Evaluating WRF-ARW v3.4.1 Simulations of Tropical Cyclone Yasi

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ABSTRACT

Tropical Cyclone Yasi was a rapidly intensifying, category 5 storm that made landfall in Queensland, Australia on the 3rd of February 2011. This study addresses the simulation of Yasi using WRF-ARW v3.4.1 in a nested domain with ERA-Interim reanalysis products as boundary conditions and 4km resolution initial conditions from the Bureau of Meteorology, Australia. The cyclone's track, timing, and central pressure evolution are very sensitive to the microphysics, convection, and boundary layer schemes and the use of tropical storm surface flux and an ocean mixed layer model. While a "best" simulation configuration is non-unique, the use of normalised root-mean-square deviation calculation of parameters at landfall demonstrates that the simulation with cumulus Modified Tiedtke scheme; microphysics Ferrier scheme; and planetary boundary layer YSU scheme, produced the least error in simulating Yasi. A change in cumulus parameter is found to cause the largest change in simulation outcome and error index. Kain-Fritsch scheme produces most accurate pressure values and Modified Tiedtke scheme gives the most accurate track.

1. Introduction

Tropical Cyclone (TC) Yasi was a rapidly intensifying storm that began cyclogenesis just northeast of Fiji on January 29th 2011. It tracked southwest, continually gaining intensity until reaching category 5 by the time it made landfall at Mission Beach on the Queensland, Australia coastline in the early hours of February 3rd 2011 (local time). The track and timing can be seen in figure 1 below.

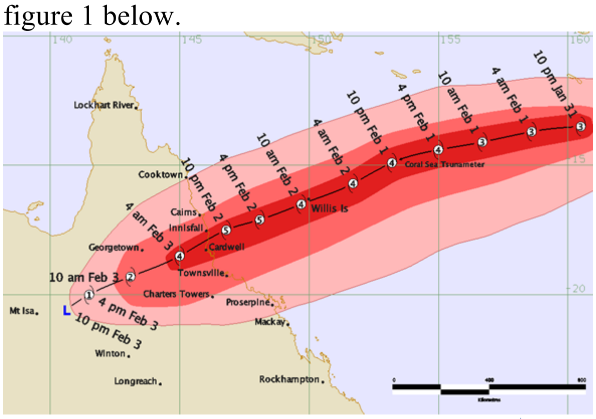

Figure 1: Track and intensity of Cyclone Yasi Jan 31st to Feb 3rd, 2011, Australian Eastern Standard Time, (Australian Bureau of Meteorology (BOM), 2011, [http://www.bom.gov.au/cyclone/history/yasi.shtml]).

On average, the TC measured 600km wide with an eye 35km wide. It produced a storm surge of up to 6m in height; wind speeds of up to 300km/h; and a minimum central pressure of 929hPa recorded at landfall (BOM, 2011) . These factors affected a large portion of the Queensland coast, including agriculture and population centres. TC Yasi negatively affected a wide portion of the Great Barrier Reef (GBR) ecosystem by causing mechanical damage to the reef structures, reducing salinity and temperature, and bringing anomalously high levels of nutrient and sediment loading into the reef lagoons as the flood waters receded from land (GBRMPA, 2011). This loading is thought to have resulted in negative secondary consequences such as coral bleaching; harmful algal blooms on corals and over whole reef areas; coral die-off; poisoning of corals and many other reef species; and Acanthaster planci outbreaks (Sweatman and Syms, 2011) and as happened after TC Larry in the same area in 2006 (Sweatman et al, 2006). The extent of the damage caused to the ecosystems and the time frame of recovery from TC Yasi is yet to be fully understood or accurately estimated.

TC Yasi was an interesting event due to its rapid intensification but also due to its situation within the very active TC season 2011 in the southwest Pacific Ocean (BOM, 2011). TC Yasi developed and tracked towards the Queesnland coastline immediately after TC Anthony. Anthony was a category 1-2 system which started as a tropical low on January 22nd and followed a meandering track through the Coral Sea. It did not make landfall until Jan 31st 2011, when Yasi had already begun to form (BOM, 2011). Due to Anthony's long duration over one area, it caused an unusual amount of vertical mixing, bringing cooler water from beneath the thermocline to the surface and depressing the sea surface temperatures (SSTs). It was therefore surprising that Yasi managed to establish and gain intensity as it tracked over this region towards the coast. The tracks of the four major TCs that affected the Queensland coastline and Coral Sea area in the 2011 TC season can be seen in figure 2 below.

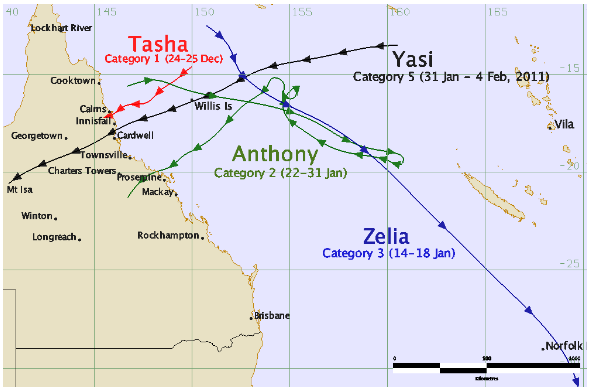

Figure 2: Tropical Cyclone activity in the western South Pacific Dec 2010 – Feb 2011 (BOM, 2011 [http://www.bom.gov.au/cyclone/history/yasi.shtml])

The circumstances and consequences of TC Yasi described above make it an important and interesting case study. It can be utilised to investigate and understand the atmospheric and oceanic conditions that governed the devastating storm's formation and life cycle. This type of analysis can be achieved with regional numerical weather modelling such as with Weather Research and Forecasting (WRF) Model. The operational guidance leading up to the event was impressively accurate in terms of track, timing and landfall location, but was less successful in capturing the intensification towards shore (BOM, 2011). This study aims to simulate the TC Yasi event using WRF-ARW v3.4.1 and explore the sensitivity of the cyclone's track, timing, minimum central pressure and pressure at landfall to the model configuration. In particular, the options and combinations of: microphysics, convection, boundary layer and the use of a tropical storm surface flux and 1-D ocean mixed layer.

2. Experiment Design and Methods

a. Model Set-up

This study uses WRF-ARW dynamic solver v3.4.1 (Skamarock et al. 2008) with a two-way nesting domain configuration. The domains were set up with a Mercator projection and parent grid and time step ratios of 1:3. The location and dimensions of the domains are detailed in table 1 and can be seen in figure 3. The inner nest's size covers the entire extent of TC Yasi's track and matches the area of 4km initial condition data provided by the Bureau of Meteorology (BOM), Australia. This is the same data that the BOM utilised as initial conditions for their simulations of TC Yasi. However, the sensitivity simulations of model physics parameters in this study were carried out with just the outer two domains; future simulations will utilise all three domains including the 4km resolution innermost nest. All three domains have 28 vertical levels, 38 metgrid levels and the top pressure level set at 50hPa.

Table 1: Specification of WRF domains for the TC Yasi simulations

Domain	Centred lat	Centred lon	NX	NY	Grid space
1	-16.018	156.382	267	147	36km
2	-16.018	156.382	505	283	12km
3	-16.018	156.382	739	484	4km

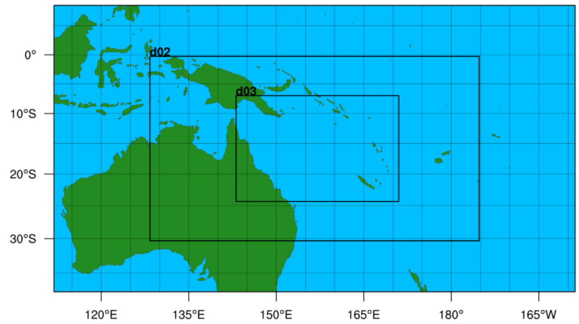

Figure 3: graphic of the 3-domain nested set up for the study: d01 36km, d02 12km, and d03 4km. The 4km grid will be used in future simulations.

Lateral boundary and forcing conditions for the model runs were provided by ERA-Interim reanalysis pressure level products (ERA); BOM high resolution initial conditions were used to initialise the model in the first time step. The simulations ran from 31st January 2011 00:00 UTC and to 4th February 2011 00:00 UTC.

b. Physics Sensitivity Simulation

The physics package parameters tested for the simulation of TC Yasi included: cumulus parameterisations (CU), which represent and define atmospheric heat and moisture, cloud tendencies and surface rainfall; the microphysics scheme (MP) which also affects and governs these physical processes; the planetary boundary layer (PBL) which represents boundary layer fluxes and exchanges such as heat, moisture and momentum and governs vertical diffusion and mixing; the

ISFTCFLX term that modifies surface bulk drag and the exchange of energy between the TC and the ocean surface; and the use of a simple one-dimensional ocean mixed layer model (OML). All other physics options were kept constant through the model runs.

Table 2: Summary of WRF physics options tested in each run

Run	ISTCFLX	OML	CU	MP	PBL
1	No	No	Default	Default	Default
2	No	No	Default	Default	Default
3	No	No	2: Betts Miller Janjic	4: WSM 5-class scheme	1: YSU scheme
4	No	No	1: Kain Fritsch new Eta	5: Ferrier new Eta	1: YSU scheme
5	No	No	3: Grell Devenyi ensemb	5: Ferrier new Eta	1: YSU scheme
6	No	No	5: Grell 3D ensemble	5: Ferrier new Eta	1: YSU scheme
7	No	No	6: Modified Tiedtke	5: Ferrier new Eta	1: YSU scheme
8	No	No	6: Modified Tiedtke	6: WSM 6-class graupel	1: YSU scheme
9	2: Donelan Cd +Garratt	No	6: Modified Tiedtke	6: WSM 6-class graupel	1: YSU scheme
10	2: Donelan Cd +Garratt	Yes 50m	6: Modified Tiedtke	6: WSM 6-class graupel	1: YSU scheme
11	No	No	1: Kain Fritsch new Eta	6: WSM 6-class graupel	1: YSU scheme
12	2: Donelan Cd +Garratt	No	1: Kain Fritsch new Eta	6: WSM 6-class graupel	1: YSU scheme
13	2: Donelan Cd +Garratt	Yes 50m	1: Kain Fritsch new Eta	6: WSM 6-class graupel	1: YSU scheme
14	2: Donelan Cd +Garratt	Yes 50m	1: Kain Fritsch new Eta	6: WSM 6-class graupel	5: MYNN 2.5 level TKE
15	2: Donelan Cd +Garratt	Yes 50m	2: Betts Miller Janjic	1: Kessler scheme	1: YSU scheme

Details of the simulations and the physics parameters used are in table 2. The resulting TC from the different physics combination simulations were analysed and contrasted by calculating:

1. The deviation in time of landfall from the observed 14:00 UTC Feb 2nd 2011 (in hrs).
2. The deviation in location of landfall from the actual location at Mission Beach (in km).
3. The deviation in landfall central pressure from the observed 929hPa (in hPa).
4. Using these three deviation values to calculate an error index for each simulation by normalised root-mean-square deviation. The lowest resultant error index (closest to zero, a perfect simulation) would indicate the most accurate simulation in terms of landfall pressure, timing and location.
5. The track, central pressure (SLP), wind shear, latent and sensible heat fluxes, and warm advection of the full duration of each of the simulations are inter-compared.

3. Results

Figure 4 depicts all the simulated TC Yasi tracks from the 31st of January 00:00 UTC for all the separate runs. At the beginning of the simulations, the tracks are fairly well clustered, but different physics options yield greater spread and deviation in the simulated track particularly towards landfall and the subsequent track afterward. The actual location of landfall is plotted as the black point. The track in orange is run 1, which was the least accurate simulation as demonstrated by its track. The tracks with the other colours represent runs 7,8,9,10 which are tightly clustered and have the most accurate landfall locations.

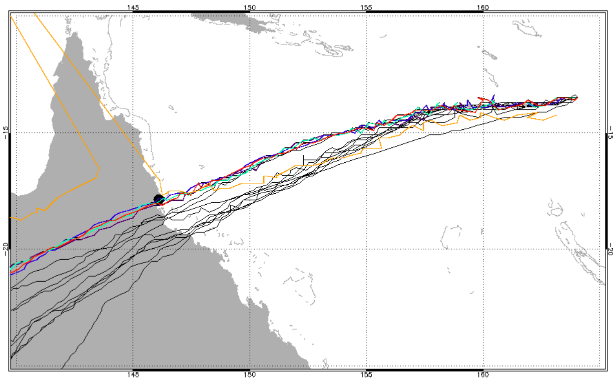

Figure 4: simulated TC tracks from each physics trial run.

However, track and landfall location are not the only important factors to consider in determining the accuracy of the simulation. Figure 5 below displays the root mean square deviation error index for each of the simulations. These calculations consider equally the landfall distance error, landfall central pressure error, and landfall time error. Figures 4 and 5 demonstrate that including the 4km resolution BOM initial condition data (the only difference between runs 1 and 2) helped to improve the track and also the overall error of the simulated TC. The TC track of run 2 does not follow the yellow track of run 1 in figure 4 and also has a visibly lower error index than run 1 in figure 5 proving that the high resolution initial condition is essential. Figure5 portrays a clustering of runs 7,8,9,10 (circled) as having the lowest error score. These simulations already produced the most accurate track and landfall location and all have CU6 (modified Tiedtke Scheme).

The results are suggesting that the cumulus parameterisation and particularly the Tiedtke Scheme are crucial in reducing error and producing a more accurate simulation of TC Yasi. Including the TC surface flux and an ocean mixed layer model (runs 9 and 10 respectively) appeared to also improve the accuracy of the simulation incrementally. Microphysics schemes 5 (Ferrier) and 6 (WSM 6-class graupel) appear to be well-suited to the simulation of TC Yasi. Comparing runs 7 and 8 indicates that using MP5 reduces the error of the simulated TC better than MP6 and comparing runs 13 and 14 suggests that PBL5 (MYNN 2.5 level TKE) may be able to improve the model performance and be more suitable than PBL1 (YSU scheme). Further testing is needed to confirm these indications.

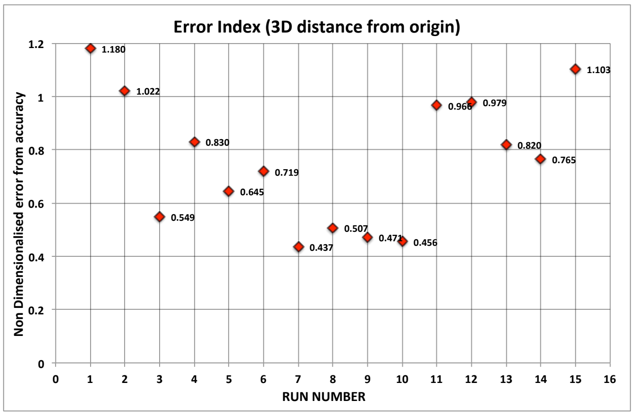

Figure 5: Normalised root-mean-square (RMS) error of each simulation.

Figures 6 and 7 demonstrate the change in central pressure of the simulated TC (hPa) over time and the track for the "best" run, (run7) and run 4 to contrast. These runs have the same physics parameters except for the CU scheme used. In run 7, Yasi has a minimum central pressure (strongest intensity) fairly early in the simulation over the open ocean and then pressure increases (intensity weakens) as it progresses and then finally pressure decreases again and the system increases in intensity a little as Yasi moves to make landfall. In reality, as figure 1 showed, TC Yasi continuously increased in intensity (decreased in pressure) right up to landfall and did not weaken over the ocean. Some of the simulations carried out in this study managed to capture the evolution and values of pressure more accurately, but then the location of landfall had a high error increasing the run's error index. These were runs 4, 11, 12, 13 which all use CU1 (Kain-Fritsch) and run 4 can be seen in figure 7. This suggests that CU1 produces more accurate pressure and intensity evolution values for Yasi but CU6 produces a much more accurate track. Decisions need to be made based on the use of this type of simulation about which variable is more important before moving on with further simulations of TC Yasi.

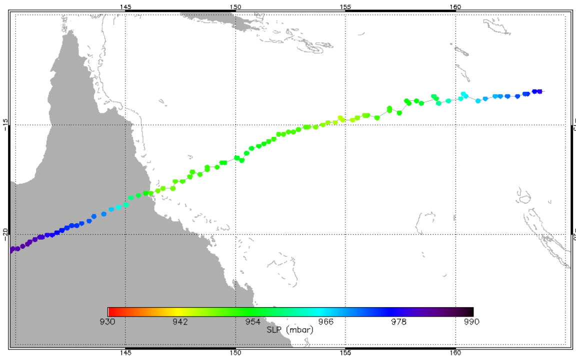

Figure 6: the min SLP (mbar) and location of the eye at each time step of the simulation for run 7.

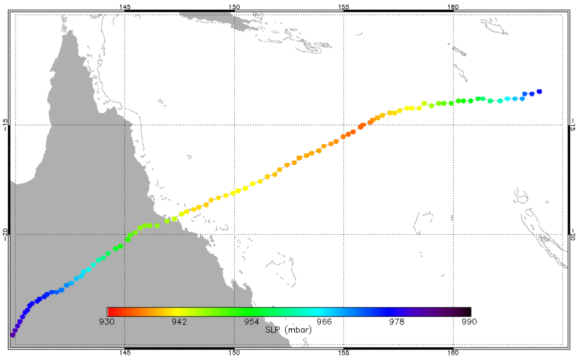

Figure 7: the min SLP (mbar) and location of the eye at each time step of the simulation for run 4.

4. Conclusions

The study has found that simulating a TC event accurately is dependent on the domain set up, initial and boundary forcing data and the chosen physics packages. From the results of this study so far, it seems that a two-way nested domain configuration with 4km high resolution initial conditions is required. CU1 produced the most realistic pressure values and changes in time and CU6 produced the most accurate tracks. Further sensitivity studies need to be continued to pinpoint the exact effect of MP and PBL parameters and how any of these results and findings may change when simulating with the inner most 4km domain and with auxiliary, accurate SST fields.

5. References:

Australian Bureau of Meteorology, (2011) [http://www.bom.gov.au/cyclone/history/yasi.shtml];

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