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Publication date:
2018

Document Version
Publisher's PDF, also known as Version of record

Citation (APA):
Imberger, M., Larsén, X. G., Du, J., & Davis, N. (2018). *Forcing Data at WRF lateral Boundary Corner and its Impact on Storm Intensification - a Case Study through mid-latitude Cyclone Christian*. Abstract from Joint WRF/MPAS User's Workshop 2018, Boulder, United States.

Forcing Data at WRF lateral Boundary Corner and its Impact on Storm Intensification – a Case Study through mid-latitude Cyclone Christian

MARC IMBERGER *, XIAOLI GUO LARSÉN, JIANTING DU AND NEIL DAVIS

1. Introduction

The importance of lateral boundary conditions of regional weather and climate models and challenges connected with them are addressed in several studies focusing on a variety of topics. This includes one of the earlier works by Warner et al. [17], who point out general difficulties and Gustafsson et al. [5], who investigate among others the influence of the lateral boundary conditions on the sensitivity of 12h forecast errors. Nutter et al. [10] address the impact of temporally interpolated lateral boundary conditions provided in coarse resolution on ensemble forecasts in a limited-area model. The study of Termonia et al. [14] uses the ALADIN [2] limited-area-model to investigate temporal resolutions for lateral boundary conditions and proposes suggestions for suitable temporal resolutions for standard forecast cases and severe storm events.

This investigation focuses on the lateral boundaries corner in the Weather Research and Forecast (WRF, [13]) model and how a large-scale feature like a mid-latitude storm event is affected when its center has to be fed very close to the corner into the outermost domain of WRF. Especially in settings where domain sizes are relatively small and fixed with time, the entering of large-scale structures which develop outside the simulation environment cannot be avoided completely and methods independently from the domain location have to be applied in order to include those cases as well. Focus of this investigation lies hereby on the effect on the storm enhancement, that is the development of the storm intensity based on the decrease of sea level pressure and the position of the storm center. Investigated settings include the effect of nudging techniques, sponge layer adjustments, changes in the forcing data product and the temporal update interval of the lateral boundary conditions on the results. The investigation is designed as a case study on cyclone ”Christian”, which took place in October 2013 and attracted attention due to its destructive effects affecting several European countries on its way towards the Baltic Sea. More information about ”Christian” (also known as ”St. Jude” storm) can be found in [8] and [1].

Section 2 describes the origin of the problem and the model specifications used in this investigation. Section 3 presents an overview of the different investigates scenarios. Following, Section 4 presents the results obtained and Section 5 finishes the abstract with summary and conclusions.

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2. Problem Description and Model Setup

a. Problem statement

Within the scope of this investigation, WRF version 3.7.1 is used. Figure 1 depicts the location and size of outermost domains used in this investigations together with the storm track of the investigated storm ”Christian”. The track is obtained from the Extreme Wind Storm Catalogue (XWS, [8],[11]). The first reference simulation builds the run using the purple domain depicted in Figure 1 (hereinafter addressed by ”REF”). The second reference case (hereinafter addressed by ”REF-South”) is obtained by using a slightly southwards moved outermost domain (Figure 1, blue domain). Both simulations are 36 hours long from the 26th (12:00 UTC) to the 28th (00:00 UTC) of October 2013 including a spin-up time for the model of 12 hours. The simulated time frame is chosen in such a way that the entrance of the storm into the domain is roughly 24 hours after initialization. Lateral boundaries are updated every 6 hours. This setup of simulation time, spin-up time and lateral boundary condition update is inspired by settings for other simulations used at the department, where it showed good performance [3].

”REF” shows a strong disagreement with the forcing data regarding the enhancement of the storm intensity and the location of the storm center (represented by the absolute value respectively the geographical position of the minimum sea level pressure). This differs from the results obtained from ”REF-South” for example in the sea level pressure field at 28 Oct 2013 UTC 0000 (cf. Figure 2 and Figure 3). Figure 3 shows a strong low pressure area over south Wales. This is not the case in Figure 2 which shows only a marginal decrease in sea level pressure over Cornwall, i.e. shifted in south-west direction compared to the low present in Figure 3. This strongly indicates a misinterpretation of the forcing data when the structure enters too close to the corner. Both domains have a physical size of 2700 km x 1800 km and a horizontal spatial resolution of 18 km and a vertical resolution of 51 vertical terrain-following pressure levels (sigma levels).

b. Parameterization schemes and other model specifications

The New Thompson enhanced bulk micro-physics scheme [16] is chosen and the RRTMG [6] scheme for short and long wave radiation with a calling period of 18 minutes is used. Cloud fraction follows the Xu-Randall method [18]. Kain-Fritsch convective parameterization scheme [7] is activated and called every 5 minutes. Land surface is modeled by the unified Noah land surface model

[15] with four soil levels. As surface and planetary boundary scheme, the Level 3 Mellor-Yamada-Nakanishi-Niino (MYNN, [9]) scheme is selected. The land use data chosen is the U.S Geological Survey (USGS) land use data, which distinguishes 24 land use categories.

If not stated otherwise, the lateral boundary conditions are forecast products from version 2 of the Climate Forecast System (CFSv2, [12]) with a resolution of 0.2 degrees (surface/flux data) and 0.5 degrees (pressure level based data) respectively.

3. Performed Investigations

Investigations in four different directions are performed to find ways to correct the underestimated intensity and displaced location of the storm center under the assumption that the simulation domain is fixed. All cases were compared with ”REF”, ”REF-South” and qualitatively compared to the driving forcing data and the storm track obtained from the Extreme Wind Storm Catalogue.

The four categories include

a. spectral and grid nudging techniques,

b. adjustment to the relaxation zone of the outermost domain,

c. change of the forcing data and

d. increase of the temporal update frequency of the lateral boundary conditions.

Within a particular category, additional sub-studies are performed to investigate the best setup.

4. Results

a. Influence of nudging techniques

Several different nudging settings are tested, which include

a. two investigations of grid nudging (activated in all layers and merely above the boundary layer),

b. two versions of spectral nudging with low wave numbers corresponding to a nudging of wavelengths above 900 km (activated in all vertical layers and merely above the boundary layer), and

c. two versions of spectral nudging with high wave numbers corresponding to a nudging of wavelengths above 100 km (activated in all vertical layers and merely above the boundary layer).

An improvement is found regarding the location of the storm center compared to the forcing data and the results obtained in REF-South. This is especially pronounced in spectral nudging performed with very high wave numbers equivalent to an nudging wave length over 100 km. The application of spectral and grid nudging yield to location shift of the storm center and to a closer agreement with the results obtained from REF-South. However, the decrease in absolute minimum sea level pressure is not as strong, i.e the storm intensity is estimated weaker than its estimation in the REF-South case.

Nudging in all vertical layers or merely above the boundary layer shows only marginal differences in the estimation of the sea level pressure. Spectral nudging with lower wave numbers representing a nudging length of 900 km is investigated and is able to correct the disagreement of the storm center location between WRF and the forcing data. However, the decrease in minimum absolute sea level pressure compared to the simulation using higher wave numbers is less (depending on the location up to 2 hPa less).

b. Influence of changes of relaxation zone

Beyond the case of a relaxation zone width of 4 grid layers in ”REF” and ”REF-South”, simulations with an extended relaxation zone of 8 grid layers (”2xRelaxZone”) and reduced relaxation zone with 2 grid layers (”HalfRelaxZone”) are performed. With regard to the sea level pressure, both methods are able to correct the displacement of the storm center but only the ”HalfRelaxZone” simulation showed an enhancement tendency of the storm intensity as observed in ”REF-South”. But similar to the nudging approaches, the decrease in absolute minimum sea level pressure is significantly smaller than in ”REF-South”. A look at the relative vorticity at the 850 hPa pressure level reveals similarities in general structural patterns and the location of the maximum relative vorticity in ”REF-South” and ”HalfRelaxZone”. The relative vorticity field in ”2xRelaxZone”, however, shows clear indications of a disturbed field due to the thick relaxation zone. This disturbance is characterized by a parallel band of high relative vorticity in the south-west of the domain following the inner relaxation layer. Those parallel structures are also visible in the other simulations, but due to the extended relaxation zone, the location of this disturbances is very close to the area of interest and therefore strongly influences the results.

c. Influence of forcing data

To investigate the influence of the forcing data, ”REF” and ”REF-South” are additionally performed using ECMWFs reanalysis data (ERA5, [4]) with a spatial resolution of 0.3 degrees. The update frequency is set to the same value as used in the reference simulations (i.e. 6-hourly). It is revealed that issues related to the disagreement in the storm center location at a certain time between WRF and ERA5 are less pronounced than in the CFSv2 data. However, unbiased comparison between the runs using ERA5 and CFSv2 is not fully possible. This is because of the forced application of light spectral nudging (nudging above wave lengths of 900 km) in the ERA5 case. This is needed due to a developing divergence between location of the storm center developing inside WRF and the location determined from the forcing data and the XWS storm track data in ”REF-South”, which is not influenced by the negative impact of the corner. Based on the positive impact of spectral nudging on the on the storm location (see Section 4a) found in the investigation using CFSv2, this might be the reason for the marginal influence of the domain on the results obtained. Independently from the usage of spectral nudging, the expected intensification as seen in ”REF-South” is not seen in any of the simulations using ERA5 and shows therefore similar behavior compared to the simulations performed with CFSv2 as forcing data.

d. Influence of update frequency

In the case of CFSv2, a reduction of the update period from six hours to three hours yield to a decrease in absolute sea level pressure of around 6 hPa in the area where the storm center is expected according to the forcing data and the ”REF-South” simulation. A further reduction down to a hourly update period results in an even higher decrease in absolute sea level pressure of around 10 hPa. A slightly lower decrease in absolute sea level pressure is also visible in the simulations driven by ERA5 using the same update intervals (every three hours and hourly).

In all cases, a higher update frequency also helped to correct the storm displacement and moved the center closer to the position obtained from the forcing data.

5. Summary and Conclusion

It is shown that the introduction of large scale features into the outermost WRF domain is demanding and that especially the lateral boundary corner is challenging and can yield to a misinterpretation of the forcing data. At least two key points have to be fulfilled in order to provide a meaningful modeling of those large scale features, which include (1) the import of the correct information from the forcing data and (2) the reduction of smoothing effects. All investigated directions are contributing to the fulfillment of the two main points in one way or anther. Strong spectral nudging with high wave numbers and a reduction in the width of the relaxation zone have been shown to be beneficial regarding to the location of the storm center and its correction in this case (correct information from the forcing data). However, the improvements only come with greater smoothing, which is especially present in the case of strong nudging. This smoothing effect affects the development of a distinguished low pressure field negatively. The biggest improvements regarding the enhancement of the storm intensity are obtained by a high frequent update of the lateral boundary conditions. The latter procedure was also able to correct the location of the storm center closer to the expected location obtained from the forcing data and ”REF-South”. The reason for improvement in both storm location and storm intensity lies in the positive effect of a more frequent update of the lateral boundary conditions on the correct interpretation of the forcing data positively without introducing additional smoothing at the same time.

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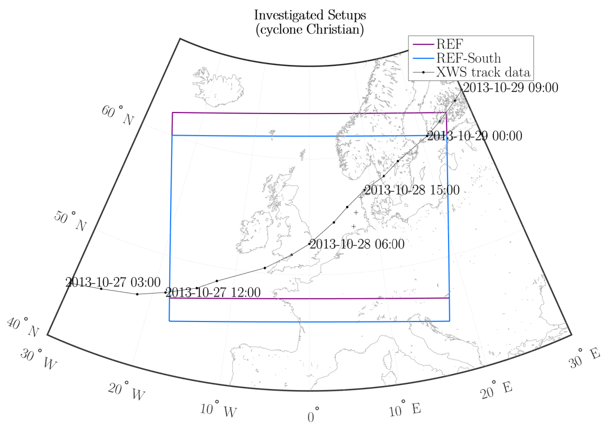

FIG. 1. Depiction of used outermost WRF domains together with the track of cyclone Christian extracted from the Extreme Wind Storm Catalogue.

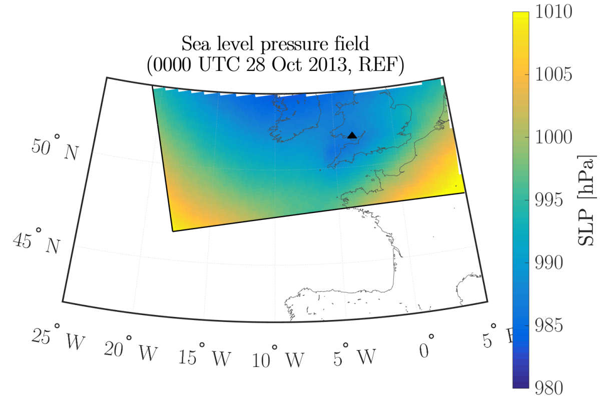

FIG. 2. Depiction of the sea level pressure obtained from "REF" simulation at 28 Oct 2013 UTC 0000. The black triangle indicates the position of the absolute minimum sea level pressure in the CFSv2 forcing data.

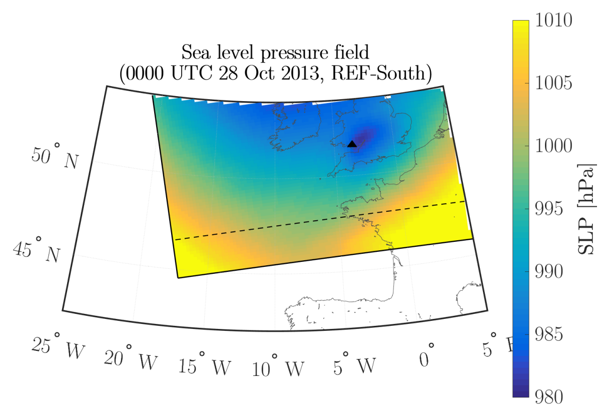

FIG. 3. Depiction of the sea level pressure obtained from "REF-South" simulation at 28 Oct 2013 UTC 0000. The black triangle indicates the position of the absolute minimum sea level pressure in the CFSv2 forcing data.

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