

Response to reviewers: os-2018-115 (Submitted to *Ocean Science*)

Seasonal and inter-annual variability of water column properties along the Rottnest continental shelf, south-west Australia by Miaoju Chen, Charitha Pattiaratchi, Anas Ghadouani and Christine Hanson.

We would like to thank and acknowledge both reviewers and the editor for their careful reading and constructive comments on the manuscript. There were no public comments. We believe that we have addressed the issues raised by reviewers and the proposed changes to the manuscript are detailed in this document. We trust that the reviewers and the editor will find that the suggested changes will make the manuscript to be suitable for publication.

In the following, black indicates the comments by the reviewer; blue is our response to the reviewers. The text in red are changes to the manuscript.

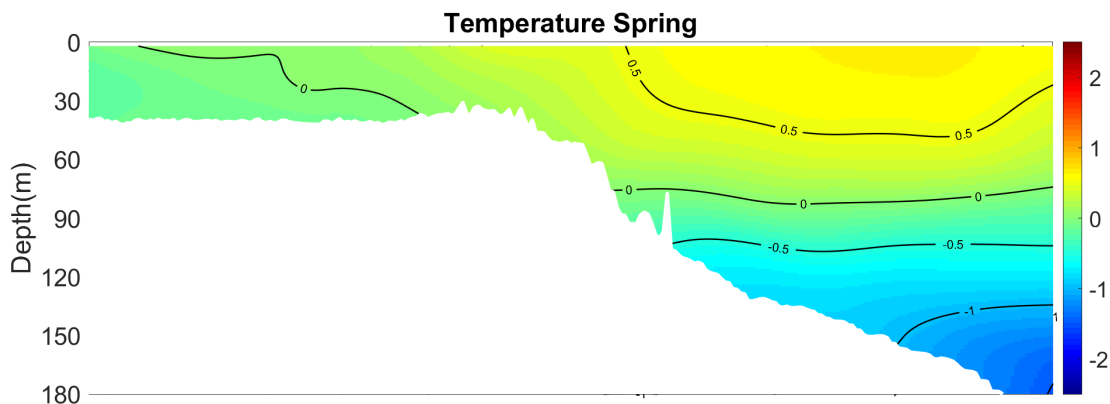
Reviewer #1

(1) The abstract is toooooooo long. Can it be shortened?

The journal guidelines does not specify a word limit for the abstract and currently consist of 360 words. At the suggestion of the referee we have revised and shortened the abstract currently it is 259 words.

(2) Colors can be deceptive. Please add contours to Figures 6,7 and 8.

At the suggestion of the referee we have included contours in Figures 6, 7 and 8. As an example, temperature distribution for spring is provided below:



(3) What do you mean by structure anomalies in Figures 6,7, and 8? Anomalies relative to a surface value? Relative to a seasonal average? Or an annual average? Please show absolute distributions or, at least, the reference value/profile that your anomalies are based on. Perhaps, you should also present seawater density distributions and discuss seasonal variations of the density structure.

Thank you for your comments. We first examined the mean values by season. However, the seasonal variation in parameters obscured the patterns and thus we presented anomalies that were calculated relative to the seasonal mean over the measurement period calculated through water depth and distance. For reference we have included absolute distributions as well as density distributions as supplementary information. The mean distribution for each parameter for the different seasons are included as a Table.

We have also modified the text to make clearer how the anomalies were calculated with the following text with a new Table added to indicate the value for the mean for each parameter over different seasons.

The text has been modified as follows:

When examining the seasonal changes it was found that the changes in the mean values obscured the seasonal variability of each parameter (temperature, salinity, and chlorophyll). Hence, in addition to presenting the measured values we also calculated anomalies to remove the influence of the seasonal variability. The procedure for each parameter (~28 million individual points) was as follows: (1) data were interpolated onto a common grid across the cross shelf transect; (2) transects were then sorted according to season: spring (September-November), summer (December-February), autumn (March-May) and winter (June-August); (3) the mean value across the whole transect (i.e. through water depth and across distance) for each season was calculated (Table 1); and, (4) the anomaly at each grid point was calculated by subtracting the seasonal mean from values at each point.

Table 1 – Mean values of temperature, Salinity and chlorophyll fluorescence for each season used to calculate the anomalies.

	Temperature (°Celsius)	Salinity	Chlorophyll fluorescence (mg/m ³)
Spring	19.4	35.35	0.49
Summer	21.9	35.61	0.46
Autumn	22.4	35.42	0.71
Winter	19.8	35.27	0.68

(4) Figure 9 is difficult to interpret. Is there a way to fill the data gaps using satellite SST? Why do you present this figure? Perhaps this would be better placed in the methodology section together with a discussion of data gaps?

It is not possible to fill the data gaps using satellite imagery (for SST or chlorophyll) as these are not surface values – rather they are depth integrated (surface 30 m) values. They are also time averaged – each line represent a single glider deployment lasting 3-4 weeks. In the methods section we have noted that as the glider moved in a saw tooth pattern, and gaps in the data occur when sampling deep waters – resulting in data gaps in the deeper waters.

We have retained this figure as we believe that it illustrates the inter-annual variability. For example it highlights the marine heat wave (red lines - summer 2011) and cooler summers (yellow line – summer 2009, 2015). Similarly the figures indicates higher salinity during these summers (red line - summers 2010, 2014, 2015). We have highlighted these in the revised manuscript:

The data highlights the interannual variability. For example, the marine heat wave during the 2011 La Niña events is evident (red lines - summer 2011) as well as the cooler summers in 2009 and 2015 (yellow lines). Similarly, higher salinities were recorded during summers 2010, 2014, 2015 that were associated with El Niño events (red lines).

(5) It would be nice to have true chl-a values rather than just data from the BBFL2SLO optical sensor. How confident are you that your fluorescence data represent true chl-a, in particular close to the seafloor? How is this bottom chl-a maximum created? Is there any reason why you decided not to discuss CDOM?

We agree with the reviewer that ‘true’ chlorophyll values will add great value to this study, and we are aware that a common practice for compensating for the variability in fluorescence yield is to calibrate a fluorometer through the statistical comparison of fluorescence readings with measurements of concentration of chlorophyll from concurrently collected water samples (Cullen and Lewis 19956; Hersh and Leo 2012). However, due to the nature of glider deployments, which operate for extended periods of time and space without human interaction, mounting a water sampling regime is neither logistically nor financially feasible.

It should be noted that only few studies have used ‘true’ chlorophyll a to define seasonal and inter-annual variability through the water column. The collection of routine water samples (say for HPLC or acetone extractions) over long time periods (e.g. years) are often not possible due to operational and financial considerations. Similar studies use satellite derived chlorophyll which is also an indirect measurement relating upwelling radiance to chlorophyll a but is also limited mainly due to yielding surface values. Thus we believe that the data presented in this paper is unique in that a long-term data set that includes the water column is presented.

However, as part of the IMOS ocean glider program we have undertaken many studies to

address the conversion/relationship between the fluorescence values from the BBFL2SLO optical sensor and ‘true’ Chlorophyll a. These were undertaken both in the laboratory (Earp et al., 2011) and in the field (Thomson et al., 2015). In the latter, we attached a glider to a rosette sampler and collected concurrent data from the glider and Niskin bottles at surface, mid-depth and bottom of the water column in 100m depth. The water samples were subjected to HPLC analyses to determine the ‘true’ Chlorophyll a concentrations. The comparison between ocean glider derived fluorescence and the HPLC Chlorophyll a concentrations was very good with $r^2 > 0.75$ ($n > 100$) in the range 0.17 to 0.21 (mg m^{-3}).

A recent study by Beck (2016) found that, through inter-comparison of chlorophyll a and Wetlabs ECOPUCK derived fluorescence on ocean gliders, the original manufacturer’s recommendation for the estimation of chlorophyll a from fluorescence provided the best estimate.

The WETLabs BBFL2SLO 3 fluorescence values were estimated using the conversions provided by the manufacturer. A recent study by Beck (2016) found that, through inter-comparison between chlorophyll a derived from HPLC and Wetlabs BBFL2SLO 3 derived fluorescence on ocean gliders, the original manufacturer’s recommendation for the estimation of chlorophyll a from fluorescence provided the best estimate.

The bottom chl-a maximum is created in many ways. The study region has very clear water and thus light penetration is large (1% light level is > 100 m). The region is oligotrophic so there are no nutrients in the water column. Our shipborne measurements indicated that the nitrate concentrations were below detection levels (Twomey et al., 2007). We believe that there is some supply of nutrients onto the bottom layer through two possible sources: (1) regeneration from the organic matter on the seabed particularly during storm events; and, (2) advection onto the shelf from offshore through upwelling – this also may indicate the sub-surface chlorophyll maximum ‘migrating’ onto the shelf.

Yes there is a very good reason why we decided not to discuss CDOM – in a region with very little riverine input the CDOM concentrations were very small – almost negligible – except during occasional storm events. When averaged over a season there was no detectable changes. Similarly backscatter (a proxy for suspended matter). Hence, this paper is addressing the variability in chlorophyll concentrations only. A paper in preparation for publication is addressing the short-term changes of order days.

(6) In our previous study (Kämpf and Kavi, 2017), we identified seasonal chl-a maxima in the Great Australian Bight in austral autumn months. Is this feature, which is not too far away from your study region, consistent with your observations? If so, please discuss this.

Thank you for the comment. We have read through Kämpf and Kavi, (2017) and included this reference and discussed in section 4 as follows:

The observed surface chlorophyll features agreed with Kämpf and Kavi (2017), who showed widespread phytoplankton blooms (chlorophyll concentrations $\sim 1\text{mg}/\text{m}^3$) during autumn and winter using satellite data along the southern Australia coastline.

(7) In the last sentence of the abstract you claim that "It is concluded that the observed seasonal and inter-annual variability in chlorophyll fluorescence concentrations were related to the changes in physical forcing (wind forcing, Leeuwin Current and air-sea fluxes)." This statement is far too general and misleading given that you didn't analyze air-sea fluxes. You also don't specify what type of air-sea flux you are referring to. Dust influences? Heat fluxes? Neither did you calculate the classical upwelling index or estimate the possible influence of mesoscale eddies that could lead to dynamic up-lift of nutrient-rich water across the shelf break or passing baroclinic coastally trapped waves.... Much more effort would be required to identify reasons of the observed variability of chlorophyll fluorescence concentrations.

We acknowledge that we have not fully elaborated on the changes to the physical forcing that contribute to the observed variability chlorophyll fluorescence concentrations. There are many different physical processes that contribute to this variability: the Reviewer has highlighted meso-scale eddies, coastally trapped waves as examples, others include diurnal upwelling and action of storms. However, all of these processes act over periods of order days or weeks. This study is concentrated on seasonal scales and higher – thus data have been averaged over a period of 3 months which does not allow for these processes to be identified – follow up publications will address diurnal upwelling and impact of storm systems.

The Reviewer questions why the classical upwelling index was calculated. There are many reasons:

1. The paper is not based on upwelling. Upwelling favorable winds occur during spring/summer but the maximum chlorophyll occur in late autumn and winter. Thus chlorophyll fluorescence concentrations are not only controlled by wind and associated upwelling
2. The classical upwelling index is not applicable to this region due to the presence of the pressure gradient due to Leeuwin Current. This was addressed in a recent paper by Rossi et al. (2013) who applied an improved composite dynamical upwelling index that accounts for the role of alongshore pressure gradients counteracting the coastal Ekman divergence. The results indicated that upwelling was sporadic along the whole coast with the occurrence of transient upwelling events lasting 3–10 days changing in space and time. The study region (at 31.5°S) consisted of up to 12 upwelling days per month during the austral spring/summer. The intensity of intermittent upwelling is influenced by the upwelling favourable winds, the characteristics of the Leeuwin Current and the local topography. As this study already exists there was no requirement to calculate the classical upwelling index in the paper. However, reference to Rossi et al. paper and its findings are included in the revised paper.

The physical forcing that influence chlorophyll concentrations are changes in wind forcing, Leeuwin Current and air-sea fluxes of heat and water. We have highlighted this in the discussion of the revised paper. We have indicated seasonal changes in each of these processes

are: (1) strong southerly winds in spring/summer, weak in autumn and storms during winter; (2) LC being weak in summer and strong in winter; and, (3) evaporation dominance in summer and cooling in winter due to changes in air-sea fluxes of heat and water that leads to the formation of dense shelf water cascades in autumn and winter. We have referred to Pattiaratchi et al. (2011) paper that describes the seasonal cycle of air-sea fluxes and its influence on the continental shelf.

(8) In the autumn of 2014, the chlorophyll fluorescence increased ($> 1 \text{ mg m}^{-3}$). Do you know why?

Thank you for your comment. Yes we do have an explanation and it explains the peak during autumn 2009. The Leeuwin current is strongest in autumn and winter (mean transport: $\sim 5\text{--}6 \text{ Sv}$) and weaker during summer (mean transport: $\sim 2 \text{ Sv}$). A recent paper by Wijeratne et al. (2018) presented results of boundary current transport around Australia from a high resolution simulation over a 15 year period. The transport across a cross-shelf section at 31.5°S extending to the deeper ocean indicated that in January/February of 2009 and 2014 the southward mean monthly transport of the Leeuwin Current was very weak, $< 0.5 \text{ Sv}$ and close to zero. In contrast during the period 2010-2013 the monthly mean transport was mainly $> 1.0 \text{ Sv}$. So how could this lead to increased chlorophyll values – one explanation is that a reduction in Leeuwin Current would lead to a shallower mixed layer during the summer. When the winter storms arrive in late autumn the shallow mixed layer broken down more easily bringing nutrients onto the upper layer that allows for higher phytoplankton growth and thus higher chlorophyll. We highlight this process in Figure 12. We have also examined the number of major storms that impacted the study region over the period April-June with the following results:

2009: 7; 2010: 2 ; 2011: 5 ; 2012: 0; 2013: 5 ; 2014: 7.

Thus over this period 2009 and 2014 had the more storms than other years, perhaps giving credence to this theory.

We have included this explanation in the final manuscript.

Reviewer #2

(1) Abstract Sentences 2 and 3 needs integration. They can be mix together integrating the information to report.

As suggested also by Referee#1 – the abstract has been revised and shortened. Sentences 2 and 3 have been integrated.

(2) Introduction Line 2. I would prefer to start the sentence like. “Among phytoplankton pigments, chlorophyll,,.”There are other pigments in phytoplankton. I think that the is chlorophyll a that was used as indicator of phytoplankton biomass or you use the total amount of chlorophyll? Depending of your answer change the sentence accordingly.

Chlorophyll a was used as indicator of phytoplankton biomass. The ocean glider measures chlorophyll fluorescence. We have revised the text as follows:

Among the phytoplankton pigments, chlorophyll *a* (denoted as chlorophyll in the following description), is an important biological indicator of phytoplankton biomass in the water column.

(3) On paragraph 25 and 30, the sentence starting by “It is major is a mechanism. . .” I think this is a typing error remove the second “is” and “a”.

We agree: the second “is” has been deleted.

(4) Page 5 paragraph 10. Please remove “highly” from the sentence Thus the RCA is a highly nutrient”. . .

We agree: the word “highly” has been deleted.

(5) Page 5 paragraph 20. “. . .are not weather limited.” The gliders were able to fly even during bad weather conditions and strong winds? If so why you mentioned that in some seasons data were not present and the graphs have gaps?

It is true that gliders are capable of collecting data in harsh weather conditions and strong winds when ship sampling is not feasible, making them ideal platforms for sustained ocean surveys. However, due to funding limitations and operation reasons (i.e. gliders were not deployed over the Christmas/New Year holidays). The sampling was started with an ambitious goal of having at least one glider operating along the sampling line at all times. This was a quite a challenge and then with decreasing funding the deployments reduced to bi-monthly and then quarterly.

The gaps present in the graphs is due to the sampling nature of the gliders that travel in a saw-tooth pattern. In shallow water the down-cast and up-casts are close together whist in deeper waters the spacing is larger resulting in missing data.

(6) Methods Page 6. Paragraph 10. Of course, this methodology is a huge advance that regular measurements performed but I was also wondering if two or three days took to complete the transect was not too much time. In very dynamic areas, like upwelling areas, you might have complete different conditions within the 3 days for adjacent areas.

We agree with the review that in very dynamic areas, water properties may change within the 3 days, which we have submitted a paper to JGR (oceans) indicating that ocean gliders are capable of capturing diurnal upwelling.

However, in this study, we are addressing the seasonal and inter-annual variability, which will not be affected by these shorter term dynamic processes. In contrast, the ocean gliders provide high spatial resolution data (~1-2 km intervals).

In addition, we have compared glider transect with satellite data (for both temperature and chlorophyll), and the surface features were consistent.

(7) Page 6 paragraph 20. Did you performed any inter- calibration exercise between the data collected from the chlorophyll fluorescence recorded and the quantification of chlorophyll (mg/m³). Again total chlorophyll or chlorophyll a only.

As part of the IMOS ocean glider program we have undertaken many inter-calibration exercises. Here, we attached a glider to a rosette sampler and collected concurrent data from the glider and niskin bottles at surface, mid-depth and bottom of the water column in 100m depth. The water samples were subjected to HPLC analyses to determine the Chlorophyll a concentrations. The comparison between ocean glider derived fluorescence and the HPLC Chlorophyll a concentrations was very good with $r^2 > 0.75$ ($n > 100$) in the range 0.17 to 0.21 (mg m⁻³) (see Thomson et al., 2015).

A recent study by Beck (2016) found that, through inter-comparison of chlorophyll a and Wetlabs ECOPUCK derived fluorescence on ocean gliders, the original manufacturer's recommendation for the estimation of chlorophyll a from fluorescence provided the best estimate.

See also response to Reviewer#1 (point 5)

(8) Page 6. Last paragraph is very confusing. I don't understand if you reach the conclusion that the data was anormal by subtracting to the seasonal mean. You say previously that you perform quality control on data. Why you don't exclude the anormal data there. . .so you won't have to deal with them again later. I think that you should try to rephrase and clarify that paragraph.

We believe that the reviewer meant page 7 (and not page 6) about the calculation of the anomalies. We do not discuss 'anormal' but 'anomalies' (def: something that deviates from the

mean). We decided to present the data as anomalies as the seasonal variation in properties obscured the variability. A detailed explanation is also included as the response to Reviewer#1 and we have included a Table of the mean values (see above). To avoid confusion and for completeness we have included the distribution of absolute values as supplementary material.

We have rephrased and re-written the paragraph – we believe that inclusion of Table 1 and the absolute values as supplementary material will remove this confusion.

(9) Results Page 8. 3.3 Methods section; first line. This information must be in Methods section and justified why there are no mean for the season for that months, if you claim that gathering of data using gliders are not weather limited.

We have moved the sentence to the methods section.

Glider data were not available mainly due to operational reasons (e.g. funding, holiday season etc) rather than limited by weather – see also response above (point 5).

(10) Page 9 Paragraph 25 Typing error. Replace 6a by 7a.

We agree: have replaced 6a by 7a.

Page 10. The 3.5 section of results were very difficult to follow because the figure 9 were not understandable and I advise rebuilding it in clearer manner.

Probably because I was confused with the figure I think that the paragraph 20 description was not correct. You have a higher chlorophyll concentration than 0.81 mg/m³ mentioned for 2009, between 10 and 20 m depth with chlorophyll concentration ranging 1.8mg/m³.

We have added additional text to make the figure clearer. The figure shows the depth mean values of temperature, salinity and fluorescence with time for all of the ocean glider transects. Figure 9 shows the same information as Figure 10 which the Reviewer stated to be very good as good evidence as different patterns between El Niño e La Niña (point 11 below). The difference is that Figure 9 shows the variation across the whole continental shelf whilst Figure 10 is the same data but at a particular distance (10 km). We have explained the relationship between the two figures in the text. As such we propose to retain this figure in the revised manuscript.

(11) Figure 10 was very good evidencing the different pattern between El Niño e La Niña.

Thank you – and we of course agree with the reviewer. No change required needed.

(12) Discussion Page 12. Line 14 (I think) Typing error : repeated.

We agree: have revised the typing error as follows:

The chlorophyll variability was related to the changes in the temperature, salinity distribution, which was linked to changes in the physical forcing: (1) the local wind field; (2) the Leeuwin current system; and, (3) air–sea fluxes, especially in terms of surface cooling and evaporation.

(13) Paragraph 20 to 25 must be in introduction.

We agree: have moved to the Introduction

(14) Paragraph 35 to 40 was already described in introduction.

We have deleted the paragraph

(15) Paragraph 25 and 35 must be integrated with the obtained data by providing examples of the physical processes. I think that your discussion must be improved by comparing your data with another data from upwelling coastal areas also impacted by El Niño and La Niña and comparing the impact results in terms of chlorophyll and consequently in productivity between areas or with former events. It is very important to bring awareness of climate change and the huge effects they have in coastal dynamics and phytoplankton biomass and overall productivity giving relevant to studies like the ones you developed.

Please also see the response to Reviewer#1 – Point 7.

One of the unique features of the study region is that it does not follow well established processes and seasonality in other regions globally. Although the study region is located in an eastern ocean basin – it is not a major upwelling region (similar say to off Peru/Chile or South Africa). This is mainly because of the presence of the Leeuwin Current which flows southwards against the prevailing upwelling favourable winds that promotes downwelling. During the summer there is shallow upwelling that results in elevated chlorophyll but is not able to sustain a large fishery. Also, maximum chlorophyll presented here are factor 10 lower than those observed off South Africa. In addition to this the maximum chlorophyll levels are observed during late autumn/early winter and thus not during the period upwelling favorable southerly winds are present. In summer the most persistent feature was the sub-surface chlorophyll maximum. Autumn is characterised by low wind speeds and winter has not prevailing wind (see Figure 2 and 3). Although other upwelling regions such as off Peru and South Africa does respond to ENSO events- mainly due to changes in the wind field, here the response is mainly due to changes in the strength of the Leeuwin Current that determines changes in the chlorophyll rather than upwelling. We have included this in the discussion.

We agree with the reviewer that climate change and the huge effects they have in coastal dynamics and phytoplankton biomass are very important and we have also included an additional paragraph to highlight that understanding inter-annual variability provides a good indication of what we may expect from climate change.

References:

- Beck M. (2016), Defining a multi-parameter optics-based approach for estimating Chlorophyll a concentration using ocean gliders. Unpubl. MSc Thesis, Dalhousie University, Canada.
- Kämpf, J., and A. Kavi (2017), On the “hidden” phytoplankton blooms on Australia’s southern shelves, *Geophys. Res. Lett.*, 44, 1466–1473, doi: 10.1002/2016GL072096.
- Rossi, V., M. Feng, C. Pattiaratchi, M. Roughan, and A. M. Waite (2013), On the factors influencing the development of sporadic upwelling in the Leeuwin Current system, *J. Geophys. Res. Oceans*, 118, 3608–3621, doi:10.1002/jgrc.20242.
- Thomson, P.G., Mantovanelli, A., Wright, S.W., Pattiaratchi, C.B. (2015). In situ comparisons of glider bio-optical measurements to CTD water properties. Australian Marine Sciences Conference, Geelong, Victoria, July 5th – 9th 2015.

Seasonal and interannual variability of water column properties along the Rottnest continental shelf, south-west Australia

Miaoju Chen¹, Charitha B. Pattiaratchi¹, Anas Ghadouani² and Christine Hanson¹

¹Oceans Graduate School & the UWA Oceans Institute, the University of Western Australia, Perth, 6009, Australia

²School of Engineering, the University of Western Australia, Perth, 6009, Australia

Correspondence to: Miaoju Chen (miaoju.chen@research.uwa.edu.au)

Abstract

A multiyear, ocean glider dataset, obtained along a representative cross-shelf transect along the Rottnest continental shelf, south-west Australia, was used to characterise the seasonal and inter-annual variability of water column properties (temperature, salinity, and chlorophyll fluorescence distribution). All three variables showed distinct seasonal and inter-annual variations that were related to local and basin scale ocean atmosphere processes. ~~Local and basin scale ocean atmosphere processes also affected the spatial distributions of the water column properties. The controlling~~ Controlling influences for the variability were ~~derived~~ attributed to forcing from two spatial scales: (a) ~~at the~~ local scale (due to, the Leeuwin Current and dense shelf water cascades, (DSWC); and, (2) ~~at the~~ basin scale (, the El Niño Southern Oscillation, (ENSO events). In spring and summer, ~~shallow inner shelf~~ waters were well mixed due to strong wind mixing and ~~the~~ deeper waters (>50-m) were vertically stratified in temperature that contributed to the ~~formation~~ presence of a subsurface chlorophyll maximum (SCM). ~~With the onset of storms in late autumn, the water column was well mixed with the SCM absent.~~ On the inner shelf, chlorophyll fluorescence concentrations were highest in autumn and winter; ~~DSWCs were also the main physical feature during autumn and winter.~~ Chlorophyll fluorescence concentration was higher closer to the sea bed than at the surface in spring, summer, and autumn. The seasonal patterns coincided with changes in the wind field (weaker winds in autumn) and air-sea fluxes (winter cooling and summer evaporation). Inter-annual variation was associated with ENSO events. Lower temperatures, higher salinity, and higher chlorophyll fluorescence ($>1\text{-mgm}^{-3}$) were associated with the El Niño event in 2010. During the strong La Niña event in 2011, temperatures increased ~~(a ‘marine heat wave’),~~ and salinity and chlorophyll fluorescence decreased ($<1\text{-mgm}^{-3}$). ~~These changes were mainly associated with changed to the strength of the Leeuwin current. Over subsequent years, the temperatures gradually decreased, the salinity increased, and the chlorophyll fluorescence continued to decrease ($<0.25\text{-mgm}^{-3}$). These changes were mainly associated with an increase in the strength of the Leeuwin current that transported warmer, lower salinity, low nutrient water into the region. In the autumn of 2014, the chlorophyll fluorescence increased ($>1\text{-mgm}^{-3}$).~~ It is concluded that the observed seasonal and inter-annual variability in chlorophyll fluorescence concentrations were related to the changes in physical forcing (wind forcing, Leeuwin Current and air-sea heat and moisture fluxes).

30

1. Introduction

Almost all life forms rely on primary production, directly or indirectly, to survive, and phytoplankton in the ocean perform most of the primary production (Field et al., 1998). Among the phytoplankton pigment, chlorophyll *a* (denoted as chlorophyll in the following description), is an important biological indicator of phytoplankton biomass in the water column. Environmental variables, such as light availability (Sverdrup, 1985; Huisman and Weissing, 1994), water temperature (Eppley, 1992; Hambright et al., 1994; Paerl and Huisman, 2008), and salinity (Karsten et al., 1995), affect phytoplankton biomass variability. Seasonal cycles of phytoplankton concentrations signify the annual growth activity in pelagic systems (Cebrián and Valiela, 1999; Winder and Cloern, 2010). The most common cycle is the spring bloom—an increase in phytoplankton concentrations in response to seasonal changes in temperature and solar radiation—which is usually present for a few weeks to months (Cushing, 1959; Sommer et al., 1986). Often a secondary peak develops in late summer or autumn (Longhurst, 1995). These seasonal phytoplankton patterns have large inter-annual variability across different geographic regions (Cebrián and Valiela, 1999; Cloern and Jassby, 2008; Garcia-Soto and Pingree, 2009). Satellite and field-based measurements have shown that in the oligotrophic waters off south-west Australia, the seasonal chlorophyll cycle (a proxy for phytoplankton biomass) is different from that in other regions, with a clear peak in chlorophyll concentrations in late autumn or early winter and minimal levels in spring and summer (Koslow et al., 2008; Thompson et al., 2011; Lourey et al., 2012). Pearce et al. (2000) found higher chlorophyll concentrations on the continental shelf than further offshore. In this paper, we present an extensive, multiyear, ocean glider dataset, obtained along a representative cross-shelf transect along the Rottneest continental shelf, south-west Australia, to explore the seasonal and inter-annual variability of water column properties (temperature, salinity, and chlorophyll fluorescence distribution). Although ocean gliders have been sampling the oceans for more than a decade, sustained observations addressing the variability at the seasonal and inter-annual scales from continental shelf regions are almost non-existent and this study addresses this shortcoming.

The Rottneest continental shelf (RCS) has several distinct bathymetric features (Figure 1a): (1) a shallow inshore region (depths < 10 m), which can be defined as a ‘leaky’ coastal lagoon with a line of discontinuous submerged limestone reefs; (2) an upper continental shelf terrace, with a gradual slope and a mean depth of ~40 m, located from ~10–40 km from the coast; (3) an initial shelf break at the 50 m isobath; (3) a lower continental shelf between the 50 and 100-m isobaths, where the depth increases sharply; and, (4) the main shelf break at the 200 m isobath.

The major current systems in the region are the Leeuwin and Capes currents (Woo and Pattiaratchi, 2008; Wijeratne et al., 2018). The Leeuwin current (LC) is a warm, lower salinity, poleward-flowing, eastern boundary current, which mainly flows along the 200 m isobath (Ridgway and Condie, 2004; Pattiaratchi and Woo, 2009). In this oligotrophic environment lower chlorophyll and nutrient concentrations (Hanson et al., 2005a; Twomey et al., 2007) and lower primary productivity (Hanson et al., 2005b; Koslow et al., 2008) characterise the LC. The LC, which is strongest in autumn and winter, transport ~5–6 Sv of water during austral winter and ~2 Sv the austral summer poleward (Feng et al., 2003; Wijeratne et al., 2018). El Niño and La Niña cycles influence the Leeuwin current: the current is weaker during El Niño events and stronger during La Niña

events (Pattiaratchi and Buchan, 1991; Wijeratne et al., 2018). Of interest to this study, the region experienced a marine heat wave in February and March 2011, which was associated with the warming related to the La Niña event defined as Ningaloo Niña (Feng et al., 2013). This event increased the Leeuwin current's volume transport in February—an unusual event at this time of the year—and resulted in unprecedented warm sea surface temperature anomalies (~5 °C higher than normal) off Australia's west coast (Feng et al., 2013).

The Capes current, which is dominant in summer, is a wind-driven, inner shelf current, generally formed in water depths < 50 m (Gersbach et al., 1999). It transports cooler, upwelling-derived water northward past Rottneest Island (Figure 1) between October and March (Pearce and Pattiaratchi, 1999; Gersbach et al., 1999).

Continental shelf processes along the Rottneest continental shelf are mainly wind driven, given the low diurnal tidal range (<0.6 m) (Pattiaratchi and Eliot, 2008). ~~The seasonal wind regime in the region can be divided into three regimes () (Verspecht and Pattiaratchi, 2010; Pattiaratchi et al., 2011): (1) spring and summer (September–February)—strong, daily sea breezes dominate, with southerly winds often exceeding 15 m/s; (2) autumn (March–May)—the transition from the summer to the winter regimes occurs, and wind speeds are usually low; and (3) winter (June–August)—storms occur frequently. Three wind systems dominate this region: sea breezes; storms (wind speeds >17 m/s), and calm periods (wind speeds <5 m/s) (Verspecht and Pattiaratchi, 2010).~~ Local sea breezes, superimposed on synoptic southerly winds (with speeds often >15 m/s), are prevalent in austral summer and spring (~~September–February~~) (Pattiaratchi et al., 1997). Storm systems are most frequent during winter (~~June–August~~), and are associated with the passage of frontal systems with the region subject to peak wind speeds to 30 m/s. These storm winds are generally north-westerly in winter and southerly in summer (Verspecht and Pattiaratchi, 2010). In the study region winter storms have a typical pattern with strong north/north-easterly winds blowing for 12 to 52 hours, followed by a period of similar duration when winds turn south/south-westerly, with no prevailing direction dominating for the duration of the storm. Summer storms have southerly winds over a period of 3-4 days that are enhanced by the sea breeze system in the afternoon. Calm wind conditions are mainly observed during autumn and winter (March–August; between winter storm fronts) and are characterized by low wind speeds (<5 m/s).

Another major feature of the dynamics is the presence of dense shelf water cascade (DSWC) on the continental shelf (Pattiaratchi et al., 2011). Western Australia experiences high evaporation rates resulting in higher salinity (density) water in the majority of shallow coastal waters. This dense water is transported across the continental shelf close to the seabed due to the density difference between the nearshore and offshore water (Pattiaratchi et al., 2011). It is a major ~~is a~~ mechanism for the export of water containing suspended material and chlorophyll away from the coastal zone. Analysis of ocean glider measurements by Pattiaratchi et al. (2011) indicated that DSWC is a regular occurrence along the RCS particularly during autumn and winter months. In autumn the dense water formation is mainly through changes in salinity resulting from evaporation whilst in winter, temperature was dominant through surface cooling. In summer, although there is a cross-shelf density (due to salinity) gradient, DSWC is not present due to wind induced vertical mixing.

Changes in phytoplankton biomass at seasonal and inter-annual timescales are important components of the total

variability associated with biological and biogeochemical ocean processes (Ghisolfi et al., 2015). The circulation along the Western Australian coast has been studied through observations and the use of ocean models (Gersbach et al., 1999; Feng et al., 2003; Woo and Pattiaratchi, 2008; Wijeratne et al., 2018); however, methods to study the biological processes in the water column have been limited to the use of satellite ocean colour data (Moore et al., 2007; Lourey et al., 2012) and shipborne observations (Hanson et al., 2005a; Pearce et al., 2006; Koslow et al., 2008). Satellite imagery is limited to processes at the sea surface as sensors are unable to image subsurface waters due to limitations in light penetration. Information on the role of physical forcing and the biological responses in the water column has been limited because of the absence of a comprehensive observational dataset. Most of the available oceanographic and biological data are restricted in time and space and are thus unsuitable to be used to study patterns across the RCS at different time and space scales.

Eastern boundaries of ocean basins are typically associated with upwelling of higher nutrient water into the euphotic zone leading to high primary productivity on the continental shelf and rich coastal fisheries (Codospoti, 1983). Oceanographic conditions off RCS are dominated by the LC that suppress upwelling and transports nutrient poor water along the continental shelf and has a negative impact on primary productivity (Koslow et al., 2008; Twomey et al., 2007). The absence of upwelling and major river systems means that the region is low in nutrients. For example, Twomey et al. (2007) reported dissolved nitrate concentrations on continental shelf and in the surface 50m further offshore were typically below detection levels ($<0.016 \mu\text{M}$). Nitrate concentrations increased rapidly beyond 150 m depth to concentrations of around $30 \mu\text{M}$. Thus the RCS is a ~~highly~~-nutrient poor environment with nutrient supply limited to that through recycling during storms and offshore supply through eddy activity (Koslow et al., 2008).

The use of ocean gliders as an observational tool has several advantages over traditional, ship-based surveys: ocean gliders have high sampling frequencies and long sampling durations (Pattiaratchi et al., 2017); the high temporal and spatial resolution data obtained with gliders may provide a better understanding of the links between the physical (meteorological and oceanographic) forcing and the phytoplankton response; all the relevant data are collected simultaneously and are not weather limited. We used a multiyear (2009–2015) ocean glider dataset (50 individual missions) along a repeated transect to examine the variability in the physical parameters and chlorophyll fluorescence concentration (a measure of phytoplankton biomass) distribution over seasonal and inter-annual timescales. The seven-year timescale included two El Niño events (2010 and 2014) and a strong, extended La Niña event (2011–2013). The aims of this paper, through the analysis of the long-term ocean glider dataset, were to: (1) examine the seasonal and inter-annual variability in chlorophyll fluorescence along the Rottneest continental shelf; (2) relate the seasonal chlorophyll fluorescence variability to changes in temperature and salinity distribution and local wind forcing; and, (3) determine the influence of the ENSO cycles on chlorophyll fluorescence. This is the first long term study of seasonal processes in the continental shelf waters along the RCS. Understanding the seasonal and inter-annual variability of coastal ocean properties including how changes in the physical parameters (temperature and salinity) influence chlorophyll distribution across the continental shelf. This enables the identification of the main mechanisms that drive the variations in phytoplankton, as represented by chlorophyll fluorescence along the RCS.

This paper is organised as follows: Section 2 describes the methods. The results of the seasonal winds and the monthly, seasonal, and inter-annual variations in the chlorophyll and physical properties are described in Section 3. In Section 4, we discuss the possible causes of the observed variability. A general conclusion is then given in Section 5.

5 2. Methods

Water column data were obtained from repeated surveys undertaken using Teledyne Webb Research Slocum electric gliders (<http://www.webbresearch.com/>) along the Two Rocks transect off Rottneest continental shelf, south-west Australia (Figure 1). The Slocum ocean glider is 1.8 m long, 0.213 m in diameter and weighs 52 kg. It is designed to operate in coastal waters of up to 200 m deep where high manoeuvrability is required under relatively strong background currents. Ocean gliders are autonomous underwater vehicles that propel themselves through the water by changing its buoyancy relative to the surrounding water (Rudnick, 2016). By alternately reducing and expanding their volume, ocean gliders can descend and ascend through the ocean water column using minimal energy. In contrast to other similar automated ocean sampling equipment (e.g. Argo floats; <http://www.argo.ucsd.edu/>), ocean gliders have wings, a rudder and a movable internal battery pack allowing them to move horizontally in a selected direction in a saw tooth pattern. This allows for the horizontal position to be controlled and to sample particular regions of the ocean. The gliders are remotely controlled via the Iridium satellite system and navigate through waypoints, fixing their position via the Global Positioning System (GPS). Each time the glider surfaces, the data and new waypoints can be relayed via satellite to and from the glider. The autonomous nature of the ocean gliders means that they are able to collect data continuously irrespective of the weather conditions.

The data set were collected over a seven year (2009–2015) period using Teledyne Webb Research Slocum Electric Gliders operated by the Integrated Marine Observing System (IMOS) Ocean Glider facility located at The University of Western Australia (Pattiaratchi et al., 2017). ~~Personnel at the Australian National Facility for Ocean Gliders at the University of Western Australia operate the gliders (Pattiaratchi et al., 2017).~~ All the ocean glider data are available through the Australian Ocean Data Network (<https://portal.aodn.org.au>). More than 200 cross shelf transects from ~50 ocean glider missions were analysed, with ~28 million individual scans obtained for each variable (temperature, salinity and chlorophyll).

Each cross shelf ocean glider transect took two to three days to complete (Pattiaratchi et al., 2011), with the gliders travelling at a mean speed of 25 km/day. The glider transects extended from ~20 m depth contour to deeper waters (the gliders have a maximum depth range of 200 m) and collected data from the surface to ~2 m above the sea bed. The gliders were equipped with a Sea-Bird Scientific pumped CTD (conductivity–temperature–depth) sensor, a WETLabs BBFL2SLO 3 parameter optical sensor (which measured chlorophyll fluorescence, coloured dissolved organic matter, and backscatter at 660 nm), and an Aanderaa oxygen optode. All the sensors sampled at 4 Hz (which yielded measurements about every 7 cm in the vertical). The actual vehicle trajectory was transposed onto the Two Rocks transect as a straight line (Pattiaratchi et al., 2011).

IMOS data streams are provided in NetCDF-4 format with ocean glider data files containing meta-data and scientific data for each glider mission. Subsequent to the ocean glider recovery, all the data collected by the glider are subject to QA/QC procedures that include a series of automated and manual tests (Woo, 2017). To maintain data integrity all of the sensors (CTD and optical sensors) are returned to the manufacturers for calibration after a period 365 days in the water. The Sea-Bird Scientific SBE 41CP pumped CTD sensor on the Slocum gliders is the same as those mounted on Argo floats and achieve temperature and salinity accuracies of $\pm 0.002^{\circ}\text{Celsius}$ and ± 0.01 salinity units, respectively.

The WETLabs BBFL2SLO 3 fluorescence values were estimated using the conversions provided by the manufacturer. A recent study by Beck (2016) found that, through inter-comparison between chlorophyll a derived from HPLC and Wetlabs BBFL2SLO 3 derived fluorescence on ocean gliders, the original manufacturer's recommendation for the estimation of chlorophyll a from fluorescence provided the best estimate. As part of the QA/QC procedures applied to the WETLabs BBFL2SLO 3 Eco Puck sensor on the Slocum gliders are subject to a series tests to track their performance, to identify faults and to quantify drift during missions due to biofouling and/or damage. These tests were undertaken in the laboratory prior to shipping of the glider, immediately prior to deployment on the vessel, and then immediately on recovery before after cleaning of the sensor face. The tests ~~are-were~~ carried out by attaching a solid standard in a holder a set distance from the sensor face and collecting engineering counts from the fluorescence, CDOM and backscatter signals over a 5 minute period. The solid standards used for fluorescence and CDOM counts, Plexiglas Satinice® plum 4H01 DC (polymethylmethacrylate, Evonik Industries), was identified by Earp et al. (2011) in a review of fluorescent standards for calibration of optical instruments as being the optimum. The ocean glider ~~deployed-deployments~~ started in 2008 and performance of ECO Puck sensors has been documented over this period. ~~This~~ included comparing consecutive scale factors following factory calibrations. Our records demonstrated the inherent stability of these sensors in their fluorescent and backscatter measurements, with the difference between fluorescence scale factors between calibrations over 8 years of service typically $< 6\%$. To measure the reliability of the instruments between factory calibrations, the fluorescent response of the instruments to a fluorescein concentration curve have been tracked between factory calibrations ensure ongoing reliability. We have also undertaken field measurements (Thomson et al., 2015); where a glider was attached to a rosette sampler and collected concurrent data from the glider and Niskin bottles at surface, mid-depth and bottom of the water column in 100m depth. Water samples were subjected to HPLC analyses to determine the 'true' Chlorophyll a concentrations. The comparison between Wetlabs BBFL2SLO 3 derived fluorescence and the HPLC chlorophyll a concentrations was very good with a correlation squared (r^2) value of 0.75 ($n > 100$) in the range 0.17 to 0.21 mg/m^3 . Field data, obtained from the north west shelf of Australia, for direct comparisons between fluorescence and Chlorophyll a (extracted using acidification techniques) indicated a correlation squared (r^2) value of 0.75 (Thomson et al., 2015).

Wind speed and direction, recorded at 30 min intervals, were obtained from the Bureau of Meteorology weather station at Rottneest Island, and located ~ 40 km south of Two Rocks transect (Figure 1a).

The focus of this paper is on the seasonal and inter-annual variability in the temperature, salinity, and

chlorophyll fluorescence concentrations across the Two Rocks transect. It was assumed that processes along this transect were representative of the cross-shelf variability across the Rottneest continental shelf. When we refer to the 'chlorophyll concentration' (units mg/m³), we are referring to the chlorophyll fluorescence as recorded by the BBFL2SLO optical sensor. Salinity is expressed as a dimensionless quantity.

5

~~When examining the seasonal changes it was found that the changes in the mean values obscured the seasonal variability of each parameter (temperature, salinity, and chlorophyll). Hence, in addition to presenting the measured values (see supplementary Figure S1) we also calculated anomalies to remove the influence of the seasonal variability. The procedure for each parameter (~28 million individual points) was as follows: (1) data were interpolated onto a common grid across the cross shelf transect; (2) transects were then sorted according to season: spring (September-November), summer (December-February), autumn (March-May) and winter (June-August); (3) the mean value across the whole transect (i.e. through water depth and across distance) for each season was calculated (Table 1); and, (4) the anomaly at each grid point was calculated by subtracting the seasonal mean from values at each point.~~ ~~When examining the seasonal changes it was found that the changes in the mean values obscured the seasonal variability of each parameter (temperature, salinity, and chlorophyll). Hence, in addition to presenting the measured values we also calculated anomalies to remove the influence of the seasonal variability. The procedure for each parameter (~28 million individual points) was as follows: (1) data were interpolated onto a common grid across the cross shelf transect; (2) transects were then sorted according to season: spring (September November), summer (December February), autumn (March May) and winter (June August); (3) the mean value across the whole transect (i.e. through water depth and distance) for each season was calculated; and, (4) the anomaly at each grid point was calculated by subtracting the seasonal mean from values at each point.~~

10

15

20

3. Results

25

3.1 Seasonal winds

The mean winds for each season from March 2010 to March 2014 showed southerly winds were prevalent in summer, autumn, and spring, followed by south/south-easterly winds (Figure 2). Summer storms, which usually lasted 36 hours, caused strong, southerly winds (> 25 m/s). The sea breeze usually contributed to the southerly winds, which reinforced the prevailing southerly winds found in the seasonal rose plots (Figure 2). In autumn, the wind speeds decreased (< 13 m/s), whereas in winter, the winds had no prevailing direction. (This is typical of winter storms, which are associated with rapid changes in the wind direction; Verspecht and Pattiaratchi, 2010). In spring, the winds were southerly, with mean wind speeds of 15 m/s. The southerly winds in the study region are upwelling favourable.

30

35

The time series of the daily mean wind speeds and directions in 2010 revealed the changes that occurred in the wind regime: from November to May (the summer regime), the winds were generally southerly, and the mean wind speeds were ~7.5 m/s in November and ~10 m/s in January and February (Figure 3). The wind speeds decreased between March and mid-May (the autumn regime), with few changes in the wind direction. Between

mid-May and October (the winter regime), winter storms caused large fluctuations in the wind speed and direction.

3.2 Seasonal temperature, salinity, and chlorophyll distribution

Typical cross-shore distributions of the seasonal variation in temperature, salinity, and chlorophyll along the Two Rocks transect during spring, summer, autumn, and winter are shown in Figure 4.

In spring (21–23 October 2013), the temperature and salinity in the upper 80 m were vertically mixed across the whole shelf. The temperature and salinity characteristics changed at the shelf break. On the upper continental shelf (< 40 m depth), the water was cooler and less saline than at lower depths (Figure 4a). High chlorophyll concentrations (up to 1.2 mg/m³) were found on the inner shelf and at the 50 m shelf break (Figure 4a), which corresponded to temperature and salinity gradients (i.e. frontal system) in the same region. A thin layer (< 10 m) of subsurface chlorophyll maximum layer (SCM) (up to 1 mg/m³) extended from the shelf break to offshore, and coincided with the halocline (and pycnocline) at about 80m depth.

In summer (28 February–3 March 2014), a plume of warm Leeuwin current water (~23.5°C) was located in the top ~30 m depth between 60 and 70 km offshore (Figure 4b). This plume cooled (to 23°C) and thinned (in the top ~5 m depth) as it moved inshore. Water on the upper continental shelf was cooler than that offshore. The salinity on the upper continental shelf (~35.7) was slightly higher than offshore (35.5); the Capes current most likely caused the cooler and saltier inshore waters. The cooler and saltier water on the upper continental shelf revealed that higher density water was present on the shelf and a small, dense shelf water cascade (DSWC) was present inshore of the shelf break. A subsurface chlorophyll maximum (up to 1.2 mg/m³), between 50 and 110 m depths (at the pycnocline), was located from the shelf break to offshore.

In autumn (18–21 May 2009), the nearshore waters were saltier and cooler (21°C) than the offshore waters (22.5°C) (Figure 4c). The offshore waters were well mixed except in the bottom 20m. A plume of salty (35.7) and cooler (21°C) water, which extended to ~60 km across the entire continental shelf and depths > 180 m, was observed inshore and indicated the presence of a DSWC. The maximum chlorophyll concentration (1.3 mg/m³) was located on the upper continental shelf in the shallow pycnocline. The chlorophyll levels were generally higher in the DSWC than they were in the surface waters on the upper continental shelf. In the offshore waters, higher chlorophyll water was uniformly distributed in the surface mixed layer to depths of 60 m close to the shelf break and depths > 120 m farther offshore (Figure 4c).

In winter (9–11 August 2012), the temperature increased from 18°C inshore to 20.7°C offshore, and the water column was generally vertically mixed (Figure 4d), except between 10 and 20 km on the upper continental shelf. The salinity was uniformly distributed inshore and in most offshore regions. Maximum chlorophyll (> 1 mg/m³) concentrations were found along the inner shelf between 10 and 20 km and corresponded to the region of vertical and horizontal temperature and salinity gradients.

The ocean glider data indicated vertical and horizontal stratification across the shelf and the temperature and

salinity distribution across the shelf changed seasonally. The temperature and salinity characteristics on the upper continental shelf were often different from those farther offshore. High chlorophyll concentrations were found in regions with strong temperature and salinity gradients and thus density. These maximum values occurred in the vertical (e.g. the SCM in summer and autumn) and the horizontal (e.g. at the shelf break in spring and winter).

3.3 Monthly mean water masses and chlorophyll concentrations

The monthly mean temperature and salinity were calculated year round, except during July, September, November, and December because only a single ocean glider transect was available in each of these months. The temperature and salinity structure showed that from January to March (summer to early autumn), the inshore waters (< 40-m depth) were warmer (~21.1–23.0°C) and the salinity decreased (35.81 to 35.77) (Figure 5a). From March to August (autumn to winter), the temperature (23.0 to 19.0°C) and salinity both decreased (35.77 to 35.22). From August to January (winter to early summer), both temperature (18.9 to 21.1°C) and salinity increased (35.22 to 35.8). Offshore water (> 40 m depth) showed a similar seasonal pattern to that of the inshore waters (Figure 5b). Except that from January to March, the salinity decrease in offshore waters (from 35.71 to 35.54) was larger compared to inshore waters and from August to January, the offshore water temperature dropped slightly before increasing to 21.0°C.

Spatially averaged chlorophyll concentrations for the inshore waters revealed significant seasonal variability. Higher chlorophyll concentration values were reached between March and August (autumn to winter), with a maximum of 1.12 mg/m³ reached in May and decreased to a minimum of 0.36 mg/m³ in February. The chlorophyll concentration values for offshore waters were less variable with highest values in May (maximum of 0.85 mg/m³) and lowest in February (minimum of 0.43 mg/m³). Higher chlorophyll concentrations corresponded with warmer and less saline water for both the inshore and offshore waters.

3.4 Seasonal distribution

Over the seven-year study period (January 2009–March 2015), the vertical structure of the seasonal mean data for the Rottneest continental shelf revealed variability in the temperature, salinity, and chlorophyll concentrations. Anomalies are defined as departures from the seasonal average, with positive (negative) values higher (lower) than the seasonal average. The anomalies allowed us to examine the relative changes in water properties across the whole transect for each season.

Temperature anomaly

Seasonal temperature anomaly in the continental shelf waters differed from those further offshore, seaward of the shelf break (Figure 6). During spring, the temperature anomaly indicated that water to be vertically well mixed on the continental shelf (Figure 6a) with warmer water offshore. In summer, the warmer surface water extended across the entire continental shelf (Figure 6b). Water along the middle of the shelf (5–20 km from the coast) was slightly cooler, most likely due to the influence of the Capes Current. In autumn and winter, the upper shelf waters were cooler than the offshore waters. The temperature anomalies were mostly negative, with the lowest values (–1°C) attained close to the coast (between 0 and 7 km) (Figures 6c–d).

The largest variability in the offshore waters was associated with the thermocline depth (temperature anomaly of about -1.0°C). In spring, the thermocline was almost horizontal and located at ~ 120 m depth. In summer, the thermocline was located higher in the water column (~ 70 m depth), with a slight inclination (deeper in the offshore). In autumn, the thermocline depth increased to 100 m, with a more pronounced inclination. The thermocline inclination in summer and autumn was most likely due to upwelling processes when the winds were upwelling-favourable (Figure 2). In winter, the thermocline was absent because the Leeuwin current dominated the offshore waters.

Salinity anomaly

In summer and autumn, the salinity anomaly was higher on the upper shelf than in the offshore waters, mainly because of evaporation (Figures 7b, c). A cross-shelf salinity gradient was also present. The salinity was more uniform in the surface waters offshore. In spring, high salinity water was present at >100 m corresponding to the colder water (Figure 7a). In winter, salinity gradients were absent along the whole transect (Figure 7d).

Chlorophyll concentration anomaly

The chlorophyll concentration anomalies revealed there were seasonal variations in the upper shelf and offshore waters (Figure 8). Across the whole transect, high chlorophyll concentration anomalies were present in the subsurface waters (i.e. not at the surface) and along the upper shelf. In spring, the highest chlorophyll concentration anomaly was found at the shelf break (Figure 8a) and was related to a horizontal temperature gradient (Figure 6a). A subsurface chlorophyll maximum (SCM), which extended over ~ 100 m depth, was present in the offshore waters. This SCM was associated with the temperature and salinity distribution (Figures 6a and 7a). In summer, the SCM was concentrated over a smaller depth range (< 50 m) in the offshore waters. On the continental slope, seaward of the shelf break (an area of 20–30 km), the chlorophyll concentration anomalies were more diffuse, most likely because of the variation in the upwelling and the diurnal cycle (Chen et al., 2017). In autumn and winter, the SCM was absent, but the chlorophyll concentration anomalies were higher on the upper continental shelf. The autumn chlorophyll distribution corresponded to the presence of DSWCs on the upper shelf (Figures 7c and 8c).

3.5 Depth-integrated mean variability

We used a seven-year dataset of ocean glider deployments to examine the interannual variability in the temperature, salinity, and chlorophyll concentrations. ~~The water properties were depth averaged from the surface to 30 m depth were averaged to yield depth mean values~~ (Figure 9). The gliders traverse in a sawtooth pattern, and as the depth increases, the surfacing spacing increases; thus there were gaps in the data for the deeper waters. All the water properties showed seasonal changes, but in this section, we focus on the interannual variability. The data highlights the interannual variability. For example, the marine heat wave during the 2011 La Niña events is evident (red lines - summer 2011) as well as the cooler summers in 2009 and 2015 (yellow lines). Similarly, higher salinities were recorded during summers 2010, 2014, 2015 that were associated with El Niño events (red lines).

The year-to-year summer temperature range was $> 4^{\circ}\text{C}$: the temperature was $< 20.1^{\circ}\text{C}$ in February 2010 and increased to a maximum of 24.4°C in March 2011 and also in February 2012 (Figure 9a). This maximum temperature was associated with the persistent La Niña event in 2011-2012. In winter, the year-to-year temperature range was $> 3^{\circ}\text{C}$: the temperature was $> 21.2^{\circ}\text{C}$ in 2011 and decreased to a minimum of 18.4°C in 2012 and 2014.

The concurrent depth-averaged salinity time series showed the waters were less saline (34.9) in August 2011 than they were in other years (Figure 9b). In March 2015, the highest salinity value (~ 35.9) was measured on the upper shelf. The lowest value (~ 35.5) was attained in 2011 and was associated with the warmer water.

The depth-averaged chlorophyll concentrations also had strong interannual variation (Figure 9c), with values ranging from 0.81 mg/m^3 in May 2009 and 2010 to 1.8 mg/m^3 in May 2014. The largest range in the chlorophyll concentrations was from March 2011 (chlorophyll concentration of 0.88 mg/m^3) to March 2014 (chlorophyll concentration of 0.14 mg/m^3). The lowest value of 0.18 mg/m^3 was also recorded in March 2013.

Time series of the depth-averaged (surface 30 m) temperature, salinity, and chlorophyll measured 10 km from the coastline revealed strong seasonal and interannual variability, especially in response to El Niño and La Niña events (Figure 10). Information presented in Figure 10 includes the same ~~information~~ as that shown in Figure 9, except that variations at a single point (10 km) are shown as a time series. The seasonal cycle (Section 3.3; Figure 5a) indicated warmer, saltier water was present in summer and cooler, less saline water in winter.

In 2009/10, a moderate El Niño event occurred, which resulted in lower temperatures and higher salinity during the first half of 2010. The El Niño weakened the Leeuwin current, which entrained cooler, saltier water into the region from offshore (e.g. Woo and Pattiaratchi, 2008). The chlorophyll values were $\sim 1\text{ mg/m}^3$, with a slight elevation in winter due to the seasonal bloom (Figure 10).

The 2009/10 El Niño was followed by a strong, extended La Niña between 2011 and 2014. The ocean glider data (Figure 10) captured several El Niño and La Niña effects on the water column properties: (1) a maximum temperature ($> 24^{\circ}\text{C}$) was recorded in February 2011, which was an increase of $> 4^{\circ}\text{C}$ from 2010. From 2011 to 2014, summer temperatures decreased; (2) a significant drop in salinity (> 0.5) occurred from 2010 to 2011. This salinity decrease was mainly due to a stronger Leeuwin current transporting lower salinity water into the region. From 2011 to 2014, the salinity increased; (3) chlorophyll decreased from $\sim 1\text{ mg/m}^3$ in 2011 to $< 0.25\text{ mg/m}^3$ in early 2014 and then increased in May 2014.

3.6 Temperature, salinity, and chlorophyll during a storm event

The ocean glider data obtained from 17 to 28 April 2013 revealed a storm caused vertical mixing in the water column and transported high chlorophyll water from the SCM to the surface. The first two transects (17–20 April 2013) were collected under low wind ($< 5\text{ m/s}$) conditions (Figure 11). The water column was vertically stratified because of the presence of a DSWC on the upper shelf and a thermocline in the offshore waters (Figures 12a,b). On the upper shelf, higher chlorophyll water was present in the DSWC's bottom layer. In the

deeper waters, the higher chlorophyll water was associated with the SCM (Figures 12m, n).

5 On 20 April, the winds increased to > 10 m/s. The winds were initially southerly and then changed to westerly and continued to 23 April (Figure 11) causing vertical mixing of the water column. On the upper shelf, the DSWC was eroded such that by 25 April, the temperature and salinity were vertically mixed in the water column (Figures 12e, k). On 28 April, when the winds decreased, the salinity on the upper shelf was vertically stratified (Figure 12l).

10 The winds and the vertical stratification also affected the chlorophyll distribution. Initially, high chlorophyll concentrations were found in the DSWC on the upper shelf close to the seabed and in the SCM in the offshore waters (Figure 12m). As the winds increased, the chlorophyll concentration became uniform through the water column across the whole transect (Figure 12q). Note that the wind, although not strong (~ 10 m/s), was able to mix the water column to ~ 80 -m depth in the offshore waters and erode the thermocline and thus the SCM. The SCM likely reformed (Figure 12s); however, with reduced solar heating and convective cooling, the stratification would have weakened, which would have led to a well-mixed water column in late autumn and
15 early winter.

4. Discussion

In this paper, simultaneous water column data of ocean properties (temperature, salinity and chlorophyll fluorescence) together with meteorological data were used to examine the seasonal and inter-annual variability along the Rottneest continental shelf. Acquisition of multi-year sustained ocean observations using shipborne sampling is difficult (relative cost and weather dependence) and thus many studies have used satellite remote sensing data of sea surface temperature and ocean colour to determine season and inter-annual variability on continental shelves (e.g. Nieto and Melin, 2017; Kilpatrick et al., 2018). However, satellite derived data only provide information on the spatial variability on the surface of the ocean and thus variability in the sub-surface is unknown. Autonomous ocean gliders provide data from the sub-surface and have been used as a platform to collect multi-year sustained observations from the coastal ocean in mid-Atlantic Bight (Schofield et al., 2008). In this paper, ocean glider data collected along a single transect along the RCS shelf over the period 2009-2015 are presented. The data indicated distinct seasonal and interannual variation in temperature, salinity and chlorophyll concentrations. Due to the low tidal range (~0.6 m; Pattiaratchi and Eliot, 2009), tidal effects in the region were minimal. Previous studies in the region undertaken using remotely sensed imagery and limited shipborne observations have highlighted the seasonal variability (Lourey et al., 2006; Pearce et al., 2006; Fearn et al., 2007; Koslow et al., 2008; Pattiaratchi et al., 2011).

~~The seasonal wind regime in the region can be divided into three regimes (Pattiaratchi et al., 2011): (1) spring and summer (September–February)—strong, daily sea breezes dominate, with southerly winds often exceeding 15 m/s; (2) autumn (March–May)—the transition from the summer to the winter regimes occurs, and wind speeds are usually low; and (3) winter (June–August)—storms occur frequently.~~

The study region is located at 32°S, close to the critical latitude (30°S), where the inertial period is 24 hours. Because the diurnal sea breeze system also has a ~24 hour period, resonance occurs, which generates near-inertial waves (Mihanović et al., 2016; Chen, 2018). Field measurements revealed that near-inertial waves force the thermocline to oscillate at a diurnal timescale, with a vertical excursion > 50 m (Mihanović et al., 2016; Chen, 2018). This vertical excursion of the thermocline causes the thermocline to migrate along the continental slope on a diurnal timescale. This process has a strong influence on the sub-surface chlorophyll maximum (SCM) interaction at the continental slope: the chlorophyll anomaly indicates higher concentrations along the slope between water depths 50 m (shelf break) and 120 m (Figure 8b).

~~The main oceanic forcing in the region is the Leeuwin current, which flows along the 200 m depth contour and transports warm, low salinity water southward. The Leeuwin current is weakest in October, begins to accelerate in April, and reaches maximum speeds in June. The Leeuwin current transport decreases from July to October and then increases over summer (Wijeratne et al., 2018).~~

The study region is located in a Mediterranean climate zone, with hot, dry summers and mild, wet winters. The annual evaporation rate exceeds 2 m (Pattiaratchi et al., 2011). There are no major land-based freshwater inputs to the region. Although the Swan River discharges at Fremantle, its freshwater component is low because rainfall is low during summer and autumn, and the river discharge is mainly deflected south in winter. The

combination of evaporation and cooling is such that in summer, coastal heating and evaporation result in a band of warm, high salinity water close to the coast; in winter, the nearshore waters are cooler (through heat loss to the atmosphere) and less saline (Pattiaratchi et al., 2011).

5 The impacts of all the physical forcing at the seasonal scale were reflected in the temperature and salinity (T/S) distribution across the shelf. The (T/S) structure across the continental shelf showed the water was warmest on the upper shelf between January and March whilst the salinity increased (Figure 5). The warming was due to high solar insolation and the higher salinity through evaporation. From March to August, both the temperature and salinity decreased. This temperature decrease was due to atmospheric heat loss despite the transport of
10 warmer water into the region by the Leeuwin Current. The salinity decrease was due to the advection of lower salinity water from the Leeuwin current. From August to January, both the temperature and salinity increased because of the increasing solar insolation and evaporation. The offshore waters showed a similar seasonal pattern.

15 In general, both inshore and offshore chlorophyll concentrations were higher in autumn and winter (March to August) than they were in spring and summer. Maximum values were attained in May for the inshore (1.1 mg/m³) and offshore waters (0.85 mg/m³). The chlorophyll difference between summer and winter inshore (0.75 mg/m³) was larger than it was offshore (0.45 mg/m³). A similar seasonal pattern was found in studies conducted over the past two decades. Pearce et al. (2000) found offshore chlorophyll concentrations between 1979 and
20 1986 were highest between May and August. Fearn et al. (2007) found a clear seasonal cycle, with maximum values attained between May and July from 1997 to 2004.

The main differences between spring/summer and autumn/winter were found in the water column structure, especially in the offshore regions. The offshore waters were vertically stratified in spring and summer and
25 vertically mixed in autumn and winter (Figures 6–8). The pycnocline in spring and summer initiated the SCM. Koslow et al. (2008) observed the summer SCM in a layer above the nutricline at 100 m depth when the water column was stratified. The nearshore autumn bloom coincided with the DSWCs, which regularly occur in autumn (Pattiaratchi et al., 2011). In winter, high chlorophyll concentrations were uniformly distributed inshore because of winter cooling and storm-induced mixing of the water column (Longhurst, 2007; Koslow et al., 2008;
30 Chen et al., 2017).

Our results are in broad agreement with those of Koslow et al. (2008), who used ship-based sampling data and satellite remote sensing data to study phytoplankton in the same region. Koslow et al. (2008) found that: (1) the primary productivity and chlorophyll concentrations were lower offshore in summer when the water column
35 was stratified and most of the chlorophyll was contained in the SCM; (2) phytoplankton blooms in late autumn and winter coincided with the period when the Leeuwin current flow was strongest, and the winter bloom was due to cooling and storms, which promoted mixing of the upper water column. We also observed higher autumn and winter chlorophyll concentrations and a vertically mixed upper water column in the offshore region. In addition, the surface chlorophyll features agreed with Kämpf and Kavi (2017), who show widespread
40 phytoplankton blooms (chlorophyll concentrations ~1mg/m³) during autumn and winter using satellites data

along the southern Australia coastline.

5 One of the unique features of the study region is that it does not follow well established processes and seasonality in other regions globally. Although the study region is located in an eastern ocean basin – it is not a major upwelling region (similar say to off Peru/Chile or South Africa). This is mainly because of the presence of the Leeuwin Current which flows southwards against the prevailing upwelling favourable winds that promotes downwelling (Pattiaratchi and Woo, 2008). Rossi et al. (2013) applied a composite dynamical upwelling index that accounted for the role of alongshore pressure gradients counteracting the coastal Ekman divergence. The results indicated that upwelling was sporadic along the whole WA coast with the occurrence of
10 transient upwelling events lasting 3–10 days changing in space and time. The study region (at 31.5°S) consisted of up to 12 upwelling days per month during the austral spring/summer. The intensity of intermittent upwelling was influenced by the upwelling favourable winds, the characteristics of the Leeuwin Current and the local topography. This the system is very different to other eastern boundaries. Also, maximum chlorophyll values presented here are factor 10 lower than those observed off South Africa. In addition to this maximum
15 chlorophyll levels were observed during late autumn/early winter and thus not during the period upwelling favourable southerly winds are present. In summer the most persistent feature was the sub-surface chlorophyll maximum when strong upwelling favourable winds occurred. Autumn was characterised by low wind speeds and winter does has not contain any persistence in the prevailing winds (see Figure 2 and 3). Although other upwelling regions such as off Peru and South Africa does respond to ENSO events- mainly due to changes in
20 the wind field, here the response is mainly due to changes in the strength of the Leeuwin Current that determined changes in the chlorophyll concentrations rather than upwelling.

25 An indication of the role of the Leeuwin Current (LC) and the wind regime influencing the chlorophyll concentrations are lighted in the autumn peaks in 2009 and 2014. The LC is strongest in autumn and winter (mean transport: ~5–6 Sv) and weaker during summer (mean transport: ~2 Sv). Wijeratne et al. (2018) presented results of boundary current transport around Australia from a high resolution simulation over a 15 year period. The transport across a cross-shelf section at 31.5°S extending to the deeper ocean indicated that in
30 January/February of 2009 and 2014 the southward mean monthly transport of the LC was very weak (< 0.5 Sv). In contrast during the period 2010-2013 the monthly mean transport over these months was > 1.0 Sv. Here, the weaker LC leads to a shallower mixed layer during the summer. Thus, when the storms arrive in late autumn the shallow mixed layer is broken down more easily bringing nutrients onto the upper layer that allows for higher phytoplankton growth and thus higher chlorophyll. The vertical mixing by storms were highlighted in Figure 12. Also the number of major storms that impacted the study region over the period April-June were as follows:
35 2009: 7; 2010: 2; 2011: 5; 2012: 0; 2013: 5; 2014: 7. i.e. the period 2009 and 2014 had more storms compared to other years. The autumn chlorophyll concentrations 2009 and 2014 were related to a weaker LC and the incidence of increased number of storms.

In summary, the observed patterns of seasonal variability in the chlorophyll concentrations were related to the changes in the water's physical properties, which were affected by the seasonally changing physical forcing.
40 These findings were similar to those from Vidal et al.'s (2017) study of the Iberian continental shelf, which is a

region with similar dynamics (e.g. eastern poleward boundary current, upwelling-favourable winds) to the Rottneest continental shelf. Vidal et al. (2017) found that the physical forcing's frequency and intensity affected the chlorophyll variability.

5 In spring and summer, the offshore waters were vertically stratified, with a surface mixed layer and a well-defined pycnocline; the Leeuwin current was weak and located farther offshore (Pearce and Pattiaratchi, 1999). The strong, sustained winds mixed the upper water column to > 50 m depth. The pycnocline prevented nutrients moving from beneath the pycnocline; however, the high light penetrating into this region allowed the SCM to form. At the shelf break, the pycnocline moving along the slope and on the upper shelf caused higher chlorophyll concentrations at the shelf break and in the bottom layer. In spring, the higher chlorophyll concentrations at the shelf break were located where there were temperature gradients between the upper shelf and the offshore waters (i.e. a shelf break thermal front was present; Figures 6 and 8).

4.1 Interannual variability

15 The ocean glider dataset collected between 2009 and 2015 revealed strong interannual variability in the region (Figure 10). Local and basin-scale ocean forcing affected the coastal hydrography (temperature and salinity) and biological variables (chlorophyll). Pearce and Feng (2013) analysed large-scale (monthly), satellite-derived, sea surface temperature data and found that coastal water temperatures off south-west Australia varied interannually and were linked to the ENSO cycle. During La Niña events, a strong Leeuwin current transported warm water southwards (Pattiaratchi and Buchan, 1988; Pearce and Philips, 1988; Feng et al., 2003, 2008), whereas during El Niño events, the Leeuwin current was weaker with generally lower water temperatures (Pattiaratchi and Buchan, 1988; Pearce et al., 2006). Several ENSO events occurred during the study period (<http://www.bom.gov.au/climate/enso/Inlist/>): (1) the 2009–2010 El Niño; (2) the 2010–2013 La Niña; and (3) 2014–2015 neutral conditions.

25 The study region experienced a 'marine heat wave' in February and March 2011, which was related to a La Niña event and defined as Ningaloo Niña (Feng et al., 2013). This event increased the Leeuwin current's volume transport in February—an unusual event at this time of the year—and caused high sea surface temperature anomalies (~5 °C higher than normal) off Australia's west coast (Feng et al., 2013). It affected extensions and contractions in species distributions and variations in recruitment and growth rates of species, and caused coral bleaching and the mass death of marine life, with short-term and long-term impacts (Pearce et al., 2011). The glider data revealed that extreme depth-integrated (upper 30 m) temperatures (up to 3.5 °C above average) occurred in March 2011 and February 2012 (Figure 9).

35 The glider data captured the transition between the 2009–2010 El Niño and the extended 2011–2014 La Niña (Figure 10). Large changes in the temperature (increase > 4°C) and salinity (decrease by 0.5) occurred between the El Niño and the La Niña events. The temperature decreased and the salinity increased over the same period, with an accompanying decrease in the chlorophyll concentration from ~1 mg/m³ in 2011 to < 0.25 mg/m³ in early 2014. A strong Leeuwin current, which transported warmer, low salinity, low nutrient water from the north

to the south, affected the interannual variability in the temperature and salinity and most likely the chlorophyll concentration. A small decrease in the number of winter storms between 2011 and 2014 (Wandres et al., 2017) might also have reduced local recycling of nutrients (Chen et al., 2017).

5 The extended impacts of the heat wave were also found in temperate reef communities in Western Australia, with the loss of kelp forests, which were replaced by seaweed turfs (Wernberg et al., 2016). Here the marine heat waves forced the contraction of a 100-km area of extensive kelp forests and the replacement of temperate species in the reefs by species characteristic of subtropical and tropical waters. Wernberg et al. (2016) reported that the heat wave effects persisted for many years, and almost five years after the heat wave, the kelp forests
10 had not recovered. The decrease in the chlorophyll concentrations between 2011 and 2014 showed the heat wave affected the pelagic and benthic ecosystems over an extended period.

5. Conclusions

A seven-year, high-resolution ocean glider dataset was used to study the seasonal and interannual variability across the Rottnest continental shelf and indicated that the temperature, salinity, and chlorophyll concentrations
15 had a strong, seasonal and interannual variability. Controlling influences for the seasonal variability were from changes in the wind forcing, dense shelf water cascades (DSWC) and the Leeuwin Current scale, boundary and shelf current systems whilst interannual variability was through El Niño Southern Oscillation (ENSO) events. In spring and summer, the shallow waters were well mixed through wind mixing and the deeper waters (> 50 m) were vertically stratified in temperature that contributed to the formation of a subsurface chlorophyll maximum (SCM). With the onset of storms in late autumn, the water column was well mixed with the SCM absent. On the
20 inner shelf, chlorophyll concentrations were highest in autumn and winter; DSWCs were also the main physical feature during autumn and winter. Chlorophyll concentration was higher closer to the sea bed than at the surface in spring, summer, and autumn. The seasonal patterns coincided with changes in the wind field (weaker winds in autumn) and air–sea fluxes (winter cooling and summer evaporation). Inter-annual variation was associated
25 with ENSO events. Lower temperatures, higher salinity, and higher chlorophyll fluorescence were associated with the El Niño event in 2010. During the strong La Niña event in 2011, temperatures increased and salinity and chlorophyll fluorescence decreased. These changes were mainly associated with an increase in the strength of the Leeuwin current that transported warmer, lower salinity, low nutrient water into the region. Over subsequent years, the temperatures gradually decreased, the salinity increased, and the chlorophyll continued to
30 decrease. In the autumn of 2014, the chlorophyll increased. It is concluded that the observed seasonal and inter-annual variability in chlorophyll concentrations were related to the changes in physical forcing. The results have strong implications for how coastal dynamics and phytoplankton biomass may respond to climate change.

Acknowledgments and data

The ocean glider data used in this paper were collected as part of the Integrated Marine Observing System
35 (IMOS) by the Ocean Glider located at the University of Western Australia. IMOS is a national collaborative research infrastructure program, supported by the Australian Government through the National Collaborative Research Infrastructure Strategy (NCRIS). The meteorological data were obtained from the Bureau of

Meteorology. Funding for this study was provided by International Postgraduate Research Scholarship, Australian Postgraduate Award and University Postgraduate Award. The authors acknowledge the support of Dennis Stanley, Paul Thompson, Kah Kiat Hong, and Mun Woo in the tasks associated with the deployment, recovery, piloting, and data QA/QC of the ocean gliders. All the ocean glider data are available through the Australian Ocean Data Network (<https://portal.aodn.org.au>).

5

Table 1 – Mean values of temperature, Salinity and chlorophyll fluorescence for each season used to calculate the cross-shelf anomalies.

	<u>Temperature</u> <u>(°Celsius)</u>	<u>Salinity</u>	<u>Chlorophyll</u> <u>fluorescence</u> <u>(mg/m³)</u>
<u>Spring</u>	<u>19.4</u>	<u>35.35</u>	<u>0.49</u>
<u>Summer</u>	<u>21.9</u>	<u>35.61</u>	<u>0.46</u>
<u>Autumn</u>	<u>22.4</u>	<u>35.42</u>	<u>0.71</u>
<u>Winter</u>	<u>19.8</u>	<u>35.27</u>	<u>0.68</u>

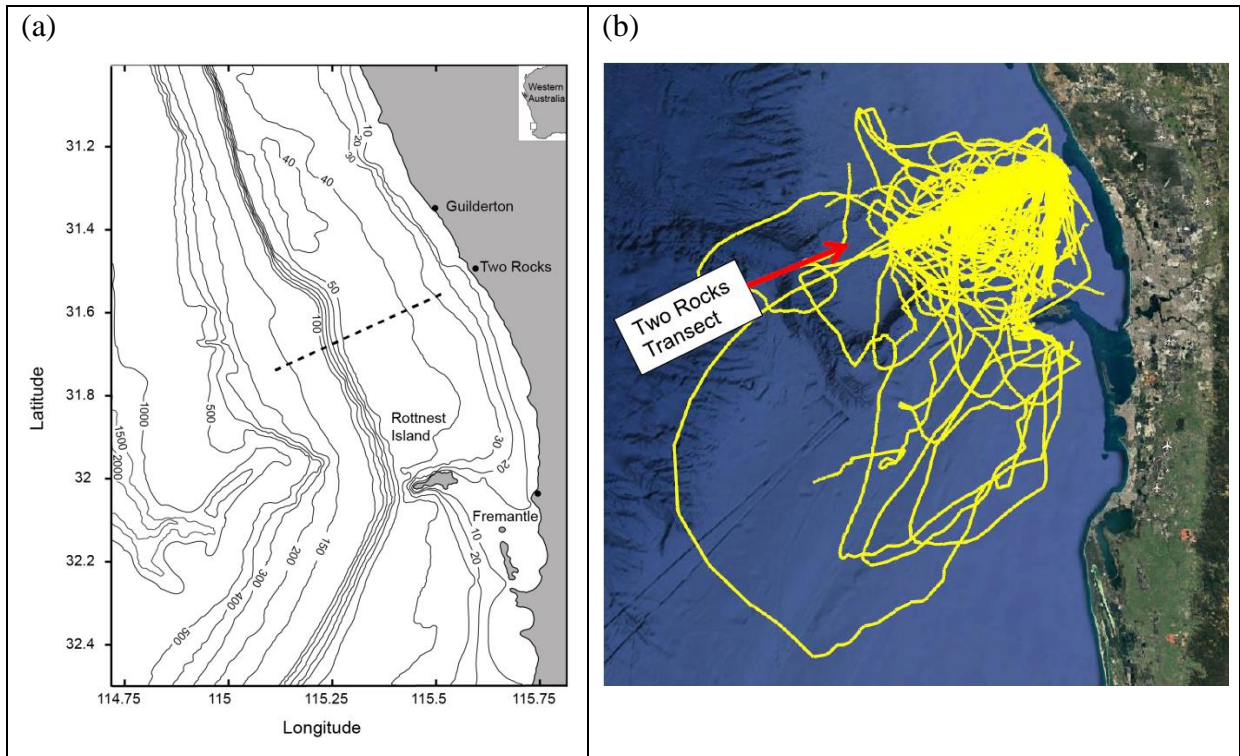


Figure 1: (a) The study area. The dashed line denotes the location of the glider transect. Bathymetric contours are in metres; (b) tracks of all the Slocum ocean glider deployments from 2009 to 2015.

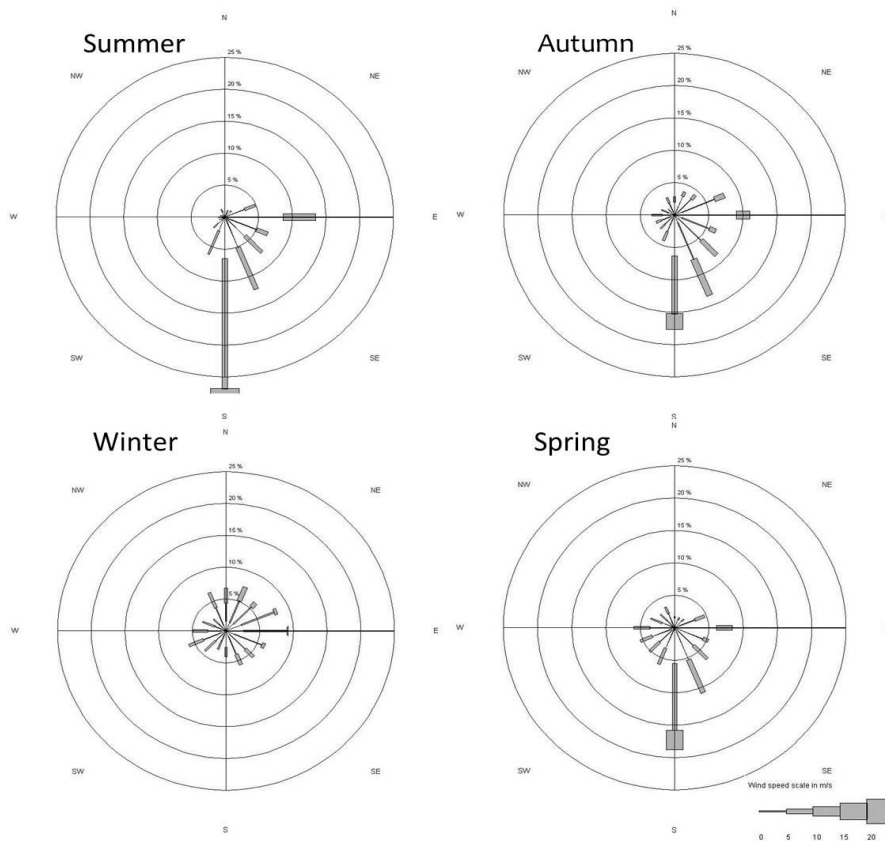


Figure 2: Seasonal wind rose climatology for 2010–2014.

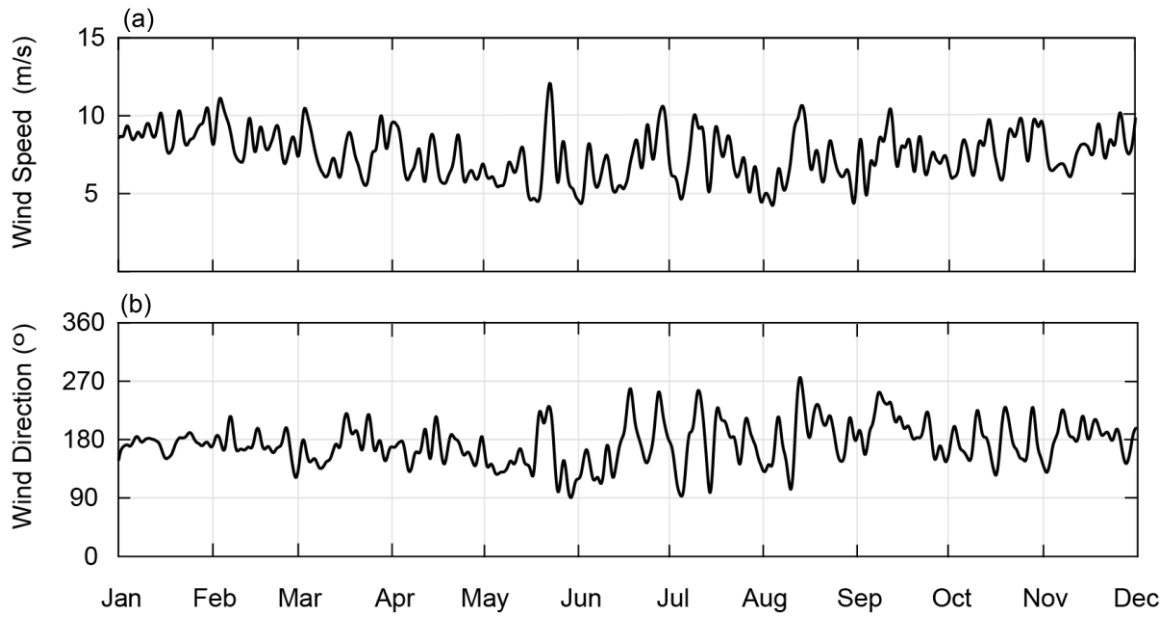


Figure 3: Time series of the (a) mean daily wind speeds and (b) wind direction in 2010 recorded at the Rottne Island meteorological station (Figure 1).

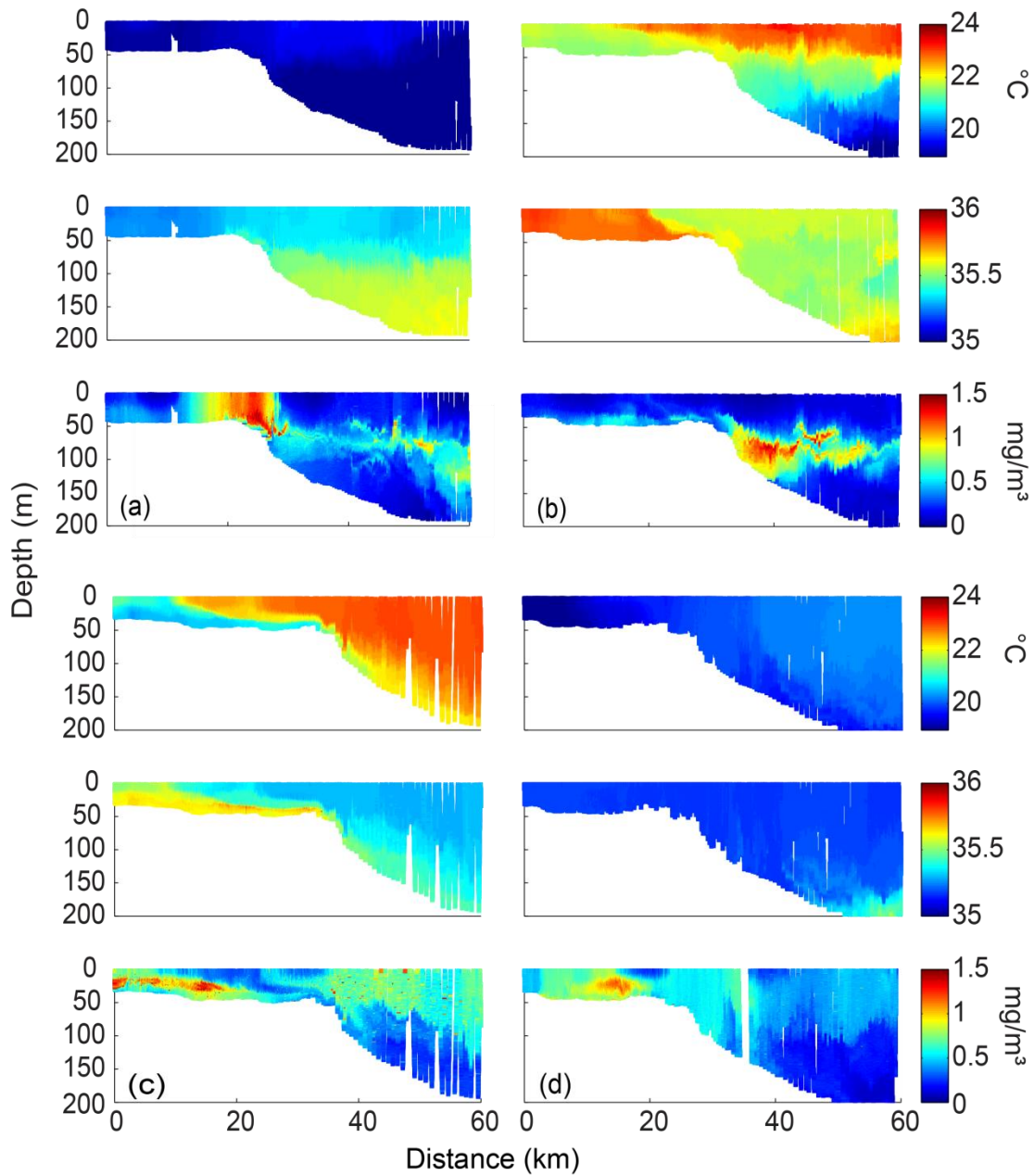


Figure 4: Cross-shelf transects of temperature ($^{\circ}\text{C}$), salinity, and chlorophyll (mg/m^3) obtained along the Two Rocks transect in (a) spring (21–23 October 2013); (b) summer (28 February–3 March 2014); (c) autumn (18–21 May 2009); and (d) winter (9–11 August 2012).

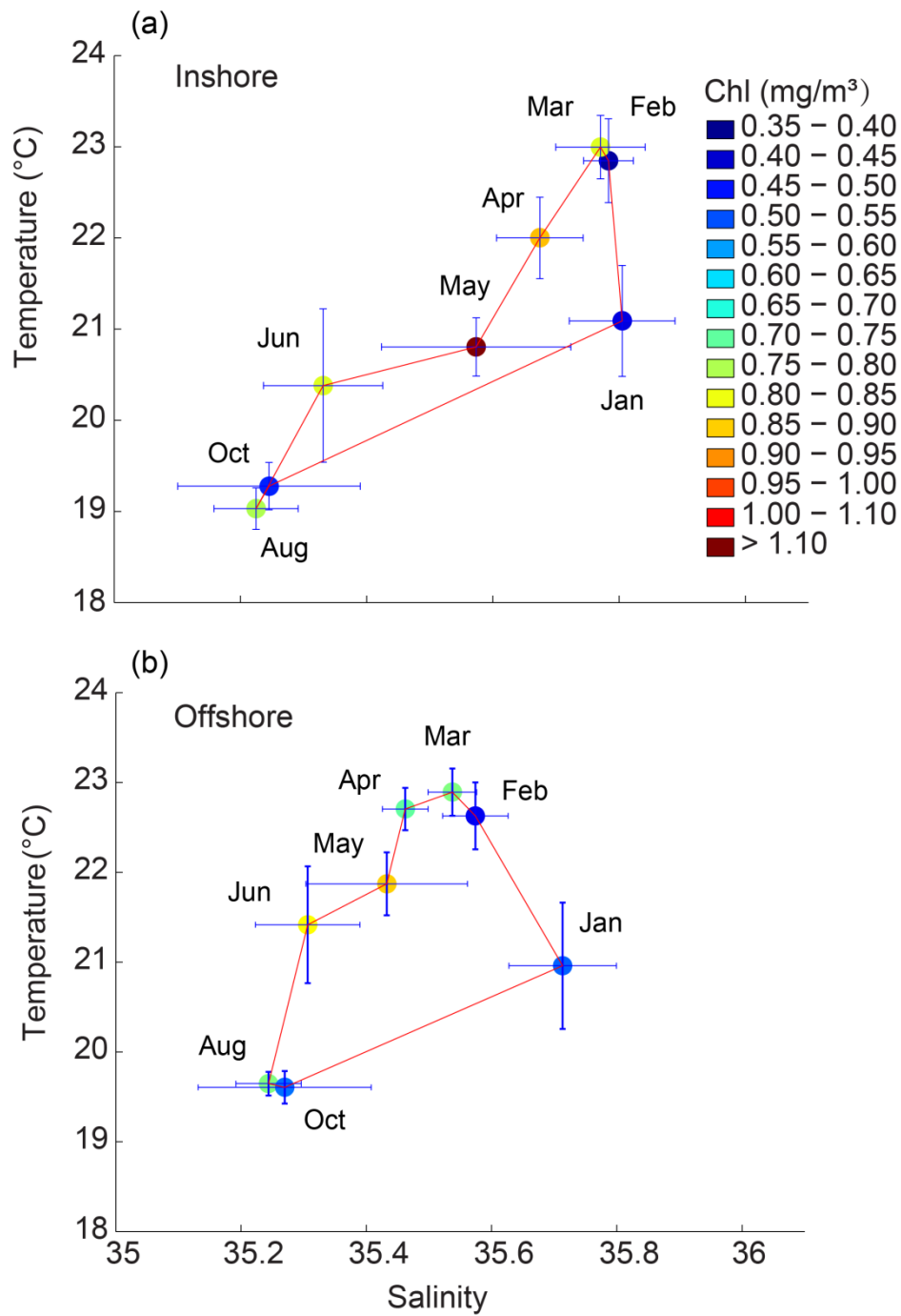


Figure 5: Monthly averaged temperature–salinity diagram with the chlorophyll (Chl) values (mg/m³) for the Two Rocks transect between 2009 and 2015. The horizontal error bars indicate the standard deviation of salinity, and the vertical error bars indicate the standard deviation of temperature.

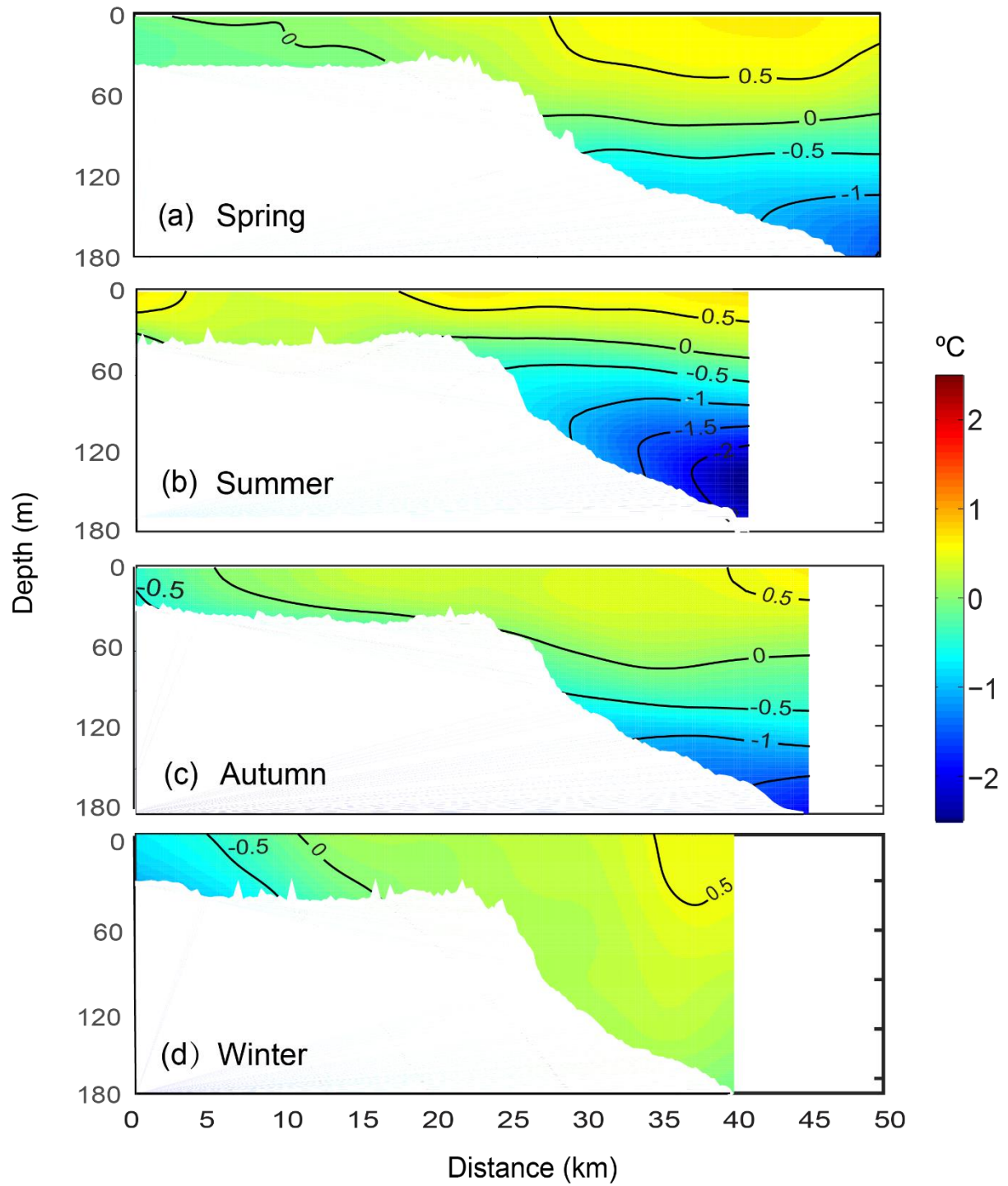


Figure 6: Mean vertical structure anomaly of the temperatures (°C) in (a) spring, (b) summer, (c) autumn, and (d) winter, averaged seasonally over distance and depth across the Rottneet continental shelf between 2009 and 2015.

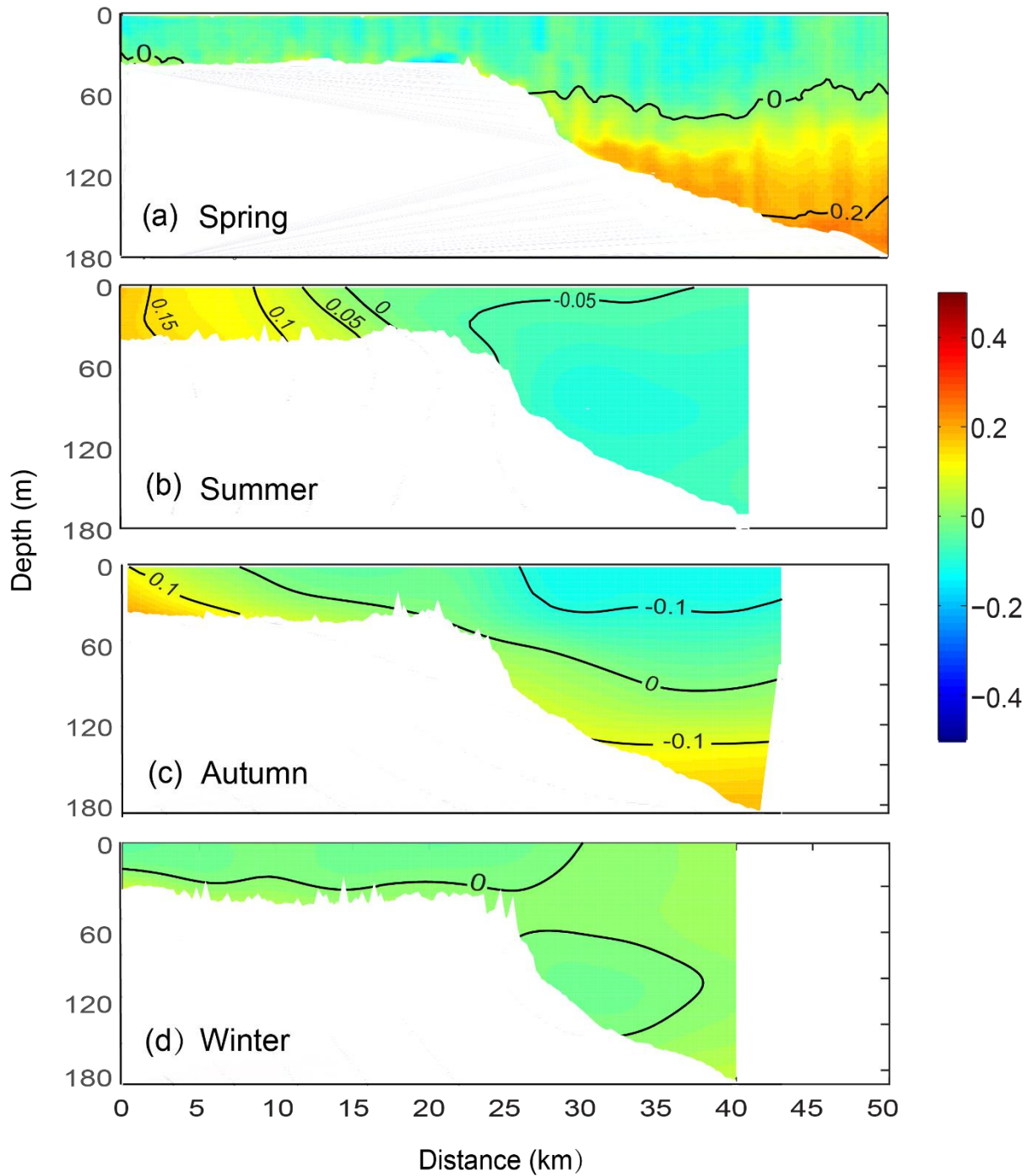


Figure 7: Mean vertical structure anomaly of the salinity in (a) spring, (b) summer, (c) autumn, and (d) winter, averaged seasonally over distance and depth across the Rottneest continental shelf between 2009 and 2015.

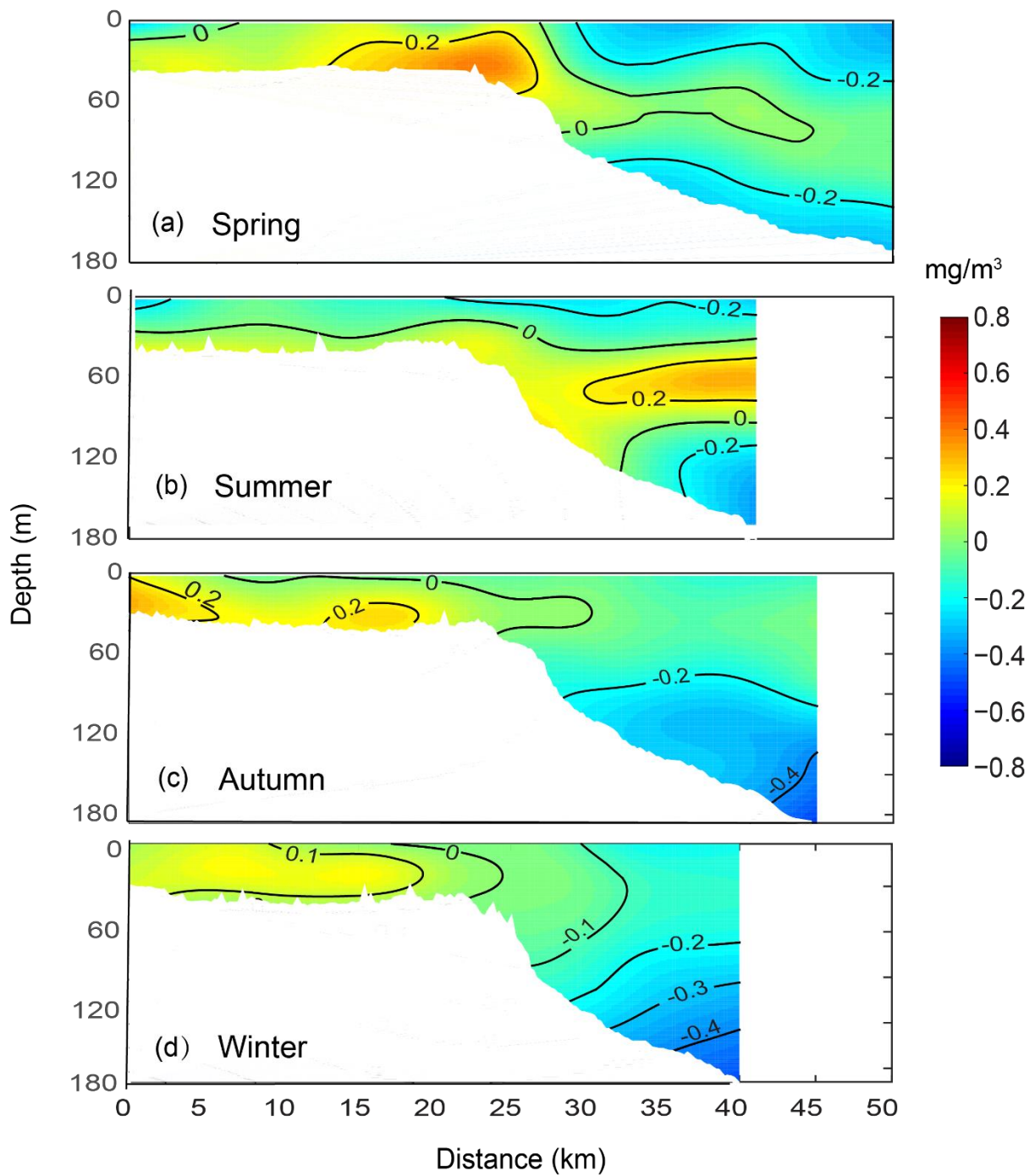


Figure 8: Mean vertical structure anomaly of the fluorescence (mg/m^3) in (a) spring, (b) summer, (c) autumn, and (d) winter, averaged seasonally over distance and depth across the Rottneest continental shelf between 2009 and 2015.

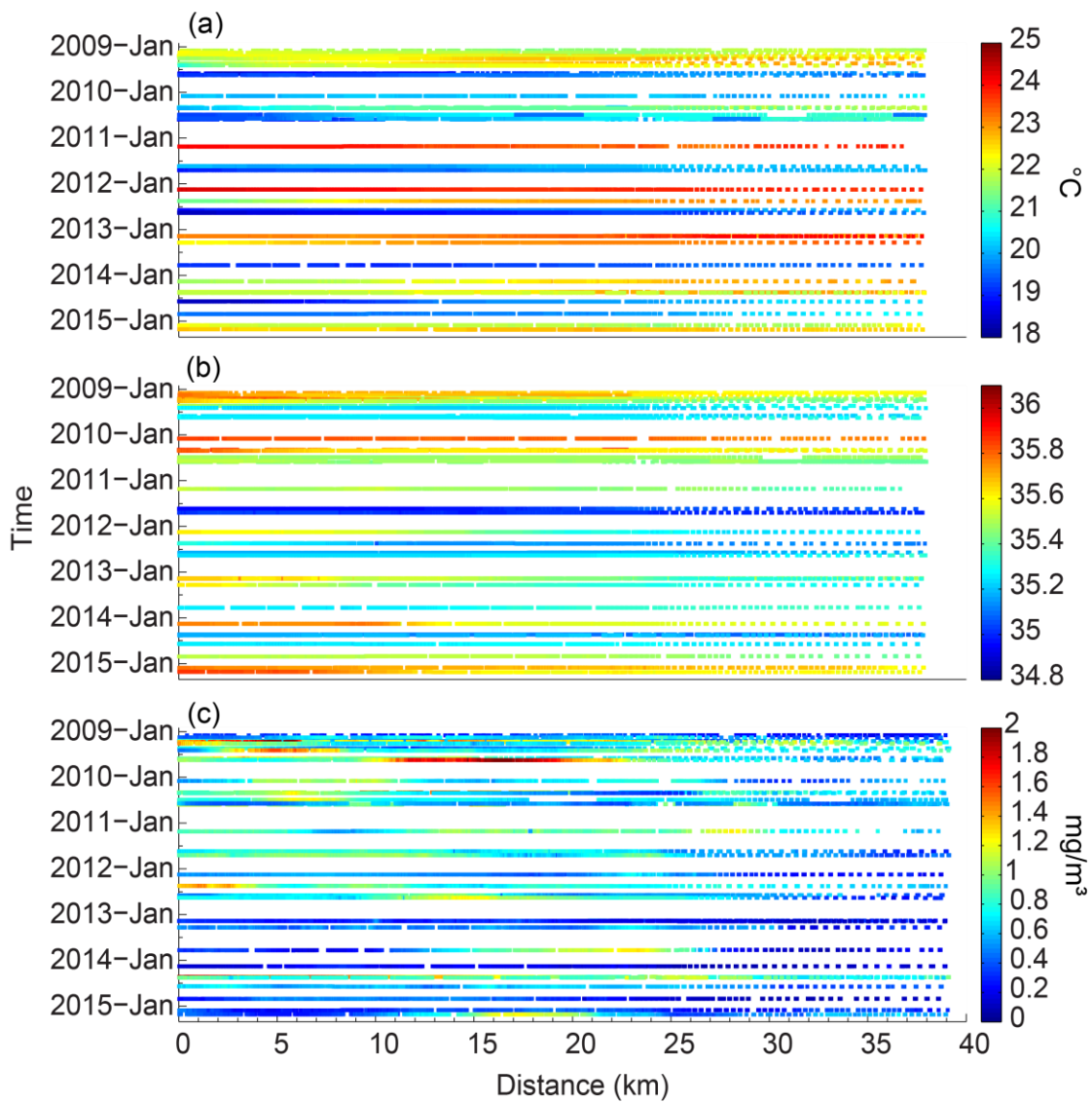


Figure 9: Time–distance series of the (a) temperature ($^{\circ}\text{C}$), (b) salinity, and (c) chlorophyll (mg/m^3), averaged for the top 30 m of water along the Rottneft continental shelf between January 2009 and March 2015. Zero distance (0 km) denotes the start of the glider transect.

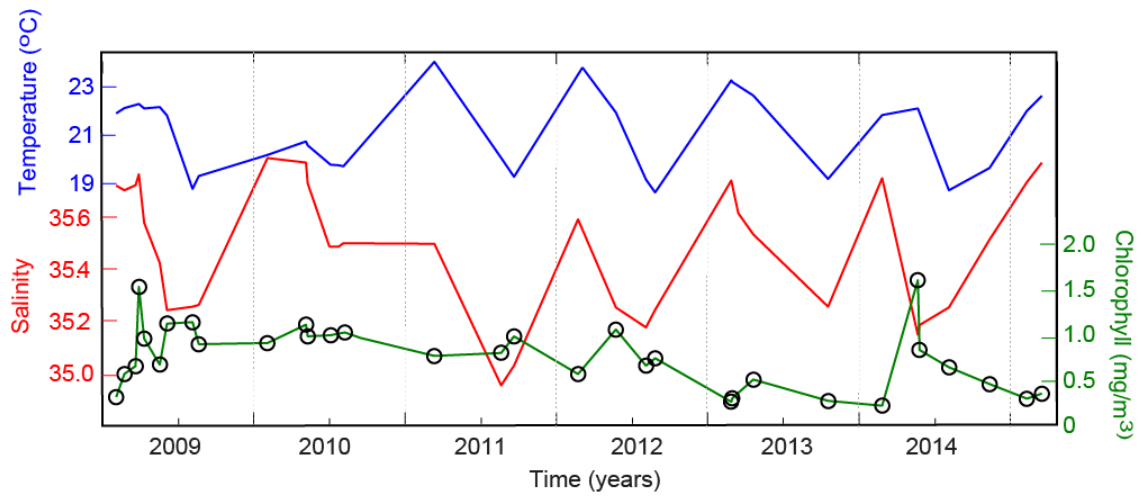


Figure 10: Time series of the depth-averaged temperature, salinity, and chlorophyll 10 km from the start of the glider transects.

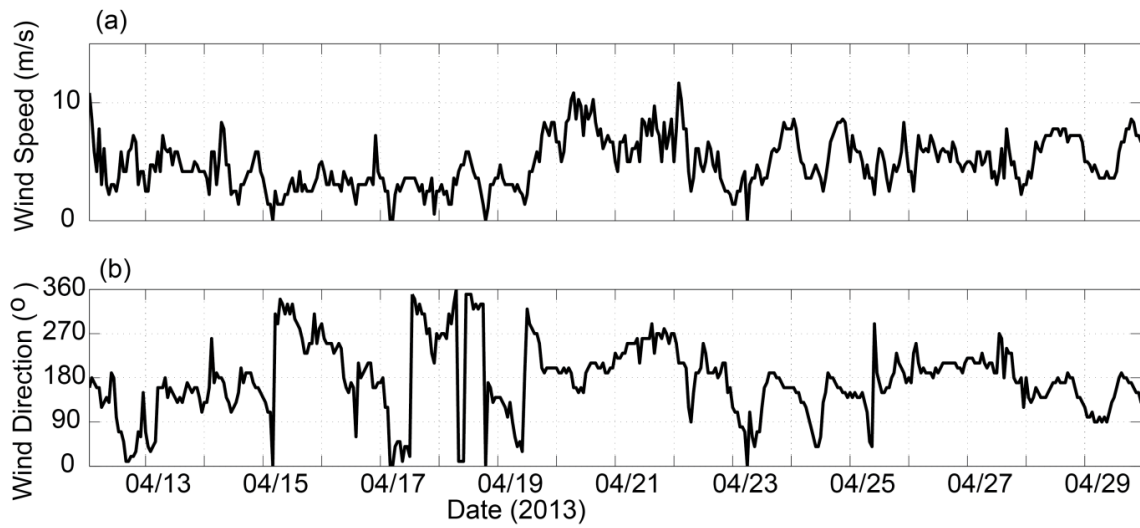


Figure 11: (a) Wind speed (m/s) and (b) wind direction (°) along the Rottneast continental shelf between 12 and 30 April 2013.

5

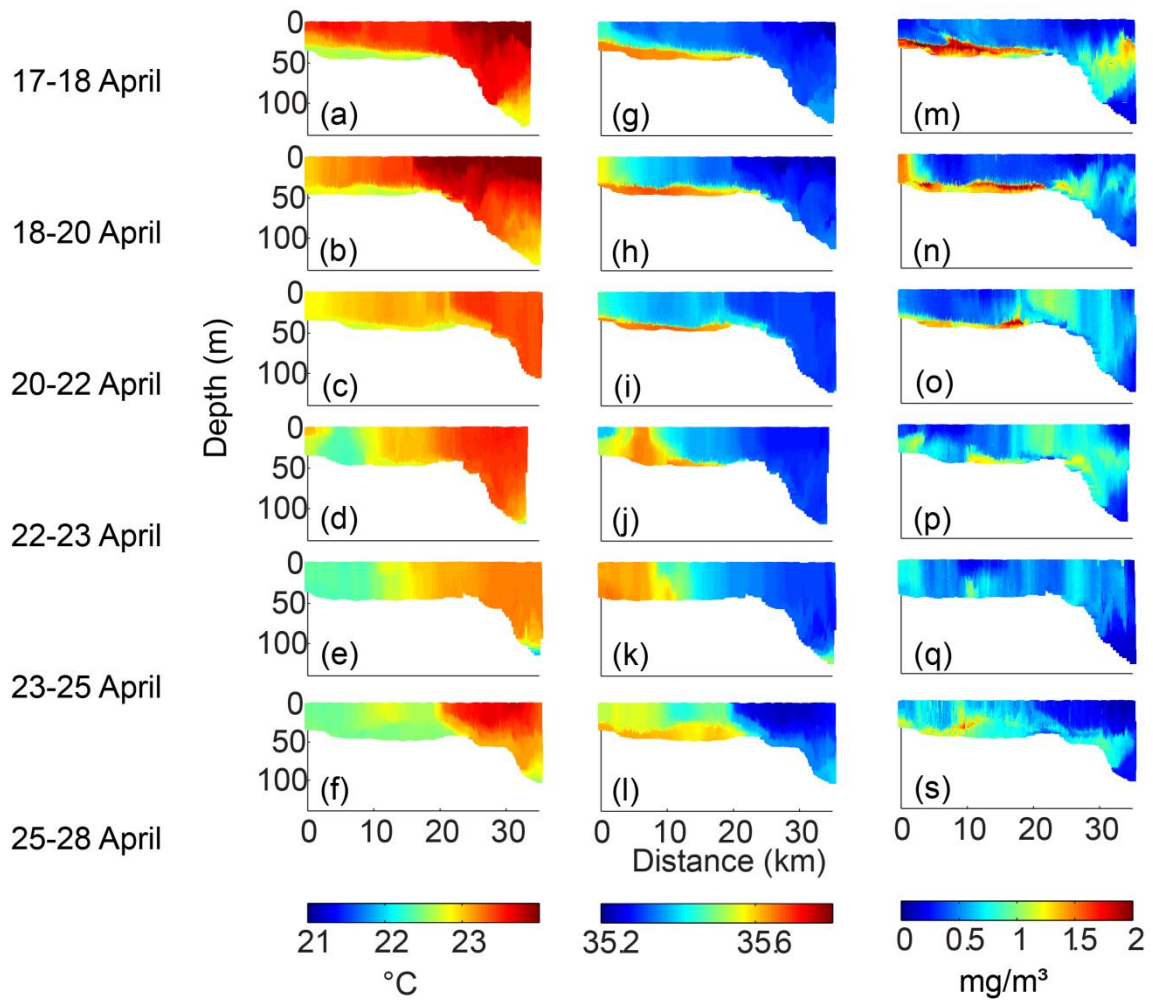


Figure 12: Vertical cross-sections of (a–f) temperature (°C), (g–l) salinity, and (m–s) chlorophyll (mg/m³) across the Rottneest continental shelf between 17 and 28 April 2013 obtained with the ocean glider.

References

[Beck M.: Defining a multi-parameter optics-based approach for estimating Chlorophyll a concentration using ocean gliders. Unpubl. MSc Thesis, Dalhousie University, Canada. 2016](#)

- Branch, G. M., Bustamante, R. H. and Robinson, T. B.: Impacts of a ‘black tide’ harmful algal bloom on rocky-shore intertidal communities on the West Coast of South Africa, *Harmful Algae*, 24, 54–64, doi:10.1016/j.hal.2013.01.005, 2013.
- Cebrián and Valiela: Seasonal patterns in phytoplankton biomass in coastal ecosystems, *J Plankton Res*, 21(3), 429–444, doi:10.1093/plankt/21.3.429, 1999.
- Chen, D., He, L., Liu, F. and Yin, K.: Effects of typhoon events on chlorophyll and carbon fixation in different regions of the East China Sea, *Estuarine, Coastal and Shelf Science*, 194, 229–239, doi:10.1016/j.ecss.2017.06.026, 2017.
- Cloern, J. E. and Jassby, A. D.: Complex seasonal patterns of primary producers at the land–sea interface, *Ecology Letters*, 11(12), 1294–1303, doi:10.1111/j.1461-0248.2008.01244.x, 2008.
- Cushing, D. H.: The seasonal variation in oceanic production as a problem in population dynamics, *ICES J Mar Sci*, 24(3), 455–464, doi:10.1093/icesjms/24.3.455, 1959.
- Earp, A., Hanson, C. E., Ralph, P. J., Brando, V. E., Allen, S., Baird, M., Clementson, L., Daniel, P., Dekker, A. G., Fearn, P. R. C. S., Parslow, J., Strutton, P. G., Thompson, P. A., Underwood, M., Weeks, S. and Doblin, M. A.: Review of fluorescent standards for calibration of in situ fluorometers: recommendations applied in coastal and ocean observing programs, *Opt Express*, 19(27), 26768–26782, 2011.
- Eppley, R. W.: Chlorophyll, photosynthesis and new production in the Southern California Bight, *Progress in Oceanography*, 30(1), 117–150, doi:10.1016/0079-6611(92)90010-W, 1992.
- Fearn, P. R., Twomey, L., Zakiyah, U., Hellere, S., Vincent, W. and Lynch, M. J.: The Hillarys Transect (3): Optical and chlorophyll relationships across the continental shelf off Perth, *Continental Shelf Research*, 27(12), 1719–1746, doi:10.1016/j.csr.2007.02.004, 2007.
- Feng, M.: Annual and interannual variations of the Leeuwin Current at 32°S, *Journal of Geophysical Research*, 108(C11), doi:10.1029/2002JC001763, 2003.
- Feng, M., McPhaden, M. J., Xie, S.-P. and Hafner, J.: La Niña forces unprecedented Leeuwin Current warming in 2011, *Scientific Reports*, 3, 1277, doi:10.1038/srep01277, 2013.
- Field, C. B., Behrenfeld, M. J., Randerson, J. T. and Falkowski, P.: Primary Production of the Biosphere: Integrating Terrestrial and Oceanic Components, *Science*, 281, 237, doi:10.1126/science.281.5374.237, 1998.
- Gallop, S. L., Verspecht, F. and Pattiaratchi, C. B.: Sea breezes drive currents on the inner continental shelf off southwest Western Australia, *Ocean Dynamics*, 62(4), 569–583, doi:10.1007/s10236-011-0515-3, 2012.
- Garcia-Soto, C. and Pingree, R. D.: Spring and summer blooms of phytoplankton (SeaWiFS/MODIS) along a ferry line in the Bay of Biscay and western English Channel, *Continental Shelf Research*, 29(8), 1111–1122, doi:10.1016/j.csr.2008.12.012, 2009.
- Gersbach, G. H., Pattiaratchi, C. B., Ivey, G. N. and Cresswell, G. R.: Upwelling on the south-west coast of Australia—source of the Capes Current?, *Continental Shelf Research*, 19(3), 363–400, 1999.
- Ghisolfi, R. D., Silva, M. P. da, Santos, F. T. dos, Servino, R. N., Cirano, M. and Thompson, F. L.: Physical Forcing Mechanisms Controlling the Variability of Chlorophyll-a over the Royal-Charlotte and Abrolhos Banks—Eastern Brazilian Shelf, *PLOS ONE*, 10(2), e0117082, doi:10.1371/journal.pone.0117082, 2015.

- Greenwood, J. E. and Soetaert, K.: Interannual variability in the seasonal cycle of chlorophyll in the Leeuwin Current off the southwest Western Australian coast, *Journal of Marine Research*, 66(3), 373–390, doi:10.1357/002224008786176043, 2008.
- Hambright, K. D., Gophen, M. and Serruya, S.: Influence of long-term climatic changes on the stratification of a subtropical, warm monomictic lake, *Limnol. Oceanogr.*, 39(5), 1233–1242, doi:10.4319/lo.1994.39.5.1233, 1994.
- Hanson, C. E., Pesant, S., Waite, A. M. and Pattiaratchi, C. B.: Assessing the magnitude and significance of deep chlorophyll maxima of the coastal eastern Indian Ocean, *Deep Sea Research Part II: Topical Studies in Oceanography*, 54(8–10), 884–901, doi:10.1016/j.dsr2.2006.08.021, 2007.
- Huisman, J. and Weissing, F. J.: Light-Limited Growth and Competition for Light in Well-Mixed Aquatic Environments: An Elementary Model, *Ecology*, 75(2), 507–520, doi:10.2307/1939554, 1994.
- [Kämpf, J. and Kavi, A. : On the “hidden” phytoplankton blooms on Australia’s southern shelves, *Geophys. Res. Lett.*, 44, 1466–1473, doi: 10.1002/2016GL072096. 2017.](#)
- Karsten, U., Barrow, K. D., Mostaert, A. s. and King, R. J.: The osmotic significance of the heteroside floridoside in the mangrove alga *Catenella nipae* (Rhodophyta: Gigartinales) in Eastern Australia, *Estuarine, Coastal and Shelf Science*, 40(3), 239–247, doi:10.1016/S0272-7714(05)80008-3, 1995.
- Kilpatrick, T., Xie, S.-P., Miller, A., J. and Schneider, N.: Satellite observations of enhanced chlorophyll variability in the Southern California Bight, *Journal of Geophysical Research: Oceans*, 0(ja), doi:10.1029/2018JC014248, n.d.
- Koslow, J. A., Pesant, S., Feng, M., Pearce, A., Fearn, P., Moore, T., Matear, R. and Waite, A.: The effect of the Leeuwin Current on phytoplankton biomass and production off Southwestern Australia, *Journal of Geophysical Research*, 113(C7), doi:10.1029/2007JC004102, 2008.
- Liu, C. and Tang, D.: Spatial and temporal variations in algal blooms in the coastal waters of the western South China Sea, *Journal of Hydro-environment Research*, 6(3), 239–247, doi:10.1016/j.jher.2012.02.002, 2012.
- Longhurst, A., Sathyendranath, S., Platt, T. and Caverhill, C.: An estimate of global primary production in the ocean from satellite radiometer data, *J Plankton Res*, 17(6), 1245–1271, doi:10.1093/plankt/17.6.1245, 1995.
- Longhurst, A. R. and ebrary, I.: *Ecological geography of the sea*, 2nd ed., Burlington, MA : Academic Press.: <http://trove.nla.gov.au/version/42162902>, 2007.
- Lourey, M. J., Dunn, J. R. and Waring, J.: A mixed-layer nutrient climatology of Leeuwin Current and Western Australian shelf waters: Seasonal nutrient dynamics and biomass, *Journal of Marine Systems*, 59(1–2), 25–51, doi:10.1016/j.jmarsys.2005.10.001, 2006.
- Lourey, M. J., Thompson, P. A., McLaughlin, M. J., Bonham, P. and Feng, M.: Primary production and phytoplankton community structure during a winter shelf-scale phytoplankton bloom off Western Australia, *Mar Biol*, 160(2), 355–369, doi:10.1007/s00227-012-2093-4, 2012.
- Mihanović, H., Pattiaratchi, C. and Verspecht, F.: Diurnal Sea Breezes Force Near-Inertial Waves along Rottneest Continental Shelf, Southwestern Australia, *J. Phys. Oceanogr.*, 46(11), 3487–3508, doi:10.1175/JPO-D-16-0022.1, 2016.
- Moore, T. S., Matear, R. J., Marra, J. and Clementson, L.: Phytoplankton variability off the Western Australian Coast: Mesoscale eddies and their role in cross-shelf exchange, *Deep Sea Research Part II: Topical Studies in Oceanography*, 54(8–10), 943–960, doi:10.1016/j.dsr2.2007.02.006, 2007.

- Nieto, K. and Mélin, F.: Variability of chlorophyll-a concentration in the Gulf of Guinea and its relation to physical oceanographic variables, *Progress in Oceanography*, 151, 97–115, doi:10.1016/j.pocean.2016.11.009, 2017.
- Paerl, H. W. and Huisman, J.: Blooms Like It Hot, *Science*, 320(5872), 57–58, doi:10.1126/science.1155398, 2008.
- Pattiaratchi, C. and Buchan, S.: Implications of long-term climate change for the Leeuwin Current., 1991.
- Pattiaratchi, C., Hegge, B., Gould, J. and Eliot, I.: Impact of sea-breeze activity on nearshore and foreshore processes in southwestern Australia, *Continental Shelf Research*, 17(13), 1539–1560, doi:10.1016/S0278-4343(97)00016-2, 1997.
- 10 Pattiaratchi, C., Hollings, B., Woo, M. and Welhena, T.: Dense shelf water formation along the south-west Australian inner shelf, *Geophys. Res. Lett.*, 38(10), L10609, doi:10.1029/2011GL046816, 2011.
- Pattiaratchi, C. and Eliot, M.: Sea level variability in South-West Australia: from hours to decades, pp. 1186–1198, World Scientific Publishing Company., 2009.
- [Pattiaratchi, C., Woo, M.: The mean state of the Leeuwin Current system between North West Cape and Cape Leeuwin. *Journal of the Royal Society of Western Australia*, 92, 221-241. 2009.](#)
- 15 [Pattiaratchi, C., Woo, L. M., Thomson, P. G., Hong, K. K., Stanley, D.: Ocean Glider Observations Around Australia. *Oceanography*, 30\(2\), 90-91. 2017.](#)
- Pearce, A. F. and Feng, M.: The rise and fall of the “marine heat wave” off Western Australia during the summer of 2010/2011, *Journal of Marine Systems*, 111–112, 139–156, doi:10.1016/j.jmarsys.2012.10.009, 2013.
- 20 Pearce, A. F. and Phillips, B. F.: ENSO events, the Leeuwin Current, and larval recruitment of the western rock lobster, *ICES J Mar Sci*, 45(1), 13–21, doi:10.1093/icesjms/45.1.13, 1988.
- Pearce, A. F., Lynch, M. J. and Hanson, C. E.: The Hillarys Transect (1): Seasonal and cross-shelf variability of physical and chemical water properties off Perth, Western Australia, 1996–98, *Continental Shelf Research*, 26(15), 1689–1729, doi:10.1016/j.csr.2006.05.008, 2006.
- 25 Ridgway, K. R. and Condie, S. A.: The 5500-km-long boundary flow off western and southern Australia, *J. Geophys. Res.*, 109(C4), C04017, doi:10.1029/2003JC001921, 2004.
- [Rossi, V., Feng M., Pattiaratchi, C., Roughan, M. and A. M. Waite: On the factors influencing the development of sporadic upwelling in the Leeuwin Current system, *J. Geophys. Res. Oceans*, 118, 3608–3621, doi:10.1002/jgrc.20242. 2013.](#)
- 30 Rudnick, D. L.: Ocean Research Enabled by Underwater Gliders, *Ann Rev Mar Sci*, 8, 519–541, doi:10.1146/annurev-marine-122414-033913, 2016.
- Schofield, O., Kohut, J., Aragon, D., Creed, L., Graver, J., Haldeman, C., Kerfoot, J., Roarty, H., Jones, C., Webb, D. and Glenn, S.: Slocum Gliders: Robust and ready, *J. Field Robotics*, 24(6), 473–485, doi:10.1002/rob.20200, 2007.
- 35 Steedman, R. K. and Craig, P. D.: Wind-driven circulation of Cockburn Sound, *Mar. Freshwater Res.*, 34(1), 187–212, doi:10.1071/mf9830187, 1983.
- Sverdrup, H. U.: On Conditions for the Vernal Blooming of Phytoplankton, *ICES J Mar Sci*, 18(3), 287–295, doi:10.1093/icesjms/18.3.287, 1953.

~~Thomson, P.G., Mantovanelli, A., Wright, S.W., Pattiaratchi, C.B. (2105). In situ comparisons of glider bio-optical measurements to CTD water properties. Australian Marine Sciences Conference, Geelong, Victoria, July 5th–9th 2015.~~

Thompson, P. A., Bonham, P., Waite, A. M., Clementson, L. A., Cherukuru, N., Hassler, C. and Doblin, M. A.: Contrasting oceanographic conditions and phytoplankton communities on the east and west coasts of Australia, Deep Sea Research Part II: Topical Studies in Oceanography, 58(5), 645–663, doi:10.1016/j.dsr2.2010.10.003, 2011.

Thomson, P.G., Mantovanelli, A., Wright, S.W., Pattiaratchi, C.B.: In situ comparisons of glider bio-optical measurements to CTD water properties. Australian Marine Sciences Conference, Geelong, Victoria, July 5th – 9th 2015.

Twomey, L. J., Waite, A. M., Pez, V. and Pattiaratchi, C. B.: Variability in nitrogen uptake and fixation in the oligotrophic waters off the south west coast of Australia, Deep Sea Research Part II: Topical Studies in Oceanography, 54(8), 925–942, doi:10.1016/j.dsr2.2006.10.001, 2007.

Verspecht, F. and Pattiaratchi, C.: On the significance of wind event frequency for particulate resuspension and light attenuation in coastal waters, Continental Shelf Research, 30(18), 1971–1982, doi:10.1016/j.csr.2010.09.008, 2010.

Vidal, T., Calado, A. J., Moita, M. T. and Cunha, M. R.: Phytoplankton dynamics in relation to seasonal variability and upwelling and relaxation patterns at the mouth of Ria de Aveiro (West Iberian Margin) over a four-year period, PLOS ONE, 12(5), e0177237, doi:10.1371/journal.pone.0177237, 2017.

Wandres, M., Pattiaratchi, C. and Hemer, M. A.: Projected changes of the southwest Australian wave climate under two atmospheric greenhouse gas concentration pathways, Ocean Modelling, 117, 70–87, doi:10.1016/j.ocemod.2017.08.002, 2017.

Wernberg, T., Bennett, S., Babcock, R. C., Bettignies, T. de, Cure, K., Depczynski, M., Dufois, F., Fromont, J., Fulton, C. J., Hovey, R., Harvey, E. S., Holmes, T. R. H., Kendrick, G. A., Radford, B. T., Santana-Garcon, J., Saunders, B. J., Smale, D. A., Thomsen, M. S., Tuckett, C. A., Tuya, F., Vanderklift, M. A. and Wilson, S.: Climate-driven regime shift of a temperate marine ecosystem, Science, 353, 169–172, doi:10.1126/science.aad8745, 2016.

Wijeratne, S., Pattiaratchi, C. and Proctor, R.: Estimates of Surface and Subsurface Boundary Current Transport Around Australia, Journal of Geophysical Research: Oceans, 123(5), 3444–3466, doi:10.1029/2017JC013221, 2018.

Winder, M. and Cloern, J. E.: The annual cycles of phytoplankton biomass, Philosophical Transactions of the Royal Society B: Biological Sciences, 365(1555), 3215–3226, doi:10.1098/rstb.2010.0125, 2010.

Woo, M. and Pattiaratchi, C.: Hydrography and water masses off the western Australian coast, Deep Sea Research Part I: Oceanographic Research Papers, 55(9), 1090–1104, doi:10.1016/j.dsr.2008.05.005, 2008.

Woo, M. 2017. Australian National Facility for Ocean Gliders (ANFOG) Data Management User Manual http://imos.org.au/fileadmin/user_upload/shared/ANFOG/ANFOG_DataManagement_UsersManual_v5.01_Mar30.pdf.

Zaker, N. H., Imberger, J. and Pattiaratchi, C.: Dynamics of the Coastal Boundary Layer off Perth, Western Australia, Journal of Coastal Research, 23(5), 1112–1130, 2007.