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Reply to reviewer 2

We would like to thank the reviewer for their comments on the paper. Below the reviewers comments are in black and the responses in blue italics. Changes to the paper are shown in red in the revised paper.

General comment

The paper explores a connection between SST anomalies and atmospheric cyclones in the North Atlantic. The paper is concise and well written.

Thank you.

My major concern is that the authors used a cyclone dataset, while their main finding relates more to cold fronts that are possibly associated with cyclones. I suggest adding a dataset on the location of fronts and calculating anomalies behind objectively identified cold fronts (perhaps within a cyclone area or independently) rather than deducing the location of fronts within cyclones.

See response to specific point 22.

Specific comments

1. Why only 2013/14 season is taken into account to calculate cumulative effect of the passage of multiple cyclones.There must be some other anomalous seasons.Tilinina et al. 2018 (https://doi.org/10.1175/MWR-D-17-0291.1) investigate anomalously high heat fluxes in the North Atlantic during winter and related those to the cyclone activity. They concluded that the area of interaction between cyclones and anticyclones is very important for a heat flux anomaly. I wonder if this is also true for the summer season and it will also be nice to see some analysis on this.
   This is an excellent suggestion and one that was also made by reviewer 1. We have started to apply our cyclone masking technique to other years and seasons. However, including this analysis would increase the length of the paper significantly. Therefore, we will publish this work as a separate publication to avoid a very long paper.

2. l. 3: are the processes not fully understood or not quantified?
   'Quantified' is probably more correct so we have changed the wording in the abstract.

3. l.29: I believe it should be Rudeva and Gulev (2011)
   We agree, this citation has been changed.

4. 5. l33: should it be left-rear quadrant?
   The SST cooling can be in either the right or left-rear part of the cyclone depending on the cold-front orientation. Therefore, this has been changed to 'rear part of the cyclone'.

5. l.41: I'd add 'ocean' surface mixed layer
   Changed.

6. l.89-92: you say 'MLD is the depth at which the density difference . . .. reaches 0.01 kg/m3' and then 'the density difference MLD can overestimate MLD'. Define MLD otherwise then.
   We have clarified that the overestimation of MLD using the density difference definition occurs predominantly in the deep convective regions and not over the entire North Atlantic domain. Since we focus on the mid-North Atlantic this does not influence our results.

7. l.98-100: 200 most intense cyclones - how does that number compare with the total number of cyclones for 1989-2009? How intense are those cyclones (perhaps, add a pdf intensity for all cyclones and those 200). As you focus on the North Atlantic, I'd suggest 30-70N, instead of 90N (though looking at the track in fig. 1 it will hardly make a difference for the results). Consider showing this area in Fig.1.
   Between DJF 1989/1990 and DJF 2008/2009 there were 1050 cyclones identified with their maximum intensity in the North Atlantic domain. The top 200 cyclones represent the top 19% of the entire North Atlantic distribution as shown in figure 1. We have decided not to include this figure, but have stated the percentage of the total cyclones in the text. As the reviewer states, the tracks of the most intense cyclones will not change if the North Atlantic domain is reduced along it's northern boundary, therefore we have not reanalysed the data.

8. l.105-113: How composites are built should be better described here. It is only in sec. 4.1 that we find out that the radius of composites is 30deg (it is also mentioned in fig 4 caption). I believe that the rotation of composites does not help interpretation of the results as meridional gradients in some plots get also rotated (e.g., fig. 4), I'd recommend skipping this step.
   We think that the reviewer must have missed this information, as it is stated in the first sentence of section 2.4 in which we describe the cyclone-relative compositing. Performing the rotation ensures that mesoscale features such as warm and cold fronts are approximately aligned and are not smoothed out by the compositing. We agree that this will also rotate meridional gradients, but feel that it is important to align the features we are interested in otherwise the composites become washed out. Therefore we have retained this step of the analysis.

9. l.111: Following your comment on the rate of intensification and decay, I think a pdf will be helpful (together with a pdf of intensity mentioned in my earlier comment)
   Dacre et al. (2012) (their figure 2(c)) shows the mean intensification and decay rates of the top 200 cyclones as well as the spread around the mean. As the pdf has already

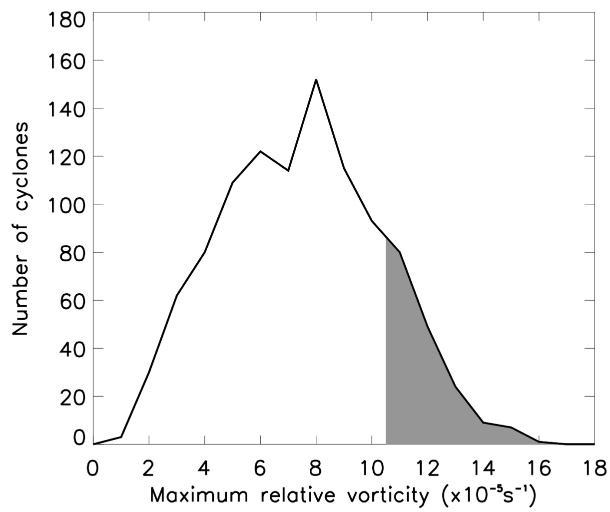

Figure 1: Maximum relative vorticity reached by all 1050 north Atlantic cyclones. The grey shading represents the part of the distribution that includes the 200 most intense cyclones.

been published we have not included it in this paper but have referred to the published figure in the revised text.

10. l.116: give a range for the meridional gradient
The meridional gradient is 50 $Wm^{-2}1000km^{-1}$. *This has been added to the text.*

11. Figures 1 and 2: Add Qsw,Qlw, etc. to the captions (as in other figures)
Added.

12. l.143: check the figure number
Corrected.

13. l.152: SST tendencies are discussed in the next section
Reference to SST tendency analysis has been removed.

14. l. 163: 'westward direction': as the composites are rotated it is hard to say where the west is.
'Westward direction' has been changed to 'behind the cyclone'

15. L 159:164: how much are sensible and latent heat fluxes in summer different to those in winter in previous studies (in Tilinina et al. 2018 and Rudeva and Gulev 2011)? From this you may possibly deduce a potential effect of cyclones on SST in winter (which can also be estimated directly in another paper)
We have not yet performed this analysis for any other seasons but this is a good suggestion and we will consider this in our future work.

16. l.165: this sentence suggests that wind should also be shown in fig 5b
The text about the winds now only refers to figure 5a.

17. Fig 3b and d: fix colours in the colour scale (blue - negative, yellow/red - positive)
We feel that the colourbar is clear so have not changed the figure.

18. Fig.4: I'd comment that positive values are into the surface in the caption.
This is already mentioned in the caption so we have not made any changes.

19. Fig.5: add 'air' to panel (a) caption
Added.

20. l.225-232: this paragraph should be in Methods
The section describing the cyclone masking has been moved to the methods section.

21. Fig.9: The relative sizes of the circles are wrong: if the big circle is 30 deg, as the small circle has a 14 deg radius.
The schematic has been re-drawn to better reflect the relative size of the circles.

22. l.237: I do not get why the mask shows the cyclone along the trailing cold front. It suggests that cold fronts always extend along the cyclone centres in the last 30 hours. If that is your assumption, that needs to be proved. As I said at the beginning of the review, I think you need objectively identified cold fronts instead of what has been invented here.
We have attempted to show that cold fronts roughly extend along the cyclone centres in the last 30 hours by showing 2 examples of the masking application in figure 10. We decided to use a cyclone tracking algorithm rather than a cold front tracking algorithm because it is the advection of cold dry air behind the cold front which creates the anomalous surface flux. Identifying relatively cold and/or dry airmasses without the co-location with cyclonic winds would not result in large heat flux.

23. Fig 10: Maybe swap the panels to have 24 Dec on the right and 20 Dec on the left
We are unsure why changing the ordering of the figure would improve the clarity of the paper so we have not swapped the panels around.

24. l.245: 14-18% - what variable does it relate to?
Following modifications to the text in response to other comments this sentence has been removed.

25. l249, 250 : fig 11c and 8f, respectively
We have changed the figure references.

26. Fig11: perhaps I missed it, but was QN due to cyclones calculated for all cyclones in 2013/14, or the strongest? Fig. 11c shows SSTQN due to cyclones or any Qn? I think 11c should be due to cyclones only. Can you explain why strong negative anomalies in the west of the North Atlantic (fig. 11c) are not seen in fig. 11d? I'd say that 11d matches well with 11a, which makes sense, but anomalies in the west North Atlantic in 11d are confusing
To clarify, Q_N in figure 11(a) was due to all cyclones in 2013/2014 not just the strongest.

Figure 11(c) showed ΔSST_{QN} due to the total Q_N anomaly combined with the climatological MLD. In response to a comment from reviewer 3 we now use the monthly varying MLD for 2013/2014.
The SST tendency anomaly for the 2013/2014 season is determined by subtracting the climatological SST tendency from the 2013/2014 SST tendency. The SST tendency anomaly can be separated into the anomaly associated with (i) anomalous Q_N (term 1 in equation 1), (ii) anomalous MLD (term 2 in equation 1) and (iii) anomalous entrainment through the base of the mixed layer, Q_{ENT} (term 3 in equation 1). We refer to the sum of these quantities as the SST tendency anomaly due to air-sea interactions (ASI), $\Delta SST^{'}_{ASI}$, given by;

$$\Delta SST^{'}_{ASI} = \frac{Q^i_N - \overline{Q_N}}{\rho c_p \overline{h}} + \frac{Q^i_N}{\rho c_p}\left(\frac{1}{h^i} - \frac{1}{\overline{\overline{h}}}\right) + \frac{Q^i_{ENT} - \overline{Q_{ENT}}}{\rho c_p \overline{h}}, \quad (1)$$

where i represents the 2013/2014 values and the overbar represents the 1989-2015 climatological values. Since we have no measurements of the entrainment flux anomaly across the ocean boundary layer it is estimated to be 20% of the surface Q_N anomaly (Stull (1988)). Neglecting contributions made by wind driven turbulence.
$\Delta SST^{'}$ due to anomalous Q_N is shown in figure 2(a). This closely resembles the Q_N anomaly (figure 11a in the original paper) with anomalous cooling in the mid-North Atlantic where the flux are negative, and anomalous warming (less cooling than climatology) in the Gulf Stream and Norwegian Sea regions. $\Delta SST^{'}$ due to anomalous MLD is shown in figure 2(b). This has the opposite pattern to figure 2(a) since larger negative Q_N results in deepening of the MLD via mixing by negatively buoyant water. Thus the large $\Delta SST^{'}$ in the west-North Atlantic are the result of the MLD being anomalously shallow in the 2013/2014 season. The sum, $\Delta SST^{'}_{ASI}$, accounts for 68% of the total $\Delta SST^{'}_{TOT}$ in 2013/2014.

We have also calculated both Q_N and $\Delta SST^{'}_{ASI}$ due to the environmental flow and when cyclones are present. Cyclones embedded within the environmental flow are associated with 68% of the total Q_N anomaly, more than double the Q_N due to the environmental flow anomaly only (32%). However, due to significant compensation between $\Delta SST^{'}$ due to anomalous Q_N (figure 3(a)) and $\Delta SST^{'}$ due to anomalous MLD (figure 3(c)) the $\Delta SST^{'}_{ASI}$ when cyclones are present (figure 3(e)) accounts for 41% of the observed ΔSST compared to 28% when cyclones are not present. Sections 4.1 and 4.2 have been re-written to clarify these points.

27. l.255: is it entrainment of the cold air?
This sentence refers to the entrainment of cold water into the ocean mixed layer from below. This has been clarified in the text.

28. l.265: As the mask stretches backwards from the cyclone centre, it captures the cold sector. However, the effect of the warm sector remains not assessed (which can also be done if warm fronts are identified).
The cyclone masking methodology was designed to capture the anomalous flux occurring behind the cold front and therefore the reviewer is correct, the effect of the warm sector

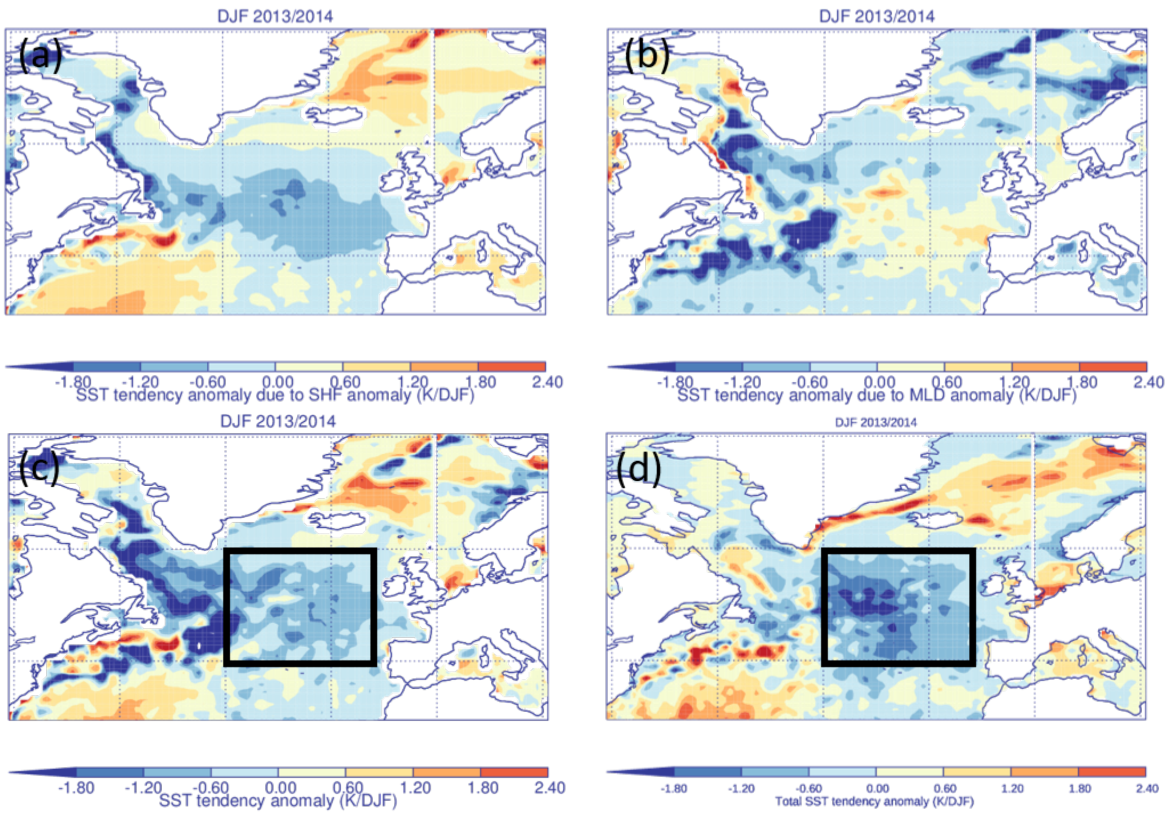

Figure 2: Anomalous SST tendency due to 2013/2014 (a) Q_N anomaly, (b) MLD anomaly and (c) Q_N, MLD and entrainment anomaly. (d) Total SST tendency anomaly.

(outside the 14° radius) is not assessed. This can be seen in the examples in figures 10(e) and (f) which capture the anomalously high flux behind the cold front but not the anomalously low flux ahead of the cold front (in the warm sector). However, it is also clear that the negative anomalies behind the cold front are 2-3 times larger in magnitude than the positive anomalies in the warm sector. We have tested the sensitivity of the results to increasing the mask radius to 16° and the contribution of cyclones to the total heat flux anomaly in the mid-north Atlantic increases from 68% to 71%. Therefore, making the mask larger, and thus including more of the warm sector, actually increases the contribution from cyclones. The results of the sensitivity test are already reported in the paper so we have not altered the text.

29. Fig. 7 suggests that the warm sector will have relatively small effect during the max development, but at other stages of cyclone lifecycles the balance might be different.
Figure 7 shows the SST change due to Q_N only at 3 stages in the cyclone lifecycle (max

-24, max and max +24). We have also analysed the SST changes at max -48 and max -36. The effect of the warm sector appears to reduce during these very early stages of cyclone development.

Technical comments

1. The word 'flux' is often used in plural form (e.g., flux occur). My preference is either to say 'flux occurs' or 'fluxes occur'.
   We have changed 'flux occur' to 'flux occurs' throughout the paper.

2. l. 73: magnitudes
   Corrected.

3. l.101: position is
   As cyclones is plural, we think that position 'are' rather than 'is' the correct wording.

4. l.126, 166,173: Figure shows
   As figure is singular, we think that 'show' rather than 'shows' in the correct wording on these lines.

5. l.128: 'teh' to 'the'
   Corrected.

6. l.135: put comma after 4000Jkg-1K-1
   Corrected.

7. l. 137: change 10's to 10s
   Corrected.

8. l.147: remove 'are'
   Removed.

9. Fig 7: 'Normalised' and 'negative' should start with a small letter
   Corrected.

10. l.246: remove 'is'
    Removed.

Stull R.B. (1988) Convective Mixed Layer. In: Stull R.B. (eds) An Introduction to Boundary Layer Meteorology. Atmospheric Sciences Library, vol 13. Springer, Dordrecht

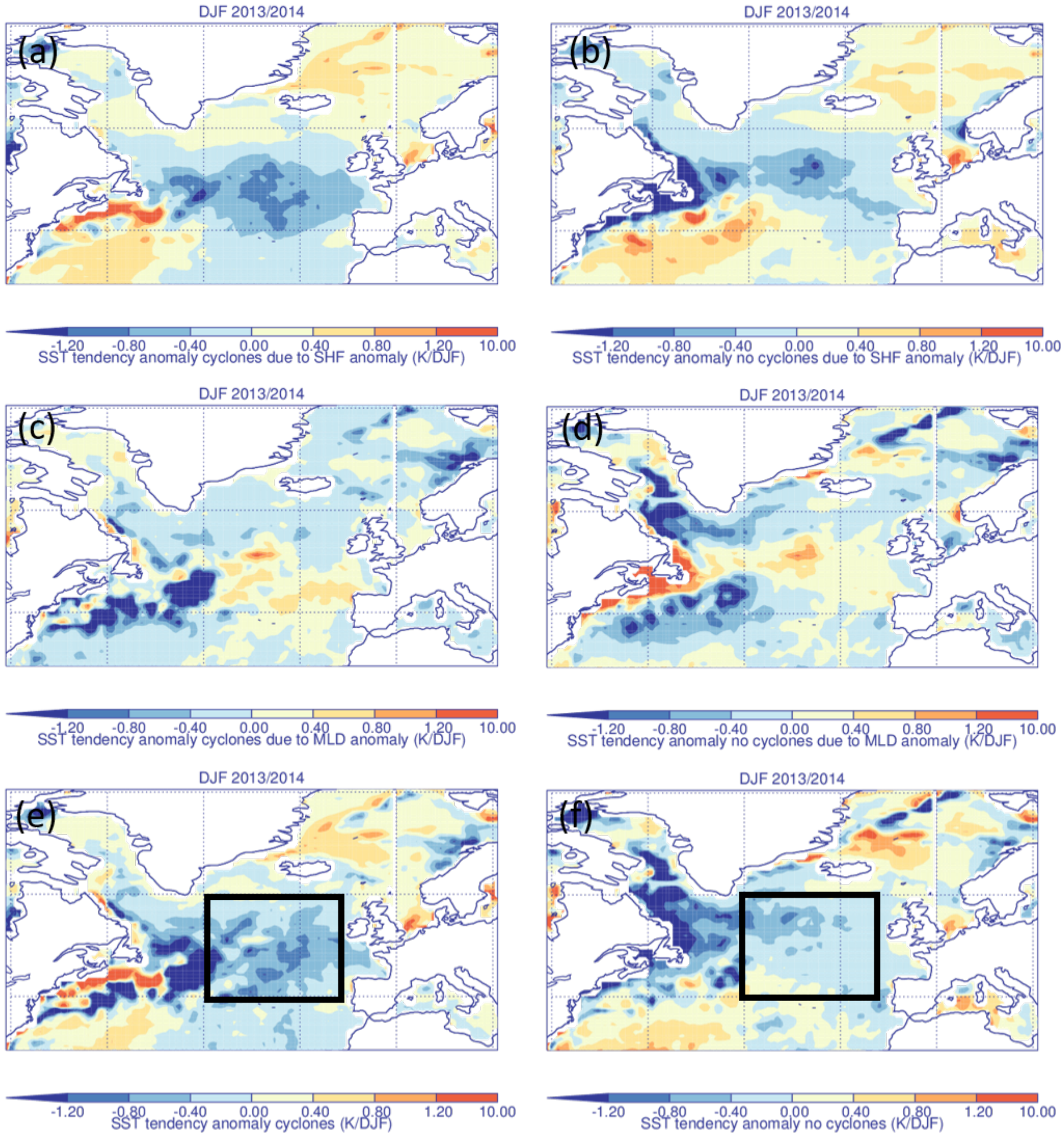

Figure 3: 2013/2014 anomalous SST tendency associated with (a) Q_N anomaly due to cyclones, (b) Q_N anomaly due to not associated with cyclones, (c) MLD anomaly when cyclones present, (d) MLD anomaly when cyclones not present, (e) sum of Q_N, MLD and entrainment anomalies when cyclones present and (f) sum of Q_N, MLD and entrainment anomalies when cyclones not present.