Multi-scale subseasonal forecasts using an unstructured grid global model - a TC and Heatwave Case Study

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Abstract

In traditional practice, weather forecasts typically span up to two weeks, while climate forecasts begin at the seasonal timescale and extend further. Consequently, there exists a gap between weather and climate predictions in the subseasonal to seasonal (S2S) range. There is a growing demand within operational prediction and application communities for forecasts that bridge this gap, providing predictions between daily weather forecasts and seasonal climate outlooks. A global model with an unstructured grid mesh is utilized for this study to examine the forecast skill. Additionally, ensemble forecasting is taken into account, which involves running multiple simulations with slightly different initial conditions to capture uncertainties in the forecast. These ensemble forecasts are integrated for a period of 23 to 27 days, allowing for an extended prediction window beyond the typical forecast horizon. Results indicate that the model can give reasonable predictions on the development of a super Typhoon at lead times up to 10 days ahead of its peak intensity. Signal of a heat wave in southern China associated with the subsidence heating from TC outflow was also predicted reasonably well, despite variability among members existed due to disparity in the predicted TC tracks. Additionally, we carried out sensitivity tests on the use of radiation schemes on model cloud fraction. It is also found that the use of Xu and Randall generates more realistic cloud cover than Sundqvist, and resulting in greatly improving the evolution of synoptic scale weather systems over the western North Pacific consequentially.
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grid global model - a TC and Heatwave Case Study

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Key Points:
• Subseasonal to seasonal (S2S) forecast is an emerging and rapidly developing area of Numerical Weather Prediction (NWP) forecast
• Ensemble global model with unstructured grid mesh for S2S forecast
• Typhoon and heatwave on S2S forecast
• Sensitivity test on cloud fraction parameterization scheme
Abstract
In traditional practice, weather forecasts typically span up to two weeks, while climate forecasts begin at the seasonal timescale and extend further. Consequently, there exists a gap between weather and climate predictions in the subseasonal to seasonal (S2S) range. There is a growing demand within operational prediction and application communities for forecasts that bridge this gap, providing predictions between daily weather forecasts and seasonal climate outlooks. A global model with an unstructured grid mesh is utilized for this study to examine the forecast skill. Additionally, ensemble forecasting is taken into account, which involves running multiple simulations with slightly different initial conditions to capture uncertainties in the forecast. These ensemble forecasts are integrated for a period of 23 to 27 days, allowing for an extended prediction window beyond the typical forecast horizon. Results indicate that the model can give reasonable predictions on the development of a super Typhoon at lead times up to 10 days ahead of its peak intensity. Signal of a heat wave in southern China associated with the subsidence heating from TC outflow was also predicted reasonably well, despite variability among members existed due to disparity in the predicted TC tracks. Additionally, we carried out sensitivity tests on the use of radiation schemes on model cloud fraction. It is also found that the use of Xu and Randall generates more realistic cloud cover than Sundqvist, and resulting in greatly improving the evolution of synoptic scale weather systems over the western North Pacific consequentially.

Plain Language Summary
In the past, weather forecasts usually covered up to two weeks, while climate forecasts started at the seasonal timescale and went even further. This left a gap between weather and climate predictions in the subseasonal to seasonal (S2S) range. Now, there's a growing demand among forecasters and application communities for predictions that fill this gap, offering insights between daily weather forecasts and seasonal climate outlooks. S2S prediction helps bridge the gap between short-range weather forecasts and long-range seasonal outlooks. Many decisions in various sectors depend on forecasts within this extended-range lead time, leading to a strong demand for this new generation of forecasts. To address these needs, we use an ensemble global model with an unstructured grid mesh for S2S forecasts. The results show that the model gives reasonable predictions for super typhoon development up to 10 days ahead of its peak intensity. It also accurately predicted a heatwave in southern China despite variability in predicted tropical cyclone tracks. Sensitivity tests on cloud fraction for radiation schemes revealed that using the Xu and Randall scheme produces more realistic cloud cover than the Sundqvist scheme, resulting in improved evolution of synoptic-scale weather systems over the western North Pacific.

1 Introduction
Subseasonal to seasonal (S2S) forecasts refer to weather predictions of a range between 2 weeks and a season, which bridges the gap between short- to medium-range meteorological forecasts (up to 10 days) and seasonal projections (3 - 6 months) (Kirtman et al., 2014; Vitart et al., 2017; Manrique-Suñén et al., 2020). These forecasts are valuable for a wide range of applications, providing insights into weather patterns and trends that can impact various sectors such as agriculture, water resources, public health and renewable energy (White et al., 2017; Merryfield et al., 2020; Mariotti et al., 2020). Short- to medium-range forecasts are often viewed as an initial value problem, where the forecasts are highly sensitive to the initial state of the atmosphere (Stan et al., 2022). Beyond synoptic time scales, the memory from the initial conditions gradually reduces, while impacts from other Earth system components with slower variability (e.g. land and sea) start to increase. In the subseasonal range, the effect from the former greatly declines but the latter is still not dominant (Manrique-Suñén et al., 2020). This explains the complexity of intraseasonal variability and the difficulty of performing numerical weather predictions on this time scale.
Despite the skill and reliability of S2S forecasts remains a major challenge, predictions on the subseasonal scale have significant socio-economic value, as this time scale is critical for decision-making in mitigating potential disasters brought by extreme weather events (Vitart et al., 2017).

Currently, there is no consensus on the best strategy for S2S forecasts. Some centers produce subseasonal forecasts by extending the model integration time of medium-range weather forecast systems, while some deploy models for seasonal and climate projections (Vitart et al., 2017; Manrique-Suñé et al., 2020). Currently, operational S2S forecasts are generated at uniform horizontal resolutions of around 0.5° × 0.5° to 1.5° × 1.5°, with frequencies ranging from daily to weekly intervals (Stan et al., 2022). Regarding the fact that these operational models implement uniform resolutions across the globe, we are motivated to test the capability of a global numerical weather prediction (NWP) model on an unstructured grid with variable resolution in producing S2S forecasts. At the present time, seamless global models, such as the Model for Prediction Across Scales (MPAS) (Skamarock et al., 2012) developed by the National Center for Atmospheric Research (NCAR), have emerged as widely utilized tools for studying weather and climate systems such as tropical cyclones (Davis et al., 2016; Michaelis & Lackmann, 2019) and Kelvin waves (Hsu et al., 2020). With the major breakthrough in the grid structure of NWP models, MPAS-A has been deployed to study the potential benefits of using tropical channel refinement in idealized environments (Martini et al., 2015) and its capability in medium-range convection-permitting ensemble forecasts (Schwartz, 2019), etc. MPAS-A uses spherical centroidal Voronoi tessellations (SCVT) for an unstructured horizontal staggered C-grid (Thuburn et al., 2009; Ringler et al., 2010), and a terrain-following hybrid vertical coordinate (Klemp, 2011) to solve a set of compressible non-hydrostatic equations for the atmosphere by making use of a split-explicit time integration scheme (Klemp et al., 2007). One virtue is that the unstructured grid supports transition from a basic coarse resolution to a higher resolution in one or multiple refinement regions without abrupt resolution change. It is believed to ameliorate many issues associated with the traditional mesh refinement strategy of one-way and two-way grid nesting. Moreover, past idealized experiments have revealed that employing variable-resolution meshes can reduce numerical errors related to wave propagation across regions with varying resolutions, compared to traditional nested grid setups in regional models (Skamarock et al., 2012; Park et al., 2014).

However, MPAS-A has some disadvantages, such as its slow mesh generation which limits its customization, and the requirement for the application of the smallest integration time step across all cells, leading to significant computational costs when using large, varying resolution ratios. To broaden its applicability, a model called CPAS (Clustertech Platform for Atmospheric Simulations atmospheric model) has been developed based on MPAS-A to address the aforementioned limitations. Two useful techniques are applied. First is Hierarchical Time-Stepping (HTS), which essentially avoids cells with large grid spacing from using small timesteps unnecessarily, enabling MPAS-A to be used on meshes with large range of resolutions with affordable computational resources (Ng et al., 2019; Cheung et al., 2022). The other is Customizable Unstructured Mesh Generation (CUMG), which is an efficient mesh generation algorithm that allows mesh refinements with arbitrary shapes, locations and horizontal resolutions. It generates SCVTs that satisfy the original formulation of MPAS-A dynamical core. The use of HTS and CUMG in CPAS were separately tested to produce very similar results to MPAS-A in a selection of meteorological episodes (Ng et al., 2019; Tse et al., 2020). Recent developments of CPAS have been presented at the 2023 Joint WRF and MPAS Workshop (Cheung et al., 2023). Moreover, a 200m local resolution application demonstrated the model’s capability in simulating localized weather conditions, crucial for ultra-high-resolution predictions (Sze et al., 2022). Overall, CPAS allows the optimization of computational resources on regional weather patterns, and potentially capturing localized weather extremes beyond medium-range timescale forecasts.
In this paper, we focus on an episode in 2023 when two extreme weather events coexisted within the East Asian and western north Pacific region. A super Typhoon first developed over western north Pacific Ocean, followed by the occurrence of a heat wave in southern China. To simulate the events, an ensemble of S2S forecasts is run using the CPAS atmospheric model on a HPC platform (https://cpas.earth/), using an unstructured grid with locally convection-permitting resolutions around the Greater Bay Area (GBA) in southern China.

The experiment is set up in order to test the capability of the model in capturing weather extreme signals and variability in the targeted region. The paper is structured as follows: the selected case study and model configurations are first described in section 2, results and analysis on extreme weather events are presented in section 3, discussions on model sensitivity tests on parameterization schemes presented in section 4, and conclusions in section 5.

2 Data and Methodology

2.1 Data Source

The Global Forecast System (GFS) is a global weather forecast model developed by the National Centers for Environmental Prediction (NCEP, 2015). It has a base horizontal resolution of 0.25° (approximately 28km) between grid points and forecasts up to 16 days. In this study, the analysis fields from the GFS model are used as the initial conditions for the CPAS simulations. The Integrated Forecasting System (IFS), on the other hand, is a global numerical weather prediction system developed and maintained by the European Centre for Medium-Range Weather Forecasts (ECMWF). At the highest resolution, it provides forecasts with a horizontal resolution of around 9 km, extending up to 10 days ahead. It is used, together with NCEP-GFS, as benchmarks for assessing the performance of TC forecasts. The ERA5 reanalysis, the fifth iteration of the ECMWF atmospheric reanalysis (Hersbach et al., 2020), is produced by the Copernicus Climate Change Service (C3S) at ECMWF. It provides a comprehensive record of the global atmosphere and land surface starting from 1950. In this study, the ensemble simulations are evaluated against the ERA5 reanalysis field to assess the forecast error anomalies.

2.2 Case Study

To explore the sub-seasonal prediction skill of CPAS, ensemble forecasts from the end of May till mid-June 2023 were performed. During this period, tropical cyclone (TC) Mawar (reaching super typhoon intensity) developed over western North Pacific. Following its genesis at about (5°N, 150°E) on 20 May 2023, the storm was steered steadily and reached east of Luzon by 30 to 31 May. As Mawar started to recurve near Taiwan from 1 to 2 June, its movement became slower and acquired a more eastward component progressively. Together with the intensification of an upper-level westerly trough, the storm moved towards Japan and finally became an extra-tropical system under a more baroclinic environment.

At the same time, when TC Mawar was located east of Luzon Strait and Taiwan, a strong heat wave impacted southern China. From 26 to 29 May 2023, the anticyclone aloft over southern China strengthened, leading to fine and hot weather in the region. During 30 May to 1 June, subsidence related to the circulation of TC Mawar caused extremely hot weather. Temperatures of 35 to 37°C were recorded across many locations in southern China, while parts of GBA and southern Guangxi reached 37 to 40°C (Figure 1b). On 31 May, a daily maximum temperature of 34.7°C was recorded at the Hong Kong Observatory, with the daily mean (31.4°C) and minimum (29.6°C) among some of the highest in the station’s historical record (HKO, 2023).
2.3 Model Configurations and experimental design

The CPAS model (version 1.1.1) adopted for this study is based on the Model for Prediction Across Scales-Atmosphere (MPAS-A v7.3) and height-based terrain-following vertical coordinate system (Klemp, 2011) is used that default 55 zeta levels provided by MPAS-A is used in simulations and shown in Table A1 in the appendix. The implemented Hierarchical Time-Stepping (HTS), which uses shorter (longer) timesteps for finer (coarser) resolution grids (Cheung et al., 2022), allows CPAS to save 62.3% of computational resources compared with MPAS-A which uses uniform timesteps globally.

Over the GBA, a convection-resolving grid spacing of 4 km is implemented. 8-km resolution is used for most of the south China Sea and the oceanic region east of the Philippines, in order to cover TC tracks typical for the summer months in this area. It is relaxed to 16 km over East Asia, 32 km over the Northern Hemisphere and 64-km for the rest of the globe.
Table 1. Model configurations for this experiment.

<table>
<thead>
<tr>
<th>Model configuration</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>CPAS version</td>
<td>v1.1.1</td>
</tr>
<tr>
<td>Microphysics scheme</td>
<td>WSM6</td>
</tr>
<tr>
<td>Cumulus parameterization scheme</td>
<td>New Tiedtke</td>
</tr>
<tr>
<td>Planetary boundary layer (PBL) scheme</td>
<td>Shin-Hong</td>
</tr>
<tr>
<td>Gravity wave drag by orography (GWDO) scheme</td>
<td>YSU</td>
</tr>
<tr>
<td>Longwave radiation scheme</td>
<td>RRTMG</td>
</tr>
<tr>
<td>Shortwave radiation scheme</td>
<td>RRTMG</td>
</tr>
<tr>
<td>Surface layer scheme</td>
<td>Monin-Obukhov</td>
</tr>
<tr>
<td>Land surface scheme</td>
<td>Noah</td>
</tr>
<tr>
<td>Cloud fraction for radiation scheme</td>
<td>cld fraction (icloud=1)</td>
</tr>
<tr>
<td>Topographic Correction for Surface Winds (topo_wind) to Represent Extra Drag from Sub-grid Topography and Enhanced Flow at Hill Tops</td>
<td>topo_wind=2</td>
</tr>
</tbody>
</table>

Table 1 gives a summary of the model physics schemes adopted for these simulations. They include the WRF Single-moment 6-class Scheme (WSM6) for microphysics (S. Hong & Lim, 2006), the new Tiedtke Scheme for cumulus parameterization with a scale-aware factor applied below 15 km resolution (Bechtold et al., 2014; Zhang & Wang, 2017; Wilt & Wang, 2020; Wang, 2022), the Shin-Hong Scale-aware Scheme for Planetary Boundary Layer (PBL) physics (Shin & Hong, 2015), the Orographic Gravity Wave Drag Scheme (Kim & Arakawa, 1995; S.-Y. Hong et al., 2008; Choi & Hong, 2015), the RRTMG Shortwave and Longwave Schemes (Iacono et al., 2008), the Monin-Obukhov Surface Layer Scheme (Jiménez et al., 2012), and the Unified Noah Land Surface Model (Tewari, 2004). Additional options include the Topographic Correction for Surface Winds (topo_wind) to Represent Extra Drag from Sub-grid Topography and Enhanced Flow at Hill Tops being set to option 2 (Mass & Ovens, 2011), and the cloud fraction for radiation scheme by Xu and Randall (Xu & Randall, 1996). Finally, for the extended forecast experiment, 16 ensemble members were integrated; initial conditions at 00, 06, 12 and 18 UTC from 20 and 23 May 2023 were taken from the analysis fields of the respective GFS runs. Each simulation was carried out until 00 UTC of 16 June 2023. The length of integration, therefore, ranges from 23 to 27 days.

In the context of variable mesh resolutions, there exist a gray zone problem in which the dynamics are partially resolved in a range of spatial scales, making it crucial to use scale-aware schemes to transition between different resolution regimes. For example, the cumulus parameterization represents the precipitation processes, including surface rainfall, atmospheric heating and drying in the model. The gray-zone of the scheme occurs within the 1-10 km range, where the resolution transitions from parameterized precipitation to resolved convective scales. To tackle this challenge, a scale-aware version of the new Tiedtke scheme is selected to handle convection across the mesh transition zones.
3 Results

3.1 TC Track Behaviour

We first examine the forecasted TC tracks from the CPAS model utilizing a vortex tracker developed by the Geophysical Fluid Dynamics Laboratory (GFDL) (Biswas et al., 2018). This tracker program analyzes the forecast meteorological field to estimate the position of the vortex center at each forecast time step, producing the storm tracks throughout the simulation. The algorithm also provides essential metrics for the forecasted storm, including intensity parameters such as maximum 10-m winds and minimum mean sea level pressure (MSLP), among others. Figure 3(a) shows model TC tracks produced by 16 ensemble integrations, together with TC best-track from the China Meteorological Administration (CMA) (black solid line) (Ying et al., 2014; Lu et al., 2021). Note that for CPAS predictions, cooler (warmer) colors denote those with earlier (later) initial conditions (ICs). Overall, the simulations mostly captured the recurving behavior of the TC. The performance of the model integrations are analysed by separating into two stages: north-westward movement in the earlier stage (24 - 29 May), and north-eastward movement following recurvature (30 May - 2 Jun).

In the early stage, the ensemble spread of the tracks was relatively small. It could be seen that earlier ICs tended to produce slightly more southward tracks. For ICs starting from 20230521 00UTC, the tracks tend to be more consistent with observations. For all members, the forecasted intensities are close to reality (Figure 3(b)). With this consideration, the ensemble spread was relatively small and a high level of confidence existed among the ensemble members during this period. At the time when the cyclone reached its peak intensity on 26 May, the system began to slow down; while the model could reproduce the peak intensity, it failed to capture the timing of its subsequent weakening. In fact, the timing of the change in storm movement direction also varies from one member to another; some recurved earlier than actual, while some penetrated deeper into Luzon Strait or made landfall over Taiwan before making the turn. It is also worth noting that the weakening of the cyclone starting from 27 May was missed and delayed by all members of the ensemble. The forecast track strongly depends on the synoptic environment, such as the strength of the subtropical high and the intensification of the upper level trough, which will be discussed in section 3.3.

3.2 TC Track Intensity

Figure 4 shows the averaged track errors for the whole CPAS ensemble, computed as a function of model forecast hours. The errors are also compared with those from GFS and ECMWF deterministic forecasts. For the direct positional error (DPE, Figure 4(a)), performance of forecasts labeled by T+48 hours or earlier are comparable to GFS and ECMWF. CPAS was outperformed by GFS for T+48 to T+120 hours, but still comparable to ECMWF. Afterwards, both CPAS and ECMWF give DPE lower than that of GFS (i.e. after T+120 hours). It is noteworthy that, overall, the CPAS track errors are on par with ECMWF predictions.

We also decomposed the TC track errors into its along-track (ATE) and cross track (CTE) components (Heming, 2017). Positive (negative) ATE indicates a fast (slow) bias in the forecast TC movement. For all models, there was a tendency to overestimate the movement speed, as indicated by the overall positive ATE throughout the simulations (except for GFS during the recurring period). CTE gives information on the deviation perpendicular to the direction of movement, with positive (negative) CTE indicating deviation to the right (left) of the actual trajectory (Heming, 2017). For CPAS forecasts with T+48 to T+168 hours, the CTE is found to be negative. This is consistent with Figure 3, which shows that, near Taiwan, model tracks tend to be found west of the CMA best track.
Figure 3. (a) CPAS forecasted TC tracks of the 16 initial conditions, tracked using GFDL vortex tracker. Colored tracks indicate forecasted tracks of each ensemble member. Black track indicates the actual track of TC Mawar (CMA best track). Markers represent daily locations of the TC center at 00 UTC; (b) Time series of TC Intensity represented by minimum central MSLP.

Figure 4. (a) Mean direct positional error; (b) Along-track error; and (c) cross-track error of TC tracks forecasted by CPAS, GFS and ECMWF. Numbers below the x-axis represent the sample size. Sample sizes are smaller for GFS and ECMWF due to missing data.
Next, we examine the TC intensity forecasts. Overall, it is worth mentioning that, for forecasts with earlier ICs (before T+120 hours), the TC intensity error from CPAS was much smaller than GFS and ECMWF. In Figure 5, a small positive bias in mean central pressure was found for CPAS, with magnitude at least 50% smaller than ECMWF and GFS. For these runs with early ICs, CPAS tends to slightly overestimate the TC intensity, in contrast to GFS and ECMWF in which there are underestimations. For forecasts later than T+120 hours, CPAS has a tendency to overestimate the intensity. Remarkably, ECMWF exhibited an underestimation of both central pressure and wind speeds during the latter portion of the forecast period.

![CPAS Mean TC Intensity Error](image1)

**Figure 5.** (a) Mean error in TC central pressure; and (b) mean error in maximum wind speed of TC forecasted by CPAS, GFS and ECMWF (National Center for Atmospheric Research, 2023). Numbers below the x-axis represent the sample size. Sample sizes are smaller for GFS and ECMWF due to missing data.

### 3.3 Synoptic Conditions in East Asia and Western North Pacific

To better understand the TC track behavior, synoptic background from the CPAS outputs are also examined. Figure 6(a) gives the 500hPa geopotential height and MSLP fields based on the T+168 hour forecast (valid on May 29). Compared with ERA5 data on the same day in Figure 6(b), the strength and reduced extent of the subtropical high was underestimated, which was found to be common across all ICs (figures not shown). This was due to a common cold bias in the lower atmosphere, leading to the contraction of the atmospheric column hence decreased geopotential height values. This was particularly evident in intermediate ICs (e.g. on 20230522). In these simulations, the subtropical high was substantially weaker than the reality, where only the part to the north of the TC was captured. The high pressure ridge was weak and has retreated eastwards, both at surface and upper levels. In early and late ICs, a similar but smaller weak bias was observed.

The largest variability of the simulated TC tracks among the ensemble members was the timing and degree of recurving. In CPAS, TC Mawar started reducing speed and changed course from north-westwards to northwards on 29 May. In some early ICs (20230520 06
Figure 6. Spatial distribution of 500hPa geopotential height (shadings) and mean sea level pressure (contours), valid at 20230529 00 UTC. Left: (a) CPAS initialized at 20230522 00 UTC (T+168 hours). Right: (b) ERA5 reanalysis field.

Figure 7. Vertically averaged wind speed (shadings) and streamlines over 200 - 700 hPa levels, weighted by the density of air, valid at 20230528 00 UTC. (a) CPAS initialized at 20230520 00 UTC (T+192 hours); (b) CPAS initialized at 20230523 12 UTC (T+108 hours); (c) CPAS initialized at 20230522 12 UTC (T+132 hours); (d) ERA5 reanalysis field.
UTC and 12 UTC), recurvature occurred 1-2 days ahead of actual. This is likely related to weaker or the eastward retreat of the subtropical high; the resulted weaker steering flow can cause slower TC movement in the western North Pacific.

For some other ICs (20230520 18 UTC - 20230521 18 UTC; 20230523 12 UTC and 18 UTC), the location of recurvature deviated westwards, reaching further into Luzon Strait and approaching Taiwan before turning north. These ensemble members predicted a much stronger subtropical high to the north of the TC than the earlier counterparts (Figure 7(b)). The ridge also persisted longer than the reality. This resulted in a further westward movement of the storm due to strong and persistent steering to the west. The remaining ICs captured the timing and location of the recurvature well (20230522 00 UTC - 20230523 06 UTC; see Figure 7(c)). In these simulations, despite the significant underprediction on the strength of the subtropical high, the general synoptic environment and the associated flow still resembled the reality (Figure 7(d)). These factors have led to relatively realistic cyclone tracks being predicted.

It is noticed that the motion of the TC following recurvature varied considerably among the ensemble members. A majority of the tracks were deviated to the south (Figure 3(a)). This is believed to be associated with the relative strengths of the subtropical high over Western North Pacific and the upper level westerly trough over eastern China. With the generally decreased strength of the subtropical high, both the upper level jet and troughs could extend more equatorward. As a result, there is stronger eastward steering flow in the latitudes just south of Japan, leading to the deviated TC tracks in the vicinity.

### 3.4 Extreme Heat Event in Greater Bay Area (GBA)

![Figure 8](image-url)  
**Figure 8.** Probability density plots of (a) temperature at 850 hPa; (b) temperature at 2m height, averaged over the area indicated in Figure A1. Red dotted lines represent forecasted variables from each ensemble member. Blue shading indicates the probability density of the variables across the ensemble members, at 0.5°C and 1°C intervals, respectively. Red solid lines in (a) and (b) represent the ground truths for temperature variables (ERA5 for (a) and ground station observations for (b), averaged over the same area).
During the heatwave associated with air subsidence in the periphery of TC Mawar, GBA was one of the locations with the strongest heat intensity. Here we examine the temperature predictions for the land areas over GBA. Figure 8 (a, b) shows the probability density of temperatures at different levels during 25 May - 16 June 2023, forecasted by the 16 ensemble members, averaged over land grid boxes in Figure A1. Temperature at 850 hPa (Figure 8(a), hereby referred to as T850) indicates the property of the general air mass affecting the area, while 2-m temperature (Figure 8(b), hereby referred as T2m) represents the air temperature experienced at ground level. These variables were compared against observations, from ERA5 and ground weather station measurements respectively (red solid line).

It can be seen that the model was able to capture the heat wave event 7-10 days ahead. From both figures, maximum temperatures have been gradually rising from 25 - 29 May, due to the increased heating under clear-sky conditions brought by the intensifying anticyclone aloft. It was then followed by a sharp upward trend from 29 May to 1 June. Maximum T2m reached around \( \sim 35 - 36^\circ C \), averaged over all ensemble members, with individual members reaching 37 degrees on 30 - 31 May. There was a high level of correspondence between predicted and station temperatures. The peak in T850 was also captured well by the majority of the ensemble members.

Figure 9 gives the spatial distribution of the likelihood of 2m temperatures exceeding 37 and 35\(^\circ\)C respectively, on 31 May 2023. The probability refers to the proportion of ensemble members with temperatures surpassing the thresholds. Results indicate that areas with high probability of exceeding 37\(^\circ\)C matched observations well (see Figure 2). In particular, there is a high level of consensus on extreme heat in the area surrounding the Pearl River Delta and coastal regions of western Guangxi. For the 35\(^\circ\)C threshold, signals were more widespread across coastal Southern China coasts.

![Figure 9. Spatial probability distribution plots of daily maximum temperature at 2 meters exceeding: (a) 37\(^\circ\)C; and (b) 35\(^\circ\)C, on 31 May 2023.](image-url)

In the lower atmosphere, a relatively large model spread existed in T850 following the peak (Figure 9(a)). This indicated a larger uncertainty in the timing of cooling following the heat wave. On 1 June, heavy showers and squally thunderstorms occurred over inland Guangdong and Hong Kong (HKO, 2023), leading to significant drops in temperatures in the region. The uncertainty is likely associated with the capability of the model in predicting this rainfall event. From Figure 9(c), signals for slight to moderate rainfall (5 - 25 mm in 6 hours) existed among a number of members. This has created the discrepancy in temperature forecasts between the members (figures not shown).
Concerning the variability of the forecasted intensity of the heatwave, it was found that the model’s capability in predicting extreme temperatures was strongly tied with the accuracy of TC track and intensity predictions. Figure 10 shows the ensemble member TC tracks corresponding to a weak, as well as those to a strong heatwave signal in GBA. For the ensemble member initialized at 20230520 06 UTC, the TC had a fast bias, which also recurved early with a westernmost longitude around 129°E. This was one of the members predicting the lowest temperatures during the heatwave episode. This is consistent with the fact that, on 31 May, when TC Mawar was centered to the east of Taiwan, the forecasted position was already situated to the east of Japan due to the over-estimated movement speed. Therefore, the sinking motion induced by the TC had minimal impact on the GBA region. Other runs similarly predicting eastward deviated tracks tended to give a smaller warming trend for similar reasons. On the other hand, the members predicting the strongest heat wave signals corresponded to TCs reaching much further west, traversing the east of Luzon Strait and approaching the coasts of Taiwan before recurving (e.g. Figure 10(b)). Due to the much closer distance to southern China, the impact of the warming due to subsidence was greater. Members with TC tracks analogous to Figure 10(b) generally had slower movement speeds when changing its direction of movement, leading to a longer stay over the areas hence more prolonged and intense heat waves.

4 Discussions

In this study, it was found that the choice of cloud fraction parameterization scheme plays a substantial role in shaping the synoptic conditions represented in the model. This exerts notable effects on the prediction of the targeted weather systems for this study, ultimately impacting the accuracy and reliability of the forecasts. In this section, their implications are further investigated to enhance our understanding and improve forecast performance. The cloud fraction scheme is responsible for the calculation of horizontal cloud fractions, defined as the percentage of area of a grid covered by clouds. The two options for cloud fraction scheme in CPAS are based on Xu and Randall (Xu & Randall, 1996) (“cld_fraction”) and Sundqvist (Sundqvist et al., 1989) (“cld_fraction_thompson”), which correspond to ‘icloud’ options 1 and 3 in the Weather Research and Forecasting Model.
Predictors of cld\_fraction include relative humidity and saturation vapor mixing ratio. Meanwhile, cld\_fraction\_thompson uses a grid-scale dependent threshold for cloud fractions based on relative humidity, and has distinct coefficients for grid cells over the land and sea. The computed amount of clouds within a grid cell would directly impact the amount of shortwave radiation reaching the Earth’s surface, as well as subsequent cloud-radiation interactions and their feedback mechanisms.

In the upper panels of Figure 11, outgoing longwave radiation (OLR) fields were plotted to examine the spatial distribution of clouds forecasted by CPAS using the two cloud fraction schemes. These figures could be compared against thermal infrared satellite imageries (Figure 11(c)). It is worth noting that the brightness temperature fields retrieved by the satellites are not directly equivalent to the OLR fields. The former is derived based on the amount of radiation received within a narrow band of wavelength, while the latter is approximated by radiation schemes through integrating over a larger spectrum of wavelengths. Despite the fundamental difference between the fields, it is sufficient for a qualitative comparison on the amount of clouds from CPAS model outputs against the reality.

Figure 11. (a, b) Spatial distribution of all-sky top-of-atmosphere outgoing longwave radiation flux (OLR) from CPAS model outputs, initialized at 20230520 12 UTC, valid at 20230529 00 UTC (T+204 hours), using (a) cloud\_fraction; (b) cloud\_fraction\_thompson. (c) Himawari 9 thermal infrared image at 20230529 00 UTC (Channel 13, central wavelength 10.4\mu m)
The validity time of Figure 11 is 20230529 00 UTC, when TC Mawar reached maturity and was about to recurve towards Japan. This also corresponded to the time when the subtropical high over Western North Pacific started showing significant negative bias against reality. From Figure 11(a) and 11(c), the amount of cloud cover predicted by cld_fraction roughly matched against observations. The amount of deep convective clouds at the cyclone’s spiral cloud bands resembles much of the reality, although lacking some low to mid clouds in the periphery. Over the ocean, the distribution of cloud-free regions was considerably realistic. A simple comparison against Figure 11(b) revealed a much greater coverage of clouds generated by cld_fraction_thompson over cld_fraction, indicated by the extensive low OLR values around the cyclone. The spatial extent of low OLR values were overly extensive when contrasted against satellite image (Figure 11(c)), indicative of exaggerated amounts of high or deep clouds.

The amount of cloud cover directly impacted the radiation budget at the surface, subsequently affecting the overall thermodynamics of the atmospheric column. The reduced shortwave radiation reaching the surface due to greater cloud coverage using cld_fraction thompson caused a stronger cold bias in the lower atmosphere (Figure 12). The inflated negative errors were observed both over inland China and oceans to the south of Japan, where excessive clouds were located. Decreased vertically-averaged temperatures at the lower atmosphere was associated with the compression of the atmospheric column, inducing lower heights of the 500 hPa level. This was believed to have led to increased negative bias in the 500 hPa geopotential height field across nearly the entire domain. (Note: the dipole near the TC center is due to the shift in TC position). As a result, the use of cld_fraction_thompson has worsened the already underestimated strength of subtropical high.

The significant impact of cld_fraction_thompson on the synoptic environment in the forecast fields have led to altered behavior of targeted weather systems in this study. For example, the forecasted cyclone track for TC Mawar experienced a general eastward shift, compared to the run using cld_fraction (Figure 13). The diminished steering force associated with the weaker subtropical high resulted in an eastward deviation of the TC position. A systematic cold bias was also observed in the heat wave signals over GBA, corresponding to the cooler lower atmosphere as previously discussed.

Based on the better representation of cloud covers, and the subsequent impacts on the synoptic environment in the simulations, cld_fraction was preferred over cld_fraction_thompson as the cloud fraction scheme for the set of ensemble integrations in this study.
Figure 13. CPAS forecasted track for TC Mawar, tracked using GFDL vortex tracker. Model initialized at 20230520 12 UTC. Colored tracks indicate forecasted tracks of each ensemble member. Black track indicates the actual track of TC Mawar (CMA best track). Red and blue tracks represent the runs using cld\_fraction and cld\_fraction\_thompson respectively. Markers represent daily locations of the TC center at 00 UTC.

5 Conclusions

In this study, we have experimented the capability of CPAS atmospheric model - a global model using an unstructured grid with locally convection-permitting resolution - on forecasting weather extremes on a subseasonal time scale. During the period of interest, super typhoon Mawar developed over the western North Pacific Ocean. The storm also caused severe heat waves over southern China associated with subsiding air from the outflow of the TC, as the storm moved across sea areas to the east of Luzon Strait and Taiwan. Using an ensemble integration of 16 members with 6-hourly consecutive model initial times, all members were able to simulate the recurvature of TC Mawar, up to a model lead time of 10 days. The performance of CPAS in TC forecasts was comparable to other operational NWP models. The behavior of the TC tracks were strongly dependent on the large-scale circulations in the vicinity of the cyclone, which were affected by the interactions between the subtropical high pressure ridge and the westerly trough. Meanwhile, CPAS was also able to simulate the extreme heat wave over the GBA area in southern China, where a majority of the ensemble members captured the sharp increase in temperatures, reaching a maximum of over 37°C. The variability in the intensity was found to be closely correlated with the forecasted TC track. Concerning the effect of model parameterization schemes on the CPAS forecasts, the cloud fraction for radiation scheme was found to have a significant impact on the simulated synoptic environment. The use of cloud\_fraction\_thompson scheme combined with other physics parameterization schemes generated excessive cloud covers, resulting in a strong cold bias in the lower atmosphere as shortwave radiation received at the surface was greatly reduced. Consequently, this had led to a weak bias in the strength of the subtropical ridge over the western North Pacific Ocean, impacting TC tracks and heat wave signals. The use of cloud\_fraction scheme was found to generate more reasonable
cloud covers and partially solve the error in the subtropical high, albeit a weak bias still exists.

The results presented in this paper is a breakthrough in numerical weather prediction on the S2S timescale. Traditional S2S forecasts usually have coarser resolutions due to considerations on computational resources. Using a global numerical weather prediction model with locally-refined resolution like CPAS allows a better representation of meteorological conditions in the region of interest, while optimizing the computational cost by focusing resources in those areas. In the future, this opens up possibilities for detecting risks of localized weather extremes on a longer time scale.

Acknowledgments
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6 Open Research and Data Availability Statement
Model experiments for this research are conducted at the high-performance computing cluster provided by ClusterTech Limited. The data that support the findings of this study are openly available in Zenodo (https://doi.org/10.5281/zenodo.11398573).

Appendix A Supplementary Materials

Figure A1. Selected grid points for analyzing CPAS temperature forecasts in the Greater Bay Area.

References
Table A1. Heights of defined zeta levels used in the model

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Every point represents forecast positions at intervals of 6h
Figure 2.
Figure 4.
CPAS Mean TC Track Error
TC Sample size: 16
Direct Positional Error (DPE) [km]

(a)

Along-Track Error (ATE) [km]

(b)

Cross-Track Error (CTE) [km]

(c)

Forecast time (hour)
Figure 5.
Figure 6.
Figure 7.
Figure 8.
CPAS S2S Ensemble Forecasts
Greater Bay Area
init: 20230520 00UTC - 0523 18UTC (n=16)

850hPa Temperature - Probability for 0.5°C intervals

2m Temperature - Probability for 1°C intervals
Figure 10.
Every point represents 6-hourly forecast position.
Figure 11.
Figure 12.
Figure 13.
Figure A1.