DEPENDENCE OF DEEP CONVECTION SCHEMES ON HORIZONTAL GRID-SPACING IN MPAS: DIFFERENCE IN FORMULATION AND IMPACT ON FORECASTS

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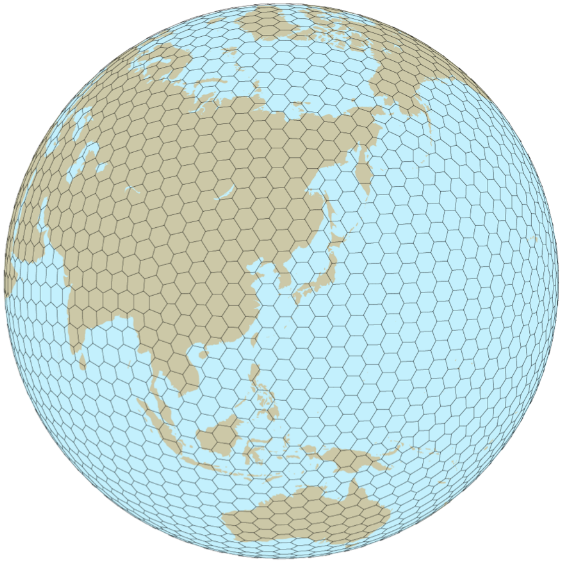
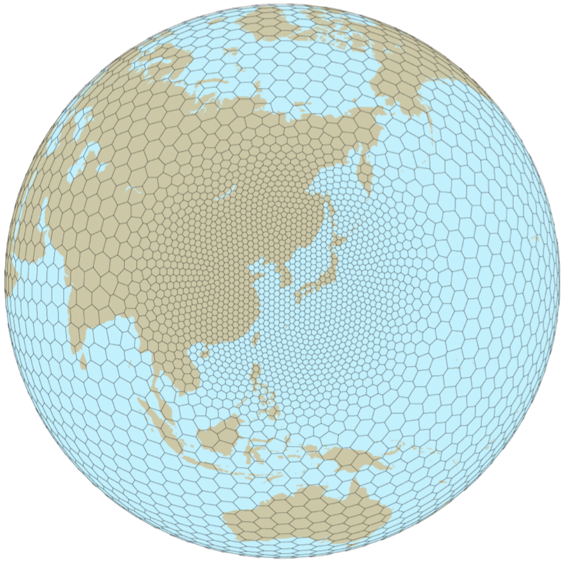
OUTLINE

1. The Model for Prediction Across Scales (MPAS).
2. Contrasting the Grell-Freitas (GF) versus Multi-Scale Kain-Fritsch (MSKF) convective parameterizations.
3. Impact on forecasts using a variable-resolution mesh in MPAS.
4. Upscaling effects.
5. Summary.

MODEL FOR PREDICTION ACROSS SCALES (MPAS)



Global uniform-resolution mesh



Global variable-resolution mesh

- Horizontal discretization is based on unstructured centroidal Voronoi meshes with selective grid-refinement.
- Horizontal discretization is comprised of mostly hexagons, some pentagons, and a few triangles and 7-sided cells.

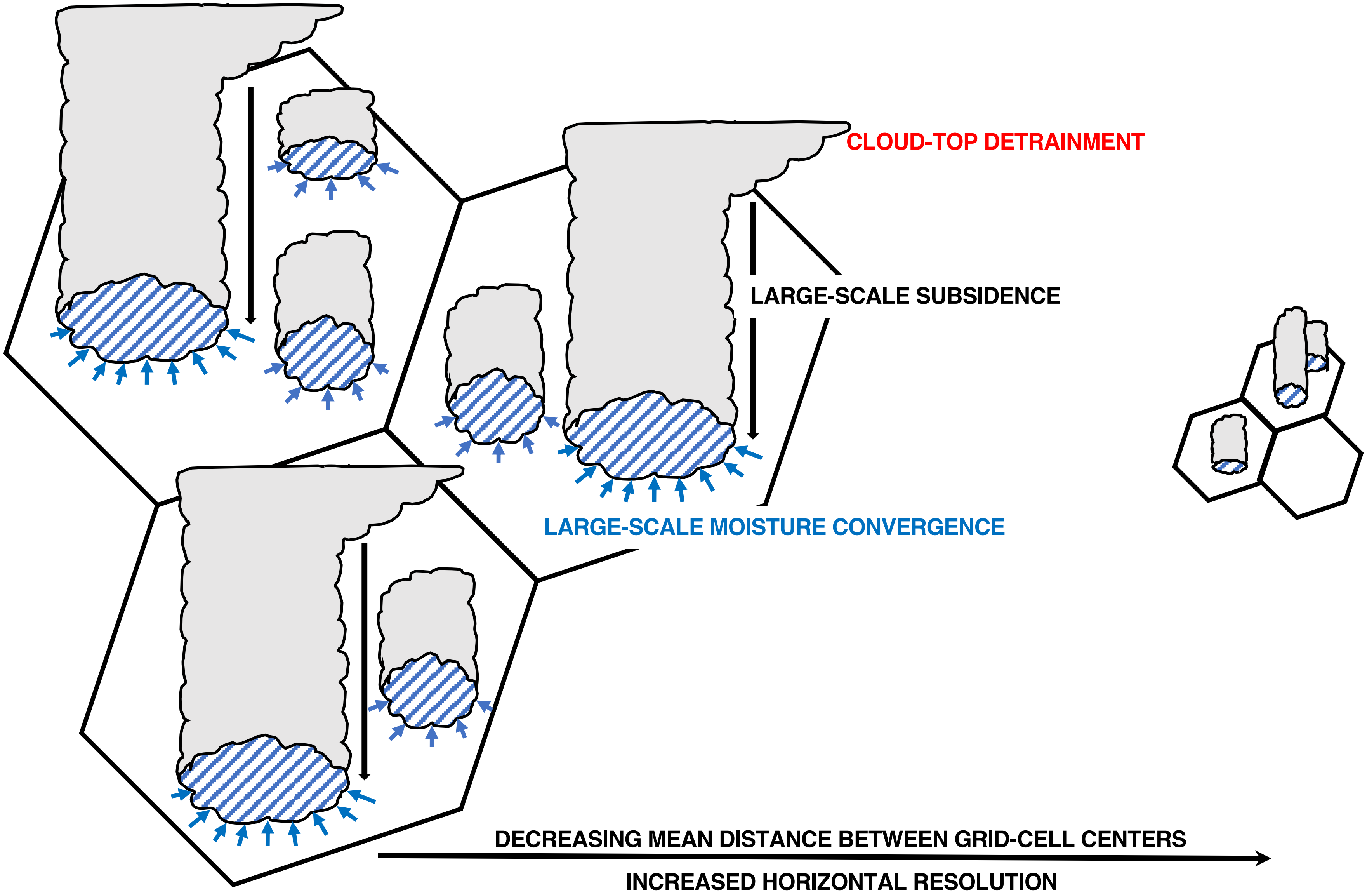
ADVANTAGES OF USING MESH REFINEMENT

- We avoid issues related to updating the lateral boundaries of the regional domain, or issues related to nesting and nudging.
- We have two-way feedbacks between the coarser and refined regions.

CHALLENGES

- **COST**: Currently, the time-step is the same in the coarse and refined regions, and is the one needed over the refined area of the global mesh.
- We need to *have scale-aware* physics schemes, or physics that can be used from hydrostatic down to nonhydrostatic scales, particularly deep convection and cloud microphysics.

ADAPTED FROM ARAKAWA AND SCHUBERT (Fig 1; 1974) FOR MPAS MESHES



CLOUD-TOP DETRAINMENT

LARGE-SCALE SUBSIDENCE

LARGE-SCALE MOISTURE CONVERGENCE

DECREASING MEAN DISTANCE BETWEEN GRID-CELL CENTERS

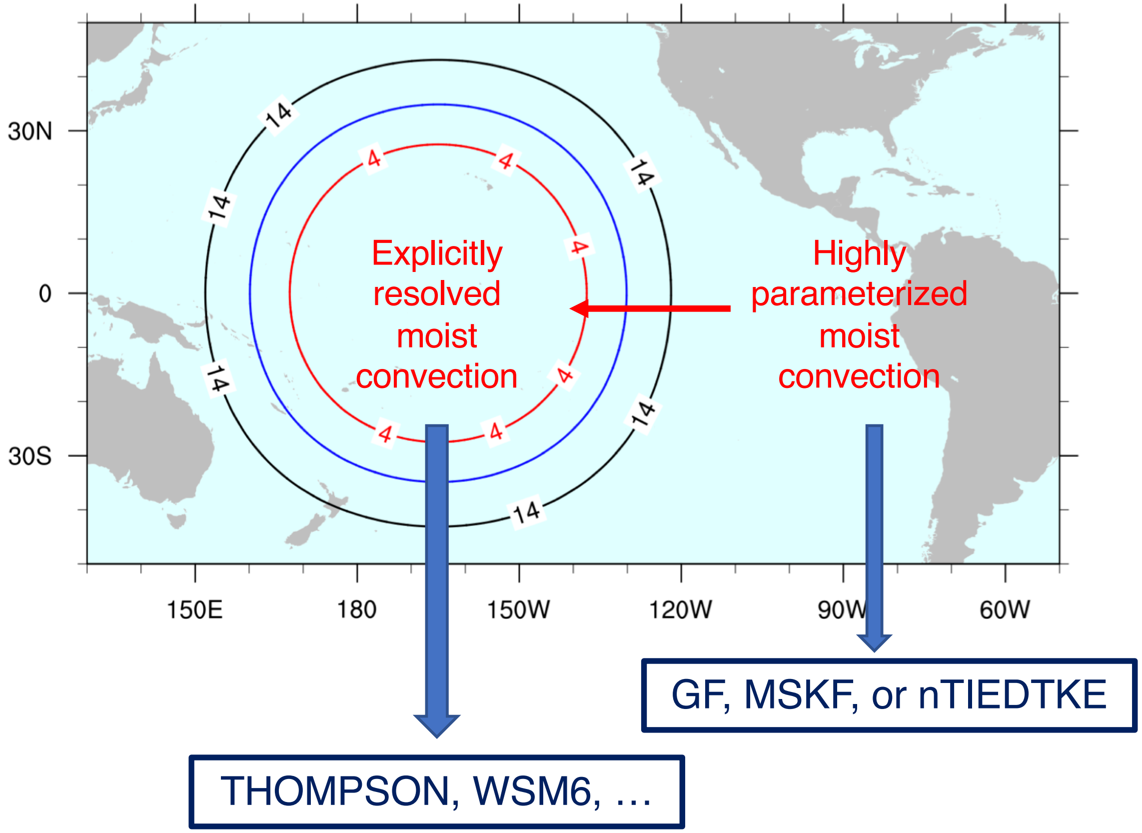
INCREASED HORIZONTAL RESOLUTION

SCALE-AWARE CPs AND VARIABLE-RESOLUTION MESHES IN MPAS

➢ Moist physics (subgrid-scale convection and grid-scale cloud microphysics) are responsible for restoring atmospheric stability.

➢ The effect of a scale-aware CP of deep convection is to gradually hand over restoring atmospheric stability to the grid-scale cloud microphysics as horizontal resolution increases. This occurs along the transition zone between the coarse and refined areas of the global variable-resolution mesh.

15-3 km variable-resolution mesh centered over the Pacific Ocean



Explicitly resolved moist convection

Highly parameterized moist convection

GF, MSKF, or nTIEDTKE

THOMPSON, WSM6, …

TWO APPROACHES TO MODIFY NON SCALE-AWARE TO SCALE-AWARE CPS

GRELL FREITAS (GF)

Grell and Freitas 2014; Fowler et al. 2016; Freitas et al. 2018

- Follows Arakawa and Wu (2013) to scale the cloud base mass flux as a function of the area of the convective updraft (σ).

$$\boxed{M_{Bsca} = (1 - \sigma)^2 \, M_B}$$

M_{Bsca}: Scaled mass flux.

M_B: Original mass flux.

- σ is simply parameterized as:

$$\boxed{\sigma = \frac{\pi R^2}{A} \text{ and } R = \frac{0.2}{\varepsilon}}$$

Simpson and Wiggert (1969)

A: Area of updraft.

R: Half-width radius.

ε: entrainment rate.

MULTI-SCALE KAIN-FRITSCH (MSKF)

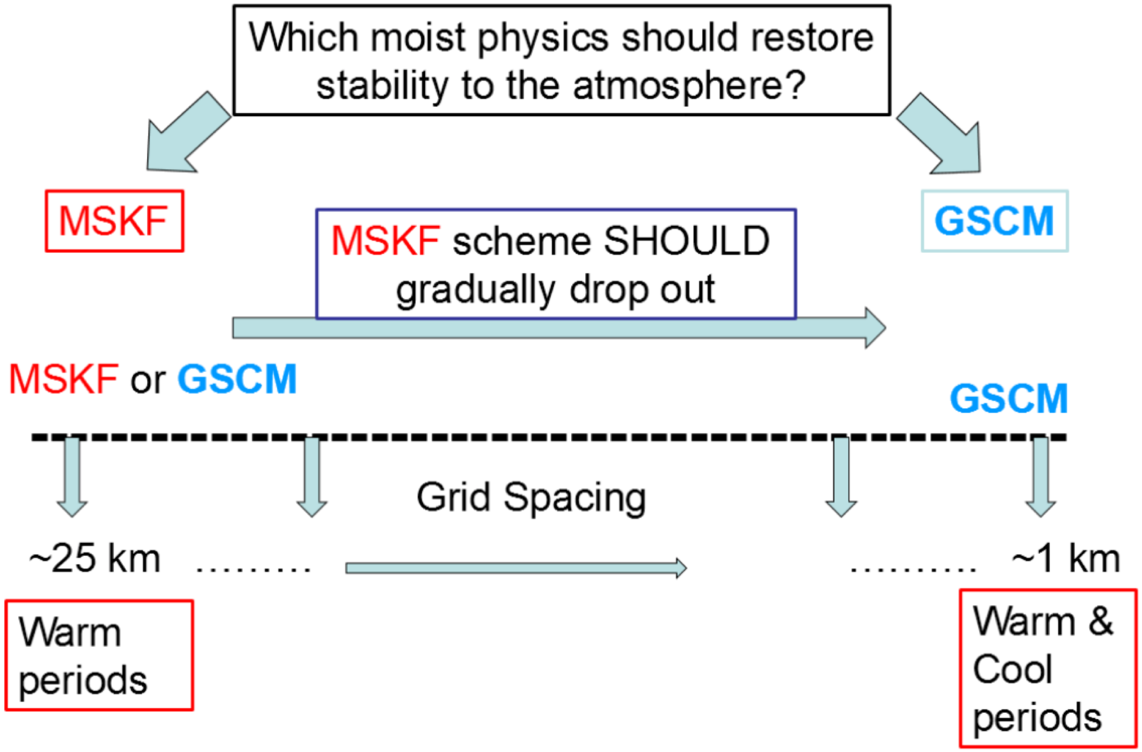
Zheng et al. 2016; Glotfelty et al. 2019

- Unlike GF, MSKF does not compute σ. Instead, MSKF choose to modify convection parameters used in the original Kain-Fritsch (Kain, 2004) CP.
- MSKF scales the convective time-scale.
- MSKF scales the stabilization capacity (i.e. CAPE).

MULTI-SCALE TIEDTKE (nTIEDTKE)

- Unlike GF, and as MSKF, nTIEDTKE does not compute σ. Instead, nTIEDTKE choose to modify convection parameters used in the original Tiedtke (1989) CP.
- nTIEDTKE scales the convective time-scale.
- nTIEDTKE scales the coefficient for conversion from cloud water to rain water.

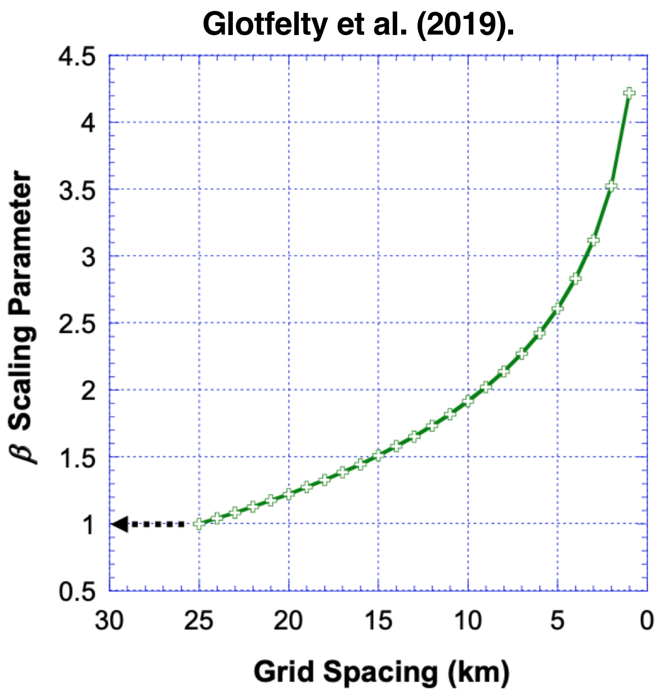
THE MULTI-SCALE KAIN-FRITSCH (MSKF) CONVECTIVE PARAMETERIZATION



Schematic for scale dependency of subgrid scale (MSKF) and grid scale cloud microphysical (GSCM) schemes. MSKF=Multi-Scale Kain-Fritsch scheme; GSCM=Grid scale Cloud Microphysics scheme.

Glotfelty et al. (2019).

MSKF (continued): The scaling parameter (β)



Variation of β parameter used in the MSK scheme (Zheng et al., 2016).

- The Kain-Fritsch (KF; Kain 2004) CP was designed for a horizontal resolution of about 25 km.
- MSKF uses a single scaling factor (β) to modify the basic KF convection parameters:
  1. The convective adjustment time-scale (τ).
  2. The stabilization capacity (A_e).

$$\beta = 1 + ln\left\{\frac{25}{\Delta x}\right\}$$

Δx is the horizontal grid-resolution (km).

MSKF (continued): DYNAMIC CONVECTIVE ADJUSTMENT TIME-SCALE (τ)

- τ is the time needed to restore stability to the atmosphere by removing convective instabilities.
- In the original KF, τ is set to 3600s for deep convection and 2400s for shallow convection.
- In MSKF, τ is modified following Bechtold et al. (2008):

$$\boxed{\tau = \frac{H}{W_{CL}}\beta = \frac{H}{(\delta\ M_b\ A_e)^{1/3}}\beta}$$

- *β is the scale factor, δ is a parameter varying between 0.75 and 1.2.*
- *H is the depth of the convective cloud.*
- *W_{CL} is the cloud-averaged vertical velocity for shallow or deep cloud.*
- *M_b is the cloud base mass flux; A_e is the convective available potential energy.*

MSKF (continued): DYNAMIC CONVECTIVE ADJUSTMENT TIME-SCALE (τ)

- MSKF further expresses M_b as a function of the sub-cloud layer velocity (W_{sb}), or:

$$\boxed{\tau = \frac{H}{(\ \delta\ \alpha W_{sb}\ A_e)^{1/3}}\beta}$$

- *α is the non-dimensional Tokioka parameter (Tokioka, 1988).*
- *W_{SB} is the sub-cloud layer velocity, expressed as:*

$$W_{sb} = \sqrt{3.8\,u_*^2 + 0.22 W_c^{*2} + 1.9\,u_*^2 \left(-Z_{LCL}/L\right)^{2/3}}$$

- *u_* is the surface friction velocity.*
- *W^{*2}_c is the convective velocity.*
- *ZLCL is the height of the LCL.*
- *L is the Monin-Obukhov length.*

MSKF (continued): STABILIZATION CAPACITY (SC)

- KF (Kain 2004) restores atmospheric stability by removing about 90% of the total CAPE (A_e):

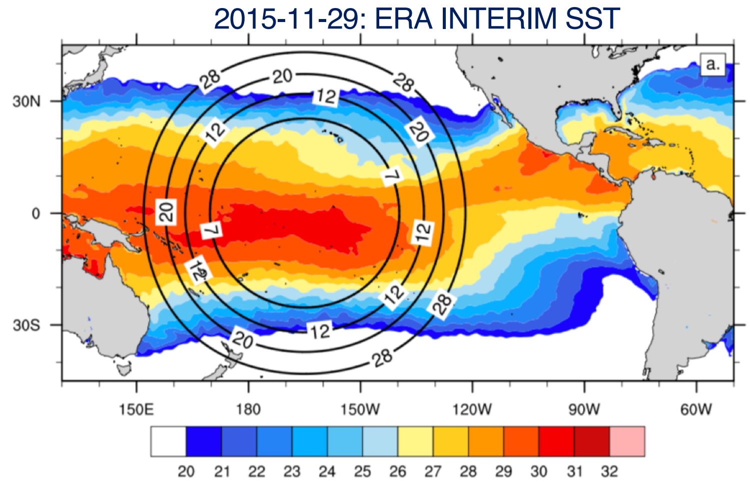
$$\boxed{A_e^r = (1-\gamma)A_e}$$

$\gamma = 0.1$

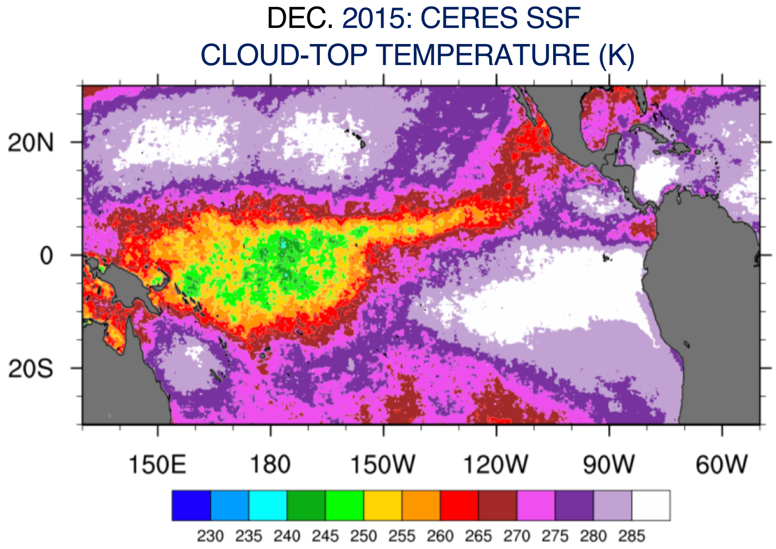
- MSKF gradually hands over restoring atmospheric stability to the grid-scale microphysics by scaling γ as a function of β, or:

$$\boxed{A_e^r = (1-\gamma\beta)A_e}$$

30 km UNIFORM-MESH AND 30-6 km VARIABLE-MESH NUMERICAL EXPERIMENTS



2015-11-29: ERA INTERIM SST

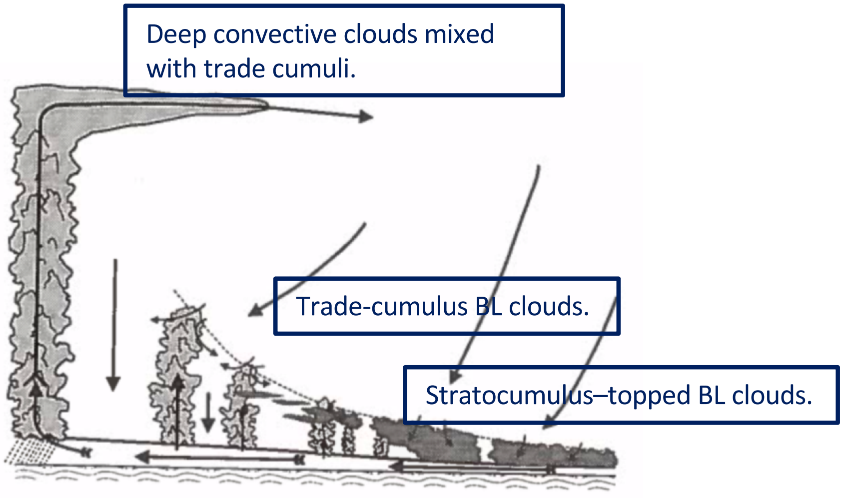


DEC. 2015: CERES SSF
CLOUD-TOP TEMPERATURE (K)

4 30-day experiments for December 2015 with the scale-aware Grell-Freitas (GF) and Multi-Scale Kain Fritsch (MSKF) convection schemes

GFu: 30 km uniform mesh with GF
GFv: 30-6 km variable mesh with GF

KFu: 30 km uniform mesh with MSKF
KFv: 30-6 km variable mesh with MSKF



Deep convective clouds mixed with trade cumuli.

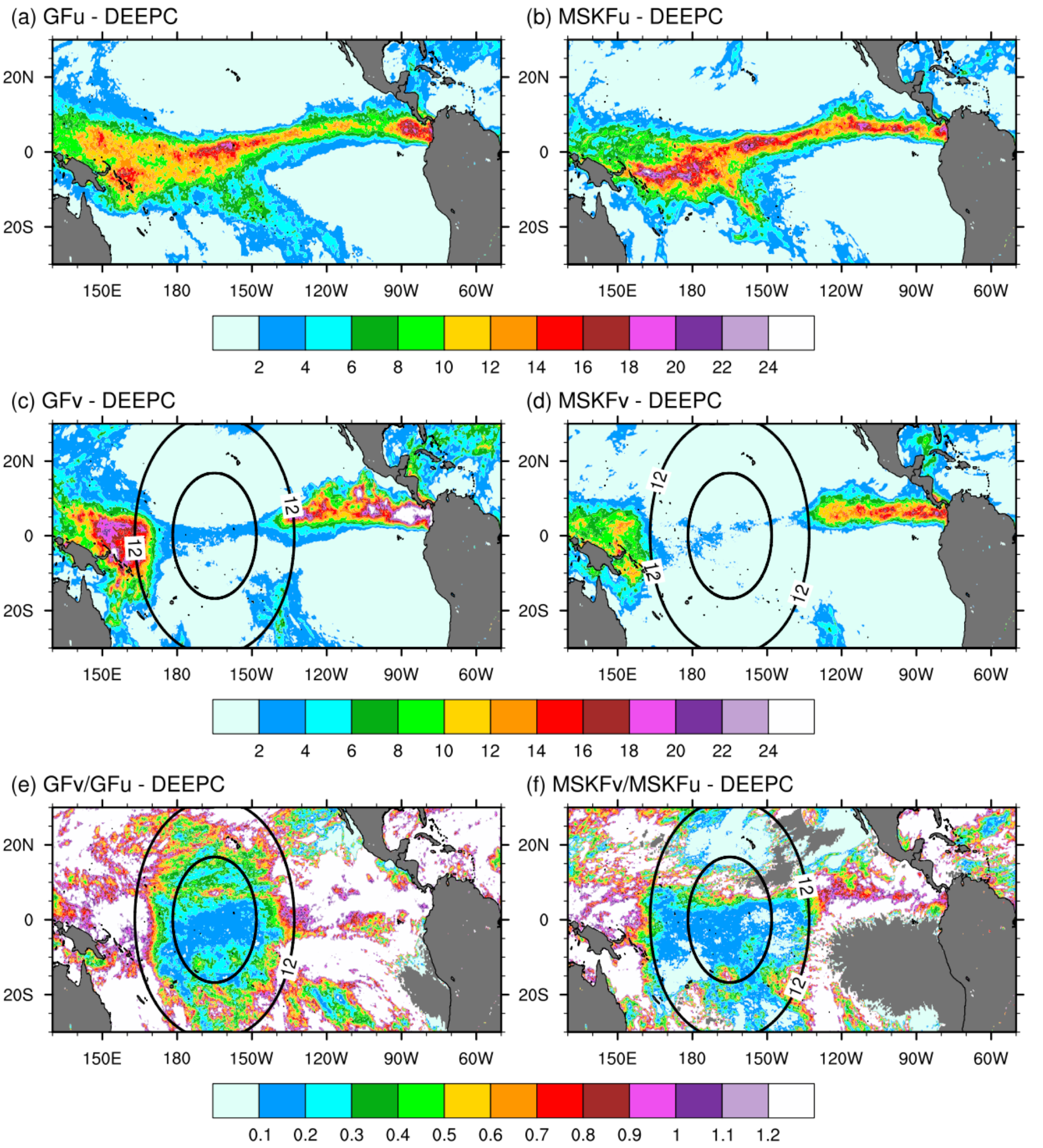
Trade-cumulus BL clouds.

Stratocumulus–topped BL clouds.

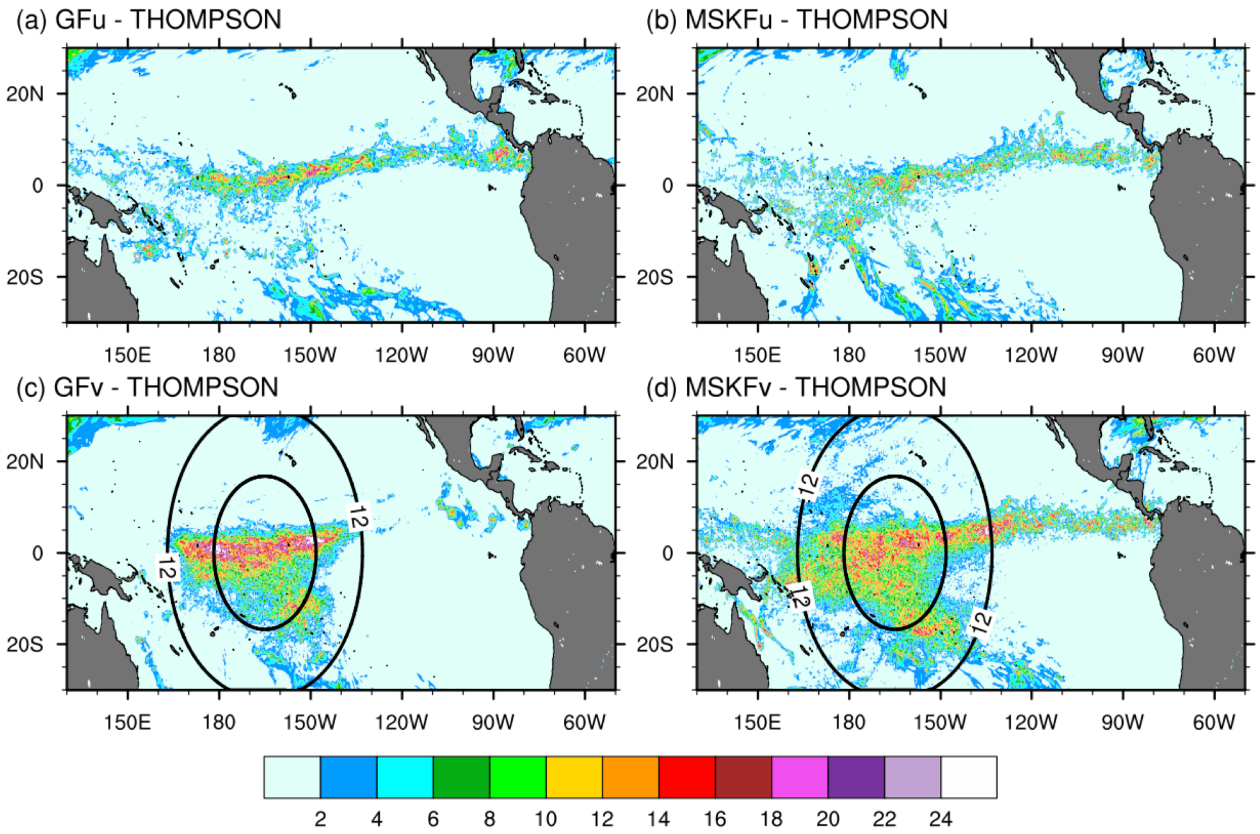
Fig. 14.7 Structure of the tropical atmosphere, showing the various regimes, approximately as a function of sea surface temperature.

From Atmospheric Convection, K. Emmanuel, 1994

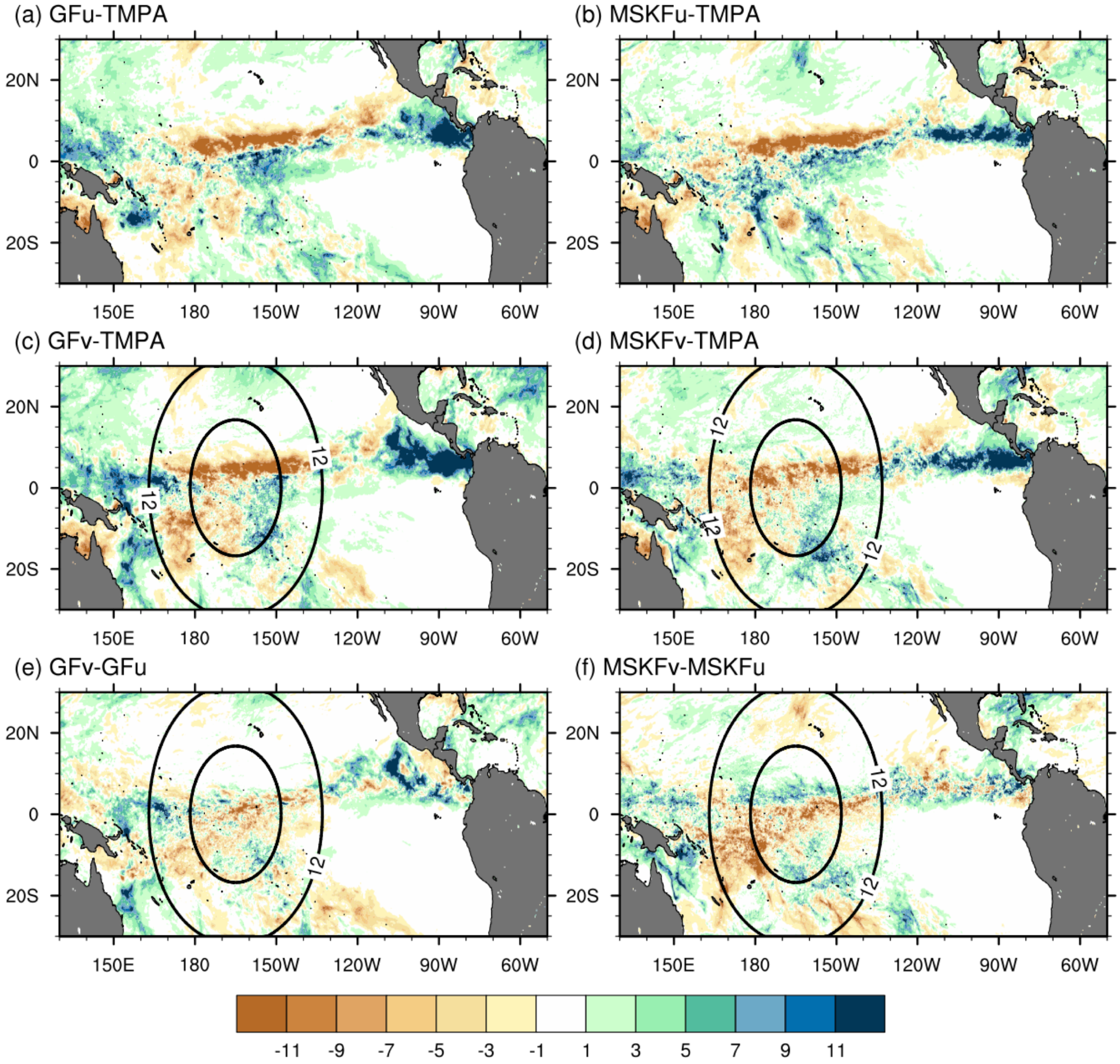
CONVECTIVE PRECIPITATION RATE (mm day^{-1})



GRID-SCALE PRECIPITATION RATE (mm day^{-1})



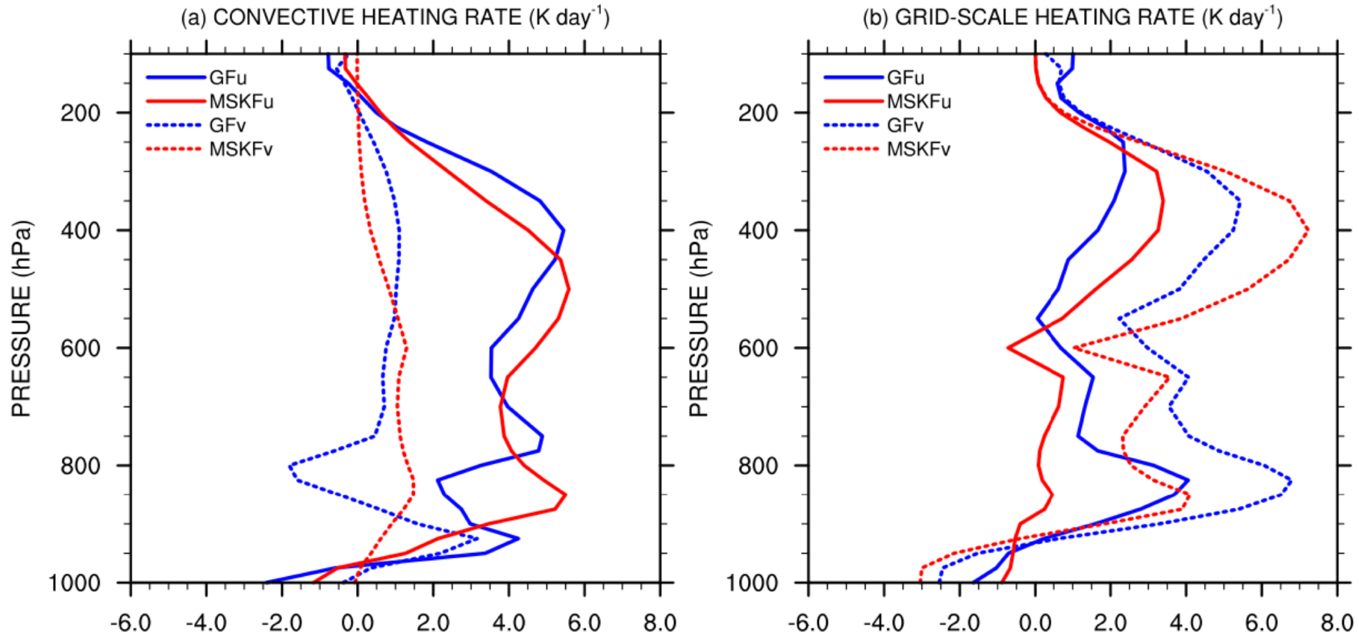
TOTAL PRECIPITATION RATE DIFFERENCE (mm day^{-1})



mm day^{-1}	CP	LSP	TOT
GFu	10.0	6.1	16.1
GFv	1.9	12.1	14.0
MSKFu	10.9	4.9	15.8
MSKFv	1.7	11.8	13.5
TMPA			20.7

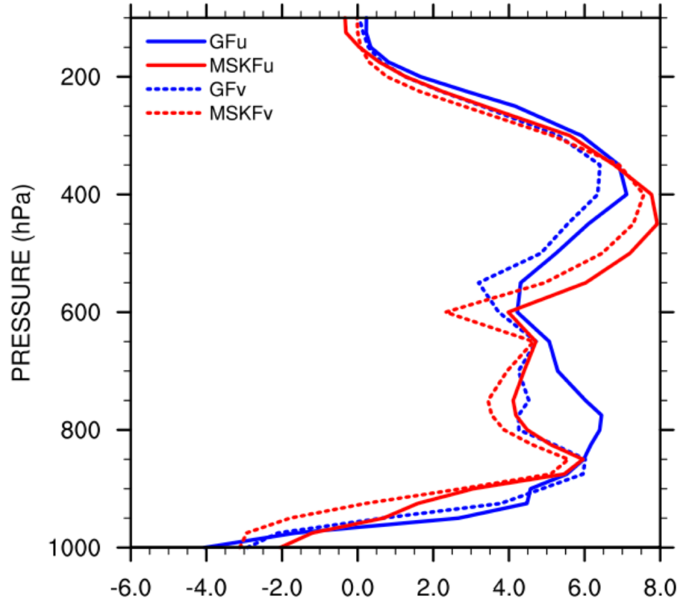
Area-mean convective, grid-scale, and total precipitation rates over refined area of the mesh.

HEATING RATES OVER REFINED MESH (K day^{-1})


(a) CONVECTIVE HEATING RATE (K day^{-1})

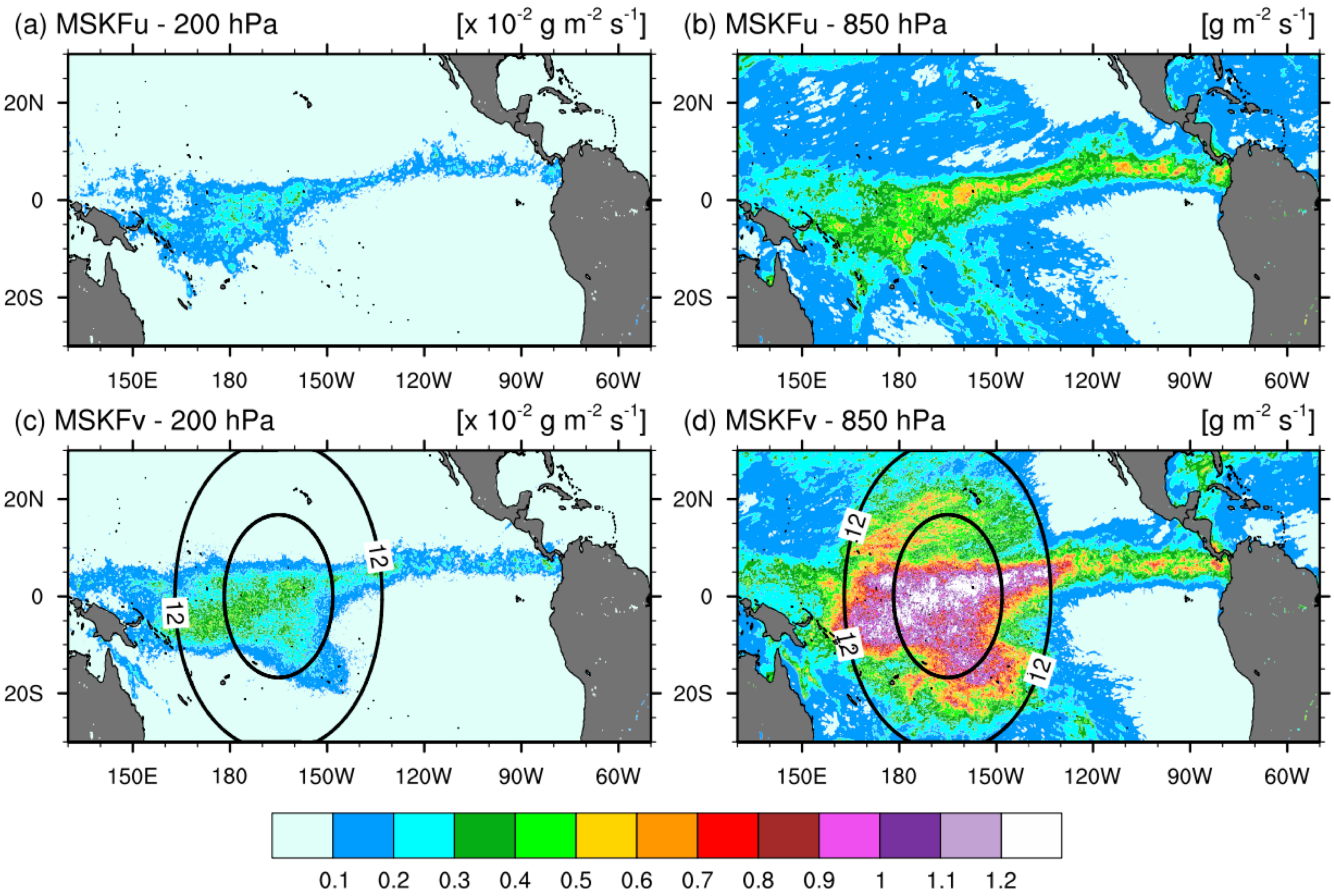
(b) GRID-SCALE HEATING RATE (K day^{-1})

(c) TOTAL HEATING RATE (K day^{-1})

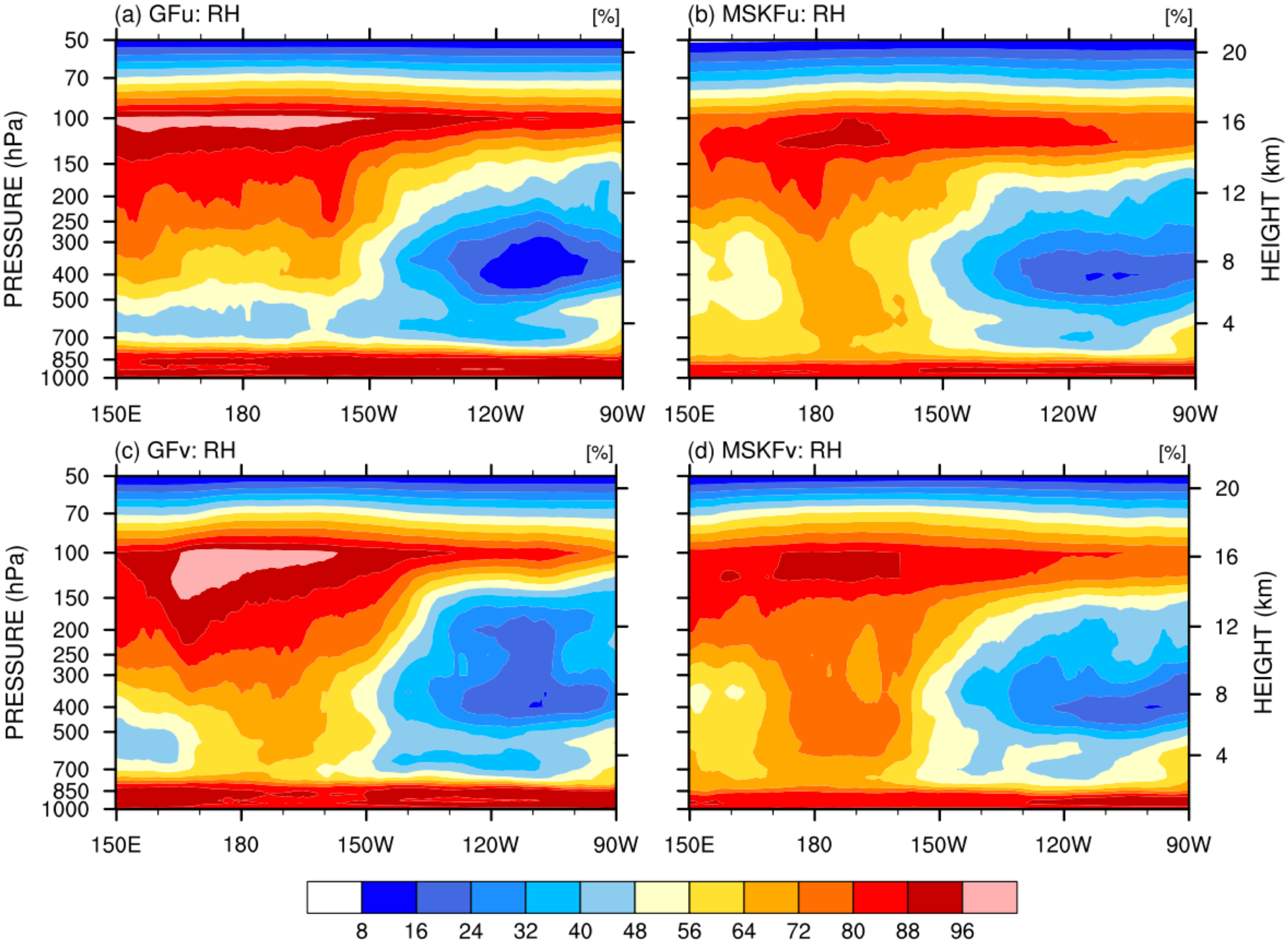


As horizontal resolution increases, GF and MSKF, deep convection gradually converts to precipitating shallow convection.

UPWARD MOISTURE FLUX



RELATIVE HUMIDITY (%)

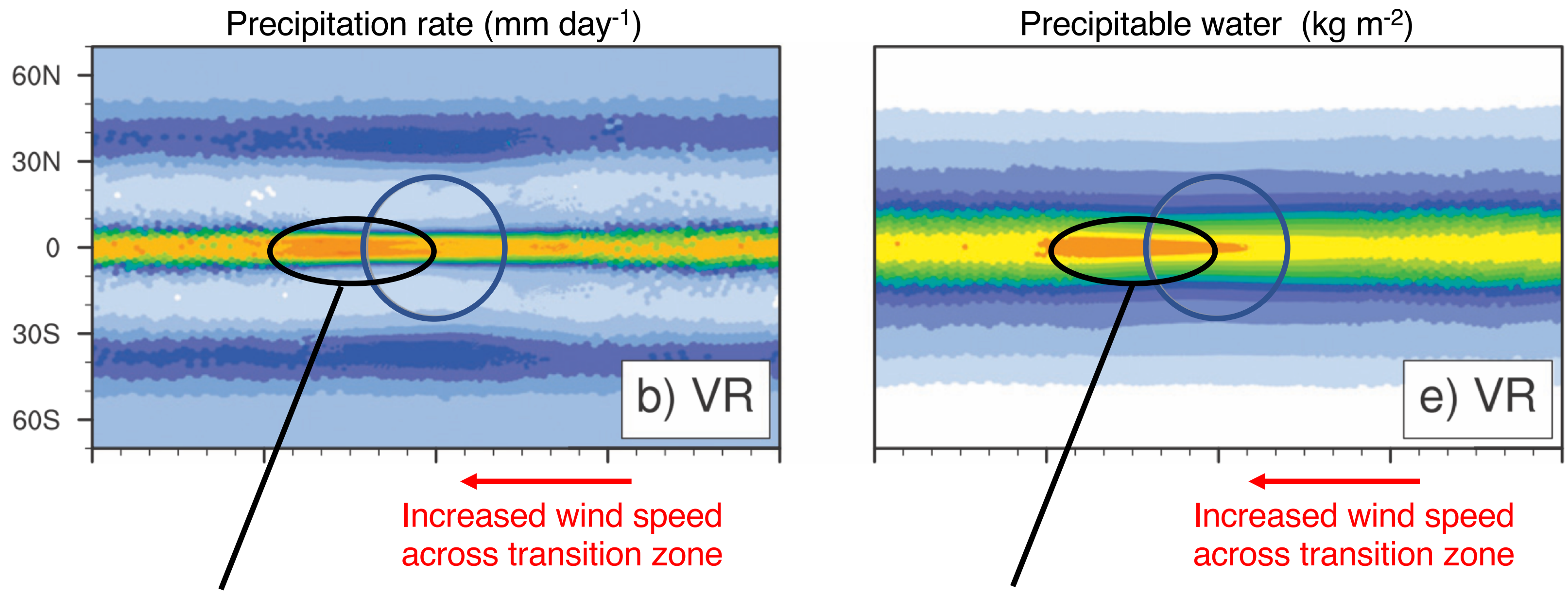


CPs AND VARIABLE-MESHES IN MPAS: UPSCALING EFFECTS

***Upscaling effect**: difference over the coarse area of the mesh between the variable- and uniform-resolution experiments.*

Rauscher et al., 2013

HYDROSTATIC 240-30 km VARIABLE-RESOLUTION MESH



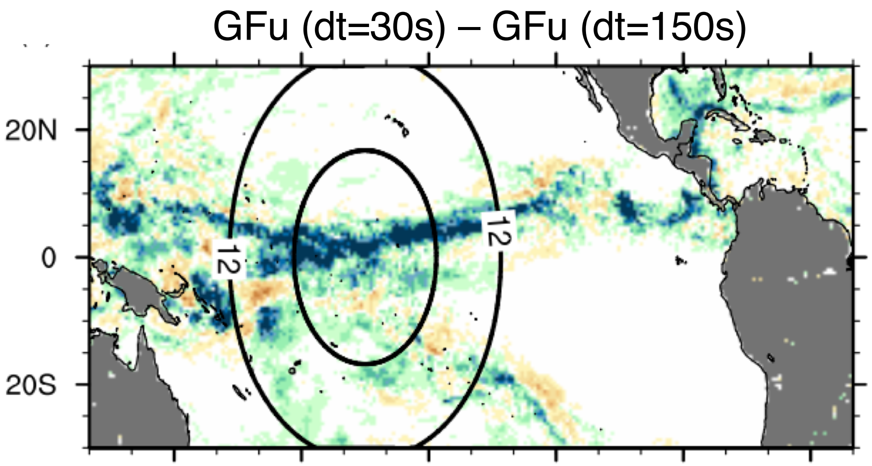
Increased wind speed across transition zone

Increased wind speed across transition zone

Increased precipitation

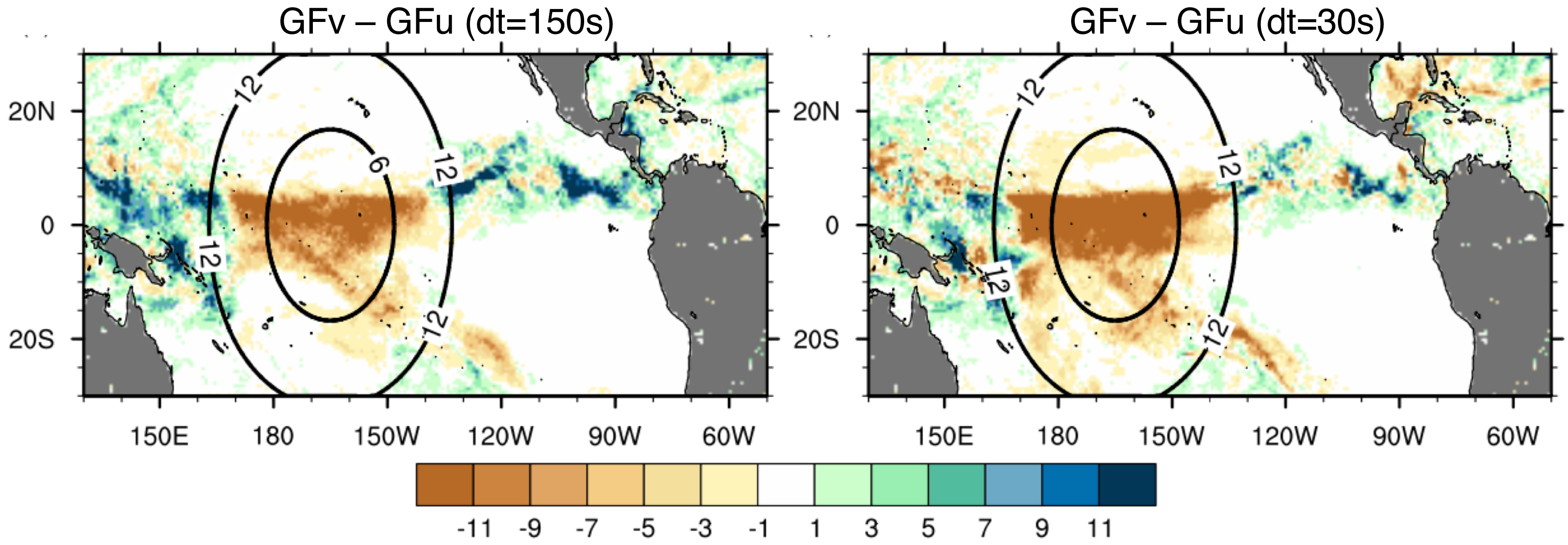
Increased moisture

DEPENDENCE OF GF ON MODEL TIME-STEP



Increased convective precipitation with decreasing time-step.

Upscaling effect:
Increased in convective precipitation remains large regardless of the time-step. Further analysis is needed using GF, MSKF, and nTiedtke.



SUMMARY

- The role of a scale-aware CP using variable-resolution in MPAS is to hand over restoring atmospheric stability from the *subgrid-scale CP* to the grid-scale cloud microphysics scheme as horizontal resolution increases.

- We distinguished between two kinds of scale-aware CP of deep convection:
  - GF which scales the mass flux as a quadratic function of the size of the convective updraft.
  - MSKF (nTiedtke) which scales the convective time-scale and other convective parameters of their non scale-aware counterpart, but without including the size of the convective updraft.

- Over the refined area of the mesh, results show:
  - Decreased (increased) convective (grid-scale) precipitation, transition of a deep CP to a shallow precipitating CP.

- For regional climate applications within a global framework, upscaling effects need to be assessed carefully.

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