Development of Customized Variable-Resolution CPAS for Meteorological Simulation

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1. Introduction

- The **ClusterTech Platform for Atmospheric Simulation (CPAS)** is a **cloud-based service platform for global numerical weather prediction** based on the Model for Prediction Across Scales – Atmosphere (MPAS-A), which implements
  - (i) Customizable Unstructured Mesh Generation (CUMG)
    - An in-house implementation based on the Ocean-Land-Atmosphere Model (OLAM).
    - Enables local mesh refinement in arbitrary shape using user-defined horizontal resolution at any desired location.
    - Results in 100% well-staggered mesh and guarantees NO obtuse Delaunay triangle.
  - (ii) Hierarchical Time-Stepping (HTS)
    - Applies different time-steps to cells of different sizes, resulting in tremendous speed-up of the model run-time, particularly for meshes with large resolution variation.
  - (iii) Result Visualization
    - Semi-interactive, Jupyter Notebook style user interface.
- This study evaluates the model run-time and performance of a **CPAS customized 128-to-1 km mesh** in comparison with the **MPAS-A standard 60-to-3 km mesh** in three historical scenarios.

2. CPAS Customized Mesh vs MPAS-A Standard Mesh

- The **CPAS customized 128-to-1 km mesh** and **MPAS-A standard 60-to-3 km mesh** differ in (i) shape, (ii) span, (iii) number of refinement regions, and (iv) range of resolution variations.

Mesh	No. of Horizontal Cells	Refinement Region(s)
CPAS 128-to-1 km	126,515	Several arbitrary-shaped refinement regions
MPAS-A 60-to-3 km	835,586	One circular refinement region

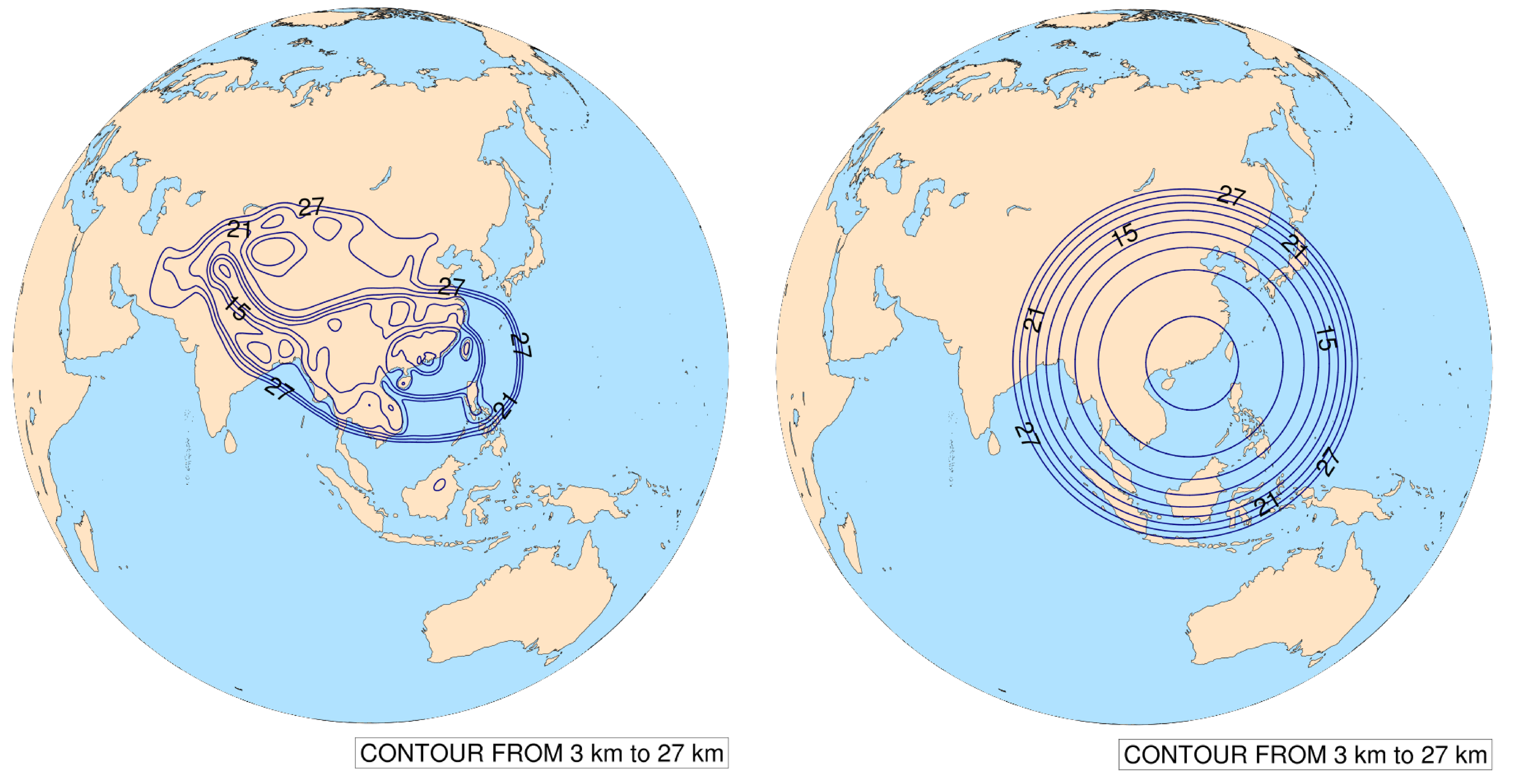

Fig. 1 *Mesh resolution for (a) the CPAS 128-to-1 km mesh and (b) the MPAS-A 60-to-3 km mesh drawn on orthographic projection maps centered on 10.0° N, 105.0° E*

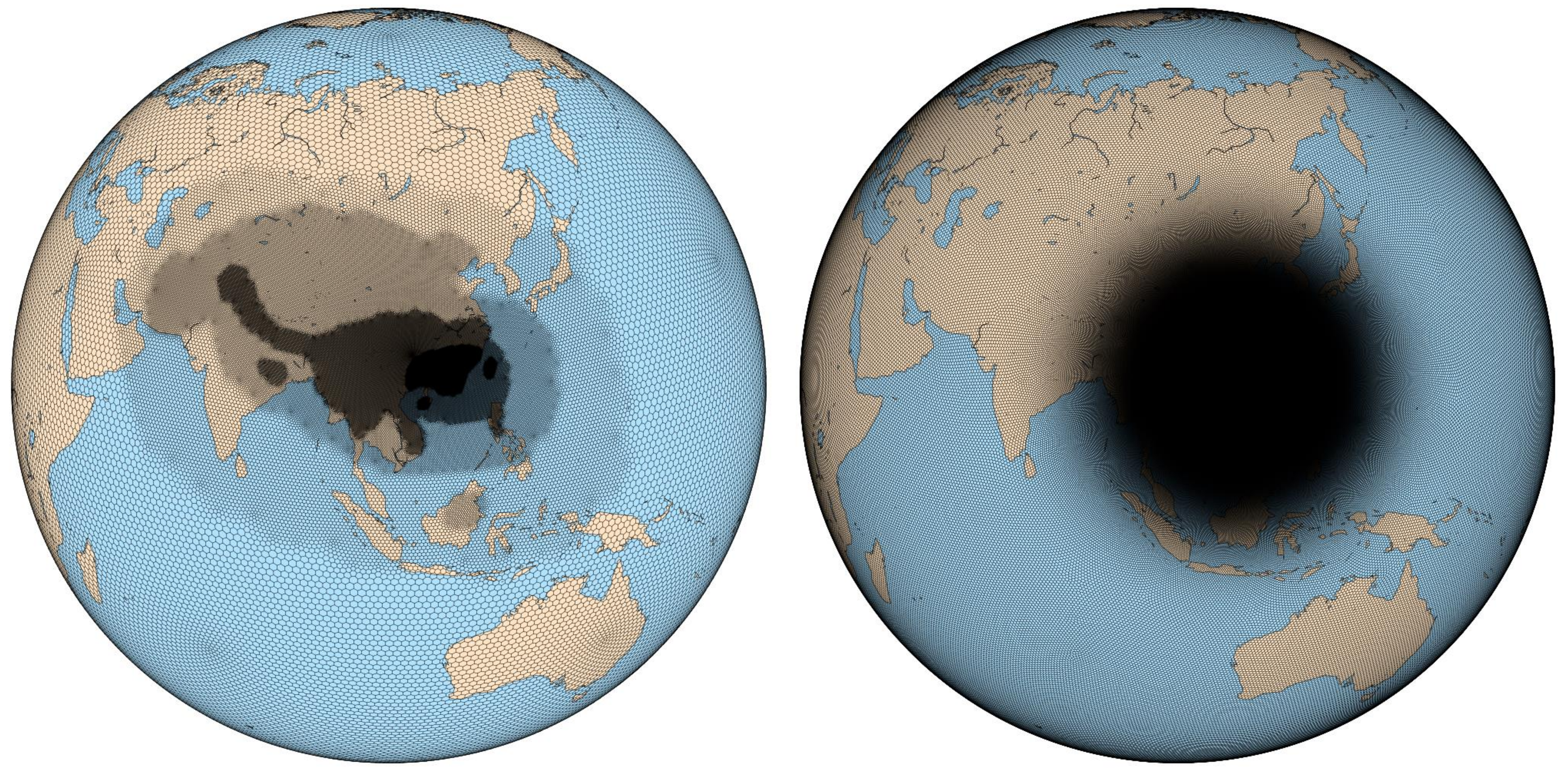

Fig. 2 *Voronoi cells for (a) the CPAS 128-to-1 km mesh and (b) the MPAS-A 60-to-3 km mesh drawn on orthographic projection maps centered on 10.0° N, 105.0° E*

2.1 Mesh Quality

- The **CPAS 128-to-1 km mesh** generated using CUMG has better mesh quality than the **MPAS-A 60-to-3 km mesh** in most quality metrics, namely cell quality, angle-based triangle quality, and triangle quality.

Aspects to Measure	Quality Metrics
Regularity of the cell	Cell Quality $= \frac{l_{min}}{l_{max}}$
Regularity of the interior angles of the dual	Angle-Based Triangle Quality $= \frac{\theta_{min}}{\theta_{max}}$
Regularity of the edges of the dual	Triangle Quality $= \frac{(a+b-c)(b+c-a)(a+c-b)}{abc}$

**Dual: Delaunay triangulation of the Voronoi tessellation*

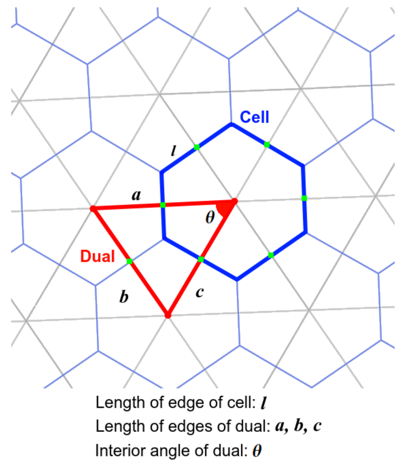

Fig. 3 *Voronoi cell (blue) and dual (red)*

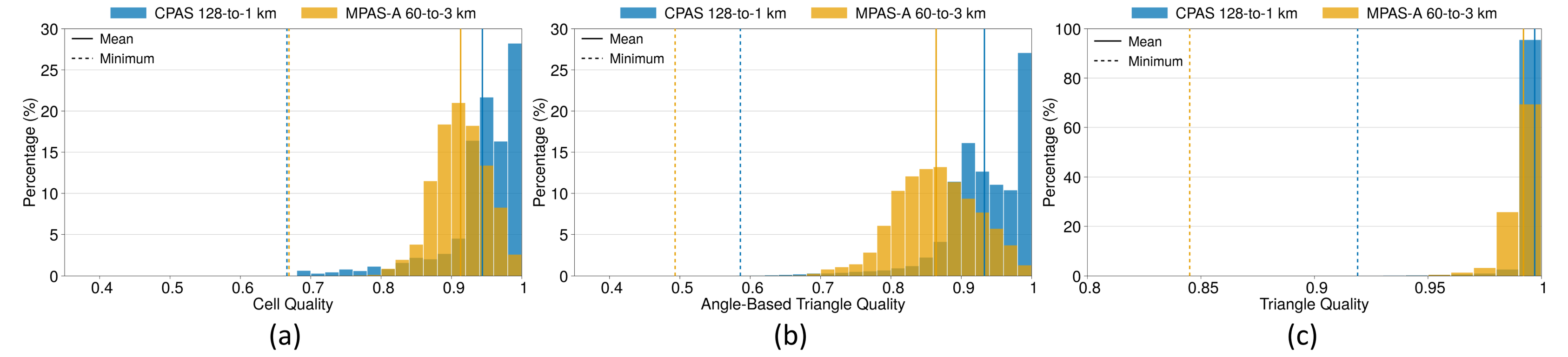

Fig. 4 *Mean (solid line) and minimum (dashed line), and distribution of mesh qualities for the CPAS 128-to-1 km mesh (blue) and the MPAS-A 60-to-3 km mesh (yellow): (a) cell quality (b) angle-based triangle quality (c) triangle quality*

2.2 Assignment of HTS Levels

- The HTS level is assigned on each mesh cell based on its horizontal resolution. The smaller the mesh cells, the higher the HTS levels, and the smaller the time-step during model integration.

Mesh	No. of HTS Levels	Time-steps of Each HTS Level (ascending)
CPAS 128-to-1 km	8	300 s, 150 s, 75 s, 37.5 s, 18.75 s, 9.375 s, 4.6875 s, 2.34375 s
MPAS-A 60-to-3 km	5	150 s, 75 s, 37.5 s, 18.75 s, 9.375 s

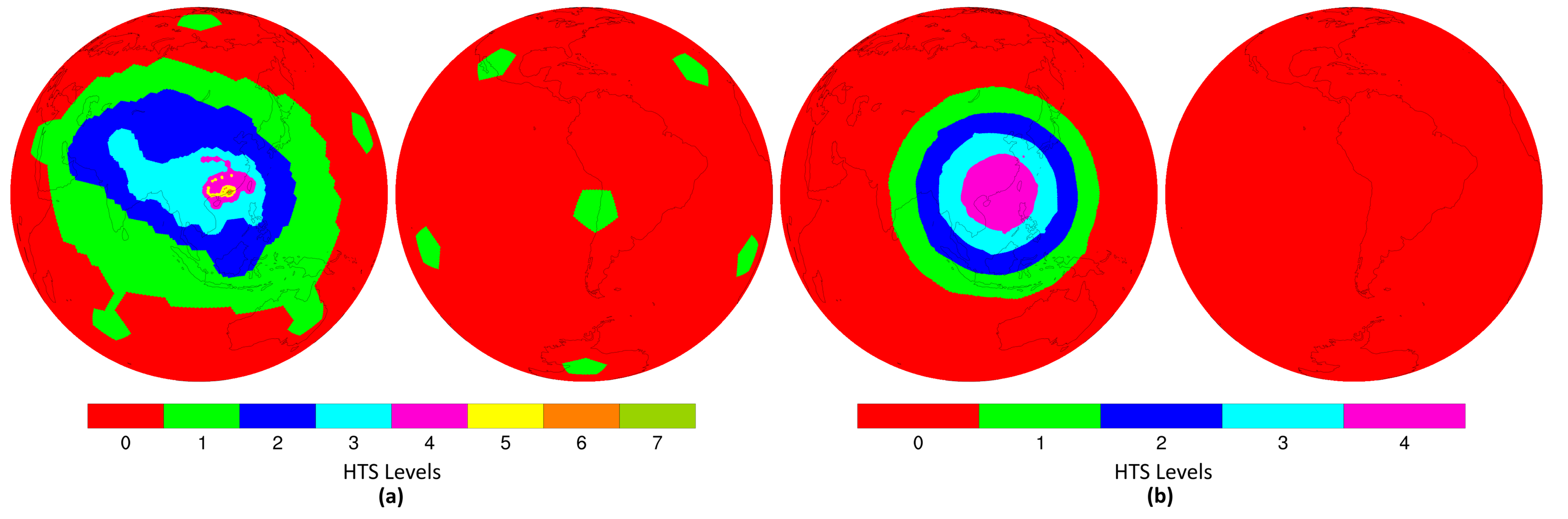

Fig. 5 *Spatial distribution of HTS levels assigned on (a) the CPAS 128-to-1 km mesh and (b) the MPAS-A 60-to-3 km mesh drawn on orthographic projection maps centered on 10.0° N, 105.0° E (left) and 10.0° S, 75.0° W (right)*

3. Model and Hardware Configurations

Table 1. *Model configuration*

Configurations	Choices
Initial condition	ERA-interim (0.75° x 0.75°)
Vertical levels (Top)	55 (30 km; ~12 hPa)
Convection	New Tiedtke (WRF v3.8.1) (switched off below 9 km)
Microphysics	WSM6 (WRF v3.8.1)
Land surface	NOAH (WRF v3.3.1)
Planetary boundary layer	YSU (WRF v3.8.1)
Radiation	RRTMG (WRF v3.8.1)

- Compiled and run using
  - (i) Single-precision floating point,
  - (ii) 4 server nodes each with a 68-core Intel Knights Landing (KNL) processor,
  - (iii) `OMP_NUM_THREADS=4`
  - (iv) `OMP_STACKSIZE=128M`

4. Results and Discussions

A. Efficiency Evaluation

- HTS boosts every major component in CPAS dynamic core in all cases using both standard and customized meshes, resulting in considerable speedup when compared to non-HTS.

**'physics driver': Routine considering all physical parameterization procedures listed in Table 1 except microphysics.*

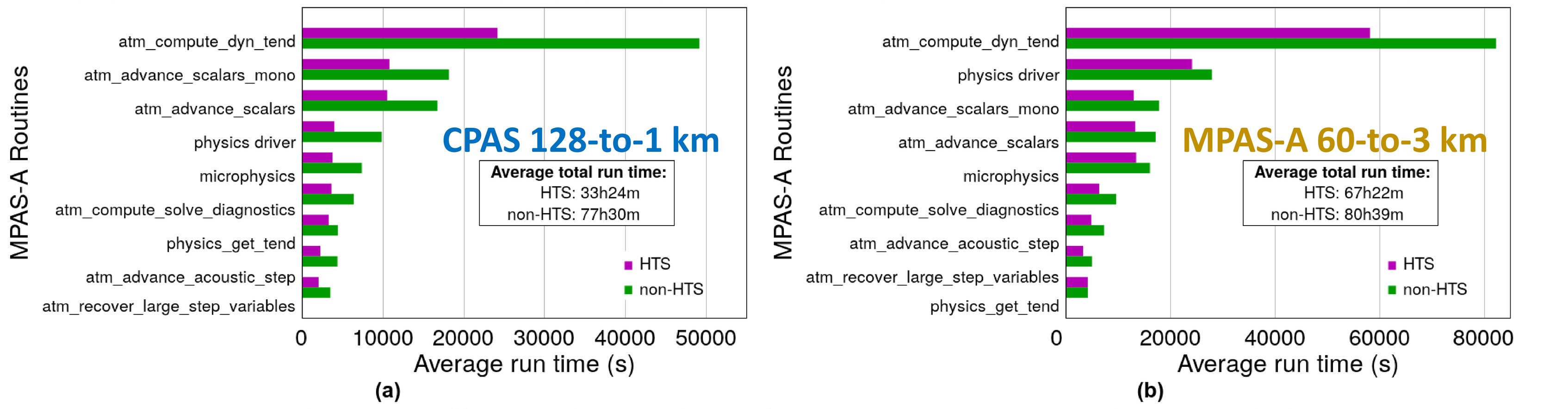

Fig. 6 *Averaged timing profile over 3 historical cases between HTS (magenta) and non-HTS (dark green): (a) the CPAS 128-to-1 km mesh (b) MPAS-A 60-to-3 km mesh*

CPAS 128-to-1 km Average: 56.8 % time saving (2.33x speedup)	
Speedup	**Routine(s)**
1.91x	`'microphysics'` and `'atm_advance_acoustic_step'`
2.01x	`'atm_compute_dyn_tend'`
2.45x	`'physics driver'`

MPAS-A 60-to-3 km Average: 16.5 % time saving (1.20x speedup)	
Speedup	**Routine(s)**
1.50x	`'atm_compute_solve_diagnostics'`, `'atm_advance_acoustic_step'` and `'atm_recover_large_step_variables'`

**Speedup: Quotient of execution time for non-HTS and HTS*

B. Performance Evaluation

- Simulation results were validated through comparison with the National Centers for Environmental Prediction (NCEP) Final (FNL) Operational Global Analysis.
- Taylor's skill score for various forecast variables within the area of interest (a lat-long box covering 3 km refinement region of the **MPAS-A 60-to-3 km mesh**) were computed.
- All forecast variables in the 5-day simulation show comparable performance between HTS and non-HTS for both meshes, indicating the validity of the CPAS customized mesh running in HTS.

Case 1: Passage of a Cold Front

Case 2: Heavy Rainfall

Case 3: Passage of A Tropical Cyclone

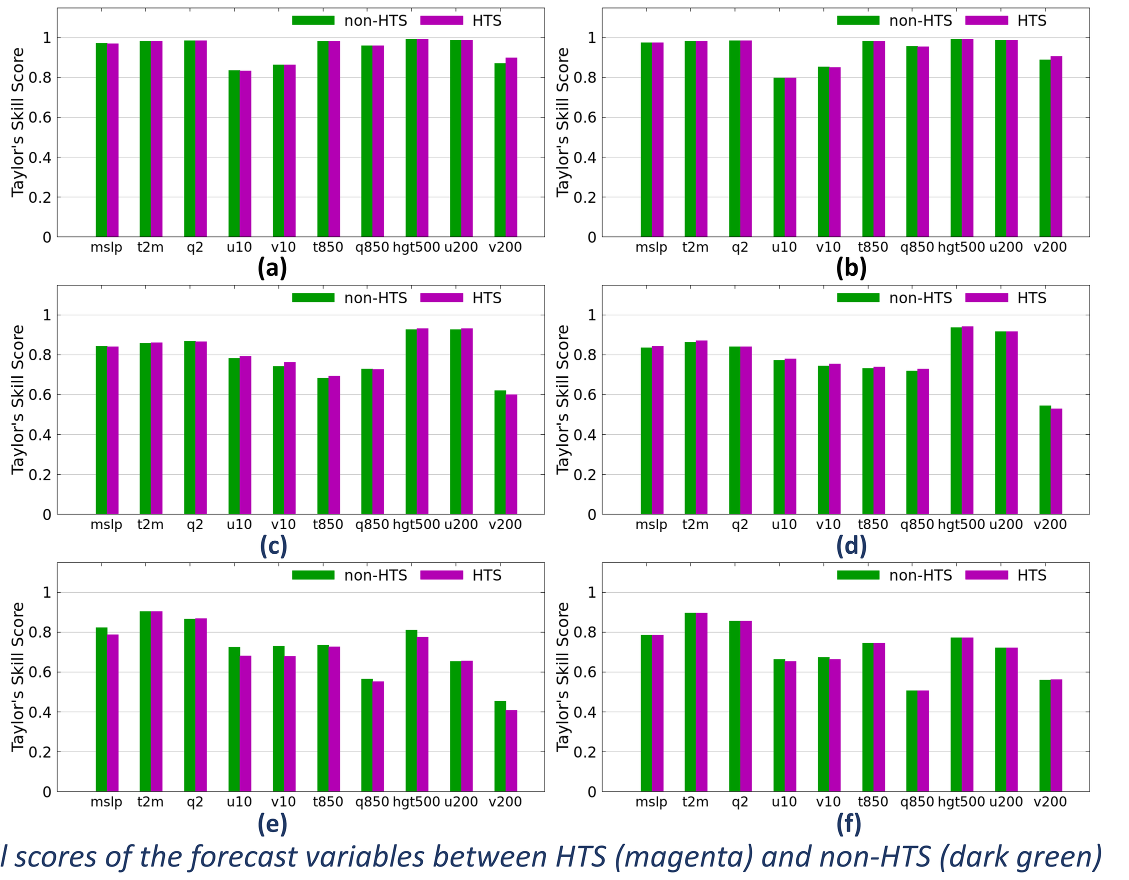

Fig. 7 *The Taylor's skill scores of the forecast variables between HTS (magenta) and non-HTS (dark green) for comparison with FNL reanalysis: the CPAS 128-to-1 km mesh (left), MPAS-A 60-to-3 km mesh (right)*

5. Conclusions and Remarks

- This **CPAS 128-to-1 km mesh** shows better quality than the **MPAS-A 60-to-3 km mesh** in most quality metrics. In general, mesh generated by CPAS' have better quality than those generated by traditional Lloyd-based methods.
- Promising model performance along with remarkable speed-up using HTS illustrate the validity and feasibility of high resolution local/regional forecast in daily operational manner.
- Study of modelling accuracy using CPAS' mesh can be found in Lui *et al.* (2019). It analyzed the simulated tracks and intensities of western north Pacific tropical cyclone using CPAS' customized variable-resolution meshes with comparison to the Weather Research and Forecasting (WRF) model.

**Lui et al. (2019) used JIGSAW-GEO-based mesh generation algorithm in an early version of CPAS; further modeling result analysis will be carried out using the current OLAM-based meshes.*

Poster Presentation (Lui *et al.* 2019)