Response to reviewers for Biogeosciences Discuss., 11, C2753-C2755, 2014:

Anonymous Referee #1:

This manuscript by Gille et al. provides an overview of large scale wind stress curl fields and SST and some analysis of wind stress, upwelling, mixing and SST. Though there are limited contributions to novel science and methods, the manuscript is an essential part of physical background and forcing mechanisms in the Kerguelen Islands and its vicinity and necessary information needed for the KEOPS 2 project. I recommend this manuscript for publication on BGD. Here are some specific comments:

Thanks to the reviewer for a supportive and helpful review. Here we have responded to each of the comments.

1) Abstract: "... High wind speeds typically correlate with cold sea surface temperatures, implying that wind mixing leads to enhanced vertical mixing. Negative windstress curl also correlates with cold SSTs, implying that Ekman pumping can further enhance upwelling, and coupling between winds and SSTs associated with mesoscale eddies can locally modulate the wind-stress curl..." This is a general concept and not necessarily included in the abstract while it is difficult to understand from this abstract what detailed studies conducted in this manuscript. There is a need of outline what this manuscript studied and conclusions.

The abstract has been revised to better indicate the contributions provided by this paper. The sentences highlighted by the reviewer have been revised to emphasize that these findings are demonstrated in our calculations:

> Results show that in the Kerguelen region, cold SSTs correlate with high wind speeds, implying that wind-mixing leads to enhanced vertical mixing. Cold SSTs also correlate with negative wind-stress curl, implying that Ekman pumping can further enhance upwelling.

We've also edited the final portion of the abstract to provide more information about our findings regarding the wind-stress curl dipole in the wind shadow of Kerguelen and the wind-induced upwelling during the KEOPS-2 field program. The abstract now concludes:

> Kerguelen has a significant wind shadow on its downwind side, which changes position depending on the prevailing wind and which generates a wind-stress curl dipole that shifts location depending on wind direction. This leads to locally enhanced Ekman pumping for a few hundred kilometres downstream of the Kerguelen Plateau; Chl-a values tend to be more elevated in places where wind-stress curl induces Ekman upwelling occurs than in locations of downwelling. During the October-November 2011 KEOPS-2 field program, wind conditions were fairly typical for the region, with enhanced Ekman upwelling expected to the north of the Kerguelen Islands.

2) Introduction: In the first paragraph, a better literature review is needed such as the papers by Measures et al (2010) on iron source and transport in the Drake Passage, by Hopkinson et al (2007, 2013) on iron limitation and enhancement on primary production, Park et al (2008) on vertical

mixing of iron, van Beek et al (2008), Charette et al (2008) and Dulaiova et al (2009) on iron source and horizontal/vertical transport. The literature provides a useful background information for the study in this manuscript.
We've added references to Hopkinson et al. (2007), Charette et al. (2007), van Beek et al. (2008), Blain et al. (2008), Park et al. (2008a), Park et al. (2008b), Dulaiova et al. (2009), and Measures et al. (2012). (In the "Web of Science" we did not find a 2008 paper by Charette et al or a 2010 paper by Measures et al, so if the reviewer had specific publications in mind, we would be grateful for full reference information.) We have also expanded and clarified some of the discussion of KEOPS-1 results and have added references to the new KEOPS-2 findings. Since the paper has been submitted to a special collection associated with KEOPS-2, other papers in the same volume will provide more thorough literature review covering the biological and chemical aspects of the project so we have aimed to focus the introduction primarily on the physical processes that control iron availability.

3) Page 8375, last paragraph: "... While wind-driven upwelling appears to play a central role in determining variability... " Suggest changing "central role" to "one of key roles" because there are many other important processes such as wind mixing as discussed, and upwelling associated with fronts and eddies.
This is a good point. We've changed the wording to say "wind-driven upwelling appears to help determine variability ..." This seemed to be a concise way to express the point raised by the reviewer.

4) Page 8378, line 1: "... Fig. 1f shows mean SST from ..." Suggest changing to "Mean SST from ... is shown in Fig. 1f." This suggestion is also applied to other "Fig. xx shows ..." in this manuscript.
Where possible, we have tried to avoid passive voice constructions, as they make English-language text difficult to read. Instead we have merged this sentence with the subsequent sentence to read, "For October-November 2011, when the KEOPS-2 field program took place, SSTs from WindSat are used (Figure 1f)."

We have made similar modifications in reference several other figures.

- For Figure 2a: "We correlate wind speed and SST (Figure 2a), using the method of partial correlations to control for the impact of surface heat fluxes (Baba et al., 2004)."
- For Figure 4: "More than 50% of the time, winds are from the west or west-northwest (Figure 4), giving rise to the distinct pattern of negative wind-stress curl to the northeast of the Kerguelen Island,...."
- For Figure 6a (now 7a): "A rose histogram for wind direction for October-November, 2011 (Figure 7a) indicates that the prevailing wind directions during KEOPS-2 were consistent with prevailing wind directions shown in Figure 4 for the 2002-2009 time period."
- For Figure 7b: "The time-mean wind-stress curl for October-November, 2011 (Figure 7b) is consistent with historical trends and indicates negative wind-stress curl, so upwelling favorable conditions, to the northeast of Kerguelen."

5) Page 8378, the 2nd paragraph: "... Sea surface geostrophic velocity anomalies (relative to a temporal mean from 1992-1999) were produced by the SSALTO/DUACS project, which computes them based on a multi-satellite altimeter product ..." I have some difficult to understand what is the definition of "which." Do you mean "... Sea surface geostrophic velocity anomalies (relative to a temporal mean from 1992-1999) were produced by the SSALTO/DUACS project based on a multi-satellite altimeter product?"
This is a good suggestion. We've made the change.

6) Methodology: Reading through this section, my comments are (1) most of information is well developed and used in the past so that they just need to be mentioned with citations, (2) the justification using these variables based on previous studies by others should be mentioned in the Introduction recognizing their original contributions, and then validated these variables in the Discussion section, and (3) because the methodology will be relative short, the data and methods can be combined into one section.
We have shortened the methodology section to three relatively concise paragraphs. After some discussion, we have concluded that we would prefer to retain the methodology section heading, since we feel that this is helpful to readers, and that readers should be able to reconstruct the core details of the approach without needing to track down additional literature. This is particularly important for this paper, since the methodology is drawn from the physical oceanography literature and may be unfamiliar to readers of *Biogeosciences.*

7) Results: Though I am in favor to mix results from the study, validation of results, discussions and comparisons to literatures in one section, there is a need of a clear pattern for a reader to follow. If it is getting too difficult, the traditional separation between results, discussion and summary is a better way to organize the manuscript. I am not against the current way to organize this section which the authors decided to take. But I do suggest having a clear organization from results, comparison to others and hypotheses based on results. For example, in Page 8380 Section 4.1, the first paragraph starts from a literature review, and then followed by discussions on Figure 2. It is difficult to understand if the results in Figure 2 supports the results from literature, or they agree/disagree to each other.
The Results section has been revised to focus first on the results and then on the interpretation, as suggested by the reviewer. The opening paragraph of the section now reads:

> We correlate wind speed and SST (Figure 2a), using the method of partial correlations to control for the impact of surface heat fluxes (Baba et al., 2004). Through most of the Southern Ocean, in year-round data high wind speeds correlate with cold SSTs, implying that wind-induced mixing deepens the mixed layer and brings cold water and nutrients to the surface (Kahru et al., 2010), and during spring and summer this can promote phytoplankton growth (Carranza and Gille, 2014). (In winter and early spring when stratification is low, high winds can deepen the mixed layer and move phytoplankton out of the euphotic zone, resulting in low Chl-a (Kahru et al., 2010), but the focus of this study is on spring and summer.) As hypothesized, wind speed and SST are negatively correlated (blue) almost everywhere, except in some locations to the north of Kerguelen. Positive correlations (red) fall along the Subantarctic Front and Polar Front

> of the ACC, which represent the primary axes of the current; here changes in SST can feedback on the winds. This positive correlation associated with the mesoscale vanishes when we high-pass filter the data to consider synoptic storm effects (Carranza and Gille, 2014), implying that large-scale storms suppress eddy feedback effects.

Similarly we have revised discussions of the other figures presented in section 4.1 to focus first on showing the results and then on interpreting them.

8) Summary and Discussions: There are significant discussions in the Results section on variations of stress curls and correlations. But the discussions on the comparison of this work with results from other studies are quite weak. There are a series of studies done by Park et al on small-large circulation patterns and mixing, and by McCartney and Donohue (2007) on large circulation. There are significant similar patterns in results between this and those studies.
Thank you for these suggestions. We have revised the discussion to provide further context based on prior studies. In doing this, we have read a number of the suggested Park et al papers, which have proved extremely useful in providing context for these results. The McCartney and Donohue (2007) paper is interesting but we did not readily see how to incorporate it into this discussion, since McCartney and Donohue focus largely on bottom water, which is likely deeper than the shelf waters that influence productivity in this region, and they do not consider wind forcing or nutrients. However, in the final two papers of the Summary section, we have added references to a number of the KEOPS-1 and KEOPS-2 studies of this region.

Anonymous Referee #2:

The manuscript titled "Wind-induced upwelling in the Kerguelen Plateau Region" by lead-author Dr. Sarah Gille details an analysis of estimates of surface stress, sea surface temperature and near-surface CHL made from satellite observations. The study draws the following conclusions: (1) The wind stress magnitude and surface stress curl are influenced by both air-sea interaction and orographic effects in the Kerguelen Plateau region. (2) Enhanced wind stress acts to cool the oceans surface through increased vertical mixing. (3) Enhanced wind stress and Ekman pumping can bring nutrients from the oceans interior into the sunlit surface ocean, potentially generating the observed spring-time CHL bloom.

The manuscript is well written and clearly describes how the analysis was carried out. The results appear to be robust and overall the conclusions are concise and supported by the results. This paper requires only minor revisions.
Thanks to Referee #2 for this careful and helpful review.

The following suggestions and clarifications are provided to help the reader understand the analysis procedure and to help strengthen the suggested link between Ekman pumping and enhanced CHL.

Page 8380, line 20: The authors describe that the cross correlations are computed and "controlled for the impact of surface heat fluxes." Some description of how the surface heat fluxes were accounted for and removed from the correlations is warranted in this section. Clarification of this method would also help to support a similar statement made at line 8 on page 8381.
The discussion of partial correlations at the end of the methods section has been updated to provide a bit more description of the approach: "In essence, to compute the partial correlation of wind speed (W) and SST, controlled for air-sea flux (Q_{net}), we first remove the component of the W,SST correlation that could be explained because both W and SST are individually correlated with Q_{net}."

The paragraph identified by the reviewer has also been revised following the first-reviewer's comments, so that it now presents results first and discusses them subsequently. The relevant sentence now states, "We correlate wind speed and SST (Figure 2a), using the method of partial correlations to control for the impact of surface heat fluxes (Baba et al., 2004)." We have also added a bit of detail to the Figure 2 caption to indicate that the NCEP/CFSR surface heat fluxes are used.

Page 8384. It is suggested that enhanced CHL during the spring bloom could be fueled by nutrients upwelling by Ekman pumping. In support of this, the regions of relatively high and low seasonally-averaged CHL shown in Figs. 1 a-c are related to regions of negatvie and postive surface stress curl in Figs. 5 b and c. There are 2 issues that come to mind with how the authors try to link CHL and Ekman pumping.

(1) The region around Kerguelen is a HNLC area, therefore, as the authors point out, phytoplankton growth is not limited by macro-nutrients. For Ekman pumping to influence CHL, upwelled isopycnals would have to be associated with enhance iron, the limiting nutrient in this region. The authors need to explain how Ekman upwelling could bring iron to the surface by describing some of the work that has been done in the sources of iron to the region.

We have extended our review of the KEOPS-1 literature and have read some of the KEOPS-2 papers that are being submitted for this particular Biogeosciences collection. This has allowed us to expand our discussion of iron sources, both in the introduction and in the discussion. The introduction now states:

> These processes [that influence iron availability] include oceanic transport processes (which might vary the sediment content of water advected away from the island shelf) (e.g. Park et al., 2008b; van Beek et al., 2008; van der Merwe et al., 2014), and processes that influence lithogenic sources of iron from Kerguelen Island (e.g. Sanial et al., 2014), as well as local orographic influences on winds. For example, Kerguelen, which stands 1850 m tall, produces a substantial wind shadow, which in turn modifies the wind-stress curl (Chelton et al., 2004).

In Section 4, in relation to Ekman upwelling, we now comment on the presence of a sub-surface iron maximum in the region:

> KEOPS-1 observations indicate the presence of a sub-surface iron maximum at the depth of the shelf around 500 m (Blain et al., 2008)....

In Section 5, we note that the rate of Ekman upwelling, "is too slow to bring iron-enriched water to the surface either from the shallow 200-m plateau or from the sub-surface iron maximum that occurs near 500 m depth (Blain et al., 2008; van der Merwe et al., 2014) but could help bring water to the surface from the base of the spring or summer mixed layer, where the sub-surface Chl-a maximum is often found (Carranza et al., 2014).." Finally, in the last paragraph we identify the KEOPS-related papers that have considered sources of iron in the region:

> Both horizontal advection (van Beek et al., 2008; Zhou et al., 2014; Sanial et al., 2014; van der Merwe et al., 2014) and turbulent diapycnal mixing (e.g. Park et al., 2008a, 2014) are also expected to play key roles in controlling iron and macronutrient availability and biological productivity in the euphotic zone.

In addition, the original text did not always clearly distinguish between macronutrients and iron. Throughout the revised manuscript we have been more careful to use the words iron and macronutrients and to specify that iron is likely the key variable for the development of a bloom.

(2) Attributing changes in CHL to changes in Ekman pumping by pointing out that regions of enhanced and suppressed CHL are associated with negative and positive surface stress curl, respectively, is not sufficient to convince me that Ekman pumping influence CHL in this region. As the authors point out, starting at line 13 on page 8384 "numerous other processes [besides Ekman pumping] may also influence biological production on and downstream of the Kerguelen Plateau, ..." It would help their argument if they were to show that CHL was correlated with Ekman pumping. I would suggest that the authors remove any low-frequency (seasonal) variability from the CHL and Ekman pumping fields before computing this cross correlation. If maps of this cross correlation, similar to Fig. 2, are positive in the regions described in the text in paragraph 1 of page 8384, then their suggested relationship between Ekman pumping and CHL would be supported.
We have re-examined our figures. There is little evidence that Chl-a is directly correlated with Ekman pumping. This is not surprising, since Chl-a is governed by a complex range of factors, and

it has a sub-surface maximum in most of the Southern Ocean, as we now note in the introduction: “Sub-surface Chl-a maxima are nearly ubiquitous in the Southern Ocean, so satellite ocean color measurements may not be representative of total mixed-layer Chl-a (Charrassin et al., 2010; Guinet et al., 2013; Carranza et al., 2014).”

However, we do see clear evidence that the locations of Chl-a maxima shift with changes in wind direction. We have added a new Figure 6, which shows satellite-derived Chl-a concentrations (with seasonal variability removed), bin-averaged by wind direction. High Chl-a occurs in the negative wind-stress curl part of the wind-stress curl dipole. The text now draws attention to the links between the positive side of the wind-stress curl dipole an high Chl-a values:

> Negative wind-stress curl is predicted to induce upward vertical Ekman pumping velocities. While numerous factors influence Chl-a in addition to wind forcing, nonetheless Chl-a anomalies, sorted by prevailing wind direction (Figure 6), indicate higher Chl-a in the upwelling-favorable areas on the northern sides of the wind-stress curl dipoles shown in Figure 5. To the northeast of Kerguelen, a shallow plateau extends along 48°S in a region where the eddy coupling is weak (Figure 3f) but the Ekman pumping from the predominant winds is negative, leading to persistent upwelling (Figure 5c) and consistently high Chl-a blooms (Figure 1, Figure 6c).

Given the presence of a sub-surface Chl-a maximum near the base of the mixed layer, we now also suggest that Ekman upwelling may bring Chl-a to the surface where it is detected by ocean color sensors:

> KEOPS-1 observations indicate the presence of a sub-surface iron maximum at the depth of the shelf around 500 m (Blain et al., 2008) and recent profile data indicate the presence of sub-surface Chl-a maxima near the base of the mixed layer (Carranza et al., 2014). We suggest that the persistent wind-induced upwelling may bring sub-surface iron-rich or Chl-a-rich water towards the surface, particularly in the region of the shallower plateau to the northeast of Kerguelen.

Figures 1 - 3. The panel labels (a, b, c, etc..) along with titles are overlay on the figures. This makes it very difficult to read the labels and titles, especially on Fig. 3. I suggest that all labels and title be placed above the individual panels.
Thanks for this suggestion. The panel labels for all three figures have been moved to appear above the panels.

Figure 3f. The grey shading mentioned in line 9 of page 8382 is not visible.
This was inadequately explained in the text. The shading is the middle range of the color bar and may appear white in some print outs or screens. The text has been modified to state, “correlation coefficients less than 0.37 appear white or pale gray.”

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