Matthew Hecht
Editor, *Ocean Science*

Dear Dr. Hecht**,**

Thank you for giving me a chance to respond to the further criticisms of Reviewer # 2 and to submit a suitably revised paper. After reading the review, I feel the comments derive from a misunderstanding of the intent of this paper. The method I propose is NOT intended to isolate the very narrow fronts of the Southern Ocean. It is only intended to track CHANGES in their position. This is a subtle, but important distinction. I admit that in the original draft, this was not entirely clear. But I have made every effort in the second draft to make this clear. For instance, in the Introduction, I write:

"In this paper, we develop a new method to study linear shifts in the position of the fronts in the Southern Ocean, based on tracking the location of envelopes of kinetic energy measured by satellite altimetry. It is known from modeling studies that the front positions are associated with increased kinetic energy, due to instabilities in the jets and interactions with bathymetry (Thompson et al., 2010; Thompson and Richards, 2011). After demonstrating that kinetic energy computed from along-track satellite altimetry forms relatively wide envelopes of enhanced energy that occur within the probability range of jets and fronts (e.g., Chapman, 2017a), we track the positions of these envelopes from 1993 until 2016 to quantify if the envelopes have shifted south by a statistically significant amount. This is based on the assumption that if the front and jets around the front have shifted south, then the envelope of high kinetic energy should also move by a comparable amount. We do not purport that our method derives the actual position of either a front or a jet due to the relatively wide swath of enhanced kinetic energy on either side of fronts related to variability of jets. Instead, we only purport that it can indicate shifts in the frontal position, because if a front has shifted south by 100 km (for instance), then the band of enhanced kinetic energy should also shift south by a comparable amount. It is difficult to reconcile a frontal shift without a displacement of kinetic energy."

Note that the last three sentences are new, to explicitly state that I do not intend this method to be used to determine specific frontal positions at any time. I hope this will alleviate further confusion by reviewer and reader. I also now reiterate this point in the conclusion section.

I hope you find this new revised manuscript acceptable.

Cheers,

Don Chambers

Response to Reviewer # 1 (Christopher Chapman)

I appreciate your kind comments on the revised manuscript. I am glad I could answer all your concerns. Your first review was tremendously helpful. I apologize for the quality of the figures in the PDF, but that is outside of my control as they are apparently reduced in resolution in the PDF creation by the *Ocean Science* program in order to save space. The original figure files are all high-resolution (> 500 dpi) in all cases.

Response to Reviewer # 2

I appreciate your review of this paper and the obvious effort you took. Based on your additional comments, I have revised the paper slightly, as indicated below in answers to your specific comments and in the attached document with track changes turned on. I have attached the fully revised paper with track changes added so you can see where I made changes.

The major criticism appears to derive from a misunderstanding of the intent of this paper. I agree with you that the method I propose should NOT be used to isolate the very narrow fronts of the Southern Ocean. It is only intended to track CHANGES in their position. This is a subtle, but important distinction. I admit that in the original draft, this was not entirely clear. But I have made every effort in the second draft to make this clear. For instance, in the Introduction, I write:

"In this paper, we develop a new method to study linear shifts in the position of the fronts in the Southern Ocean, based on tracking the location of envelopes of kinetic energy measured by satellite altimetry. It is known from modeling studies that the front positions are associated with increased kinetic energy, due to instabilities in the jets and interactions with bathymetry (Thompson et al., 2010; Thompson and Richards, 2011). After demonstrating that kinetic energy computed from along-track satellite altimetry forms relatively wide envelopes of enhanced energy that occur within the probability range of jets and fronts (e.g., Chapman, 2017a), we track the positions of these envelopes from 1993 until 2016 to quantify if the envelopes have shifted south by a statistically significant amount. This is based on previous evidence (e.g., Thompson et al., 2010; Thompson and Richards, 2011; Chapman, 2017) that kinetic energy is highest around fronts in the Southern Ocean. Thus, if the fronts have shifted south, then it follows that the envelope of high kinetic energy should also move by a comparable amount. We do not purport that our method derives the actual position of either a front or a jet due to the relatively wide swath of enhanced kinetic energy on either side of fronts related to variability of jets. Instead, we only purport that it can indicate shifts in the frontal position, because if a front has shifted south by 100 km (for instance), then the band of enhanced kinetic energy should also shift south by a comparable amount. It is difficult to reconcile a frontal shift without a displacement of kinetic energy."

Note that the last four sentences are new (or revised), to explicitly state that I do not intend this method to be used to determine specific frontal positions at any time. I hope this will alleviate any further confusion by the reviewer and the reader. I also reiterate this point in the conclusion section.

The analysis comparing the half-power points of CKE to previously estimated frontal positions is still pertinent, however, to demonstrate that the CKE regions are close to estimated frontal positions. If they were not, then it would raise questions whether this method could be used to detect shifts.

I hope these revisions, and others discussed below in response to specific criticisms alleviates any further concerns.

Cheers,

Don Chambers

Reviewer Comment: Figures
1. All figure axes (except Figure 3) are still too small for clear readability.

RESPONSE: I apologize for the quality of the figures in the PDF, but that is outside of my control as they are reduced in resolution in the PDF creation by the *Ocean Science* program in order to save space. The original figure files are all high-resolution (> 500 dpi) in all cases. However, some figures, particularly Figures 4, 5, and 6 do have smaller fonts because of down-scaling of the figures. I have made all of these larger. I have also made the dots in Figure 7 larger.

Reviewer Comment: 2. Thank you for updating the analysis to include most recent 2016 data. Heads up: now there are differing time periods 1993-2015 and 1993-2016 between Figures 2-4.

RESPONSE: Sorry. I missed changing the caption on Figure 2, even though I changed the figure. There was no visually apparent difference between the two long averages.

Reviewer Comment: Lines 184-186
The author states, 'we develop a new method to study variability in the position of the fronts in the Southern Ocean' but no quantitative results on front variability, other than N-S shifts, are presented. Percentages are provided in lines 488-539 but this pertains to the shapes of the enhanced CKE envelopes and not the front location(s) found within the envelopes. For example, what is the standard deviation in the 8 distinct CKE half-power point values ('front latitudes') at each longitude (i.e., variability in the 'front' itself)?

RESPONSE: First, we have changed the sentence to read: "we develop a new method to study linear shifts in the position of the fronts in the Southern Ocean" to emphasize we are focusing only on shifts, not other variability. Second, we have added pertinent statistics of CKE envelope width in the results section.

Reviewer Comment: Lines 190-191
This is the most accurate statement of the study: 'we track the positions of these envelopes from 1993 until 2016 to quantify if the envelopes have shifted…'. Given that these envelopes can span more than 5 degrees latitude N-S, and that multiple (traditional) fronts can exist within one envelope, I take away that this study tracks shifts in a mean ACC position rather than individual fronts themselves, as claimed. The fact that the community is accustomed to thinking of fronts in a particular way, it is important that the author makes their definition of a 'front' as clear as possible.

RESPONSE: We stated in the revised document immediately after that statement: "This is based on the assumption that if the front and jets around the front have shifted south, then the envelope of high kinetic energy should also move by a comparable amount."

We have revised this sentence to now read: "Since kinetic energy is highest around fronts in the Southern Ocean (e.g., Thompson et al., 2010; Thompson and Richards, 2011; Chapman, 2017) , it follows that if the fronts have shifted south, then the envelope of high kinetic energy should also move by a comparable amount."

Although the first part of this revised sentence is essentially redundant with a statement two sentences earlier, we add it here to make it absolutely clear what is the basis for our analysis. I note that this assumption of the CKE shifting south is essentially the one made by proponents of the contour method (i.e., identify a front based on a contour that passes through a large dynamic topography gradient in one region, then track its shift). However, because CKE is based on gradients of SSH, it is insensitive to changes in large-scale sea level changes, unlike the contour method.

Finally, to make it clear we do not intend that this method be used to isolate specific fronts at any time, we now state:

"We do not purport that our method derives the actual position of either a front or a jet due to the relatively wide swath of enhanced kinetic energy on either side of fronts related to variability of jets. Instead, we only purport that it can indicate shifts in the frontal position, because if a front has shifted south by 100 km (for instance), then the band of enhanced kinetic energy should also shift south by a comparable amount. It is difficult to reconcile a frontal shift without a displacement of kinetic energy."

Reviewer Comment: Line 214
Describe these 'envelopes' more. I appreciate Figures 3 and 4 but this is at one specific pass in the Indian sector. How do these envelopes vary by region, etc.? What is the average meridional width/extent, etc.? What is the standard deviation in the width of the envelope at each longitude?

RESPONSE: We have added some discussion and statistics in response to this one and similar comments in Section 3 (Results and Analysis). We feel it is more relevant in this section than in the methods section. The main issue the reviewer has with the analysis appears to be concern that the width of the CKE envelope is considerably wider than the width of a single front, or that the shift in the CKE half-power point is narrower than the width of the envelope. The latter really should not be a concern. Tracking means of a distribution is a commonly utilized and robust statistical test, and we allow for appropriate uncertainty estimates that are described at the end of the Section 3. Even if an envelope is quite large, the mean (i.e., half-power point in this case) can be a robust and significant measure of its location. The envelope will definitely be wider than the width of the front, but we have addressed this in numerous previous comments and revisions, noting the envelope will exist around the fronts and not isolate a specific location of the front.

Another concern the reviewer appears to have is that the width may be greater than the distance between fronts, thus the CKE envelope may contain both fronts. This is indeed a possibility, but as we have argued, without a definitive location of a front (and climatologies differ considerably on locations), we can only use an objective measure of the approximate front location. Here, we use the envelope of enhanced CKE, without distinguishing whether this envelope is about the SAF or PF. Our argument is simply that if the fronts have moved south (which is claimed by some), then this envelope MUST also move south.

One can compare the width to the distance between fronts, and we now supply this statistics and some discussion in Section 3. However, it is not the full-width of the CKE envelope one should compare to distances between fronts, but the half-width, assuming the half-power point is in the middle of the envelope, and the "front" is also located somewhere within the envelope. Moreover, one can't compare this to the meridional distance between fronts, since the altimeter is sampling the ocean along an inclined groundtrack, leading to a longer arc of distance. One needs to compute the distance between fronts along the groundtrack. We did this, based on the Kim and Orsi climatology, since it is based on a regular gridding.

We found that the average half width of the CKE envelope was 541 km (standard deviation = 196 km), whereas the average distance between the SAF and PF along each groundtrack was 706 km, with a standard deviation of 407 km. Thus, the mean half-width of the CKE envelope was less than the mean distance between the PF and SAF, although the latter distance is more variable.

I have added two paragraphs to the Discussion in Section 3 on this:

"One may question whether the relatively wide envelopes of enhanced CKE overlap more than one front. This is a possibility, but if both fronts have moved south as some have argued (e.g., Sokolov and Rintoul, 2009b), then the CKE envelope should also shift, regardless of whether it includes one or two fronts. If the exact frontal location was known at any time, one could judge how well the CKE envelope (or half-center) point was associated with just one front. But considering the disagreement in climatologies (e.g., Figure 5) and the intrinsic variability of the front positions, this is impossible to test. One can, however, compute the distance from the CKE half-power point to the southern boundary (for those points that are nearest a climatological SAF position) and the distance with the northern boundary (for those that are nearest the PF) and compare this to the distance between the climatological positions of these fronts. Note that the distances must be computed along the groundtracks and not simply taken as the meridional distance at the longitude of the CKE half-power point.

The average distance between the half-power point and either northern or southern boundary is 541 km with a standard deviation of 196 km. The average distance between the Kim and Orsi (2014) PF and SAF along the groundtrack passes is 706 km with a standard deviation of 407 km. We used the Kim and Orsi (2014) front positions as these data were on a regular grid which made interpolation to the groundtrack positions easier and it was computed over the roughly the same time span as the CKE estimates. From these statistics, we conclude the CKE envelopes should generally only encompass either the PF or the SAF, although even if they did not, it should not preclude one from using statistics of the CKE half-power point to deduce shifts in the fronts, provided they are both shifting, as has been theorized."

Reviewer Comment: Lines 348-369
Please comment on the reasoning behind the choice to bias the methodology to the Orsi study, in particular.

RESPONSE: We do not believe that the method of initial detection "biases" the results to the Orsi front positions, as indicated by Figure 6. If we had used any other estimate, we would have found the same locations. We have added a statement at the end of the paragraph to make this clear:

"Using a lower limit, we could find more potential front positions based on CKE, but many were far from the front positions estimated by Orsi et al (1995) and other authors (e.g., Kim and Orsi, 2014; Freeman and Lovenduski, 2016a; Chapman, 2017)."

Reviewer Comment: Line 376
"The mean CKE profile pictured in Figure 3 has multiple local maxima, most likely associated with the narrow jets that surround the front." Can the author comment on how the half-power point method finds one front in this latitude band while the Orsi study finds one instance of the SACCF, two instances of the PF and one instance of the SAF (= 4 fronts) at this longitude/swath. This might suggest that the CKE method presented here can alias a front to the mean latitude of any front activity/presence (within the envelope) and not be particularly representative of a physically realistic front.

RESPONSE: The method does not find one front, it finds one envelope of enhanced CKE, as we have explicitly stated. While the Orsi study finds a strong meandering PF at this location (two crossings), other methods (e.g., Kim and Orsi; Freeman and Lovenduski) do not. The reviewer is correct that the CKE regions could envelope two fronts when they are very close to one another. However, the argument still holds that if those fronts are both shifting south (as, for example, the contour method proposes), then the CKE envelope should still shift south. We have added some discussion of this in the revised paper, following the sentence quoted in the comment:

"The mean CKE profile pictured in Figure 3 has multiple local maxima, most likely associated with variability of the narrow jets that surround the front. They may also represent two separate fronts (and frontal-related jets) that are close in space. Some frontal climatologies find the SAF and PF are separated by fewer than 100 km in the South Indian Ocean (between 30°E and 40°), the South Pacific (between 220°E and 230°E), and the South Atlantic (310°E and 330°E) (Figure 2). CKE computed in these areas may encompass energy around both fronts. However, if the fronts have both shifted south (as reported in some studies), then CKE should also shift south and so tracking CKE should observe the shifts in frontal location."

Reviewer Comment: Lines 375-386
While I appreciate the author's attempt to provide more information for this particular pass (via a modified figure to show variability and states the temporal range in number of defined maxima), this is for one distinct pass of the Indian sector. I conclude that no substantial quantitative information has been provided in the results in this iteration. Is there really no other quantitative information that the author can provide for this work? For example, mean and standard deviation in number of maxima or width of envelope, etc. One pass surely cannot represent the full Southern Ocean.

RESPONSE: This information has been added to the Results and Analysis section, where we feel they are more relevant.

Reviewer Comment: Lines 375-376, re: Figure 3
It would be helpful for clarity to add to the end of this sentence: "The mean CKE profile pictured in Figure 3 has multiple local maxima, most likely associated with variability of the narrow jets that surround the front (defined here as the location of the half-power point)."

RESPONSE: This clarification is incorrect, as it suggests that the variability of the specific fronts is indicated by the half-power point. We precisely define the half-power point later, and so adding this parenthetical would add more confusion. Since the discussion at this point is only about the envelope of CKE and the various local peaks, we feel it is misleading to bring in a discussion of the half-power point at this spot.

Reviewer Comment: Lines 377-378
I assume these percentages are pulled from the Chapman (2017) study - could the author place their work into context? - otherwise this feels out of place/unnecessary.

RESPONSE: Thanks for pointing this out. It is out of place, and this is discussed later in relation to Figure 7. We have deleted these sentences and feel the revised paragraph reads better.

Reviewer Comment: Lines 379-380
What might this suggest about the front field?

RESPONSE: This discussion is on the presence of local peaks in CKE related to the highly-variable jet field. Even in the presence of a stationary front, the jets can still be highly variable due to non-linear interactions. We have added a statement here to emphasize this:

"Note that even with a fixed and stationary front, there may be highly variable locations of peaks in CKE around the front, due to the meandering and disappearance/formation of jets (e.g., Chapman, 2017a). Thus, tracking the specific jet locations is not an optimal method of tracking frontal shifts."

Reviewer Comment: Lines 389-390
So again, this study does not find individual fronts (even if speaking in a mean sense) but a mean latitude of frontal activity (especially as these envelopes can sometimes span ~6 deg. latitude, which is much greater than the 2-3 degree standard deviation cited).

RESPONSE: Again, we do not state (nor mean to imply) we have isolated the specific front, just the general area. We have revised the last sentence to reiterate this point yet again:

"The assumption we make in doing this is that the localized maxima are associated with variable jets, but the position of the envelope of high CKE is related to the general position of the front, and that if the front has systematically shifted then the CKE envelope will have shifted as well."

Reviewer Comment: Lines 390-420
Please be clear on how the half-power point is distinct from just a sort of 'mean latitude' of the latitude band encompassing any 'ACC activity' (the full enhanced CKE envelope being the 'ACC activity' region) — and therefore the distinction between tracking actual fronts and not just a sort of 'mean ACC position' like Gille 2014 (if in fact this study is more like the latter, fine, this just needs to be clearly articulated to the reader).

RESPONSE: I have added a comment to describe the differences:

"The assumption we make in doing this is that the localized maxima are associated with variable jets, but the position of the envelope of high CKE is related to the general position of the front, and that if the front has systematically shifted then the CKE envelope will have shifted as well. Other studies have tracked the mean latitude of the integrated transport computed between dynamic height contours that are picked to represent the southern boundary and the northern boundary that encompass all the fronts in the ACC (Gille, 2014). One issue with this approach is how to uniquely determine the northern and southern boundary contours without potentially biasing the result (e.g., using a priori fixed boundaries and ignoring they might have shifted). The method we propose will determines the boundaries of the integration uniquely for each pass based solely on the level of CKE relative to the peak of the enhanced CKE envelope. Moreover, it allows for two or more distinct CKE envelopes along each pass (i.e., related to different fronts), whereas the Gille (2014) method can only compute one mean latitude for all fronts in the between the prescribed southern and northern boundaries. Thus, our method is more flexible in determining boundaries around any particular front, provided the orientation of the groundtrack is such that the majority of jets are perpendicular to it."

Reviewer Comment: page C14, paragraph 2
1. As hoped, the addition of Figures 6 and 7 have not yet alleviated my previous concerns about actual front identification. This stems from most of my other comments here on actual frontal detection vs. a mean ACC position.

RESPONSE: I hope the several additional statements (discussed previously) noting we are not detecting specific fronts, but using shifts in the CKE envelope as a proxy for detecting shifts in the fronts will alleviate these concerns.

Reviewer Comment: 2. I don't believe the addition of Figure R2 to the manuscript is necessary. As I understand it, the Chambers 'front' would then be defined as the half-power point (not plotted here but) located to the south of the other studies' fronts (between 50 and 51S; same as red dot in Figure 3)? If thinking in terms of actual named fronts, the Chambers front detection method would find an equivalent PF at this particular location, not the SAF. And when comparing to Figure 7, this appears to be the mean latitude of the colored variability area.

RESPONSE: Thanks for confirming the additional figure is not necessary. All we attempt to say is that the true front should be somewhere around the half-power point, within the envelope. The important thing is that if the front has shifted, this envelope (and half-power point) should also shift. We have stated this several times already and don't believe it is necessary to state it once again here.

Reviewer Comment: page C3, paragraph 3
Thank you for testing this. I don't think that including the one sentence you provided as a response will take up too much space in the manuscript and will only benefit transparency: 'We find that mean front positions are not sensitive to choice of x-year periods.'

RESPONSE: The following comment was added at the end of the section, noting that we focus on the shift in the half-power point, not it's specific location:

"We tested different averaging periods (ranging from 1- to 4-years), but found the estimate in overall shift of the half-power point over the 24-year period was insensitive to the choice."

Reviewer Comment: Figure 6
1. I understand that the author added Figure 6 to boost the argument for/robustness of the presented methodology (given that the mean half-power point lies near previous climatologies) but it does not necessarily confirm that the methodology is actually locating fronts at a given time. As in the first review, I still feel strongly that the text of the manuscript misrepresents/misstates what is actually being performed.

RESPONSE: We have revised the manuscript in several places to make it clear we are not trying to detect exact locations of fronts with the method, merely identifying envelopes and tracking how they have shifted. Showing the mean-half power points along with front climatologies indicates the locations are reasonably near those estimates (and often between two different estimates) giving confidence the estimates are detecting regions of high CKE related to jets around fronts, not wind-driven mesoscale eddies.

This is discussed in the manuscript shortly after the comment:

"The comparison between CKE half-power points and front climatolgies is reassuring that the method developed in Section 2 is successfully detecting regions of high energy related to jets around fronts. Since the movement of jet positions has been used to estimate movement of the fronts (e.g., Chapman, 2017a), a comparable calculation with positions of high CKE seems reasonable."

Reviewer Comment: 2. It is very difficult to decipher individual fronts within the same color grouping (particularly the orange and blue groupings), font sizes are too small throughout, and the overall quality/resolution of the figure is low.

RESPONSE: I apologize for this. The original figure resolution is > 500 dpi, but it was reduced in the PDF creation. I have increased fonts for this figure and made some changes to the colors and line types to hopefully alleviate this problem.

Reviewer Comment: 3. Since the author claims that envelopes are being tracked, doesn't this suggest that some sort of envelope should also be indicated around your mean CKE dots as well? Single dots hide the fact that there is a known width (meridional extent N-S where CKE exceeds 200 units) that is unique to each location and time step (e.g., something like the spread in the colors plotted in Figure 7). It would help quantitatively to provide either a mean or standard deviation in the N-S width of the envelopes surrounding the mean CKE latitudes. And then going further, any detected shifts could be interpreted in light of this underlying/inherent envelope width.

RESPONSE: I created a version of the figure with the envelopes, but it made an already complicated figure even more problematic. Instead, I discuss the sizes of the envelopes relative to the approximate distance between fronts in Section 3, as discussed in a previous response.

Reviewer Comment: 4. Please comment on the result that most of the CKE method findings would appear to be the SAF, as revealed in Figure 6. I know I asked this previously but this same line of thought came up again this round. And I honestly don't know what to make of the author's response on page C15, second to last P. If anything, this confirms that this study is detecting an ACC feature but with no information on which feature unless you relate/compare to previous studies/climatologies.

RESPONSE: We have added a comment about this before discussing Figure 7.

"The majority of the estimated half-power points follow the SAF. This is most likely due to the front (and jets) moving perpendicular to the groundtracks along this front. This method will tend to only detect high CKE when the front is moving from northwest-to-southeast for an ascending pass, and from southwest-to-northeast for a descending pass. This method also only works in regions where the front is associated with highly variable jets, which does not occur at every longitude along the front (e.g., Chapman, 2017a)."

Reviewer Comment: Figure 7

Very difficult to decipher colored dots; perhaps make this a 4-panel figure with x-y plots allowing for zooming in on the frontal area (e.g., limiting the latitude range of each)?

RESPONSE: I do not understand your idea about changing the figures. I tried to make this approximately the same latitude range as Figure 6 for easy comparison. I have made the back dots indicating the half-power point larger.

Reviewer Comment: Line 546
I disagree with the implication/tone of this sentence. The fact that the various studies' climatologies don't lie on top of one another is not that the calculations that went into finding the fronts are uncertain, but is a result of different methodologies used, which includes different time periods and different data sets. Each front analysis should be treated and interpreted based on its own methodology. A caveat is different from an uncertainty.

RESPONSE: The level of disagreement between different estimates is one measure of uncertainty. Such a calculation is often done to quantify uncertainty in different climate models, for instance. If all methods found the same location, one would have a greater confidence in the ability to detect fronts in the Southern Ocean.

However, we have tried to change the tone by revising the paragraph:

"It is important to note the large differences in estimates for the same front, which indicates how difficult it is to determine fronts in a highly variable current system like the ACC. For instance, in the Indian Ocean at 50°E, Freeman and Lovenduski (2016a) find the PF at the same location that Orsi et al. (1995) found the SAF, while Kim and Orsi (2014) find it significantly farther south. The SAF determination using the contour method (Kim and Orsi, 2014) is substantially farther north than the one determined from hydrographic data (Orsi et al., 1995) at most longitudes. These differences are likely due to differences in the time-span, differences in methodologies, and uncertainty in the data utilized. All lead to a level of uncertainty in the determination of a specific front at any time."

Reviewer Comment: Line 547
Please replace the period with a colon (prior to 'For instance,…') to make clear that the author is discussing the spread in the various estimates across the different studies.

RESPONSE: This was not done. As revised, that would lead to a very long sentence. We prefer breaking into two sentences.

Reviewer Comment: Lines 552-553
This sentence is muddy. Does the author mean, "Many front location estimates, defined as the half-power points of enhanced CKE, are found within the spread of the PF or SAF across multiple studies." ?

RESPONSE: The sentence has been revised to:

"The half-power points of enhanced CKE generally occur near or between the fronts estimated by different methods (i.e., the three different PF estimates), indicating they are at least within the uncertainty bounds of frontal detection by other methods."

Reviewer Comment: Lines 554-557

I'm not sure this comparison is fair and appropriate. This study has not claimed to find the PF in particular, and in fact, most half-power points seem to lie along the SAF (as determined by using previous climatologies to compare qualitatively); we have not been provided any information on the standard deviation of the SAF. As a reader, I feel misguided here.

RESPONSE: I was using the one published estimate of variability of a front as a proxy for variability of others. I have made this more clear in the revision by adding:

"Some values are at locations either north or south of the other front estimates by as much as 3°, but it should be noted that the standard deviation of the PF estimated by Freeman and Lovenduski (2016a,b) averages 2-3°. Using PF variability statistic an indicator of variability of all fronts, one can conclude the location CKE half-power points are well within the level of expected frontal variability and so not statistically too distant from a front location."

Reviewer Comment: Line 558
'Probably a better method…' ??? The author presents the methodology but then states that a different method presented by another study (in this case, Chapman, 2017) is superior. Please address.

RESPONSE: I meant for detecting a mean front position, which this study does not attempt to do. However, to avoid confusion, I have changed the beginning to:

"Another method for determining frontal position is to examine the probability of jets occurring."

Reviewer Comment: Lines 565-567
Since this is the only discrepancy that the author points out, it warrants further discussion. Please comment. Personally, I'm curious whether this is an artifact of the half power-point methodology - it is curious that the half-power point is found between two regions to the north and south where Chapman would 'probably' find a feature (colored in this figure) and likely matches the north and south bounds of an 'envelope' identified by the author. Has the author isolated this particular region/swath and looked at the features of this envelope (like Figure 3)? Is the half-power point aliasing the front between two major peaks here?

RESPONSE: Although I do not feel discussing two points out of 150 is relevant, I have looked at this and provide a short commentary in the revised paper. First, one has to remember the groundtrack swath is not directly south-to-north, but more northwest-to-southeast (**Figure R1**). Thus, we should compare those values of the Chapman database.

Second, in these two regions, Chapman only finds a jet less than 10% of the time. If one looks at the mean CKE envelopes (**Figure R2**), Chapman finds jets on the northern side of the envelope only, and not in the center (where the half-power point is by definition) and not where the CKE has a peak. We can't explain why Chapman finds jets south of the peak CKE, as the CKE is quite low there. This could be due to either the orientation of the groundtrack with the jets, a problem in the gridded data Chapman used, or an error in Chapman's method. Confirming which is beyond the scope of this paper, especially since it only occurs with approximately 1% of the comparisons.

Based on these figures we conclude there is no aliasing of CKE half-power point between two peaks of enhanced CKE. The method works exactly as intended, finding a value in the area of highest CKE.

Our brief statement on this is:

"However, it should be noted that Chapman finds jets in the two areas north and south of these two CKE half-power points less than 10% of the time and that the northern cluster lies on the northern edge of the enhanced CKE envelope. Although the half-power points are slightly south of this along these two passes, this is due to high CKE (in excess of 200 $cm^2 s^{-2}$) down to 58°S, where Chapman (2017a) detects few jets. It is unclear why Chapman (2017a) detects few jets in this region of high CKE, but it should be noted that this represents only 1% of the samples compared."

We feel this should be sufficient to answer the reviewer's concerns without adding the figures or a longer discussion.

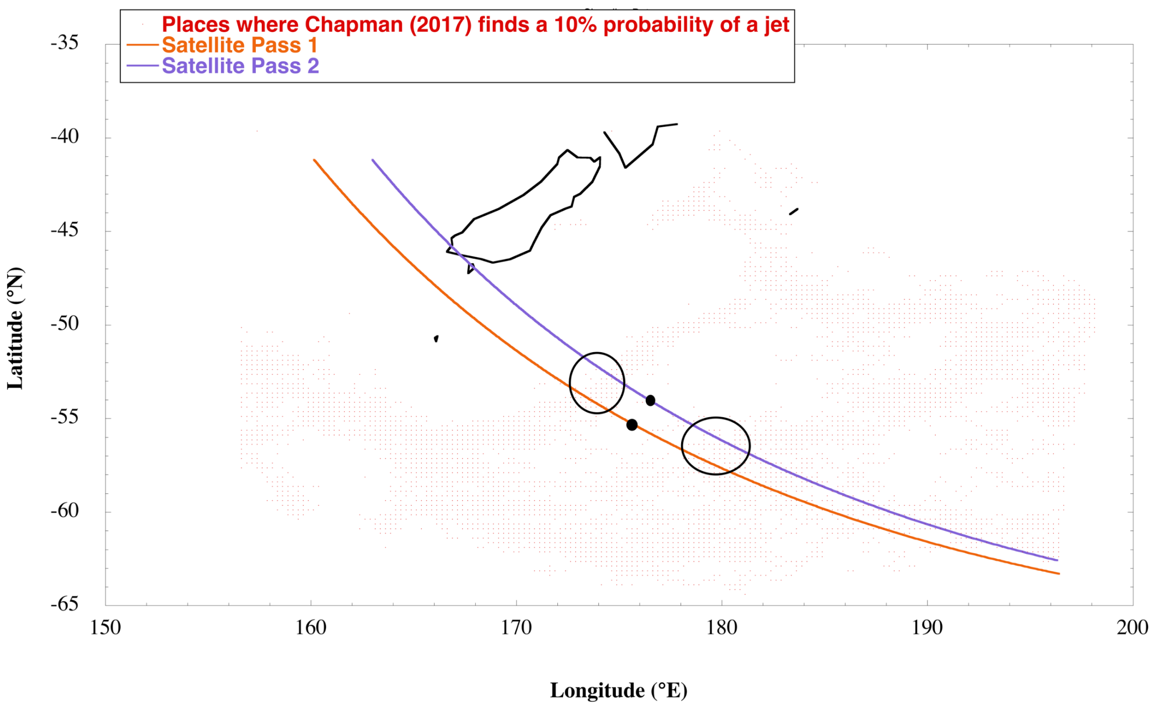

Figure R1. Groundtrack of two passes where CKE half-point does not align with probability of a jet in the Chapman database (red dots in Figure). The Black circles indicate regions where there are a relatively large number of jet locations, while the solid black dots indicate where the mean CKE half-power point was found.

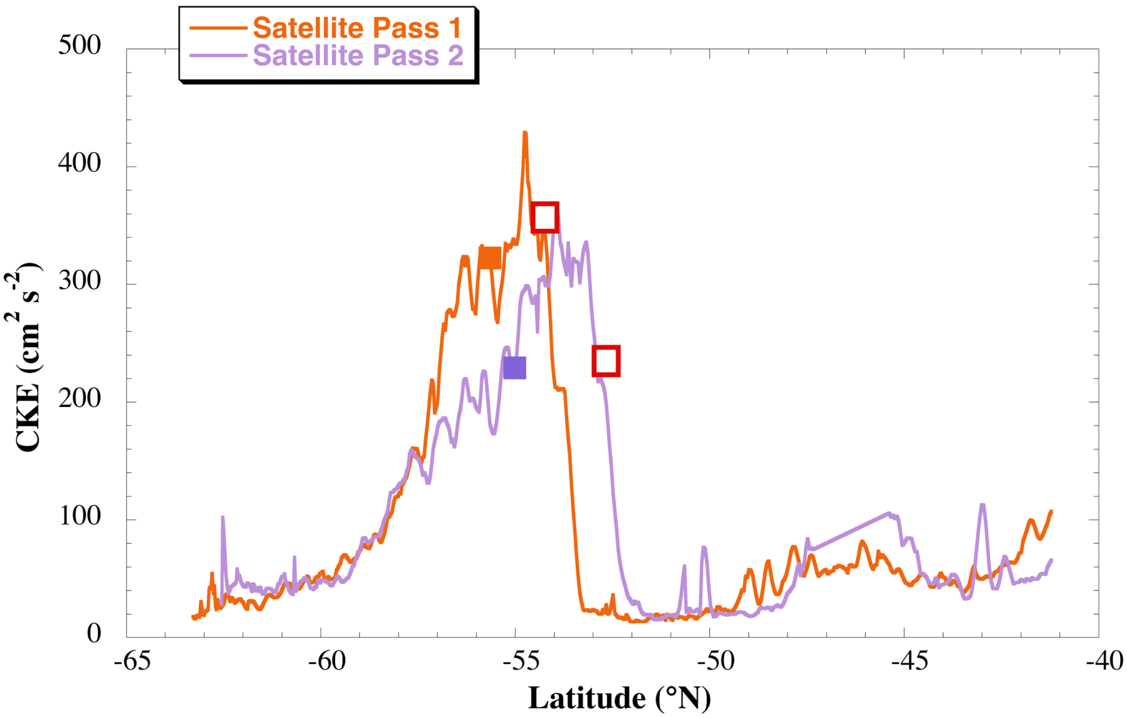

Figure R2. Mean CKE along the two passes shown in Figure R1, along with the CKE half-power point (solid squares) and the mid-point of the northern Chapman jets (open squares).

Reviewer Comment: Lines 568-571
Please update/remove casual/informal language like 'the good comparison' here.

RESPONSE: This was changed to:

"The comparison between CKE half-power points and front climatolgies is reassuring…."

Reviewer Comment: Lines 635-636
I'm not sure this claim can be made. The author makes no distinction between the PF and SAF throughout the manuscript but here, focuses on shifts in this study's SAF specifically. Please address.

RESPONSE: The reviewer has mentioned several times in this second review that the CKE half-power points cluster around the SAF and has specifically asked us to comment on this: "*…and in fact, most half-power points seem to lie along the SAF" and "Please comment on the result that most of the CKE method findings would appear to be the SAF"*. The results being discussed here (from Kim and Orsi) only examined the SAF. Since our estimates cluster around the SAF in the same region Kim and Orsi discussed, we feel it is fair to comment on the similarities and differences.

We have, however, modified the sentence slightly to read:

“We also find some locations in this region, where the CKE half-power points cluster around the SAF, also have a significant northward shift.”

Reviewer Comment: Figure 8
This study tracks the half-power points of the envelope of enhanced CKE. Therefore, they inherently have an underlying width. If we had information on the width of the CKE envelopes (i.e., ACC activity), we might also be able to confirm whether these shifts are significant given the widths (i.e., does the confidence interval associated with the change in the single point exceed the width and variability of the underlying envelope?). I guess that follows from whether the author could provide a sort of error statistic that relates the half-power point to the associated width of each envelope.

RESPONSE: The comparison of the width of the envelope to movement of the half-power point is a meaningless statistic in this case – the width will ALWAYS be significantly larger the movement of the half-power point. Examining shifts in the mean of a distribution (i.e., the half-power point in this case) is a perfectly valid and widely accepted statistic. The uncertainty is then computed based on the standard error in the determination of the mean or the variability of the mean. Only in rare cases is the standard error in the mean determination larger than the intrinsic variability. In this case, the standard error in the determination of the half-power point is of the order of 10 km, based on the sampling of the data and the failure to find a point where the integrals exactly match. Yet the standard deviation of the half-power points around the mean and the fit are much greater than this, so they drive the uncertainty in the estimated trend.

All of this is accounted for in the uncertainty bars and is described fully at the end of Section 3.

Thus, we will not add the requested statistics here in the conclusions, as they are not relevant.

Using kinetic energy measurements from altimetry to detect shifts in the positions of fronts in the Southern Ocean

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Abstract. A novel analysis is performed utilizing cross-track kinetic energy (CKE) computed from along-track sea surface height anomalies. The mid-point of enhanced kinetic energy averaged over three-year periods from 1993 to 2016 is determined across the Southern Ocean and examined to detect shifts in frontal positions, based on previous observations that kinetic energy is high around fonts in the Antarctic Circumpolar Current system due to jet instabilities. It is demonstrated that although the CKE does not represent the full eddy kinetic energy (computed from crossovers), the shape of the enhanced regions along groundtracks is the same, and CKE has a much finer spatial sampling of 6.9 km. Results indicate no significant shift in the front positions across the Southern Ocean, on average, although there are some localized, large movements. This is consistent with other studies utilizing sea surface temperature gradients, the latitude of mean transport, and probability of jet occurrence, but is inconsistent with studies utilizing the movement of contours of dynamic topography.

1. INTRODUCTION

There is as much we don't know about the circulation of the Southern Ocean as we do. Although the current system is routinely called the Antarctic Circumpolar Current (ACC), it consists of several fronts with distinct water properties to the north and south of the fronts (Nowlin and Clifford, 1982; Orsi et al., 1995; Belkin and Gordon, 1996). The most significant of these fronts, responsible for the majority of the ACC volume transport (e.g., Cunningham et al., 2003), are the Subantarctic Front (SAF) and the Polar Front (PF). However, even this is not a realistic picture of the circulation in the Southern Ocean, since at any specific time, there can be from three to ten narrow jets around the fronts that are highly variable in strength and location, masking the specific frontal boundary (Sokolov and Rintoul, 2007, 2009a, 2009b; Sallee et al., 2008; Thompson et al., 2010; Thompson and Richards, 2011; Langlais et al., 2011; Graham et al., 2012; Chapman, 2014; Gille, 2014; Kim and Orsi, 2014; Shao et al., 2015; Chapman, 2017a). Although positions of fronts have been estimated throughout the Southern Ocean, primarily using gradients of subsurface density measured from hydrographic sections (Orsi et al., 1995), contours of dynamic topography (Sokolov and Rintoul 2007, 2009a, 2009b; Langlais et al., 2011), or a combination Kim and Orsi (2014), in many places there are no strong currents that can be measured near the front position (Chapman, 2014; 2017a).

Because of the highly variable nature of jets and the lack of clear observational detection of fronts in some areas, the literature has become muddled over the difference between a front and a jet, primarily because the "front" is rarely observed at any specific time due to the high-variability of jets (Thompson et al., 2010; Thompson and Richards, 2011; Chapman 2014; 2017a). However, even in the presence of highly variable jets, methods have been developed to determine mean fronts positions in a probabilistic sense. Thompson et al. (2010) demonstrated one could define fronts in the Southern Ocean by computing probability density functions of potential vorticity in an eddy-resolving general ocean circulation model. Chapman (2014, 2017a) later showed this could also be done using localized gradients in dynamic topography (i.e., high geostrophic velocity) using satellite altimeter observations, but again, only as statistical probability. This is because these areas of enhanced gradients and velocity are more reflective of jets, which strengthen and die, appear and disappear, bifurcate and join back together. Because of this, they can only be detected on average 10-15% of the time. However, Chapman (2014, 2017a) has demonstrated that, at least in a mean sense, fronts defined by mean dynamic topography contours (commonly known as the "contour method") do lie within the probability distribution inferred from "gradient" methods.

An open question is how the fronts and jets that comprise the ACC will respond in a warming climate. Analysis of climate models (which cannot simulate jets in the Southern Ocean) suggests that as the atmosphere warms, the winds that drive the fronts and jets of the ACC will migrate south (e.g., Fyfe and Saenko, 2006; Swart and Fyfe, 2012). It should be noted, however, that the mean position of the southern hemisphere westerlies in the models lies significantly equatorward of the true position (e.g., Figure 2 in Fyfe and Saenko, 2006). Thus, it is not entirely clear whether the model is predicting a true shift in the wind position, or whether the model has not yet reached equilibrium with winds in the proper location.

Still, based on these model results, researchers have been testing the hypothesis that as winds in the Southern Ocean shift south, the frontal positions and jets will also migrate south. So far, the results are mixed. Using the contour method and tracking how the dynamic topography contours associated with a front position shift in time, Sokolov and Rintoul (2009b) found that the SAF and PF had both moved south by approximately 60 km over 15 years between 1993 and

2008. Kim and Orsi (2014) recently updated this analysis and found that while the average frontal position across the Southern Ocean indicates a strong southward shift, this is due primarily to substantial shifts only in the Indian Ocean sector. They found no significant shifts throughout the Pacific or Atlantic Ocean sectors using the contour method.

The primary assumption of these analyses is that if a contour of dynamic topography shifts south, it is uniquely caused by a front moving south. This is not necessarily true. Gille (2014) recently demonstrated that all contours in the Southern Ocean have shifted south on average, and that this follows from the observed rise in sea level – as the sea surface height rises, the contours will appear to shift south. While this breaks down at the far south and north of the ACC where dynamic topography gradients are small, these areas are far away from the PF and SAF and so have not been considered in previous analyses. Gille (2014) used a different measure to determine the position of the ACC fronts, based on the latitude of the mean surface transport of the ACC measured by altimetry, which is in essence a mean location of all the jets in the Southern Ocean. She found no significant shift on average, but considerable interannual variability, especially regionally.

Another factor other than sea level rise can cause the dynamic topography contour to shift south -- if the magnitude and width of the jet has changed. This is demonstrated in **Figure 1**, where we show the mean dynamic topography from two jet scenarios: 1) where the peak of two Gaussian shaped jets have shifted south, and 2) where the peak has not shifted, but the magnitude has decreased, the width has broadened, and the shape has become slightly skewed. Although the resulting topography profiles are not identical, they are similar, and both suggest a southward movement of dynamic topography contours.

Researchers using other methods also find little or no southern migration of the fronts or jets in the Southern Ocean as a whole. Graham et al. (2012) used a high-resolution model to show that the Polar Front and Subantarctic Front are constrained by bathymetry, even in increasing and shifting winds. Shao et al. (2015) utilized the skewness of sea level anomalies to identify front positions, and found no southward motion, but did find changes in the east Pacific correlated with the Southern Annual Mode. Chapman (2017a), using positions of fronts determined from the probability of jet locations, also found no significant southward movement, but high interannual variability. Finally, Freeman and Lovenduski (2016a) used weekly estimates of the Polar Front position determined from satellite sea surface temperature (SST) gradients to show no significant southward shift between 2002 and 2014 on average, except in the Indian Ocean. They also found a statistically significant northward shift of the PF in part of the south Pacific.

Thus, recent studies all agree that the Subantarctic Front and Polar Front have not shifted south, even though there is evidence the winds have shifted south in the austral summer months (Swart and Fyfe, 2012). It should be noted that when averaged over the full calendar year, however, there has been no significant shift in the wind position (Swart and Fyfe, 2012).

In this paper, we develop a new method to study linear shifts in the position of the fronts in the Southern Ocean, based on tracking the location of envelopes of kinetic energy measured by satellite altimetry. It is known from modeling studies that the front positions are associated with increased kinetic energy, due to instabilities in the jets and interactions with bathymetry (Thompson et al., 2010; Thompson and Richards, 2011). After demonstrating that kinetic energy computed from along-track satellite altimetry forms relatively wide envelopes of enhanced energy that occur within the probability range of jets and fronts (e.g., Chapman, 2017a), we track the positions of these envelopes from 1993 until 2016 to quantify if the envelopes have shifted

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south by a statistically significant amount. Since kinetic energy is highest around fronts in the Southern Ocean (e.g., Thompson et al., 2010; Thompson and Richards, 2011; Chapman, 2017) it follows that if the fronts have shifted south, then the envelope of high kinetic energy should also move by a comparable amount. We do not purport that our method derives the actual position of either a front or a jet due to the relatively wide swath of enhanced kinetic energy on either side of fronts related to variability of jets. Instead, we only purport that it can indicate shifts in the frontal position, because if a front has shifted south by 100 km (for instance), then the band of enhanced kinetic energy should also shift south by a comparable amount. It is difficult to reconcile a frontal shift without a displacement of kinetic energy.

Since the kinetic energy calculation is based on estimating gradients of sea level anomalies, this approach is similar to other gradient methods for detecting fronts or jets (e.g., Chapman, 2014; 2017a; Gille, 2014; Freeman and Lovenduski, 2016a). It differs from these approaches, however, in that instead of determining individual gradients and tracking these over time, it looks for regions of high gradients (i.e., high energy) surround by regions of low gradient (i.e., low energy). This allows us to detect envelopes for every time-period considered, instead of only a fraction of the time, allowing for better tracking of the change over time.

Section 2 will describe the data and methods used, while section 3 will present results, including evaluation of the method for detecting mean positions of fronts and for tracking their change over time. Section 4 will discuss the results in the context of previous studies and evaluate the usefulness of the method.

2. DATA AND METHODS

We utilize geostrophic surface current anomalies computed from the 24-year record of 1-Hz sea surface height (SSH) data along the TOPEX/Poseidon (T/P) groundtrack in the Southern

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Ocean (**Figure 2**). The altimetry data used are from four separate altimeter missions: TOPEX/Poseidon (January 1993 – January 2002), Jason-1 (February 2002 – July 2008), Jason-2 (August 2008 – August 2016), and Jason-3 (August 2016 – December 2016). Because the official TOPEX/Poseidon (T/P) geophysical data records (GDRs) have not been updated since the late 1990s, we utilize the corrected data products from the Integrated Multi-Mission Ocean Altimeter Data for Climate Research provided by Beckley et al. (2010) at the NASA PO.DAAC site (https://podaac.jpl.nasa.gov/Integrated_Multi-Mission_Ocean_AltimeterData). Jason-1 data are from the GDR-C version and were downloaded from the NASA PO.DAAC site in June 2010. Jason-2 are from the GDR-D version and were downloaded from NOAA NODC (ftp://ftp.nodc.noaa.gov/pub/data.nodc/jason2) between August 2012 and June 2016. Jason-3 are also from the GDR-D version and were downloaded from NOAA NODC (ftp://ftp.nodc.noaa.gov/pub/data.nodc/jason3) on August 7 and 8, 2017.

We utilize the 1-Hz along-track SSH data from the four altimeters and compute sea level anomalies by interpolating the DTU10 mean sea surface model (Andersen and Knudsen, 2009; http://www.space.dtu.dk/english/Research/Scientific_data_and_models/downloaddata) to the SSH location using bilinear interpolation. The DTU10 mean sea surface model is based on SSH from multiple altimeters averaged over 17 years in a rigorous and consistent manner (Andersen and Knudsen, 2009). T/P, Jason-1, and Jason-2 data were all included. All recommended geophysical and surface corrections (e.g., water vapor, ionosphere, sea state bias, ocean tides, inverted barometer, etc) have been applied, to correct for biases introduced by atmospheric signal refraction and sea state effects (e.g., Chelton et al., 2001).

We utilize this record rather than the gridded products based on mapping SSH from multiple altimeters (e.g., Ducet et al., 2000; Pujol et al., 2016), because the along-track data have a finer resolution in space (6.9 km along the groundtrack) and we recently demonstrated that the mapped altimetry data underestimated eddy kinetic energy (EKE) throughout the Southern Ocean compared to using along-track data by as much as 60-70% (Hogg et al., 2015). While the along-track sea level anomalies are filtered to reduce noise and thus may attenuate some signal, the filtering used (described later in this section), is less than that used for the mapped data, which uses observations from as long as 20 days and 200 km away to influence the mapped value. By filtering only alongtrack data, the time differences are small (a few minutes at most), and the spatial influence is less than 100 km. Tests with unfiltered data accounting for estimated random noise in the sea level anomaly data suggests attenuation of kinetic energy is minimal with this approach and, more importantly, that the shape of the kinetic energy envelope does not significantly change.

One can only compute EKE from alongtrack data at crossover points, where the ascending and descending groundtracks cross (Figure 2). Knowing the groundtrack angle with the north meridian (θ) one can compute the zonal ($d\eta/dy$) and meridional gradients ($d\eta/dx$) of SSHA directly from the gradients of SSHA for the ascending pass ($d\eta/dr_{asc}$) and descending pass ($d\eta/dr_{des}$) using simple geometry (Parke et al., 1987)

$$\frac{d\eta}{dy} = \frac{\left[\frac{d\eta}{dr_{asc}} - \frac{d\eta}{dr_{des}}\right]}{2\sin\theta}, \quad \frac{d\eta}{dx} = \frac{\left[\frac{d\eta}{dr_{asc}} + \frac{d\eta}{dr_{des}}\right]}{2\cos\theta}, \qquad (1)$$

noting that this formulation assumes the gradients represent the derivative of the northern SSHA relative to the southern SSHA (for both the ascending and descending passes). Once this is computed, the velocities can be computed directly from the zonal and meridional gradients:

$$u = -\frac{g}{f}\frac{d\eta}{dy},\ v = \frac{g}{f}\frac{d\eta}{dx}, \quad (2)$$

where g is the acceleration due to gravity, and f is the Coriolis parameter

This formulation assumes that the velocity field has not changed significantly between the times the two passes fly over the crossover point. At high latitudes, the majority of crossovers (> 78%) have a time separation of less than 3 days. At 40°, the average propagation speed of an eddy is about 3 cm s^{-1} [Chelton et al., 2007], meaning the eddy would have only been displaced by 8 km at most over this period. At higher latitudes, this is even less. Considering the diameter of eddies at these latitudes are of order 100 km [Chelton et al., 2007], the movement is not large enough to cause a significant change in velocity at the point. The primary problem with velocities computed from crossovers is the smaller number compared to using gridded data, or the time-varying, anomalous geostrophic current normal to the groundtrack (u_T). This can be computed directly from the derivative of the SSH anomaly (η) along the ground-track distance (dr) from

$$u_T = -\frac{g}{f}\frac{d\eta}{dr}. \quad (3)$$

This cross-track current is a projection of both the zonal (u) and meridional (v) components of the full anomalous velocity field. However, neither u nor v can be determined unambiguously from u_T.. Here, we merely examine the variability of u_T without making any assumptions concerning how it may be related to the full velocity, or u and v.

Because derivatives of SSHA (Equations 1 and 3) have to be computed numerically (here, center-differences are used) and η contains significant noise at the 1 Hz sampling-rate of the altimeters, we optimally interpolate η along-track using a model of the covariance of the signal and error. We used the method of Wunsch (2006, Chapter 3) and a covariance function modeled as a Gaussian with a roll-off of 98 km and random noise of 2 cm, which was determined from the autocovariance of all TOPEX/Poseidon, Jason-1, and Jason-2 SSHA data from 1993-2015 between 40°S and 65°S.

Once $u_T(t)$ was computed at each 1-sec bin along the groundtracks in Figure 2 for each 10-day repeat cycle, the cross-track kinetic energy (CKE) was computed as $\mathrm{CKE}(x,t) = 0.5\, u_T(x,t)^2$, where x here is used to denote a generic 1-sec bin along the ground track. We also computed the full EKE at the more limited crossover points as $\mathrm{EKE}(x,t) = 0.5(u(x,t)^2 + v(x,t)^2)$.

The CKE values were averaged over the entire 24-year record and examined for each groundtrack segment (both ascending and descending) to judge where CKE was exceptionally high (Figure 3). We also computed CKE using the raw values of η with no optimal interpolation and compared to that computed with optimal interpolation. The locations of high CKE were the same, although values were significantly higher with the unsmoothed data. The quiescent regions of the ocean also showed considerably more noise, making it more difficult to determine boundaries of elevated CKE. For this reason, the values determined from the optimally interpolated data were used.

Several criteria were utilized to quantify where the high CKE values were considered to be associated with fronts. First, we constrained the southern boundary to be 5° south of the Orsi et al. (1995) values of the PF and the northern boundary to be 5° north of the SAF. Secondly, we used a lower-limit for CKE of 200 $cm^2\, s^{-2}$ for detection and tested that the width of the envelope of high CKE above the lower-limit was at least 100 km. The requirement that the envelope be greater than 100 km was done to reduce the impact of eddies in an otherwise quiescent region, since the diameter of eddies in the Southern Ocean is about 100 km. The CKE lower-limit was determined via iteration with different limits. For each case, the average center of the CKE envelope averaged over 24-years (based on the mean of the first and last points to exceed the lower-limit) was computed and compared visually to the Orsi et al. (1995) front positions. 200 $cm^2\ s^{-2}$ was selected because there were a significant amount of CKE envelope centers clustered around the Orsi et al. (1995) fronts and the envelopes were found for every 10-day repeat cycle. Using a higher limit resulted in fewer detections, especially when smaller time-averages were used. Using a lower limit, we could find more potential front positions based on CKE, but many were far from the front positions estimated by Orsi et al (1995) and other authors (e.g., Kim and Orsi, 2014; Freeman and Lovenduski, 2016a; Chapman, 2017).

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An example of a detected high CKE envelope is shown in Figure 3, based on the average of CKE between 1993 and 2015 computed from T/P-Jason satellite pass 207 in the south Indian Ocean. This pass starts at 64.3°S near the prime meridian and extends to 41.2°S and 41°E longitude. There is clearly a wide envelope of enhanced CKE greater than 200 $cm^2\ s^{-2}$ between 55°S and 47°S.

The mean CKE profile pictured in Figure 3 has multiple local maxima, most likely associated with variability of the narrow jets that surround the front. They may also represent two separate fronts (and frontal-related jets) that are close in space. Some frontal climatologies find the SAF and PF are separated by fewer than 100 km in the South Indian Ocean (between 30°E and 40°), the South Pacific (between 220°E and 230°E), and the South Atlantic (310°E and 330°E) (Figure 2). CKE computed in these areas may encompass energy around both fronts. However, if the fronts have both shifted south (as reported in some studies), then CKE should also shift south and so tracking CKE should observe the shifts in frontal location.

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Figure 4 shows the behavior of CKE along this pass for different 3-year periods. Note that the number of clearly defined maxima ranges from a low of 4 for the 2014-2016 average to 9 in 1993-1995. Note that even with a fixed and stationary front, there may be highly variable locations of peaks in CKE around the front, due to the meandering and disappearance/formation of jets (e.g., Chapman, 2017a). Thus, tracking the specific jet locations is not an optimal method of tracking frontal shifts. While other studies have estimated positions of these maxima in SSHA gradients on daily intervals (e.g., Chapman, 2017a), one does not obtain a consistent number of maxima each time, making the determination of shifts difficult. Moreover, note that although there are two general peaks in CKE in the long-term mean profile, the minimum between them is still higher than 200 cm^2 s^{-2}. A minimum is also not well defined in several of the shorter averaging periods (for example, 2008-2010).

Thus, instead of attempting to track all the maxima of CKE individually – analogous to tracking steepest gradients, as in Thompson et al. (2010), Graham et al. (2012), or Chapman (2017a) – we track an estimate of the center of the envelope of enhanced CKE, as it exists in all averaging periods. The assumption we make in doing this is that the localized maxima are associated with variable jets, but the position of the envelope of high CKE is related to the general position of the front, and that if the front has systematically shifted then the CKE envelope will have shifted as well. Other studies have tracked the mean latitude of the integrated transport computed between dynamic height contours that are picked to represent the southern boundary and the northern boundary that encompass all the fronts in the ACC (Gille, 2014). One issue with this approach is how to uniquely determine the northern and southern boundary contours without potentially biasing the result (e.g., using a priori fixed boundaries and ignoring they might have shifted). The method we propose will determines the boundaries of the integration uniquely for each pass based solely on the level of CKE relative to the peak of the

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enhanced CKE envelope. Moreover, it allows for two or more distinct CKE envelopes along each pass (i.e., related to different fronts), whereas the Gille (2014) method can only compute one mean latitude for all fronts in the between the prescribed southern and northern boundaries. Thus, our method is more flexible in determining boundaries around any particular front, provided the orientation of the groundtrack is such that the majority of jets are perpendicular to it.

There are many different ways to compute a "center" of the envelope, ranging from the average of the two end points, to a centroid calculation, to computing the point where the integral of CKE over distance is balanced on both sides, which we call the "half-power point." We have selected the latter to use, as it defines a "center" closer to the peak of CKE in the envelope. This is advantageous when the CKE curve is slightly skewed, with less magnitude on one side and more on the other. Assuming that the variability (and hence CKE) would be highest near the front (i.e., what is assumed in studies using the gradient method), finding a center of the envelope that is biased toward peak CKE is a reasonable approach.

The half-power point (x_{mid}) is computed so that

$$\int_{x_{south}}^{x_{mid}} CKE(x)\,dx = \frac{1}{2}\int_{x_{south}}^{x_{north}} CKE(x)\,dx\,, \tag{4}$$

where x_{south} and x_{north} are computed by first finding the maximum of CKE in the envelope above 200 $cm^2\ s^{-2}$, then finding the first value to the north just below 25% of that peak along with the similar value to the south (shown in Figure 3). Values other than 25% of the peak were tested. Using value greater than this, up to 50%, resulted in no significant difference in the half-power point. Using values smaller resulted in some boundaries not being defined. Thus, 25% of peak CKE was considered reasonable. If multiple regions of enhanced CKE were found along the same track, this process was carried out for each of them. This was done for all the 24-year mean CKE profiles to establish the mean locations of the fronts between 1993 and 2016.

A similar procedure was done for CKE averaged over discrete 3-year intervals, starting in January 1993 and ending in December 2016. A 3-year average was used to reduce the influence of individual eddies on determining the envelope, and to reduce interannual variations in the front position, which have been observed in other studies at some locations (e.g., Kim and Orsi, 2014; Shao et al., 2015). In particular, Kim and Orsi (2014) and Shao et al. (2015) found significant correlation with the Southern Annular Mode, which has a quasi-biennial oscillation (Hibbert et al., 2010). By averaging over three years, we found 8 distinct, statistically uncorrelated samples of CKE for each groundtrack from which to deduce shifts in the half-power point. We tested different averaging periods (ranging from 1- to 4-years), but found the estimate in overall shift of the half-power point over the 24-year period was insensitive to the choice.

3. RESULTS AND ANALYSIS

The first thing tested was how well CKE represented the full EKE. If CKE does not have the same general shape as EKE, then using it as a proxy for EKE to determine high energy envelopes is not valid. After finding satellite passes with high CKE as discussed in Section 2, EKE was computed along the same pass, using the crossover method (Equations 1 and 2).

Although CKE is lower than EKE along all groundtracks (see Figure 5 for examples), the pattern of KE rise then fall is virtually identical. CKE, however, has the benefit of higher and more regular sampling. Thus, we conclude CKE is a reasonable proxy for locating front positions even though it may not be useful for quantifying the full energy of the anomalous currents.

Four general types of enhanced CKE were found (Figures 4 and 5). In most regions, the envelope in CKE is more or less symmetrical (52% of cases). Only a few profiles have two distinct regions of enhanced CKE that were identified, with a clearly defined minimum below 200 cm^2 s^{-2} between them in all time periods (3% of cases). 20% of the passes have multiple peaks that vary in time but have no consistent minimum between the peaks (i e., Figure 4), while 25% have a skewed envelope (Figure 5), with a long rise in CKE followed by a sharp drop-off. In all cases, though, the shape of the CKE envelope closely follows that of EKE, although the amplitude was attenuated, by anywhere from 25-50%. Having closer samples of CKE, however, allows for a better computation of the half-power point and possible shifts.

Figure 6 shows the locations of the half-power points determined from the mean CKE profiles, along with estimate of the front position based on different methods: density gradients from historical hydrographic sections (Orsi et al., 1995), dynamic topography contours (Kim and Orsi, 2014), and the gradient of sea surface temperature (Freeman and Lovenduski, 2016a). There are two estimates of the SAF and SACCF, and three of the PF. One of the PF estimates (from Freeman and Lovenduski, 2016a) includes the standard deviation of the daily estimates.

It is important to note the large differences in estimates for the same front, which indicates how difficult it is to determine fronts in a highly variable current system like the ACC. For instance, in the Indian Ocean at 50°E, Freeman and Lovenduski (2016a) find the PF at the same location that Orsi et al. (1995) found the SAF, while Kim and Orsi (2014) find it significantly farther south. The SAF determination using the contour method (Kim and Orsi, 2014) is substantially farther north than the one determined from hydrographic data (Orsi et al., 1995) at most longitudes. These differences are likely due to differences in the time-span, differences in

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methodologies, and uncertainty in the data utilized. All lead to a level of uncertainty in the determination of a specific front at any time.

The half-power points of enhanced CKE generally occur near or between the fronts estimated by different methods (i.e., the three different PF estimates), indicating they are at least within the uncertainty bounds of frontal detection by other methods. Some values are at locations either north or south of the other front estimates by as much as 3°, but it should be noted that the standard deviation of the PF estimated by Freeman and Lovenduski (2016a,b) averages 2-3°. Using PF variability statistic an indicator of variability of all fronts, one can conclude the location CKE half-power points are well within the level of expected frontal variability and so not statistically too distant from a front location.

One may question whether the relatively wide envelopes of enhanced CKE overlap more than one front. This is a possibility, but if both fronts have moved south as some have argued (e.g., Sokolov and Rintoul, 2009b), then the CKE envelope should also shift, regardless of whether it includes one or two fronts. If the exact frontal location was known at any time, one could judge how well the CKE envelope (or half-center) point was associated with just one front. But considering the disagreement in climatologies (e.g., Figure 5) and the intrinsic variability of the front, this is impossible to test. One can, however, compute the distance from the CKE half-power point to the southern boundary (for those points that are nearest a climatological SAF position) and the distance with the northern boundary (for those that are nearest the PF) and compare this to the distance between the climatological positions of these fronts. Note that the distances must be computed along the groundtracks and not simply taken as the meridional distance at the longitude of the CKE half-power point.

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The average distance between the half-power point and either northern or southern boundary is 541 km with a standard deviation of 196 km. The average distance between the Kim and Orsi (2014) PF and SAF along the groundtrack passes is 706 km with a standard deviation of 407 km. We used the Kim and Orsi (2014) front positions as these data was on a regular grid which made interpolation to the groundtrack positions easier and it was computed over the roughly the same time span as the CKE estimates. From these statistics, we conclude the CKE envelopes should generally only encompass either the PF or the SAF, although even if they did not, it should not preclude one from using statistics of the CKE half-power point to deduce shifts in the fronts, provided they are both shifting, as has been theorized.

Another method for determining frontal position is to examine the probability of jets occurring (Chapman, 2017a) (Figure 7). The CKE-defined mean front positions lie within the probability envelopes, giving more confidence that the CKE measure is providing a comparable measure of frontal position in many areas. The only location where CKE-defined fronts don't agree well with the probability field from Chapman (2017a) is just west of the dateline, where two points lie between levels of high jet (and hence front) probability. However, it should be noted that Chapman finds jets in the two areas north and south of the CKE half-power points less than 10% of the time and that the northern cluster lies on the northern edge of the enhanced CKE envelope. Although the half-power points are slightly south of this along these two passes, this is due to high CKE (in excess of 200 $cm^2 s^{-2}$) down to 58°S, where Chapman (2017a) detects few jets. It is unclear why Chapman (2017a) detects few jets in this region of high CKE, but it should be noted that this represents only 1% of the samples compared.

The comparison between CKE half-power points and front climatolgies is reassuring that the method developed in Section 2 is successfully detecting regions of high energy related to jets

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around fronts. Since the movement of jet positions has been used to estimate movement of the fronts (e.g., Chapman, 2017a), a comparable calculation with positions of high CKE seems reasonable. The majority of the estimated half-power points follows the SAF and is most likely due to the front (and jets) moving perpendicular to the groundtracks. This method will tend to only detect high CKE when the front is moving from northwest-to-southeast for an ascending pass, and from southwest-to-northeast for a descending pass. This method also only works in regions where the front is associated with highly variable jets, which does not occur at every longitude along the front (e.g., Chapman, 2017a).

To quantify movement of the envelope of enhanced CKE, a linear trend is fit to the 8 estimations of the half-power point from 1993-2016 for each location shown in Figures 5 and 6. Analysis of the residuals about the trend indicated they were random (lag-1 autocorrelation < 0.1 for all cases), so standard error was computed by scaling the formal error from the covariance matrix determined in ordinary least squares by the standard deviation of the residuals. This was also scaled up to account for the degrees of freedom lost by estimating the trend by sqrt(n/n_{EDOF}), where n = 8, and n_{EDOF} = 6. Finally, the 90% confidence interval was computed by scaling by 1.94 for 6 effective degrees of freedom assuming a normal t-distribution of the residuals.

The results indicate considerable regional variability in the change of the half-power point over 24 years, with large uncertainty bars (Figure 8). This is due to the substantial temporal variability in the positions, which can be seen in Figure 4, where the leading edge of the CKE envelope varies by over 1 degree of latitude (over 100 km) between 1993-1995 and 2011-2012. To better see significant changes outside the uncertainty (90% confidence) interval, one can compute the signal to noise ratio (SNR = trend/uncertainty). Examining this (Figure 9), one can see there are some regions where the half-power point has moved southward by a significant distance over the last 24 years (13.6% of points), but there are also points where it has moved north (9.6%). For the majority of points (76.8%), there is no statistically significant change, meaning no movement of the front is as likely as either a southward or northward shift due to the high variability in 3-year positions.

4. DISCUSSION AND CONCLUSIONS

The results from the analysis of the positions of enhanced kinetic energy suggest no overall shift in the frontal positions across the Southern Ocean, but some large, localized movements. The region indicative of some southward shift between 90°E and 170°E is in approximately the same area where Kim and Orsi (2014) and Freeman and Lovenduski (2016a) also reported large shifts, between 1992 to 2011 and 2002 and 2014, respectively. However Freeman and Lovenduski only examined the Polar front, and Kim and Orsi (2014) only found large shifts in the PF and the southern ACC front. They found shifts of order 50-100 km in the SAF where the points in this study cluster, which is considerably smaller than the individual shifts we find between 90°E and 170°E along the SAF. However, the overall average over the region between 90°E and 170°E (-29 km per decade, or -66.7 km in 23 years), is consistent with what Kim and Orsi (2014) found.

Kim and Orsi (2014) and Freeman and Lovenduski (2016a) also found slight northward shifts in the front positions in the southeast Pacific, between 200°E-270°E. We also find some locations in this region, where the CKE half-power points cluster around the SAF, also have a significant northward shift. Kim and Orsi (2014) found the shift of the SAF was about 30-40 km between 1992 and 2011. Our results suggest larger shifts in some areas; averaged over the area,

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our results are 46 km per decade to the north, or 106 km from 1993-2015, which is consistent with the average over the region computed by Freeman and Lovenduski (2016a) from sea surface temperature data, but for the Polar Front.

Kim and Orsi (2014) suggest that the shift of the fronts in the Indian Ocean were not directly related to shifts in winds, but instead were caused by an expansion of the Indian subtropical gyre. They linked the shift in the southeastern Pacific to wind changes related to mainly the Southern Annular Mode in that region (Kim and Orsi, 2014).

Overall, this study supports the recent studies by Kim and Orsi (2014), Gille (2014), Freeman and Lovenduski (2016a), and Chapman (2017a). All find that, while the frontal positions of the ACC are highly variable in time, there is no statistically significant shift in the fronts to the south on average. This study utilized a novel technique to reach this conclusion, which adds to the robustness of evidence that there has not been a shift in the frontal positions. Thus, while the fronts may eventually shift south in a warming climate, there is no strong evidence that it is happening at the moment.

Other studies have shown significant positive trends in the Southern Ocean that have been connected to the warming climate. These include changes in the ocean heat content in the upper ocean between the 1930s-1950s and 1990s (e.g., Böning et al., 2008; Gille, 2008), increases in the heat content of deep water between the 1990s and 2005 (e.g., Purkey and Johnson, 2010), and increases in eddy kinetic energy in the Indian and Pacific Oceans since 1993 (Hogg et al., 2015). Observational evidence of shifts in the winds, however, indicates that while there may be a slight southward shift in winds during the southern hemisphere summer, the overall yearly average shift is not significant (Swart and Fyfe, 2012). Thus, the growing consensus that fronts have not shifted to the south, on average, is consistent with observations of no significant shift in the yearly averaged winds.

The only evidence supporting a hypothesis that ACC fronts have shifted southward since the 1990s comes from mapping the location of contours of constant dynamic topography over time (e.g., Sokolov and Rintoul, 2009b; Kim and Orsi, 2014). As Gille (2014) argued and as we have demonstrated based on a simple thought experiment (Figure 1), there are other equally plausible explanations for the apparent southern shift of the contours. Considering that four different techniques – location of mean transport (Gille, 2014), maximum SST gradients (Freeman and Lovenduski, 2016a), probability of jet positions (Chapman, 2017a), and the location of enhanced kinetic energy (this study) – all agree that the fronts have not moved significantly on average, one has to conclude that the method of using dynamic topography contours to detect changes in front position is too sensitive to sea level rise be useful for determining shifts in frontal positions, although it may prove useful for determining the mean position as Chapman (2017a) has argued.

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Figure Captions

Figure 1. a) Mean dynamic topography in the Southern Ocean along a north-south meridian for three scenarios, and b) the corresponding geostrophic velocity, with positive values indicating eastward flow. The scenarios are: an initial state (dashed black line), a shift of the two fronts south by 60 km with no change in magnitude or shape of the currents (red line), and no shift of the mean of the current, but a change in the magnitude and shape (blue line).

Figure 2. Positions of the T/P, Jason-1, Jason-2 and Jason-3 groundtracks used for this study (black lines), and the the approximate locations of the Subantarctic Front (red line) and the Polar Front (blue line) as estimated by Orsi et al. (1995). The orange track shows the location of the pass used in analysis shown in Figures 3 and 4.

Figure 3. An example profile of mean CKE (1993-2016) along a ground track in the southern Indian Ocean (shown in orange in Figure 2), demonstrating the location of the half-power point and the locations of the southern and northern boundaries of the enhanced CKE envelope. See text for details of the computations.

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Figure 4. Three-year averages of CKE estimated along pass shown in Figure 2 (solid lines) along with the long-term mean from 1993-2016 (dotted line).

Figure 5. Examples of the three types of CKE profiles found (black lines), along with the value of the full EKE computed at crossover points.

Figure 6. Mean positions of fronts estimated from CKE (orange dots) along with estimates from other authors: Orsi et al. (1995) computed using hydrographic sections, Kim and Orsi (2014) based on contours of dynamic topography, and Freeman and Lovenduski (2016a) based on gradients of sea surface temperature. The Orsi et al. (1995) fronts were downloaded from https://gcmd.nasa.gov/records/AADC_southern_ocean_fronts.html. The Freeman and Lovenduski fronts were downloaded from https://doi.pangaea.de/10.1594/PANGAEA.855640 (Freeman and Lovenduski, 2016b). The Kim and Orsi (2014) fronts were provided by Yong Sun Kim upon request.

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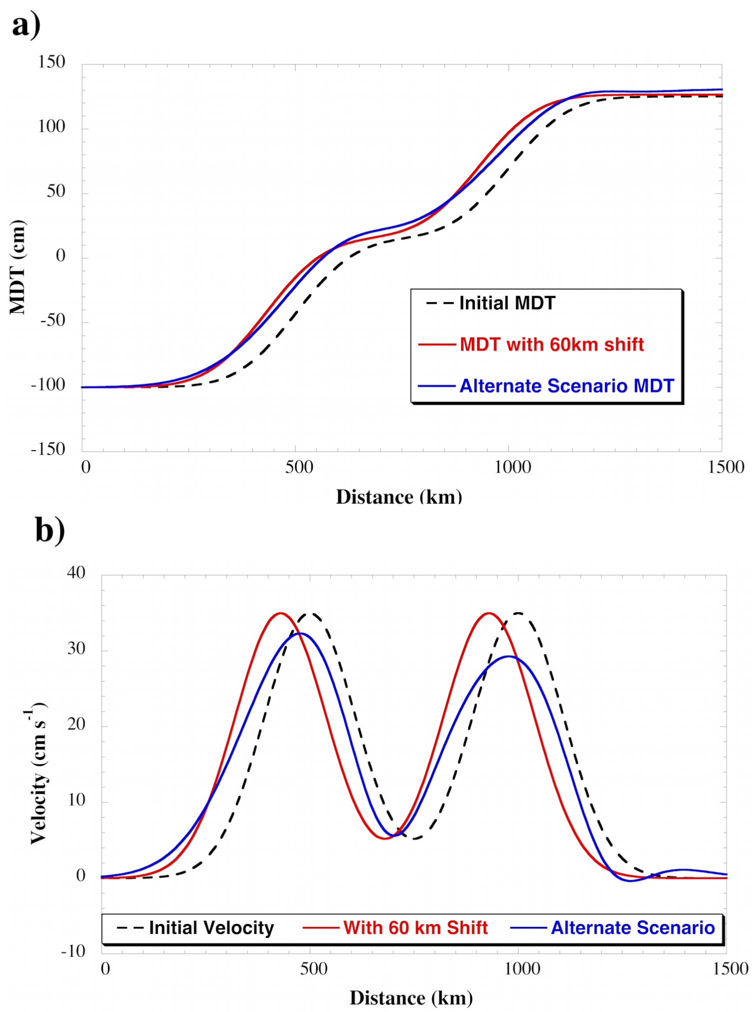
Figure 8. Estimated trend in the half-power point of CKE for each location shown in Figures 6 and 7, as a function of latitude. Error bars represent the 90% confidence interval.

Figure 9. SNR (trend/error in Figure 8). Values larger than 1 indicate a statistically significant northern shift. Values smaller than -1 indicate a statistically significant southern shift. Values between ± 1 indicate no statistically significant shift.



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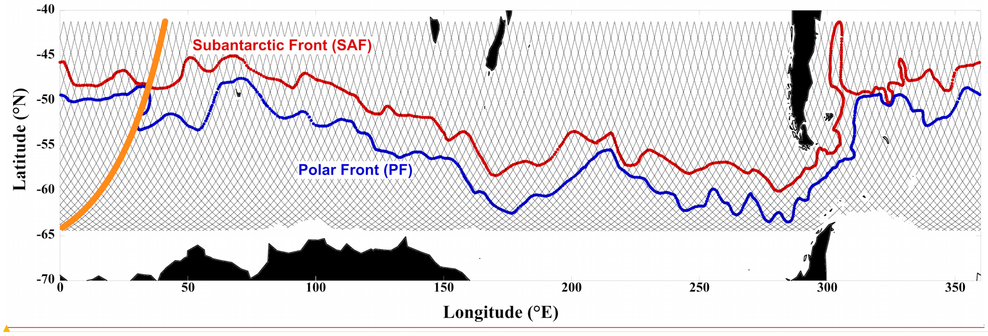

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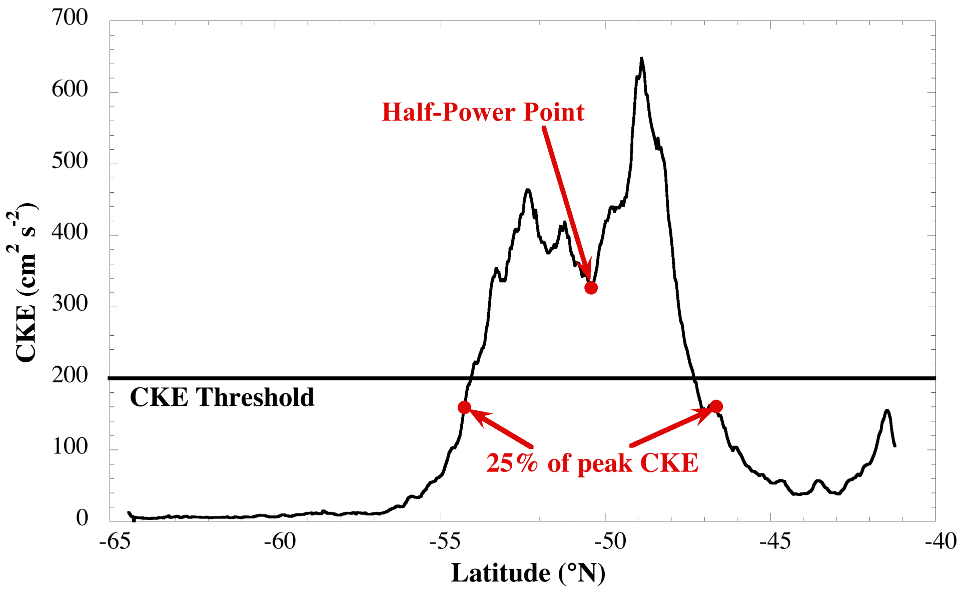

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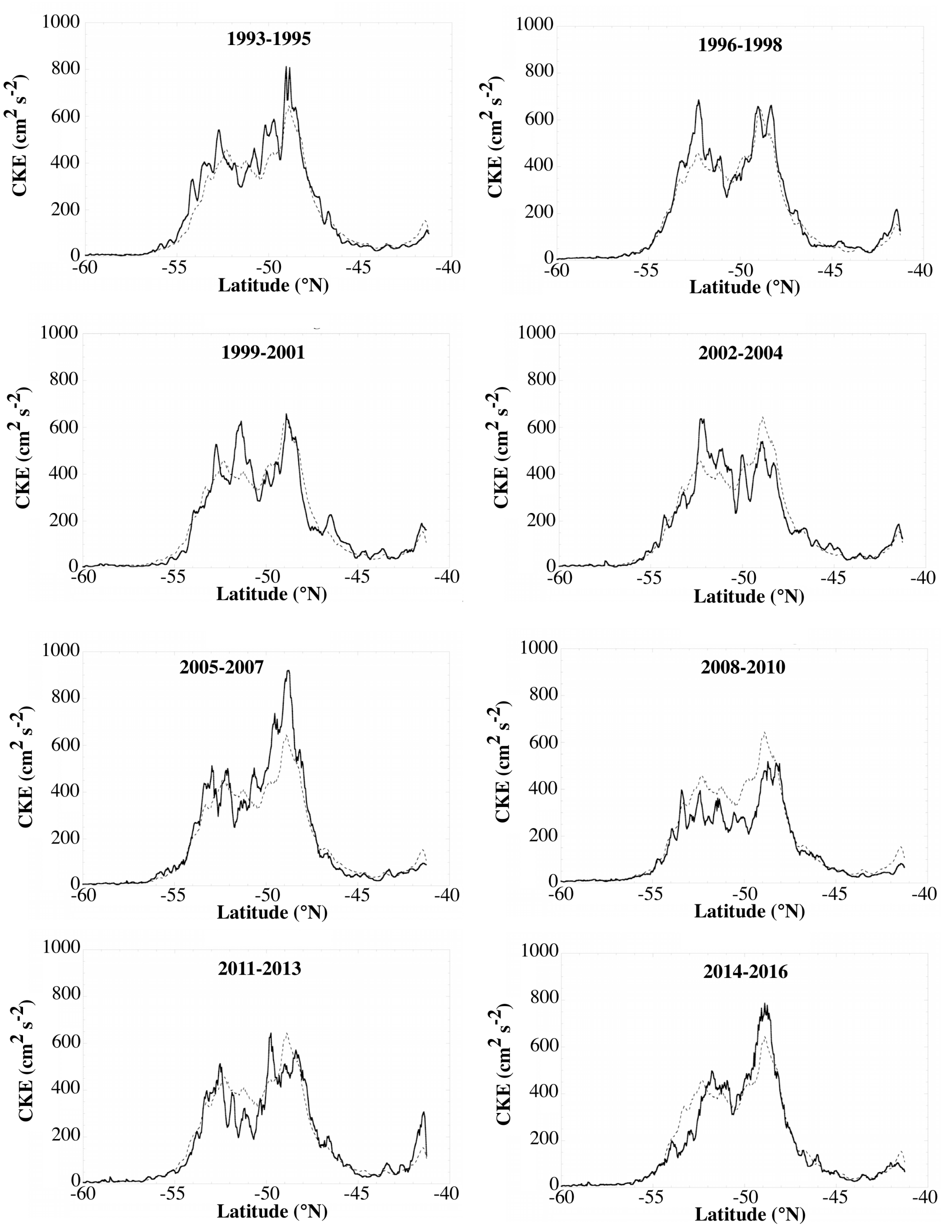

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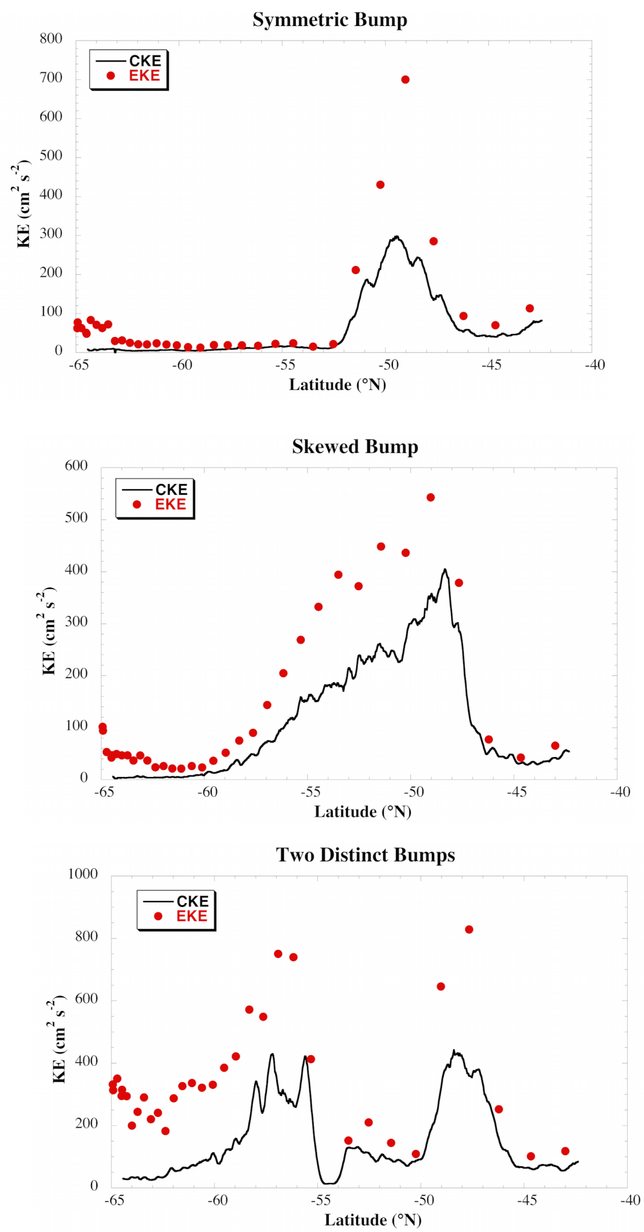

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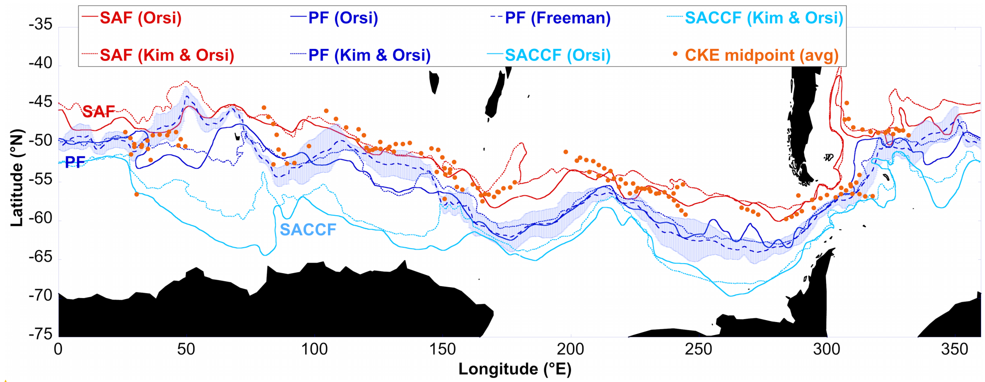

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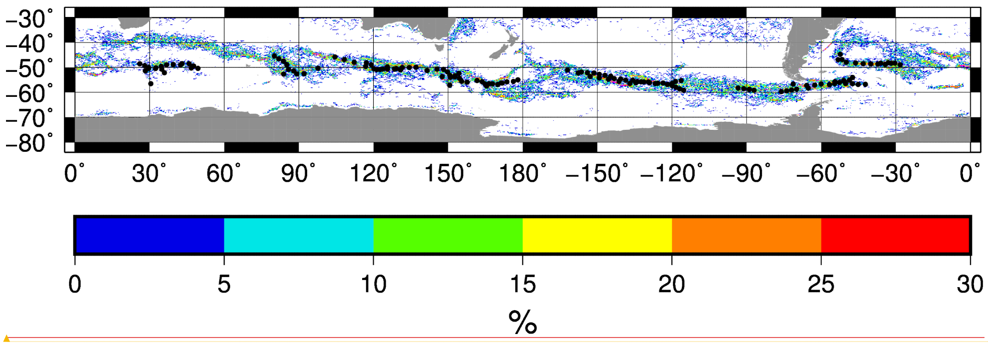

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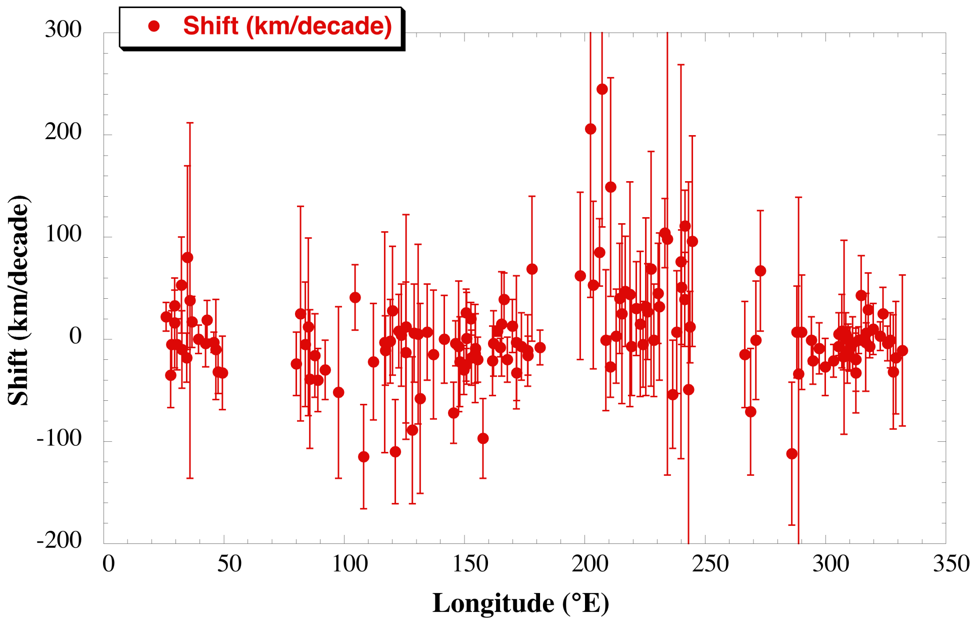

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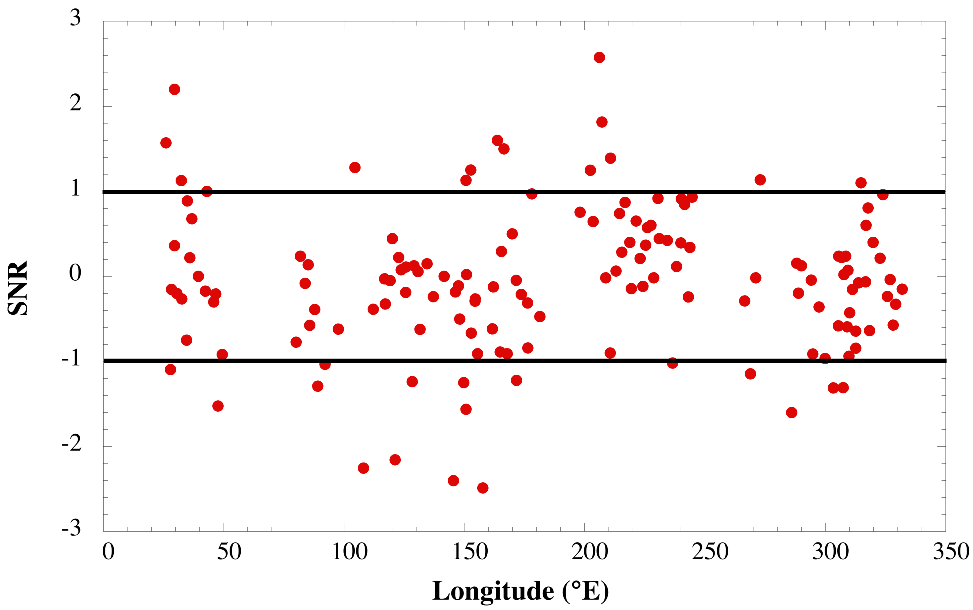

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