Investigation of the Development of Tropical Storm Nicholas based on Global and Regional Climate Data

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Abstract

This paper studies the simulation of Cyclone Nicholas that occurred close to the coastal area of Western Australia and fell on the mainland of Southwestern Australia. The simulation was conducted via a dynamical downscaling model, Weather Research and Forecasting (WRF), to obtain a higher resolution with reference to the regional climate data. The model simulation is generated using a global reanalysis of climate data for the initial and lateral boundary conditions. We investigated the response of the tropical storm to the model regarding the track and intensity using a modified Kyklop method that appears more appropriate for a landfall cyclone. Our study suggests that the regional climate data computed by the model deviates from the storm track of the global climate data forcing field. In this study, the track of the simulated storm is parallel to the satellite data, but it is shifted slightly to the east, closer to the mainland. Nevertheless, the model simulation can implement the intensity of the storm as strongly as the observation, while the forcing data delivers substantial underestimation.

Keywords: cyclone, dynamical downscaling, simulation WRF, hazard, coastal.

1. Introduction

A tropical cyclone is a weather phenomenon caused by atmospheric conditions, humidity and sea surface temperature (Hsu *et al.,* 2019). Cyclones are storms with exceptional strength and a wide radius (Hernández *et al.,* 2021). This phenomenon generally occurs in tropical oceans with warm temperatures (Sobel *et al.,* 2021; Wakeford *et al.,* 2023). Notwithstanding that they primarily occur in the oceans, tropical cyclones have a significant impact that can cause damage both at sea and on land, for instance strong winds, heavy rain and extreme waves that disrupt shipping and can potentially submerge and sink ships at sea (Mendelsohn, 2019). While on land, strong winds are fatal and can destroy buildings, vehicles, as well as other places and objects in their path (Sobel *et al.,* 2021). In addition, tropical cyclones also cause storm surges or sea level rises, such as high tides that come suddenly and are dangerous when they reach land (Akhter *et al.,* 2023).

Tropical cyclones frequently occur in Australia's oceans and impact the coastal and mainland region (Mashao *et al.,* 2023). Tropical cyclones Jacob and George occurred on 2-12 March 2007. Approximately one year later, Cyclone Nicholas occurred between 11-20 February 2008 and cyclone Marcus on 14-27 March 2018 (Ningsih *et al.,* 2020). Cyclone Nicholas had a tremendous impact as it made landfall by hitting Western Australia (Alcantara and Ahn, 2023). The impact was felt not only in Australia, but also across Indonesia (Ningsih *et al.,* 2020; Amaral *et al.,* 2023). These storms occurred relatively close to Indonesian territory and contributed to the occurrence of waves and a rise in sea level on the southern coast of Indonesia (Andraju *et al.,* 2019).

Moreover, Cyclone Nicholas, which occurred in Western Australia, also generated high wave phenomena and sea level anomalies on the western coast of Sumatra and the southern coast of Java and Bali (Anushka *et al.,* 2018). The cyclone struck suddenly and posed a significant hazard as it fell on the mainland (Mortlock *et al.,* 2023; Xi, et al 2023). According to the summary issued by the Australian government, Cyclone Nicholas was a severe typhoon with the wind speed increasing by around 10 to 13 km/h (Aragon *et al.,* 2016).

Previous studies have investigated tropical cyclones for various purposes. For example, Quaill *et al.,* (2019) observed the experiences of people with physical disabilities before, during and after a cyclone in Australia to provide input into implementing the Disability Inclusive Disaster Risk Reduction (DiDRR) policy. In addition, Bell *et al.* (2022) investigated the economy-wide repercussions of the biophysical damage due to Cyclone Debbie in Australia using multi-region economic input–output (MRIO) analysis to determine the storm's impact on supply chains (Sondermann *et al.,* 2023). However, Bell *et al.* (2022) determines TC-wind speed ARIs from a series of tropical cyclone datasets to predict the likelihood of extreme winds. Subsequently, Bruyère *et al.,* (2019) created a physically based landfall tropical cyclone scenario based on the occurrence of severe Cyclone Debbie in Australia in 2017 to support the risk assessment. Likewise, Anushka *et al.* (2018) facilitated typhoon disaster preparedness in the Wet Tropics bioregion of Australia by evaluating the individual adaptive capacity and social capital.

Parker *et al.* (2018) developed simulations with the Weather Research and Forecasting (WRF) model to determine the impact of climate change on the features of the tropical cyclones in north-eastern Australia. WRF allows researchers to generate simulations that reflect actual data (Vinet *et al.*, 2020). In addition, WRF provides a relatively flexible and robust operating system for forecasting (Andraju *et al.*, 2019; Boutin *et al.*, 2023). It should be noted that WRF is appropriate for research and weather forecasts (Mostafa *et al.*, 2022). Understanding the characteristic response of cyclones to a downscaling model such as WRF can improve the prediction quality, which may estimate the impacts of cyclones more accurately. Therefore, in line with the work of Parker *et al.* (2018), this study investigates the cyclone response compared to the WRF model by reconstructing Cyclone Nicholas which occurred in Australia in 2018. We compare the development of Cyclone Nicholas based on the global climate data and the regional climate data obtained from the WRF simulation. To evaluate the path of the cyclone, we compare both climate data and the satellite data, in terms of the track and intensity of the cyclone (Bruyère *et al.*, 2019).

2. Research Methods

This section covers the methods applied in this study, information on the study area, along with the dataset for the numerical simulation. To obtain the regional climate data over the ocean and coast of Western Australia, we downscale the global climate data using a numerical weather prediction model, Weather Research and Forecasting (WRF) model. To trace the development of the cyclone, we modify the Kyklop method so that it can be applied to investigate the track and the intensity of a landfall cyclone. Subsequently, we evaluate the development of Cyclone Nicholas from global and regional climate data against satellite data. Figure 1 shows the framework employed in this study.
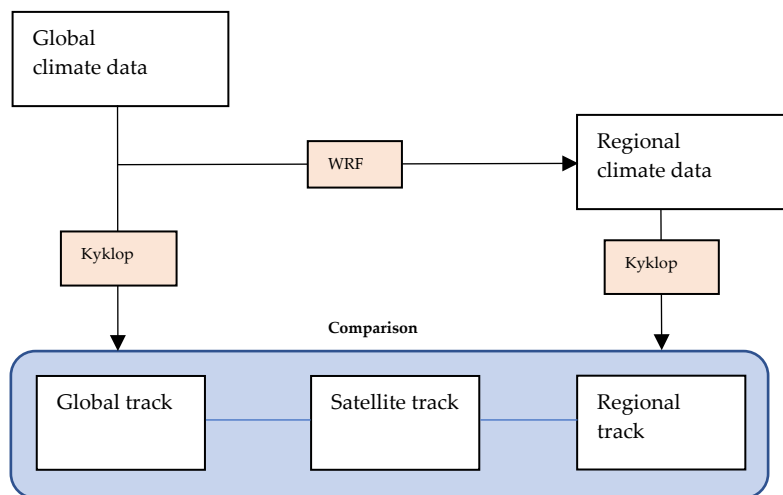

Figure 1. Framework of the study.

2.1. WRF model

Numerical Weather Prediction (NWP) is a system that supports research on the atmosphere and weather forecasts. The WRF model is a NWP that has been extensively exploited because of its ease of use and relatively accurate results (Gaur *et al.*, 2021; Taylor *et al.*, 2023). The WRF model is a compressible Euler equation, including a non-hydrostatic equation on a regional scale. This study implemented the non-hydrostatic equation in the WRF version 3.8.1. (Chan *et al.*, 2023) downloaded from the official MMM NCAR website. The WRF model was developed as a result of the collaboration between the National Centre for Atmospheric Research (NCAR), National Centre for Environmental Prediction (NCEP), Forecast System Laboratory of the NOAA (NOAA/FSL) and Air Force Weather Agency (AFWA). Further details of the WRF model pertaining to the dynamics, primitive equations, numeric and physics were presented by Cheung *et al.* (2023).

In this study, the WRF model was applied to downscale Cyclone Nicholas from a general circulation model (GCM), i.e., NCEP FNL reanalysis data. The model simulation is configured on a 10 km spatial grid size. It is limited to 27 levels in the vertical direction and dimensions of 400 x 400 grid points in the longitude and latitude directions. The model applied tropical physics suite in conjunction with the cloud microphysics scheme produced by Lin (Chutia *et al.*, 2019; Torrez *et al.*, 2023). Moreover, it integrated the cumulus parameterisation scheme of Kain-Fritsch, the

planetary boundary layer (PBL) parameterisation scheme of Mellor-Yamada-Janjic TKE and the surface layer scheme of the Eta Similarity Scheme (Delfino *et al.,* 2023).

2.2. Kyklop method

To track the evolution of the cyclone, the Kyklop method is implemented with various adjustments. The main area of the tropical storm is detected where the wind speed is more extensive than 16.5 km/h, the temperature is higher than 298.15 K and the surface pressure is less than 1000 Pa. These parameters are different from the parameter value used in Franco *et al.* (2017) and Latifah and Adytia (2019). The chosen parameters are based on the minimum error between the model result and the observation (Denniston *et al.,* 2023; Yang *et al.,* 2021). The eye of the cyclone is an area with relatively low wind speed and cloud located at the centre of the cyclone. Unlike the Kyklop method (Franco *et al.,* 2017) that detects the eye of the cyclone centred on the main area of the storm, we modified the method by excluding the eccentricity as it is less suitable for a landfall tropical cyclone. Instead, the eye of the cyclone is estimated by the maximum wind speed or the minimum sea level pressure (Gaur *et al.,* 2021).

2.3. Study Area

The study area is Western Australia which is located at latitudes 89°E to 130°E and longitudes 0°S to 38°S (see Figure 2). Australia has a varied climate with four seasons in most of its territory and a tropical climate in the north. Northern Australia is a tropical cyclone growth area where cyclones commonly occur between November and April. This particular region experiences an average of 11 cyclones a year, although only four to five cyclones make landfall that substantially impacts the environment, society and the economy (Gorja *et al.,* 2023). Most cyclones are formed in large cloudy areas because of the South Pacific Convergence Zone and the movement of the monsoon winds in southern Indonesia and northern Australia.
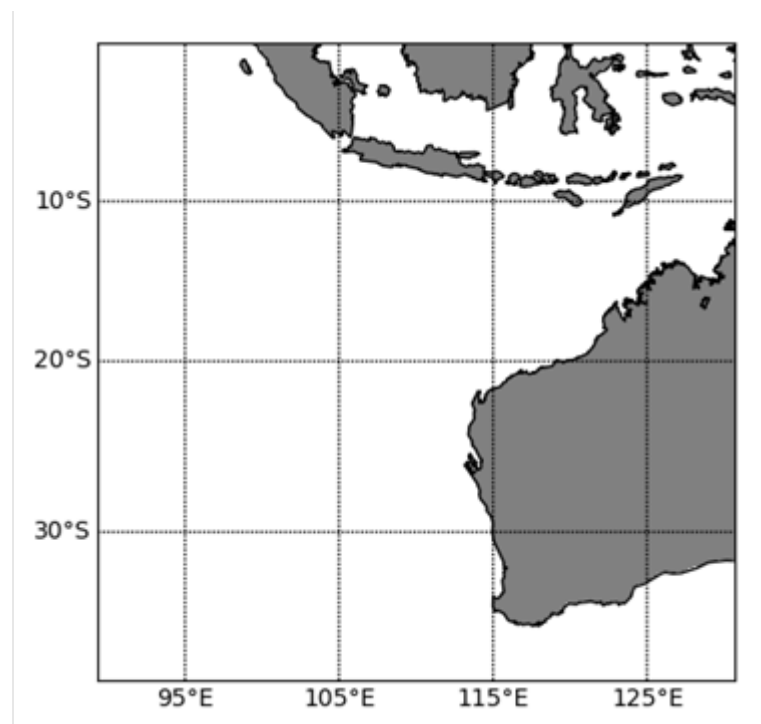

Figure 2. Domain for the WRF simulation.

2.4. Dataset

The geographical static data provided by Mesoscale and Microscale Meteorology (MMM) Laboratory, the National Centre for Atmospheric Research (NCAR) was employed for the WRF simulation, consisting of topography, land use and soil type (Mortlock *et al.,* 2023; Wang *et al.,* 2019). The atmospheric dataset from the National Centres for Environmental Prediction Final Operational Global Analysis (NCEP-FNL), is applied for the dynamic atmospheric data from 9-20 February 2008. The data's spatial resolution is 10, with a time step of six hours for the lateral boundary condition. The atmospheric variables include air temperature, sea surface temperature, sea level and surface pressure, zonal and meridional winds, geopotential height, relative humidity, land characteristics, ice cover, vorticity, vertical motion and ozone (Parker *et al.,* 2018; Quaill, Barker and West, 2019). For model validation, the simulation results are compared with the best

track summary for Cyclone Nicholas from the Bureau of Meteorology in Australia (Quaill *et al.,* 2019). In addition, the spatial wind and sea level pressure pattern, the maximum wind, as well as the minimum sea level pressure are also compared with the dataset from KITAMOTO Asanobu, National Institute of Informatics (Halladay *et al.,* 2023).

3. Results and Discussion

3.1. Cyclone track

Cyclone Nicholas was a very slow-moving storm, averaging between 4 and 10 km/h on 16 February 2008, as summarised in the report issued by the Australian Government (2008). The report also explained that the wind speed increased to 10-13 km/h and the storm lasted for ten days. This is consistent with the cyclone remodelling by the WRF model, which occurred from 11 to 20 February 2008. Figure 3 illustrates the track or path of Cyclone Nicholas' eye. Cyclone Nicholas began to form on 11 February 2008 in the Indian Ocean off northeastern Australia (Wasko *et al.,* 2023). The path of the cyclone begins at latitude 120° E and longitude 15°S. It subsequently heads in a southwesterly direction along Australia's outer coastline, disappearing inland at latitude 115° E and longitude 25° S (Wakeford *et al.,* 2023).
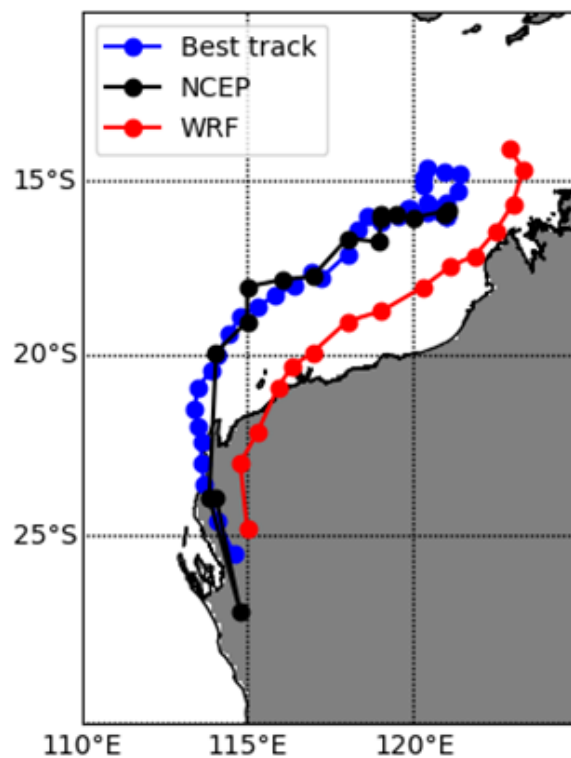

Figure 3. The track of Cyclone Nicholas.

Besides comparing the cyclone track, we observe the spatial pattern changes of the wind speed and the sea level pressure during the cyclone on 16-19 February 2008 in Figure 4. The satellite images in Figure 4, show the storm as large thick clouds moving in a clockwise direction. This is also shown in the wind direction in both the WRF simulation and the NCEP (Luu *et al.,* 2023). The strong winds occurred on 16-17 February 2008, then reduced the next day. Afterwards, the storm travelled down to the southwest for three days and began to dissipate on 19 February 2008 when the cloud was noted to reduce in size. The results of the NCEP and WRF, confirm that the sea level pressure and wind speed form a vortex with a lower sea level pressure and a faster wind speed towards the eye of the storm (Chen *et al.,* 2017). The WRF simulation exhibits more extreme wind speed over larger regions than NCEP (Chutia *et al.,* 2019). Moreover, the sea level pressure at the eye of the cyclone, indicated by the dark blue in the WRF simulation, is much lower than the NCEP (Moreno *et al.,* 2023).
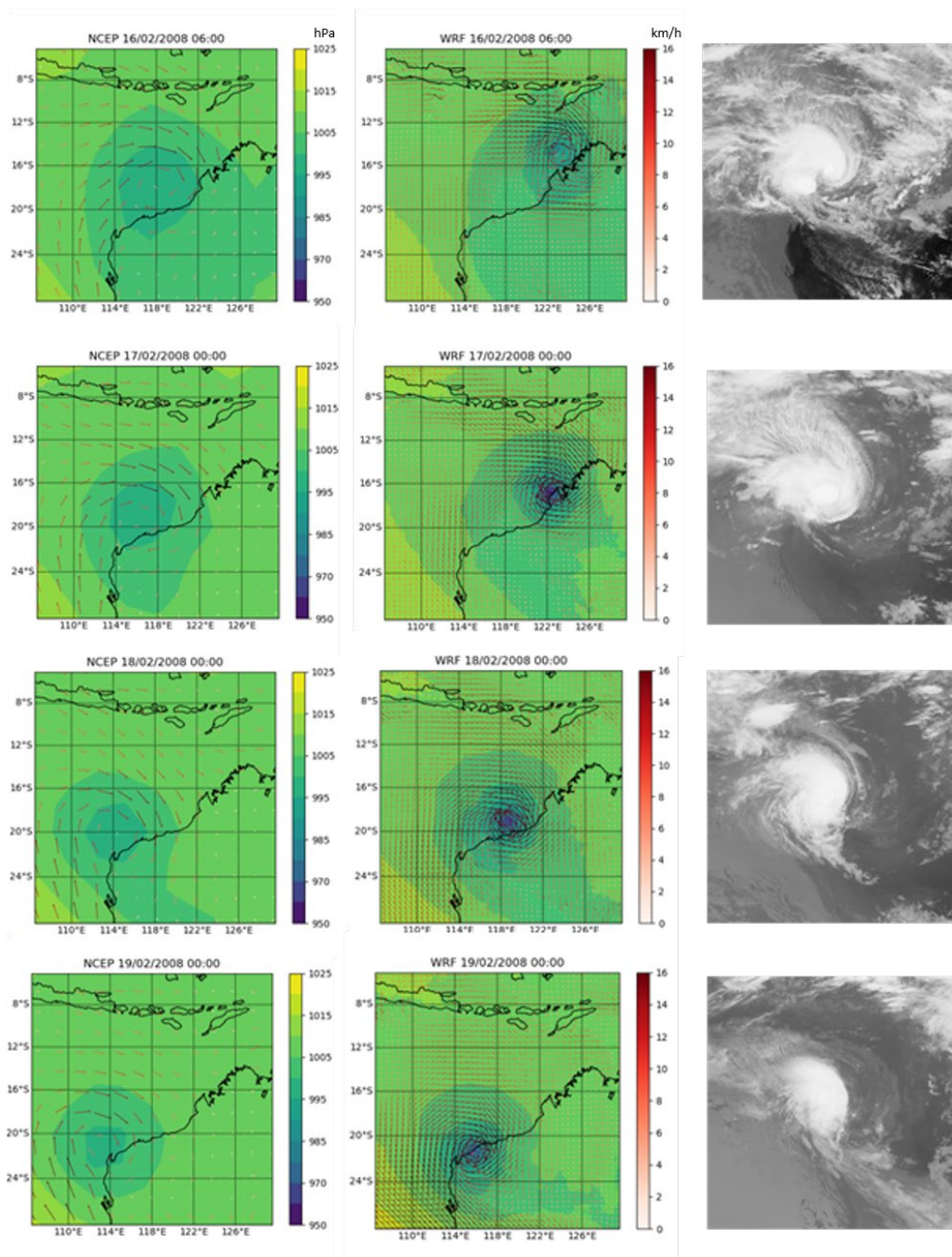
Figure 4. Sea level pressure overlaid by Cyclone Nicholas' wind field on 16-19 February 2008. From left to right: bi-linear interpolated NCEP, WRF simulation, satellite images.

3.2. Cyclone intensity

Figure 5 indicates the changes in wind speed. Figure 6 presents the sea level pressure in Cyclone Nicholas based on the best track, NCEP and WRF model simulation. Despite no significant changes in wind speed and sea level pressure during the storm being observed in the NCEP, the WRF model simulation presents comparable results with the observation (Hsu *et al.,* 2019). The WRF model can estimate the maximum wind speed (40 km/h) and the minimum sea level pressure (950 hPa) during the storm (Moon *et al.,* 2021). Both variables have two days delay from the observation. The increase in the wind speed and the decrease in the sea level pressure in the most suitable track began on 14 February 2008, while those specific changes began on 16 February 2008 in the WRF model simulations. Prior to 14 February 2008, the wind speed values from the NCEP, WRF and observations ranged between 15-20 km/h. Subsequently, the WRF value and the observations increased and peaked at 40 km/h on 17 February 2008, although the NCEP remained the same. The wind speed from the WRF delivers a better comparison with observation data at the beginning and the end of the simulation. This also is in agreement with the study

conducted by Quitián *et al.,* ([2021](#)). On 14 – 17 February 2008, the WRF displayed a negative bias toward the observation data.

Concurrently, the sea level pressure begins at around 1000 hPa and then diminishes at the storm's peak to 950 hPa in relation to the observation and 960 hPa regarding the WRF on 17 February 2008 (see Figure [6](#)). The WRF model simulation illustrates an underestimation except in the initial two days, with the highest bias being 30 hPa on 15 February 2008. In the first and last three days, the simulation captures the intensity of the observation data.
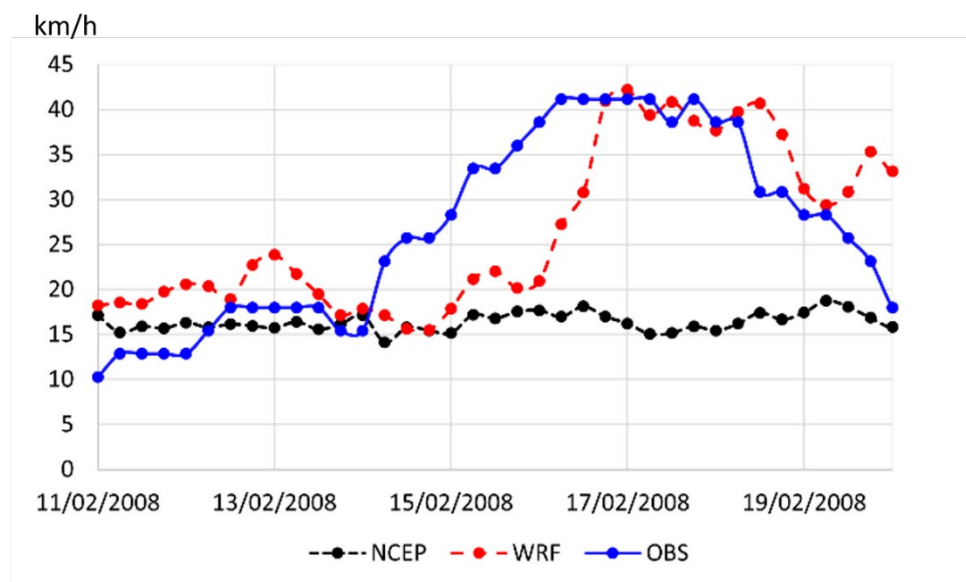
Figure 5. The maximum wind speed during the storm. Data observation (OBS) was retrieved from Kitamoto Laboratory (2023).
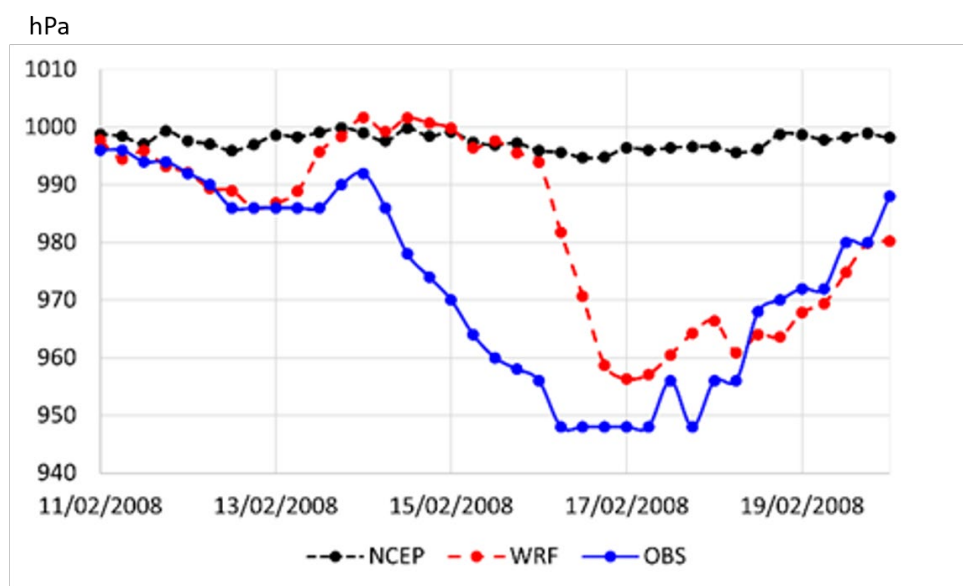
Figure 6. The sea level pressure during the storm. Data observation (OBS) was retrieved from Kitamoto Laboratory (2023).

3.3. Discussion

Observing the track of the cyclone, the cyclone generated by the WRF model is similar to the path witnessed in the NCEP and observation, although the WRF track shifts towards the east, which is closer to the mainland. The deviation track of the WRF also occurred in the study of tropical cyclone tracks in the Western North Pacific by Huang *et al.* ([2022](#)), in which the WRF model also established an underestimation of the speed and intensity. In our case study, the different track commences at the initial stage, but the track gap between the model and the observation is smaller in the final stage of the cyclone. This observation is also noted in the research undertaken by

Munsi *et al.* (2021) in the simulation of the cyclone track by the WRF, which exhibits deviation to some extent during the initial period of the genesis stage compared with the IBTrACS observation.

The study completed by Lui *et al.,* (2021) confirmed that the WRF model underpredicts the intensity and its trend. The same behaviour is also observed in our study. The underestimation could be related to the low intensity in the forcing field, resulting in a gap between the simulation tracking and the best tracks mentioned previously. The drawbacks associated with the WRF model were also discovered in the study conducted by Huang *et al.* (2022), Jaffrés *et al.* (2023), as well as Latifah and Adytia (2019), where the model revealed good accuracy in connection with the cyclone track, but it overestimated the cyclone intensities.

Previous research has considered at the accuracy of the WRF model in forecasting tropical storm trajectories. For example, one research examined the direct positioning errors (DPEs) in the WRF model low storm track predictions across the Philippines and determined that the model contained displacement errors (Moon *et al.,* 2021). Different research evaluated the global and regional WRF models in track errors for four typhoons during the 2011 season and ascertained that the regional WRF model had lower track errors (Yu, 2022). As also stated in the study undertaken by Munsi *et al.* (2021), notwithstanding that the WRF model simulation can reproduce the maximum stages of the cyclone systematically, the initial track should be carefully handled so that the deviation can be minimised. Not only are they the consequences of the forcing data, but the deviations might also stem from the sensitivity parameters of the model itself (Zhang *et al.,* 2019).

As presented in this study and previous studies, even though downscaling approaches such as the WRF model contribute more comprehensive climatic information, significant errors can still occur (Lui *et al.,* 2021). Further research to improve the robustness of the WRF model in simulating cyclone tracks and intensities is essential. A comprehensive study should thoroughly examine the sensitivity between the cyclone track and intensity, particularly in the early stages, together with the forcing field or with the model parameterisation (Li *et al.,* 2023). Likewise, an additional study is necessary to investigate strategies to enhance the accuracy of downscaling approaches (Lockwood *et al.,* 2023).

4. Conclusion

Substantial errors may still occur among the added values of a downscaling method when providing more comprehensive climate information. This study illustrates the cyclone track deviation during Cyclone Nicholas on 9-20 February 2008 remodelling by the Weather Research and Forecasting (WRF) model, while the forcing data in the NCEP presents a good track. However, the physical changes in sea level pressure and wind speed cannot be captured by the NCEP. Granting that the intensity is weak at the initial stage of the cyclone in the WRF model simulation, the WRF model can reflect the condition of the cyclone by exhibiting a significant change in sea level pressure and wind speed. This weak intensity during the initial stage may be the consequence of an initial error in the cyclone track because the track only shifted to the east. Simultaneously, the pattern follows the observation correctly. The dependence between the cyclone track and intensity, principally in the initial stage, should be investigated further in future studies, given that it may relate to the forcing field.

Author Contributions

Conceptualisation: Intan Nuni Wahyuni, Ayu Shabrina; **methodology**: Intan Nuni Wahyuni, Ayu Shabrina; **investigation**: Intan Nuni Wahyuni, Ayu Shabrina; **writing—original draft preparation**: Intan Nuni Wahyuni, Ayu Shabrina, Fadhil Lobma, Arnida L. Latifah ; **writing—review and editing**: Intan Nuni Wahyuni, Ayu Shabrina, Fadhil Lobma, Arnida L. Latifah ; **visualisation**: Intan Nuni Wahyuni, Ayu Shabrina. All authors have read and agreed to the published version of the manuscript.

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