Resolution Sensitivity of the GRIST Nonhydrostatic Model From 120 to 5 km (3.75 km) During the DYAMOND Winter

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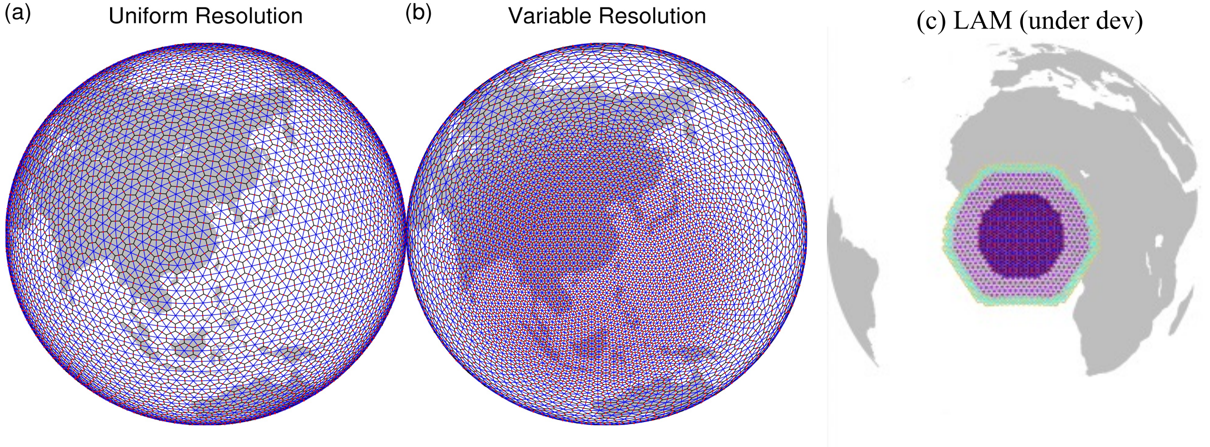
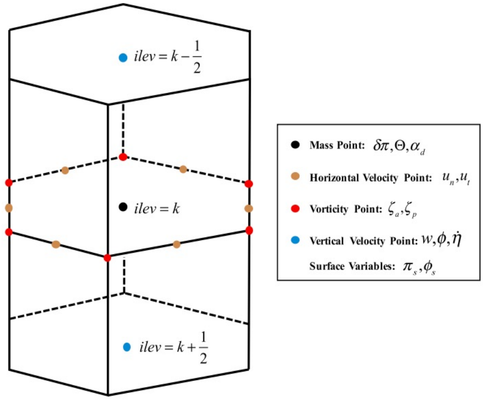
- Layer-averaged dry-mass vertical discretization
- Unstructured hexagonal C-grid horizontal operators
- Split dry core-tracer-physics coupling
- Multiple physics suites

PhysW physics suite	**PhysC physics suite**
(days to months/years)	**(years to centuries)**

Initial physics suites ported from two community models maintained by NCAR



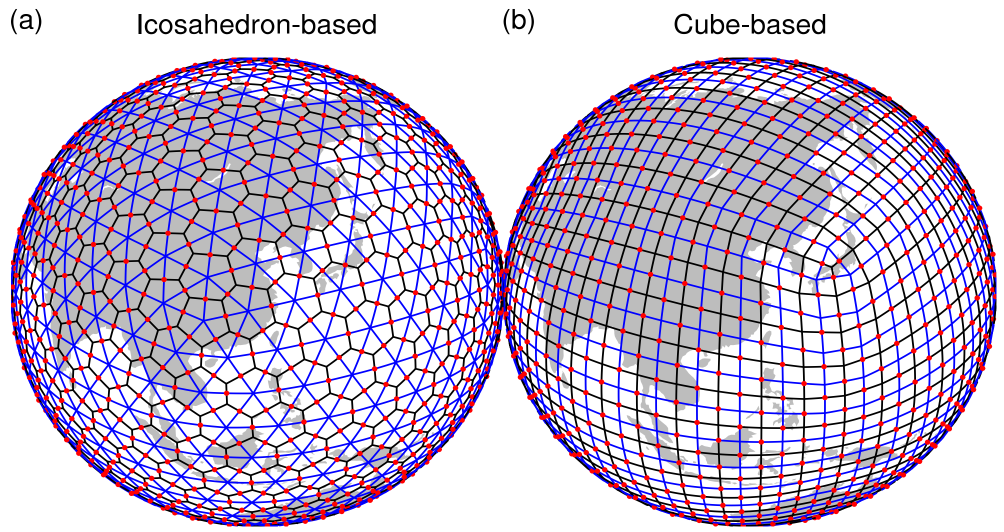
- Icosahedron-like Voronoi grid
- Domain: Global; Global Var-Res; *limited-area*



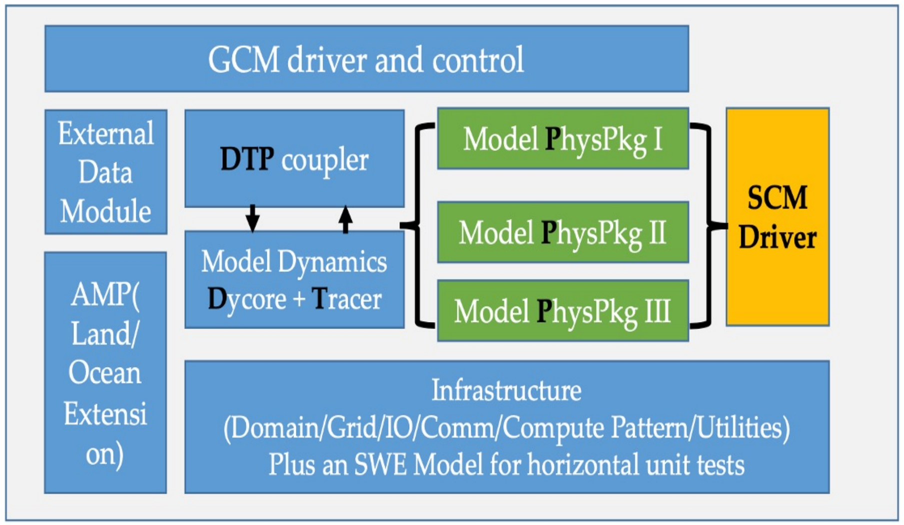
- Metric term due to coordinate transform is converted to a layer-integrated/averaged product
- Advection and pressure-gradient terms are consistently discretized around a control volume

A final chain in the 1st-round GRIST model development

Unstructured grid model



GRIST model architecture



Phase 0 — Infrastructure & SWM (Parallelization)

Phase 1 — 3D dry & moist dynamical core (Parallelization; Hydro- & Non-hydrostatic)

Phase 2 — Model with PDC capability (Full physics suite)

Phase 3 — Aqua Planet (SCM → Full physics suite)

Phase 4 — Real-world AMIP test (Surface model)

Phase 5 — **Kilometer-scale test** research & operation (Next-step iteration…)

Model: Global-to-Regional Integrated Forecast System

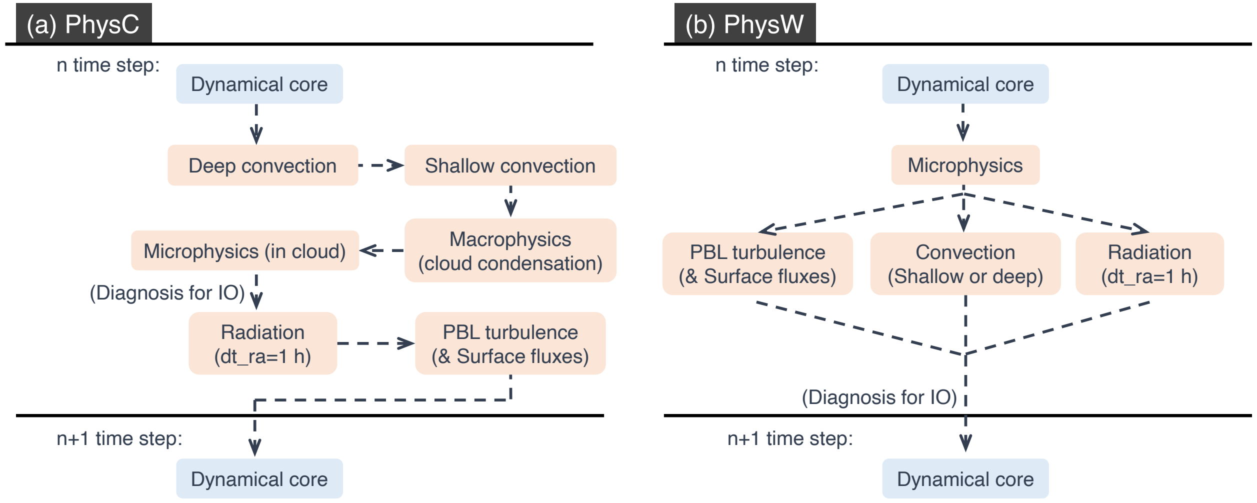
➢ GRIST model development was initially started in response to explore unified weather-climate modeling

A Unified Model Framework + Dynamical Core

- Hydro- and **Nonhydrostatic dynamics** in a single workflow
- Layer-averaged dry-mass vertical discretization
- Unstructured hexagonal C-grid horizontal operators
- Split dry core-tracer-physics coupling
- Multiple physics suites

✓PhysW physics suite **(days to months/years)**	**PhysC physics suite** **(years to centuries)**

Dynamics (~87%): dry core: ~61% with nh-solver: 22%; tracer transport: ~25%
Physics (~11%): mp: wsm6; pbl: ysu; rad: rrtmg; lsm: noah-mp



● The main structural difference between PhysC and PhysW lies in the treatment of **dynamics-microphysics coupling**

● Cloud Radiative Forcing is most sensitive to this difference (TOA energy balance)

● For GSRM, dynamics-microphysics has to be coupled more tightly to better represent explicit model convection

PhysW: AMIP simulations with cumulus parameterization

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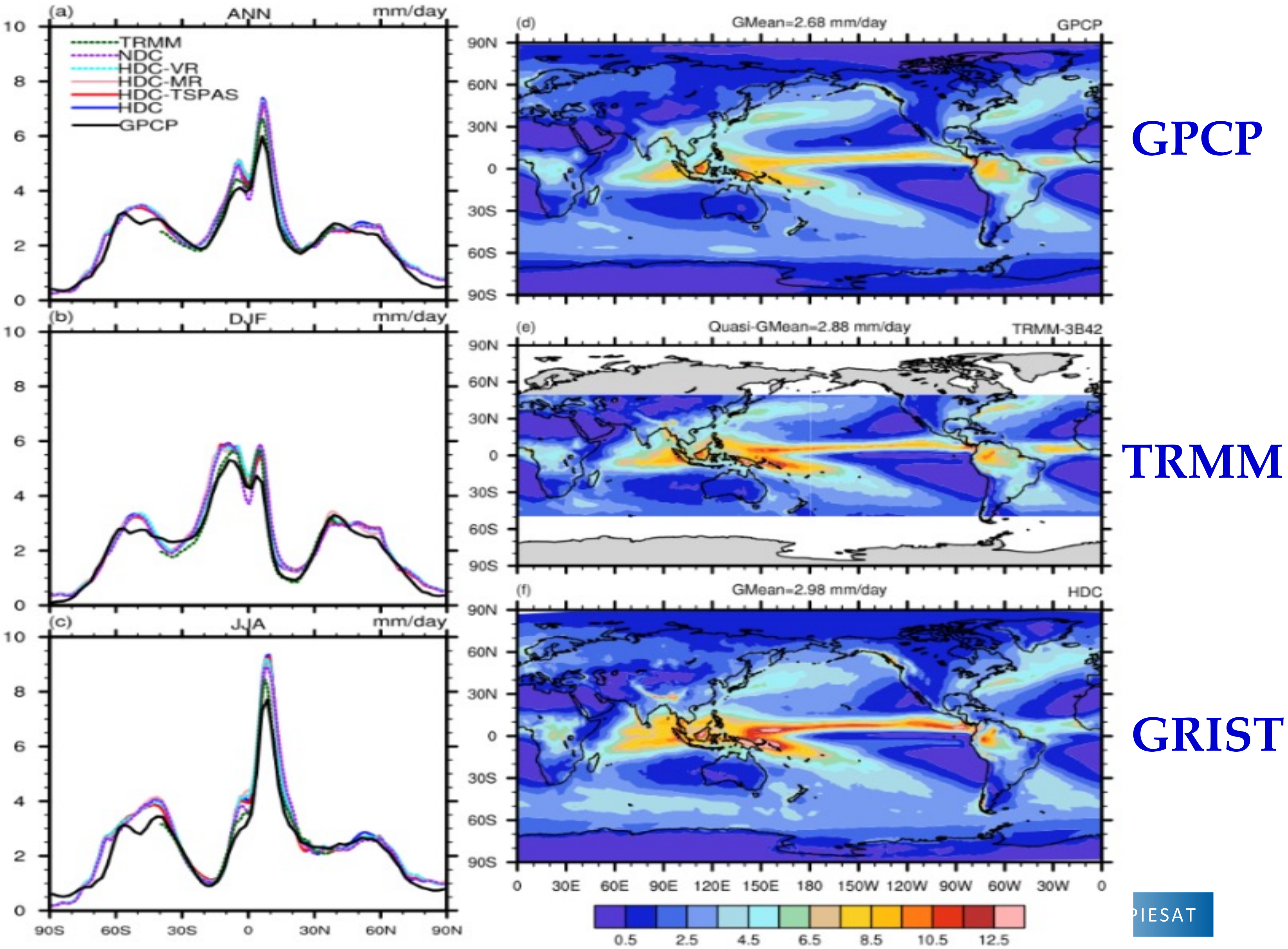
- AMIP simulations show good agreement with observations with regard to global precipitation and other large-scale climatic features at ~1-degree

- TOA radiation balance needs man-made tuning to get a close-to-zero budget (droplet radius, cloud fraction, …)

- Compared with another ”climate-model” configuration of GRIST (Li et al. 2022), precipitation performs better while energy balance is worse.



Two AMIP simulations of GRIST at ~1-degree

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AMIPW: Zhang et al. 2021, JAMES

Table 4
Global Averages for Some Important Climate Quantities

Variable	OBS	HDC	NDC	EAMv1LR
SWCF	−47.1	−54.5	−56.5	−49.3
LWCF	26.1	20.4	20.7	24.5
Allsky-SW TOA	240.5	240.8	238.9	239.4
Allsky-LW TOA	239.8	238.2	237.3	239.0
Allsky-Net TOA	0.85	2.6	1.6	−0.5
Surface SW down	186.6	188.8	186.3	184.6
Surface LW down	345.2	341.6	342.2	344.8
Sensible heat flux	19.3	24.0	24.5	19.2
Latent heat flux	87.9	88.4	87.5	89.8
Precipitation	2.7	2.98	2.95	3.1

Note. Decimal numbers are truncated with one position (except precipitation). OBS and EAMv1LR results cite Table 3 of Rasch et al. (2019). All GRIST simulations are from the 10-year average. SW: shortwave, LW: longwave, CF: cloud radiative forcing, TOA: top of the atmosphere. Unit: W/m^2 for flux, mm/day for precipitation.

AMIPC: Li et al. 2022, JGR-A

Table 3
Global Mean Radiation for Each Model

	ZM-UW	DP	DP_cape	DP_c1	DP_c2	OBS
Net TOM radiation, W m^{-2}	0.9	1.4	0.5	2.0	1.0	
OLR_TOA, W m^{-2}	241.8	240.4	238.2	239.5	241.8	239.7
SW_TOA, W m^{-2}	244.8	244.0	240.8	243.6	244.9	240.5
SW cloud forcing, W m^{-2}	−49.1	−49.8	−52.9	−50.1	−48.8	−47.2
LW cloud forcing, W m^{-2}	20.8	22.7	24.8	23.5	21.3	26.1
Energy budget at surface, W m^{-2}	1.8	2.3	1.3	2.8	1.8	

- When cumulus scheme is active, AMIPW tends to underestimate liquid clouds
- In AMIPW, clouds have to be tuned more light (reduce droplet radius) for TOA energy balance, leading to overly strong Net CRF
- Some consistent behaviors also found in SCM modeling

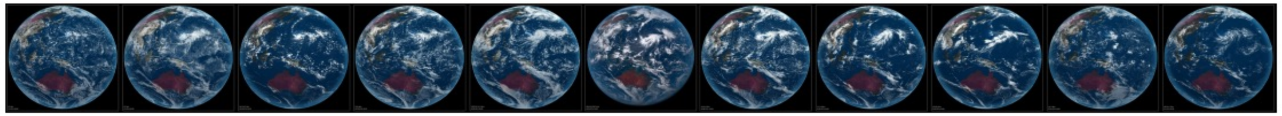
- Li, X., Y. Zhang, X. Peng, B. Zhou, J. Li, and Y. Wang, (2023), Intercomparison of the weather and climate physics suites of a unified forecast/climate model system (GRIST-A22.7.28) based on single column modeling. *Geosci. Model Dev. Discuss.*, 2023(1-31.doi:10.5194/gmd-2022-283.

Understanding an "explicit-convection" model

- Understanding the behavior of "explicit-convection" of a fixed model system from ~100km to ~km scale
- Assessing fine-scale resolving capability of GRIST with increasing resolution (e.g., convergence behavior)
- Understanding the correspondence between GSRM and its own coarse-resolution version (w/ cumulus parameterization), in terms of the large-scale features

Model and Experiment

- DYAMOND winter protocol
- 120km (G6), 60km (G7), 30km (G8), 15km (G9), 5 km (G9B3) for 40 days; 3.75 km (G11) for 12 days; 30 vertical layers
- ~2.1 SDPD on 1600 *Intel Xeon Gold* CPU cores, 40TB raw data
- 5-km data submitted to DKRZ is from the first GRIST-GSRM run
- The model formulation is a simplified configuration based on the previous AMIP(W) modeling setup (https://doi.org/10.1029/2021MS002592)



PROJECT DYAMOND 2nd PHASE - THE WINTER

DANIEL KLOCKE, TOMOKI MIYAKAWA

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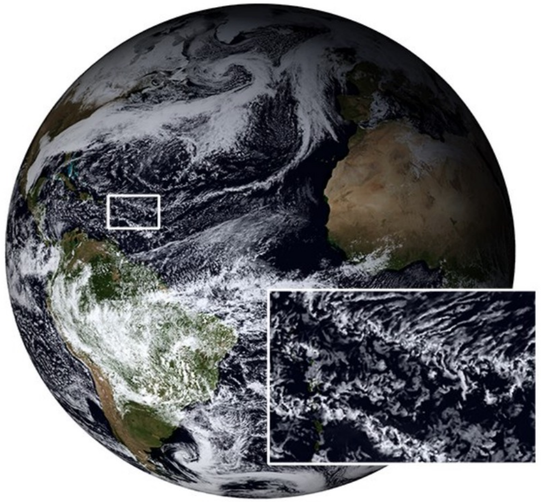

Intercomparison between two highest resolution runs

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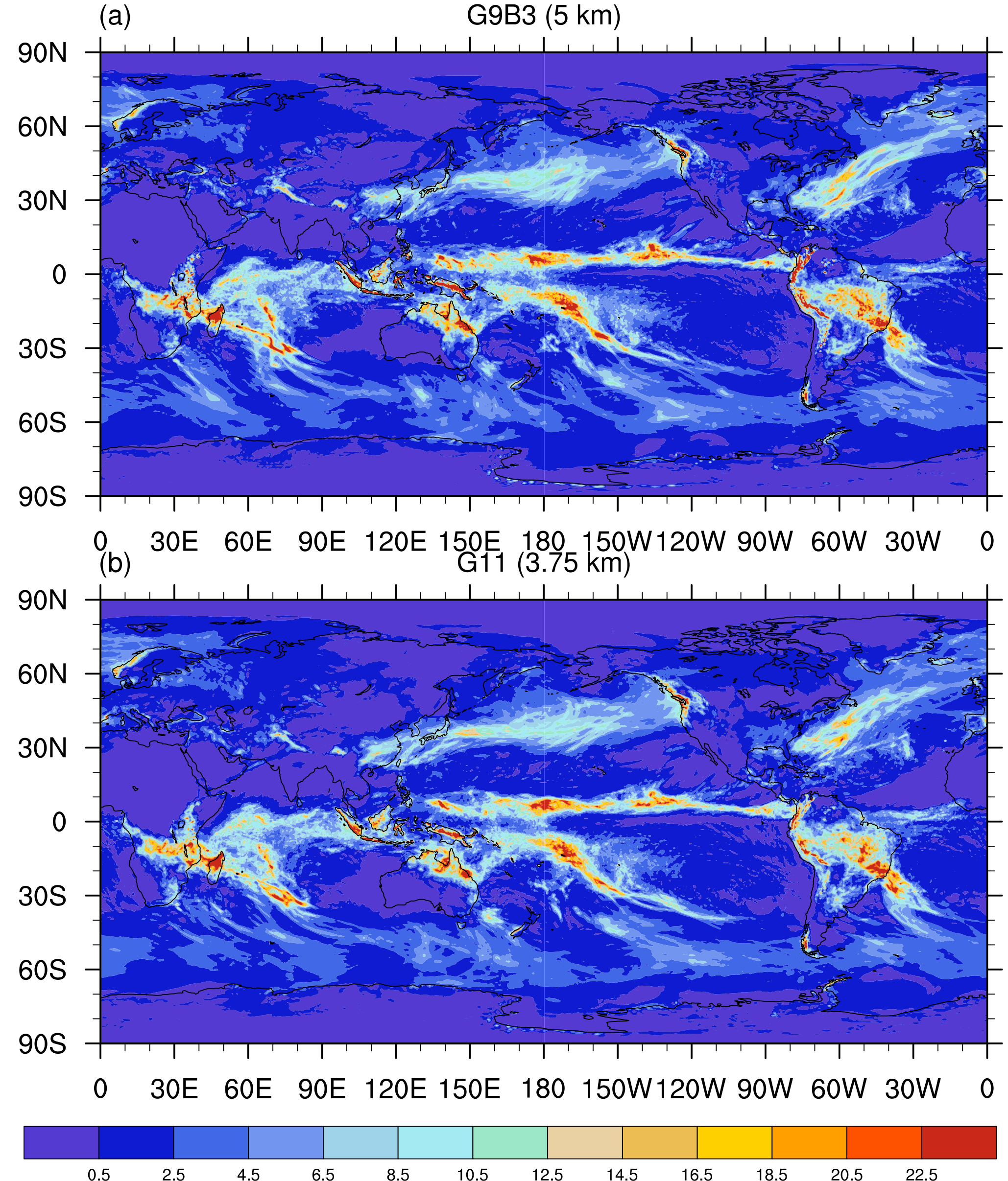
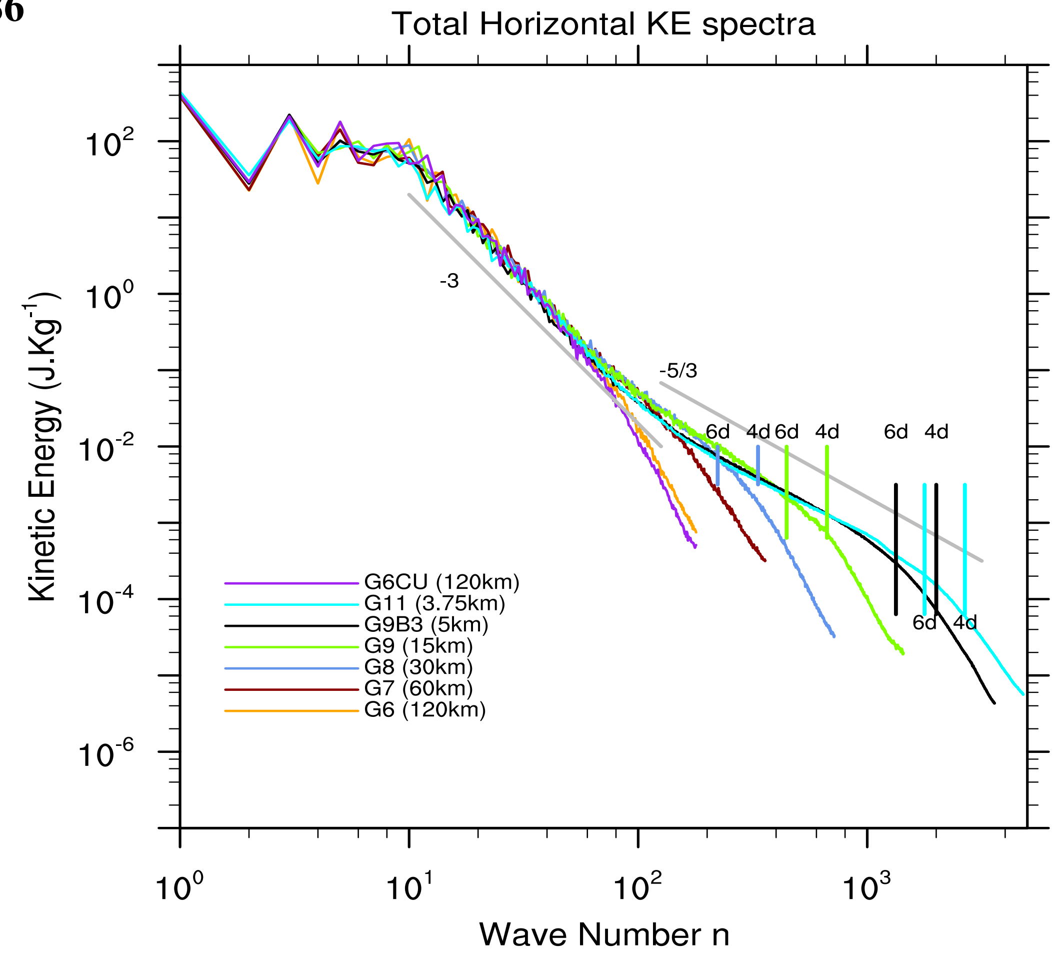
Spatial correlation coef between 5 km and 3.75 km is ~0.86



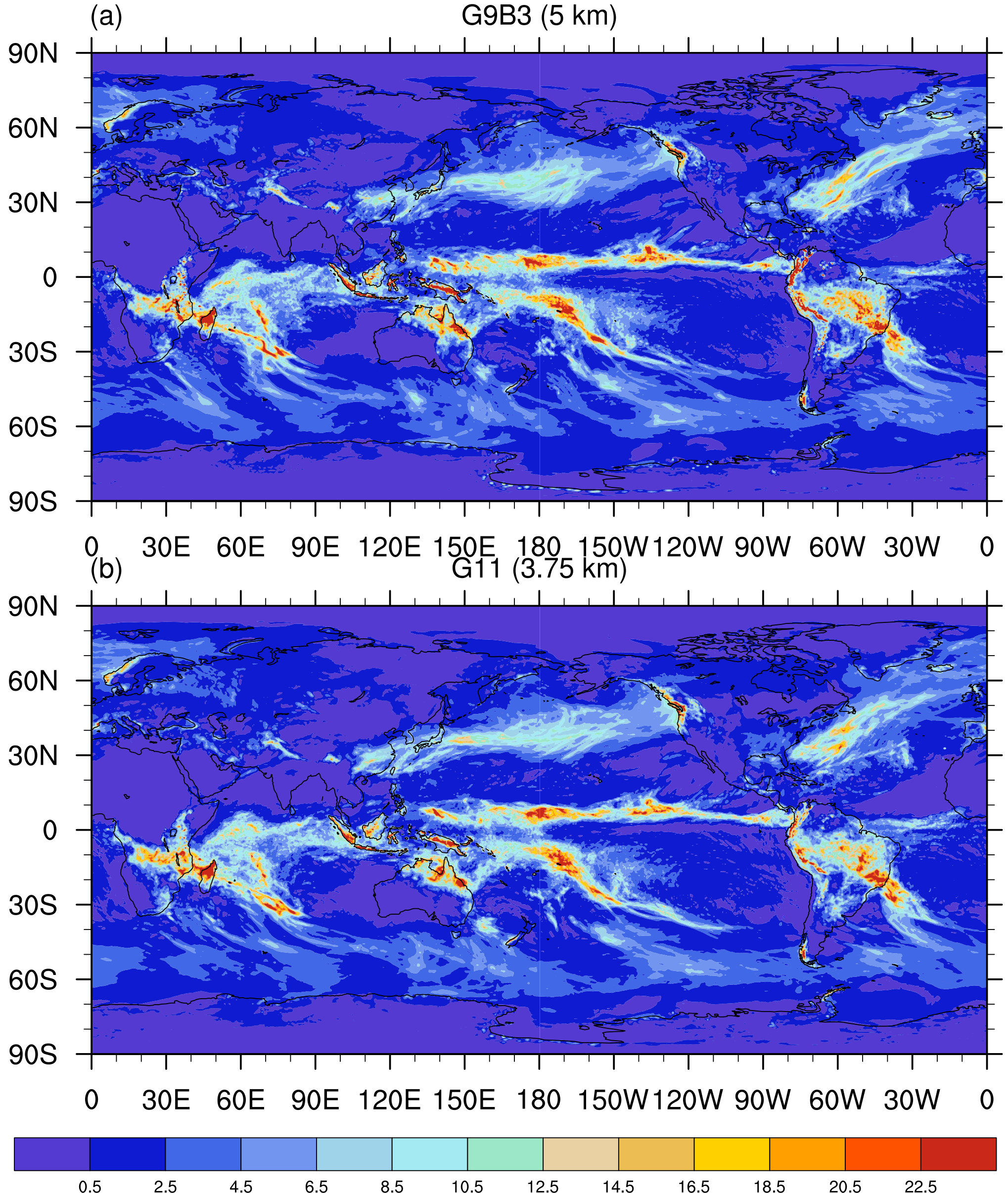


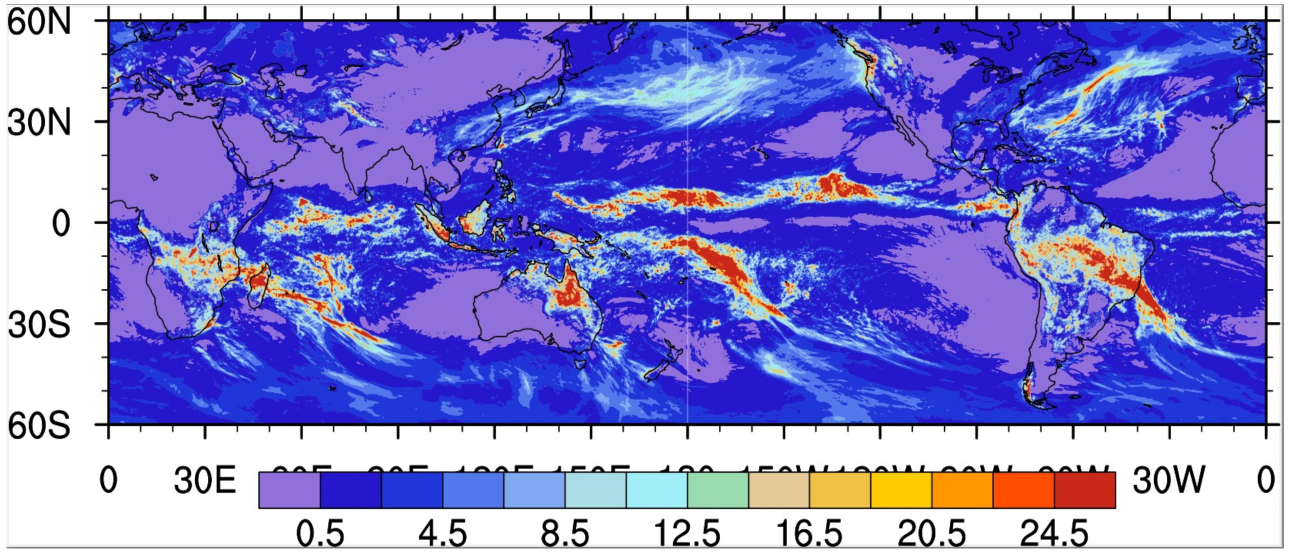
● Global 5-km and 3.75-km are rather close in terms of mean precipitation rates and KE spectra except for those very high wave-number systems

● Effective resolution: ~6dx; from 4dx to 2dx, KE quickly dissipates, where dx is nominal grid spacing

PhysC and PhysW at 5 km

Spatial correlation coef between 5 km and 3.75 km is ~0.86

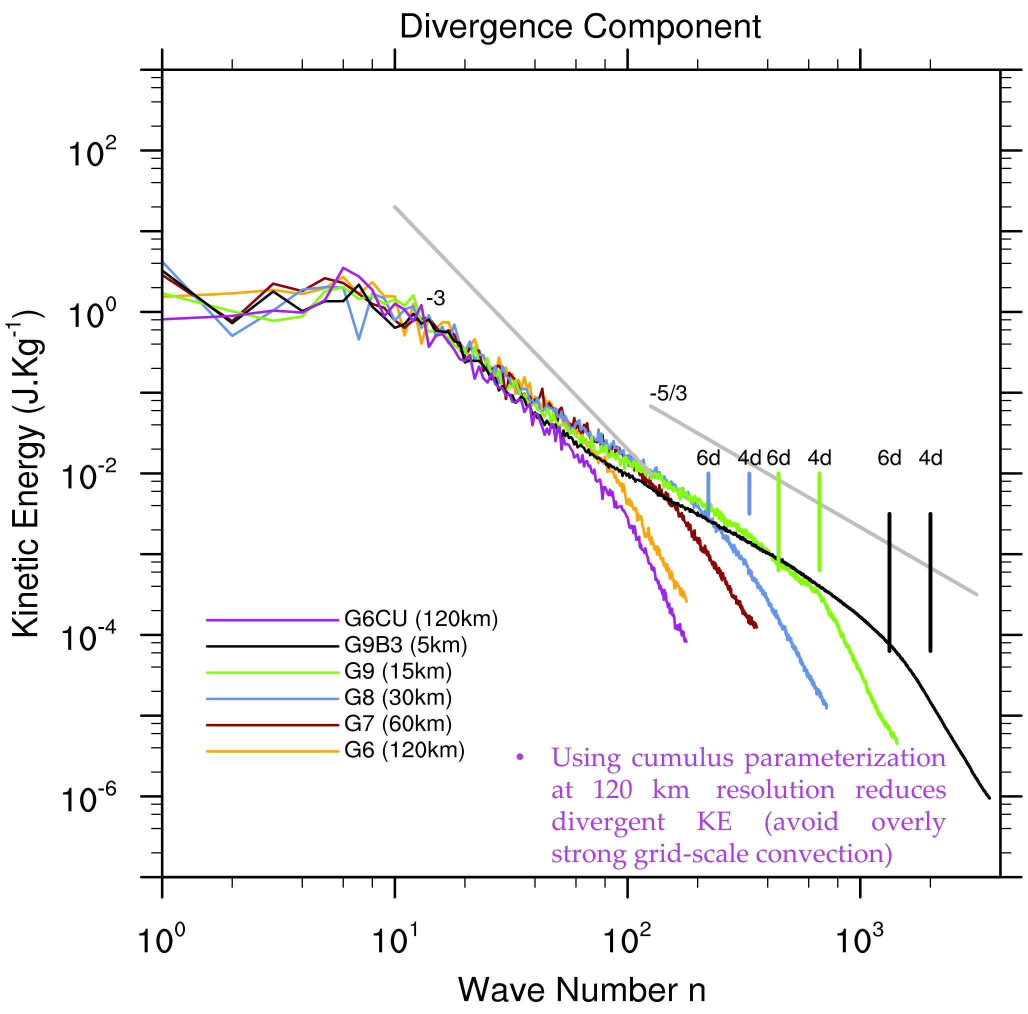


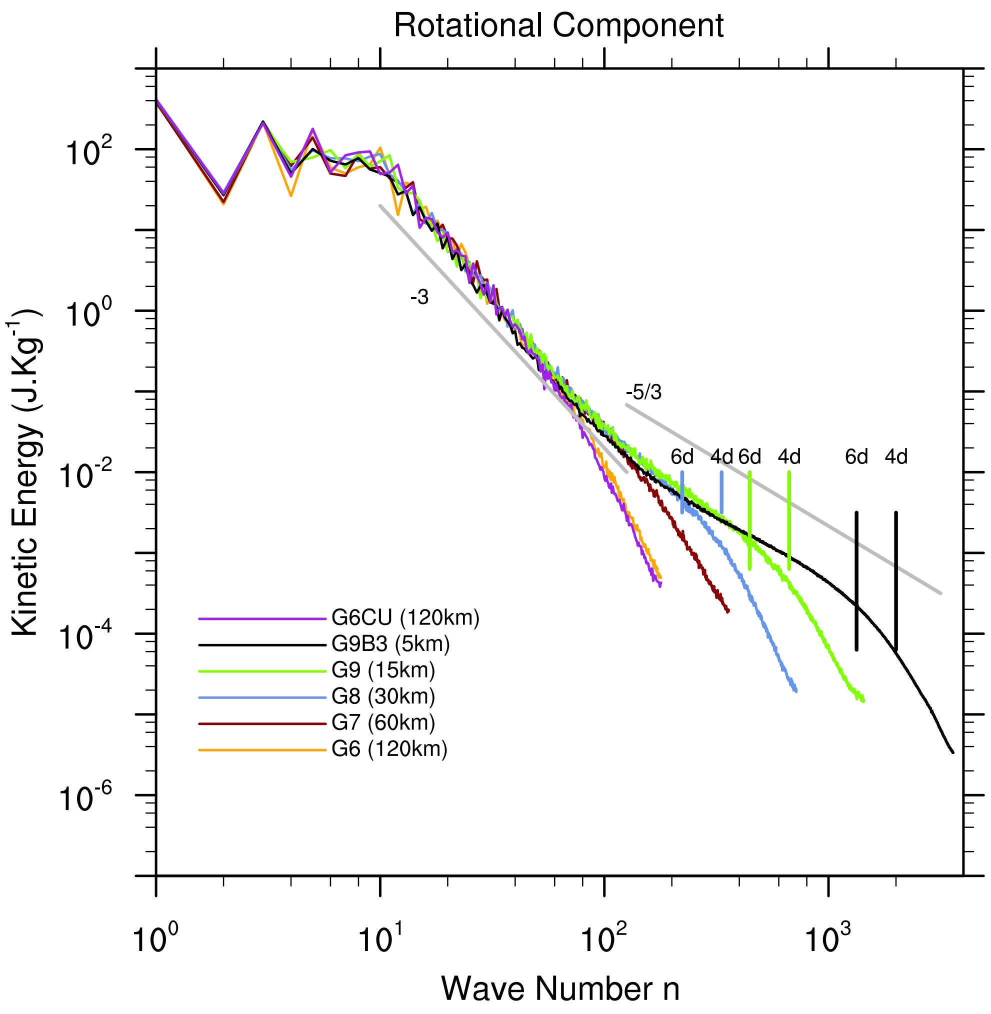


GRIST with the PhysC suite at 5 km (10 days)

- Overly strong precipitation
- More time consuming (+86% with a cheaper hydrostatic core)

Kinetic energy spectra: divergence and rotational part





- The rotational component dominates at all resolutions
- Slope transition from -3 to -5/3 is clear, large-scale is contributed by the rotational part, while meso-to-cloud scale is contributed by both, but the rotational part still dominates
- Using parametrized convection or not mainly affects the divergent part of KE spectra (G6 vs G6CU)

Global precipitation

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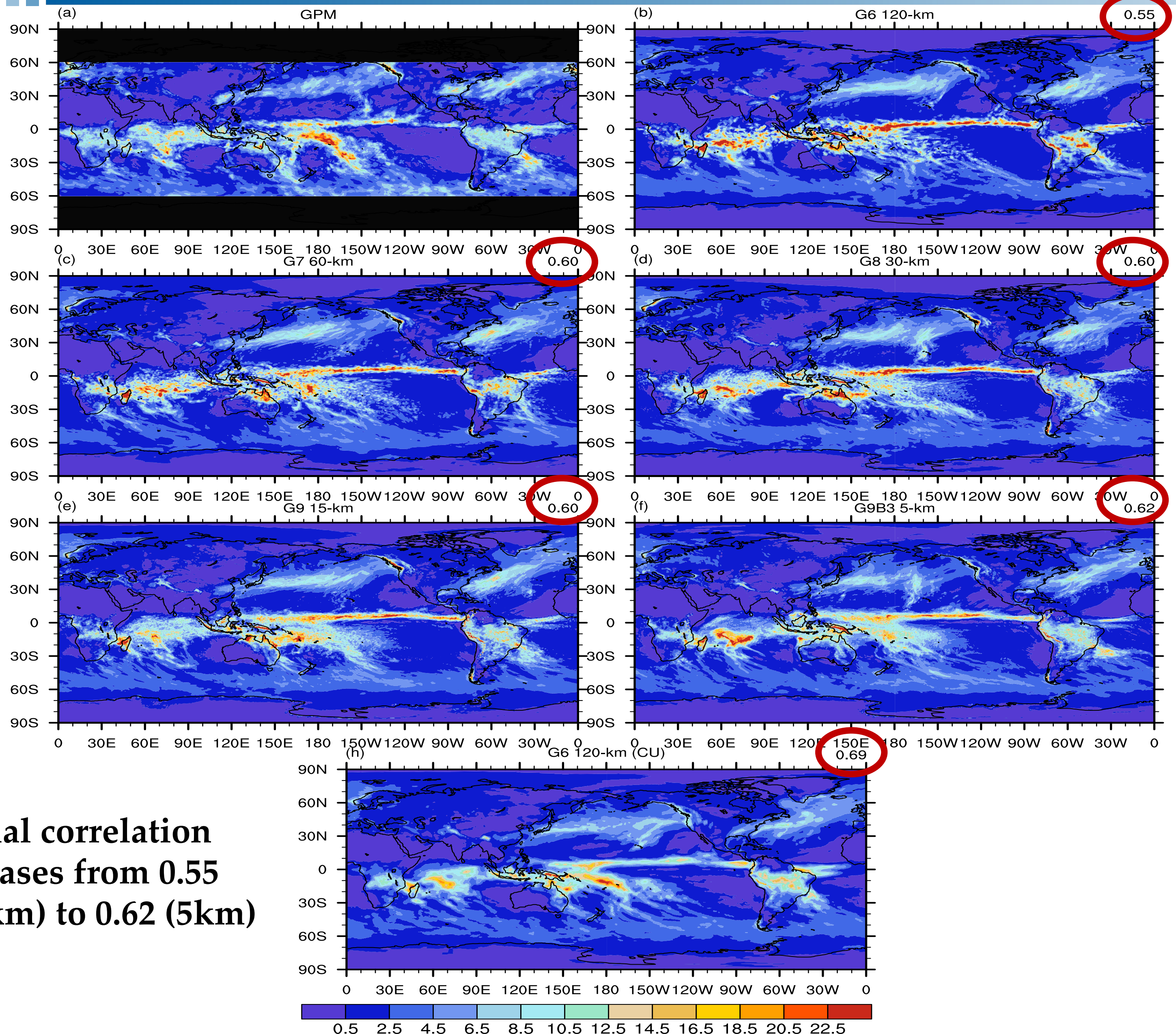

Spatial correlation increases from 0.55 (120km) to 0.62 (5km)

- 5-km generates better coarse-resolution features among all explicit-convection simulations, with incrementally improved spatial correlation from low to high res.
- Large-scale features are slightly worse than a parameterized coarse model

Global precipitation: mean state and PDF distribution

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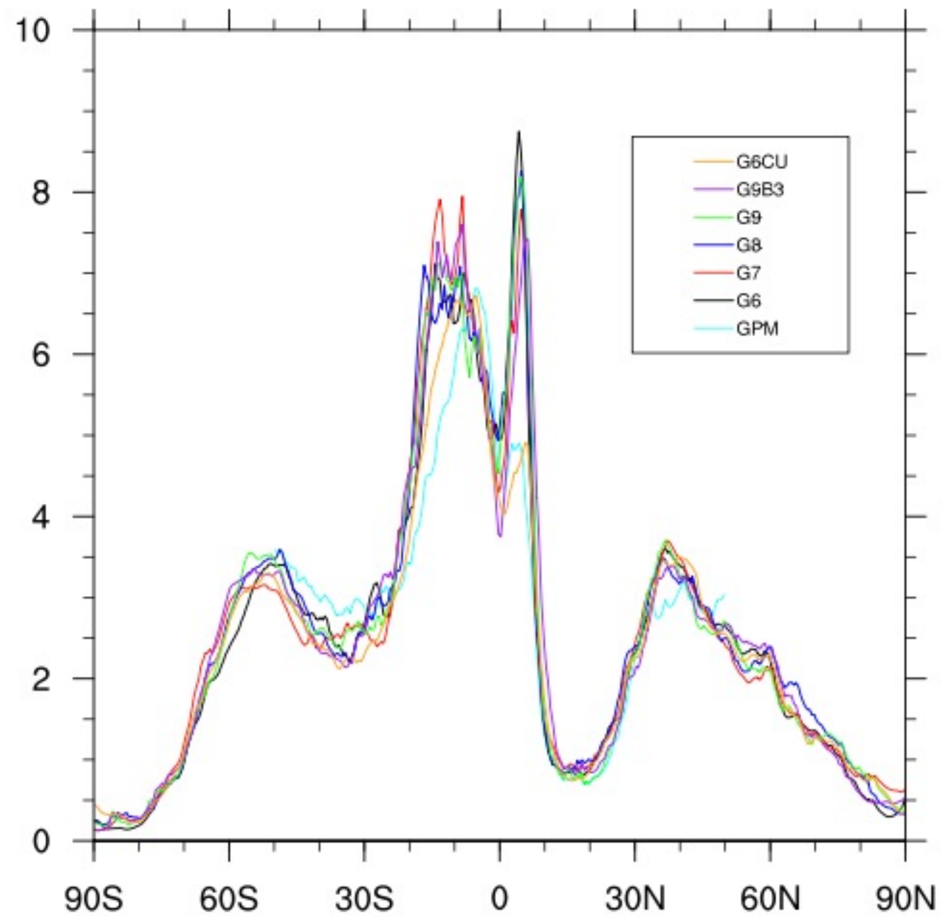
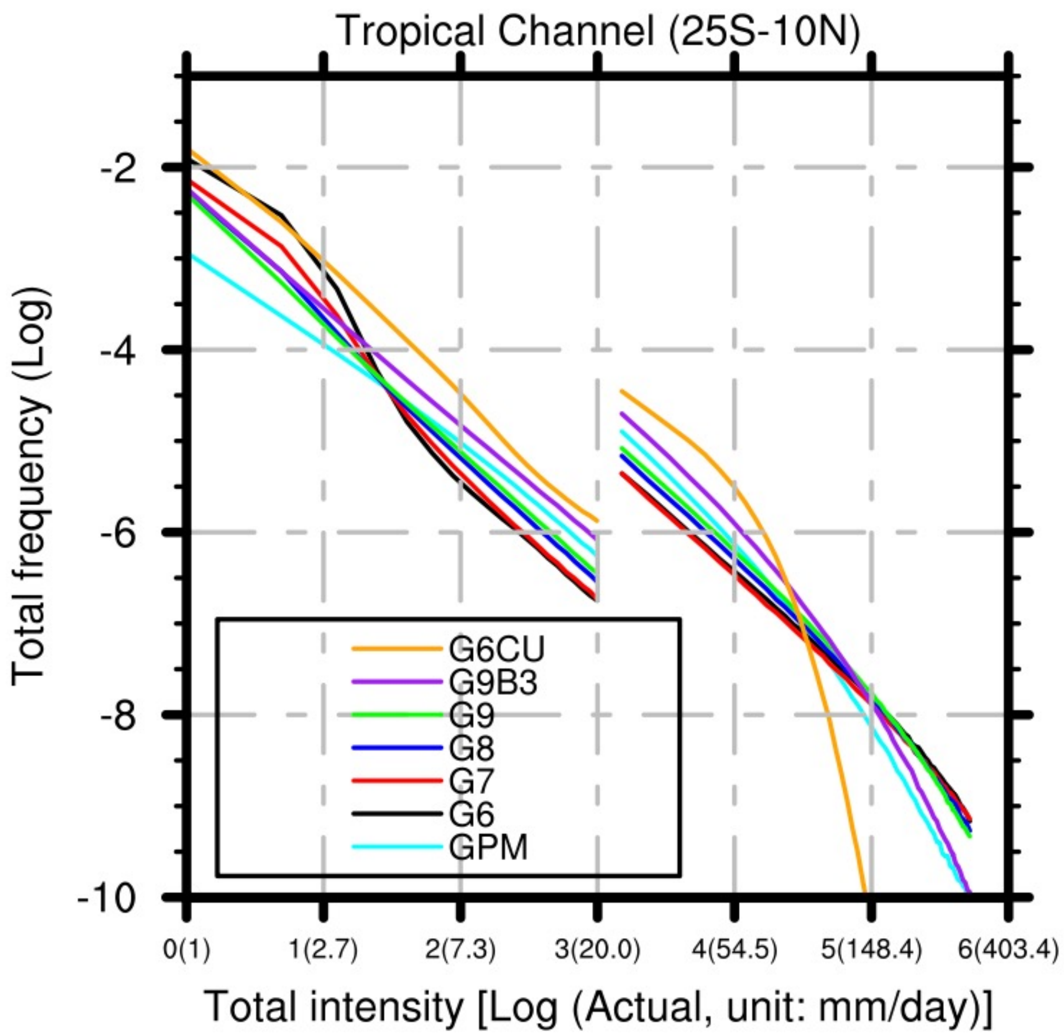
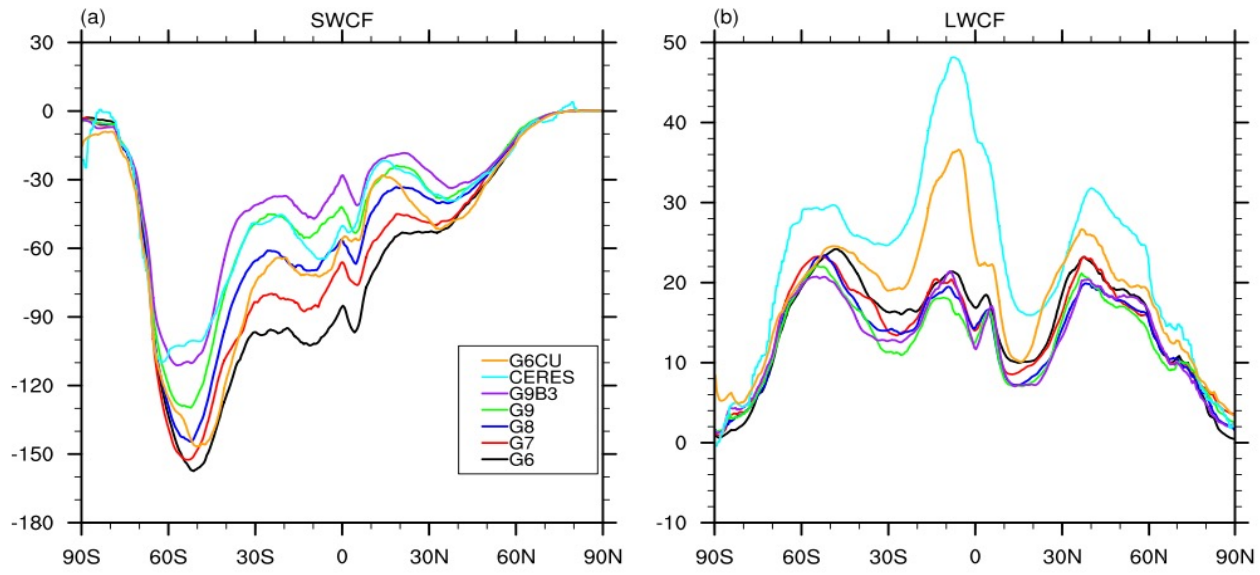
Zonal averaged precipitation rate



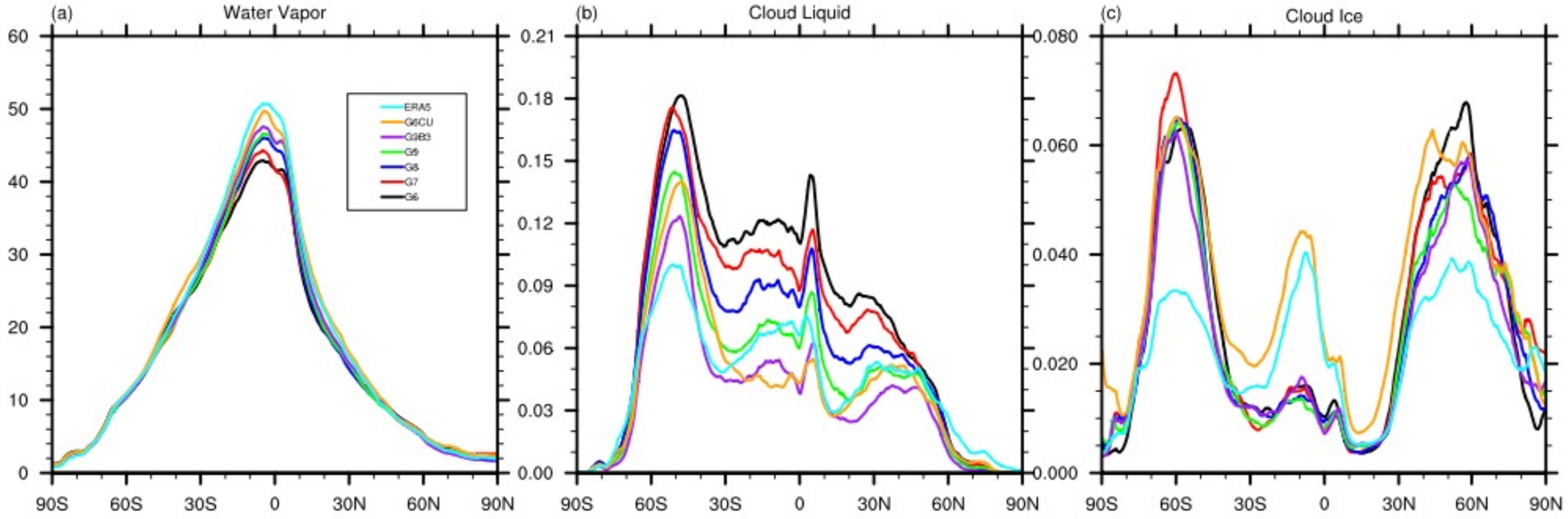
Frequency-intensity spectra



Cloud properties and cloud radiative forcing

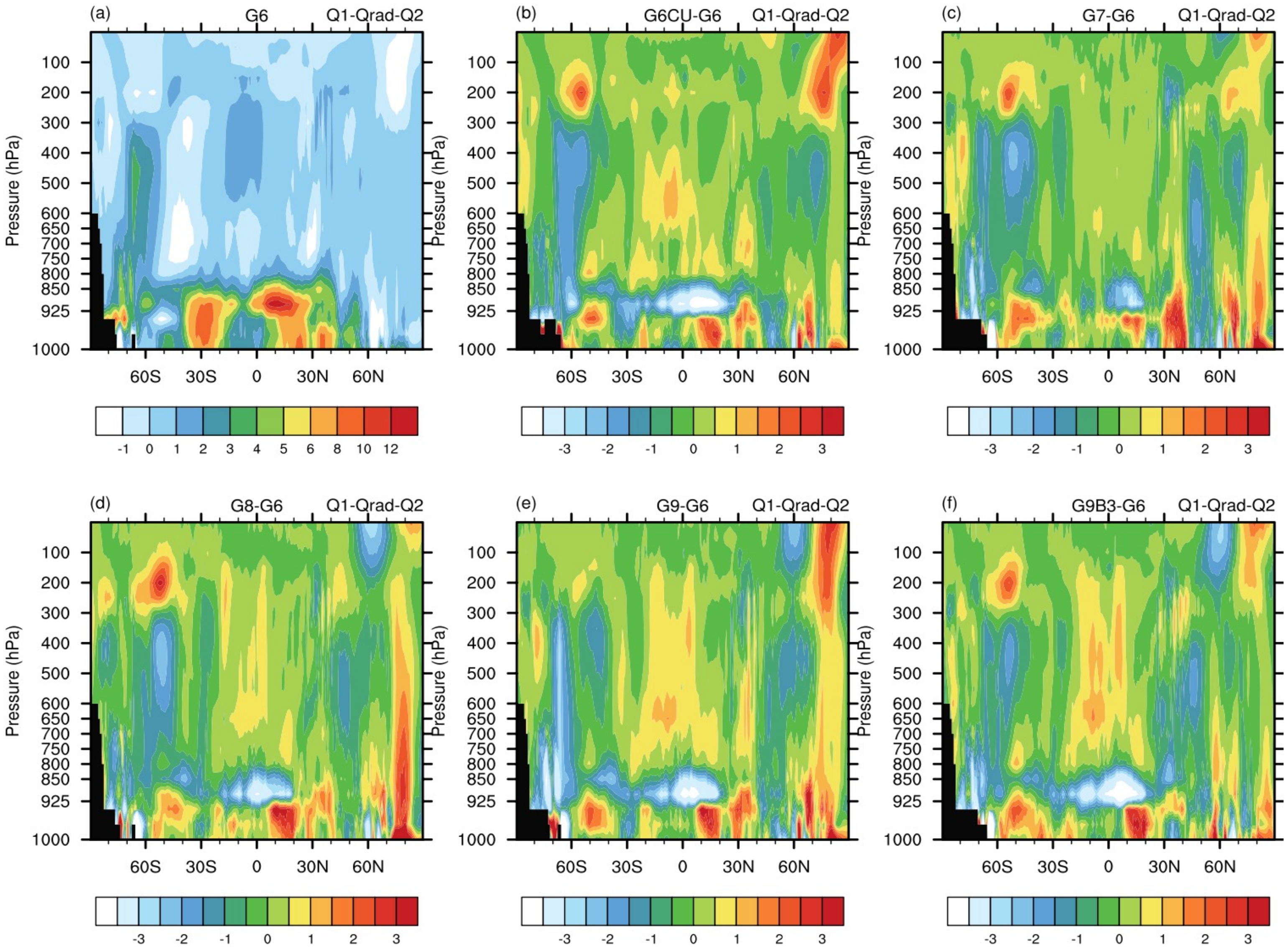


- Much more cloud water generation in the absence of parameterized convection for coarse resolutions (overly strong grid-scale adjustment to stabilize the model atmosphere)
- Cloud ice/LWCF insensitive across resolution (likely due to microphysics formulation)



- 5 km explicit-convection and 120-km parameterized-convection have more similarities than other runs in terms of large-scale features

Interaction between cumulus ensemble and large-scale flow



$$\frac{Q_1}{c_p} = \frac{\partial T}{\partial t} + \boldsymbol{V} \cdot \boldsymbol{\nabla} T - \omega \left(\frac{RT}{c_p p} - \frac{\partial T}{\partial p} \right),$$

$$\frac{Q_2}{c_p} = -\frac{L \left(\frac{\partial q}{\partial t} + \boldsymbol{V} \cdot \boldsymbol{\nabla} q + \omega \frac{\partial q}{\partial p} \right)}{c_p},$$

- Residual method, sub-resolving scale heating/drying

- Eddy activities show that the bulk effect of finely resolved model convection of GSRM on the large-scale flow corresponds to that produced by parameterized convection exerted directly on a coarse-resolution model

Summary

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● GRIST nonhydrostatic model exhibits reasonable resolution sensitivity across ~100 km- ~a few km resolutions, in the absence of parameterized convection
● Fine-scale features become incrementally improved as the resolution is refined (e.g., KE spectra; rainfall frequency-intensity spectra)
● Large-scale features of 5-km explicit-convection model overall converge to that of 120-km coarse-resolution parameterized-convection model
● The interaction between "cumulus ensemble" and large-scale flow as quantified by Q1-Q2-Qrad shows similarity between GSRM and parameterized-convection coarse-resolution model
● Switching off cumulus parameterization at too coarse resolution (e.g., 120 km) leads to overly strong responses of microphysics and associated condensational drying/heating (a direct response of the MP scheme)
● Cloud ice and LWCF shows insensitivity to resolution (model-specific issue)

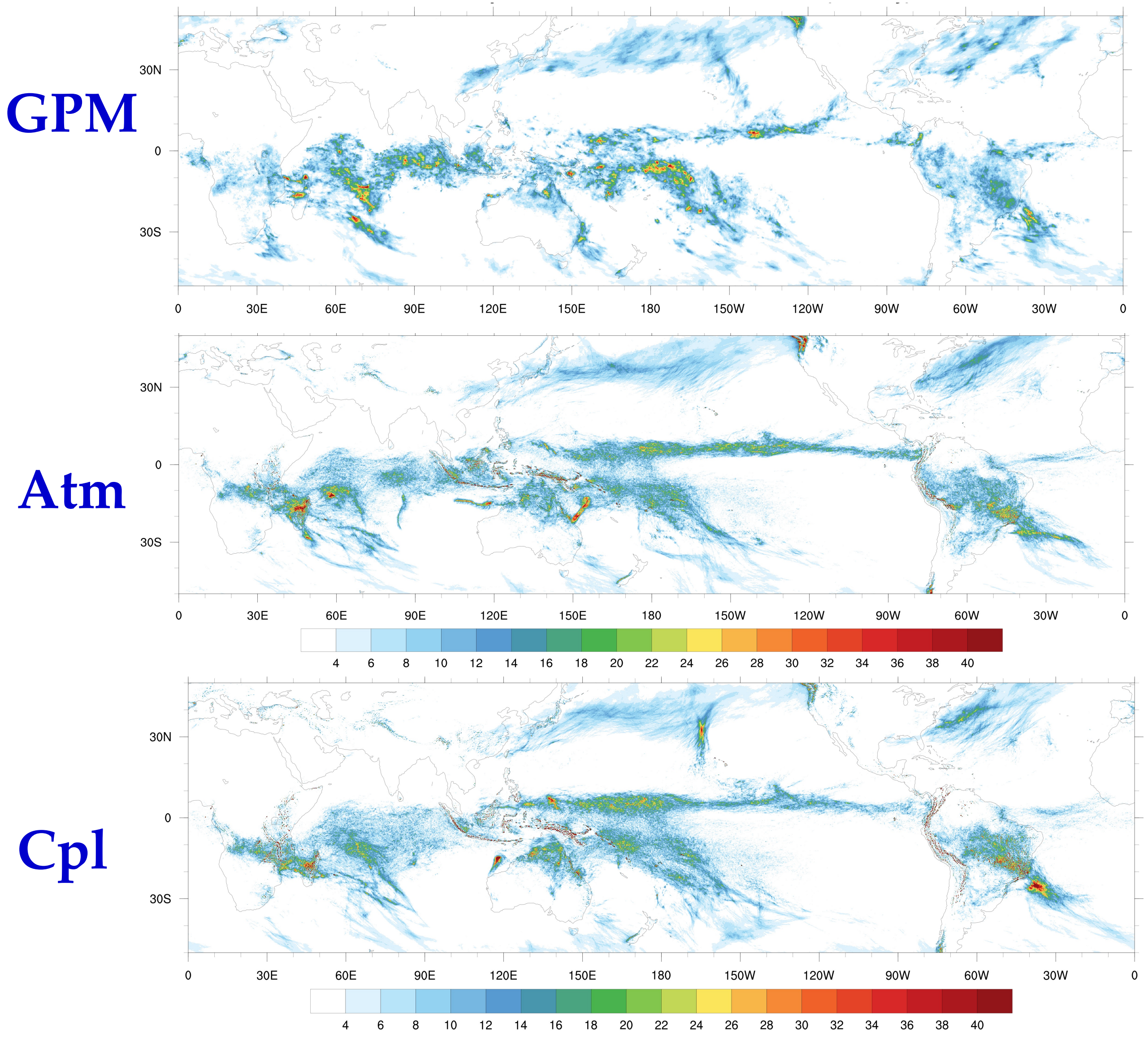
References:

1. Zhang Y, Yu R, Li J et al (2021) AMIP Simulations of a Global Model for Unified Weather-Climate Forecast: Understanding Precipitation Characteristics and Sensitivity Over East Asia. Journal of Advances in Modeling Earth Systems 13 (11):e2021MS002592. https://doi.org/10.1029/2021MS002592

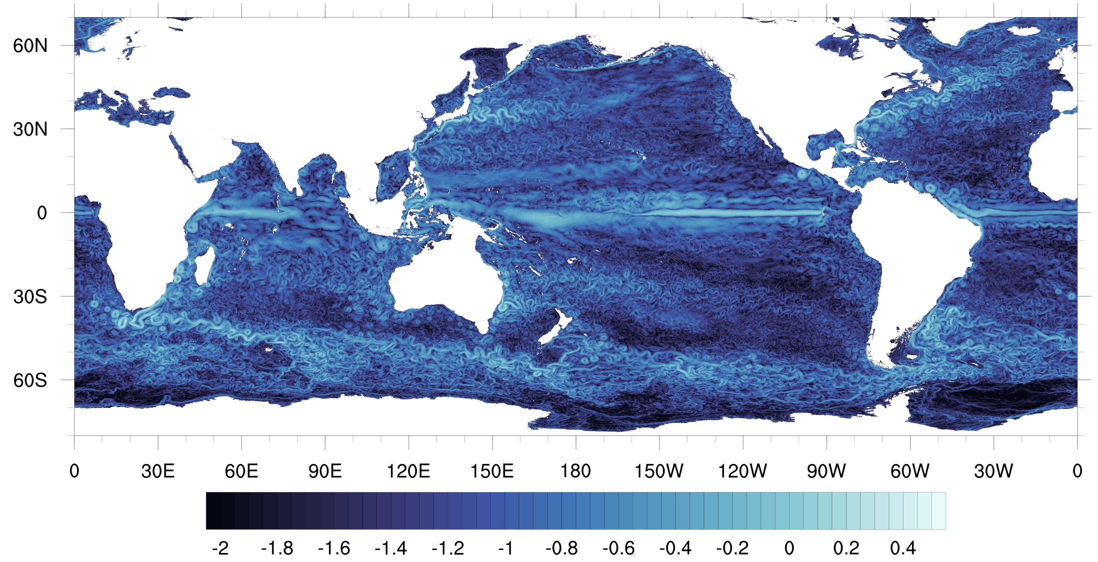
2. Zhang Y, Li X, Liu Z et al (2022) Resolution Sensitivity of the GRIST Nonhydrostatic Model From 120 to 5 km (3.75 km) During the DYAMOND Winter. Earth and Space Science 9 (9):e2022EA002401. https://doi.org/10.1029/2022EA002401

Ocean-Atmosphere coupled simulation

Mean precipitation amount



100m-depth flow speed



- An ocean-atmosphere coupled simulation based on GRIST-GSRM and MOM6 has been established and was also subject to the DYAMOND winter protocol (5km; from Dr. Xinyao Rong)

- The atmosphere simulation is overall consistent between single and coupled simulations (e.g., rainfall)

Future work and plan

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- **GSRM modeling and data**

  Intercomparison of regional features with variable-resolution simulation

  Leverage GSRM data for ML-based model physics development

- **The 2nd–round model development**

  GRIST-LAM

  Physics and LSM improvement

  Mixed precision

  Heterogeneous porting and acceleration

- **DA and operational workflow**

Thank you.

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