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Sensitivity of WRF-ARW simulations to the choice of physics parameterisation schemes when reconstructing Tropical Cyclone Ita (2014)

T. Kloetzke[1], M.S. Mason[1] and R.J. Krupar III[1]

[1]School of Civil Engineering, University of Queensland, St Lucia, Queensland 4072

Abstract

Tropical Cyclone (TC) Ita was a rapidly intensifying storm that made landfall as a Category 4 TC on 11 April 2014 near Cooktown, North Queensland. The Advanced Research - Weather Research and Forecasting (WRF-ARW) model has been used to reconstruct TC Ita with various combinations of physical parameterisation schemes implemented to assess their ability to accurately reproduce storm characteristics. The National Center for Environmental Prediction (NCEP) reanalyses data was used for boundary and initial conditions, and simulations were run on a 10 km grid with a nested 3.3 km storm-following nest. The TC's position, central pressure and wind speed were not well reproduced by WRF-ARW and were found to be sensitive to the choice of cumulus (CU), microphysics (MP) and boundary layer (PBL) schemes. The default WRF-ARW physics configuration, including the Kain-Fritsch cumulus scheme, WRF Single-Moment 3-Class Microphysics (WSM3), and the Yonsei University (YSU) boundary layer parameterisation, exhibits the smallest track error of all parameterisation schemes considered. Each Cumulus scheme, when combined with WSM6 microphysics or the Mellor–Yamada–Nakanishi–Niino (MYNN) boundary layer package produced the smallest central pressure error.

Introduction

Tropical Cylone (TC) Ita was the strongest storm to make landfall on the Queensland coastline since TC Yasi (2011). It formed over the Salomon Sea on 2 April, 2014 (Figure 1) as an area of low pressure. Ita gradually intensified and drifted westward over the next few days before strengthening to a Category 1 cyclone on 5 April (BOM, 2014). Ita continued its intensification and westward movement and brought heavy rainfall to the Milne Bay Province (southeast Papua New Guinea) as a Category 3 cyclone three days later. On 10 April, Ita rapidly intensified to a Category 5 event before making landfall near Cape Flattery as a Category 4 cyclone on midday 11 April. A maximum wind gust of about 44 ms^{-1} was recorded at the Cape Flattery Automatic Weather Station (AWS).

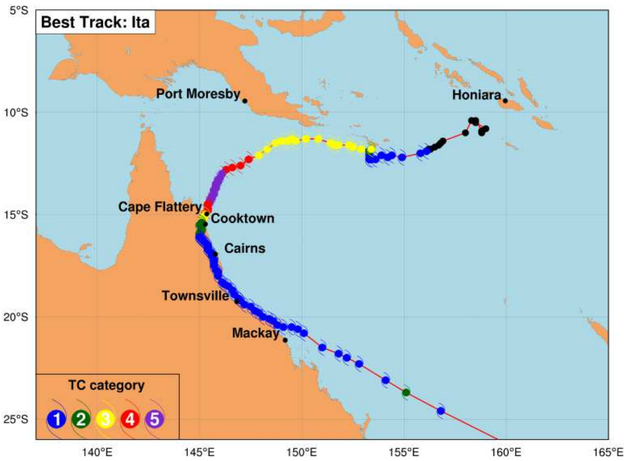


Figure 1. Bureau of Meteorology best track of TC Ita.

After landfall, Ita followed a southerly track passing approximately 20 km to the west of Cooktown as a Category 2 storm. A maximum 3-second gust wind speeds of 34 ms^{-1} was recorded at the Bureau of Meteorology's Cooktown Airport AWS (10 m elevation), with maximum 3-second gusts of 26-28 ms^{-1} recorded by SWIRLnet towers (3.2 m elevation) located across a range of sites between the eye of the storm and Cooktown (Mason and Henderson, 2015). Minor damage to approximately 200 structures and major damage to 16 buildings was reported (BOM, 2014). A maximum storm surge height of approximately 1.1 m was recorded and caused relatively little damage due to its timing with the low astronomical tide (BOM, 2014). Ita weakened to a Category 1 cyclone as it continued southward along the coast of Queensland. The storm moved offshore between Townsville and Mackay as a Category 1 storm then underwent extratropical transition as it moved away from the Queensland coast.

Forecasting and/or modelling TC track and intensity has been a major operational and research challenge for decades. It requires numerical simulation techniques that utilise different physical parameterisation schemes to model small scale processes, unable to be directly simulated (i.e. sub-grid processes). Raju et al. (2011), Parker et al. (2013), and Islam et al. (2015), for example, studied how these schemes influence TC track and intensity throughout the entire life of the storm, showing that choice of cumulus, microphysics and planetary boundary layer (PBL) physics schemes significantly change track and intensity properties of a simulated storm. As such, the decision about which of these sub-grid schemes to implement is important.

This paper presents initial work carried out to investigate how choice of cumulus, microphysics and boundary layer schemes influence storm characteristics when attempting to numerically reconstruct TC Ita. This study utilises the Weather Research and Forecasting (WRF) model (Skamarock et al, 2008) for all numerical simulations. The Advanced Research version (WRF-ARW) is implemented here, which allows ready comparison between a range of sub-grid schemes and their influence on storm-scale parameters (i.e. intensity and track position). A limited number of grid resolution and initial condition sensitivity tests were also undertaken. This paper will report results of these inter-model tests with the aim of identifying an optimal combination for the reconstruction of this event and its wind field at landfall.

Experimental Design and Methodology

Model configuration

This study utilises the WRF-ARW version 3.7.1 (Skamarock et al, 2008) in a moving nest configuration with the vortex-following option turned on. Following Parker et al. (2013) the two chosen domains are set up with grid and time step ratios of 1:3 with 30 vertical height levels. Domain one (d01) includes 230 × 230 grid points with a 10 km horizontal resolution, whereas domain two (d02) has a grid spacing of 3.3 km on a 220 × 220 grid. Figure 2 illustrates the spatial domain extent of d01 and the position within this domain of d02 on 9 April at 12 UTC, two days prior to landfall. A high-resolution version of these grids are also discussed in the results section, where d01 grid spacing is reduced to 3 km and d02 to 1 km.

All model runs used a time step of three hours and simulated the period between 9 April, 12 UTC through 14 April, 12 UTC, or 5 April, 00 UTC to 14 April, 12 UTC. All initial and boundary conditions are sourced from the 1° × 1° NCEP final operational model global tropospheric analyses data (NCEP, 2000). These include air temperature, humidity, hydrostatic pressure, sea level pressure, surface winds, and upper level winds.

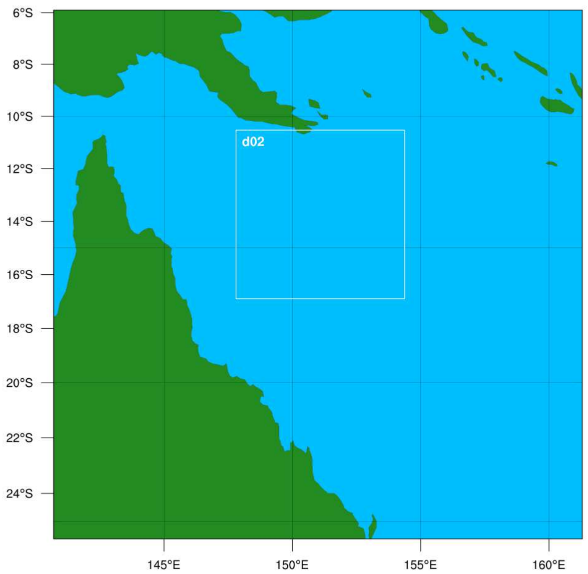


Figure 2. WRF-ARW pre-processing domain configuration with horizontal grid space of 10 km (d01) and 3.3 km (d02).

Sensitivity analysis

Testing the sensitivity of WRF-ARW model output to the physics schemes selected is crucial to explore the model strengths and weaknesses. In principle, once a suitable physics combination has been found, it is possible to further examine processes, such as the evolution of vertical wind profiles during landfall and the modulation of the near-surface wind field when interacting with topography. To evaluate the suitability of any combination of physics scheme, their resulting bias in track position and storm intensity (i.e. minimum central pressure) has been calculated with reference to TC Ita's track in version v03r08 of the International Best Track Archive for Climate Stewardship (IBTrACS) database (Knapp et al, 2010). No attempt is made to integrate these biases into a single bias value, but instead they are presented and discussed separately.

Although various physics options are available in WRF-ARW, this study focuses on testing cumulus (CU) schemes, microphysics (MP) options, and PBL parameterisations that are known to influence TC track and intensity, but have been widely used in WRF TC simulations (e.g. Raju et al., 2011, Parker et al., 2013, Islam et al., 2015). Of these, cumulus schemes are responsible for defining the thermodynamic state and its vertical stability, microphysics options influence the parameterisation of cloud particles and precipitation drops and, the PBL scheme parameterizes the heat, moisture and momentum transfer between the surface and the layers above. In total, 27 simulations were run and analysed using three of each CU, MP, and PBL schemes, with acronym definitions provided in the following dot points. The default configuration (Run 1, KF_wsm3_YSU) uses the Kain-Fritsch (KF) CU, WSM3 MP, and YSU PBL physics schemes (Skamarock et al, 2008).

- *Cumulus (CU) schemes*: KF CU scheme (KF), modified Tiedtke CU scheme (MF), Betts–Miller–Janjic CU parameterisation (BM) scheme,
- *Microphysics (MP) schemes:* WRF Single-Moment 3-class (WSM3) and WSM6 MP schemes, Eta Ferrier (EF) MP scheme,
- *Planetary boundary layer (PBL) parameterisation*: Yonsei University (YSU) PBL physics, the PBL Mellor–Yamada–Janjic (MYJ) package, and the MYNN Level 2.5 PBL scheme.

Results

The first simulation conducted involved running the reconstruction with the default physics configuration (KF_wsm3_YSU) on the default grid (d01: 10 km, d02: 3.3 km). This setup replicates that used in several previous TC simulation studies (Gentry and Lackmann, 2010, Raju et al., 2011, Parker et al. 2013, Islam et al. 2015). Figure 3 displays TC Ita's track and intensity for this run and the IBTrACS best track for the event. Of note is that the initiation position is reasonably well aligned on 5 April. Given simulations are initiated using reanalysis data, and not the best track, this is not always the case. By 7 April, however, tracks begin to diverge when the simulation takes a sharp northerly deviation due to a northward directed steering flow. After 27 hours the simulated track returns to a more westerly heading in-line with the observed Best Track. As the storm moves closer to the coastline its intensification reasonably follows the best track, but makes a southerly shift, which in the simulation occurs too early and the storm fails to intensify as the actual event did. The simulated track then only very slowly intensifies over the next 36 hours to a minimum central pressure of 952.5 hPa, and remains approximately 150 km offshore. The default model configuration therefore underestimates the storm central pressure by approximately 22 hPa and grossly misrepresents the storm track.

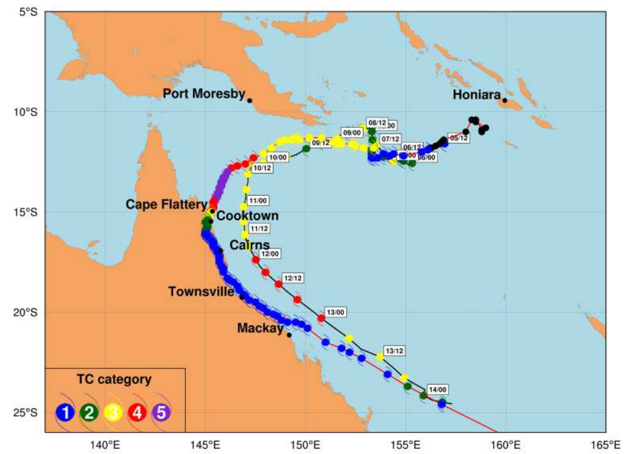
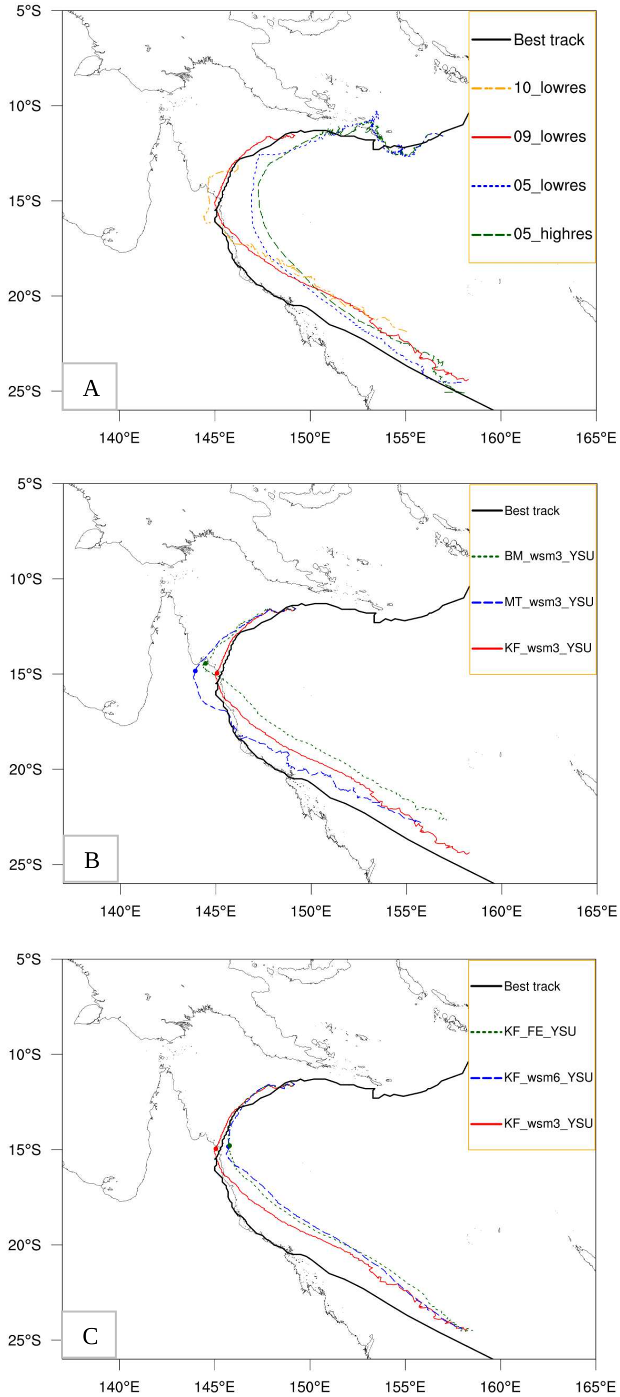


Figure 3. IBTrACS best track (red line) and intensity along with WRF-ARW (black line) modelled track and intensity for TC Ita.

To investigate whether this poor model performance was due to issues around grid resolution, a higher resolution grid (d01 = 3 km, d02 = 1 km) was implemented. Figure 4A shows the high resolution run starting on 5 April (05_highres, green line) along with the default run (Run 1) displayed as a blue line (05_lowres). Although both tracks behave similarly during the first three to four days, the high resolution run shows no significant improvement to the track behaviour and in fact stays further off the coast than the default run. Both simulations exhibit similar minimum pressure traces throughout their life cycles (Figure 5A). It was therefore decided that the default grid resolution was appropriate for progressing this research forward.

Another possible cause of simulation error was hypothesised to be linked with poor replication of steering flow in the initial and boundary conditions. To investigate this, several model initialisation dates were tested. Three initialisation dates were trialled, 5 (i.e. default run), 9 and 10 April at 12 UTC, and simulation results for each are illustrated in Figure 4A. The closest agreement to Ita's path was found for the 9 April, 12 UTC (09_lowres, red line) initialisation. Given this simulation makes landfall at a similar time to the best track, it also performs reasonably well when viewing the minimum pressure (Figure 5A), at least with regard to the shape of the time history. Although, the best track and the 09_lowres simulation differ after landfall, all subsequent simulations were initiated from this date/time. The following section expands on the influence each particular family of physics schemes has on both storm track and intensity.



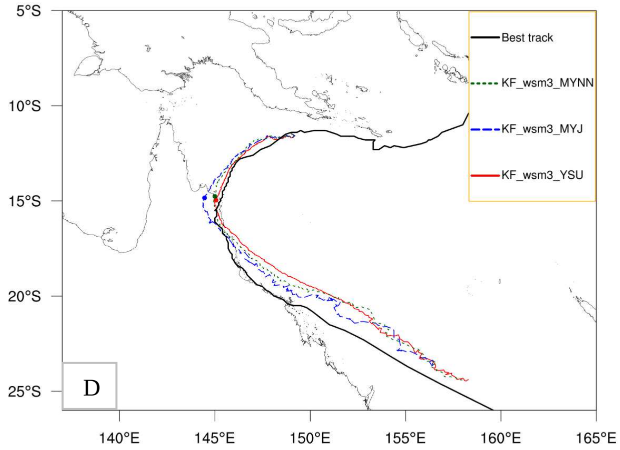


Figure 4. WRF modelled tracks and best track (black) of TC Ita for A) different starting times and grid size, B) CU schemes variation, C) MP scheme variation, and D) PBL scheme variation. Landfall points according to the best track landfall time are indicated with coloured dots.

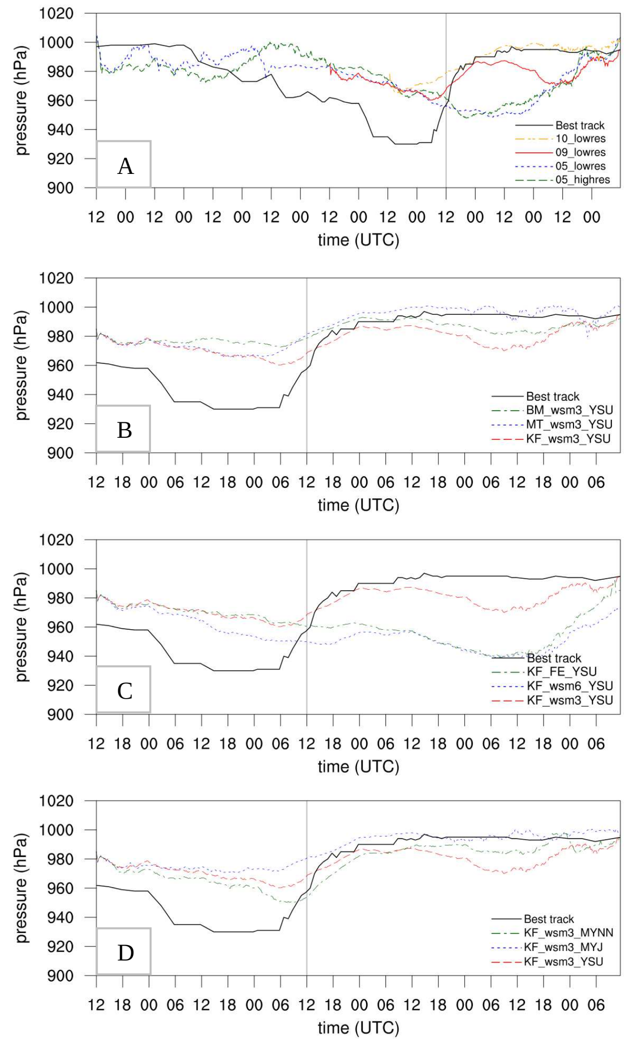


Figure 5. Pressure shapes for tracks in Figure 4 with time at landfall (grey vertical line).

CU schemes

Figure 4B shows a selection of three simulation tracks where the MP and PBL schemes were held constant, and only the three CU schemes were varied. Results show that the runs including the KF scheme have smaller track position errors, with respect to the best track, than the MF or BM cumulus options. This is confirmed when considering all sensitivity runs (i.e. not just those shown), and it is found that KF simulations exhibit a mean track position error of 88.5 km, while the MF and BM cumulus parameterisations generate errors of 99.4 km and 141 km, respectively. Simulated storms incorporating the two latter schemes also exhibit a mean landfall point around 117.3 km northwest of the best track position, whereas those using the KF scheme only have a mean landfall position error of approximately 46 km. Of the individual scheme combinations tested, the KF cumulus scheme, WSM3 microphysics, and the YSU PBL parameterisation was found to exhibit the lowest mean track error of around 65 km.

MP schemes

Changing MP schemes largely leads to changes in the simulated storm intensity (i.e. pressure). For the three simulations shown in Figures 4C and 5C, tracks remain spatially close to each other up to landfall but the minimum central pressure varies by up to 20 hPa over this period. Overall, the WSM6 was found to produce the lowest pressure values and the highest wind speeds. However, no events reproduced the sharp drop in pressure (~30 hPa) that occurs 36 hours prior to landfall, and none were able to rectify the 20 hPa deficit introduced by the initial conditions. Where events made landfall, the increase in pressure seen in the best track was reasonably simulated.

PBL schemes

Similar to the MP scheme's sensitivity investigation, simulated tracks with PBL scheme variation show only small deviations, as illustrated in Figure 4D. Here, the MYNN PBL scheme was found to produce the lowest central pressure values and highest wind speeds compared to the other simulations. However, the lowest central pressure error was found in the combination of MT CU scheme, FE MP scheme, and the MYNN PBL parameterisation.

Discussion

Graphical output of all sensitivity runs (not shown) shows that while each track differs, they all exhibit consistent features. For example, most simulations show a sharp change in track direction (south-westerly to south-easterly) when approaching the coast. This shift does not occur at the same time for all simulations, but is consistently simulated. Across all runs, and for the entire simulation period, the mean track error is approximately 110 km. Due to the differing physics options, a spread exists in the simulated tracks, which becomes greater as the storm approaches landfall. The mean track error at this point (11 April, 12 UTC) was 93.5 km, with about 89% of tracks actually making direct impact onto the mainland. Following this time simulated track consistently lie to the north of the best track.

Overall, the best track's lowest central pressure is 930 hPa, which is not well captured by any of the simulations. Part of the reason for this is the initial 20 hPa offset in central pressure introduced because simulations are initiated from course reanalysis data. The inability of the storm to rapidly intensify is perhaps, in part, a consequence of this, but no simulations reproduce this storm behaviour either. Vortex bogussing or other artificial methods for decreasing the initial cyclone intensity will need to be explored if this error is to be overcome. In the latter part of simulated tracks, a large spread in central pressures was observed. This is believed to be caused by the storm interactions with land, and for those simulations that kept storms well offshore, prolonged, and in some cases re-intensifying periods of low central pressures were observed. Overall, a mean root mean square error (RMSE) of about 24.4 hPa is calculated for the storm central pressure throughout its life cycle. This error is not consistent along the entire storm track, and at landfall it was reduced down to 14.2 hPa.

Conclusions

A series of WRF-ARW simulations were run in an attempt to reconstruct TC Ita and its wind field. A range of physical parameterisations schemes were tested to determine an optimal combination for this event. Is was found that the model was incapable of reproducing the best track data with 27 different physics combinations and 1° x 1° reanalysis data initiation files. Some improvement in track behaviour was possible through changes to model initiation dates, but the inability to begin events with deep enough central pressures and then intensify them means it is unlikely a reconstruction will be possible without artificial modification of either initial files or model boundary conditions. Methods for doing this will be explored in future work.

Acknowledgments

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