Tropical cyclone intensification and extratropical transition under alternate climate conditions: a case study of Hurricane Ophelia (2017)

Reviewer 2

Overall assessment: In general, I find this study both interesting and valuable to the scientific community. It provides insights into the response of post-tropical cyclones to a warmer climate and their potential impacts on regions like Western Europe. Additionally, the study explores the physical mechanisms behind changes in the storm's structure, behavior, and impact in response to various warming and cooling scenarios. However, I do have some concerns and/or required clarifications. These are highlighted in subsection below. I suggest publishable with major revisions, since I believe the authors need to make some rather substantial text modifications and additions to fine-tune the message of this study. I think the manuscript will be publishable after some more work.

We thank the reviewer for their kind words and their time and effort taken to review our manuscript.

Major comments:

1) **Introduction: The introduction is generally well-written, providing the background and motivation for this study. However, the specific research question or hypothesis could be clearer. For example, explicitly stating what the paper aims to address or how it intends to fill a gap in the current literature would strengthen the introduction further. Additionally, details about the chosen case could be moved to later sections (e.g., Section 3.1; this section is too short), allowing the introduction to remain focused and concise, while the authors briefly mention it. Aside from the introduction, the following sections are quite similar, with only a few lines presented in each.**

We thank the reviewer for suggesting the clarification. We will move the case study details into their own section and clarified the aim of the paper.
The end of the introduction will be adjusted to:

"There have been many case studies on PTCs in the last several decades, especially in the North Atlantic (Atallah and Bosart, 2003; Evans and Hart, 2008; Feser et al., 2015; Galarneau et al., 2013; Jung and Lackmann, 2019; McTaggart-Cowan et al., 2004; Thorncroft and Jones, 2000). However many of these focused on US-impacting storms, and those that do impact Europe are only studied in current climate conditions. As far as the authors are aware, no specific case studies have been done on Europe-impacting transitioning storms incorporating climate change factors. In this study, we therefore aim to fill this gap by examining the changes in the structure, behaviour, and impacts of

Hurricane Ophelia under alternate climate scenarios, paying particular attention to the changes in Ophelia's ETT. We use a ΔT approach utilizing the Regional Atmosphere Community Model (RACMO) model. The results show that Ophelia becomes a larger and stronger storm under warmer climate conditions. The outcomes can be used to demonstrate the increased risk posed by the expected increase in such storms under climate change conditions"

2) **Introduction: It would be helpful to include a brief outline of the paper, as this can guide the reader and give them an idea of what to expect in each section.**

We appreciate the suggestion, and have added such an outline to the introduction.

"Section 2 provides a description of the case study. The data and methods used in this paper are described in Section 3. We present the results of our analyses in Section 4 and discuss the study in Section 5. Finally we conclude the paper in Section 6."

3) **Section 2: This section contains numerous subsections, many of which are only a few lines long. Please consider consolidating these subsections to make the content more concise. For example, sections 2.6.1 and 2.6.2 can be combined.**

Upon recommendation of the reviewer, we have combined the subsections of 2.6 into one section, simply titled "Quantifying Extratropical Transition". Additionally, sections 2.4 and 2.5 have been combined into "Cyclone tracking and Footprint".

4) **Lines 220-222: If this is the case, I think the large deficit in MSLP (e.g., 912 hPa) should not be captured in these simulations either. There seems to be misrepresentations somewhere in the dynamical processes that prevent the storm from achieving the gradient wind balance. Additionally, if the authors used instantaneous maximum wind speeds recorded at specific time intervals (e.g., hourly output data; please also specify the frequency of output from your simulations), they might have missed the actual maximum wind speed that occurred between these intervals. On the other hand, as the authors described, IBTrACS provides 1-min average maximum sustained wind speed.**

To the first point, while the model is limited in how realistically it represents the gradient wind balance, it still represents a storm that looks realistic in terms of wind field and overall structure. This is not uncommon for regional models, for instance Arpège can also severely overestimate TC intensity but still generally has a realistic representation (Chauvin et al., 2020). There is clearly a limitation to the model here, but the simulations do well otherwise to represent the intensity and evolution of Ophelia.

To the second point, we have used instantaneous maximum wind (hourly output data). We have added this to the manuscript to further clarify our process. However, as a final note, there are no direct observations of Ophelia, only estimates based on satellite representation (Stewart, 2018). We have no way of ruling out that Ophelia at some point had an actual core pressure of 930-940hPa, albeit unlikely.

5) **Lines 223-225: After October 16, it is possible that all the simulated storms begin interacting with land, which could significantly influence wind speed. Although the +2~+4 storms are located further west compared to the cooler ones, their larger storm radius suggests they may begin interacting with land. Line 243 may support this speculation. Please consider adding information about the size of the simulated storms for clarification.**

This is a possibility, but this would mainly be the outer regions of the storm, which may not have as much effect on the peak intensity of the storm, which is present near the core of the storm, which is still far out at sea (hundreds of km away). Additionally, the 10m wind footprints in Figure 8 don't seem to support this hypothesis of land interaction. The contour plot in Figure 8 shows a westward movement of the 20 m/s contours under warmer scenarios, indicating a shift *away* from land.

A different contributing factor to the similarity in peak wind speed between may be that despite the storms in the warmer scenarios having a much deeper central pressure, they also grow in size. We therefore believe that the pressure gradients, which directly influence the peak wind speeds, are quite similar amongst the different climate runs, thereby keeping the wind speeds approximately the same across the different runs.

To better understand this, we will do an analysis of storm size based on the sizes found in Figure 4(c), combined with a distance from land calculation to determine at what time each storm starts interacting with land based on the 17 m/s boundary. Also, we will examine the pressure gradients around the storm in each simulation to determine if this also contributes to the weakening in wind speed.

6) **Lines 293-295: Do the authors have any insights on why warmer storms remain symmetric for longer? The parameter B, determining the onset of ET, basically represents the difference in atmospheric thickness between the left and right sides of the storm, and since all the experiments are conducted under uniformly warmed or cooled conditions, there shouldn't be any temperature gradient differences among them. Additionally, it seems there are no noticeable differences in their locations at the onsets.**

Figure 4 shows that the storms in warmer conditions become stronger than the storms in cooler conditions. Stronger storms can pump more heat into the atmosphere (as seen by the higher values of $-V_T^U$ in Figure 6). This allows them to better condition the atmosphere around them and create a larger environment conducive to strengthening in which the storm can move. Thus the left/right sided difference that is measured for the B parameter takes longer to get close to the core. To better illustrate this, we will add a supplementary figure looking at geopotential height differences of the 500 km radius circles for each of the storms at several times.

7) **Lines 345-346: I think this statement is true depending on cases. Typically, TCs undergoing extratropical transition experience an expansion of their wind field, with the radius of maximum winds increasing and the overall wind structure becoming broader and more asymmetric. Additionally, as these storms interact with upper-level waves, their translational speed often accelerates significantly, similar to that of extratropical cyclones. Please consider revising or rephrasing this discussion.**

We thank the reviewer for their contribution to this discussion. We will be editing the discussion read the following:

"TCs bring a different structure and impact footprint than ETCs: in general, TCs are stronger (in terms of wind speed) storms than ETCs. TCs also have only slight wind field asymmetry due to the influence of lower translation speed and vertical wind shear. These influences, however, are larger in ETCs which therefore show larger wind field asymmetries (Jones et al., 2003).
PTCs can display a mixture of TC and ETC characteristics, especially while they are still transitioning from one to the other. As they undergo ETT, the radius of maximum wind increases and the entire wind field expands and becomes more asymmetric (Evans et al., 2017). Their translation speed also often increases as a result of interaction with upper level jets, which adds to the wind field to produce stronger wind speeds even as the pressure-induced wind field weakens (Hart & Evans, 2001). As such, PTCs can bring high wind speeds similar to TCs over a large area like ETCs, increasing the potential damages."

8) **Figure A1: Do the five different initialization times lead to significant differences in storm size? For the simulations initialized on 14 and 15 Oct, no significant differences are seen in tracks. As discussed in the main manuscript, all the storms in these sets of simulations have similar storm size, so they are less affected by the beta drift? If the warmer storms become larger, does the hypothesis that beta drift drives the westward shift of the warmer storms still hold? Beta drift should become more pronounced at higher latitudes.**

We thank the reviewer for their thoughts on this. We have produced several figures to help answer this, these can be found in the Appendix.

Storm size

We investigated this phenomenon by plotting the storm size as in Figure 4(c) for each of the initialization times and for each of the ΔT levels (see Figures R1 and R2).

All initialization times show a difference in storm size, though to varying degrees (Figure R1). This is most pronounced in the earlier initialization times, and only very minimal in the 15 October initialized simulation. We also see that for the same level of ΔT, storms initialized earlier have a larger storm size than those initialized later (Figure R2). This is likely related to the same issue mentioned in lines 460-461 and 471-472 : the earlier the simulation is started, the more time it has to adjust to the alternate climate conditions. Additionally, the earlier the simulation starts, the more time the storms have to diverge from one another.

Beta Drift

While the storm sizes *do* increase with increasing ΔT, beta drift is calculated with the R_{max} instead of the 17 m/s wind contour. Our choice for still using storm size for much of our analysis is motivated by the impacts section of our research: areas outside the R_{max} zone can still experience powerful impacts.

The R_{max} values tend to decrease at the beginning of the simulation, with the warmer simulations showing a much sharper decrease than the cooler simulations (Figure R3, left column). This can also be seen in the contraction of the eye in the storm size plots of Figure R1. At the same time we see an increase in maximum windspeed (Figure R3, middle column). All of these point to a strengthening of the storms due to a conservation of angular momentum. Beta drift, as a combination of these two factors, shows an initial decrease followed by a gradual increase and general stratification by applied ΔT (Figure R3, right column).

In the 14 and 15 October simulations, the difference in R_{max} between the simulations is not as pronounced. Additionally, there is not as much time for the slow expansion of the R_{max} after the initial strengthening decrease, but before the rapid increase also visible in the storm size plots (Figure R1).

Therefore, while we do see an overall larger starting value of the beta drift in the later simulations due to higher latitude and higher starting Vmax, due to the lack of adjustment time we do not see a large spread of track locations as we see in earlier simulations.

9) Beta drift: It appears that the calculated beta drift among the simulations converges to values within 0.3 m/s after 15th Oct., while the jet streams on 16th show a more diverse distribution (Fig. B2). Could this variation in jet stream distribution be driving the track divergence, rather than the beta drift? Related to this question, Lines 253-256: However, during this period, the warmer storms do not show a noticeable westward shift in their tracks. The significant divergence becomes apparent after the 15th, when the beta drift converges.

We agree with the reviewer that the jet variation is involved in the track divergence, as explained also in Section 3.2.3. However we believe that the track divergence is due to a combination of both the beta drift and the jet variation.

Figure B3 only included the beta drift and R_{max} until the 16th of October because after this, due to the rapid expansion of the R_{max} associated with the ETT, it was difficult to see the more subtle variations in the beta drift in the tropical and transition phases of the storm. Figure R4 shows the more complete version of Figure B3. We see there that the beta drift values diverge there, with the +4 °C simulation obtaining the highest value of peak beta drift, and the -2°C the lowest.

With the exception of the -1°C simulation, the relationship of storms in warmer simulations experiencing stronger beta drift is maintained (see Table R1). The high beta drift of the -1°C scenario can be attributed to an anomalously high R_{max}.

Ranking	Simulation	Peak beta drift (unconvolved) (m/s)
1	+4	4.72
2	-1	4.44
3	+3	4.38
4	+2	4.18
5	+1	4.17
6	0	4.14
7	-2	3.21

Minor specific points:

1) **Line 80: Please complete the sentence.**

   We completed the sentence by filling in the reference that mistakenly was not inserted. Additionally, we added the equation for the wind speed conversion to make this clearer.

2) **Lines 106-109: Consider rephrasing these lines.**

   We will adjust these lines to:

   "The initialization time for the RACMO simulations is 12 October 2017 00 UTC. We initially ran six RACMO simulations of Ophelia with initialization times of 00 UTC on 09 – 14 October 2017. The tracks and central pressure profiles of these simulations are shown in Figure B1.

   The simulations initialized on 9, 10, and 11 October were not able to capture the observed strengthening of Ophelia as a hurricane and had quite large track deviations from the IBTrACS best track. The simulation initialized on 13 October strengthened rapidly, surpassing the observed pressure values substantially, but also showing large track deviations. The 14 October simulation had a more reasonable track and smaller pressure deficit, but due to its late start it would not be possible to examine the ETT properly. As such, we chose the 12 October initialization. This is quite close to the 12 October 2017 13 UTC initialization time chosen by Rantanen et al. (2020) when they modeled Ophelia, citing a similar problems with lack of strengthening. "

3) **Figure B1: The IFS is not represented in this figure. Are the solid lines derived from GFS forcing data? Please clarify the figure caption.**

   We thank the reviewer for pointing out this mistake, we will adjust the figure caption to read:

   "Track (a) and minimum central pressure (b) for Hurricane Ophelia for the current climate downscaled RACMO simulations with GFS boundaries with varying initialization times. The black dashed line is the IBTrACS observations, and the pressure time series derived from the ERA5 reanalysis and the GFS analysis data are included in (b)."

4) **Figure 3: Please add the storm's daily locations to the inset figure.**

   We have added the daily locations to the inset figure, both for the RACMO and GFS simulations.

5) **Line 204: This study does not use the PGW approach. Need to be rephrased.**

Following the reviewer's suggestion, we have decided to omit the term PGW and change this to "alternate climate scenarios".

6) **Figure 4(c): Please clarify this figure. It seems the authors are trying to show storm size based on the 17 m/s threshold. What exactly does the y-axis value represent? Is it latitudinal distance, and if so, relative to what? The storm centers?**

We apologize for the confusion. Figure 4(c) shows the extent of 10 minute sustained 17 m/s wind in a slice through the storm centre, in degrees relative to that centre point. As both reviewers raised this concern, the caption will be adjusted to read:

"*Track (a), minimum central pressure (b), north-south diametric slice of extent of 10-minute sustained 17 m/s wind, in degrees relative to storm centre (c), and 10-minute sustained 10m maximum wind (d) of Hurricane Ophelia for the alternate climate downscaled RACMO simulations with GFS boundaries, initialized at 12 October 2017 00 UTC. Dashed line (black dots in (d)) are IBTrACS observations. (a) Circles plotted at 00 UTC of the date indicated. Shading in (c) is the extent of the 0°C simulation.*"

7) **Line 249: Please consider providing the formulation applied in this study so that readers can better understand the environmental factors contributing to the shift in the simulated storms.**

We thank the reviewer for the suggestion, and will add the respective formulas to the manuscript:

$$BD = 0.72B^{-0.54}r_{max}^2\beta$$

where $$B = \frac{r_{max}^2\beta}{V_{max}}$$

8) **Lines 345-346 and others: What does Bft mean?**

We apologize for the confusion. Bft is short for Beaufort, a wind categorization system commonly used in (Western) Europe. We will clarify this term in the text.

Appendix

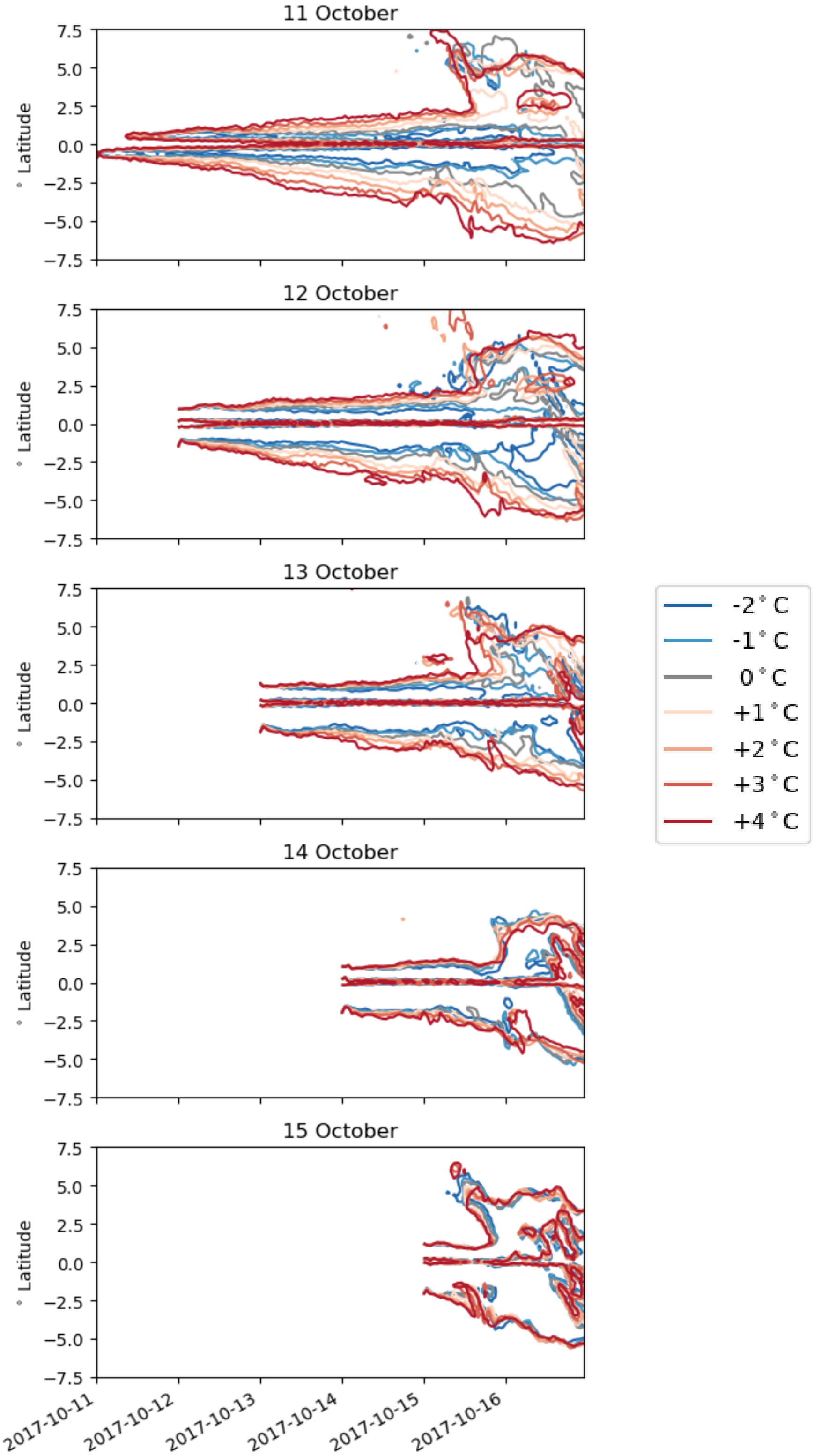

Figure R1: North-south diametric slice of extent of 10-minute sustained 17 m/s wind, in degrees relative to storm centre for each of the 5 simulation times and 7 ΔT levels, grouped by simulation time.

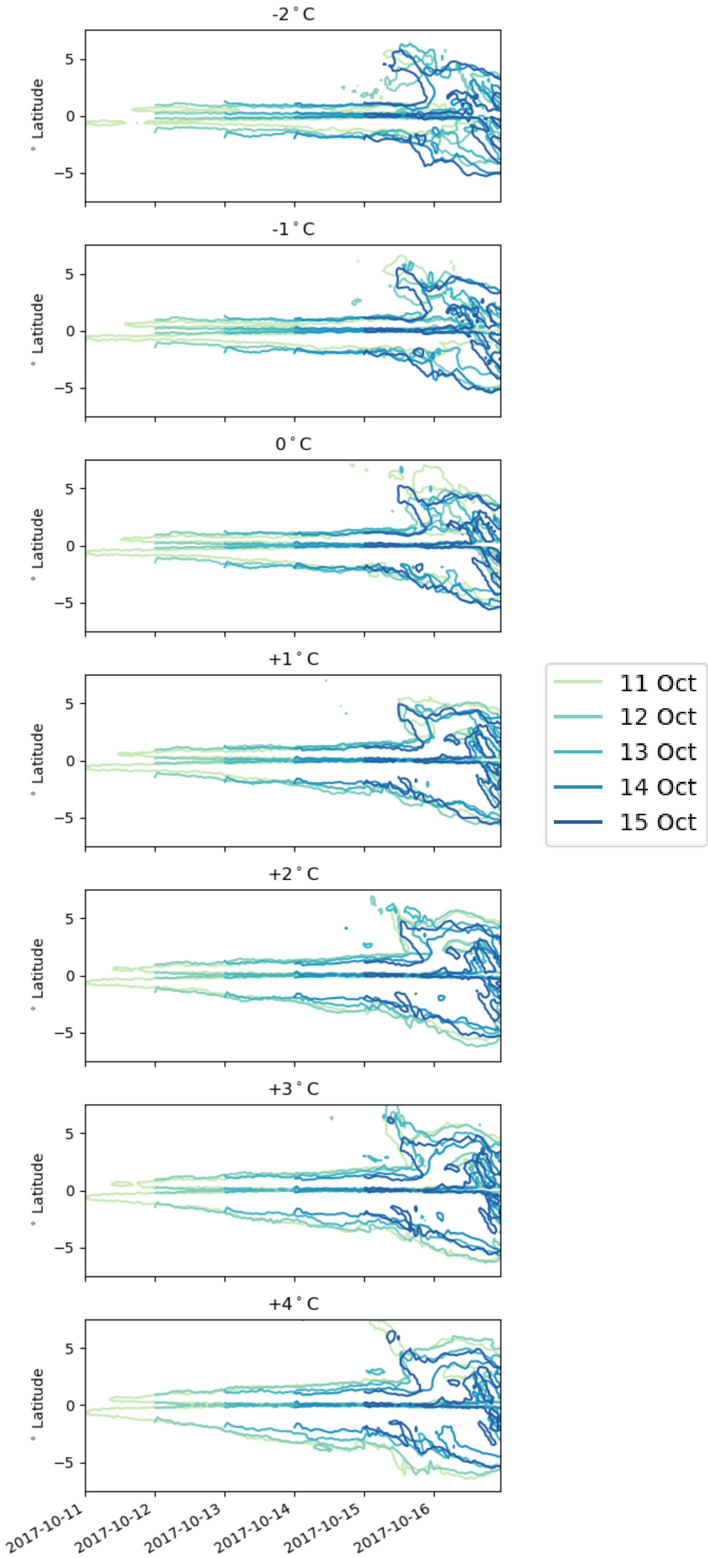

Figure R2: As in Figure R1 but grouped by ΔT level.

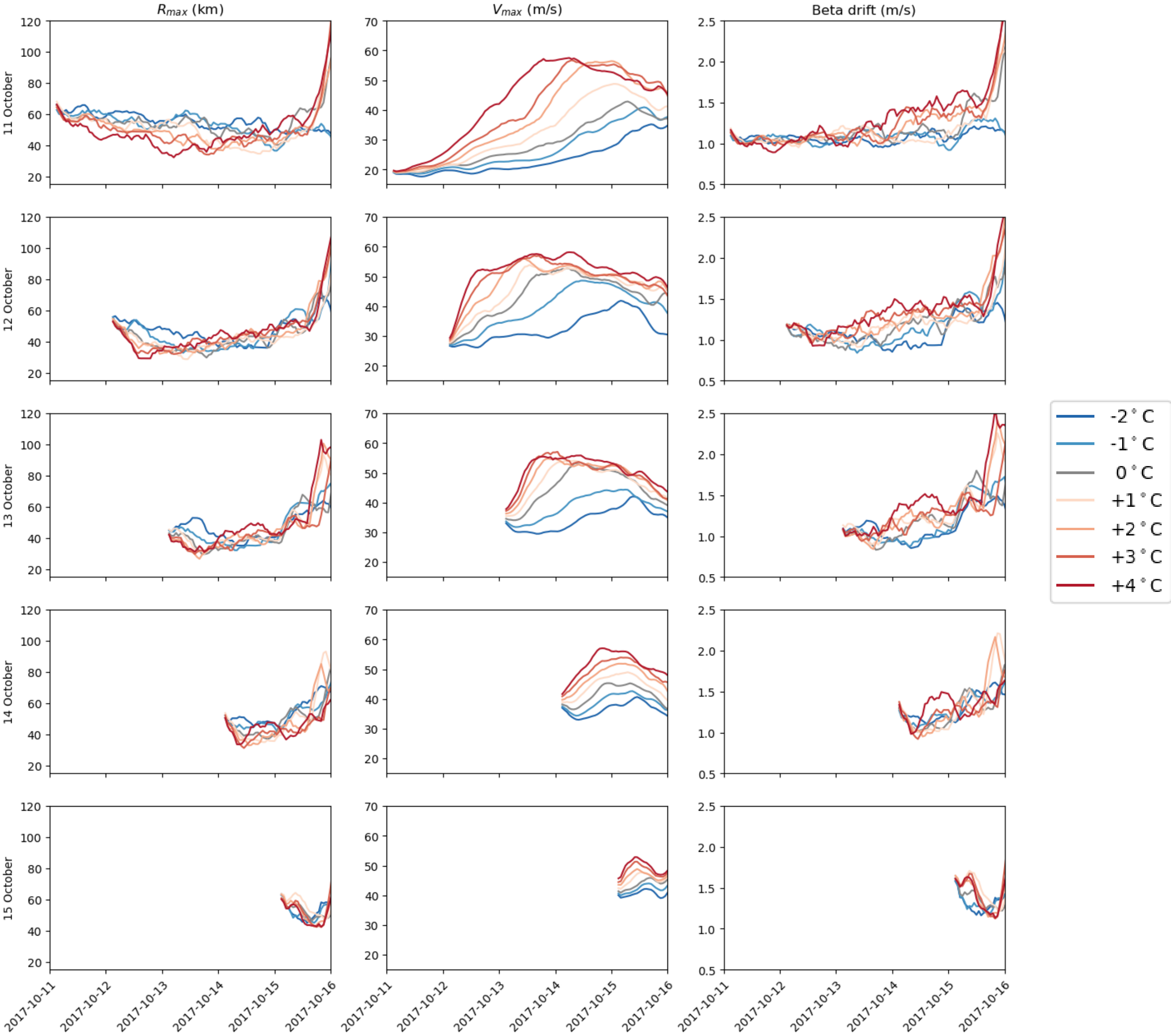

Figure R3: R_{max}, V_{max}, and Beta drift for the 5 simulation dates (11-15 October) and 7 ΔT levels (-2 to +4). 6 hour convolution applied to all variables, so plotting starts at 6 hours past initialization time as labelled. Time axis capped at 2017-10-16 to examine tropical phase.

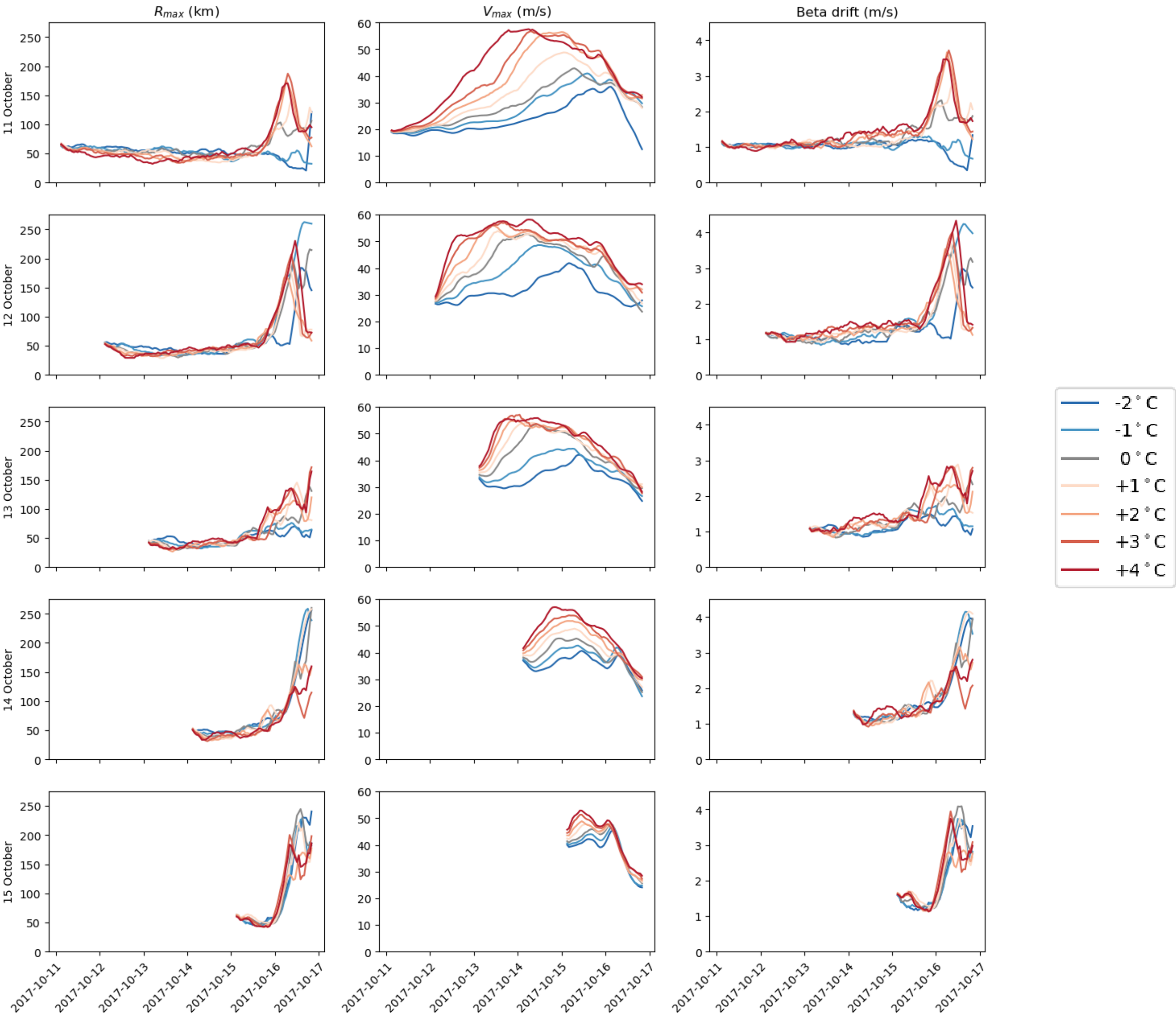

Figure R4: As in Figure R3 but for the full simulation. 6 hour convolution means plotting stops at 16-10-2017 18 UTC.

Chauvin, F., Pilon, R., Palany, P., & Belmadani, A. (2020). Future changes in Atlantic hurricanes with the rotated-stretched ARPEGE-Climat at very high resolution. *Climate Dynamics*, *54*(1), 947–972. https://doi.org/10.1007/s00382-019-05040-4

Evans, C., Wood, K. M., Aberson, S. D., Archambault, H. M., Milrad, S. M., Bosart, L. F., Corbosiero, K. L., Davis, C. A., Pinto, J. R. D., Doyle, J., Fogarty, C., Galarneau, T. J., Grams, C. M., Griffin, K. S., Gyakum, J., Hart, R. E., Kitabatake, N., Lentink, H. S., McTaggart-Cowan, R., … Zhang, F. (2017). *The Extratropical Transition of Tropical Cyclones. Part I: Cyclone Evolution and Direct Impacts*. https://doi.org/10.1175/MWR-D-17-0027.1

Hart, R. E., & Evans, J. L. (2001). A Climatology of the Extratropical Transition of Atlantic Tropical Cyclones. *Journal of Climate*, *14*(4), 546–564. https://doi.org/10.1175/1520-0442(2001)014<0546:ACOTET>2.0.CO;2

Stewart, S. R. (2018). *Tropical Cyclone Report: Hurricane Ophelia, 9–15 October 2017*. National Hurricane Center.