Interactive comment on “Mixed layer depth variability in the Red Sea” by Cheriyeri P. Abdulla et al.

Referee #2

Received and published: 1 May 2018

General comments:

The paper is generally well-executed and well-written, although it does need some editing. The authors say that MLD results are not available from previous research, but I am not competent to judge that, so I will take them at their word on that point.

There is a lot of good material here, but I also have reservations about some of it. These comments are summarized below. Please note that these comments are not in order of importance, but are in the order I encountered the material in the paper.

The bottom line is that the basic description is well-done and should be published.

The special latitude bands identified in the correlation plot are not proven to be real, at least to my satisfaction, but the Tokar Gap signal at 19N is interesting and corresponds to a clear “tongue” in the MLD climatology.

I’m ignoring a rule I agree with that we cannot just point to features in a plot and interpret these without a “null” test that the feature could be noise, but we’ll discuss that more down below.

The paper would be much better if you were to get rid of the AVISO SLA analysis and Section 3.3 and the other latitude bands and focus on the overall description and the Tokar Gap results, again see discussion below.

I should say that after writing this review I read the comments by the first anonymous reviewer. This person gives a very thorough review, and we have points of agreement and disagreement. I think the major disagreement is how we view the material concerning the Tokar Gap winds and subsequent eddy spin-up. I really liked this material, but the first reviewer perhaps did not like it so much. I think this is for the authors and the editor to sort out.

Reply:

Thank you very much for your precious comments and suggestions on the manuscript. They were very helpful in improving the manuscript. The reply to specific comments are given below and the manuscript is modified accordingly.

Specific comments:

SC#1:

L40 – I am not sure that "deep water formation" is appropriate. Common usage of that term is for NADW and ABW. Perhaps "intermediate water formation"? At the least tell us how deep this high salinity water reaches.

Reply:

The RSOW is an intermediate water formed in the northern part of Red Sea as part of the convection activity, which propagate through Bab-el-Mandab strait to the Gulf of Aden (Alsaafani & Shenoi 2007) and later spreads to the Indian Ocean, whose signature reaches into the south Indian Ocean about 6000 km away from the source (Beal et al., 2000). The sentence is corrected accordingly.

The earlier text in the manuscript:

It is one of the important deep water formation regions, and its signature reaches into the Indian Ocean (Beal et al., 2000).

The modified text in the manuscript:

It is one of the important intermediate water formation regions in the world (Red Sea Outflow Water, RSOW), formed mainly due to the open ocean convection in the northern Red Sea [Sofianos and Johns, 2003], which propagates through Bab-el-Mandab to the Gulf of Aden (Alsaafani and Shenoi 2007) and later spreads to the Indian Ocean, whose signature reaches into the south Indian Ocean about 6000 km away from the source (Beal et al., 2000).

SC#2:

L95 – 1 by 1 degree spacing is very coarse for this region. With such a model can you really expect to resolve the scales that are important in the Red Sea?

Reply:

We have crosschecked the estimates from reanalysis flux products (Tropflux and OAflux) with previous studies in the Red Sea, and found that the variability are consistent with observations (Sofianos and Johns 2003, Murray and Johns 1997, Tragou et al. 1999, Sofianos et al. 2002, Farrar et al. 2009 and Yu and Weller 2007). Further, the variability of the flux parameters (Net heat flux and evaporation. Precipitation is negligible) along the main axis of the Red Sea is relatively smooth, and the general variability can be captured with 1 by 1 degree spacing. Therefore, the Tropflux and the OAflux estimates can be used to understand general variability of these parameters.

In the case of wind, which vary relatively rapid comparing to heat and fresh water flux terms, we have used high resolution winds (0.312°x0.312° spatial grid) from CFSR (Climate Forecast System Reanalysis).

SC#3:

L108-115 – The AVISO SLA is HIGHLY suspect in the Red Sea for resolving eddies. Yes, they grid it at quarter degree spacing, but how much actual data is there? Also, their covariance functions for the OI are not tuned to the Red Sea in general, or to the Tokar Gap in particular. See below, too, but I would remove the AVISO SLA eddy material and focus on the Tokar Gap analysis that doesn't require it.

Reply:

The SLA data from AVISO is used just for a broad and qualitative understanding on the changes in sea level in the Red Sea. We have used the merged data from all satellite estimates. Red Sea has considerable number of satellite tracks from different satellites (Fig.). Further, the AVISO SLA data have been used by previous studies also for the Red Sea region, for example Zhan et al., (2014), Papadopoulos et al., (2015) and Taqi et al., (2017).

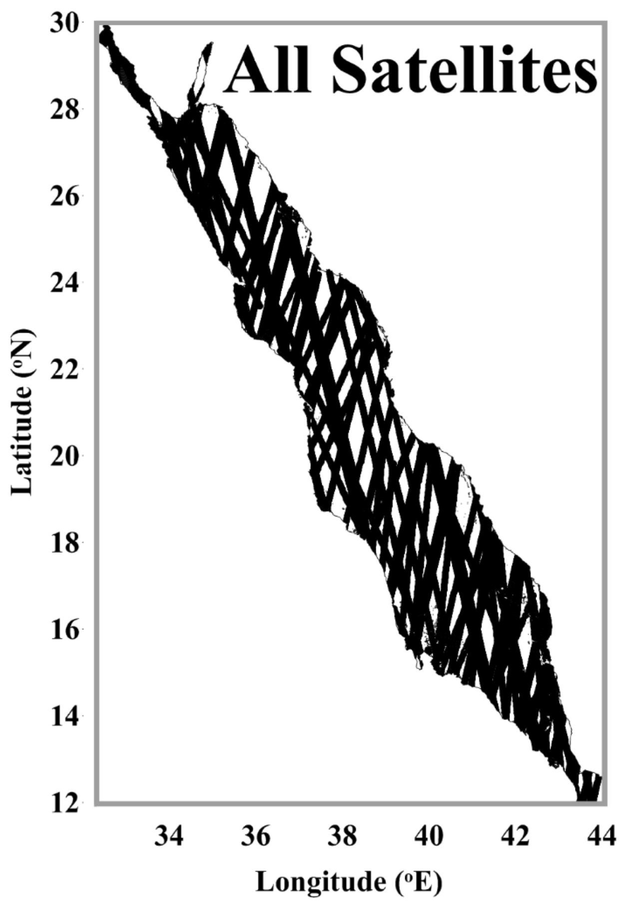

Fig.1 Satellite tracks in the Red Sea.

We agree that a more precise and quantitative estimation of the sea level variability may require further improvements in the AVISO product. But, the SLA data are providing a qualitative understanding of the sea level changes in the Red Sea. We have also compared the geostrophic currents from the hydrographic measurements (profiles collected during different cruises) and from AVISO SLA. Both are matching well. Apart from this, the ADCP measurements carried out by Sofianos and Johns (2007) show the presence of eddies in the

Red Sea, which are well matching with gridded SLA estimates from AVISO for the same period. This gives us confidence to use SLA estimates in the present analysis, at least for a qualitative understanding of the sea level variability.

SC#4:

L122-129 – Well-done to switch to an along-axis coordinate system and to do the analysis in an along-axis, time space. Nice!

Reply:

Thank you for appreciating the work.

SC#5:

L150-162 – I'm worried that we are over-interpreting in this section. The general seasonal pattern in clear, but the along-axis changes are not so clear. Without error bars it is difficult to tell when we are interpreting real changes, or just noise.

Reply:

The error (observed standard deviation from monthly mean value) is mentioned in the text at appropriate locations in the revised manuscript. For the entire climatology, the standard deviation is less than 10 m for >95% cases, while active mixing zone show relatively higher standard deviation.

The observed relatively larger deviation during winter especially in the northern latitudes is due to the measurement of profiles during the ongoing mixing process. In addition, the convection process in the northern Red Sea show considerable interannual variability. This resulted in wide range of MLD values and relatively large standard deviation from the mean value.

The modified text in the manuscript:

A Hovmoller diagram of the monthly MLD climatology is presented in Fig. 3. The deepest MLD is observed in February and the shallowest during May-Jun. A significant annual variability is observed in the Red Sea. The maximum value of climatological mean MLD is observed in February at the northern Red Sea while the minimum noticed at various instances, especially during summer months. The MLD of individual profiles in the northern Red Sea has a wide range values from 40 to 120 m mainly due to the presence of active convection process, while some of the profiles show MLD deeper than 150 m in consistence with Yao et al., (2014). Apart from the northern deep convection region, the south-central Red Sea between 18 °N-21 °N (53±5 m) and 14 °N-16 °N (48±9 m) also experienced deeper MLDs during the winter, which is separated by a shallower MLD around 17 °N (44±14 m). During July to September, the region around 19° N experienced a deeper mixed layer in contrast with the general pattern of summer shoaling over the entire Red Sea.

The deepening of the MLD begins in October throughout the Red Sea. The winter cooling and its associated convection strengthen by December, with an average MLD>50 m. Compared to other parts 201 of the Red Sea, during November and December, relatively shallower MLDs were witnessed at approximately 16° N-17° N, and 24.5° N-26.5° N. The winter deepening of the MLDs intensifies by January and continues throughout February. In contrast to the general pattern of deeper MLDs in the 204 northern latitudes, the area between 24.5° N and 26.5° N shows a relatively shallow MLD almost throughout the year, especially in the winter.

The mixed layer starts to shoal gradually by the end of February, and the MLDs of most areas decreases to 20±7 m by April. Summer shoaling is comparatively stronger in the 15° N-18° N latitude band, and the detected mean MLD is < 15 m. Individual observations revealed that many profiles have MLDs < 5 m. In general, the shallow mixed layers are predominant from April to September, while this prevails until October in the far north. In the south-central Red Sea, the shallow mixed layer exists for only a short period, from April to June.

SC#6:

L160 – As an example of the comment I just made, I cannot make any sense of a "general pattern of deeper MLDs in the latitudes". I just cannot see in Figure 2 where this statement comes from! You will need to be much more specific to convince me of this and it will also require appropriate error estimates. You lose little by sticking to the bigger picture and skipping the "wiggles", although the "tongue" at the latitude of the Tokar Gap is interesting (see below).

Reply:

The latitudinal variability in the MLD is clear during winter, with deepest MLD in the north and shallow in the south with deeps/shallows in between. Due to this reason, we used the term "general pattern of deeper MLDs in the northern….". We have removed this part of the sentence from the text.

The earlier text in the manuscript:

In contrast to the general pattern of deeper MLDs in the northern latitudes, the area between 24.5° N and 26.5° N shows a relatively shallow MLD almost throughout the year, especially in the winter.

The modified text in the manuscript:

The area between 24°N and 27°N shows a relatively shallow MLD almost throughout the year, especially during winter.

SC#7:

L205 and Figure 5 – I like this plot, but some estimate of the degrees of freedom needs to be made so that we know whether the structure in the curve real or just statistical fluctuations. And, as usual, the degrees of freedom estimate should consider red noise and not assume white, or independent, noise.

Reply:

We have tested the statistical significance of the correlation values. The estimated p-value, t-value and the effective degree of freedom show that the correlation values are significant at 95%. We have tabulated the above stated parameters for a single case (for correlation between NHF and MLD) in the Table given below.

Table.1 Statistics for the correlation between NHF (net heat flux) and MLD.

Latitude (N)	**P-value**	**Effective degree of freedom (timesteps=420. 35*12 months)**	**t-value based on Bretherton et al, (1999)**	**t-value for 95% confidence level from "T table"**
13	3.20E-09	269.6597	4.842266	1.650517
13.5	0.002644	282.5494	2.477852	1.650256
14	1.38E-06	243.9125	3.726658	1.651123
14.5	5.33E-19	237.3118	7.015846	1.651308
15	3.80E-20	218.1968	6.965186	1.651873
15.5	1.76E-12	174.2134	4.667594	1.653658
16	6.64E-23	219.8966	7.552761	1.651809
16.5	2.61E-32	222.1904	9.367547	1.651746
17	2.53E-56	189.838	12.41162	1.652913
17.5	7.79E-41	182.2344	9.824286	1.653269
18	6.43E-80	163.4437	14.81243	1.654256
18.5	8.99E-47	183.8425	10.77849	1.653177
19	6.06E-45	178.4458	10.34322	1.653459
19.5	2.85E-72	164.7387	13.79153	1.654141
20	5.32E-85	159.815	15.35839	1.654433
20.5	2.37E-86	156.5116	15.38553	1.654617
21	2.27E-74	203.4905	15.67503	1.652394
21.5	3.67E-92	156.3192	16.19286	1.65468
22	7.40E-92	144.0271	15.4933	1.655504
22.5	4.43E-56	204.1266	12.83679	1.652357
23	4.79E-56	237.2501	13.84296	1.651308
23.5	1.15E-65	302.7621	17.48819	1.649898
24	5.63E-112	139.1993	17.98179	1.65589
24.5	1.68E-87	144.9487	14.95348	1.65543

25	4.46E-87	216.5994	18.25168	1.651906
25.5	1.10E-53	218.3447	12.89109	1.651873
26	2.70E-51	128.179	9.546686	1.656845
26.5	6.08E-35	179.0278	8.820048	1.653411
27	1.74E-74	122.4401	12.13284	1.657439
27.5	1.35E-78	151.0859	14.05475	1.655007

SC#8:

L211-215 – I think we are over-interpreting again. These are very small "wiggles" and 2 of the 5 do not even show the pattern you assert, meaning all three curves moving down together. Again, if you want to interpret these small changes, then you have to do a much more thorough job on the statistics to convince us that we're not just looking at random fluctuations.

Reply:

As mentioned in reply to the previous comment (SC#7), the observed fluctuations are statistically significant at 95% confidence level. The statistical results based on p-value, t-test and degrees of freedom has shown that the parameters (heat flux, freshwater flux and wind stress) correlation coefficients are significant at 95% confidence level.

We have repeated the analysis after smoothening MLD climatology for 1 degree along the latitude and figures are given below.

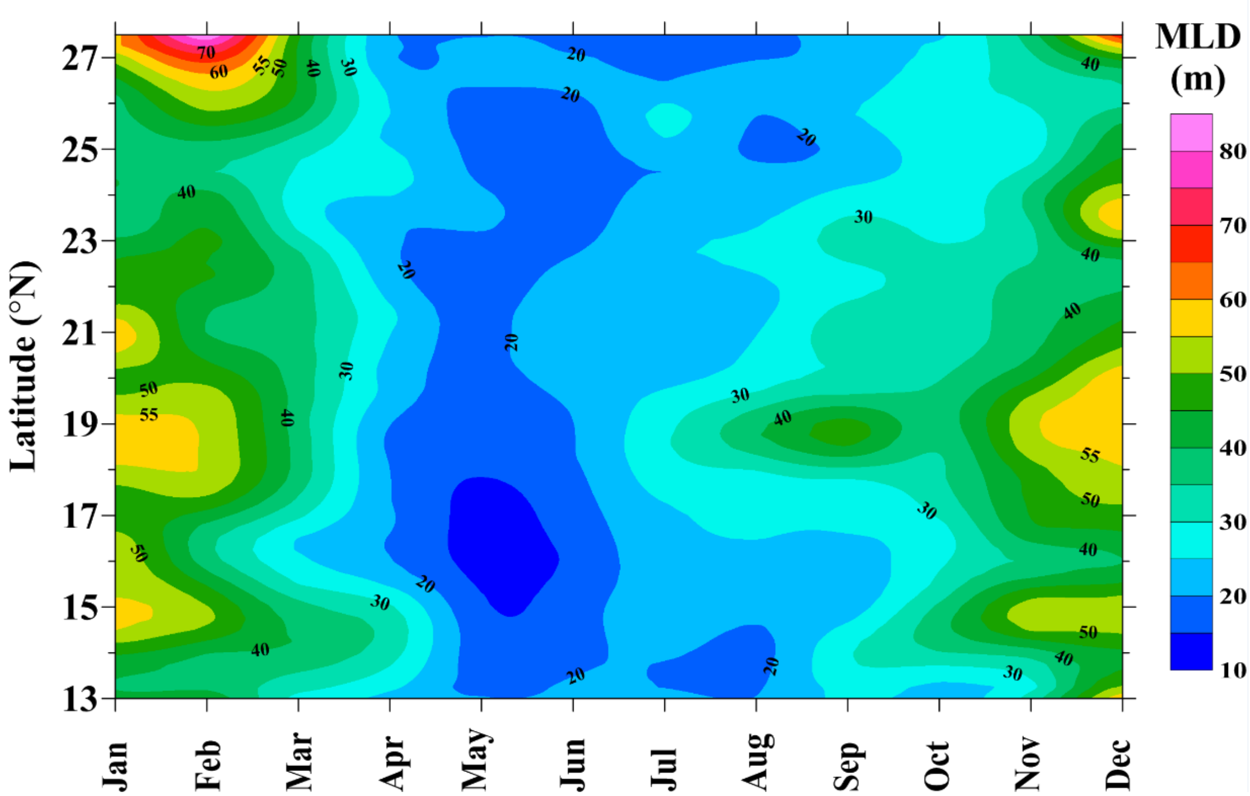

Fig.2 MLD climatology smoothed along latitude for 1 degree.

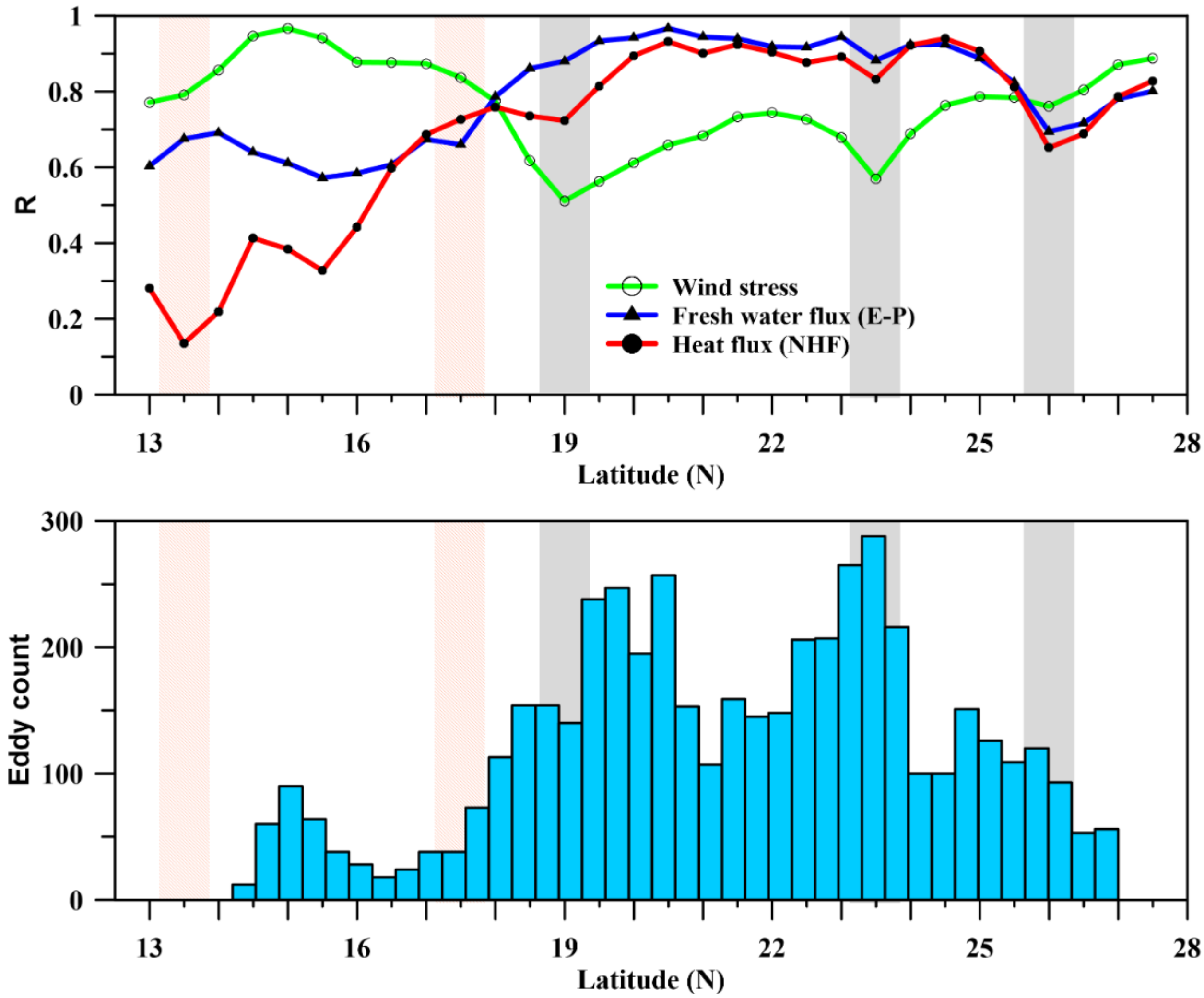

Fig.3 a) The correlation between MLD and atmospheric forces for smoothed MLD climatology, and b) the number of eddies in the Red Sea for the period 1992-2012.

The MLD climatology and correlation curves show a smoothed, but similar structure. A decreasing pattern can be seen correlation values at 19N (clear in wind-stress and heat flux), at 23N (clear in all three forces) and at 26.5N (clear in heat flux and freshwater flux). The correlation drops around 13.5N and 17.5N are less visible. Additionally, a drop around 15N also can be seen associated

Believing that the smoothening may remove some of the small-scale features, we would like to use the original MLD climatology (without smoothening) and previous version of the correlation curve in the manuscript.

SC#9:

L216, all of Section 3.3 – As I mentioned above, the analysis using the AVISO SLA is highly questionable here. I think this entire section, and basically all use of AVISO, is not necessary for this paper. You have some good results, but by pushing too far you run the risk of most readers doubting everything. Please note that I am trying to be constructive here and help to improve the paper. I like the paper as a whole, but really do not like this section.

Reply:

The Sea level anomaly estimate from AVISO is a merged product of multiple satellite tracks. It is true that the research based on SLA has to be carried out with caution, especially in smaller regions like Red Sea. As mentioned in reply to comment SC#3, the Red Sea has considerable number of satellite tracks. Further, multiple studies have already been carried out based on this data. The previous studies show that AVISO SLA estimates can still provide the general picture of sea level changes in the Red Sea. Our study, based on SLA, is only looking to the main locations of eddies in the Red Sea.

SC#10:

L258-260, Figure 6 – This is a continuation of the previous comment. You say that there is a good match with the number of eddies and the latitude ranges you identified earlier from the correlation curves, but I simply do not see that. And since we're just doing the analysis "by eye", then my eye is as good as yours. You really have to do some statistics if you want to make this point. And once again, none of these things are core results of your paper.

Reply:

We agree that few of the correlation drops are not matching with the eddy locations. We have mentioned the same in the manuscript also.

The correlation drops locations matching with eddies:

1. At 19°N: matching with the locations of Tokar region and eddies observed by Zhan et al 2014.
2. At 23°N: matching with eddies observed by Zhan et al 2014.
3. At 26.5°N: matching with eddies observed by Papadopoulos et al., 2015

The correlation drops locations not matching with eddies:

1. At 13.5°N: The Red Sea is very narrow at 13.5°N and close to Bab-el-Mandab strait. Moreover, complex dynamics associated with the exchange of surface and subsurface waters between the Red Sea and the Gulf of Aden occurs in this region. The complexity of this region prevents linking the MLD variability directly to atmospheric forcing or eddies.
2. At 17.5°N: The region at approximately 17.5° N is between the two eddy-driven downwelling zones at approximately 15° N and 19° N (Fig. 2). Mass conservation requires upwelling to replace the downwelling water. The MLD climatology shows shallow mixed layers throughout the year at 17.5° N, which could be due to possible upwelling. Further investigation is required to unveil the dynamics associated with this region.

The drops in correlation at 23°N and 26.5°N are matching with eddy locations. The drop at 19°N is matching with the Tokar region and eddies. indicating the effect of eddies. As mentioned above, the other two locations (13.5°N and 17.5°N) need further investigations to unveil the associated dynamics.

SC#11:

L277, all of Section 3.4 – Much better! Looking at the 19N signal where the Tokar Gap is, and showing the actual wind results rather than AVISO eddy counts is much more convincing. And note that this is the only latitude band where I see convincing results. It’s well-known that strong winds through mountain gaps generate the eddy signals you infer (search for results on the Hawaiian Ridge and the Gulf of Tehuantepec), so you do not need the questionable AVISO results in order to rationalize the “tongue” in Figure 2 at 19N. This is a very nice result.

Reply:

Thank you very much for your appreciation.

We agree that mountain gap winds can generate eddy signals in the underlying sea. Therefore, the SLA snapshots are not necessary to show the impact of Tokar winds and associated deepening in MLD to the right of the wind jet and shoaling to the left. We keep SLA maps in figure just for helping the reader to easily understand the position of profiles influenced by mountain gap winds.

References:

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