Reviewer #3:

This paper aims to quantify the impact of air-sea interactions during extreme cyclone events on the structure of the atmospheric and oceanic boundary layers. This is addressed by performing two 33-year simulations using coupled (CPL) and atmosphere only (STD) models. First the cyclone climatologies from the CPL and STD simulations are compared to an atmospheric reanalysis dataset (ERA5). Then the climatological SST fields during extreme cyclones from the CPL and STD are compared to satellite-based SST dataset (MED-REP-L4). Next, the CPL and STD atmospheric fields are compared and finally the evolution of the ocean structure in the CPL simulation is compared to and ocean reanalysis dataset (CMES). I found the paper a bit confusing to read and the grammar is incorrect in many places. The motivation for the analysis and importance of the study needs more emphasis before the paper can be considered to be suitable for publication.

We thank the Reviewer for dedicating time to review our manuscript and for the detailed observations that have raised the quality of the paper.

The valuable feedback has helped us improve the clarity of the work and better emphasise its results and novelty. Specifically, we have significantly revised the Results section to provide a more detailed explanation of the physical mechanisms behind the differences in the atmospheric processes between CPL and STD during extreme Mediterranean cyclones and to address the specific questions raised by the reviewer.

In addition, we have revised the conclusion to emphasize the novelty of the study. Specifically, we modified lines 432-434, as follow:

"*This study investigates for the first time (to the best of our knowledge) how extreme Mediterranean cyclones affects simultaneously the atmosphere and the ocean at different vertical levels, comparing two high-resolution RCM simulations, one atmosphere-ocean coupled (CPL) and one atmosphere stand-alone (STD), over the period 1982-2014*.",

and lines 454-456, as follow:

"*This research highlights the ability of the coupled model to coherently simulate the entire atmosphere-ocean system, thus providing new insights into how sea surface energy is redistributed between the atmospheric boundary layer and the ocean mixed layer, and how this impacts the precipitation and the wind speed during extreme cyclone events*.".

Please note that figures 4, 7 and 9 have been revised following the reviewers' comments. The figures now show latent and sensible heat fluxes, 10 m wind speed, potential temperature lapse rate, convective precipitation and total (large scale + convective) precipitation.

Please also note that the text-line references mentioned in our responses correspond to the revised manuscript.

Below, the Reviewer will find our detailed, point-by-point, answers.

General comments:

1 There are fairly large differences between the CPL/STD cyclone climatologies and ERA5, shown in figs 2 & 3, which are dismissed as small in the paper. Do these differences result in differences in the cyclone-climatology atmospheric fields (precipitation, pbl height, 10m wind speed, evaporation and 2m specific humidity)? Figure 4 does not compare with ERA5 fields so it's not possible to determine the answer to this question.

We thank the Reviewer for this comment. We agree that one may indeed argue that differences among the RCMs and ERA5 are fairly large in Figs 2&3. Nevertheless, differences do not reject the suggestion that "similar" (rather than "identical") spatial distributions, track characteristics and seasonal cycles are followed by all three datasets. This should be an expected result. As also discussed in our replies to Reviewers 1 and 2:

the most intense Mediterranean cyclones are formed due to large scale forcing, i.e. the intrusion of upper tropospheric systems as a result of Rossby wave breaking over the Atlantic Ocean (Flaounas et al., 2022). This upper tropospheric forcing is identically introduced to the two simulations through the boundary conditions. Furthermore, their characteristic length scale allows their realistic reproduction even at relatively coarse resolutions as the ones in ERA5. The development of cyclones though might depend on both the large scale forcing and diabatic forcing due to convection within the cyclone systems. The latter is strongly dependent on the parametrisation, resolution and -therefore- on the underlying SST. In such climate-scales numerical experiments, one should expect thus that cyclones formation should be rather "similar" in the two simulations, but cyclones development might change at the extent that an extreme cyclone is more diabatically driven than developed due to baroclinic instability (i.e. due to the upper level forcing which should be less sensitive to SST). As a conclusion, if we regard a cyclone system as the outcome of large-scale processes (external to the cyclone system) and small-scale processes (internal to the cyclone system), then we should expect atmosphere-ocean coupling to have a stronger effect on the physical processes of the cyclone systems, and a rather weaker effect on their formation distribution and track characteristics. We have modified Fig. 3 and included this discussion in the revised manuscript (section 3.1, "Climatology of extreme Mediterranean cyclones") as follow (L247-271):

"*Figure 3 instead shows the maps of cyclone centre densities (CCD; Neu et al. 2013, Flaounas et al. 2018a) for ERA5 and the differences in CCD between ERA5 and RCMs. The CCD is defined as the absolute number of occurrences of the 500 most intense cyclone centres. To highlight the cyclones' area of influence, each centre is represented by a circular area with radius of 1.5 degrees around the tracked minimum SLP point. Compared to ERA5, both RCMs tend to capture the main regions of frequent cyclogenesis (over the gulf of Genoa, over the Adriatic and Aegean Seas and the marine areas close to Cyprus). This can be expected since the most intense Mediterranean cyclones are formed due to large scale forcing, i.e. the intrusion of upper tropospheric systems as a result of Rossby wave breaking over the Atlantic Ocean (Flaounas et al., 2022). This upper tropospheric forcing is identically introduced to the two simulations through the boundary conditions. However, cyclones seasonality and location also depend on diabatic forcing due to convection within the cyclone systems, as well as on the basin's orography. Both RCMs show a higher occurrence of cyclones in summer and spring (Fig. 2d and Fig. S1 in supplementary) and compared to ERA5, they tend to underestimate the CCD over the Mediterranean Sea while overestimating it over land and over the Aegean and Levantine Sea (Fig. 3b and c). Differences between the two RCMs and ERA5 arise primarily from the different resolution, dynamics and physical parameterisation. These factors influence how the models reproduce key processes, such as. the impact of orography on cyclone dynamics and the role of convection in deepening the cyclones, resulting in local deeper minima of SLP over Mediterranean areas with complex land-sea distribution. Therefore, differences from ERA5 should not be taken purely as a weakness of RCMs, but rather as a result of differences when reproducing atmospheric processes. Indeed, the magnitude of these differences is comparable to the one found in previous studies (Flaounas et al., 2018a; Reale et al., 2022) and thus RCMs should be expected to deviate from reanalysis. In contrast, changes in the SST distribution have a minor impact on the dynamics of the cyclones, leading to small differences between STD and CPL, primarily in the location of cyclone minima over the sea (Fig. 3d). In conclusion, cyclone systems arise from a combination of large-scale processes (external to the cyclone) and small-scale processes (internal to the cyclone). In this context, atmosphere-ocean coupling is expected to have a stronger influence on the physical processes within the cyclone systems, and a rather weaker effect on their formation, distribution, and track characteristics.*"

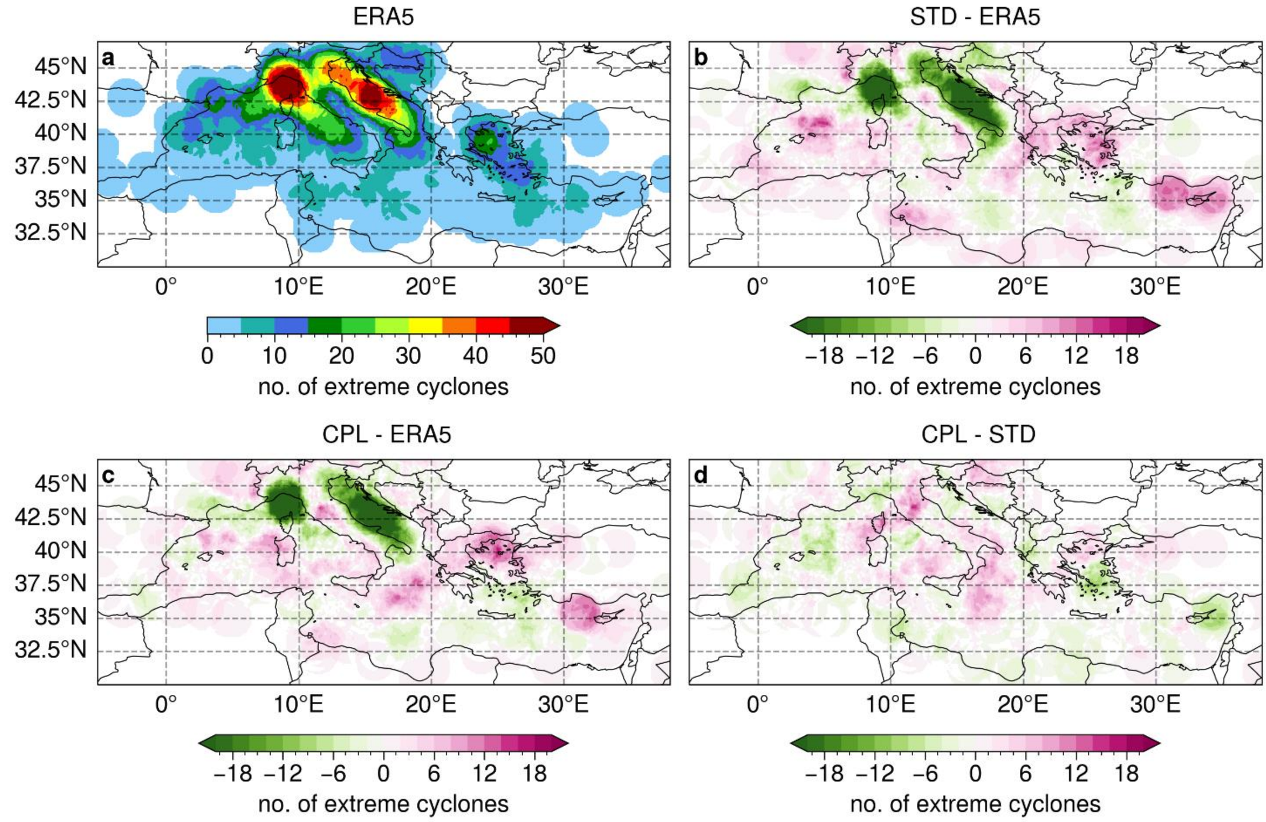

Figure 3: Number of occurrences of cyclone centre densities (CCD) for the 500 most intense cyclones in ERA5 (a), along with CCD differences between STD and ERA5 (b), CPL and ERA5 (c), and CPL and STD (d). To highlight the cyclones' area of influence, each centre is represented by a circular area with radius of 1.5 degrees around the tracked minimum SLP point.

In addition, we attached below the comparison of the atmospheric fields during the 500 most intense cyclones in ERA5, STD and CPL (Figs. A1, A2, A3). In figure A1 we show the distribution of the fields during the 500 most intense cyclones in ERA5, while in figures A2 and A3, we show the differences of STD and CPL with ERA5, respectively. The RCMs tend to underestimate the surface heat fluxes over the sea (Fig A2a, b; Fig. A3a, b), to overestimate the sensible heat over land, especially in the north Africa region (Fig A2b; Fig. A3b), and to present a slightly higher stability of the PBL (higher potential temperature lapse rate) over the south and east Mediterranean Sea (Fig A2d; Fig. A3d). The surface wind speed is higher for the RCMs in most regions (Fig A2c; Fig. A3c), likely due to the higher resolution and different physical parametrisation in WRF, while the convective precipitation is underestimated by RCMs especially over the coastal area. Finally, looking into the total (convective and large-scale) precipitation differences, the RCMs simulate a stronger precipitation over the sea, while over land tend to overestimate it in mountainous regions (Alps, Pyrenees and Greek and Turkish mountains) and underestimate it on the west coasts of Italy and Balkans.

This analysis has not been included in the manuscript because the focus of the study is not to validate the RCMs against ERA5, since is already done by Anav et al. (2024). Instead, our paper investigates how the atmosphere-ocean coupling, resulting in a differing SST distribution between CPL and STD configuration, influences the key atmospheric processes associated with extreme cyclones. We clarified this in the revised manuscript (section 2.2, "storm track method"), as follow (L153-156):

"*A storm track method is applied to both ERA5 reanalysis and RCM simulations. To note that the comparison of the models with ERA5 is restricted to the evaluation of the RCMs' ability to reproduce the climatology of the extreme cyclones, in terms of their seasonal cycle, track characteristics and spatial distribution. In fact, the full evaluation of the RCMs against ERA5 was already performed by Anav et al. (2024).*"

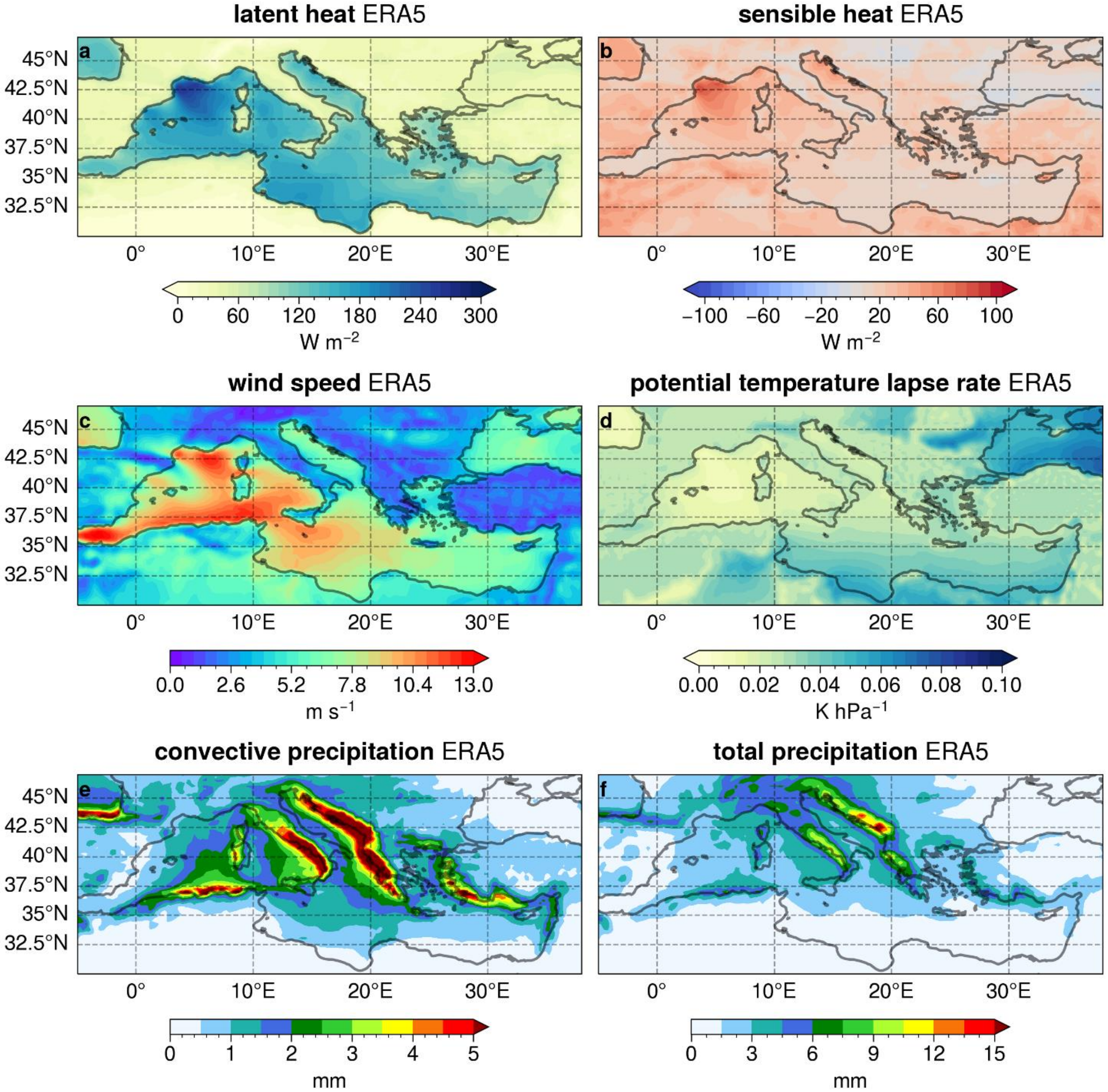

Figure A1: Maps for latent heat flux (a), sensible heat flux (b), 10 m wind speed (c), potential temperature lapse rate (d), convective precipitation (e) and total (large-scale + convective) precipitation (f) from ERA5 during the 500 most intense cyclones.

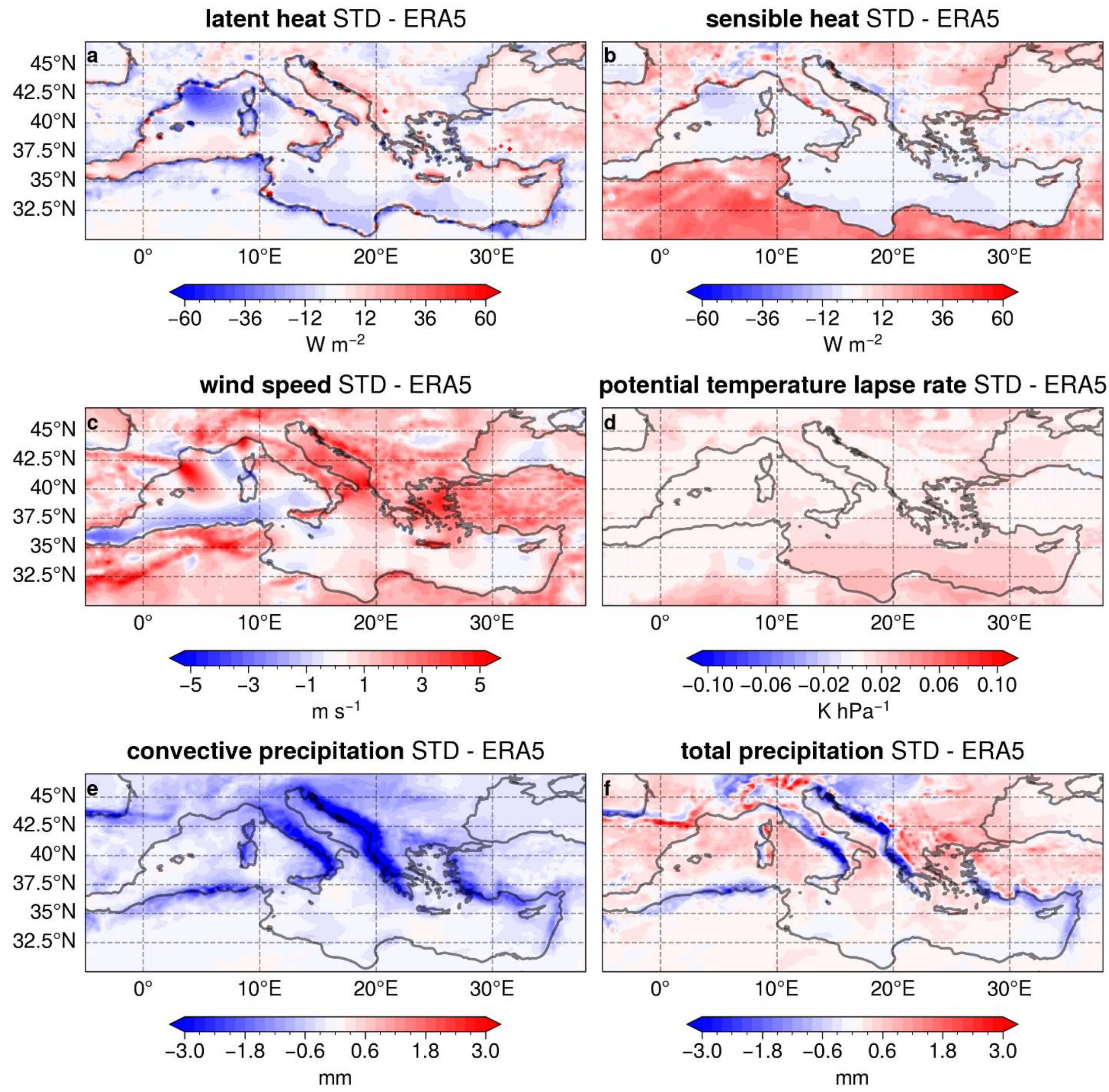

Figure A2: Maps of the differences between STD and ERA5 during the 500 most intense cyclones for latent heat flux (a), sensible heat flux (b), 10 m wind speed (c), potential temperature lapse rate (d), convective precipitation (e) and total precipitation (f).

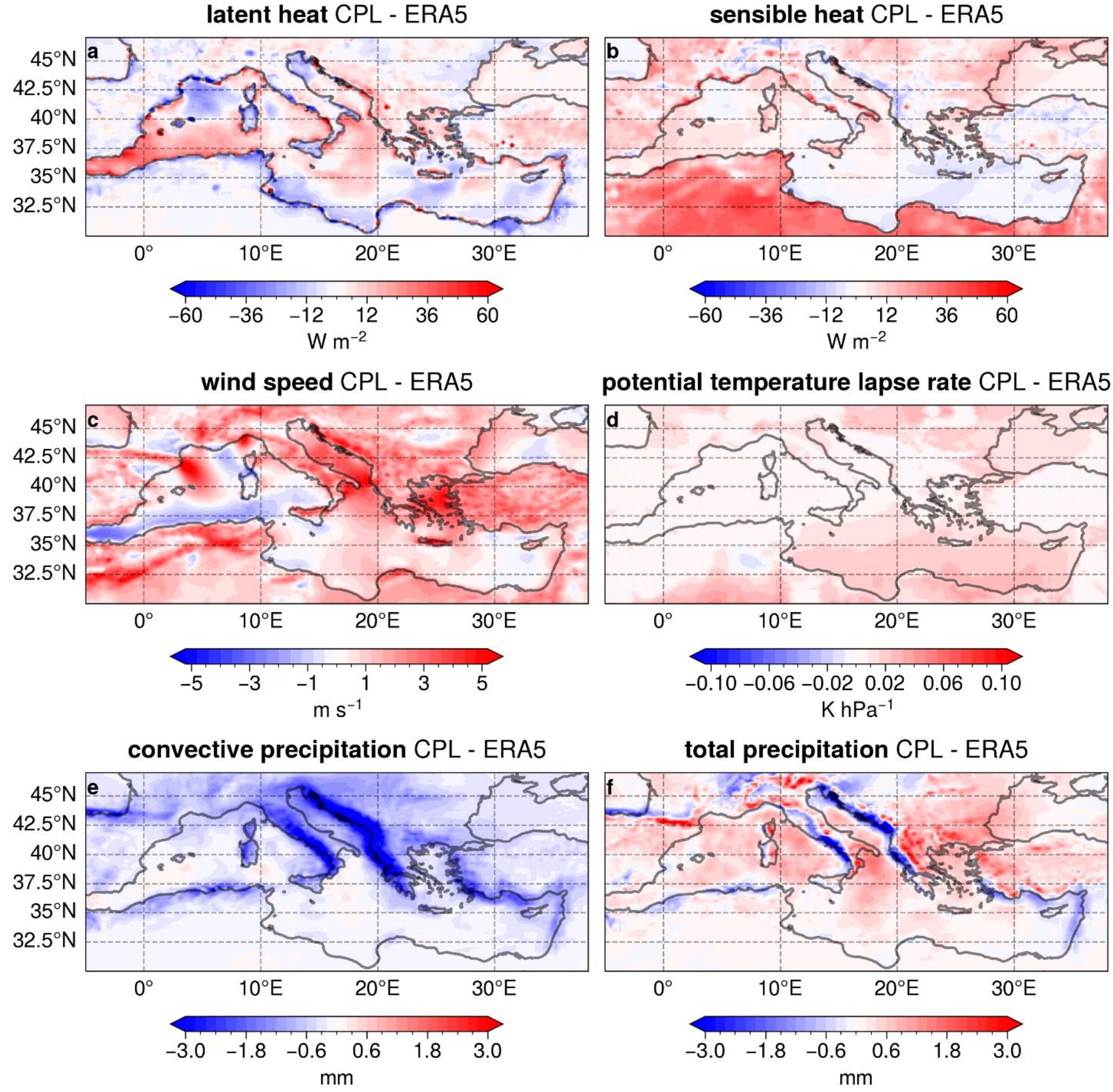

Figure A3: Same as figure A2 but for CPL.

2 There are large differences between CPL and satellite-based SST cyclone climatology fields (0.5K) shown in figs 5 and 6. Unsurprisingly, these differences go on to dominate the spatial maps shown in figures 7 and 8, as demonstrated by the high correlations in figure 9. I was missed the importance of this result. The authors have demonstrated that differences in SSTs leads to large differences in the atmospheric fields, but what is the link to the extreme cyclones. Are the SST differences larger during cyclone events than non-cyclone events, and thus accurate prediction of extreme cyclones is important? If so, do the noncyclone climatologies also need to be included to demonstrate this?

We thank the Reviewer for this thoughtful comment. Figure 5b and c show respectively the SST difference between CPL and STD during the winter extreme cyclones and on climatological scale. The two figures are very similar, thus indicating that the SST differences during cyclone events are not larger than the climatological differences. However, this significant climatological SST difference has a greater impact on the atmospheric processes during extreme cyclones than on climatological scale, due to enhanced air-sea exchange of energy, wind speed and convection during cyclonic events (Fig. S2 below). The new Figure S2, added in the supplementary material, shows the atmospheric fields when considering only extreme cyclones or the climatological scale in winter (DJF) for STD. Similar results are also found for CPL (not shown).

In response to the reviewer's question, we also added comments in section 3.2 of the revised manuscript (L298-305) as follow:

"*It is interesting to note that, in the winter climatology, the total precipitation are much smaller compared to cyclone events. This can be explained by the intense baroclinic forcing during winter cyclones that trigger convection and intensify the winds at the surface, enhancing the transfer of energy from the sea to the atmosphere and thus increasing the vertical transport of heat and moisture. Figure S2 in supplementary shows the differences between cyclones composite fields and climatological fields in winter for STD (same results for CPL, not shown), where is clear the higher latent heat, (Fig. S2a), sensible heat (Fig. S2b) and 10 m wind speed, the lower stability (S2d) and the stronger precipitation (Fig. S2e, f) in the areas of cyclones' locations. This highlights the greater importance of the Mediterranean SST as source of energy for the cyclones when the air-sea exchange processes are stronger, with intense precipitation and wind speed*."

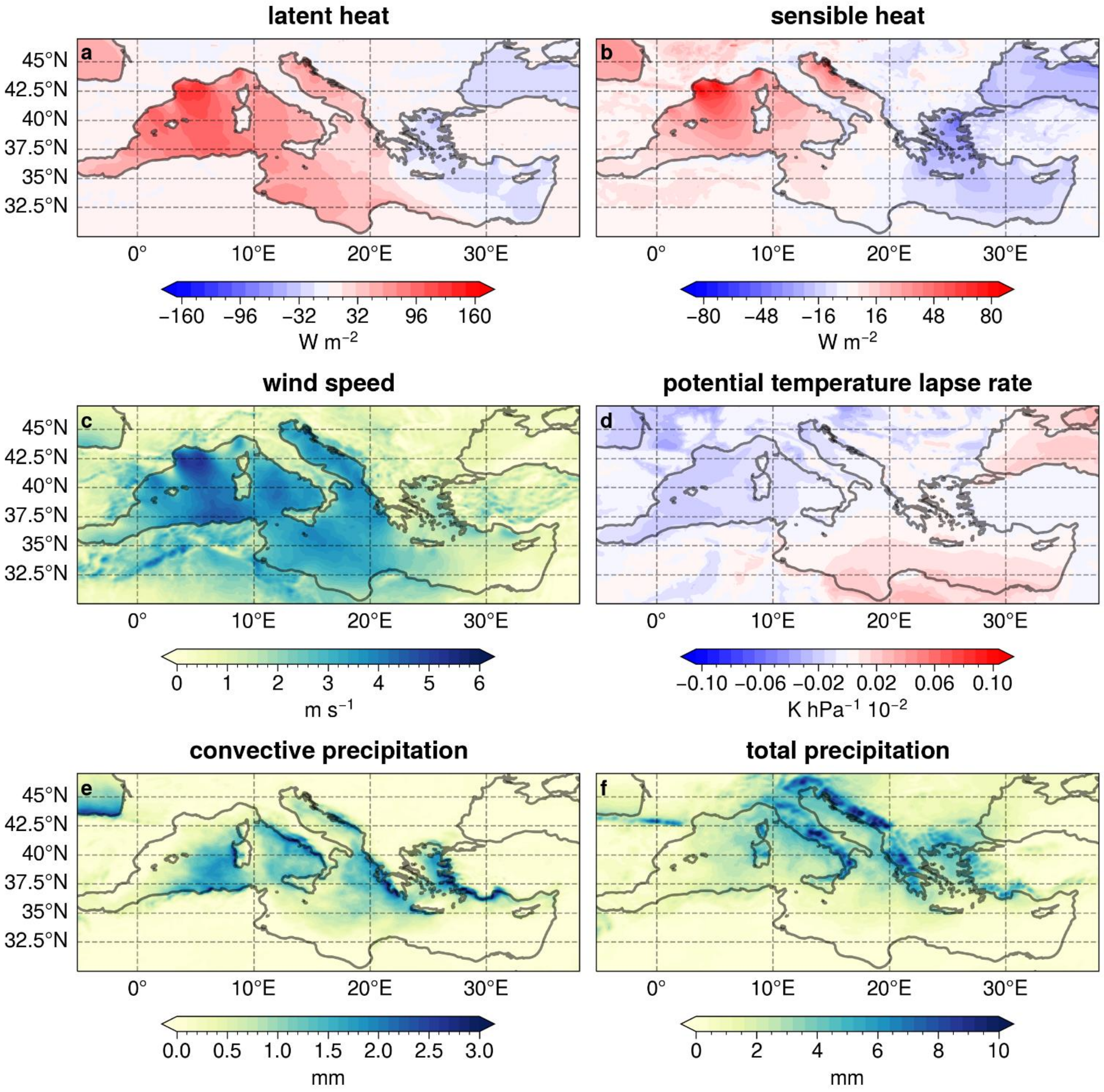

Figure S2: Maps of the differences in latent heat flux (a), sensible heat flux (b), 10 m wind speed (c), potential temperature lapse rate (d), convective precipitation (e) and total (large-scale + convective) precipitation (f) between cyclones and climatological scales for STD in winter (DJF).

3 Figure 10 is the most interesting result because it removes the removes the bias in SST and thus allows a comparison of the effect of coupling. What causes the difference between CMEMS and STD SST evolution (using daily ERA5 SST) prior to the cyclone event?

We thank the reviewer to raise this interesting question. The CMEMS MED-Currents (Escudier et al. 2021) is a high-resolution (1/24°) Mediterranean Sea physical reanalysis, while the ERA5 uses two different SST dataset with different nominal resolutions, i.e. HadISST2 (Δx = 0.25deg, Titchner and Rayner, 2014) before September 2007 and OSTIA (Δx = 0.05deg, Donlon et al., 2012) afterwards. However, the Copernicus Climate Data Store provides the SST field only at 0.25° horizontal resolution for the whole period.

It is interesting to note that the CMEMS reanalysis is forced by atmospheric fields of ERA5. Thus, the different SST between CMEMS and ERA5 (SST in STD) is probably related to the different ocean model implemented, resolution and assimilated observations. In the work of Escudier et al. 2021 they compare the CMEMS MED-Currents only with the previous version of the Mediterranean reanalysis and not with ERA5 SST. So, further research would be needed to investigate what causes the differences in SST between CMEMS and ERA5 reanalysis and this goes beyond the scope of the present paper.

Specific comments:

1 Line 12, 13: ENEA-REG, Med-CORDEX, ERA5, WRF, MITgcm acronyms need to be defined. Is it important for the general reader to know the names of these datasets and models? If not, please consider writing the abstract using more general language and leave the detailed acronyms to the main body of the paper.

We have revised the abstract to use more general language and avoid the use of acronyms.

2 Line 24: What do the authors mean by the 'effectiveness' of the coupled model?

We have corrected "effectiveness" with "ability in lines L24-26 as follow:

"*The analysis shows the ability of the coupled model to coherently represent the dynamic and thermodynamic processes associated with extreme cyclones across both the atmosphere and the ocean*."

3 Line 54: Which side of the Alps is the 'leeward side'? Surely, this depends on the wind direction?

The Reviewer is correct. The leeward side of the mountains corresponds to the downwind side and so depend on the wind direction.

4 Line 80: What do the authors mean by 'proper' air-sea coupling effects?

By "proper" air-sea coupling effect, we refer to the influence of the coupling on atmospheric fields, specifically related to the direct exchange of information between the atmospheric and ocean models and not dependent on the impact of the different SST distribution on the atmosphere. For clarity, we modified the sentence as follow (L79-81):

"*Berthou et al. (2014, 2015, 2016) found that only a minor part of the change in precipitation was strictly due to the air-sea coupling effects, while the long-term difference in SST between the simulations was responsible for most of the change*"

5 Line 107: Why is the role of SST and air-sea fluxes on extreme events expected to be stronger in the Autumn season?

We have added in the introduction (L107-110) the physical reason and the references on why the air-sea fluxes are expected to be stronger in the autumn season, as follow:

"*For a more comprehensive analysis, two seasons are considered: the winter (DJF) when the cyclones are more intense and frequent (Campins et al., 2011; Flaounas et al., 2022) and autumn (SON) when the role of the SST and the air-sea fluxes on extreme events is expected to be stronger (Miglietta et al., 2011a; Ricchi et al., 2017). The enhanced surface fluxes in autumn result from the combination of relatively high SSTs, which are near their annual peak, and upper-level cold-air intrusions.*"

6 Line 163: 500 cyclones represent almost 20% of the cyclone distribution. This does not seem particularly extreme.

The reviewer is correct. From a statistical point of view, the 500 most intense cyclones do not represent the "extremes" of the distribution, but we also needed to guarantee to have enough cyclones at least in DJF and SON season. We simply use the term "extreme" as a way to refer to the "500 most intense" (in terms of minimum SLP) cyclones.

7 Line 175: I found the terminology q-gradient ambiguous. Why not use static stability or potential temperature lapse rate which are more standard terms for such a metric?

We have changed the terminology in "potential temperature lapse rate", as suggested by the reviewer.

8 Line 216: Why is a radius of 1.5o around the cyclone centre chosen? This seems to suggest that the enhanced surface fluxes occur very close to the cyclone centre and are axisymmetric. Is this supported by any analysis?

We thank the reviewer to point out this shortcoming. The total area of influence of the cyclones is on average larger than a circle with 1.5° radius. For instance, Flaounas et al. 2016 used a circular area with a radius that vary dynamically according to the relative vorticity field in the vicinity of the cyclones centre. They found that the median of all cyclones' effective area is of the order of 500 km, while their 5th and 95th quantile is of the order of 150 and 1050 km, respectively. In the ocean analysis (section 3.5 in the revised manuscript) we choose to use a smaller area of influence to have a greater amount of grid points over the Sea concentrated around the minima of the cyclones and not closed to the land and/or the islands where the ocean is too shallow. The distribution of the cyclone's minima with their effective area of influence is shown in supplementary in figure S7.

9 Figure 2: This figure shows that there is some seasonal dependence on the performance of the CPL and STD model simulations when compared to ERA5 for predicting the number of cyclones. Is there also seasonal dependency in the other statistics (intensity, lifetime and speed)?

The Reviewer is correct, the RCMs tend to overestimate the intense cyclones in spring and summer and underestimate them in winter compared to ERA5. However, the main statistics are not affected by this seasonality behaviour. For instance, in winter the RCMs present similar statistics compared to ERA5, as shown in figure A4 below, and similarly to Figure 2.

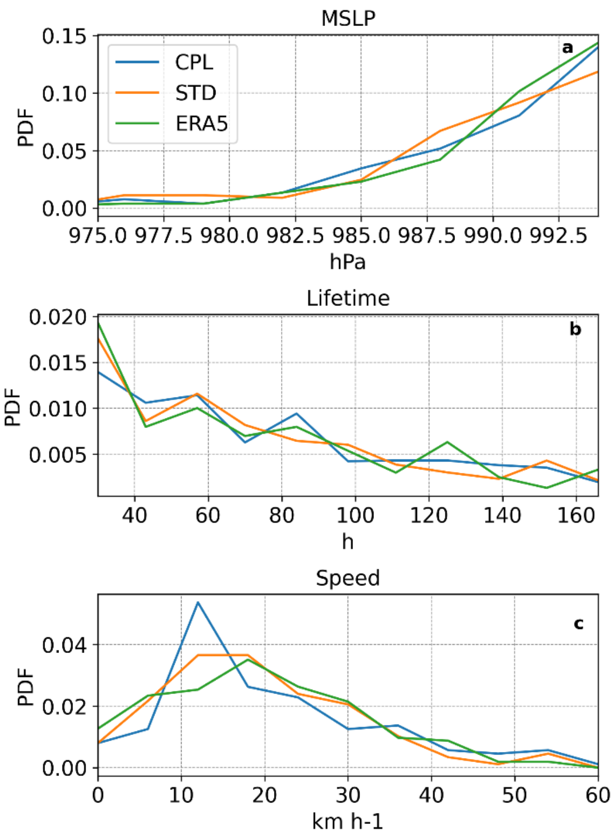

Figure A4: Statistics, intensity (a), lifetime (b) and speed (c) of the extreme cyclones in winter (DJF) for STD, CPL and ERA5.

10 Figure 3: The maxima in frequency of cyclones in CPL model, over land, does not correspond to maxima in the STD simulation. Furthermore, the frequency over the ocean reduces in the CPL simulation. Therefore, I do not think the evidence supports the statement on line 230 that 'the spatial distribution of extreme cyclones is similarly reproduced by the models compared to ERA5' or on line 241 that 'differences between STD and CPL are limited and non-significant'. Perhaps difference plots would demonstrate the similarity or differences in the simulations more clearly?

We thank the reviewer to raise this doubt. We have changed the paragraph in section 3.1 to clearer explain and support the analysis of the differences between the RCMs and ERA5 and between the models themselves. In addition, we have changed figure 3 where we added the difference plots. Please see the discussion in the first general comment and refer to the revised text (lines 247-271) mentioned there.

11 Line 264: How do the cyclones 'turn into precipitation when they reach the coast'? Do you mean that at the coast, orographic ascent causes water vapour to be converted into water droplets, which then grow into precipitation droplets?

The reviewer is correct, we referred to the orographic mechanism that trigger convection over coastal areas. We have changed the paragraph to better explain the precipitation distribution associated to the winter extreme cyclones (L289-293) as follow:

"*This precipitation pattern is associated with winter cyclones generally coming from the west, as indicated by Flaounas et al. (2015) and Raveh-Rubin and Flaounas (2017) and interacting with the complex orography of the basin, increasing precipitation over coastal areas. The distribution of convective precipitation (Fig. 4e) is mainly concentrated over the sea, where the potential temperature lapse rate is low (i.e., low atmospheric* *stability, Fig 4d), and close to the coastal regions where the sharp transition between sea and land fosters the convection processes*."

12 Line 267: Can the authors expand on their statement that the transition between sea and land fosters the convection processes? Are you referring to convergence at the coast?

The reviewer is correct, we were referring to the convergence and then convection processes in the coastal areas, especially in Italy and Balkans. Please refer to the comment 11 and the revised text (L289-293) mentioned there.

13 Figure 4: How do these composites differ from the full winter climatology? Perhaps anomaly fields could be shown?

Please see the discussion in the second general comment, where we have shown anomaly fields between cyclones-composite and climatological scale atmospheric fields (Fig. S2 in supplementary). This helps us to highlight the stronger surface fluxes, wind speed and precipitation during the cyclonic events and to emphasise the importance of the results.

14 Fig 6: The order of the figures is different to that in figure 5 which confused me for a while.

We have corrected both figure 5 and 6 in the revised manuscript.

15 Fig 7: The order of the figures is different to those in fig 4. Could they be reordered to be consistent?

We have corrected figure 4 in the revised manuscript which now shows the same atmospheric fields and follows the same order of figure 7.

16 Figure 8: Since these fields are similar to those shown in previous figures, I do not think they add much to the analysis.

We have changed figure 8 by showing only the temperature and specific humidity fields at 950 hPa and 850 hPa. These figures help us to prove that the SST differences have an impact throughout the entire PBL and not only at the surface. In fact, the vertical transport processes provide an increase of energy at different vertical level, destabilizing the PBL and making the atmosphere of the CPL warmer and moister at both 950 hPa and 850 hPa.

17 Line 304: Reference is made to latent and sensible heat fluxes. Could these fields be shown instead of evaporation, wind speed, specific humidity and theta gradient? They are directly responsible for increasing the vertical exchange of heat and moisture between the Mediterranean Sea and overlying atmosphere so would be more relevant.

The reviewer is correct, and we have added in the analysis the latent and sensible heat fluxes instead of the evaporation field.

18 Figure 10: It appears that the MLD deepens more in the CPL model than in the CMEMS, why is this?

We thank the reviewer to point out this interesting question. The reviewer is correct, the CPL model simulates a deeper MLD than the reanalysis. Likely, this depends on the different forcings coming from the atmospheric models (WRF in CPL and ERA5 in CMEMS) and intrinsic differences in the ocean models. However, further research would be needed to investigate the physical reason in detail, and this goes beyond the scope of the present paper.

19 Figure 10: It is interesting that the MLD is twice as deep in winter than in autumn. Is this why the change in SST is so much smaller in winter?

The reviewer is correct. In winter the mixed layer is much deeper and thus, the effect of the cyclones on ocean properties is weak, with a very low cooling of the temperature throughout the entire mixed layer depth. In autumn instead, the shallower mixed layer and the ocean stratification favour the upwelling processes caused by the strong winds during cyclones that enhance the surface moisture and heat releases in the atmosphere and, in turns, lowers the temperature of the ocean.

20 Line 417: Is there evidence to support the statement that extreme cyclone significantly influences the Mediterranean climate? By climate, do the authors mean the long-term average conditions?

There are several studies that demonstrate the strong influence of the cyclones on the Mediterranean climate. With climate we mean the long-term average conditions, the variability and the extremes. We talked about that in the introduction (L46-53) as follow:

"*Multiple studies indicate that cyclones in the Mediterranean region account for at least 70% of extreme rainfall events (Catto and Pfahl, 2013; Jansa et al., 2001; Nissen et al., 2013; Pfahl et al., 2014; Pfahl and Wernli, 2012), with deep convection and warm conveyor belt processes being the main contributors to heavy rainfall (Flaounas et al., 2018b, 2019). Additionally, these cyclones are responsible for the majority of extreme wind storms (Hewson and Neu, 2015; Nissen et al., 2010, 2014) and for the formation of high-impact weather events (Llasat et al., 2010, 2013). Those events produce a high variability in the evaporation and precipitation fields, playing a significant role in the Mediterranean Sea water budget (Flaounas et al., 2016; Romanski et al., 2012)*."

Typographical errors

1. Line 20: 'Planet' should be 'planetary'.

2. Line 20: 'mixing of the turbulent processes' should be 'mixing by the turbulent processes'.

3. Line 98: 'insights on how' should be 'insights into how'.

4. Line 117: 'than STD' should be 'as STD'.

5. Line 174: 'planet boundary layer' should be 'planetary boundary layer'.

6. Line 179: What is the 'e' after STD? Is this a typographical error?

7. Line 226: 'upscaled at ERA5 resolution' should be 'upscaled to ERA5 resolution'

8. Line 290: 'norther' should be 'northern'.

9. Line 350: 'THETA' is represented as q elsewhere.

10. Line 53: 'Not statistically significant differences' should be 'statistically insignificant differences'.

We have corrected all the typographical errors, thanks for pointing them out.