

Reviewer Comment 1, F. d'Ovidio, and *author response*:

Major comments

The paper provides an analysis of the role of mesoscale eddies in the Southern Ocean on primary production, in terms of chlorophyll anomalies detected by remote sensing associated to them. Methodologically, the paper follows very closely some previous works, in particular Gaube et al. 2014, which were more focused on the global ocean. In respect to previous works, this manuscript has fine tuned the methodology, and discussed the results in the specific context of the Southern Ocean. The main original result in this manuscript is the finding of a strong seasonal signal in the mesoscale imprint on chlorophyll anomalies. This result and other more incremental findings are not surprising, but are very well discussed in terms of the previous literature and in terms of the biogeochemical activity of the Southern ocean (with possibly one direction of improvement which is described below). As a consequence, I find this manuscript as a useful contribution to the understanding of the role of mesoscale eddies on primary production in the Southern Ocean, even in its current form.

Thank you for the supportive review. We have amended the manuscript according to the detailed comments below.

Additionally we have added minor changes to the text aimed at further clarifying the manuscript that were not in response to particular reviewer comments. These changes did not alter any qualitative or quantitative conclusions from the original manuscript.

Comment a

1. There is however one issue that may improve further the manuscript. One of the main concept treated by the paper, is stirring, and in particular the imprint of stirring induced by the mesoscale eddies on the mesoscale anomalies of the chlorophyll field. The manuscript explains that the stirring created by a mesoscale eddy can create a local deformation of a pre-existing chlorophyll gradient and I agree with this statement. However, this is not all about stirring. In fact, if I think to the imprint of stirring and chlorophyll in the Southern ocean, the main effect that comes to my mind is not the generation of local chlorophyll anomalies, but the huge plumes of chlorophyll induced when stirring by mesoscale eddies modulates iron delivery in a non-local way, preconditioning the blooms of this region. An analysis of this effect is not in the scope of this paper, and it has been done elsewhere (for instance, d'Ovidio et al. Biogeosciences 12, 2015; Ardyna et al. GRL 44, 2017). Nevertheless, I feel that the submitted manuscript should stress more that what the authors intend here for eddy stirring, is only the local effect of stirring, while other non-local effects of stirring by mesoscale activity also exist, and actually they are a prominent driver of the bloom extension and intensity in the Southern Ocean. In fact, it would

be interested to know whether there is a signature of this non-local stirring effect in the analysis presented, for instance by finding stronger anomalies downstream of likely iron sources like the continental shelves present in the region. Or as a possible alternative explanation of the asymmetries in the chlorophyll anomalies. I am certainly biased in this comment by my own work on the subject, therefore the authors are free to find some other papers instead of the two indicated above to add to their discussion. But in any case, I feel that the discussion on stirring merits to be extended.

2. *Thanks for pointing out this additional non-local effect of eddies on chlorophyll and the associated references. To accommodate your comment and the main comment of the second reviewer, Volker Strass, we have included in the Discussion section a paragraph on the potential effects of eddies on chlorophyll/biogeochemical rates which we do not consider in our analysis (see below); further, we have added the attribute "local" to "stirring" in several places throughout the manuscript; and, yes, indeed, we tend to find positive anomalies, both for cyclones and anticyclones downstream of shelves (see also below, p19L9ff).*
3. *We added in the Discussion section p19L16ff: "An additional possible explanation is the offshore advection of iron trapped in the nearshore region by eddies that fuels extra growth in the offshore waters, as suggested e.g., for Haida eddies in the North Pacific [Xiu et al., 2011], or for eddies passing the Kerguelen Plateau [D'Ovidio et al., 2015]."*
p20L25: "Furthermore, we may underestimate the overall effect of mesoscale eddies on Chl also because of additional effects of mesoscale eddies that are not considered in our analysis. Such effects include the impact of smaller mesoscale features, and of submesoscale processes near the edges of eddies [Woods, 1988, Strass, 1992, Martin et al., 2002, Lévy, 2003, Klein and Lapeyre, 2009, Siegel et al., 2011], e.g., eddy-jet interactions and associated horizontal shear-induced patches of up- and downwelling. Such features are included in our analysis only insofar as they have rectified effects on the larger mesoscale Chl patterns resolved by the data we use. Another effect we do not consider is non-local stirring [D'Ovidio et al., 2015], the contribution of eddies to lateral dispersion outside the eddies' cores in interaction with the ambient flow. This effect, for instance, shapes iron plumes downstream of shelves along the ACC, thus preconditioning Chl blooms [Ardyna et al., 2017]. Therefore, we note that the overall effect of mesoscale eddies on biogeochemical rates may be larger than suggested by our analysis of the mesoscale, local imprint of eddies on Chl. Finally, we note that our analysis does not include the effect of submesoscale processes outside eddies as well as any unstructured turbulence in general."
Further we added the reference of Ardyna et al in the context of the non-zonality of the Chl p10L1ff: "A few exceptions break this mostly zonal picture for Chl [Ardyna et al., 2017], and also for δ Chl.", and of the seasonality of the imprint of eddies, p10L10.

Minor comments

Comment b

1. timescale of chlorophyll: chlorophyll is just a pigment. Referring to the timescale of a bloom, or of phytoplankton demography, should be more appropriate.
2. *Thanks for the comment, we have adjusted the text accordingly (see below).*
3. *We have changed time scale of Chl to time scale of phytoplankton biomass changes in the section Causes of δ Chl by advective processes (p3L13ff).*

References

- M. Ardyna, H. Claustre, J. B. Sallée, F. D’Ovidio, B. Gentili, G. van Dijken, F. D’Ortenzio, and K. R. Arrigo. Delineating environmental control of phytoplankton biomass and phenology in the Southern Ocean. *Geophys. Res. Lett.*, 44(10):5016–5024, 2017. ISSN 19448007. doi: 10.1002/2016GL072428.
- F. D’Ovidio, A. Della Penna, T. W. Trull, F. Nencioli, M. I. Pujol, M. H. Rio, Y. H. Park, C. Cotté, M. Zhou, and S. Blain. The biogeochemical structuring role of horizontal stirring: Lagrangian perspectives on iron delivery downstream of the Kerguelen Plateau. *Biogeosciences*, 12(19):5567–5581, 2015. doi: 10.5194/bg-12-5567-2015.
- P. Klein and G. Lapeyre. The oceanic vertical pump induced by mesoscale and submesoscale turbulence. *Annu. Rev. Mar. Sci.*, 1:351–375, 2009. doi: 10.1146/annurev.marine.010908.163704.
- M. Lévy. Mesoscale variability of phytoplankton and of new production: Impact of the large-scale nutrient distribution. *J. Geophys. Res.*, 108(C11):3358, 2003. ISSN 0148-0227. doi: 10.1029/2002JC001577.
- A. P. Martin, K. J. Richards, A. Bracco, and A. Provenzale. Patchy productivity in the open ocean. *Global Biogeochem. Cycles*, 16(2)(2), 2002. doi: 10.1029/2001GB001449.
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- V. H. Strass. Chlorophyll patchiness caused by mesoscale upwelling at fronts. *Deep Sea Res. Part A. Oceanogr. Res. Pap.*, 39(1):75–96, 1992. doi: 10.1016/0198-0149(92)90021-K.

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- P. Xiu, A. P. Palacz, F. Chai, E. G. Roy, and M. L. Wells. Iron flux induced by Haida eddies in the Gulf of Alaska. *Geophysical Research Letters*, 38(13): L13607, 2011. ISSN 0094-8276. doi: 10.1029/2011GL047946.

Reviewer Comment 2, V. Strass, and *author response*:

Major comments

General Appraisal

Comment a

1. The paper presents the results of a truly impressive data analysis of the effects of mesoscale eddies on sea surface chlorophyll in the Southern Ocean, comprising an extensive and widely new look into the regional and seasonal variation of these effects. In respect of how those interesting results are set into scientific context, however, the paper has severe weaknesses. I think these weaknesses can be overcome by rewriting major parts of the manuscript, sections 1, 4 and 5 in particular.
2. *Thank you for the positive assessment regarding our analysis, and for providing comments and references to better set our paper into context.*
3. *We have included the additional references and modified sections 1, 4 and 5 according to the above comment and the detailed comments below. Additionally we have added minor changes to the text aimed at further clarifying the manuscript that were not in response to particular reviewer comments. These changes did not alter any qualitative or quantitative conclusions from the original manuscript.*

Specific Comments

Comment b

1. The mesoscale ocean dynamics govern the range from a few kilometres to a few hundreds of kilometres horizontally. The data used in the study by Frenger et al., collected by satellite remote sensing, provide a horizontal resolution of 1/3 of a degree for eddies (Aviso SLA) and 0.25° for the concentration of sea surface chlorophyll (ESA GlobColour Project product), i.e. approx. 37 km and 28 km in latitude, respectively. In consequence, only the larger fraction of mesoscale eddies is investigated. This needs, but is not yet, be made clear in the paper.
2. *We have included a sentence in the Method and Discussion section to clarify the constraints due to the resolution of the satellite data.*
3. *p6L9 "The resolution capacity of Aviso SLA allows for the analysis of the larger mesoscale eddies with minimum diameters of about 50 km at 65°S and 100 km at 30°S [Chelton et al., 2011, Frenger et al., 2015]."*

Comment c

1. Eddies, or the mesoscale dynamics in general, affect phytoplankton hence the chlorophyll concentration in various ways, particularly by time-variable horizontal and vertical advection and associated transports of nutrients, and by vertical current shears that control stratification and subduction hence the light environment which phytoplankton cells experience. (In the Southern Ocean, where most macro-nutrients are abundant, it is likely the mesoscale upwelling of the primary production-limiting micro-nutrient iron that enhances biological production in the ACC with its meandering fronts; Hense, et al., Regional ecosystem dynamics in the ACC: Simulations with a three-dimensional ocean-plankton model, J. Mar. Systems, 2003.) Vertical velocities, and therefore possible upwelling of nutrients, but are known to be most intense at the smallest part (≤ 10 km) of the mesoscale range (Martin et al., Patchy productivity in the open ocean, Global Biogeochem. Cycles 2002; Lévy, Mesoscale variability of phytoplankton and of new production: Impact of the large scale nutrient distribution, J. Geophys. Res., 2003; Klein & Lapeyre, The oceanic vertical pump induced by mesoscale and submesoscale turbulence, Annu. Rev. Mar. Sci. 2009). The relevance of those small scales has been noted initially by Woods (Mesoscale upwelling and primary production, in Toward a theory on biological–physical interactions in the world ocean, ed. B. J. Rothschild, Dordrecht Kluwer, 1988), who raised the hypothesis that key to understanding the plankton patchiness which was revealed with the advent of satellite chlorophyll images, lies in the dynamics of mesoscale jets, where dynamical constraints limit upwelling to horizontal dimensions of about ten kilometres. This hypothesis received first observational support in 1992 (Strass, Chlorophyll patchiness caused by mesoscale upwelling at fronts, Deep-Sea Res. I). These latter two publications, by the way, would close the glaring time gap of the literature review given in the Introduction (p.1, lines 20 – 22.) between the cited advent of satellite chlorophyll images (Gower et al. 1980) and Doney (2003).
2. *Thank you for these points and the additional references. Our objective is not to discuss in our paper processes ≤ 10 km, that is submesoscale processes (which appear to be the focus of the points above/below). These are, even though connected to the mesoscale, a separate field of study, and we certainly do not wish to claim to resolve direct submesoscale effects in the data we use. Hence, we have included the suggested references and tried to make very clear throughout the text that we focus on the larger mesoscale as resolved by the satellite data we use for the study. Further, we have included in the Discussion section a paragraph on the potential effects of eddies on chlorophyll/biogeochemical rates which we do not consider in our analysis (see also Reviewer Comment 1 by Francesco d’Ovidio, and below)*
3. *p20L25: "Furthermore, we may underestimate the overall effect of mesoscale*

eddies on Chl also because of additional effects of mesoscale eddies that are not considered in our analysis. Such effects include the impact of smaller mesoscale features, and of submesoscale processes near the edges of eddies [Woods, 1988, Strass, 1992, Martin et al., 2002, Lévy, 2003, Klein and Lapeyre, 2009, Siegel et al., 2011], e.g., eddy-jet interactions and associated horizontal shear-induced patches of up- and downwelling. Such features are included in our analysis only insofar as they have rectified effects on the larger mesoscale Chl patterns resolved by the data we use. Another effect we do not consider is non-local stirring [D'Ovidio et al., 2015], the contribution of eddies to lateral dispersion outside the eddies' cores in interaction with the ambient flow. This effect, for instance, shapes iron plumes downstream of shelves along the ACC, thus preconditioning Chl blooms [Ardyna et al., 2017]. Therefore, we note that the overall effect of mesoscale eddies on biogeochemical rates may be larger than suggested by our analysis of the mesoscale, local imprint of eddies on Chl. Finally, we note that our analysis does not include the effect of submesoscale processes outside eddies as well as any unstructured turbulence in general.”.

Comment d

1. The presumably most important horizontal scale for stimulating phytoplankton growth, as explained above, unfortunately is not resolved by the present study. Moreover, most of the above-mentioned studies have demonstrated that up- and downwelling predominately are driven by changes in time of the mesoscale flow field (related to the development of frontal meanders due to baroclinic instability, frontogenesis by eddyeddy interaction etc.). For the ACC, Strass et al. (Mesoscale frontal dynamics: Shaping the environment of primary production in the Antarctic Circumpolar Current, Deep-Sea Research II, 2002) have shown with an in situ study that the acceleration/deceleration of a frontal jet by interaction with an eddy creates a pattern of up- and downwelling cells and of chlorophyll patches on a much smaller horizontal scale than that of the involved eddy. Frenger et al. in their present study, however, analysed only eddies that were tracked over at least three weeks, hence eddies which were not subject to much change in time. Both by the selection of eddies of larger size and of low temporal change, Frenger and co-authors likely introduce a bias towards eddies of rather limited impact on biological production and biogeochemical rates. Their conclusion that eddydriven stirring and trapping dominate over biogeochemical effects therefore seems not robust but rather a result of the horizontal/time scale bias. This requires an honest and thorough discussion.
2. *See also response above. We agree that additional effects of the smaller mesoscale and of the submesoscale on shorter time scales are important for biogeochemical rates; even with our focus on the larger mesoscale, we*

were starting out with the hypothesis that these eddies affect biogeochemical rates. Yet, our conclusion is valid, that the Chl imprint we find of the scales that our data do resolve can be explained largely by advection. This conclusion does not negate that effects on biogeochemical rates may be at play, too. To try to accommodate your concern, and the main comment by Francesco d'Ovidio, that overall biogeochemical effects may be underestimated, we included a paragraph in the Discussion section (see response to comment above), and highlighted throughout the text that we focus on the larger mesoscale.

3. See previous comment/response.

Comment e

1. Throughout their ms Frenger and co-authors associate cyclonic eddies with thermocline lifting and anticyclonic eddies with thermocline deepening. Undisputable is that cyclones display a lifted thermocline and anticyclones a deepened thermocline. However, whether or not the thermocline moves up or down after eddies have been fully formed is in contestation. It may well be the reverse of the indicated way, i.e. that during eddy slow-down due to processes such as eddy-induced Ekman pumping, the thermocline in cyclones moves downward and in anticyclones upward (e.g. Gaube et al., 2014). I therefore recommend the authors use to a more careful wording, i.e. lifted/deepened instead of lifting/deepening.

2. We much appreciate this comment.

3. We replaced "lifting/deepening" with "lifted/deepened" throughout the text.

Comment f

1. On p. 20, lines 30-31 the authors bring forward the argument that anticyclones cause an abatement of grazing pressure, without providing a reference. In general I would doubt that a reference for this argument exists, which could be considered representing the widely accepted and unquestioned state of knowledge regarding mesoscale variability of grazing. Therefore, I consider this argument pure speculation, and suggest remove it from the ms.

2. We would like to keep this hypothesis, yet, to make clear that it is a mere hypothesis/speculation, we rephrase the respective sentences mentioning grazing (see below).

3. p20L4: "Hypothetically, an alleviation of grazing pressure [...]", and p21L22: "and, more speculatively, with an abatement of grazing pressure caused by anticyclones via deepened mixed layers,".

Technical Issues

Comment g

1. Fig. 4 should be enlarged to full-page size to enhance its readability in the pdf-version of the paper, and the caption therefore be shifted to next page, if possible.
2. *We agree; yet, we do not see how the Biogeosciences LaTeX template (which does not allow to use additional packages) would allow us to do this; we will ask the editorial/production team at the publication stage to enlarge the figure.*

Comment h

1. Caption Fig 6 associates autumn with the months January to May, what is certainly not correct. If the given months are valid, then the season should be termed high summer – autumn or so.
2. *Thank you.*
3. *We have adjusted the caption of Fig 6 to "a the region R2 (SSH -60 to -40 cm, January to May) and b for region R3 (SSH -50 to -15 cm, July to September)."*

References

- M. Ardyna, H. Claustre, J. B. Sallée, F. D’Ovidio, B. Gentili, G. van Dijken, F. D’Ortenzio, and K. R. Arrigo. Delineating environmental control of phytoplankton biomass and phenology in the Southern Ocean. *Geophys. Res. Lett.*, 44(10):5016–5024, 2017. ISSN 19448007. doi: 10.1002/2016GL072428.
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- V. H. Strass. Chlorophyll patchiness caused by mesoscale upwelling at fronts. *Deep Sea Res. Part A. Oceanogr. Res. Pap.*, 39(1):75–96, 1992. doi: 10.1016/0198-0149(92)90021-K.
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Imprint of Southern Ocean mesoscale eddies on chlorophyll

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Abstract. Although mesoscale ocean eddies are ubiquitous in the Southern Ocean, their average spatial and seasonal association with phytoplankton has ~~to-date~~ not been quantified ~~in-detail~~ systematically yet. To this end, we identify over 100,000 ~~eddies~~ mesoscale eddies with diameters of 50 km and more in the Southern Ocean and determine the associated phytoplankton biomass anomalies using satellite-based chlorophyll-a (Chl) as a proxy. The mean ~~eddy-associated Chl anomalies~~ (Chl anomalies, δChl), associated with these eddies, comprising the upper echelon of the oceanic mesoscale, exceed $\pm 10\%$ over wide regions. The structure of these anomalies is largely zonal, with cyclonic, thermocline ~~lifting~~ lifted, eddies having positive anomalies in the subtropical waters north of the Antarctic Circumpolar Current (ACC) and negative anomalies along ~~the ACC~~ its main flow path. The pattern is similar, but reversed for anticyclonic, thermocline ~~deepening~~ deepened eddies. The seasonality of δChl is weak in subtropical waters, but pronounced along the ACC, featuring a seasonal sign switch. The spatial structure and seasonality of the mesoscale δChl can be explained largely by lateral advection, especially local eddy-stirring. A prominent exception is the ACC region in winter, where δChl is consistent with a modulation of phytoplankton light exposure caused by an eddy-induced modification of the mixed layer depth. The clear impact of mesoscale eddies on phytoplankton may implicate a downstream effect on Southern Ocean biogeochemical properties, such as mode water nutrient contents.

1 Introduction

Phytoplankton account for roughly half of global primary production (Field et al., 1998). They form the base of the oceanic food web (e.g., Pomeroy, 1974) and drive the ocean's biological pump, i.e., one of the Earth's largest biogeochemical cycles with major implications for atmospheric CO_2 and climate (Sarmiento and Gruber, 2006; Falkowski, 2012). Yet, our understanding of the processes controlling their spatio-temporal variations is limited, particularly at the oceanic ~~mesoscale, i.e., submesoscale~~ to mesoscale, that is at scales of ~~10 the order of 0.1~~ to 100 km ~~-It is well-established that eddies, the most prevalent mesoscale features that also~~ (e.g., reviews by Lévy, 2008; McGillicuddy Jr., 2016; Mahadevan, 2016). We here focus on mesoscale eddies, i.e., the vortices with diameters of 50 km or more, and thus leave out the submesoscale variations. This choice is largely driven by the spatial resolution of the data we employ, but it is also motivated by the fact that mesoscale eddies have been shown to dominate the ocean's kinetic energy spectrum (Stammer, 1997; Chelton et al., 2011b), and affect phytoplankton in a major ~~manner~~ -In fact, eddies are way (Lévy, 2008; McGillicuddy Jr., 2016). In comparison, the contribution of the submesoscale

to the variance in kinetic energy is smaller, and its role for phytoplankton variability, although potentially large (Mahadevan, 2016) is not well characterized. In contrast, mesoscale eddies have been recognized to be among the most important drivers for the spatio-temporal variance of phytoplankton biomass (e.g., Doney et al., 2003; Glover et al., 2018) as has been noted already from the analyses of some of the very first ocean color satellite images of chlorophyll (Chl), a proxy for phytoplankton biomass (Gower et al., 1980). Despite decades of work since this discovery, the mechanisms governing the interaction of phytoplankton with mesoscale eddies remain poorly understood, even though there is a broad consensus that different sets of mechanisms dominate in different regions and at different times, and that the different polarity of the mesoscale eddies tends to induce signals of opposite sign (Denman and Gargett, 1995; Lévy, 2008; McGillicuddy Jr., 2016).

Lateral advection arising from local stirring of eddies has been argued to be a major driver globally. The argument is based on the observed correlation of the magnitude of eddy-associated chlorophyll-Chl anomalies, δChl , and the larger-scale Chl gradient ambient to eddies (Doney et al., 2003; Uz and Yoder, 2004; Chelton et al., 2011a; O'Brien et al., 2013). Further, it has been suggested that advection of Chl by eddies via trapping, i.e., the enclosing and dragging along of waters, causes δChl (Gaube et al., 2014), particularly in boundary current regions characterized by steep zonal Chl gradients. Numerous other potential mechanisms through which eddies affect phytoplankton have been identified, including modifications of mixed layer depth, (e.g., Bracco et al., 2000; McGillicuddy Jr. et al., 2007; D'Ovidio et al., 2010; Siegel et al., 2011; Gaube et al., 2013, 2014; Dufois et al., 2016; Gruber et al., 2011), including vertical and lateral advection of nutrients, restratification and vertical mixing, thermocline lifting, and providing of spatial niches and providing spatial niches through isolation of waters. These mechanisms modulate the phytoplankton's light exposure, their nutrient availability or their grazing pressure, i.e., they affect their net balance between growth and decay. Thus, in contrast to the physical mechanisms of stirring and trapping where phytoplankton is being advected merely passively, these mechanisms create eddy-associated phytoplankton biomass anomalies by altering their biogeochemical rates.

In the Southern Ocean, an area of light and iron limitation of phytoplankton (Boyd, 2002; Venables and Meredith, 2009), with distinct Chl heterogeneity (Comiso et al., 1993), and abundant with eddies (e.g., Frenger et al., 2015), individual eddies have been found to modulate Chl through many of the above processes (e.g., Strass et al., 2002; Ansrorge et al., 2010; Lehahn et al., 2011; Kahru et al., 2007). Here, we aim (i) to provide a reference estimate of the long-term mean chlorophyll average seasonal Chl anomalies associated with mesoscale eddies in the different regions of the Southern Ocean, distinguishing anticyclones and cyclones, and (ii) to discuss the mechanisms likely causing the observed imprint. The Southern Ocean is a region rich in eddies and important for setting the global distribution of biogeochemical tracers. Previous studies average imprint. Previous studies have used eddy kinetic energy as a proxy for eddy activity rather than sea level anomalies (SLA), which does not allow a distinction by polarity of eddies (Comiso et al., 1993; Doney et al., 2003), did not focus on the Southern Ocean (Chelton et al., 2011a; Gaube et al., 2014), or lacked a discussion of the seasonality of the relationship. We show here that the imprint of cyclones and anticyclones on Chl mostly is of opposite sign, largely zonal, and features a substantial seasonality along the ACC. Our results indicate that most of this mesoscale imprint can be explained by advection of Chl by the eddies.

Our approach is to identify individual eddies based on satellite estimates of SLA and combine those with satellite estimates of Chl (Chelton et al., 2011a; Gaube et al., 2014). We discuss possible mechanisms playing a role based on large-scale Chl

gradients (Doney et al., 2003; Chelton et al., 2011a; Gaube et al., 2014) and the local shape of the average imprint of eddies on Chl (Chelton et al., 2011a; Gaube et al., 2014; Siegel et al., 2011).

2 Methods and data

We first introduce our analysis framework before describing the methods and data sources. This permits us to explain the approaches we use to assess the potential mechanisms explaining the δChl associated with Southern Ocean mesoscale eddies.

2.1 Analysis framework

Fundamentally, mesoscale eddies can lead to local phytoplankton biomass anomalies through either advective processes, i.e., the spatial reshaping of existing gradients, or through biogeochemical fluxes and transformations that lead to anomalous growth or losses of biomass. In the following, we present these potential mechanisms in more detail, and how we estimate their importance.

2.1.1 Causes of δChl by advective processes

~~Eddies~~ Mesoscale eddies may cause δChl as they laterally move waters, i.e., horizontally advect waters including their Chl characteristics. This mechanism may lead to δChl if (i) a lateral Chl gradient is present that is sufficiently steep at the spatial scale of the eddy-induced advection (Gaube et al., 2014), and (ii) the time scale of advection matches the time scale of ~~the growth and loss of Chl~~ phytoplankton biomass changes (Abraham, 1998). ~~The time scale of Chl~~ This time scale is order of days to weeks, possibly months, with the lower boundary representing roughly the reactivity time scale of ~~Chl~~ phytoplankton biomass governed largely by the growth rate of the phytoplankton, and the upper boundary the potential ~~maintenance of Chl concentrations~~ sustenance of phytoplankton biomass via recycling of nutrients within the mixed layer. Concerning the spatial scale of advection by eddies, we distinguish two effects, ~~labeling them that we have labelled~~ stirring and trapping, respectively. ~~With stirring~~ Stirring, we refer to the (Siegel et al., 2008; Chelton et al., 2011a; Gaube et al., 2014; McGillicuddy Jr., 2016) refers to the local distortion of a large-scale Chl gradient due to the rotation of an eddy, as illustrated in ~~Figure Fig.~~ Figure Fig. 1a (left column, with black arrows indicating the eddy rotation and associated advection), ~~see also~~. The turnover time scale associated with the rotation of eddies is order of days to a few weeks, which matches the time scales of ~~Chl~~ phytoplankton reactivity. The spatial scale of stirring is given by the spatial extent of an eddy and is somewhat larger than the eddy core, as defined based on the Okubo-Weiss parameter (Frenger et al., 2015), i.e., that is several tens to several hundred-hundreds of kilometers.

Next to stirring, eddies ~~may~~ advect material properties due to their intrinsic lateral propagation (~~Figure Fig.~~ Figure Fig. 1a, right column). We refer to the ability of eddies to transport fluid along their propagation pathway in their core as trapping. ~~The~~ (e.g., Flierl, 1981; Gaube et al., 2014; McGillicuddy Jr., 2016). The upper time scale of trapping is given by the typical lifespan of Southern Ocean eddies, which is weeks to months (Frenger et al., 2015), i.e. it may match the longer time scale of ~~Chl~~ phytoplankton biomass changes. Propagation speeds are small (an order of magnitude smaller than rotational speeds) which implies that the

majority of eddies tends to die before they can propagate far. ~~The~~ Thus, the fraction of very long-lived eddies that propagate over distances exceeding a few hundred kilometers is small (Frenger et al., 2015).

A necessary condition for *trapping* to happen is that the eddies' swirl velocity is larger than their propagation speed (Flierl, 1981), a condition generally met for mid- to high-latitude eddies (Chelton et al., 2011b). Indeed, observations of eddies carrying the signature of their origin in their cores support the *trapping* effect, ~~and so~~ (Bernard et al., 2007; Ansgore et al., 2010; Lehahn et al., 2011), as does the modeling study by Early et al. (2011). ~~Yet, likely only few eddies are truly efficient in their~~ Even though the trapping is never perfect (Beron-Vera et al., 2013; Haller, 2015). ~~They tend to continuously exchange some fluid with their surroundings, i.e., their trapping is limited by them being permeable. Nevertheless,~~ we expect eddies to be able to drag along some entrained waters for some time, hence displacing these waters for some distance as they propagate. This may be sufficient to displace waters from e.g., the south to the north of an ACC front along an intense Chl gradient, leading to δChl through (permeable) *trapping*.

2.1.2 Causes of δChl by local biogeochemical processes

~~Eddies~~ Mesoscale eddies affect the biogeochemical/physical properties that control the ~~rates of biogeochemical processes~~ local rates of growth and loss of phytoplankton (biogeochemical rates) in their interior through many mechanisms. These include, e.g., the stimulation of phytoplankton growth through enhanced nutrient concentrations or increased average light levels, or the modification of predator-prey encounter rates, affecting the mortality of phytoplankton (~~Figure Fig.~~ 1b). Even though these effects have been analyzed and discussed for decades (see review by McGillicuddy Jr., 2016), their overall impact on productivity continues to be an issue of debate. The canonical lifelong vertical pumping of nutrients by thermocline ~~lifting cyclones~~ lifted cyclones (Falkowski et al., 1991, indicated as black circle in Fig. 1b) has been challenged to be a major player (Oschlies, 2002; Gaube et al., 2014), and multiple other mechanisms have been proposed how eddies may affect phytoplankton biomass. These include a modification of vertical mixing through changes of stratification (wiggly lines in ~~Figure Fig.~~ 1b) and eddy current-wind interactions causing thermocline displacements (eddy swirl currents and winds are indicated as black and thick white arrows in ~~Figure Fig.~~ 1b), resulting in modifications of nutrient supply and light exposure of phytoplankton (e.g., Llido, 2005; McGillicuddy Jr. et al., 2007; Mahadevan et al., 2008; Siegel et al., 2011; Xiu et al., 2011; Lehahn et al., 2011; Boyd et al., 2012; Mahadevan et al., 2012; Dufois et al., 2016). The prevailing lack of data of ~~sufficiently highly temporally resolved sub-surface~~ temporally sufficiently highly resolved subsurface observations hampers a systematic large-scale observationally-based assessment of the role of effects of ~~eddies on mesoscale eddies on the local~~ biogeochemical processes.

2.1.3 Assessing mechanisms causing δChl

We employ two sets of approaches to assess the mechanisms causing δChl . In the first ~~set of approaches~~, we diagnose whether the environmental conditions are ~~actually~~ met for supporting a major contribution of a particular set of ~~mechanism~~ mechanisms. Namely, we assess if lateral Chl gradients sufficiently support advective effects of eddies to explain δChl ~~(see Sect. 2.3 for~~ technical detail).

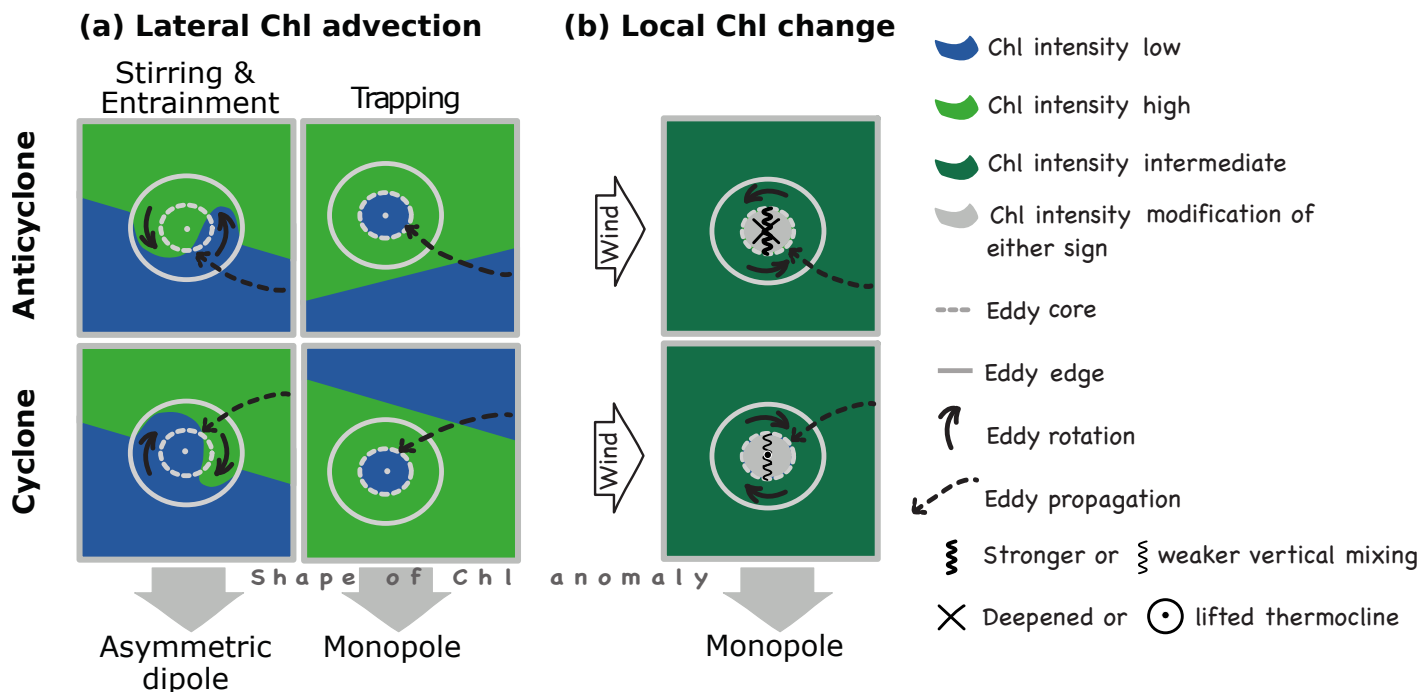


Figure 1. Schematic illustrating the mechanisms of how eddies may impact chlorophyll (Chl), separated-distinguished by anticyclones (top row) and cyclones (bottom row), for the southern hemisphere; a shows the effects of advection (lateral displacements) of Chl due to the eddies' rotational speed (*stirring*, left column) and lateral propagation (*trapping*, right column); *trapping* and *stirring* can cause δChl of either sign, depending on environmental Chl gradients; b shows multiple potential effects eddies may have on Chl by affecting biogeochemical processes, including modification of nutrient supply and light exposure through thermocline lifting or deepening (circle/cross) and modified vertical mixing (wiggly lines), and eddy current-wind interactions (black and thick white arrows), in turn causing thermocline displacements; the. The local shape of δChl is anticipated to look different depending on the mechanism active, i.e. a monopole δChl is expected for all eddy-effects except for *stirring* where an asymmetric dipole is expected (Figure inspired by Siegel et al. 2011, Figure 1).

In the second set of approaches we diagnose the spatial-pattern-shape of δChl associated with eddies as this spatial signature tends to differ between the two major sets of processes, i.e., advective-processes-the advective process *stirring* and biogeochemical rates (Siegel et al., 2011). Eddies that are-associated-with, for instance, *stirring* are stir are anticipated to have a dipole shape (Figure-shaped δChl (Fig. 1a, left column), as they distort the underlying gradient field, with the rotation of the eddy determining the orientation of the dipole. In contrast, most mechanisms associated with modifications of the biogeochemical rates cause a monopole patternshape, irrespective of polarity (Figure-Fig. 1b). This is a consequence of the mesoscale δChl tending to be caused by anomalies in the nutrient supply or light availability, which are altered inside eddies in a radially symmetric manner. Also-the The advective *trapping* mechanisms tend to also cause a monopole pattern-shape of δChl (Figure-Fig. 1a, right column), but they-rate-based mechanisms can be distinguished from the-rate-based-mechanisms-by-either-trapping-for instance by their history, or their tendency to trap the anomalies very tightly in the inner domain of the eddy. -The-rate-based

~~mechanisms, in contrast, often have monopole patterns that extend more broadly over the eddy, or are, in certain case, even strongest at the edges~~ (McGillicuddy Jr., 2016). ~~Here, we suggest effects on biogeochemical rates due to eddies to~~ Rate-based mechanisms presumably play a role in regions and seasons where the potential for advective effects is insufficient to explain the observed eddy-induced δChl ; ~~i. e., we diagnose them largely~~. Here we diagnose these as a residual.

5 Some complexity is added in to the interpretation of the spatial pattern by the fact that the ~~asymmetry of the dipole pattern dipole shape~~ arising from *stirring* ~~causes also a monopole pattern (Figure tends to be asymmetric (Fig. 1a))~~. Such an asymmetry was suggested by Chelton et al. (2011a) to arise from the westward propagation of eddies and the leading (mostly western) side of an eddy affecting upstream unperturbed waters, resulting in a larger anomaly at the leading than compared to the trailing side of an eddy, with the latter stirring already perturbed waters. Also, the eddy may entrain some of the westward upstream waters
10 into its core, labeled here lateral entrainment or permeable *trapping* (Hausmann and Czaja, 2012; Frenger et al., 2015). Indeed, averaged over an eddy's core, *stirring* will only cause a net anomaly if the dipole associated with *stirring* is asymmetric. It is not obvious how to quantify ~~such an asymmetry~~ this effect. Independent of ~~its the dipole~~ asymmetry, we will qualitatively discuss the potential maximum δChl induced by *stirring* :-

(see Sect. 2.4 for technical detail). We note that advection by an ambient larger-scale flow does not affect the *stirring*
15 mechanism. For instance, the eastward Antarctic circumpolar flow in the Southern Ocean makes eddies propagate eastward in an Eulerian sense, ~~nevertheless they propagate while still propagating~~ westward in a Lagrangian sense -, relative to the ACC and ambient Chl.

2.2 Data

To assess the relationship between ocean eddies and Chl anomalies, we use the data set of Southern Ocean eddies and their
20 characteristics as derived and described in detail in Frenger et al. (2015). The data set contains ~~about more than~~ 1,000,000 snapshots of mesoscale eddies identified in weekly maps of Aviso SLA and defined based on the Okubo-Weiss parameter. Eddies with positive and negative SLA are defined as anticyclones and cyclones, respectively. We consider here only eddies tracked in the region 30°S to 65°S over at least three weeks in the time period between 1997 and 2010, i.e., the operation time period of the SeaWiFS satellite-based sensor ~~(see below), in the region 30~~. The resolution capacity of Aviso SLA allows for the
25 analysis of the larger mesoscale eddies with minimum diameters of about 50 km at 65°S to 65 and 100 km at 30°S (Chelton et al., 2011b; Frenger et al., 2015).

For Chl we use the ~~merged~~-ESA GlobColour Project product (<http://www.globcolour.info>, case-1 waters, ~~merged~~) which merges several sensors according to Maritorena and Siegel (2005), with a spatial and temporal resolution of 0.25° and one
30 day, respectively. We choose a merged product for Chl as the merging on average doubles the spatial coverage of the daily data in the Southern Ocean, ~~on average~~ (Maritorena et al., 2010). Of the ~~data of the up to~~ three available sensors, i.e., SeaWiFS (SeaStar), MODIS (Aqua) and MERIS (Envisat), SeaWiFS generally features the best spatio-temporal coverage, but its contribution drops below 40% in high latitudes and partly in the western ocean basins of the Southern Hemisphere. For these areas after 2002, SeaWiFS data were complemented with MODIS as well as MERIS data. We average the Chl data to weekly fields to match the temporal resolution of the eddy dataset. The combined eddy Chl-dataset is publicly available at

<http://dx.doi.org/10.3929/ethz-b-000238826>.

To examine the δChl of eddies, we compare the Chl averaged over their core to background fields of Chl. For the latter, a monthly climatology of Chl proved not to be appropriate due to high spatio-temporal variability of Chl unrelated to eddies. Hence, we obtain the background fields the following way: we apply a moving spatio-temporal Gaussian filter (Weierstrass transform, spatial filter similar to e.g., Siegel et al. 2008, with 2σ of 10 boxes/ \sim 200 km at 45°S , 8 boxes/ \sim 200 km and 1 week in longitudinal, latitudinal and temporal dimensions, respectively) to each of the weekly Chl fields. We then subtract the resulting result from the original fields to produce δChl fields. The δChl fields are not sensitive to the selected σ . The choice of a rather small spatiotemporal filter makes δChl amplitudes smaller compared to if a larger filter is chosen, producing a conservative estimate of δChl . In order to generate spatial maps of δChl , we averaged all eddy associated anomalies of the respective eddy polarity into $5^\circ \times 3^\circ$ longitude/latitude boxes.

Prior to all-our analysis we log-transform Chl, due to Chl being lognormally distributed (Campbell, 1995). We frequently give δChl is frequently given in percentage difference relative to the background Chl as

$$\delta\text{Chl} = \left[\exp \left(\log(\text{Chl}_e) - \log(\text{Chl}_{bg}) \right) - 1 \right] \times 100 = \left(\frac{\text{Chl}_e}{\text{Chl}_{bg}} - 1 \right) \times 100$$

with subscripts e and bg denoting *eddy* and *background*, respectively. Where we show absolute δChl on a logarithmic scale, we use the base 10 logarithm.

Regarding the spatial, i.e., geographical analysis, geographical, that is spatial, analyses, we use on the one hand the positions of the main ACC fronts (Polar Front, PF, and Subantarctic Front, SAF) as determined by Sallée et al. (2008). On the other hand, we make use of a climatology of sea surface height (SSH) contours (Maximenko et al., 2009), which are representative for-of the long-term geostrophic flow in the area. The mean positions of the PF and SAF align approximately with the mean SSH contours of about -40 cm and -80 cm, respectively. We select the -20 cm SSH contour to separate waters of the southern subtropical gyres to the north of the ACC, referred to as subtropical waters from waters in the "ACC influence area", referred to as ACC waters. This choice is based on both, a tendency for net eastward propagation of eddies south of this contour (Frenger et al., 2015) indicating advection by the ACC mean flow, and a seasonal sign switch of δChl , which will be addressed later in the paper. Waters south of the PF/-80 cm SSH we refer to as Antarctic waters. Finally, we use mixed layer depths derived from Argo floats, available at <http://www.locean-ipsl.upmc.fr> (<https://doi.org/10.17882/42182>).

2.3 Analysis of environmental Chl conditions

Using the data presented in the previous section, we calculate a monthly Chl climatology. Based on this climatology we derive we derive the potential δChl ($\hat{\delta}\text{Chl}$) eddies may induce due to lateral advection (Figure-Fig. 1a): in-In order to assess the $\hat{\delta}\text{Chl}$ emerging from *stirring* in the Southern Ocean, we compute the climatological meridional Chl gradient at the spatial scale of individual eddies, here taken as two eddy radii ($\hat{\delta}\text{Chl}_{\text{stir}}$). To assess the $\hat{\delta}\text{Chl}$ emerging from *trapping*, we estimate the Chl variation along individual eddies' pathways by computing the difference of the climatological Chl at the very location of an eddy origin-and-the-and at the location of its origin ($\hat{\delta}\text{Chl}_{\text{trap}}$). We use for this difference the climatological Chl at the present

~~month of the very~~ location of the eddy ~~at the present month ($\delta\text{Chl}_{\text{trap}}$)~~ to consider the effects of the seasonal Chl variations, assuming that potentially trapped Chl would seasonally covary with the Chl at the place of the eddy's origin.

2.4 Analysis of the ~~spatial~~ shape of δChl

We compute the composite spatial ~~shape pattern~~ of Chl and δChl associated with ~~mesoscale~~ eddies the same way as ~~done in~~
5 ~~was done by~~ Frenger et al. (2015) for sea surface temperatures: ~~we~~ ~~We~~ extract a squared subregion ~~of side lengths of 10 eddy~~
~~radii~~ for each individual eddy from the weekly maps of SLA and Chl, centered at the eddy ~~center~~. ~~We rotate~~ ~~'s center~~. ~~The~~
~~side lengths of the subregion are 10 eddy radii each, implying an implicit scaling according to the eddy size~~. ~~We rotate the~~
Chl snapshots according to the ambient Chl gradient and average ~~them~~ over all eddies to produce the eddy composite. Note
that the estimate of the magnitudes of the dipole and the ~~average~~ ambient Chl gradient (see below) tend to be slightly weaker
10 without rotation. Nevertheless, as averages are taken over regimes of largely similar orientation of the ambient Chl gradient
(see Discussion ~~section~~ ~~Sect.~~ 4), our conclusions do not depend on whether we rotate ~~the~~ snapshots or not.

Further, we decompose the ~~eddy-induced spatial average composite spatial pattern~~ δChl ~~pattern~~ into a monopole (MP) and
dipole (DP) ~~pattern component~~ by first constructing the monopole by computing radial averages of δChl around the eddy's ~~s~~
center, i.e., $\delta\text{Chl}(r)_{\text{MP}} = \overline{\delta\text{Chl}(r)}$, where r is the distance from the eddy's ~~s~~ center. In the second step, we calculate $\delta\text{Chl}_{\text{DP}}$ as a resid-
15 ual, i.e., by differencing the monopole pattern from the total signal. Even though this residual approach captures in the dipole
structure any non-monopole pattern, experience has shown that the $\delta\text{Chl}_{\text{DP}}$ typically feature dipoles (Frenger et al., 2015). In
the final step, we quantify the amplitudes of the monopoles and the dipoles, assess the contribution of the two components to the
spatial variance of the total signal based on the sum of variances (var), i.e. ~~$\text{var}(\delta\text{Chl}) = \text{var}(\delta\text{Chl}_{\text{MP}}) + \text{var}(\delta\text{Chl}_{\text{DP}}$~~ ~~$\text{var}(\delta\text{Chl}) = \text{var}(\delta\text{Chl}_{\text{MP}}$~~
and compute the local Chl gradient at the scale of two eddy radii, as an estimate of the potential maximum contribution of ~~stir-~~
20 ~~ring~~ to δChl .

2.5 Handling of measurement error and data gaps

~~As the error of the satellite retrieved Chl for each individual eddy can easily be as large as the anomaly, an individual eddy~~
~~An individual eddy δChl signal may be undetectable even~~ with in-situ measurements (Siegel et al., 2011), ~~and it may be easily~~
~~smaller than the error of the satellite retrieved Chl~~. The significance of our results, ~~which we test based on t-tests~~, arises from
25 the ~~very~~ large number of analyzed eddies. ~~A reduction of the sample size due to~~, ~~which totals about 600'000 eddy snapshots~~
~~across the entire Southern Ocean. This is substantially smaller than our original data set, largely due to the~~ missing Chl data
arising from frequent cloud cover in the ~~SO may affect the significance: On average for 45~~ Southern Ocean. For 33 % of the
eddies ~~identified by SLA, the corresponding~~ Chl data was entirely missing. ~~Missing values~~, and for 75 % of eddies at least
~~part of the data was missing. The average missing data over eddies~~ due to cloud ~~cover-only cover only~~ (leaving aside missing
30 data due to the polar night) increase from 2018 % at 30°S to 6063% at 65°S. Anticyclones exhibit a higher percentage of data
gaps than cyclones (4748 % versus 42% ~~% averaged over the Southern Ocean~~), which can be explained by the impact of their
sea surface temperature anomalies on cloud cover (Park et al., 2006; Small et al., 2008; Frenger et al., 2013). ~~We account for~~

the issue of missing data by spatio-temporally aggregating the data. The significance of the results at the 95% level is tested based on t-tests as the data are about normally distributed in the log-space.

3 Results

3.1 Imprint of mesoscale eddies on Chl

5 3.1.1 Mean imprint

Averaged across the entire Southern Ocean and all seasons, we detect a significant, although small, mean imprint of mesoscale eddies on Chl (Supplementary Figure S1) for both anticyclonic (warm-core, SLA lifting and thermocline deepening high SLA, and deepened thermocline) and cyclonic (cold-core, SLA deepening and thermocline lifting low SLA, and lifted thermocline) eddies. The overall mean δChl associated with anticyclones is -4 %, while that for cyclones is of even smaller magnitude, i.e., +1 %. Though small, both anomalies are actually statistically significant ($p < 0.05$). The distributions around these small means are very broad, however, with many anticyclones and cyclones having both, positive or negative δChl , depending on the region and time of the year. The long tails of the distributions, corroborated by visual inspection of the individual δChl of eddies, suggest anomalies that are substantially larger than the mean. Thus, it appears that by averaging the signals in time and space, a substantial amount of information is lost. As a consequence, it is more insightful to disentangle the signals and to examine the regional and seasonal variation of δChl .

3.1.2 Spatial variability of imprint

The maps of the annual mean imprint of cyclonic and anticyclonic eddies on Chl clearly supports support this hypothesis of a strong regional cancellation effect (Figure Fig. 2). First, the regional mean signal associated with eddies is indeed much larger than suggested by the mean δChl across the entire Southern Ocean. In fact, around a quarter of the analyzed grid cells have absolute δChl larger than 10 %, and in a significant number of grid cells with the mean absolute δChl exceeds exceeding several tens of percent (Figure in a substantial number of grid cells (Fig. 2b,c). Second, the signals associated with mesoscale eddies of either polarity vary in sign across the different regions with regions of strong enhancements bordering regions with strong reductions (see also Figure 1 in Gaube et al. 2014). In the broadest sense, the pattern is zonal in nature, reflecting the zonal nature of the climatological Chl distribution (Figure Fig. 2a).

For anticyclones, δChl is clearly negative in subtropical waters, i.e., the waters north of the SSH = -20 cm, and in the regions around the western boundary currents (Figure Fig. 2b). These prevailing negative δChl are is contrasted by mostly positive δChl along the ACC. Cyclones have a largely similar spatial pattern, but of opposite sign (Figure Fig. 2c): Prevailing prevailing positive δChl in subtropical waters are opposed mirrored by a band of negative, yet weaker anomalies along the ACC. South of the ACC, in Antarctic waters, the pattern of δChl is spotty for anticyclones as well as cyclones, with anticyclones and cyclones featuring average positive and negative δChl , respectively. In summary, SLA and δChl are largely negatively correlated in subtropical waters north of the ACC, and positively correlated along the ACC.

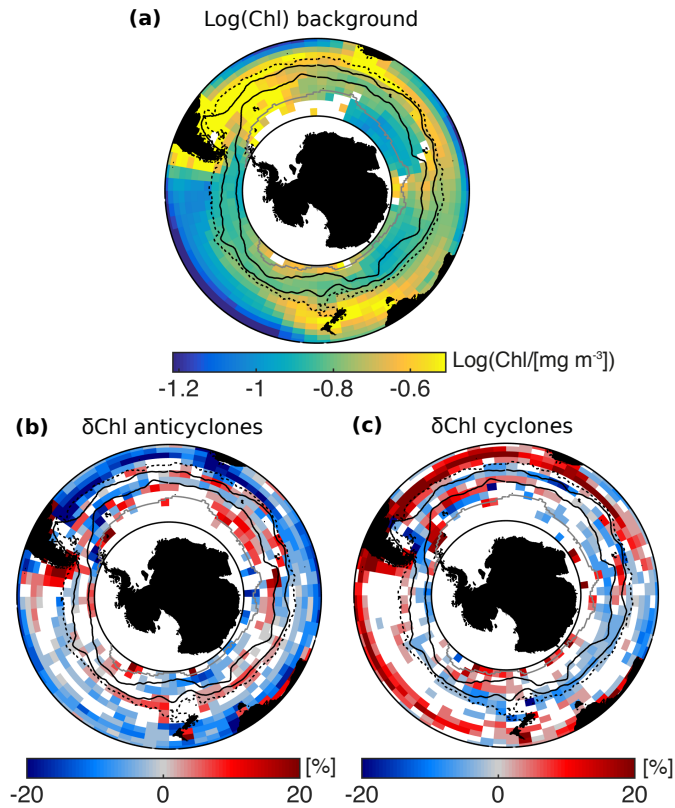


Figure 2. Spatial distribution of chlorophyll anomalies (δChl) associated with eddies; a Logarithm (base 10) of climatological Chl for reference, and mean δChl of **b** anticyclones and **c** cyclones; δChl are the average of anomalies of eddies existing at least 3 weeks in $5^\circ \times 3^\circ$ longitude-latitude-grid boxes; white boxes indicate insufficient data (less than three data points) or anomalies insignificantly different from zero (t-test, $p=0.05$); solid black lines mark the main branches of the ACC (Subantarctic and Polar fronts); the dashed black line denotes the -20 cm SSH contour and the solid gray line the northernmost extension of sea-ice cover.

A few exceptions break this mostly zonal picture for Chl (Ardyna et al., 2017), and also for δChl . An exceptional area of negative δChl for cyclones in the subtropical waters of the eastern Indian Ocean disrupts the zonal band of largely positive anomalies. Also, δChl in coastal/shelf areas often are distinct from open-ocean δChl . A clear signal emerges south and southwest off of the Australian and west of the South-American coasts, west of New Zealand, and more subtly east of, east of the Kerguelen Islands and the Drake Passage (see also Sokolov and Rintoul 2007; D’Ovidio et al. 2015), where δChl tends to be positive for both anticyclones and cyclones.

3.1.3 Seasonality of imprint

The pronounced zonal bands of δChl for mesoscale anticyclones and cyclones persist over the year, but tend to migrate meridionally (Figure Fig. 3a-d, middle/right columns), thereby following the pronounced seasonality of Chl (Figure Fig. 3a-d, left

column; Thomalla et al. 2011; Sallée et al. 2015; Ardyna et al. 2017). The seasonality of δChl is larger along the ACC and in Antarctic waters compared to subtropical waters. In the subtropical gyres, δChl of anticyclones and cyclones are negative and positive, respectively, i.e., SLA and δChl are negatively correlated all year round. Here, δChl shows a weak peak in austral summer when climatological Chl is smallest (Figure Fig. 3c). In the ACC regions and in Antarctic waters, a striking feature is the seasonal change in the sign of δChl (Figure for both cyclones and anticyclones (Fig. 3b-d)).

This becomes even more evident when inspecting the zonally averaged Chl and δChl as a function of season and SSH, i.e., plotted in the form of a Hovmoeller diagram (Figure Fig. 4). Along the ACC, anticyclones exhibit negative δChl in winter to spring concurrent with deep mixed layers, followed by positive δChl in summer to autumn (Figure Fig. 4b). Cyclonic δChl patterns are opposite, featuring negative δChl in spring-summer to autumn, with close to zero to positive δChl in winter to spring (Figure Fig. 4c). This implies that SLA and δChl are positively correlated summer to autumn, followed by a negative correlation in winter to spring. This-The sign switch of the correlations shows a seasonal lag towards Antarctic waters, with positive correlations prevailing autumn to winter, and negative correlations prevailing spring to summer, resulting in the aforementioned apparent southward migration of the sign switch of the seasonality of δChl over the course of the year.

3.2 Causes for the imprint

3.2.1 Advection

To assess if advective mechanisms are sufficient to explain the contribution of advective mechanisms to the observed δChl associated with eddies in the Southern Ocean, we contrast the observed changes against the advective potentials, i.e., the potential it with the potential of eddies to cause δChl through Chl advection, that is with the potentials $\hat{\delta\text{Chl}}_{\text{stir}}$ associated with stirring and the potential $\hat{\delta\text{Chl}}_{\text{trap}}$, associated with trapping (Figures 4d-g, Method section Sect. 2.3). If the patterns and magnitudes match, one may conclude that Southern Ocean eddies cause The closer the observed δChl merely through lateral advection of Chl. We begin with a discussion of the potential of stirring is to these potentials, the more important the respective processes would be in causing this signal.

In the northern domain, i.e., in subtropical waters (here SSH larger $\sim 20\text{ cm}$), the sign of $\hat{\delta\text{Chl}}_{\text{stir}}$ tends to agree with δChl throughout the year for both anticyclones and cyclones (Figures 4b-e). So does the seasonal variation of the magnitude of $\hat{\delta\text{Chl}}_{\text{stir}}$, with the largest magnitudes found in summer to autumn. Also the regional variations match, such as a weaker $\hat{\delta\text{Chl}}_{\text{stir}}$ and δChl in the Pacific sector compared to the Atlantic and Indian Ocean sectors (Figure Fig. 3, middle/right columns and Supplementary Figure S2, left column).

Also, along the ACC and its northern flank in summer to autumn, $\hat{\delta\text{Chl}}_{\text{stir}}$ and δChl agree in sign, and are of the same order of magnitude. Finally, along the southern ACC and in Antarctic waters, $\hat{\delta\text{Chl}}_{\text{stir}}$ mirrors the seasonal sign switch of δChl , and the apparent seasonal southward migration of the zonal bands of δChl (Figures 3 and 4b,e-b-e). Thus, it appears that stirring can already explain a good fraction of the observed δChl (i) in subtropical waters outside of those characterized by winter deep mixed layers, (ii) along the ACC and its northern flank in summer to autumn, and (iii) south of the ACC.

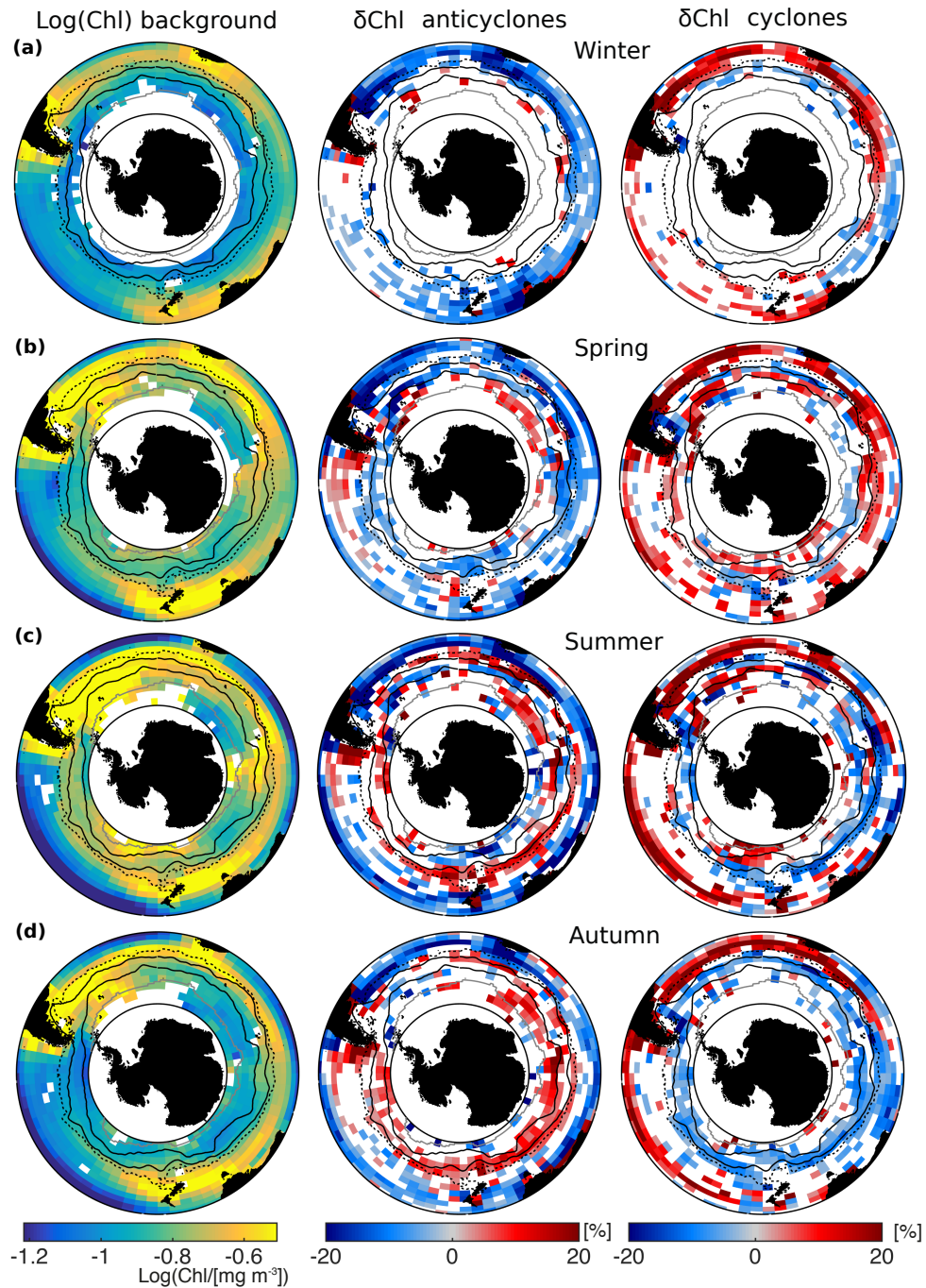


Figure 3. Seasonality of chlorophyll anomalies (δChl) associated with eddies; Austral **a** winter (JJA), **b** spring (SON), **c** summer (DJF) and **d** autumn (MAM) for anticyclones (middle) and cyclones (right); The logarithm (base 10) of climatological Chl is shown for reference (left). Otherwise as Figure-Fig. 2.

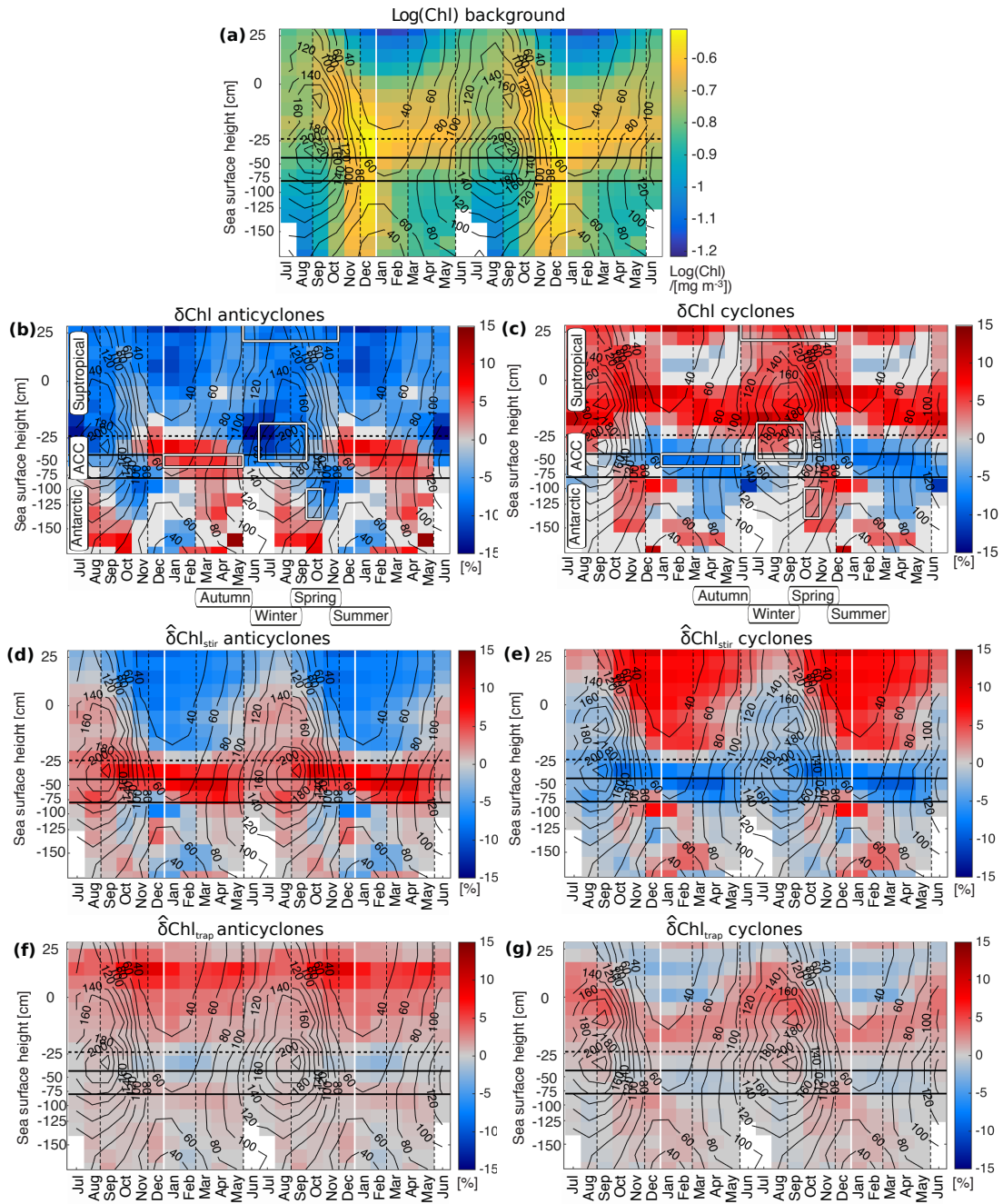


Figure 4. Seasonality of chlorophyll anomalies (δChl) associated with eddies, and potential of eddies to cause δChl through lateral advection ($\hat{\delta\text{Chl}}$); Seasonality of chlorophyll anomalies (δChl) associated with eddies, and potential of eddies to cause δChl through lateral advection, i.e., $\hat{\delta\text{Chl}}_{\text{stir}}$ for stirring and $\hat{\delta\text{Chl}}_{\text{trap}}$ for trapping. **a Base 10 logarithm of climatological Chl for reference, and; **b, c** δChl related to **b** anticyclones and **c** cyclones, respectively; **d, e** advective potentials (Method Sect. 2.3) due to *stirring* by anticyclones and cyclones, respectively; **f, g**, advective potentials due to *trapping* by anticyclones and cyclones, respectively. In **a**, δChl are the mean of all eddies existing at least 3 weeks binned in monthly sea surface height (SSH) bins so that boxes roughly are of equal area; δChl in all subpanels, values that are not significant (t-test, $p > 0.05$) are colored in light gray, missing insufficient data (less than three data points) in white; solid black lines mark the ACC (approximate positions of the Subantarctic and Polar fronts); the horizontal dashed black line denotes the -20 cm SSH contour, the vertical dashed lines seasons; solid black contours show averaged mixed layer depths in meters; note that the**

That ~~The reason underlying the strong potential of stirring has the potential to produce the observed δChl in large parts due to a sufficiently large average ambient gradient of Chl, is corroborated by the actual observed local shape of δChl (Method section 2.4)~~ is the presence of strong average ambient gradients of Chl. For instance: ~~averaged over eddies in Averaged over mesoscale eddies in northern~~ subtropical waters in ~~the northern domain in~~ winter to spring, ~~the average absolute gradient~~ (Method Sect. 2.4), ~~the absolute gradient of Chl~~ at scales of two eddy radii is 7 % for both anticyclones and cyclones, ~~and the compared to the absolute~~ maximum δChl ~~of 10~~ % and 9 %, respectively (Figure Fig. 5a, see numbers at the bottoms of left two panels). ~~Similarly, A similar correspondence is found along the ACC and its northern flank (Figure in summer to autumn (Fig. 6a), the average Chl gradient at the scale of eddies in summer to autumn,~~ and in Antarctic waters in spring (Figure Fig. 5b), ~~are of similar magnitudes as δChl ,~~ supporting that *stirring* alone may largely explain ~~the~~ observed δChl (Figure Fig. 6a; anticyclones: gradient of 9 % and maximum δChl of 5 %; cyclones: gradient of 9 % and maximum δChl of ~~+11~~ %; and Figure Fig. 5b; anticyclones: gradient of 5 % and maximum δChl of ~~-66~~ %; cyclones: gradient of 5 % and maximum δChl of 5 %).

The advective potential for the other lateral advective mechanism, i.e., ~~trapping~~ *trapping*, $\hat{\delta}\text{Chl}_{\text{trap}}$, partly ~~opposes~~ *counteracts* and partly enhances $\hat{\delta}\text{Chl}_{\text{stir}}$ (Figures 4d-g). For instance, for cyclones along the ACC in summer to autumn, *trapping* possibly contributes to a δChl (11 %) signal that is slightly larger than the Chl gradient at two eddy radii (9 %), and the contribution of the variance of the monopole is increased compared to anticyclones (Figure Fig. 6a, 96 % versus 87 %). Yet, overall the trapping potential $\hat{\delta}\text{Chl}_{\text{trap}}$ is weak compared to δChl (Figure Fig. 4b,c,f,g), and outweighed by $\hat{\delta}\text{Chl}_{\text{stir}}$.

3.2.2 ~~Biogeochemical~~ *Local biogeochemical rates*

Even though advective processes and particularly *stirring* appear to be the dominant driver for the *mesoscale* eddy-associated ~~chlorophyll Chl~~ anomalies, there are nevertheless a few places where the magnitudes of the potentials for advective effects are too weak compared to the observed δChl or of opposite sign. These are the places where variations in the *local growth and loss processes, i.e., variations in the local* biogeochemical rates may be the dominant driver.

The most prominent instance is found along the northern ACC, *a region* associated with the seasonal sign switch of δChl (Figures 4b-g, blue boxes in Figure Fig. 7a). Here, anticyclones switch to negative δChl in the presence of deep mixed layers ~~whereas both,~~ *whereas both* $\hat{\delta}\text{Chl}_{\text{stir}}$ and $\hat{\delta}\text{Chl}_{\text{trap}}$ suggest positive δChl . The shape of the local imprint of anticyclones in the respective region and season (Figure Fig. 6b) indicates that indeed, the lateral Chl gradient *is small* at the scale of eddies (5 %) *is small* compared to the maximum absolute amplitude of δChl (17 %). Further, *a the* decomposition of the local shape of δChl *into a monopole and a dipole* suggests that *stirring causes (dipole) supports* an anomaly of the opposite sign *than compared to the observed* δChl , consistent with Figure Fig. 4d. Given that *trapping similarly would cause would cause also* a weak anomaly of the opposite sign (Figure Fig. 4f), we hypothesize that eddy-induced changes in the biogeochemical rates are responsible for the negative δChl in winter and spring in the northern ACC.

Similarly, the sign switch of δChl of cyclones in the same region cannot be explained based on $\hat{\delta}\text{Chl}_{\text{stir}}$ (Figure Fig. 4e). The local shape of Chl corroborates that also for cyclones *stirring in of* the average ambient Chl gradient induces an anomaly of the opposite sign (Figure Fig. 6b). In contrast to $\hat{\delta}\text{Chl}_{\text{stir}}$, $\hat{\delta}\text{Chl}_{\text{trap}}$ for cyclones is of the same sign as δChl (Figure Fig. 4g), indicating a potential contribution of *trapping* to positive δChl under deep mixed layers. Yet, as noted in the previous paragraph,

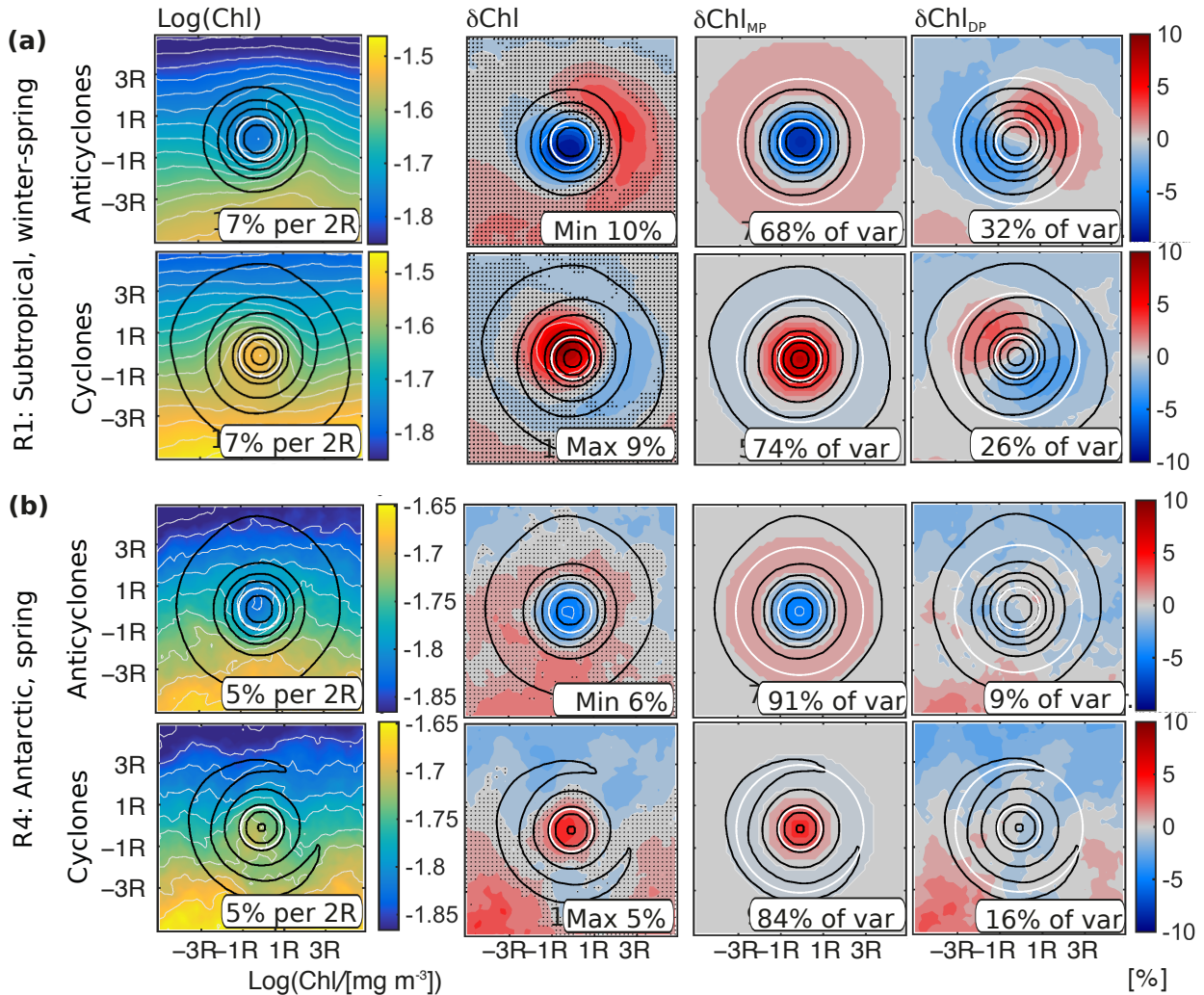


Figure 5. Attribution of stirring/trapping components to average of mesoscale eddy chlorophyll (associated Chl) in regions: a Chl and δChl in region R1 (SSH larger 10 cm, June to November) and b in region R4 (SSH -140 to -100 cm, March-October), indicated as white boxes in Figures 4b,c and 7; for anticyclones (the top rows) and cyclones (the bottom rows); (for the cyclones, the left column) shows the logarithm (base 10) of Chl and (second, the middle left) the δChl (stippling marks insignificant anomalies), decomposed into (second the middle right) a one the monopole component, MP, and (the right) one the residual component (approximately the dipole component, DP) contribution (see text for details and cartoon in Figure Fig. 1); The sea level anomaly contours are shown in black (0.05 spacing, normalized before averaging); the inner and outer white circles indicate the eddy core and area used for the computation of the contribution to the variance of δChl of the monopole and the dipole, respectively; text in panels denotes (left) the meridional Chl gradient at two eddy radii, (second left) the maximum or minimum of the anomaly, (second right and right) the contribution to the variance of the anomaly pattern of the monopole and dipole, respectively; before averaging, the individual eddy snapshots are scaled according to the eddy's radius (R) and rotated according to the ambient instantaneous Chl gradient.

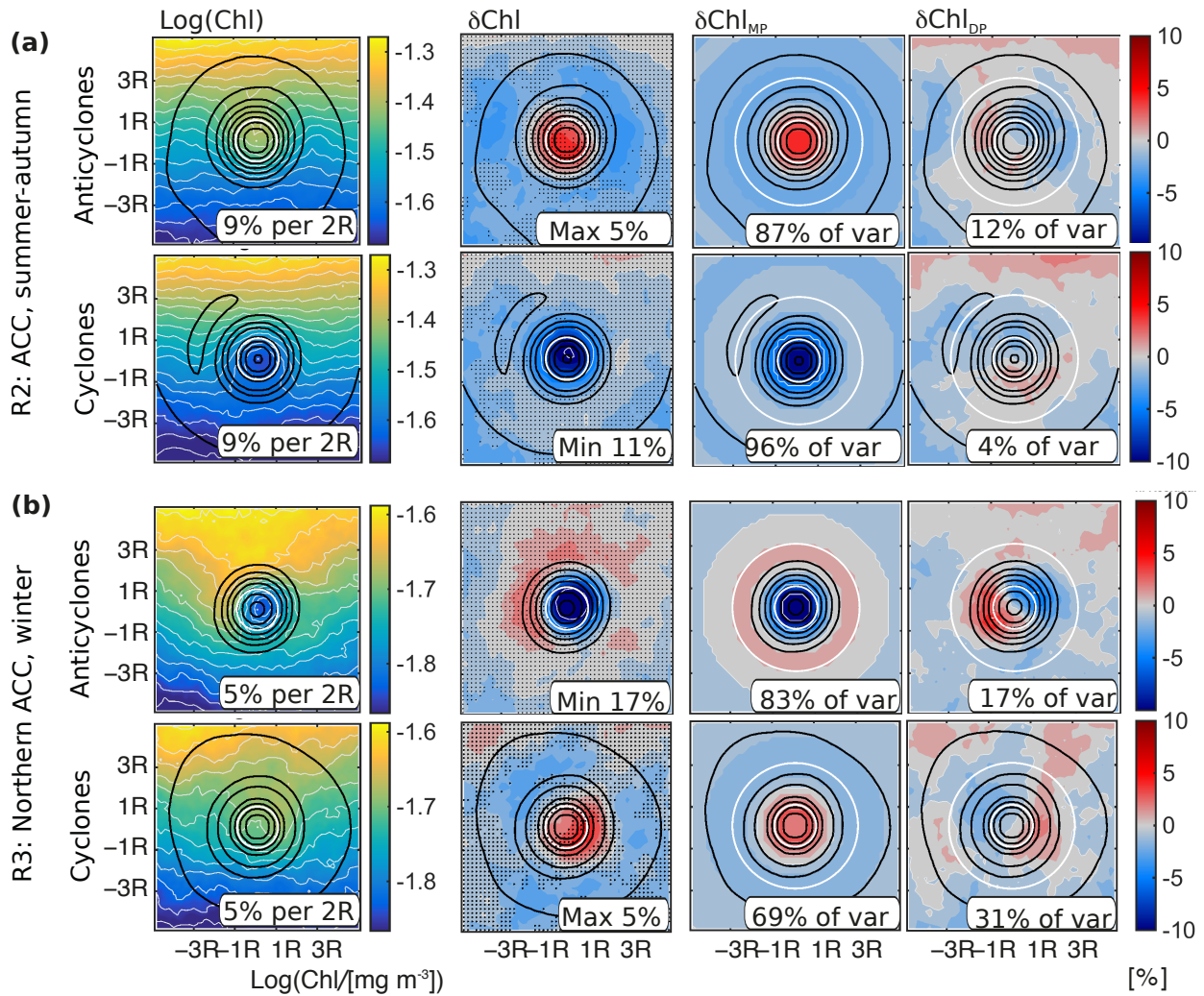


Figure 6. Attribution of stirring/trapping components; same as [Figure Fig. 5](#) but for a **autumn-ACC-waters-the region** R2 (SSH -60 to -40 cm, January to May) and **b** for **region R3 northern-ACC-winter-deep-mixed-layer-waters** (SSH -50 to -15 cm, July to September); **average**. The regions are indicated with boxes in [Figure Fig. 7](#).

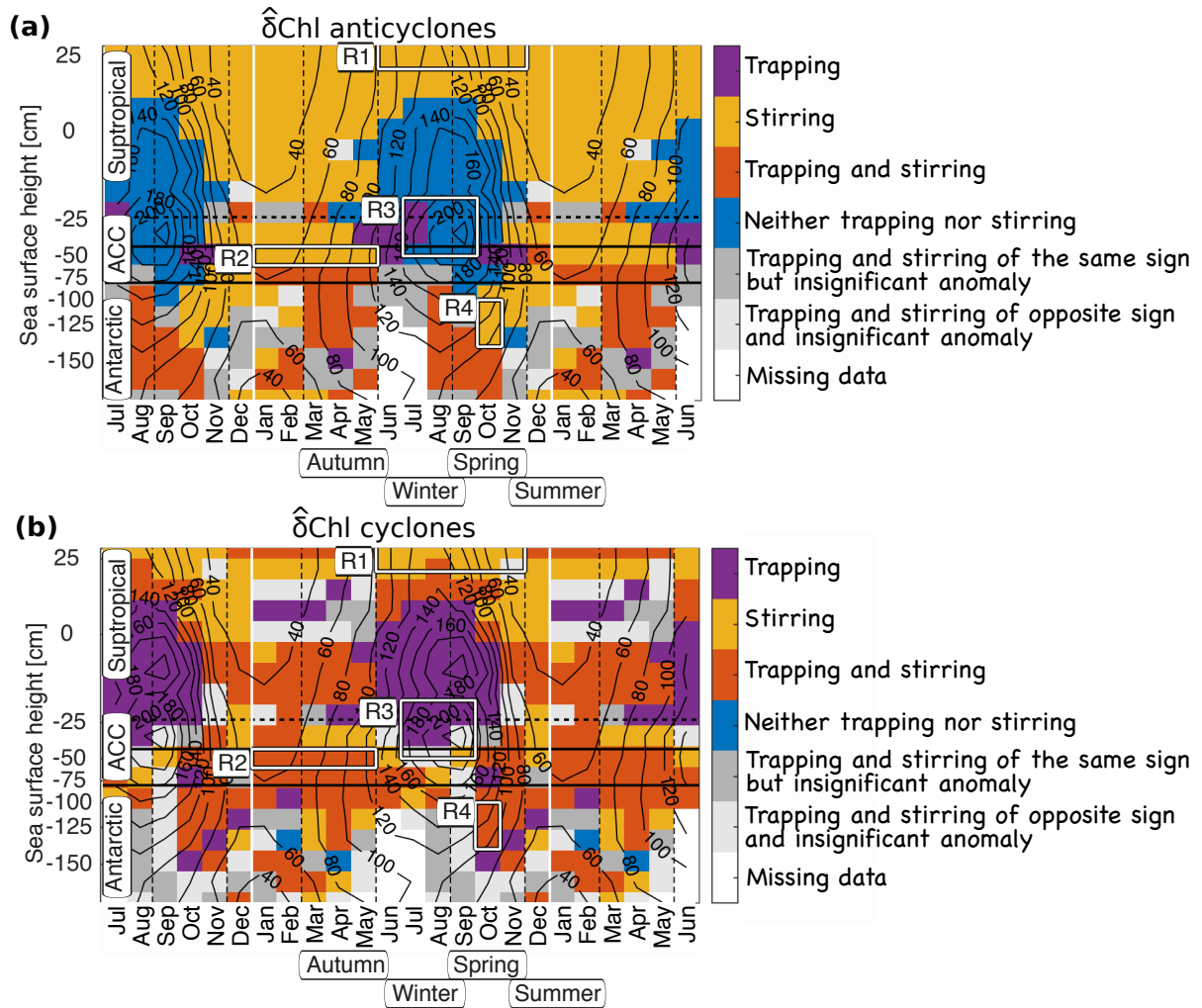


Figure 7. Regions of potential of eddies ($\hat{\delta}\text{Chl}$) to cause chlorophyll anomalies (δChl); due to Hovmoeller diagram of the likely processes controlling the chlorophyll anomalies (δChl) in **a anticyclones and **b** cyclones: stirring (yellow), trapping (purple), a combination of the two (red) or non-neither of the two; for **a** anticyclones and **b** cyclones; legend: sign of eddy induced δChl agrees with sign of potential Trapping effect (blue), Stirring effect, with the sign latter often interpreted to be the consequence of both changes in the local growth or losses (Trapping and stirring biogeochemical rates), or with. A region is colored if the sign of none of the two (Neither trapping nor stirring); see potential effect is the same as the observed one, and if δChl is significant. See text for details; white boxes indicate regions R1 to R4 used for composite Figures 5/6. The data were binned in monthly sea-surface height bins.**

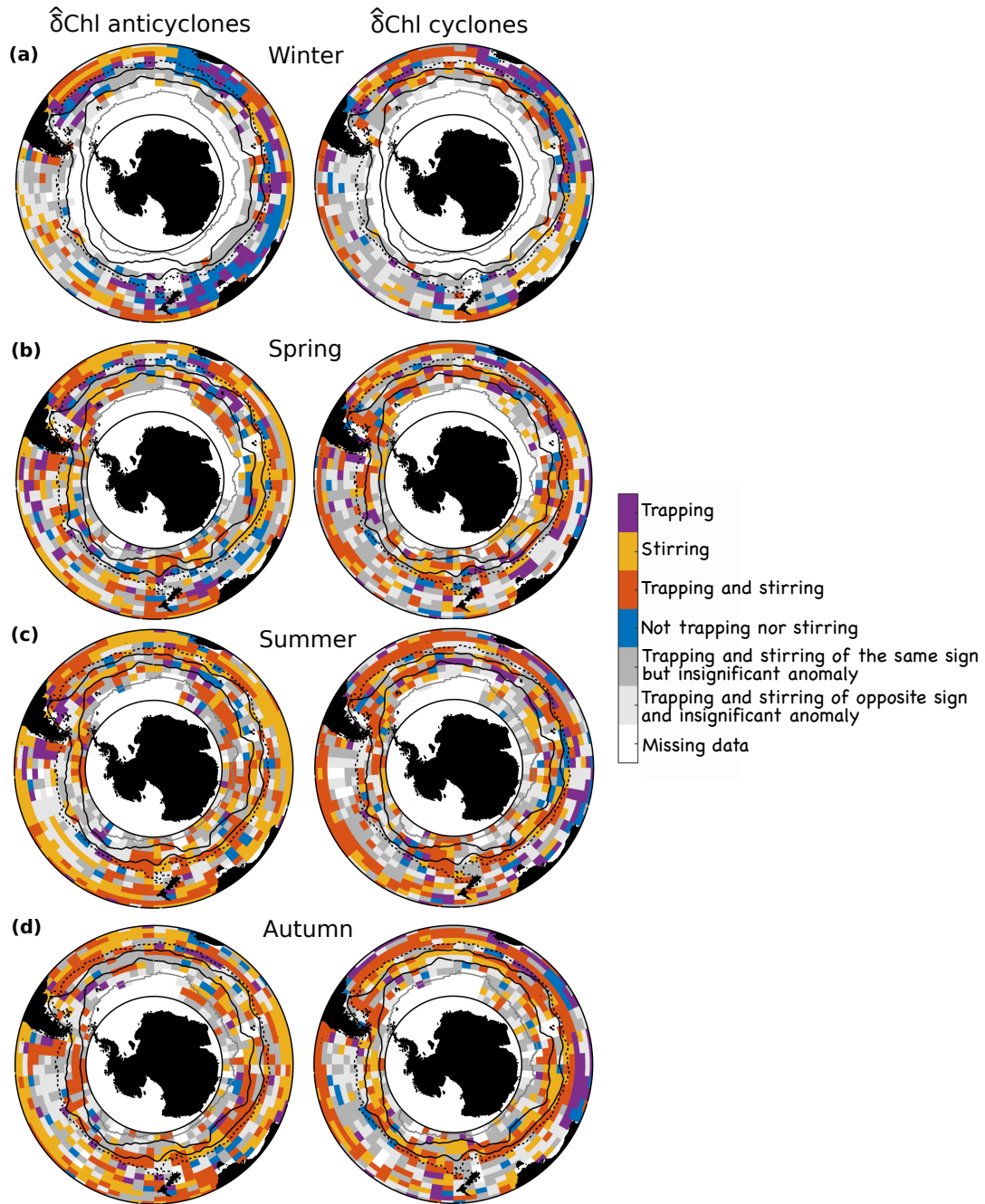


Figure 8. Seasonality of potential of eddies ($\hat{\delta}\text{Chl}$); Austral **a winter, **b** spring, **c** summer and **d** autumn for anticyclones (left) and cyclones (right).** Maps of the distribution of the likely processes controlling the chlorophyll anomalies (δChl) for austral **a** winter, **b** spring, **c** summer and **d** autumn for anticyclones (left) and cyclones (right). The method and legend is the same as used in figure 7. Otherwise as Figure Fig. 2.

the magnitude of $\hat{\delta}\text{Chl}_{\text{trap}}$ is small, hence the contribution by *trapping* is limited. Further, *trapping* is not of the same sign as δChl for cyclones everywhere in the region either (see blue boxes [Figure Fig. 8a,b](#), right column). Hence, ~~an effect of eddies on biogeochemical rates is required also for cyclones in winter deep mixed layers~~ the likely explanation for the δChl in cyclones in regions with deep winter mixed layers is that eddies also modify the local biogeochemical rates.

5 Effects of eddies on biogeochemical rates also may play a role in other regions or seasons, ~~too~~. For instance, the magnitudes of $\hat{\delta}\text{Chl}_{\text{stir}}$ and $\hat{\delta}\text{Chl}_{\text{trap}}$ appear too weak to explain δChl in subtropical waters in winter and spring (Figures 4d-g/5a). Further, ~~the closed Chl contours are associated with the eddy cores that cannot origin from local lateral entrainment associated with stirring (Figures 5/6, left columns). Also the generally weak potential $\hat{\delta}\text{Chl}_{\text{trap}}$ is too weak fails to explain the closed Chl contours and the associated~~ strong monopole component of δChl that contributes about 70 to 100% to the variability of the
10 δChl shape (Figures 4f,g/5/6): ~~The local shape of Chl shows closed Chl contours associated with eddies despite the weak $\hat{\delta}\text{Chl}_{\text{trap}}$ (Figures 5/6, left columns), suggesting an effect.~~ Both of these points support that effects on biogeochemical rates ~~that~~ may enhance the δChl monopole.

4 Discussion and synthesis

The zonal pattern of the ~~eddy induced Chl anomalies, δChl~~ δChl ~~identified here for the Southern Ocean is similar to that~~ seen
15 in global ocean-based analyses. ~~Also the magnitude of δChl is similar north of the ACC to what~~ described by Gaube et al. (2014) ~~reported on a global basis. Yet, along the ACC we find more widespread and more intense δChl than the global study, especially in summer and autumn.~~ Regional across the world's oceans. Analogous to the results of our analyses, they also found spatial variations in the sign of δChl associated with either cyclonic and anticyclonic eddies ~~have been reported previously.~~ Such regional variations are considerable also in the Southern Ocean. In contrast, seasonal variations have been reported to be
20 relatively weak globally. Yet, there are also substantial differences, especially along the ACC, where, e.g., the δChl is more widespread and more intense than previously acknowledged. Further, the seasonal variations in the Southern Ocean appear to be stronger than elsewhere (Gaube et al., 2014), except, perhaps, for the eastern Indian Ocean and the South China Sea (Gaube et al., 2013; Guo et al., 2017). ~~And seasonal~~ Possibly, the underappreciated δChl along the ACC is due to previous conflation of seasonal anomalies of opposite sign, resulting in a much weaker annual signal. To our knowledge, such seasonal changes in
25 the sign of δChl in a particular region have ~~to our knowledge~~ not been reported before. Hence, the strong seasonality with a seasonal change in the sign of δChl along the ACC and south of the ACC appears to be rather specific to the Southern Ocean.

The ~~spatial and seasonal spatiotemporal~~ variability of δChl may not be that surprising in hindsight, given that the same mechanism, e.g., advection can lead to either positive or negative signs for the same polarity depending on the sign of the lateral gradient. In addition, several mechanisms may be involved simultaneously, so that small differences in their relative importance
30 can lead to substantial differences in the net sign of the response (Siegel et al., 2011; Gaube et al., 2014; McGillicuddy Jr., 2016). ~~In the end, we~~ Nevertheless, we have demonstrated that most of the eddy induced signatures of δChl in the Southern Ocean are likely due to *stirring*, a mechanism that has been shown to control δChl in the low to mid-latitude ocean as well (Chelton et al., 2011a). ~~But we showed also that there are several other regions/seasons where other~~ Stirring is an effective

mechanism for eddies to cause δChl as eddy rotation is omnidirectional and thus necessarily perpendicular to the ambient Chl isolines. This fact combined with the steep meridional Chl gradients in the Southern Ocean favor *stirring* as the driving mechanism for δChl . *Stirring* in such an environment of meridional Chl gradients supports Chl anomalies of a banded, zonal structure, similar in pattern and magnitude to the actual observed δChl , in most regions and seasons. *Stirring* is also favored compared to *trapping* by the fact that the majority of the eddies are relatively short lived and also have low translational speeds, such that the average eddy does not get far during its lifetime. This means that the eddy is much more likely to efficiently stir the environmental gradient due to its rotation than to move great distances up or down the gradient.

Next to *stirring*, our work elucidated also the importance of the other processes, namely ~~trapping~~ and changes in biogeochemical rates appear dominant. To illustrate this, we took the Hovmoeller diagram of Figure 4 and identified the dominant mechanism based on the results of the analyses of the two advective potentials (Figure 5, in certain regions and at certain times. This leads to a relatively complex mosaic of dominance across space and time in the Southern Ocean (Fig. 7).

This synthesis figure (Figure 7) reveals that the dominance of *stirring* as the sole mechanism is limited to the subtropical waters outside of deep regions with deep winter mixed layers, and for anticyclones along the northern ACC in summer to autumn (Figure Fig. 7, yellow). Our results suggest that *trapping* contributes to δChl for anticyclones along the southern ACC in summer to autumn and in Antarctic waters in autumn and spring, and to δChl of cyclones in most regions and seasons, except for subtropical waters in winter to spring parts of the subtropical waters (see also Figure Fig. 8a, south and southwest of Australia). Yet, the magnitude of the potential of *trapping* is generally weaksmall, with the exception, perhaps, of a few specific regions, such as by eddies originating from the eastern boundary currents, and those to the southeast of the Kerguelen Islands, and in the Drake Passage (Supplementary Figure S3). They, see also Gaube et al., 2014). In these regions, eddies tend to move westward across transitional regions of coastal to off-shore waters, i.e., down intense down intense zonal Chl gradients (Supplementary Figure S2, right column), with a resulting positive δChl , e. g., in the southeast Pacific or southeast of Kerguelen Islands and Drake Passage. In these regions, carrying their high initial Chl with them. This tends to result in positive δChl is positive year round for both anticyclones and cyclones (Figure Fig. 3). A possible explanation next to advection of Chl An additional possible explanation is the offshore advection of iron trapped in the nearshore region by eddies that fuels extra growth in the offshore waters, as suggested e.g., for Haida eddies in the North Pacific (Xiu et al., 2011). A substantial effect of *trapping* to cause δChl in boundary currents corroborates previous results, or for eddies passing the Kerguelen Plateau (D'Ovidio et al., 2015).

The nevertheless overall The weaker role of *trapping* relative to *stirring* is consistent with (i) a propagation distance of eddies over their lifetime that is on average smaller than two eddy radii, meaning that the scale of impact due to eddy propagation tends to be smaller than the one due to eddy rotation, and (ii) an can be explained by the inherently westward propagation of mesoscale eddies, meaning a propagation largely along Chl isolines, as zonal Chl gradients typically are much smaller than meridional Chl gradients.

Moreover, a weak An additional reason is the aforementioned short propagation distance of an average eddy. Moreover, the efficiency of *trapping* signal also is anticipated as is often also reduced owing to the trapped waters from the eddies' origins will be diluted along the eddies' pathways. Eddies tend to not trap perfectly but continuously leak and entrain waters ambient

~~to their cores being diluted along their pathways~~ (Beron-Vera et al., 2013; Wang et al., 2015; Haller, 2015). ~~The importance of such lateral entrainment or permeable trapping is supported by the pronounced monopole contributions to the shapes of the local~~ This dilution effect may help to explain also the puzzling observation that despite ~~stirring being the dominant process overall, the spatial structure of the δChl imprint within the eddies is much more monopole than dipole~~ (Figures 5,6). ~~The dipole contributions are relatively weak despite the comparatively steep ambient Chl gradients favoring stirring. In summary we hypothesize that the relative weakness of the dipoles stems from lateral entrainment of Chl into the eddies' cores, resulting in a pronounced asymmetry of the dipoles and a large monopole part in the~~ This can be resolved by hypothesizing that the lateral entrainment weakens the dipole component of the δChl ~~decomposition~~ generated by stirring, while strengthening the monopole component (see illustration in ~~Figure Fig.~~ 1a).

10 The clearest case for a substantial contribution of changes in biogeochemical rates on δChl was found for the northern ACC region during winter and spring, when the mixed layers are deep (~~Figure Fig.~~ 7, blue), and correlations of Chl and SLA are negative. The associated negative δChl of anticyclones is consistent with the mechanism of an amplification of ~~large-scale~~ the prevailing light limitation in the deep mixed layers (Boyd, 2002; Moore and Abbott, 2002; Venables and Meredith, 2009; Fauchereau et al., 2011): ~~Anticyclones~~ As a result of their suppressing the thermoclines, anticyclones tend to deepen ~~isopycnals, causing deeper mixed layers of the mixed layer depths by~~ several tens of meters ~~and weaker mixed layer stratification~~, especially in winter (Song et al., 2015; Hausmann et al., 2017; Dufois et al., 2016). Hence, phytoplankton within the mixed layer will be exposed to reduced mean ~~radiation light levels~~ in anticyclones as compared to ambient waters, ~~and vice versa leading to lower Chl levels. The opposite is the case~~ for cyclones.

Our result of a pronounced monopole shape of δChl despite the weak trapping potential suggests that also ~~In the same~~ region in summer to autumn, ~~positive correlations of SLA and the weak trapping potential, the pronounced monopole shape of δChl and the closed Chl contours suggest that the δChl are~~ is at least partly caused by the effects of eddies on the local biogeochemical rates. Here, ~~the positive correlations of SLA and δChl could arise due to eddy-induced modifications of the prevailing iron limitation could be modulated by eddies, with an abatement of.~~ Anticyclones could reduce the iron limitation and ~~associated~~ lead to positive δChl ~~caused by weakly stratified anticyclones in~~ owing to their being more weakly stratified, ~~leading to intensified vertical mixing in the high wind conditions and associated intensified vertical mixing, and vice versa for cyclones. Moreover, of the Southern Ocean, bringing more iron from below to the surface. Vice-versa, the iron limitation could be enhanced by cyclones owing to their weaker vertical mixing~~ (Dufois et al., 2016; Song et al., 2018). Hypothetically, ~~an~~ alleviation of grazing pressure due to reduced predator-prey encounter rates in deepened mixed layers in anticyclones could ~~further~~ favor positive δChl , ~~again vice versa and more shallow mixed layers could increase grazing pressure~~ for cyclones. Thus, 25 we argue that along the northern ACC, the seasonal sign switch of δChl could be explained by varying degrees of light and iron limitation and grazing pressure over the course of the year (Smetacek et al., 2004; Carranza and Gille, 2015; Le Quéré et al., 2016).

Finally, along the southern ACC and in Antarctic waters in autumn to spring, the potentials of *stirring* and *trapping* often-times are of the same sign. However, δChl associated with eddies is insignificant ~~in these waters in many places~~ (dark gray

regions, ~~Figure Fig. 7~~). Presumably, these situations ~~when δChl are insignificant arise because~~ arise because the eddy effects on biogeochemical rates oppose the local biogeochemical rates may almost perfectly cancel the advective effects.

~~We note that our~~ Our analysis is constrained to the surface ocean, hence three ~~aspects caveats~~ need to be kept in mind:

(i) one potential issue are non-homogeneous vertical Chl profiles, e.g., the presence of unrecognized subsurface Chl maxima.

5 ~~As in previous studies, we assume that in our focus region, at the core latitudes of the Southern Ocean across the ACC,~~ But subsurface Chl maxima presumably are not prominent in our area of study (Sallée et al., 2015), as wind speeds are high and mixed layers deep, promoting well-mixed Chl levels over the upper ocean; further, surface and mixed layer depth integrated analyses provide similar results in terms of SLA-Chl correlations (based on model simulations, Hajoon Song, pers. communication comm.), supporting the feasibility of assumption that an analysis of surface Chl is representative for the total Chl
10 in the water column. (ii) ~~Modification modification~~ of mixed layer depths by eddies may result in a surface Chl concentration modification due to a dilution effect. Especially in winter to spring, when the mixed layers are deep, we cannot exclude that this effect contributes to negative and positive the observed δChl for anticyclones (deepening thermocline) and cyclones (lifting thermocline), respectively. Yet as noted in (i), surface and mixed layer depth integrated analyses provide similar results in a model simulation. ~~Further, given the considerable spatio-temporal variation of δChl across the Southern Ocean dissimilar to~~
15 ~~mixed layer depth variations, this is likely not the major factor responsible for δChl . Finally,~~ (iii) ~~potential~~ Potential effects of eddies on phytoplankton growth presumably occur mostly in the lower euphotic zone and may thus be expressed more weakly at the surface ~~where they are detected by satellite sensors~~ (McGillicuddy Jr. et al., 2007; Siegel et al., 2011). We therefore note that ~~effects of eddies on~~ because our study is based on ocean surface data it may underestimate the total effect of mesoscale eddies on biogeochemical rates.

20 Furthermore, we may underestimate the overall effect of mesoscale eddies on Chl also because of additional effects of mesoscale eddies that are not considered in our analysis. Such effects include the impact of smaller mesoscale features, and of submesoscale processes near the edges of eddies (Woods, 1988; Strass, 1992; Martin et al., 2002; Lévy, 2003; Klein and Lapeyre, 2009; Siegel et al., 2011), e.g., eddy-jet interactions and associated horizontal shear-induced patches of up- and downwelling. Such features are included in our analysis only insofar as they have rectified effects on the larger mesoscale
25 Chl patterns resolved by the data we use. Another effect we do not consider is non-local stirring (D'Ovidio et al., 2015), the contribution of eddies to lateral dispersion outside the eddies' cores in interaction with the ambient flow. This effect, for instance, shapes iron plumes downstream of shelves along the ACC, thus preconditioning Chl blooms (Ardyna et al., 2017). Therefore, we note that the overall effect of mesoscale eddies on biogeochemical rates may be underestimated in this surface
30 based study larger than suggested by our analysis of the mesoscale, local imprint of eddies on Chl. Finally, we note that our analysis does not include the effect of submesoscale processes outside eddies as well as any unstructured turbulence in general.

5 Summary and Conclusions

The prevalent and strong correlations between anomalies in surface Chlorophyll Chl and mesoscale variability have triggered substantial research, but many unresolved issues remain, particularly ~~associated with the question of~~ regarding their causes

(Lévy, 2008; Gaube et al., 2014; McGillicuddy Jr., 2016). With this study, we aim to provide an observational reference for the seasonal climatological δChl associated with mesoscale eddies across the Southern Ocean, a region where the detailed regional and seasonal relationship of eddies and Chl previously had not been ~~considered. We have obtained the estimate by combining discussed. To this end, we combined~~ satellite estimates of Chl with ocean ~~eddies-mesoscale eddies (diameters larger than ~50~~ 5 ~~km)~~ identified based on satellite estimates of SLA. ~~A-The very~~ large number of collocations of eddies and Chl allowed us to retrieve statistically robust results despite ~~the~~ frequent data gaps and ~~the~~ high spatio-temporal variability of Chl.

We found ~~δChl associated with eddies of~~ ~~→~~ ~~a relatively complex pattern of Chl anomalies associated with mesoscale eddies,~~ ~~i.e., δChl , with many anomalies exceeding $\pm 10\%$ of their mean value~~ over wide areas in the Southern Ocean. The ~~large-scale patterns are positive and negative anomalies for cyclones~~ ~~δChl for cyclones is positive~~ in subtropical waters ~~and,~~ ~~but negative~~ 10 ~~along the ACC;~~ ~~respectively~~; anticyclones show a similar pattern, but of opposite sign. A pronounced seasonality of the imprint is apparent especially along the ACC and in Antarctic waters, featuring a sign switch of the anomaly over the course of the year.

While multiple mechanisms may be at play at the same time to cause ~~the observed~~ δChl (Gaube et al., 2014; McGillicuddy Jr., 2016), our analyses ~~based on climatological Chl gradients, eddy rotation and propagation pathways, and the local shape of δChl of eddies lead us to conclude suggest~~ that lateral advection due to *stirring* by eddies and associated lateral entrainment and permeable *trapping* ~~have the potential to~~ explain a large fraction of ~~Southern Ocean eddy-induced~~ ~~the observed~~ δChl . ~~This conclusion is based on our analysis of the climatological Chl gradients, eddy rotation and propagation pathways, and the local shape of the δChl of eddies.~~ 15

A prominent region and season where eddy-induced advection is insufficient to explain δChl are the northern ACC characterized by deep mixed layers in winter to spring and the seasonal sign switch of δChl in the same region: Here, winter to spring negative and positive δChl of anticyclones and cyclones, respectively, are consistent with an enhancement and reduction of deep mixed layer light limitation. The opposite signs of δChl in summer to autumn are consistent with an abatement of ~~grazing pressure caused iron limitation~~ by anticyclones via ~~deepened mixed layers, or iron limitation via~~ a relatively weak stratification facilitating vertical mixing, and, ~~more speculatively, with an abatement of grazing pressure caused by anticyclones via~~ 20 ~~deepened mixed layers; and~~ vice versa for cyclones. In other regions and seasons our analysis does not exclude a modulation of δChl by effects of eddies on biogeochemical rates, even though our results suggest that lateral advection ~~has the potential to be the is likely the~~ dominant mechanism.

Future work may include ~~to further investigate the extent of lateral entrainment and permeable trapping of eddies versus non-local trapping, and to test the investigation of~~ where and when Southern Ocean eddies substantially affect biogeochemical rates, such as through modulation of alternating roles of iron and light limitation ~~and as well as~~ grazing pressure along the ACC (Song et al., 2018). The growing number of sub-surface biogeochemical measurements across eddies may be of help ~~collected by biogeochemical floats, gliders and seals here, such as those collected by the growing number of biogeochemical floats (<http://biogeochemical-argo.org>).~~ In addition, targeted experiments with numerical ocean-biogeochemical models with the option to alternately switch on and off Chl ~~sources-sinks would be useful~~ ~~sources and sinks could be employed~~ to shed 30 light on the questions ~~of~~ what the role of eddy-effects is on Chl ~~sources-sinks~~ ~~sources and sinks~~ relative to advection, for

higher trophic levels (Nel et al., 2001; Godø et al., 2012), or for the intensity-magnitude and structure of export (Waite et al., 2016). Furthermore, ~~numerical models would allow us~~ such models could be used to assess if these effects of eddies on Chl substantially affect Southern Ocean biogeochemistry, ~~such as of mode and intermediate waters which form from winter deep mixed layers, supply~~. Of particular interest are their modifications of the mode waters that originate from the Southern Ocean region with deep winter mixed layers. This is crucial, as these mode waters supply the low latitude ocean with nutrients and sequester a substantial amount of anthropogenic carbon (Sarmiento et al., 2004; Sallée et al., 2012). The final thread is the expansion of this work to smaller scales, and perhaps also more ephemeral turbulent structures, such as fronts.

Data availability. The identified eddies we used in this study including their Chl characteristics are publicly available (<http://dx.doi.org/10.3929/ethz-b-000238826>). Other presented data are available from the corresponding author upon request.

10 *Author contributions.* I.F., N.G., and M.M. conceived the project, I.F. carried out the analyses, all authors contributed to the writing of the manuscript.

Competing interests. The authors report no competing financial interests.

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