H. F. Dacre, S. A. Josey, A. L. M. Grant

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Reply to reviewer 3

I 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 Authors present an interesting analysis using ERA-Interim data to address the question how extratropical cyclones influence the SST in the Atlantic. They showcase one particular year that featured a significant SST anomaly and try to attribute a large fraction of this anomaly to anomalous cyclone activity in the same winter. The manuscript is well written and the figures are clear, though the panel labels are sometimes difficult to see as they are on top of shaded figures. Overall, the paper presents a valuable contribution to the field and employs a novel diagnostic to attribute the surface fluxes to individual cyclones.
Thank you.
However, there are several points in the paper that need further clarification, which are indicated in the comments below.

Specific comments

1. The mixed layer calculation has a caveat, because the authors assume that the depth has no variations throughout the year when they make seasonal budgets. One particular issue with that is that as the mixed layer depth changes, the sea state properties, in particular the stratification below the mixed layer, become important when the mixed layer depth increases. The actual heat content in the mixed layer will depend on the sea state below the mixed layer as well when net surface flux causes mixing. The entrainment of sea water below the column would need to be considered when the fluxes imply a net change in mixed layer depth. It would thus be interesting if the authors also show the seasonal tendency of the mixed layer depth in figure 3, not only the tendency in SST. Given the actual change of mixed layer depth together with the ocean stratification below the mixed layer could yield an estimate of the entrained energy into the changed mixed layer from below. This additional term in the heat budget could be accounted for and contrasted with the net surface forcing of the SST tendency.
   Figure 1 shows the climatological MLD and MLD seasonal tendency. The MLD and

MLD tendency patterns are very similar with greatest deepening of the mixed layer occurring where the average MLD is deepest. We have not added the additional figure to the paper but added that 'On average the MLD deepens by 50% *between December and February outside the deep convection regions' to the paper text*.

The reviewer is correct that the entrainment of sea water at the base of the ocean mixed layer is important. Figure 2(a) shows the 2013/2014 SST tendency anomaly, $\Delta SST'$*, that is associated with anomalous* Q_N*. As expected* $\Delta SST'$ *due to anomalous* Q_N *closely resembles the* Q_N *anomaly (shown in figure 9(f) in 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. Small differences are due to spatial inhomogeneity in the North Atlantic climatological MLD. Figure 2(b) shows the 2013/2014* $\Delta SST'$ *that is associated with anomalous MLD. The 2013/2014 MLD is shallower than the climatological average over much of the domain, particularly near the Gulf Stream region, and deeper than climatology in the mid-Atlantic region. In the mid-North Atlantic the enhanced negative* Q_N *results in negative buoyancy and mixing, deepening the MLD. Thus, the surface flux decreases the temperature over a deeper layer of the ocean than usual which reduces the direct SST cooling due to* Q_N*. At the same time, the increased MLD entrains colder water at the base of the ocean mixed layer which cools the surface indirectly. This effect is estimated to be* 20% *of the* Q_N *anomaly (Stull, 2012). Neglecting contributinos made by wind driven turbulence. Figure 2(c) shows the sum of the SST tendency anomaly due to anomalous* Q_N*, MLD and entrainment (referred to as the SST tendency anomaly due to air-sea interactions in the paper,* $\Delta SST'_{ASI}$*). It shows the same tripole pattern as the* $\Delta SST'_{TOT}$ *(figure 2(d)) which has an average SST cooling amomaly of -1.0K in the mid-North Atlantic region (black box in figures 2(d)). The largest discrepancies occur along the east coast of North America suggesting that ocean dynamics is responsible for transporting warmer water into these regions via the western boundary currents. In the mid-North Atlantic region, the* $\Delta SST'_{ASI}$ *accounts for* 68% *of the observed anomalous cooling in the mid-North Atlantic. This figure and explanation has been added to the paper.*

2. Regarding the methodology of cyclone frequency, it is not clear if every cyclone is counted multiple times for the track densities of if some kind of anti-aliasing was employed. This would also influence how storm track activity is defined, as fewer but slower moving storms would yield a higher storm activity in terms of cyclone density compared to the same number of cyclones in a season with hizher phase velocity. It would be great if the authors could further clarify how the cyclone track densities were calculated and how exactly one can thus understand an increased activity of cyclones. It would also be of interest if there were more extreme cyclones that particular year of interest, especially as the authors limit their analysis to the more intense systems.
In this paper the effect of propagation speed is taken into account in the masking methodololgy since multiple timesteps for a single cyclone contribute to the seasonal climatological cyclone-related Q_N*. As a result, the high mask fraction over the UK in the 2013/14 season occurred because there were both a higher than average number of cy-*

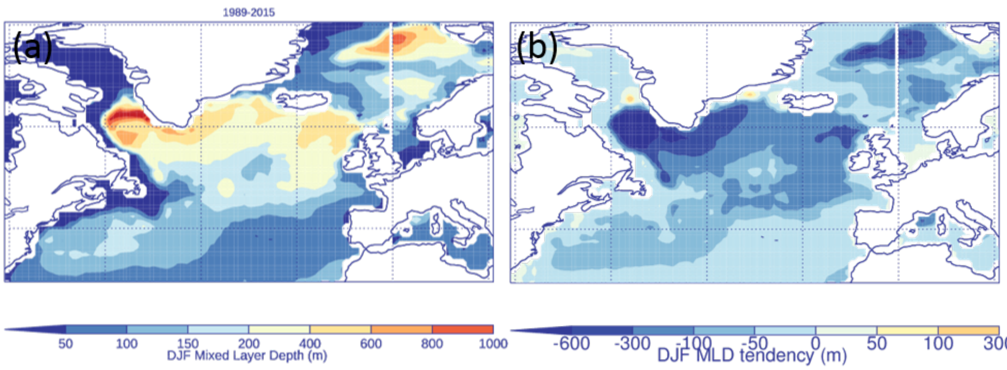

Figure 1: North Atlantic DJF 1989-2015 (a) mixed layer depth and (b) mixed layer depth seasonal tendency (m).

clones and because the cyclones slowed down becoming quasi-stationary over the UK. This clarification of the methodology has been added to the text. The analysis for the 2013/2014 season is not limited to intense cyclones as all cyclones are considered.

3. A large fraction of the fluxes in the Gulf Stream region are associated with cold air outbreaks, of which a significant fraction is not necessarily associated with cyclones in the storm track region. Could the reduced QN fluxes in 2013/2014 south of the Gulf Stream region as well as in the Nordic Seas be thus actually associated with a reduced number of cold air outbreaks? For the Nordic seas, which also feature a significant anomaly in the presented analysis, Papritz and Spengler (J. Clim., 2017) showed that cold air outbreaks account for the larges fraction of the surface fluxes in this region. Thus, the apparent anomalies are most likely mainly attributable to variations in cold air outbreaks and maybe only indirectly or in a reduced way associated with extra-tropical cyclones. Papritz and Grams (GRL, 2018) investigated the weather regimes associated with cold air outbreaks in the region of interest in the manuscript at hand. It would be interesting to put their findings and the given role of cold air outbreaks on the surface fluxes in the region in context with the presented findings.
It is possible that the reduced Q_N flux in the Gulf Stream region and in the Nordic Seas are associated with cold air outbreaks. Indeed, in the revised version of the paper we attribute these positive heat flux anomalies to the environmental flow pattern which was anomalously zonal, potentially reducing cold air outbreaks. Therefore we have added this explanation to the paper and referenced the papers suggested.

4. In addition to cold air outbreaks, the role of cold fronts for surface fluxes in the Gulf Stream region has also been discussed recently, e.g., Parfitt and Czaja (2016) and other recent studies by the first author. It would be great if the authors could provide further context of the presented work to these studies.
Since we have focussed our analysis on the mid-North Atlantic region and not the Gulf Stream we have not included a detailed discussion of the relationship between this work and that presented by Parfitt and Czaja (2016). However, in future studies we will extend this work to other regions so we thank the reviewer for this reference.

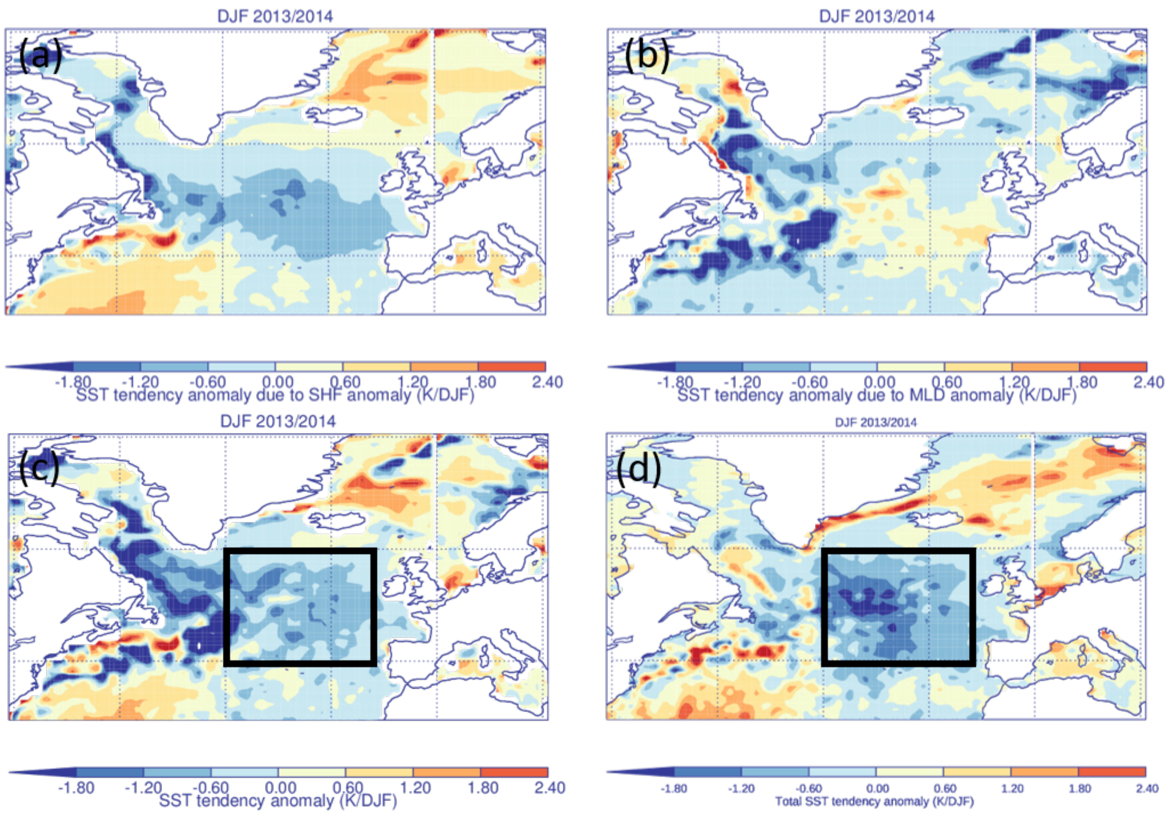

Figure 2: $\Delta SST'$ due to 2013/2014 (a) Q_N anomaly, (b) MLD anomaly and (c) air-sea interaction anomaly. (d) $DeltaSST'_{TOT}$.

5. The method to define the QN with the cyclone masks is not clear enough. It is difficult to follow what is actually summed up. At each time t for a given cyclone, the position of the cyclone and the preceding 30 hours positions are used, but is this done for every timestep in the cyclone evolution? How would this differ to just taking the swath with circles around all cyclone positions along the entire cyclone track? It would be great if the authors could provide further details about the employed method.
The reviewer is correct. The mask method is performed for every timestep in the cyclone evolution, which is equivalent to taking a swath with circles around all positions along the cyclone track, but only the track in the preceeding 30 hours, not the entire length of the track. We have made this method clearer in the revised paper.

Technical comments

1. P1 L7: The connection between the "cold wake" and "climatological variability" is not quite clear in this sentence. How is the size of the cold wake associated to climatological

variability?
Here we specifically refer to climatological variability in the SSTs. We have clarified this in the text.

2. P1 L21: The argument about the role of cold fronts has also been discussed more recently, e.g., Parfitt and Czaja (2016) and other recent studies by the first author. What is the context of the presented work to these studies?
Links to more recent work is made in the introduction (lines 46 onwards). We have added a reference to Parfitt and Czaja (2016) in this section.

3. P2 L29: After citing the study by Zolina and Gulev (2003), the reader is a bit confused about the thus far identified fluxes associated with extratropical cyclones. If there is a controversy, it would be great if the authors could further highlight these conflicting results and possibly indicate as to why they are conflicting or if they will address these contrasting results.
We have expanded the description of the results in this paper which suggest at least partial cancellation of the flux anomalies associated with cyclones.

4. P2 L28" . . . of the wind driven. . .
Corrected.

5. P2 L44: The authors comment on the role of ocean dynamics in the western Pacific, where oceanic advection probably plays a dominant role. However, the reader is left wondering if not similar arguments would also apply to the western Atlantic, the focus of this study, where strong oceanic currents are present. Are there no studies quantifying the role of oceanic anomalies in the western Atlantic? Good if the authors can also comment on the region of their interest in this context.
We have included a reference to Buckley et al. (2015) who also find that in the Gulf Stream region, ocean dynamics are important in setting the upper-ocean heat content anomalies on interannual time scales and that air–sea heat flux damp anomalies created by the ocean.

6. P2 L51: Another, more direct, connection between cold air outbreaks, cyclones, and the low-level baroclinicity in the western Atlantic is provided by Papritz and Spengler (2015) as well as Vanniere et al. (QJ, 2017).
Papritz and Spengler (2015) is cited in the previous sentence so we have not added a further citation here.

7. P5 L128: "the winter"
Corrected.

8. P7 L140: See general comment about change of mixed layer depth throughout season. Some additional discussion about the influence of mixing and entrainment in the ocean would be valuable.
See response to general comment 1.

9. P7 L144: "heat fluxes occur"
Changed to 'heat flux occurs'.

10. P7 L147-149: This is also the argument of a recent study by Ogawa and Spengler (2019), who also emphasized the role of synoptic eddies on the climatological fluxed in the mid and higher latitudes.
Thank you for this reference, we were not aware of this paper. A citation to this work has been added.

11. P9 L183: "the cyclone lifecycle"
Corrected.

12. P11 L203: "the surface flux"
Corrected.

13. P12 L216: It is not necessarily obvious from the referenced figures that the storm track was more active, see general comment on cyclone track densities.
See response to specific comment 2.

14. P13 L223: It is difficult to see how the QN anomaly and the storm track anomaly is "consistent". There appear to be more cyclones detected over the Gulf Stream region in the anomalous winter, though the net negative QN fluxes in this region appear to be reduced when compared to climatology. How can this be reconciled with the previous findings of the cyclone relative QN fluxes and SST changes?
We agree that the relationship between the Q_N anomaly and storm track anomaly is not clear close to the continental regions where ocean dynamics are dominant. For this reason we have chosen to focus on the mid-Atlantic region only in the paper. We have re-written the text to emphasise that the anomaly in the mid-Atlantic region is consistent with the shift in the storm track, with cyclones travelling more zonally from the US towards western Europe rather than north-eastwards towards Iceland.

15. P14 L225 and following: The methodology is not quite clear, see also general comments.
See response to general comment 2.

16. Fig. 9 caption: "red crosses show"
Corrected.

17. P15 L246: "conclusion does not"
Corrected.

18. P16 L250: It is not clear that the results indicated in this paragraph consider the data based on the cyclone swaths from the previous section.
We have re-written this section of the paper to respond to comments from reviewer 2.

19. P16 L254: The actual percentage of the SST difference cannot be really directly contributed to the fluxes, as it is a mix of local fluxes and advection, as well as entrainment from below that caused the total change. There can be compensating effects that cannot be accounted for in such a crude attribution without actually calculating a full budget considering all tendency terms.
We agree that several factors contribute to the SST tendency anomaly and that they might be compensating. We have estimated the SST tendency anomaly due to (i)

anomalous Q_N , (ii) anomalous MLD and (iii) anomalous entrainment. Therefore, we have performed a more complete analysis of the air-sea interactions and indeed there are compensating effects which are now described in the revised paper.

20. P17 L262: Can the authors comment further on the relative contributions of potential other effects that make the attribution to individual cyclones difficult?
We have decomposed the total SST tendency anomaly due to Q_N into three components (see figure 1). We have attributed the difference between the sum of these components (referred to as air-sea interactions) and the total SST tendency anomaly to be due to advection. We note that there are significant assumptions in this method but are confident that the main conclusion that cyclones enhance SST cooling in the mid-North Atlantic region is robust.

21. P17 L266: The statement about "higher than average cooling" appears to be rather regionally confined and there were also larger areas where this particular season featured reduced air-sea heat exchange. The authors should comment on this complex structure and put it in context to the observed cyclone distribution. Especially the western Atlantic area with reduced fluxes appears difficult to explain given the increased number of cyclones (Fig. 8f, 11d).
Over almost the entire domain cyclones decrease the SSTs. The reduced air-sea heat exchange over the Gulf Stream and Norwegian Sea is controlled by the environmental flow anomaly. This explanation has been added to the paper text.

Buckley, M.W., R.M. Ponte, G. Forget, and P. Heimbach, 2015: Determining the Origins of Advective Heat Transport Convergence Variability in the North Atlantic. J. Climate, 28, 3943–3956, https://doi.org/10.1175/JCLI-D-14-00579.1

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