

# Simulating Tropical Cyclone over the South-west Indian Ocean with MPAS: Sensitivity to cloud microphysics schemes

## Semester Project

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Semester: Fall-2021

Date: November 26, 2021

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## 1 Introduction

Tropical cyclones (TCs), one of the strongest atmospheric features, are known for massive destruction of properties and human lives, because they are associated with strong winds, heavy rains, and storm surges [TROPICAL CYCLONES]. Since the beginning of the 20th century, TCs have affected more than 629 million people and killed more than 1.33 million people in the tropics [Doocy et al., 2013]. TCs, which usually form over warm tropical oceans ( $\geq 26^{\circ}\text{C}$ ), are warm-core low-pressure systems with 100 - 1000 km diameter. Once established, TCs sustain their strength by absorbing warm moisture as they continue to enlarge and will last as long as the atmospheric and oceanic conditions remain favourable over the ocean. After making a landfall, TCs can last for seven days and cause severe damages as they move inland or along the coastline [Doocy et al., 2013]. The TCs that form over the Southwest Indian Ocean (SWIO) are a threat to the neighbouring countries, but Madagascar, Mauritius and La Reunion experience the most devastating and destructive impacts of the TCs, followed by the extensive coastline and the borders of Zimbabwe and Mozambique [Tropical cyclones in the South West Indian Ocean]. For instance, in 2017, Tropical Cyclone Dineo (name of a tropical cyclone), which formed on 13th February and made a landfall over Mozambique on 15th February [Moses and Ramotonto, 2018]. Dineo produced heavy rains ( $> 200\text{mm day}^{-1}$ ) and damaging winds in Inhambane (southern province in Mozambique) and destroyed around 20000 homes, directly affected about 130,000 people, and killed seven people. Its widespread torrential rains and the associated storm surge produced massive floods that killed about 271 people and caused damages that exceeded \$ 200 million in Zimbabwe (USD 2017) [Cyclone Dineo. , 2020, 3 15]. Although Dineo weakened on February 17th, its remnant low still triggered heavy rainfall with flooding in Botswana. The flooding destroyed 650 households and public infrastructures (e.g. bridges, hospitals, schools, and fields), leaving hundreds of people homeless and poor (especially the low-income earners) [Moses and Ramotonto, 2018]. A month after the landfall, the impacts of Dineo landfall induced an outbreak of cholera that infected 1,200 people and killed 2 people in Mozambique and Malawi [Cyclone Dineo. , 2020, 3 15]. Despite the devastating impacts TCs over the region, from our best knowledge, there are still no reliable systems for providing early warning on TC occurrences over region. Hence, there is a need for more studies on how to improve simulation and prediction of TC characteristics over the SWIO. This will help reduce the devastating impacts of TCs in the region.

### 1.1 Problem Statement

Model for Prediction Across Scales (MPAS) cloud microphysics schemes: Weather Research Forecast (WRF)-Single-Moment-Microphysics Class 6 (WSM6) and Thompson, have a significant influence in the simulation of TC; however, according to past research, the capability of these two microphysics schemes in simulating TCs over the SWIO have not been tested yet. So comparing and analysing the influence of these microphysics schemes during simulations would help us to understand which scheme is best to use and under which available conditions. This will improve predictions of TCs over the basin and will reduce on the devastating damages caused by TCs ahead of time.

### 1.2 Aim and objectives

This project aims to evaluate the capability of MPAS in simulating TC Dineo and examine the sensitivity of TC Dineo to two prominent cloud microphysics schemes: WSM6 and Thompson over the SWIO basin.

The three specific objectives are:

- To describe the characteristics of TC Dineo.
- To evaluate how MPAS simulates TC Dineo over the SWIO basin.
- To compare the sensitivity of WSM6 and Thompson in the simulation of TC Dineo over the SWIO basin.

## 2 Model Description

MPAS models use centroidal Voronic tessellations in their horizontal meshes, which provide a common software framework that gives an infrastructure for producing parallel execution, input, output, high-level driver program and other software infrastructure. The supported important features of MPAS - Atmosphere (MPAS-A) include fully-compressible, non-hydrostatic dynamics, split-explicit Runge-Kunta time integration, Exact conservation of dry-air mass and scalar, Positive-definite and monotonic transport options, Generalised terrain-following hight coordinate. Unstructured variable-resolution (horizontal) mesh integrations for the sphere and Cartesian planes is also a supported vital feature of MPAS-A [ucar, n.d.].

Version 6.0 of MPA-A consists of parameterizations of physical processes that are taken from the WRF Model. Explicitly Parameterizations of physical processes supported by MPAS-A include Radiation, Land-surface, Surface-layer, Boundary-layer, Convection, Cloud microphysics [ucar, n.d.]. Table. ?? shows the set of parameterizations of physical processes and their respective schemes.

MPAS-A consists of two main components, i.e., the model and initialization, built as cores within the MPAS software framework. Both the model and initialization make use of software infrastructure and the same driver program but they are compiled as separate executables. The model component consists of physics and atmospheric dynamics. The initialisation component consists of components for creating initial conditions for the atmospheric and land-surface state and updating files for the sea-surface temperature (SST) and sea ice [ucar, n.d.]. Figure. 1 shows model components within the MPAS framework. As shown in the Figure. 1 the init\_atmosphere (on the left) and atmosphere (on the right) are built as separate cores within the framework (MPAS superstructure). Both cores are symbolically linked to the MPAS common infrastructure (at the bottom).

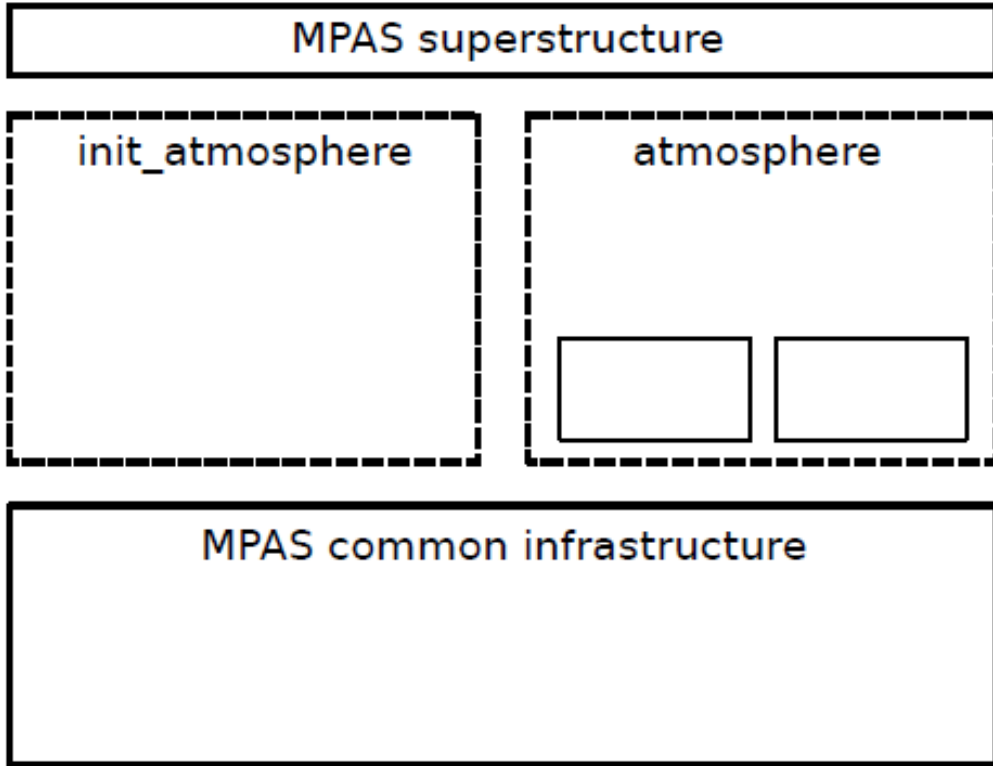


Figure 1: The initialization and model components [ucar, n.d.]

### 2.1 Literature Review

Several studies have shown that MPAS is one of the atmospheric models that have great potential for providing reliable early warning information on TC occurrence and characteristics over the SWIO. Furthermore, MPAS has been frequently used to simulate different atmospheric features and processes, including real-time weather, seasonal forecasting of tropical cyclones, tornadoes, and convection [ncar.ucar.edu. , n.d.]. For instance, Hashimoto et al. [2016] used MPAS to reproduce the frequency and locations of North Atlantic TCs using mesh refinement over the North Atlantic ocean. They show that MPAS simulations perform better than the Weather Research and Forecasting System (WRF) simulation because the smooth transitions between two grid resolutions in MPAS (i.e., variable mesh grid) helps the model to simulate smoother and more realistic

mid-level jet structures and seasonal cloud patterns than the WRF simulations, which is influenced nested boundary condition problems. Harris and Lin [2014] also show that MPAS performs better than the High Resolution Model (HiRAM) in simulating the frequency of TCs. Although HIRAM can run at high resolution, it ignores computation of vertical acceleration, and its representation of thunderstorms and convection are still small compared to those in observation and MPAS simulations. However, despite the great potential of MPAS in simulating TCs, no studies have investigated its capability in simulating tropical cyclones over the SWIO.

## 2.2 Dynamic core and physics of MPAS

The effect of physical processes on state variable evolution is modelled or represented using a generic term called Model physics. The effect of these processes is observed either when these processes like radiation, phases of changes of water species are not contained in the Navier-stokes equations or when convective cells within coarse spatial resolution simulations are not resolved on the model mesh. Processes not to be resolved on the model mesh is caused by the failure of the structures to be represented on the mesh ( $L < 2\Delta x$ ), where  $L$  is the length of the grid and  $\Delta x$  grid spacing. Inaccurate representation of present structures on the mesh in the dynamics below the effective resolution also causes physical processes not to be resolved on the model mesh. The physics operates on cell-centered variables. The radial-basis-functions reconstruction and cell-edge normal velocities are used to compute the global mesh and the components of cell-centered velocity [Atmospheric physics].

The Physics in MPAS is divided into several parameterisations: microphysics, surface-layer, land-surface, short wave radiation, long wave radiation, boundary layer, convection, gravity wave drag by orography, and cloud fraction for radiation. Each parameterisation consists of different schemes for example, WSM6, Thompson and Kessler schemes are contained in microphysics, Noah is the only scheme in land-surface whereas Tiedtke, New Tiedtke, Kain-Fritsch, and Grell-Freitas are schemes in convection parameterization etc.

Successful simulations of TCs with any atmospheric model depend on how well microphysics processes are represented in the model. Microphysics contains resolved water vapour, cloud, and precipitation formation processes [Skamarock, 2008]. For this study's case, the capability of the two microphysics schemes: WSM6 and Thompson in the simulation of TC Dineo over the SWIO basin are compared. The selection of these two microphysics schemes is based on the fact that WSM6 is a default scheme in microphysics and has to be compared with either Kessler or Thompson. Thompson is selected over Kessler because it is uniquely coupled with the rapid radiative transfer model for general circulation models (RRTMG) radiation scheme and also has a unique cooperation with other parameterizations in the same physics suit. Therefore, it provides consistent information about cloud droplet size distributions during modelling. This makes WSM6 and Thompson the two prominent microphysics schemes to be used in MPAS during the entire simulations.

### 2.2.1 WSM6

WSM6 is developed by including graupel ( $q_g$ ) to the Weather Research and Forecasting System (WRF)-Single-Moment-Microphysics Class 5 (WSM5) prognostic variables: snow ( $q_s$ ), cloud ice ( $q_i$ ), cloud water ( $q_c$ ), and mixing ratios of water vapour ( $q_v$ ) [Federico, 2016]. WSM5 is an updated version of Weather Research Forecast (WRF)-Single-Moment-Microphysics Class 3 (WSM3) by allowing super-cooled water and mixed phase processes. WSM3 is a simple and efficient scheme that consists of snow and ice processes that makes it suitable for mesoscale grid sizes [NOAA Research]. According to the efficiency and theoretical backgrounds of WSM6, it is suitable for both cloud-resolving grids and high-resolution simulations. However, it only anticipates the mass mixing ratios of six water species [Skamarock, 2008]. In WSM6, the number of graupel particles per cubic meter of air:  $n_g(D)dD_g(m^{-4})$  follows an exponential size distribution given by:

$$n_g(D)dD_g = n_{og} \exp(-\lambda_g D_g) dD_g \quad (1)$$

where  $D_g$  is the graupel diameter,  $n_{og}(m^{-4})$  represents the intercept values.  $\lambda_g(m^{-1})$  represents the slope of the exponential distribution. This slope is given by:

$$\lambda_g = \left( \frac{\pi n_{og} \rho_g}{\rho q_g} \right)^{\frac{1}{4}} \quad (2)$$

where  $\rho_g$  and  $\rho$  represents the graupel and air density, respectively. The slope parameter is obtained by multiplying equation (1) by the drop mass ( $\frac{\pi \rho_g D_g^3}{6}$ ) and then integrate by parts three times over all diameters, and finally, the resulting quantities are equated to appropriate water contents ( $\rho q_g$ ). The graupel particle terminal velocity of diameter  $D_g$  is given by:

$$V_{Dg} = \alpha_g D_g^{b_g} \left( \frac{\rho_o}{\rho} \right)^{\frac{1}{2}} \quad (3)$$

where  $\alpha_g$  represents the empirical formula of the mass weighted speed of graupel ( $V_g$ ),  $b_g$  is the empirical formula of the mass weighted speed of snow  $V_r$ , and  $\rho_o$  represents the density of air at reference state. According to Rutledge and Hobbs [1984],  $V_g$  is obtained by integrating equation (3) and is expressed as:

$$V_g = \frac{\alpha_g \Gamma(4 + b_g)}{6} \left( \frac{\rho_o}{\rho} \right) \frac{1}{\lambda_g^{b_g}} \quad (4)$$

where  $\Gamma(\gamma)$  is a gamma function. The continuity equation for graupel is given by:

$$\frac{\partial q_g}{\partial t} = -\vec{V} \cdot \nabla_3 q_g - \frac{q_g}{\rho} \frac{\partial(\rho V_g)}{\partial z} + S_g \quad (5)$$

where  $S_g$  represents the sinks and sources of graupel.  $\vec{V} \cdot \nabla_3 q_g$  and  $\frac{q_g}{\rho} \frac{\partial(\rho V_g)}{\partial z}$  represent the 3D advection and sedimentation of graupel respectively.

### 2.2.2 Thompson

Thompson is a bulk microphysical parametrization scheme whose assumed snow size distribution depends on both ice water content and temperature. It consists of number concentration with six classes of moisture species as its prognostic variables: cloud water, graupel, cloud ice, rain, snow, and water vapour [NOAA Research]. Thompson explicitly predicts cloud ice and droplet number concentration due to its inclusion of aerosols as its cloud condensation nuclei (CCN) and ice nuclei (IN). In this scheme, snow size distribution ( $N(D)$ ) is represented by the sum of gamma and exponential distributions, as illustrated in equation (6), and snow assumes a non-spherical shape with a bulk density that varies inversely with its diameter [Skamarock, 2008].

$$N(D) = \frac{M_2^4}{M_3^3} \left[ K_o \exp \left( -\frac{M_2}{M_3} \wedge_o D \right) + K_1 \left( \frac{M_2}{M_3} D \right)^{\mu_s} \exp \left( -\frac{M_2}{M_3} \wedge_1 D \right) \right] \quad (6)$$

where  $K_o$ ,  $K_1$ ,  $\wedge_o$  and  $\wedge_1$  are snow size distribution constants.  $\mu_s$  represents the gamma size distribution shape parameter.  $M_n$  is the distribution  $n^{th}$  moment:  $M_n = \int D^n N(D) dD$ .  $M_n$  allows bulk snow density to be correctly modelled with an inverse diameter dependence in contrast to WSM6 which assumes constant snow density. The first and second term inside the brackets of equation (6) represents the exponential and gamma distributions, respectively. The sum of these two distributions accounts for the general slope of large particles and frequently observed super-exponential number of small particles. Through the use of equation (6) in the scheme enables the effective y intercept parameter to depend on both snow mixing ratios and temperature. The number concentrations (mass mixing ratios) of all forms of water species: vapour, liquid, and solid or aerosol number concentrations follow the same dominant conservation given by:

$$\frac{\partial \Phi}{\partial t} = -\frac{1}{\rho} \nabla \cdot (\rho U \Phi) - \frac{1}{\rho} \frac{\partial(\rho V_\Phi \Phi)}{\partial z} + \delta \Phi + S_\Phi \quad (7)$$

where  $\Phi$  represents the mass mixing ratio of any water species,  $U$  is the 3D wind vector,  $t$  is time,  $V_\Phi$  is the weighted fall speed of  $\Phi$ ,  $\rho$  is air density,  $z$  is height,  $\delta \Phi$  is the sub-grid scale mixing operator,  $S_\Phi$  is the microphysical process rate terms. The detailed description for newly predicted variables: number of Hygroscopic aerosol ( $N_{wfa}$ ), number of Non-hygroscopic aerosol ( $N_{ifa}$ ) i.e., ice-nucleating aerosol and number concentration of cloud droplet ( $N_c$ ) are provided respectively in equations (8) to (10).

$$\begin{aligned} \frac{dN_{wfa}}{dt} = & - \left( \begin{array}{c} \text{rain, snow and graupel} \\ \text{collecting aerosols} \end{array} \right) - \left( \begin{array}{c} \text{homogeneous nucleated} \\ \text{deliquesced aerosols} \end{array} \right) - \left( \begin{array}{c} \text{Cloud Condensation} \\ \text{Nuclei (CCN) activation} \end{array} \right) \\ & + \left( \begin{array}{c} \text{cloud and rain} \\ \text{evaporation} \end{array} \right) + (\text{surface emissions}) \end{aligned} \quad (8)$$

$$\frac{dN_{ifa}}{dt} = - \left( \begin{array}{c} \text{rain, snow and graupel} \\ \text{collecting aerosols} \end{array} \right) - \left( \begin{array}{c} \text{Ice Nuclei (IN)} \\ \text{activation} \end{array} \right) + \left( \begin{array}{c} \text{cloud ice} \\ \text{sublimation} \end{array} \right) + (\text{surface emissions}) \quad (9)$$

$$\begin{aligned} \frac{dN_c}{dt} = & - \left( \begin{array}{c} \text{rain, snow and graupel} \\ \text{collecting droplets} \end{array} \right) - \left( \begin{array}{c} \text{freezing into} \\ \text{cloud ice} \end{array} \right) - (\text{collide into rain}) - (\text{evaporation}) + (\text{CCN activation}) \\ & + (\text{cloud ice melting}) \end{aligned} \quad (10)$$

Thompson assumes that water and ice species follows a generalised gamma distribution defined in equation (11) instead of the exponential distribution.

$$N(D) = \frac{N_t}{\Gamma(\mu + 1)} \lambda^{\mu+1} D^\mu \exp(-\lambda D) \quad (11)$$

where  $\lambda$  represents the slope of the distribution,  $N_t$  gives the total number of particles in the distribution,  $D$  is the diameter of the particles, and  $\mu$  is the shape parameter of the distribution. All water and ice species are assumed to use a standard power law form in relating their mass and terminal velocity as a function of diameter. The mass ( $m(D)$ ) and terminal velocity ( $V(D)$ ) relations are given by equations (12) and (13) respectively.

$$m(D) = aD^b \quad (12)$$

$$V(D) = \left(\frac{\rho_o}{\rho}\right)^{\frac{1}{2}} \alpha D^\beta \exp(-fD) \quad (13)$$

where  $a$  and  $b$  are mass power law constants and these vary for different species,  $f$ ,  $\beta$ , and  $\alpha$  are velocity power law constants,  $\rho_o$  and  $\rho$  are the reference and moist air densities respectively.

### 3 Data Needs

The meteorological data (Climate Forecast System Reanalysis (CFSR) (ds094)) used for initializing the model to simulate TC Dineo was downloaded from the Research Data Archive (RDA) website [?]. CFSR (ds094) dataset was used because TC Dineo occurred between the period of 2011 and 2020. Before downloading the data from RDA website, the period in which TC Dineo occurred was selected starting three days before and ending three days after its occurrence, allowing the model to spin up. On downloading, two datasets, Sea Surface Temperature (SST) and pressure levels, were downloaded from the RDA. SST data sets was extracted for the entire period of occurrence of TC Dineo, i.e., 10th/02/2017 to 20th/02/2017. In contrast pressure levels were extracted for the first six hours of occurrence of TC Dineo, i.e., 13th/02/2017 at 00:00 to 13th/02/2017 at 06:00.

### 4 Calibration

## 5 Numerical Experiment Design

### 5.1 Model simulation of TC Dineo

The following steps were taken to effect model simulation: (1). We created a run directory which we named `case_studies` on the CHPC cluster. (2). Linked the `init_atmosphere_model` and `atmosphere_model` executables, physics lookup tables into the `case_studies` directory. (3). Copied the `namelist.*`, `streams.*`, files into the `case_studies` directory. (4). Downloaded 92km-25km variable resolution mesh (`x4.163842.grid.nc`) from <https://mpas-dev.github.io>, then push it to the CHPC account in the `grid_rotate` directory. (5). We used the `grid_rotate` utility by editing the `namelist.input` file to set the latitudes and longitudes to the center of interest, then use the `grid_rotate` utility to rotate the mesh to the new area of refinement (Figure 2), hence producing a new `netCDF` file used as an input in the `streamlist` file during static and terrestrial field processing. (6). Push both the downloaded datasets (SST and pressure levels) from the RDA website to the `chpc` server account into the `sst` and `press` directory respectively, run the executable file `ungrib.exe` to generate intermediate files for both sea surface temperature (SST) and pressure levels. (7). Configured the `namelist` and the `stream` files in the `init_atmosphere` directory, then run the `init_atmosphere_model` to create initial conditions. (8). Generate idealized initial conditions by interpolating the produced intermediate files with the land surface initial conditions, the created file is used as input in the `streams.atmosphere` file during model integration. Model integration simulation was simulated twice, for WSM6 and Thompson schemes. In the `namelist.atmosphere`, the `&physics` section gives as ability to choose our own schemes by changing the `namelist` variables during model integration. So this gave as chance to perform two simulations i.e., one with WSM6 with other schemes available and Thompson excluded, and finally Thompson with other schemes available and WSM6 excluded. For the case of this study, since we are using 25km variable resolution and we are interested in comparing the capability of WSM6 and Thompson microphysics schemes in simulating TC Dineo over SWIO, we used the `mesoscale_reference` suit, and override its default after the first simulation.

`Mesoscale_reference` suit contains WSM6 scheme as its default as shown in table. 1, so for the first simulations with WSM6, we don't adjust anything in the `&physics` record in the `namelist.atmosphere` file. For the second simulations, we over-ride the default and change WSM6 to Thompson scheme adding a `namelist` variable (`config_microp_scheme = 'mp_thompson'`) in the `&physics` record. This enabled the `atmosphere_model` to read Thompson scheme during integration instead of WSM6. Before running the `atmosphere_model`, we first run `build_tables` executable file to generate lookup tables for the Thompson scheme, since they were not generated initially. This is because the look up tables contain the essential Thompson physics variables necessary for model integration while running with Thompson scheme. Table. 1 illustrates default parameterization and schemes contained in the `mesoscale_reference` suit which have been tested for mesoscale resolution.

Parameterizations	Schemes
Convection New	Tiedtke
Microphysics	WSM6
Land surface	Noah
Boundary layer	YSU
Surface layer	Monin-Obukhov
Radiation, LW	RRTMG
Radiation, SW	RRTMG
Cloud fraction for radiation	Xu-Randall
Gravity wave drag by orography	YSU

Table 1: Set of parameterization schemes used by mesoscale\_reference suit

Having finished configuring the namelist.atmosphere file, the atmosphere\_model program produced history and diagnostic files for the entire period of simulation which were remapped using the convert\_mpas utility to produce a netCDF file name latlon.nc which was visualized and used to make analysis.

The Figure. 2 shows the new transformed mesh, Dineo.grid.nc, to our new area of interest rotated about  $90^\circ$  using the grid\_rotate utility.

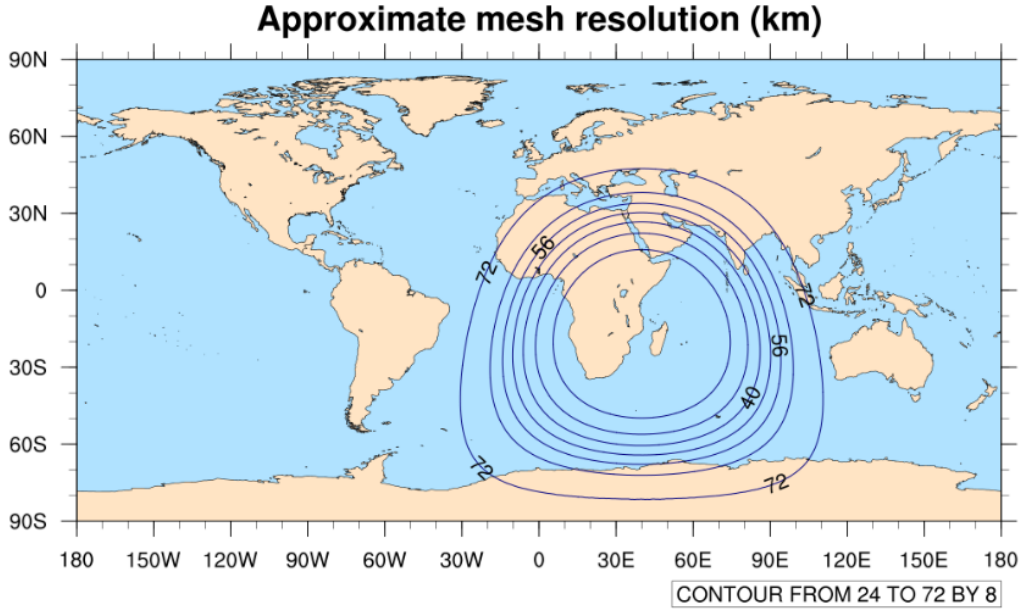


Figure 2: After the grid\_rotate

## 5.2 Detecting and Tracking TC Dineo

After diagnostic and history files were generated during model integration as explained in section 5.1 for the two schemes: WSM6 and Thompson, convert\_utility were used to generate a latlon file which contained mean sea level pressure (mslp), zonal wind component (u10), meridional wind component (v10), temperature\_250hpa, temperature\_500hpa and vorticity\_850hpa variables. All these variables were created only for the domain in which TC Dineo occurred, this simplified the tracking because we dealt with a small data set.

The objective measures that we used for detecting and tracking TC Dineo in the tracking algorithm that uses a 6 hourly output data in the latlon file are similar to that described by ? : (1). The minimum value of mslp over the entire domain termed as the centre of a low pressure system (TC) was determined. (2).  $2^\circ$  from the centre of the TC, the warm core which is the average integrated temperature between 250 hpa and 500 hpa was calculated, this core is at least  $1^\circ C$  warmer than the surrounding environment which is defined as a  $10^\circ \times 10^\circ$  block centred at the mslp. (3). The wind speed which is used to classify the intensity of TC Dineo according to Saffir Simpson scale was calculated using u10 and v10 components over the domain. Then we searched for the maximum value of the wind speed within  $5^\circ$  of the cyclone centre. (4). The minimum vorticity within  $4^\circ$  of the cyclone centre is determined. Since we are in the SWIO basin, negative vorticity is associated with a cyclone spin.

TC Dineo was detected by comparing the calculated variables above with the cyclone threshold values as follows: (1). The maximum surface wind speed within  $5^\circ$  of the cyclone centre must be greater than  $17 ms^{-1}$ . (2). The minimum vorticity must be less than  $3.5 \times 10^{-5} s^{-1}$ . (3). The warm core temperature must be at least  $1^\circ C$  greater than the surrounding environment. If the cyclone we identified satisfied the above TC criteria, it was assigned a tracking ID of 1 otherwise 0 for the respective 6 hourly intervals during each day TC Dineo occurred.

The output of the respective computed variables: Date, mslp, latitude, longitude, wind speed, vorticity and warm core temperature with there respective track IDs were visualized for the respective schemes to view the track path of TC Dineo as shown in Figure. ??.

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