vertical turbulent nitrate flux (Fig. 7b).

4. Discussion

We have presented, to our knowledge, the first simultaneous high-resolution measurements of turbulence and nitrate gradients in the shelf, slope and offshore waters of the GAB. Measurements were made at the commencement of the austral summer upwelling season. At this time, the observed along (Fig. 1) and cross-shelf (Fig. 4) distributions of temperature, salt, density and chl *a* were consistent with known response of downwelling in the cGAB and upwelling in the eGAB (McClatchie et al., 2006; Middleton and Bye, 2007; Middleton et al., 2014) and the early onset of significant seasonal upwelling observed along Bonney Coast in November 2015 (Kämpf and Kavi, 2017). Our observations support previous findings that suggest the mesoscale distribution of upwelling and downwelling across GAB occurs through interactions between the shelf orientation and topography and the summertime synoptic atmospheric forcing (Middleton and Bye 2007, Kämpf and Kavi, 2017).

The presence of warm-saline ocean surface layer overlying waters with lower temperature and salinity was observed across both transects (Fig. 4a,b). The strength of competing temperature and salinity gradients below the MLD in the shelf

and slope waters of the eGAB was enhanced through interactions with upwelled waters. Although the stability of the density stratification indicated by Tu suggested the area has a high potential for double diffusion, direct measures of Γ_{obs} indicated turbulence (i.e. shear generated) was the main mixing processes active during the study (Fig. 5). We note optimum profiling speeds of 0.1 ms^{-1} are preferred for resolving χ using the TurboMAP fast response thermistor (Gregg, 1998). These are less than those used in this study ($0.5\text{-}0.6 \text{ ms}^{-1}$) which were necessary to provide reliable estimates of ε . At times, agreement between the temperature variance spectrum and the Batchelor spectra was not as good as the corresponding agreement between the shear variance spectrum and the Nasmyth spectra. Hence the dominance of turbulence indicated by Γ_{obs} is not conclusive for this study and requires further investigations, particularly during late summer when the strength of opposing vertical temperature and salinity gradients are expected to strengthen.

Our findings show that upwelling and downwelling processes in the GAB strongly influenced the cross-shelf depth distribution of isopycnals (Fig.4) and hence the vertical distribution of nutrients (Figs. 3 and 6). For both regions, vertical fluxes due to turbulent mixing were upward due to the presence of positive vertical nutrient gradients (Fig. 6). Spatial variations in the vertical turbulent NO_x flux estimates were driven by changes in the strength of the vertical eddy diffusivity and the magnitude of the corresponding NO_x gradient (Fig. 6). Increases in $\overline{K_p}$ observed below the MLD on the shelf in the eGAB are the result of strong horizontal shear which develops as a consequence of summertime stratification and strong thermohaline differences between the warm, salty surface mixed layer and cooler, fresher waters upwelled from the continental slope. As a result, nutrient flux estimates depth-averaged between the MLD and the base of the euphotic layer, were observed to be an order of magnitude greater on the shelf in the eGAB relative to that observed elsewhere across the GAB (Fig. 7).

Measures of the depth averaged vertical turbulent NO_x flux between the MLD and the base of the E_{uz} layer (Fig. 7b) can be used to estimate the turbulent nutrient supply potentially available to support new production. Assuming the Redfield C:N ratio of 6.6 (Redfield, 1958), mean fluxes in the range $O(10^{-5} \text{ to } 10^{-4}) \text{ mmol N m}^{-2} \text{ s}^{-1}$ are capable of supporting primary productivity of between $78 \text{ and } 780 \text{ mg C m}^{-2} \text{ d}^{-1}$. Direct estimates depth integrated primary production over the euphotic zone for the

eastern and central GAB region during summer range between 130 and 3900 mg C m⁻² d⁻¹ (van Ruth et al., 2010; Kloser et al., 2017). Hence, our measures suggest the observed background turbulent supply of NO_x is capable of supporting between approximately 20 to 50 % of the total primary production. Thus turbulence, even at the lowest observed levels (Fig. 6), is an important, potentially essential, supplier of NO_x to the euphotic layer, particularly in the cGAB where year-round downwelling is expected (Middleton and Bye 2007; Middleton et al., 2014). This is evidenced by the cross-shelf bands of elevated phytoplankton biomass observed below the MLD during conditions of early summertime stratification (Fig. 4). In a global context, our observed vertical turbulent nitrate NO_x fluxes range in magnitude from upper limit estimated for the oligotrophic open ocean $O(10^{-6})$ mmol N m⁻² s⁻¹ (Lewis et al., 1986; Ledwell et al., 2008) to the lower range of values $O(10^{-4} - 10^{-3})$ mmol N m⁻² s⁻¹ reported in other temperate upwelling systems (Hales et al., 2005, 2009; Li et al. 2012).

This study, based on a modest dataset of turbulence and nutrient profiles, provides a regional snapshot that suggests the interaction of offshore waters with coastal waters on the shelf and slope are likely to be an important contributor to the nutrient fluxes which underpin shifts in lower trophic ecosystem composition and productivity observed as part of this survey (*Patten et al., 2018) and more generally across the GAB (van Ruth et al., 2010; *Patten and van Ruth, 2018). In particular, for the eastern GAB interactions between bathymetry, tides, wind forcing and internal waves (Middleton and Bye, 2007; Woodham et al., 2013) are expected lead to enhanced nutrient fluxes across a range of temporal scales which may explain the elevated levels of biomass (McClatchie et al., 2006), productivity (van Ruth et al., 2010) and ultimately fisheries (Ward et al., 2006; Eveson et al., 2015) observed in the eGAB. For the cGAB, under conditions of summertime downwelling, turbulent nutrient fluxes are expected to provide a constant background nutrient supply to the euphotic zone capable of maintaining the observed subsurface chl *a* maxima (Fig. 4). Although this study was limited to a snapshot made at the commencement of the upwelling season, the presented results highlight the importance of understanding nutrient supply processes that occur at sub-mesoscale scales and emphasize the need for greater sampling of turbulence, nutrients and phytoplankton in order to better

understand and quantify the full extent of turbulent nutrient supply variability and mixing processes in the GAB.

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Figure 1. Map and (a) bathymetry of the southern Australian shelf showing the location of cross-shelf transects sampled between November 30 to December 4, 2015 in the eastern Great Australian Bight (eGAB) and December 10 to 15, 2015 in central GAB (cGAB). Regional maps of satellite measures of (b) surface chlorophyll *a* (chl *a*) ($\mu\text{g l}^{-1}$) and (c) sea surface temperature (SST, $^{\circ}\text{C}$) and contours of sea level height (m) averaged over the period 30-November to 20-December, 2015. CTD profiles were made at all stations along each transect. Two consecutive

microstructure profiles were taken at stations identified by red markers. For both transects, microstructure profiling stations were taken at shelf (sh), upper slope (us), mid-shelf (ms) and offshore (off) stations centred on the 100, 400, 800 and 1000 m or greater isobaths, respectively. The location of Kangaroo Island (KI), Neptune Island (NI) and the Bonney Coast (BC) is shown in (b). The shelf station in the eGAB corresponds with the Integrated Marine Observing System (IMOS) Kangaroo Island National Reference Station (NRSKAI). The bathymetry of region is described by the 100, 200, 400, 800, and 3000 m isobaths contours in (b) and (c).

Figure 2. Meteorological and oceanographic indicators of upwelling in the eastern Great Australian Bight (GAB) prior to and during the sampling of cross shelf

transects in the eastern and central GAB. (a) Neptune Island wind data showing 3-hourly wind speed (ms^{-1}) and direction and (b) daily-averaged Alongshore Wind Stress (Pa). (c) Time-series of water temperature measured at 45 and 75 m depth obtained from the Integrated Marine Observing System (IMOS) Kangaroo Island National Reference Station (NRSKAI) bottom mooring located in 100 m water depth at shelf station on the eGAB transect. The temporal duration of sampling along the cross-shelf transects in the eastern and central GAB are shown by blue and red bars on the x-axis.

Figure 3. (a) Temperature-salinity plot from CTD profiling made to 800m depth along transects in the eastern and central GAB. Absolute salinity ($S_A, \text{g kg}^{-1}$) is plotted on the a-axis and potential temperature θ ($^{\circ}\text{C}$) is on the y-axis along with contour lines of potential density σ_{θ} (kg m^{-3}). (b) NO_x -density plot determined from discrete water sampling and CTD profiling. NO_x concentrations (mmol N m^{-3}) are plotted on a log scale. For (a) and (b) blue and red markers represent values for the eastern and central GAB, respectively. Identified water masses in (a) are defined according to Richardson (2015) and include; Tasmanian Intermediate Water (TIW), Tasmanian Subantarctic Mode Water (TSAMW), and South Australian Basin Central Water (SABCW). Locally formed water masses include Slope Water (SW), Mixed Slope Water (MSW), Cooled Evaporated Water (CEW) and Evaporated Water (EW).

Figure 4. Vertical transect sections to depths of 200 m constructed from CTD profiling in (a) the central GAB (cGAB) and (b) the eastern GAB (eGAB) showing the distribution of; (a1, b1) potential temperature (θ , $^{\circ}\text{C}$), (a2, b2) absolute salinity (S_A , g kg^{-1}) and (a3, b3) chlorophyll a concentration ($\mu\text{g l}^{-1}$). Contours show lines of potential density (σ_{θ} , kg m^{-3}). The location of CTD stations shown are marked as small ticks along the top and bottom x-axis. The corresponding position of microstructure stations sampled at shelf 'sf', upper slope 'us', mid-slope 'ms' and offshore 'off' stations are indicated by the labels on the top x-axis.

Figure 5. Scatter plot of the observed mixing efficiency (Γ_{obs}) and Turner angle (Tu) measured from microstructure profiling along transects in the eastern (eGAB) and central (cGAB) Great Australian Bight.

Figure 6. Vertical profiles for (a) the central Great Australian Bight (cGAB) and (b) the eastern GAB showing the measured; (a1, b1) NO_x concentration (mmol N m^{-3}), (a2, b2) NO_x gradient (mmol N m^{-4}), where C is the NO_x concentration, (a3, b3) 10-m average vertical eddy diffusivity ($\overline{K_\rho}$, $\text{m}^2 \text{s}^{-1}$) and corresponding (a4, b4) vertical turbulent NO_x flux ($\overline{F_{\text{NO}_x}}$, $\text{mmol N m}^{-2} \text{s}^{-1}$). Station labels shelf 'sf', upper-slope 'us', mid-slope 'ms' and offshore ('off') stations for each transect are indicated by the colours red, light blue, dark blue and black, respectively. Horizontal dashed lines represent the mean surface mixed layer depth ('mld') and the maximum euphotic layer depth (Eu_z) for each transect. Horizontal (x) axis on plots of the vertical eddy diffusivity and vertical turbulent NO_x flux are in logarithm scale and thick and thin lines denote the average and standard deviation, respectively.

Figure 7. Microstructure profiling derived cross-shelf distributions of the mean (a) vertical eddy diffusivity ($\text{m}^2 \text{s}^{-1}$) and (b) vertical turbulent NO_x flux ($\text{mmol N m}^{-2} \text{s}^{-1}$) depth-averaged over the water column between the mean surface mixed layer depth (MLD) and the maximum euphotic layer depth (Eu_z) for transects in the eastern (eGAB, blue lines) and central (cGAB, red lines) Great Australian Bight (GAB). Thick and thin lines denote the average and standard deviation. Station locations shelf 'sf', upper-slope 'us', mid-slope 'ms' and offshore ('off') along each transect are indicated on the x-axis.

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