Comment:

Anonymous Referee #1

Received and published: 4 March 2018

This paper attempts to define a fully physically based method to estimate a maximum precipitation that would result from tropical cyclones over a given target area, which is more or less close to the effective landing area. This method is applied to four cyclone cases. As such, the subject of this paper is obviously of great interest for HESS.

The proposed "transposition method" relies on a series of steps that are rather precisely defined: (i) define the centre and radius of the cyclonic vertex, (ii) define the meteorological background field as being the field outside of the cyclonic vertex, as well as its linear interpolation inside of the vertex, (iii) define the perturbation field by subtracting the background field to the actual field, (iv) translate/shift the perturbation field (v) linearly recombine it with the (fixed) background field, (v) run a regional atmospheric model (RAM) with the obtained initial conditions, (vi) estimate the resulting, accumulated precipitation over the target area and a given period of time (72 hours in the present study).

At first, references to the concept of Probable Maximum Precipitation (PMP) seem somewhat misleading: although the authors have been inspired by some techniques developed in PMP approaches, their goal is more precise as explicitly stated in the introduction and somewhat in the title of their paper. Furthermore, as discussed below, it seems that their study puts into question PMP rather than supports it.

Secondly, the claim that the present method is fully physically based is not obvious for at least two reasons: - whereas, the RAM can be considered as physically based on the subrange of the explicit scales, this is not the case for the parametrisation of the smallest scales that are essential for precipitation; - most other procedure steps are not physically based.

Furthermore, the linear nature of several steps (ii - iv, respectively subtracting, interpolating and adding the background field) are rather at odd with the nonlinearity of the system. It is also questionable to define the cyclonic vertex as a circle (step i), whereas the material contours of various fields are rather convoluted. A priori, these linear simplifications, as well as the parametrisation, may introduce non negligible model/method errors that should be acknowledged, despite they generate frustrations with respect to the applicative goal of the paper, namely the accuracy of the heavy precipitation estimates.

On the contrary, I believe that the authors should emphasise and promote a result of their study that is a consequence from the preserved nonlinearities of the systems. Indeed, they are right to observe and argue that these nonlinearities yield a complex sensitivity of the vertex track with respect to the initial translation of the vertex, in particular a small translation can be well sufficient to substantially modify the vertex track so that it will go over the target area. Similar observations are done and could be further developed on uncertainties resulting from the choice of the simulation starting date, therefore of its initial conditions. In particular there is a sensitivity to the relative intensity of the perturbation field, which might interfere with the aforementioned method errors (i.e., highest intensities will presumably amplify these errors). The authors are right to mention a similar sensitivity to the choice of the RAM parametrisation settings. By the way, according to the rightest hand side equation of Eq.1, it seems the authors selected the hydrostatic option of WRF, whereas it is basically a non-hydrostatic RAM.

A priori, the above results and considerations have important implications on the accuracy of the estimates of the heavy precipitations over the target area, i.e., they presumably displays a much higher variability than expected. Does it require an ensemble approach and a statistical analysis of the extremes? Does the latter put into question PMP approaches? I believe that these questions should addressed, at least tentatively, by the authors. Overall, I believe that the paper should devote more room to the methodological questions and display a terser presentation of the study cases.

Response:

Comment: At first, references to the concept of Probable Maximum Precipitation (PMP) seem somewhat misleading: although the authors have been inspired by some techniques developed in PMP approaches, their goal is more precise as explicitly stated in the introduction and somewhat in the title of their paper. Furthermore, as discussed below, it seems that their study puts into question PMP rather than supports it.

Response: The objective of this study is to prove the feasibility of using a physically based approach for the estimation of the PMP over a target basin in the eastern U.S. subject to the effects of tropical cyclones (TCs). It is true that the outcomes from this study raise serious questions regarding the legitimacy and validity of traditional PMP approaches in the case of TCs.

Comment: Secondly, the claim that the present method is fully physically based is not obvious for at least two reasons: - whereas, the RAM can be considered as physically based on the subrange of the explicit scales, this is not the case for the parametrisation of the smallest scales that are essential for precipitation; - most other procedure steps are not physically based.

Response: The authors recognize that the method presented in this paper is not “fully” physically based for the reasons provided by the reviewer. As such, the word “fully” will be removed from the revised version of the manuscript. The reason why we did not use a fully physically based approach is that such an approach does not exist yet. The Weather Research and Forecasting (WRF) model is one of the most advanced and physically based tools available to date, and this is why we used this model in our study. Yet, to the authors’ knowledge, the storm transposition method proposed in this article remains much more physically based than any other PMP estimation method proposed so far for the eastern U.S. As models and in particular the representation of the smallest scales keep improving, the legitimacy of using a regional atmospheric model (RAM) for the purpose of PMP estimation will become stronger and the benefits of this approach more obvious.

As far as the procedure steps are concerned, it is true that the vortex relocation procedure presented in this article which simply shifts the perturbation fields obtained by subtracting the background fields from the initial fields is less physically based than other preexisting vortex relocation procedures such as the vortex bogusing techniques used in forecasting.

Finally, the authors note that no cumulus parameterization was used in the simulation inner domain (see Table 1 in the article).

Comment: Furthermore, the linear nature of several steps (ii - iv, respectively subtracting, interpolating and adding the background field) are rather at odd with the nonlinearity of the system.

Response: The vortex relocation procedure presented in this study is relatively simple. The goal of this preliminary study is to prove the feasibility of a physically based approach for the storm transposition of

TCs in the Atlantic basin. More sophisticated tools are available and will be investigated in the future. For example, vortex “bogusing” is a technique that is widely employed by the forecasting community. They observed that the discrepancies between the coarse resolution of the analysis and the fine resolution of the hurricane model can cause a significant period of vortex adjustment at the beginning of the forecast which may have very prejudicial effects on the quality of the forecasts, both in terms of the storm’s track and intensity. As a result, several studies (e.g. Kurihara et al., 1993; Zou and Xiao, 2000; Hsiao et al., 2010) have proposed vortex removal procedures, vortex relocation procedures, etc. which are in general more sophisticated than the method proposed in our study. The objective of these procedures is to provide a TC in the initial condition which is as realistic as possible and which is physically and thermodynamically consistent with the background fields and with the model’s physics. Recent studies (e.g. Zou and Xiao, 2000) have used 4 dimensional variational bogus data assimilation (bogus 4D-Var) to provide a physically and thermodynamically consistent initial vortex. One difference between the aforementioned studies and our approach is that they first implant a simple axisymmetric bogus vortex (based for example on the gradient wind equations) before recovering the vortex asymmetry through different means such as 4D-Var, whereas we transposed and implanted the full vortex obtained by subtracting the interpolated background fields from the original fields. While the aforementioned vortex adjustment at the beginning of the simulation is detrimental for the purpose of forecasting, the authors believe that it is less of a problem for the purpose of design and in particular PMP estimation. Indeed, during this spinup time the RAM corrects the inconsistencies that may be present in the initial condition due to the pointed linear nature of the vortex relocation steps since the RAM numerically solves the nonlinear equations governing the conservations of mass, momentum and energy.

Furthermore, the authors emphasized in the article that several precautions need to be taken while performing the transposition exercise. Section 2 stresses that the transposition exercise should be ideally performed when the TC is moving over the ocean, far from land, and before its extratropical transition. In this case, the TC is usually relatively small and seems to be simply advected by the large scale flow.

Comment: It is also questionable to define the cyclonic vertex as a circle (step i), whereas the material contours of various fields are rather convoluted.

Response: The interpolation region was defined as a circle, not the cyclonic vortex per se. This is because of the general tendency of TCs to be somehow circular in shape. We acknowledge that the material contours of the various fields may be complicated and the fields asymmetric with respect to the storm center. Such large asymmetry is particularly likely to be encountered when the TC moves within the midlatitudes and undergoes its extratropical transition (Chan and Kepert, 2010). On the other hand, we stressed that the transposition exercise should be performed before the TC starts its extratropical transition, and ideally when it is moving over the ocean and far from land. In this case, it is likely that the material contours of the various fields should be close to circular in shape. Actually, whatever shape may be adopted for the interpolation region. We chose a circle because this is the shape that seemed the most reasonable to us given the nature of the storm under investigation.

Comment: A priori, these linear simplifications, as well as the parametrisation, may introduce non negligible model/method errors that should be acknowledged, despite they generate frustrations with respect to the applicative goal of the paper, namely the accuracy of the heavy precipitation estimates.

Response: Do the modifications brought to the initial conditions generate "errors" properly speaking in the output of the model? We do not think so. First of all, as mentioned earlier in this discussion, the RAM smoothes out the inconsistencies that may exist in the initial fields due to the nature of our vortex relocation procedure since it numerically solves the nonlinear equations governing the conservation of the mass, momentum and energy. We recall that the simulation start date is taken several days before the TC makes landfall, so that by the time of landfall and especially by the time the most intense rainfall is produced over the target area, all the fields produced by the RAM are fully consistent physically and thermodynamically.

Moreover, the authors believe that thinking in these terms is giving to much importance to the initial condition. Indeed, does the structure and intensity of the precipitation field depend more on the detailed structure of the initial vortex, or does it depend more on how the TC interacts with its environment between the simulation start date and the time of intense precipitation? Figure R1 below shows the evolution of the total precipitable water (PW) in Hurricane Frances with a 24-h time increment for the simulations corresponding to Fig. 12b and 12c in the article. Note that in this figure Hurricane Frances is located east of Puerto Rico (see also Fig. 10b in the article). We recall that only about 8 km separate the location of the initial vortices between one simulation and the other whereas the locations of landfall defer by more than 100 km. The right column in Fig. R1 shows the difference between the two. We observe that the trajectories are almost identical until Hurricane Frances approaches Florida, after which they start to diverge rapidly, with the hurricane affecting mainly Florida, Georgia and the western Carolinas in one case versus Alabama and Mississippi in the other case. It is clear in this example that the differences in the locations, structures, and intensities of the precipitation fields between one simulation and the other are due to the effects accumulated during the storm motion rather than to the details of how one initial vortex's structure defers from the other initial vortex's structure. Although the initial vortices are very close to each other, the trajectories diverge, first very slowly as the storm moves over the ocean, then much faster as the storm approaches land. In a nutshell, we think that differences between one precipitation field and another are more a function of how the TC interacts with its environment including how the moisture is advected over the region, how it interacts with the local topography and how its converges and diverges (see Fig. 9 in the article) rather than being a function of the details of how one initial vortex's structure could have been or should have been if one had used a more sophisticated vortex relocation procedure than the one used in this study.

Second, let us discuss the parameterization. Instead of "errors", the authors prefer to discuss uncertainties. This relates to a point that the reviewer raises later when proposing an ensemble approach. The traditional PMP approaches are essentially deterministic and do not in general offer any way to estimate the uncertainties associated with the PMP estimate. Although it is true that the uncertainties associated with the model's options (parameterization), with the initial condition (in particular the simulation start date), and with the dataset used to provide the initial and boundary conditions cause the PMP estimate to be also uncertain, such uncertainty can be quantified by using an ensemble approach as discussed in Section 5 of the article. The physically based PMP estimation exercise should be performed with as many combinations of the model's options (as long as each combination has been beforehand validated as discussed in the appendix), simulations start dates, and datasets for initial/boundary conditions.

Finally, although it is true that some errors (or uncertainties depending on the point of view) are associated with the physically based PMP estimate, one should not forget that a tremendous advantage of this approach is that the RAM provides the underlying mechanisms responsible for generating the extreme precipitation such as moisture transport and convergence, topographical effects, etc. In other words, although it is true that the RAM may slightly overestimate or underestimate the maximum precipitation over the target basin because of the choice of the vortex relocation procedure and the choice of the parameterization schemes, the additional information that it provides on the underlying fields responsible for causing the extreme rainfall such as integrated vapor transport, precipitable water, temperature and wind field as well as the temporal and spatial structures of these fields remains extremely valuable.

Comment: On the contrary, I believe that the authors should emphasise and promote a result of their study that is a consequence from the preserved nonlinearities of the systems. Indeed, they are right to observe and argue that these nonlinearities yield a complex sensitivity of the vertex track with respect to the initial translation of the vertex, in particular a small translation can be well sufficient to substantially modify the vertex track so that it will go over the target area. Similar observations are done and could be further developed on uncertainties resulting from the choice of the simulation starting date, therefore of its initial conditions.

Response: The goal of this study is to show the feasibility of a physically based TC transposition approach for the purpose of PMP estimation in the eastern U.S. As pointed by the reviewer, investigating the uncertainties resulting from the choice of the simulation starting date, therefore of its initial conditions is an essential issue and will be tackled in a future study.

Comment: In particular there is a sensitivity to the relative intensity of the perturbation field, which might interfere with the aforementioned method errors (i.e., highest intensities will presumably amplify these errors). The authors are right to mention a similar sensitivity to the choice of the RAM parametrisation settings.

Response: The precipitation field generated by the TC indeed depends on the relative intensity of the perturbation field. In particular, a small change in the structure of the initial vortex (not only its position) may result in different trajectories because the consequences of this change can amplify over time in a nonlinear way. However, is it appropriate to say that this is going to cause an “error” in the precipitation field generated by the TC? We do not think so. Indeed the atmospheric fields produced by the RAM are fully physically and thermodynamically consistent since the RAM solves the equations governing the conservation of mass, momentum, and energy. To this extent, how can they be wrong (as long as the model is provided with realistic initial conditions)? It might be more appropriate to interpret the precipitation fields produced by the RAM as different realizations of what a given TC could have caused. This is actually the idea behind the method proposed in the article: generating realizations of a given TC by perturbing the location of the storm in the initial conditions, with a focus on those realizations producing extreme precipitation over the target area.

Comment: By the way, according to the rightest hand side equation of Eq.1, it seems the authors selected the hydrostatic option of WRF, whereas it is basically a non-hydrostatic RAM.

Response: The hydrostatic assumption was used to estimate the integrated vapor transport (IVT) from the other fields produced by the WRF model since the WRF model does not output the IVT. We did not use the hydrostatic option of WRF for the simulations.

Comment: A priori, the above results and considerations have important implications on the accuracy of the estimates of the heavy precipitations over the target area, i.e., they presumably displays a much higher variability than expected. Does it require an ensemble approach and a statistical analysis of the extremes?

Response: As discussed previously, Section 5 in the article clearly encourages the adoption of an ensemble approach for the physically based PMP estimation in order to estimate the uncertainties associated with the model's options (parameterization), simulation start date, and dataset used for initial/boundary conditions.

Comment: Does the latter put into question PMP approaches?

Response: The latter indeed puts into question the traditional PMP approaches.

Comment: I believe that these questions should addressed, at least tentatively, by the authors. Overall, I believe that the paper should devote more room to the methodological questions and display a terser presentation of the study cases.

Response: The objective of this study is to show the feasibility of a physically based TC transposition approach for the purpose of PMP estimation in the eastern U.S. A more detailed investigation of the uncertainties associated with the parameterization, simulation start date, and dataset for initial/boundary conditions will be performed in a later study. As far as the room to the methodological questions is concerned, the authors believe that this article and in particular Section 2 already provides sufficient details on the procedure used to shift the TC in the initial condition.

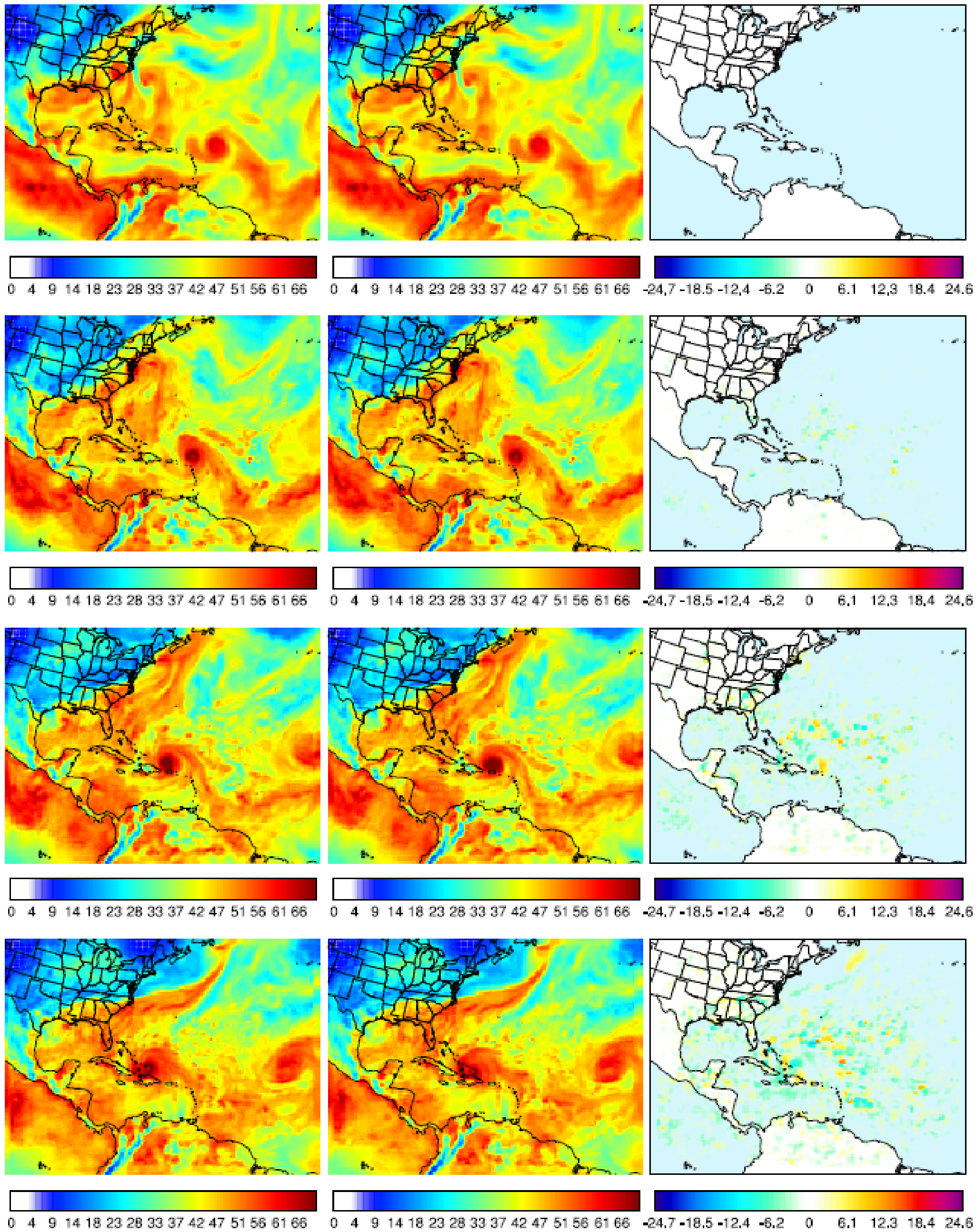

Figure R1 - Left column: evolution of the total precipitable water (mm) in Hurricane Frances with a 24-h time increment starting on 08/30/2004 00:00 UTC for the simulation corresponding to Fig. 12b in the article. Middle column: same as left column but for the simulation corresponding to Fig. 12c in the article. Right column: difference between middle column and left column.

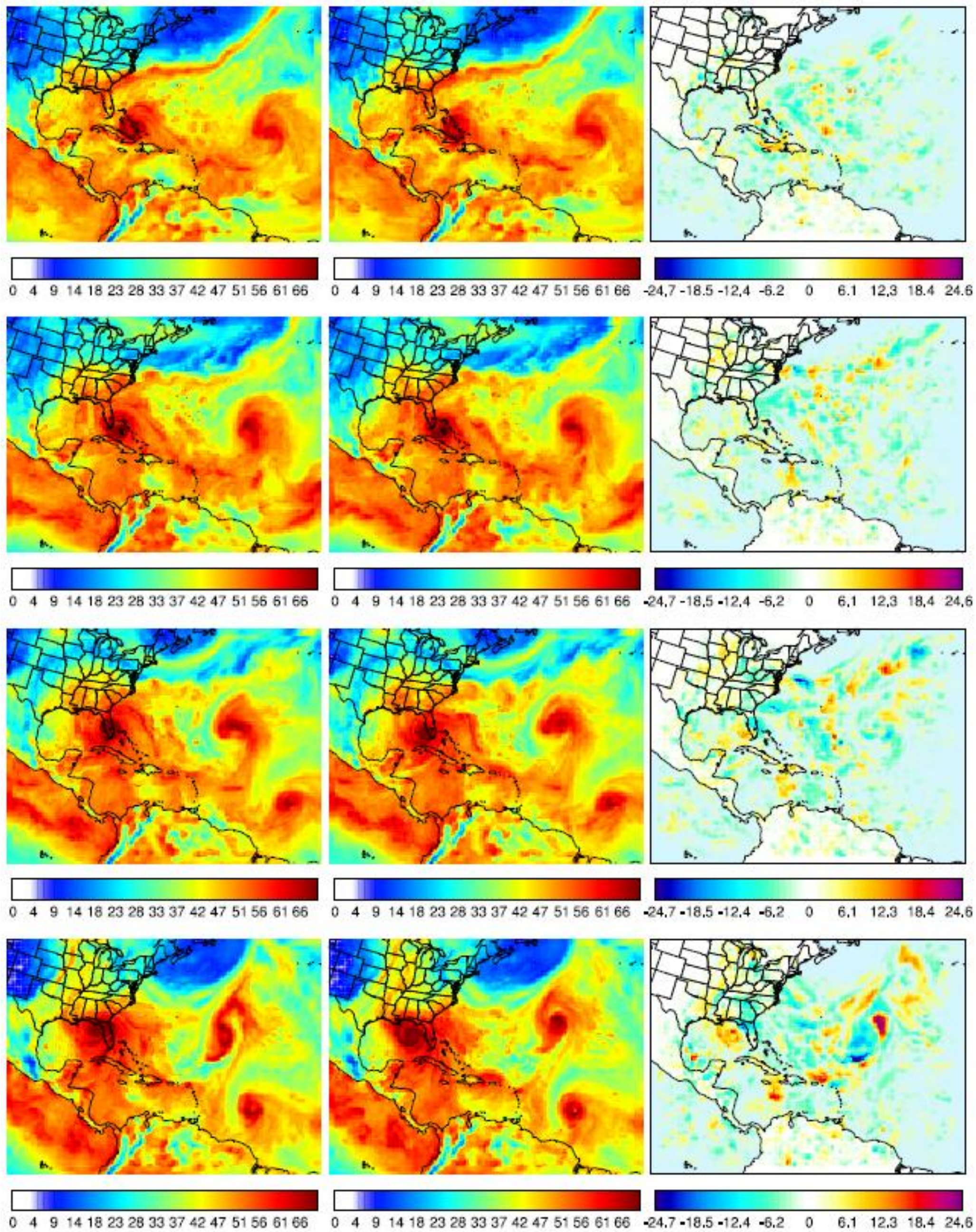

Figure R1 – continued

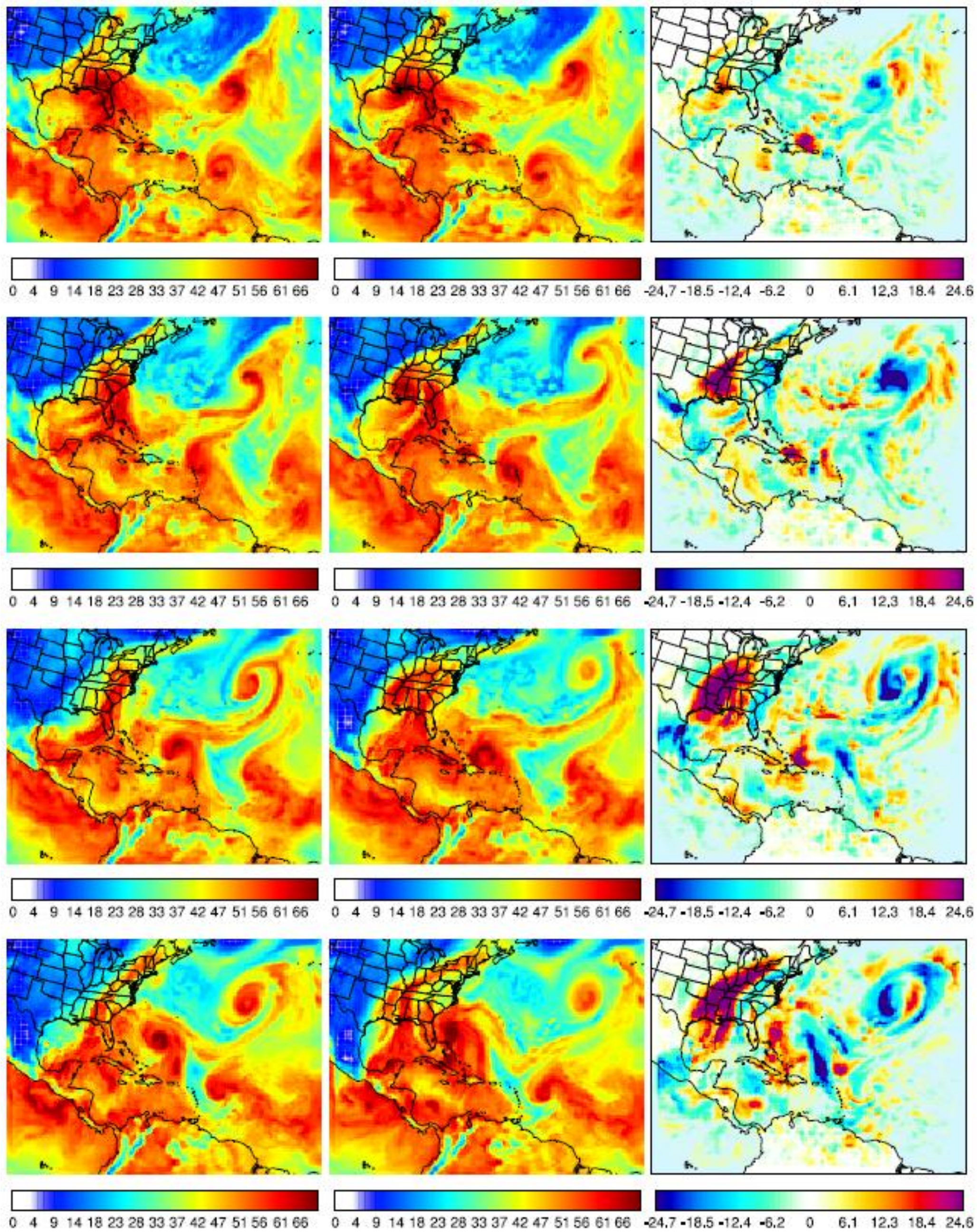

Figure R1 - continued

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