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Comparison of the cross-shelf phytoplankton distribution of two oceanographically distinct regions off Australia

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ABSTRACT

The coastline of Australia spans tropical to temperate latitudes and encompasses a highly diverse phytoplankton community. Yet little is known about environmental driving forces of compositional and distributional patterns in natural phytoplankton communities of Australia. We investigate the relationships of phytoplankton (pico-, nano-, microphytoplankton, determined by microscopy and CHEMTAX) with a variety of environmental variables along cross-shelf gradients. Case studies were conducted in two highly distinct oceanographic regions of Australia (2010/2012): the tropical-temperate Coffs Harbour region (~30°S, 153°E), where the shelf is narrow (~30 km), and the tropical Kimberley region (~16°S, 122°E), where the shelf is wide (~200 km). We distinguished three water masses in both study regions: relatively cold, nutrient-rich inshore waters; oligotrophic, stratified offshore waters; and cold, nutrient-rich deep waters. Most phytoplankton taxa (cyanobacteria, cryptophytes, dinoflagellates, haptophytes and prasinophytes) showed group-specific relationships with similar environmental variables in both regions. Diatoms occurred in nutrient-rich inshore waters in the Kimberley, whereas they were widely spread across the narrow continental shelf at Coffs Harbour. Off Coffs Harbour, a senescent bloom of the diatom *Leptocylindrus danicus* probably caused shelf-scale surface nutrient depletion. While microphytoplankton clearly increased, pico- and nanophytoplankton decreased with distance from the coast over the wide shelf in the Kimberley region. In contrast, the abundance of individual phytoplankton size-classes remained relatively constant across the narrow Coffs Harbour shelf. We conclude that general similarities exist between the relationship of phytoplankton and cross-shelf environmental variables in the two sites and assign differences primarily to the varying spatial resolution of our case studies.

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1. Introduction

Global phytoplankton dynamics are expected to be modified as a result of climate-change-induced alterations in the oceanographic environment (Hays et al., 2005; Hallegraeff, 2010). Around Australia, long-term changes in the oceanographic environment are, for example, expressed by the progressive strengthening of the East Australian Current (EAC; Ridgway, 2007). Observational data from ~60 years show increases in sea temperature and salinity of 2.28 °C century^{-1} and 0.34 psu century^{-1} at the surface at ~43°S, 148°E (Maria Island, Tasmania; Ridgway, 2007). The expected effects on the phytoplankton community include an earlier timing of the annual spring bloom, increased frequency of harmful algal blooms and species range expansions (Hallegraeff, 2010). In fact, several dinoflagellates have already been found to migrate poleward along the east Australian coast with the strengthening EAC (McLeod et al., 2012; Buchanan et al., 2014). In order to decipher such long-term trends in phytoplankton species distribution it is crucial to also have a good knowledge of the natural variability of phytoplankton in their oceanographic environment.

Coastal and shelf regions provide suitable locations for studies focussed on resolving interactions between gradients of environmental variables and phytoplankton dynamics. Depending on the width of the

Abbreviations: ITF, Indonesian Throughflow; DistLM, distance-based Linear Model; CCA, Canonical Correspondence Analysis.

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continental shelf, gradients in vertical mixing, nutrient availability and light regime can be found within a few (or a few hundred) kilometres across the shelf. Inshore waters are often nutrient-rich and well-mixed (e.g. during upwelling periods or due to tidal activity) and offshore regions can become quite oligotrophic and stratified (e.g. during summer) with a deep euphotic zone (Smayda and Reynolds, 2001). Frequently, near-shore waters are additionally impacted by anthropogenic nutrient input, which has been demonstrated to significantly shape coastal phytoplankton community structures (Fehling et al., 2012; Goodman et al., 2012; Greenwood and Craig, 2014). High turbulence has been shown to be a prerequisite for large and heavy cells, such as silicified diatoms, to stay suspended and to acquire nutrients (Kiørboe, 1993). On the contrary, small cells with high S:V ratios have been reported to prefer oligotrophic conditions, in which their small size prevents them from sinking and nutrients can be taken up efficiently (Kiørboe, 1993).

Along the Australian coast, research aimed at understanding cross-shelf variability in phytoplankton abundance, composition and distribution along environmental variable gradients, such as mixing/stratification and nutrient-accessibility, is still in its infancy. It has been shown that microphytoplankton (in particular diatom) abundance decreases with increased distance from the coast, while nano- and picophytoplankton (particularly the picoplanktonic cyanobacteria *Synechococcus* and *Prochlorococcus*) are more abundant offshore (Thompson et al., 2011a). Such size-dependent distribution patterns have been reported on a large spatial scale from the east and west coasts of Australia between 27.5°S and 34.5°S (Thompson et al., 2011a) and also in regional studies from the Coffs Harbour (30°S, 153°E, Eastern Australia; Armbrecht et al., 2014) and Kimberley coasts (~16°S, 126°E, North-Western Australia; Thompson and Bonham, 2011). Yet, detailed information on how such cross-shelf distribution patterns can be explained based on gradients in specific environmental variables, associated with coastal and offshore water masses, is still missing along the Australian coastline.

Within this study we aim to determine the relationships of pico- to microphytoplankton with specific environmental conditions (including temperature, stratification, depth, salinity and nutrient availability) that may vary along cross-shelf gradients. To additionally investigate how environmental variables and phytoplankton distribution change over different extents of the continental shelf, we compare two distinct study sites along the east and west Australian coast. The tropical-temperate Coffs Harbour region is located upstream of the point where the East Australian Current (EAC) separates eastward from the coast (~32°S). Frequent EAC-, wind-, and topographically-driven upwelling has been reported in the region, with current-driven upwelling and uplift induced along the very narrow (~30 km wide) continental shelf (Roughan and Middleton, 2002; Schaeffer et al., 2014b). Upwellings have been shown to be associated with nutrient input and phytoplankton blooms in the coastal euphotic zone along the east Australian coast (Ajani et al., 2001; Pritchard et al., 2003; Armbrecht et al., 2014), especially during spring and summer when winds and EAC strength are at their annual maximum (Rossi et al., 2014). The tropical Kimberley region (~16°S) is characterised by a broad continental shelf of ~200 km width that interacts with the Indonesian Throughflow (ITF) to generate massive tides (~10 m) promoting extensive vertical mixing (Mustoe and Edmunds, 2008; Thompson and Bonham, 2011). Despite the low seasonality in this tropical region (Tranter and Leech, 1987), phytoplankton biomass has been reported to increase as a result of the strengthening ITF during winter (Thompson and Bonham, 2011; Thompson et al., 2011b).

In this investigation oceanographic, phytoplankton abundance and pigment data collected during the formation of the winter phytoplankton bloom off the Kimberley coast in April 2010 (Thompson and Bonham, 2011) are re-analysed alongside similar data collected during a spring bloom period in the Coffs Harbour region in September 2012. Relationships between environmental variables and the microscopy- and pigment-derived phytoplankton community are investigated via multivariate analyses (where pigment data is optimised in the software CHEMTAX; Mackey et al., 1996). We hypothesise that similar environmental variables will be associated with the abundance of specific phytoplankton groups in both study regions, despite the difference in geography and oceanographic conditions. We expect to find a decrease versus an increase in microphytoplankton versus pico- and nanophytoplankton with distance from the coast, which may be more pronounced in the Kimberley region where the continental shelf is much wider than at Coffs Harbour. More specifically, we expect diatoms to be highly abundant in well-mixed inshore waters while all other taxa are predicted to occur under different combinations of temperature, stratification, depth and nutrients in both regions. In the subsequent sections we will describe the approach used in the Coffs Harbour and Kimberley regions and present the results separately for each region. Similarities and/or differences between phytoplankton responses to environmental gradients determined in the two case studies are discussed within a broader regional context.

2. Methods

2.1. Hydrographic sampling

An overview of the sampling locations, dates and the hydrographical sampling procedures including research vessels, equipment and data-post processing procedures used can be found in Table 1. Details on Conductivity-Temperature-Depth (CTD) derived degrees of stratification and fluorescence profiles are also described in Table 1. All sampling stations are shown in Fig. 1.

2.2. Phytoplankton

At Coffs Harbour, 2 L of seawater were immediately preserved using Lugol's acid solution (Sournia, 1978). After sedimentation (for 48 h) at the laboratory, phytoplankton identification and enumeration under an inverted microscope (Leica DMI3000B) followed Utermöhl (1958). A minimum of 400 cells were counted with the lower size limit discernible being 10 μm, i.e. the microphytoplankton class was best enumerated (specifically, diatoms and dinoflagellates). The exact counting procedure is described in Armbrecht et al. (2014), with the exception that all dinoflagellates belonging to the genera *Alexandrium, Gonyaulax, Heterocapsa* spp. were grouped.

On the Kimberley voyage, 1 L water samples were preserved using acid Lugol's solution for phytoplankton identification and enumeration by microscopy (Parsons et al., 1984). Post-cruise and after sedimentation (for 24 h), phytoplankton composition was analysed in 1 mL Sedgwick Rafter counting chambers under an inverted microscope (Olympus IX 71). At least 10% of the chamber were counted for cells >20 μm at 100× unless they occurred in high densities, in which case only 2% were counted. For nanoplankton, counts at 400× were completed when at least 200 cells of the dominant taxon were counted, and cells <10 μm were assigned to the group "undefined flagellates". For a detailed description of sedimentation and counting procedures see Thompson and Bonham (2011).

2.3. Pigments

At Coffs Harbour, one replicate sample for High-Performance Liquid Chromatography (HPLC) analyses was prepared by immediately filtering 2 L of water collected at the surface and DCM at all sampling locations onto 25 mm GF/F filters (Whatman, UK). Previous statistical testing of duplicate pigment samples collected in the Coffs Harbour regions has shown a strong positive correlation (R^2 between 0.992 and 1, average $R^2 = 0.997$, standard deviation = 0.002, n = 23; Armbrecht et al., under review) thus we consider our data as robust. Subsequently, filters were frozen in liquid nitrogen until further analysis (at the laboratories of the Commonwealth Scientific and Industrial Research Organisation, CSIRO, Hobart). HPLC analysis followed

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