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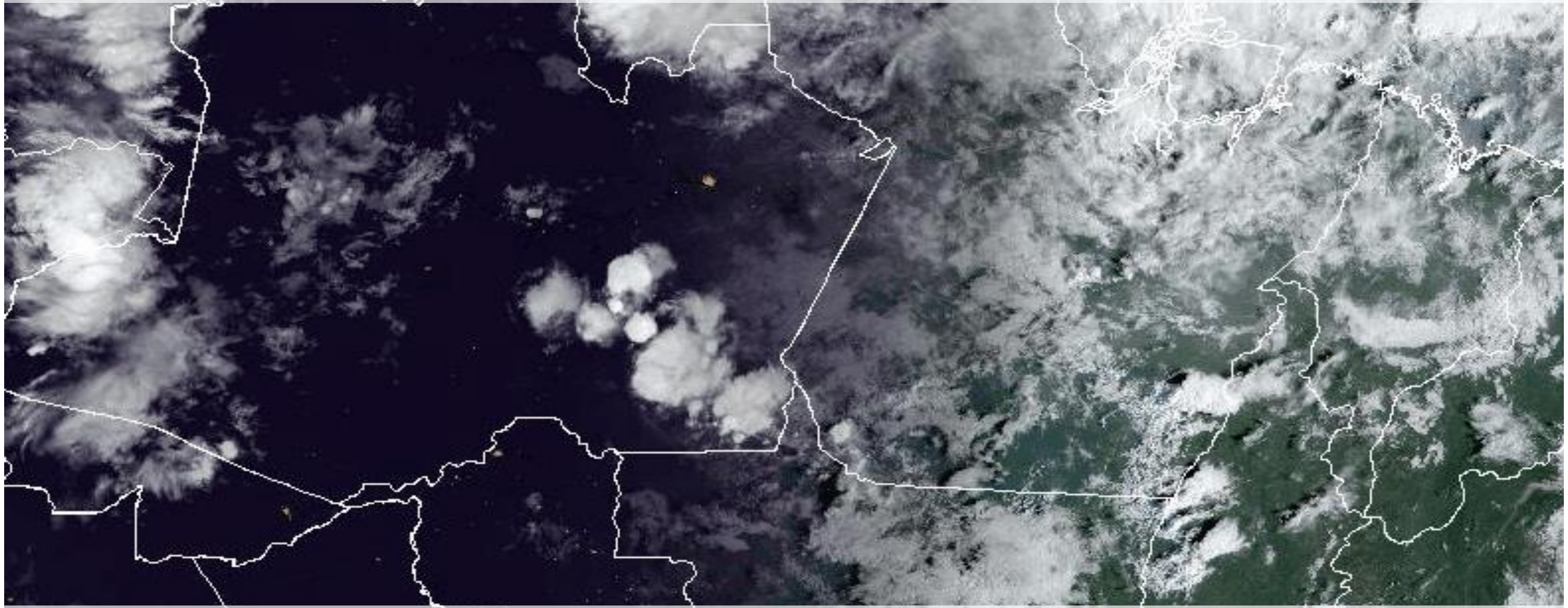
A parameterization for cloud organization and propagation by evaporation-driven cold pool edges



Saulo R. Freitas

with contributions: G. A. Grell, A. Chovert, M.A. Silva Dias, E. Nascimento

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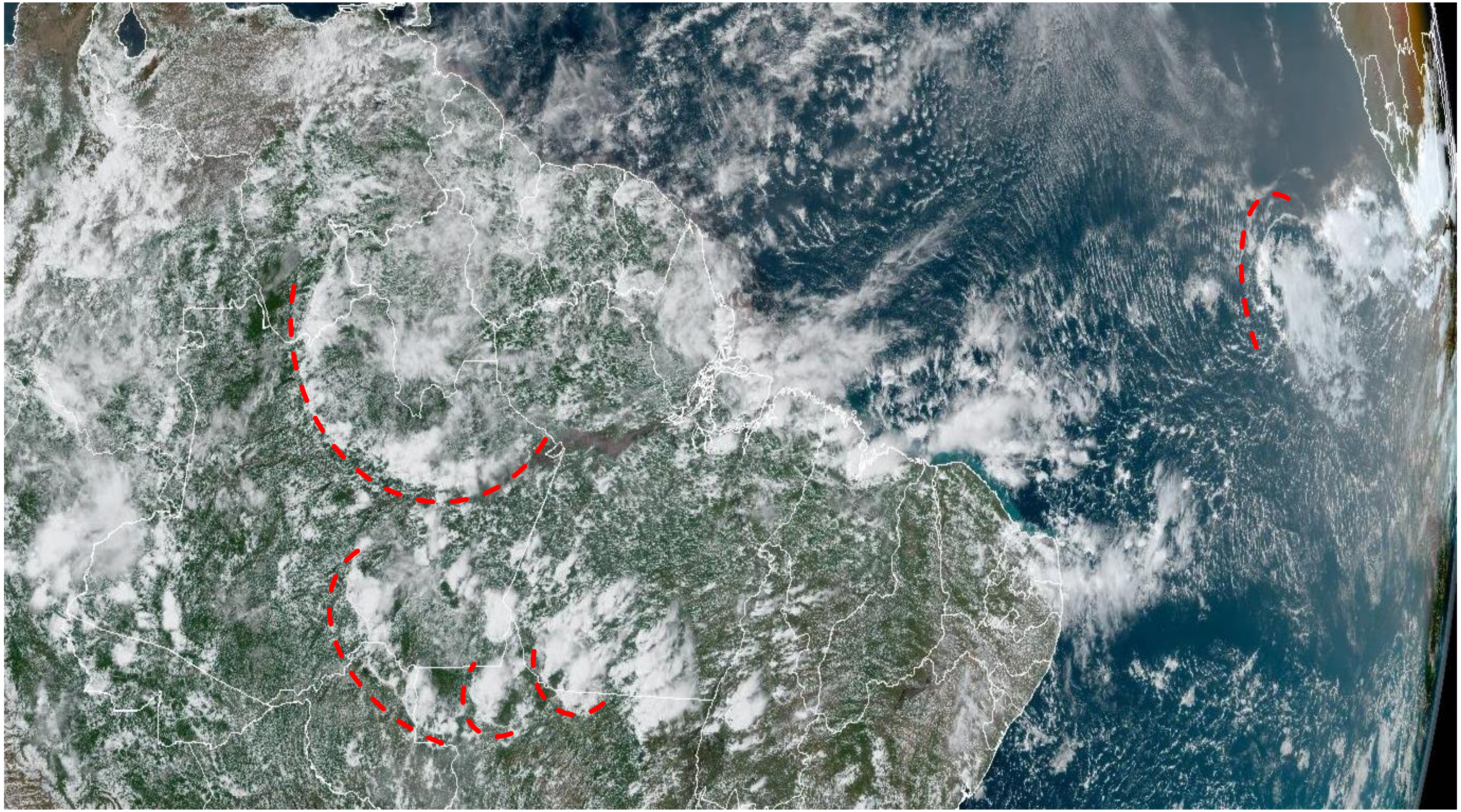
Contents

- Some examples of the phenomena we want to improve its representation in the context of low-resolution (non-convection-allowing/resolving) GRCMs
- Motivation
- CRM simulations to help the parameterization design
- The proposed parameterization
- Applications
- Summary and ways to move forward

Squall lines and associated cold pools over Amazonia



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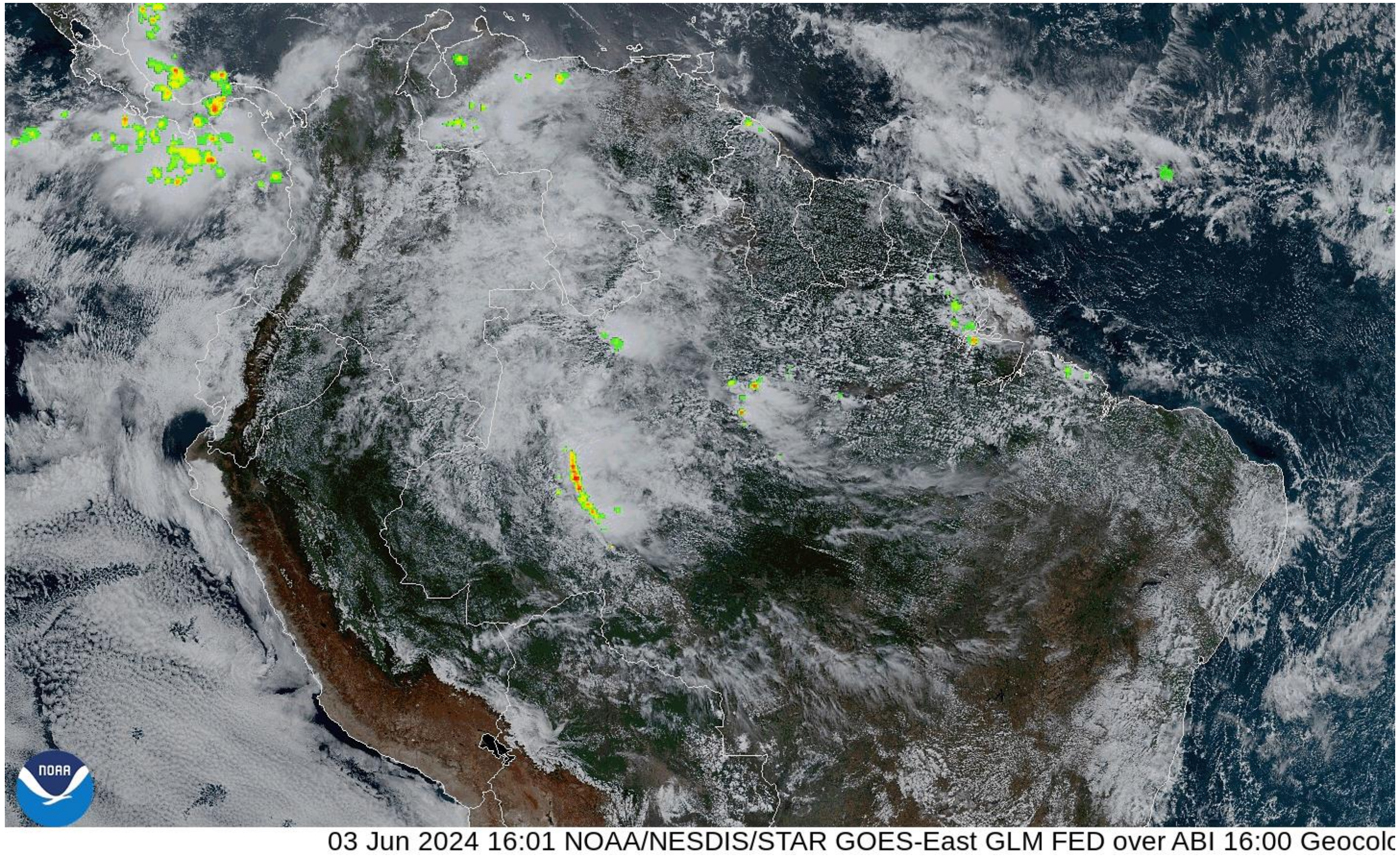
Squall lines over Amazonia and associated lightning flashes



Geostationary Lightning Mapper - Lightning flash extent
over GeoColor - 03 Jun 2024 - 1601 UTC

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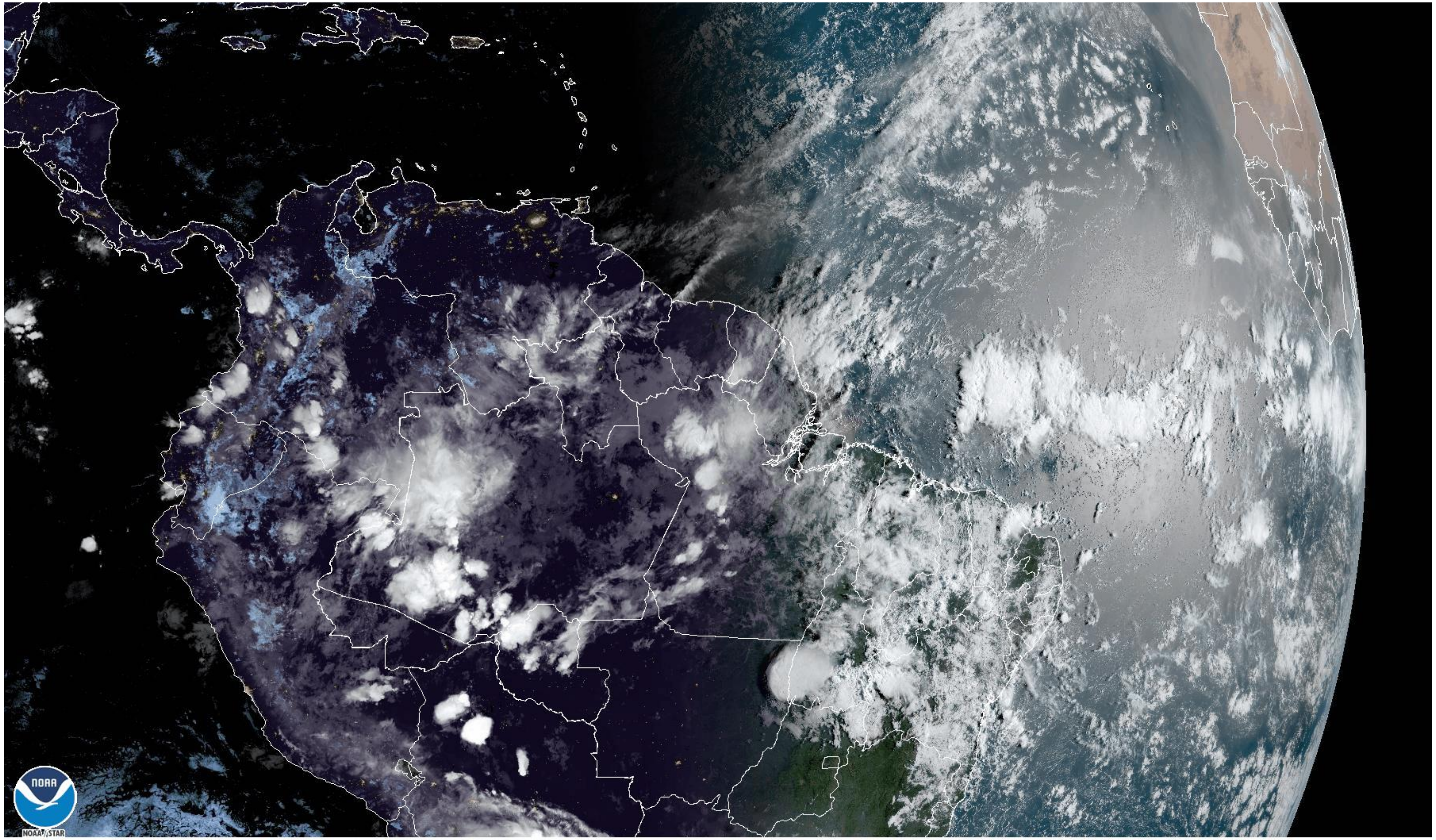
Cold pools over the central part of Brazil



26 Mar 2023 10:20Z - NOAA/NESDIS/STAR - GOES-East - GEOCOLOR Composite - NSA

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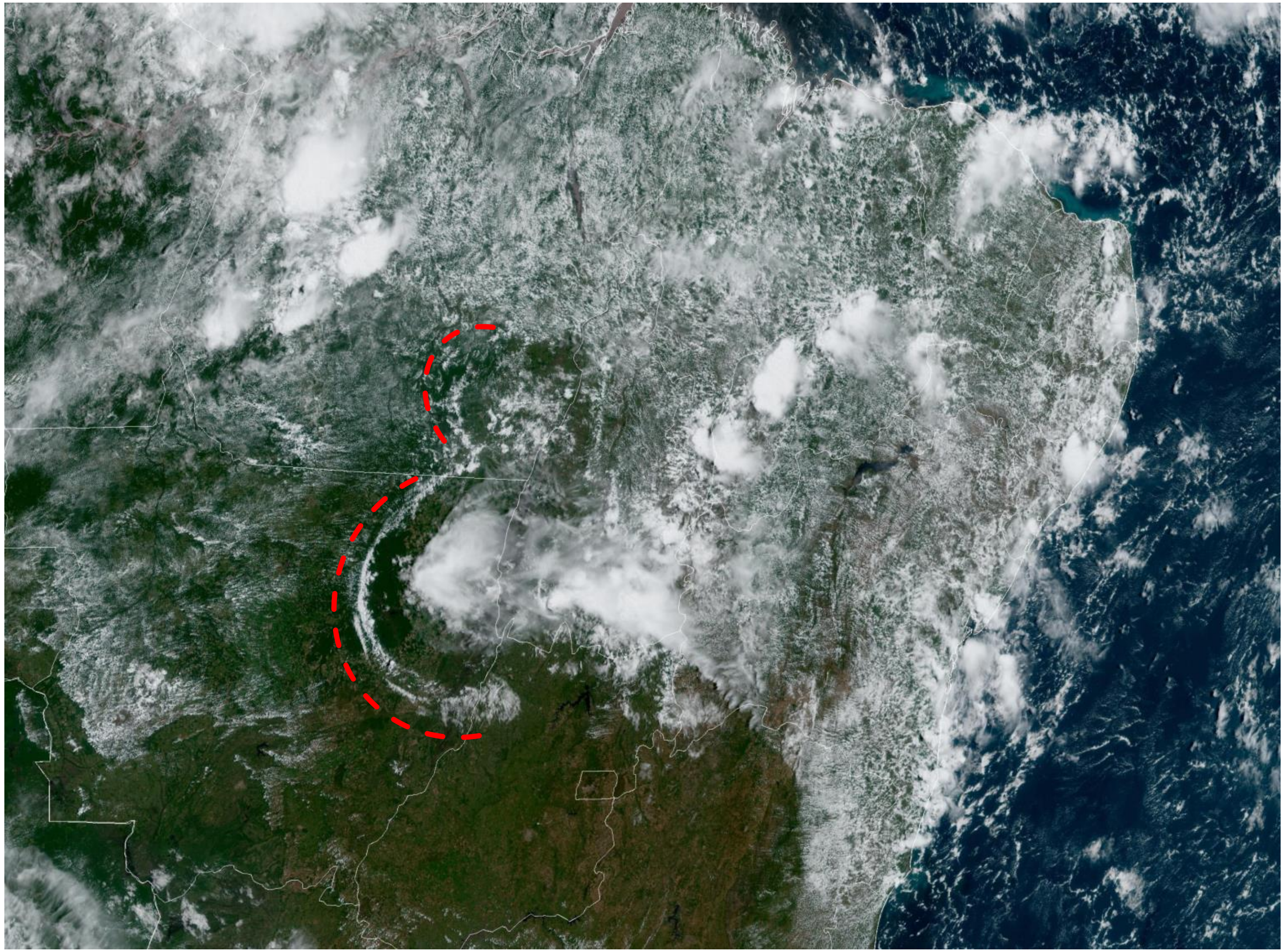

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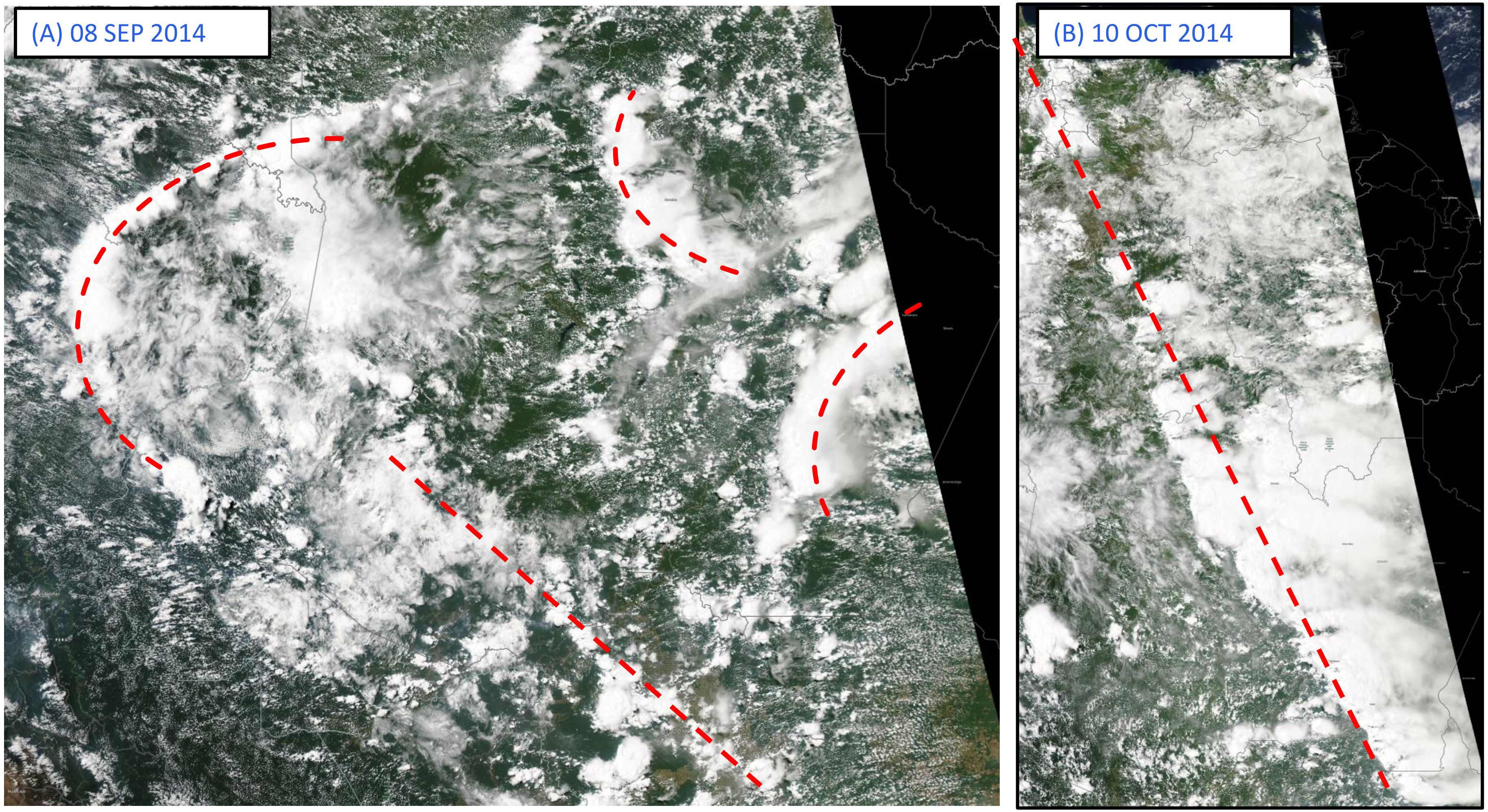
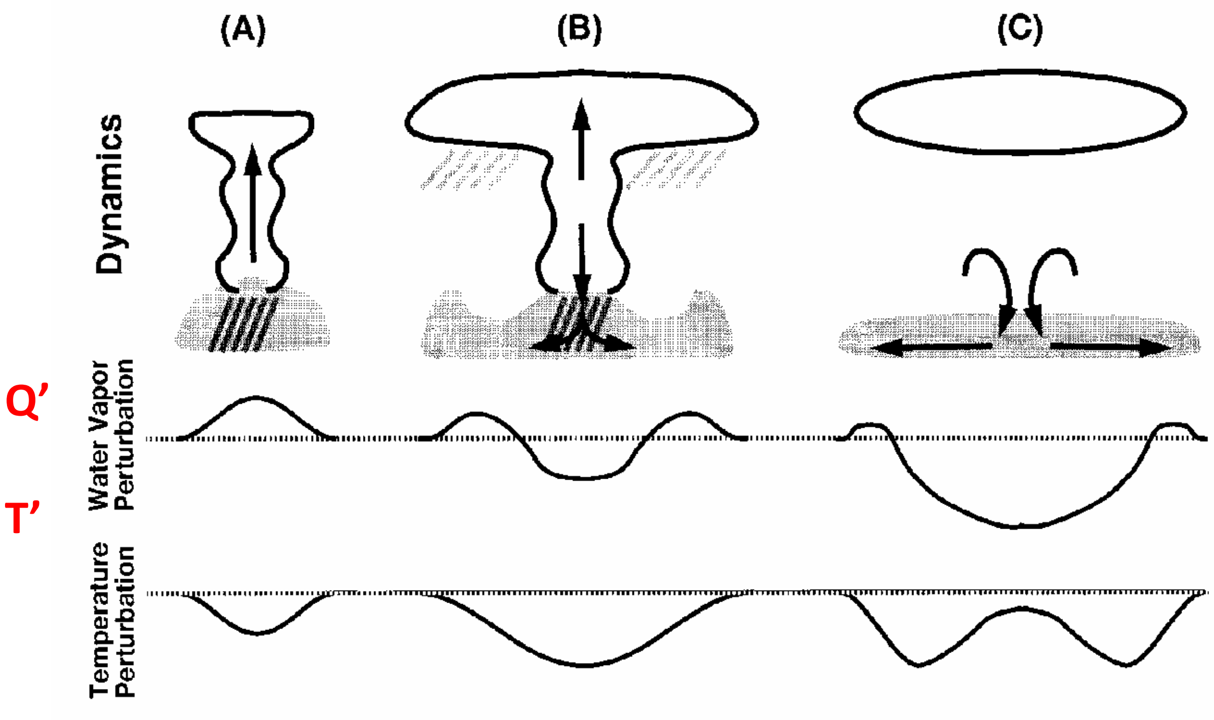
A miscellanea of organized convective systems in the Amazon basin on an ordinary day



Aqua/MODIS true-color images (doi:10.5067/MODIS/MYD02HKM.061)

Oceanic cold pools



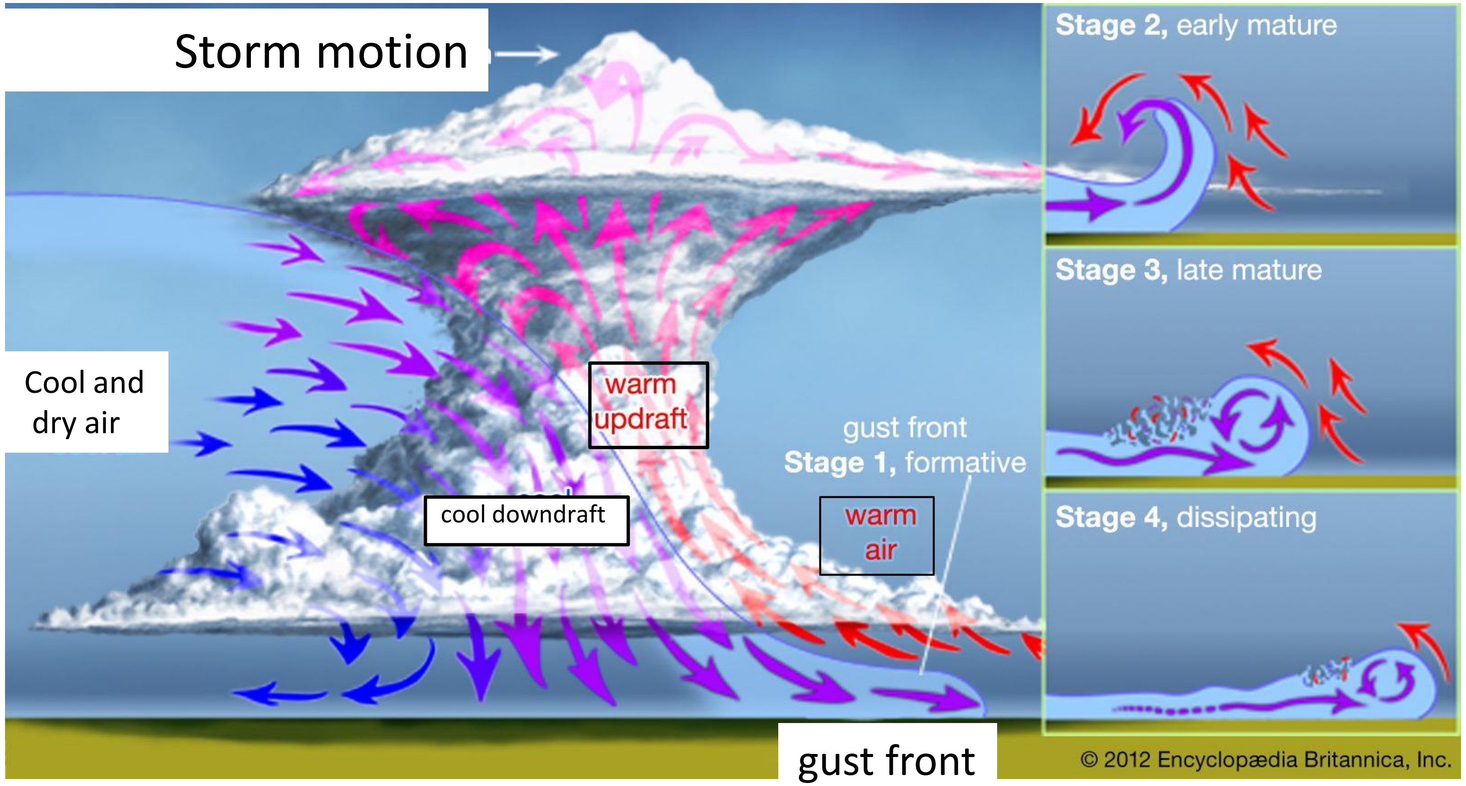
Tompkins (2001)

A) During the initial deep convection development, the sub-cloud layer is cooled and moistened by the evaporation of rainfall.

B) In the mature phase, downdrafts introduce cold, dry air into the boundary layer, and push away the moist band forming the gust fronts.

C) The edges of the cold pools contain high moist static energy (MSE) and strong mass convergence, which are prone to the development of new convective cells.

Genesis and evolution of a cold pool gust-front



https://www.britannica.com/science/thunderstorm/Thunderstorm-electrification

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Adapted from

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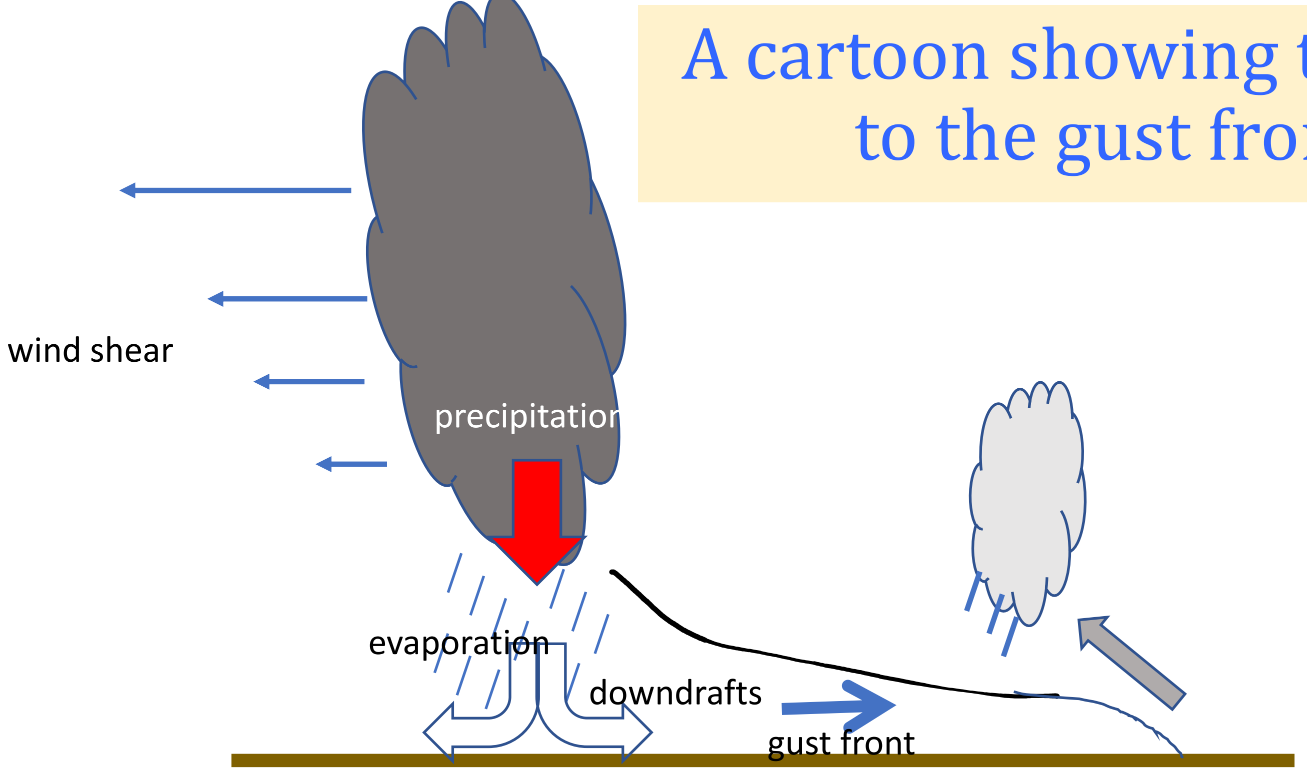
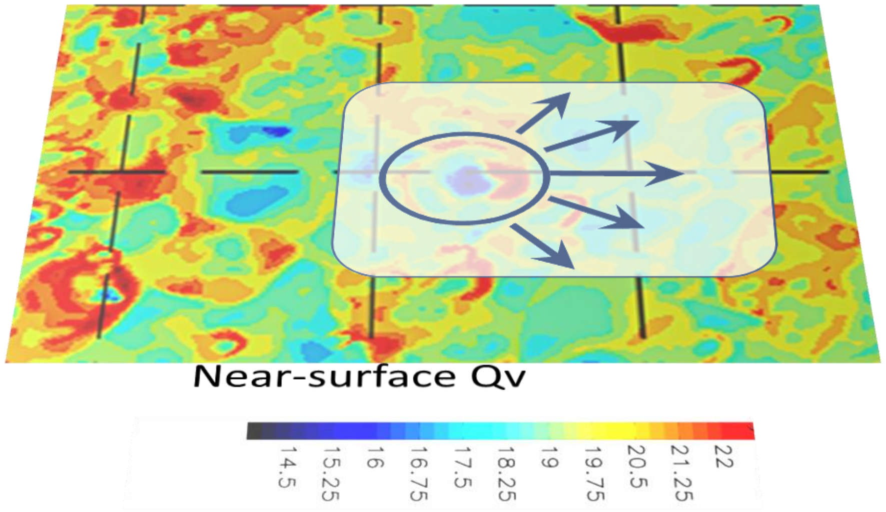
A cartoon showing the initiation of new convection due to the gust fronts associated with cold pools.



Q' < Q_env	Q' > Q_env
T' < T_env	T' < T_env
MSE' < MSE_env	MSE' > MSE_env

dynamical forcing

thermodynamical forcing



Some motivation

Including representation of cold-pool processes

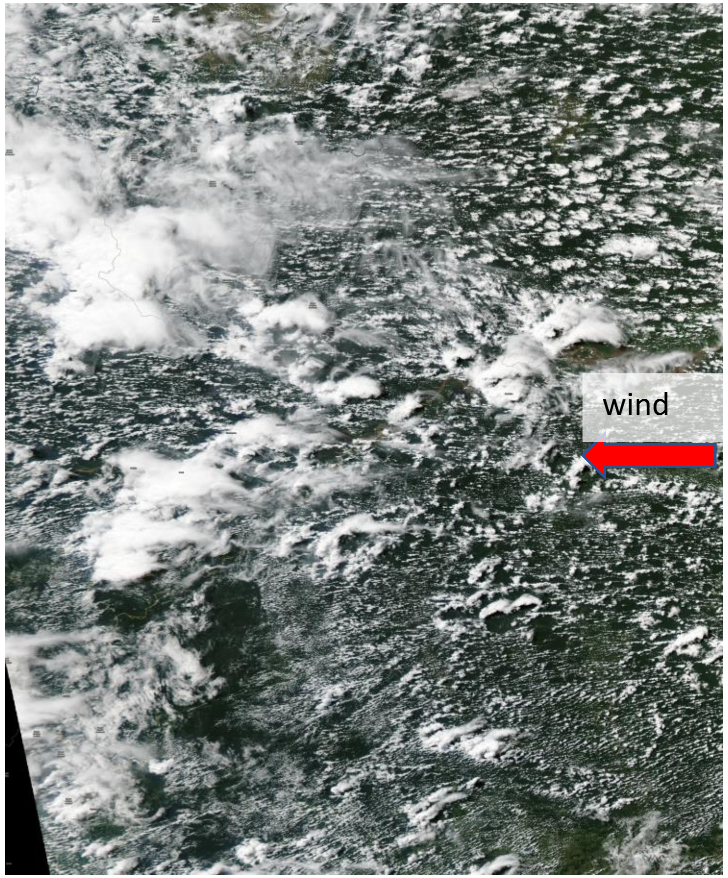
in a convection parameterization for weather and climate GCMs

- might be useful by introducing spatial-temporal correlations between convective events (memory).
- might help the diurnal cycle of precipitation.
- might help cloud organization (clustering, lifetime, and propagation) in a GCM.
- should improve the SGS emission estimation of sea salt, dust aerosols.
- ...

2 - Cloud-resolving modeling to support the parameterization design.

Cloud-resolving simulations over the Amazon Basin

BRAMS model	Freitas et al. (GMD 2017)
Spatial resolution	• Horizontal: 250 m x 250 m covering 500 x 500 km^2 over the Amazon basin • Vertical: 50 m – 500 m, top at 20km
Dynamic core	Non-hydrostatic, Boussinesq compressible (Cotton et al., 2001)
Time integration	Runge-Kutta 3rd order, 3rd and 5th order advection operators (Wicker and Skamarock, 2002)
Isotropic turbulence	Smagorinsky 1963, Hill 1974 and Lilly 1962
Monotonic advection for scalars	Freitas et al. (2011)
Cloud microphysics	hybrid single and double moment (Thompson and Eidhammer, 2014)
Radiation	RRTMG (short- and long-wave)
Surface scheme	LEAF-3 (Walko et al., 2000)



MODIS visible image
1:30 PM MAY 2017

Simulation day

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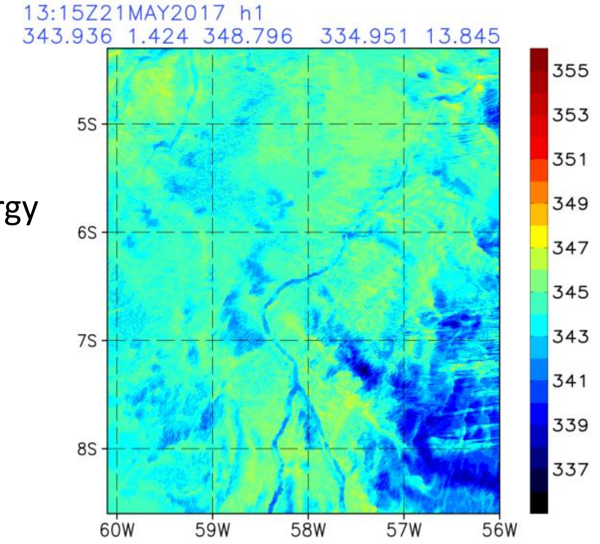
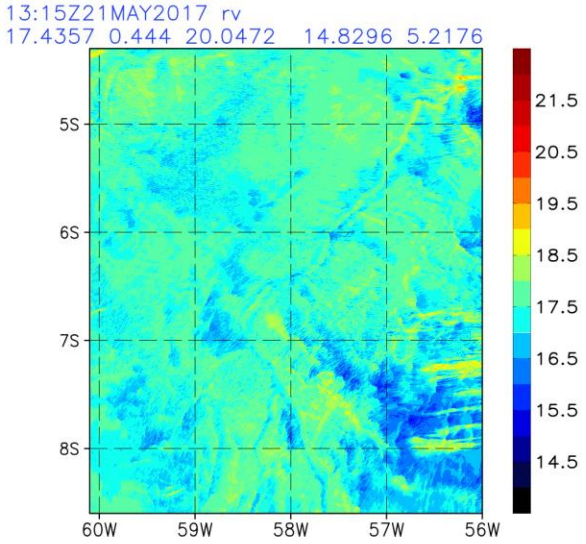
Cloud-resolving simulations over the Amazon Basin

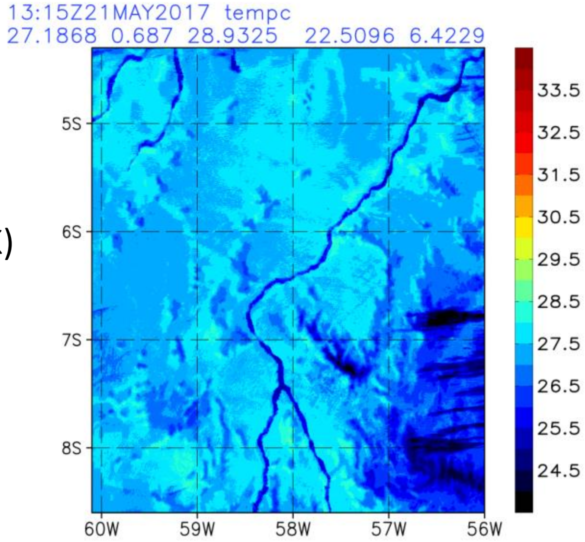
Moist Static Energy (MSE/c_p, K)

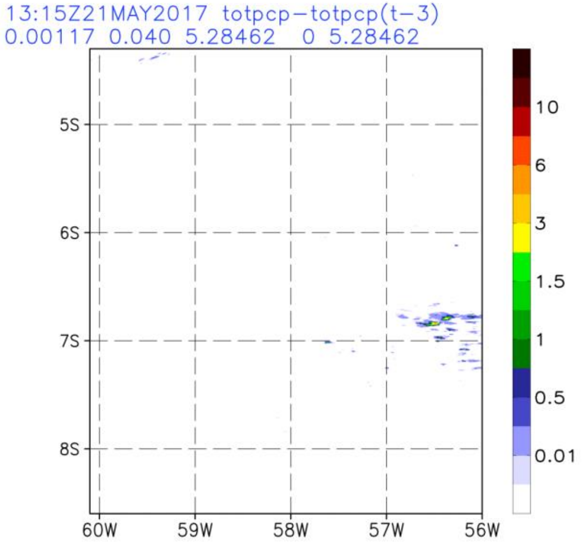




Water vapor mixing ratio ($g\ kg^{-1}$)

Temperature (K)





15mn accum. precipitation (mm)

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21 MAY 2017 – 13:00 to 20:00 UTC

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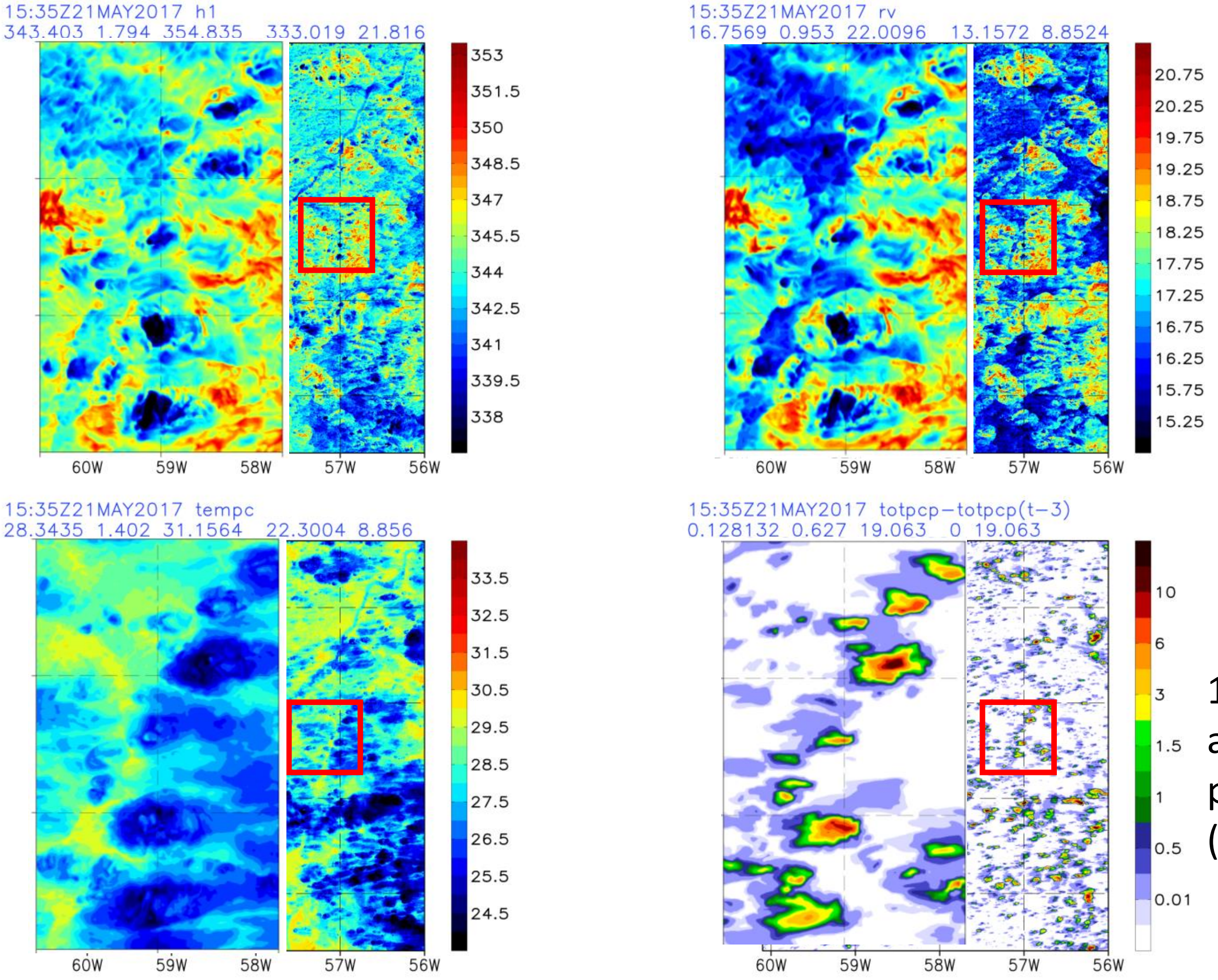
Cloud-resolving simulations over the Amazon Basin

MSE/c_p (K)

Water vapor mixing ratio (g kg^{-1})

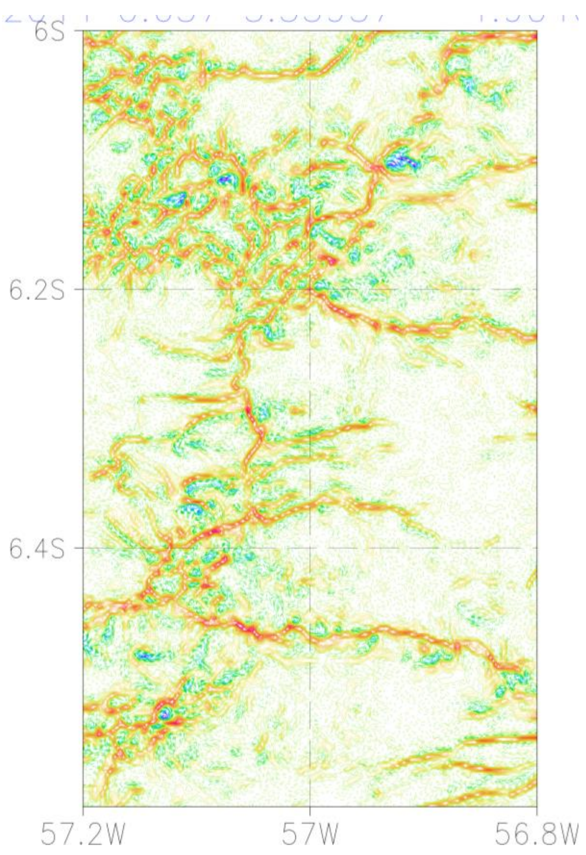
Temperature (K)

15mn accum. precipitation (mm)

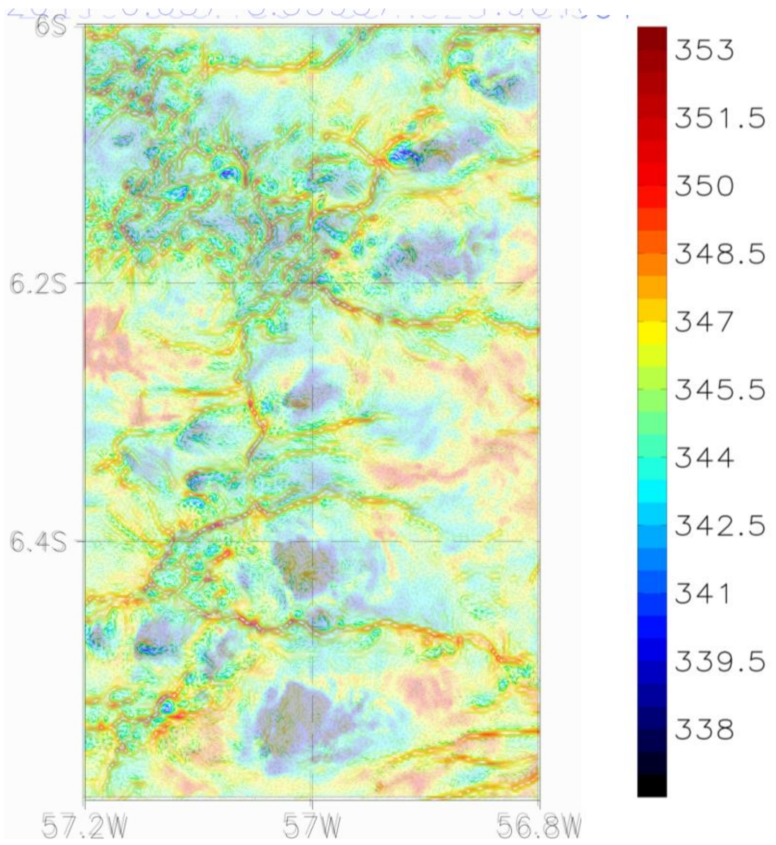


Instantaneous fields at 15:35 UTC ~ noon

Vertical velocity at ~ 400 m AGL and near surface MSE



Vertical Velocity (m/s): W > 0. W < 0.



Moist Static Energy (MSE/Cp, K)

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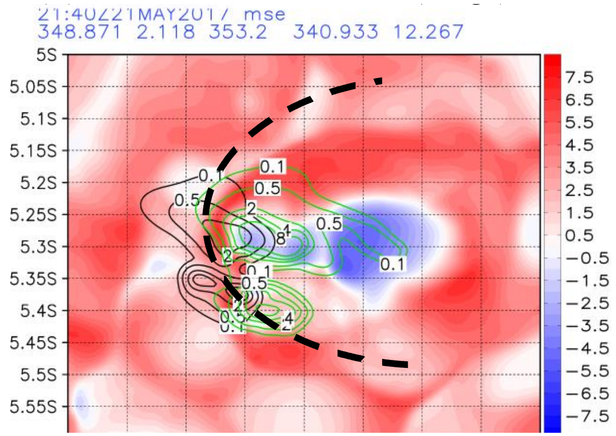
Discriminating regions at the edges and inside the cold pools

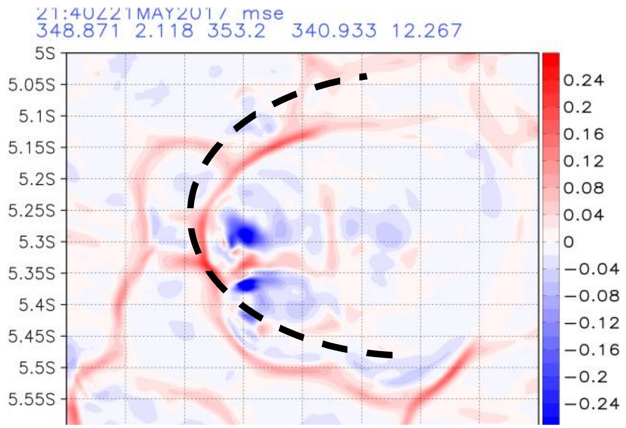
1) if W > 0.1 m/s + subsequent 30mn precipitation is > 4 mm
=> region of positive MSE anomalies (moist rings)

2) if W < -0.1 m/s + previous 30mn precipitation is > 4 mm
=> region of negative MSE anomalies or the cold pool region.

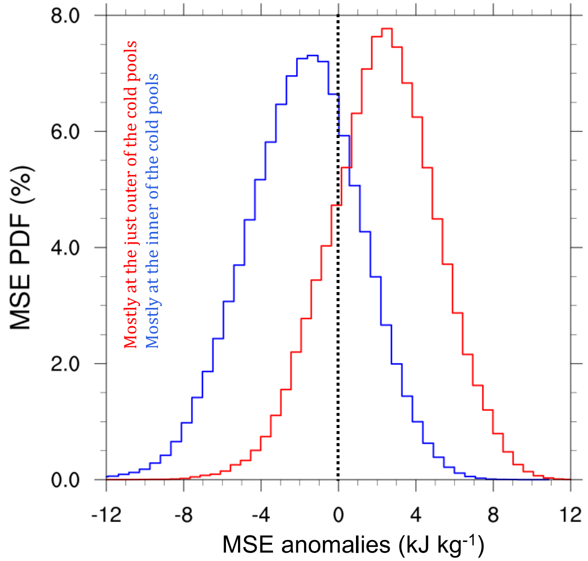
MSE anomalies (kJ kg^{-1})



Vertical velocity (m/s)



PDFs for the MSE anomalies:
Red : just outside the cold pools
Blue: in the cold pools itself



Region	Mean (kJ kg^{-1})	STD (kJ kg^{-1})
outer	2.0	2.8
inner	-2.1	3.0

Statistical indicators of the MSE anomalies PDF

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3 - A proposed parameterization.

A parameterization to account for the effects of the cold pool edges

Definition of Buoyancy-Excess (β_x)
as a measure of the sub-grid scale MSE variability due the presence of the cold pools:

$$\beta_x = -(H_d - \widetilde{H})$$

a) H_d and $\widetilde{H}$ are the downdraft and environment MSE.
b) β_x is 3-d positive-definite prognostic scalar.

a) Definition of the mean cloud layer horizontal speed $(u,v)_{mcl}$:

$$(u,v)_{mcl} = \frac{1}{p_2 - p_1}\int_{p_1}^{p_2} (u,v)_{env}\,dp$$

where p_1= 900 hPa, p_2=600 hPa. $(u,v)_{env}$ is the horizontal environment wind and p is the atmospheric pressure.

b) Following the literature as discussed before:

The gust front horizontal velocity is given by:

$$V_{gf} = \kappa\left(\int_0^D \frac{1}{1+\gamma}\frac{\beta_x}{c_p\widetilde{T}}\,g\,dz\right)^{1/2}$$

The 2-d horizontal propagation velocity of the cold pool:

$$(u,v)_{\text{prop}} = (u,v)_{mcl} + \frac{V_{gf}}{|(u,v)_{mcl}|}(u,v)_{mcl} + 0.6(u,v)_{env}$$

The maximum vertical velocity at the leading edge of the cold pool:

$$w_{gf} = \kappa\left(\int_0^D \frac{1}{1+\gamma}\frac{\beta_x}{c_p\widetilde{T}}\sin^2\alpha\; g\; dz\right)^{1/2}$$

A parameterization to account for the effects of the cold pool edges (cont.)

The proposed prognostic equation for the Buoyancy-Excess (β_x):

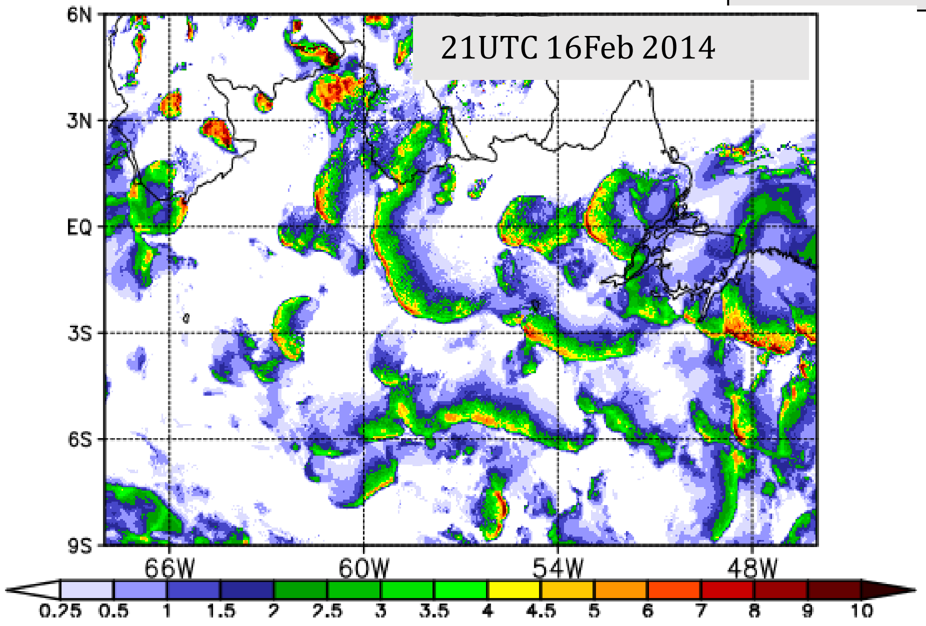
$$\frac{\partial \beta_x}{\partial t} = \underbrace{(u,v)_{prop} \cdot \nabla \beta_x}_{\text{2-d advection}} + \underbrace{\mathrm{diff}(\beta_x)}_{\text{3-d diffusion}} + \underbrace{\delta_d \beta_x}_{\text{source}} - \underbrace{\frac{\beta_x}{\tau}}_{\text{sink}}$$

2-d advection

3-d diffusion

Source term with $\boldsymbol{\delta_d}$ the downdraft detrainment mass-flux given by the Grell-Freitas convection parameterization.

Sink term with $\boldsymbol{\tau}$ the cold pool lifetime. $\boldsymbol{\tau}$ is a tunable parameter in the range of a 1–3 hours (currently 2 h).



Typical model output of the Buoyancy-Excess β_x (kJ/kg)

Application within the Grell-Freitas (GF) Convection Parameterization

1st Effect: as a boundary condition for the MSE of the updraft in the propagation direction, serving as an additional source of buoyancy for the convecting air parcels:

Closure (stability removal with non-equilibrium hypothesis): $\text{mass flux} \propto \frac{A}{\tau}$

a) Determination of the cloud work function and total water of the updraft :

$$A = \int_{z_b}^{z_t} \frac{1}{c_p \tilde{T}} \frac{Z_u}{1+\gamma} \left(H_u - \tilde{H}^*\right) g \, dz$$

with

$$H_u(z_b) = \tilde{H}(z_b) + \beta_x$$

→ Includes the MSE excess due to the water vapor rings.

$$q_u(z_b) = \tilde{q}(z_b) + \frac{\beta_x}{L_v}$$

→ The MSE excess is entirely in the form of water vapor.

b) Determination of the convective adjustment time scale:
GF solves a diagnostic equation for the sub-grid scale updraft vertical velocity (w_u)

$$\tau = \int_{z_b}^{z_t} \frac{dz}{w_u(z)}$$

with

$$w_u(z_b) = w_{gf}$$

- Makes the time scale of the updrafts overturning shorter.
- Implies on stronger convection (larger updraft mass flux at the cloud base).

2nd Effect: optional trigger function based on the kinetic energy ($E_k = \frac{1}{2} W_{gf}^2$) of the air parcels at the leading edge of the gust front. In this case, deep convection is allowed in a model column if

$$E_k > |min(A_{cin}, 0)|$$

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Grell and Freitas ACP 2014; Freitas et al. JAMES 2018, GMD 2021

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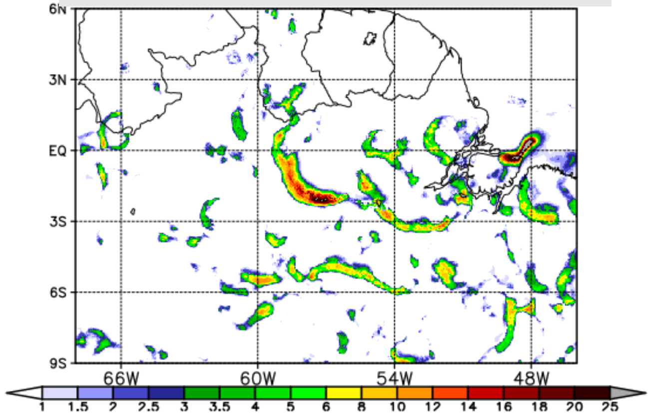
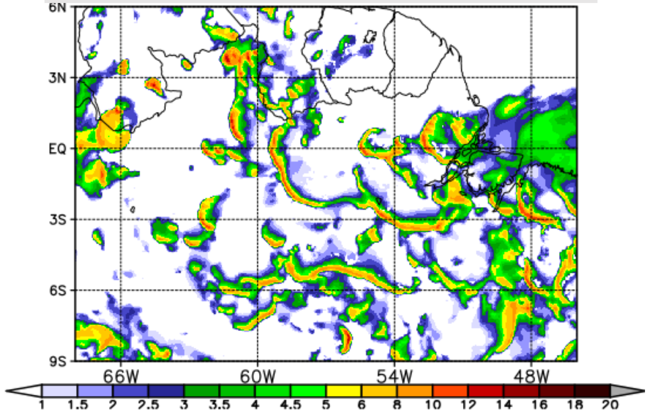
Results using BRAMS model

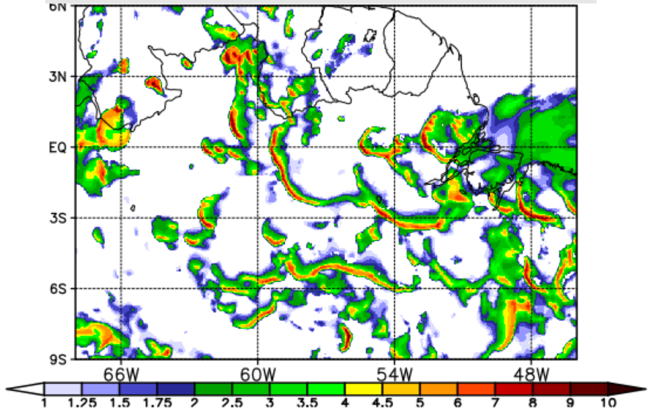
1-hourly precipitation rate (mm/h)



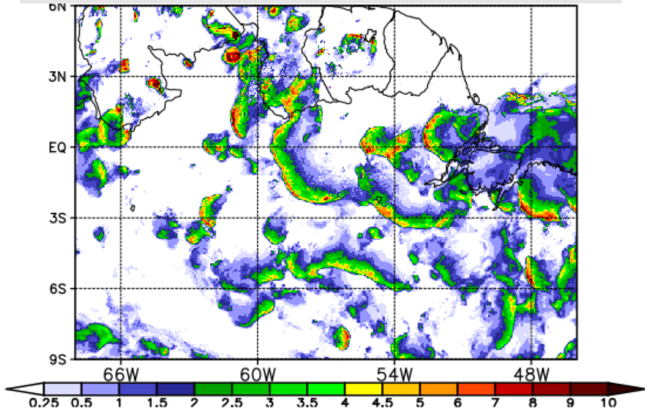
Gust front speed (m/s)



Max vertical velocity at the
edge of the cold-pool (m/s)



Near surface buoyancy-excess (kJ/kg)



Amazon Basin - model grid spacing ~ 8km - 20UTC 16Feb 2014

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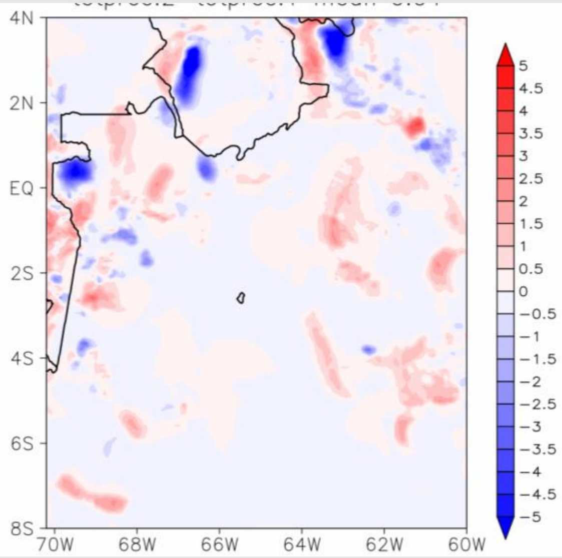
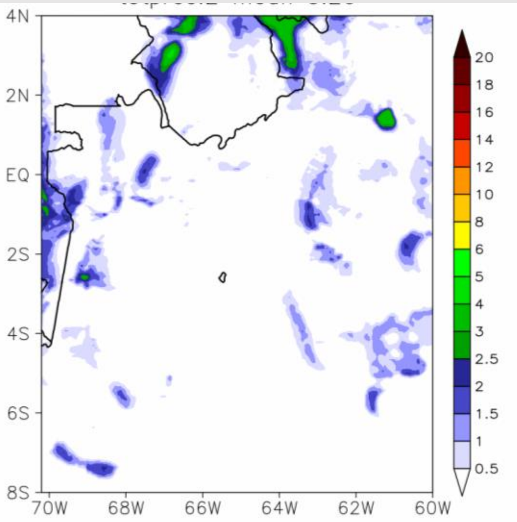
Results with BRAMS @ 8km

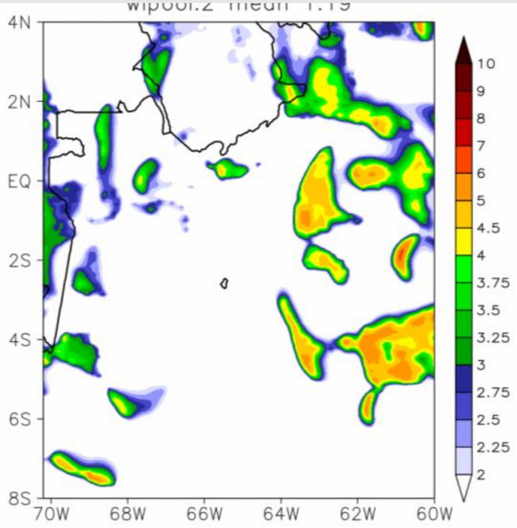
Precipitation rate (cold-pool – control) (mm/h)



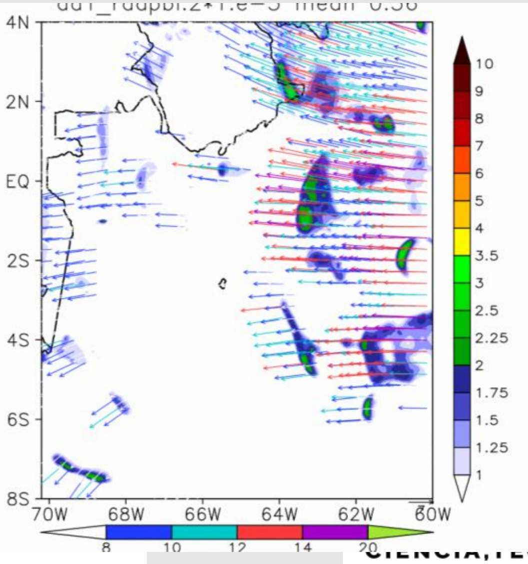
Precipitation rate (cold pool)



Max vertical velocity at the edge of the cold-pool (m/s)



Near-surface buoyancy-excess (kJ/kg)



$(u,v)_{prop}$

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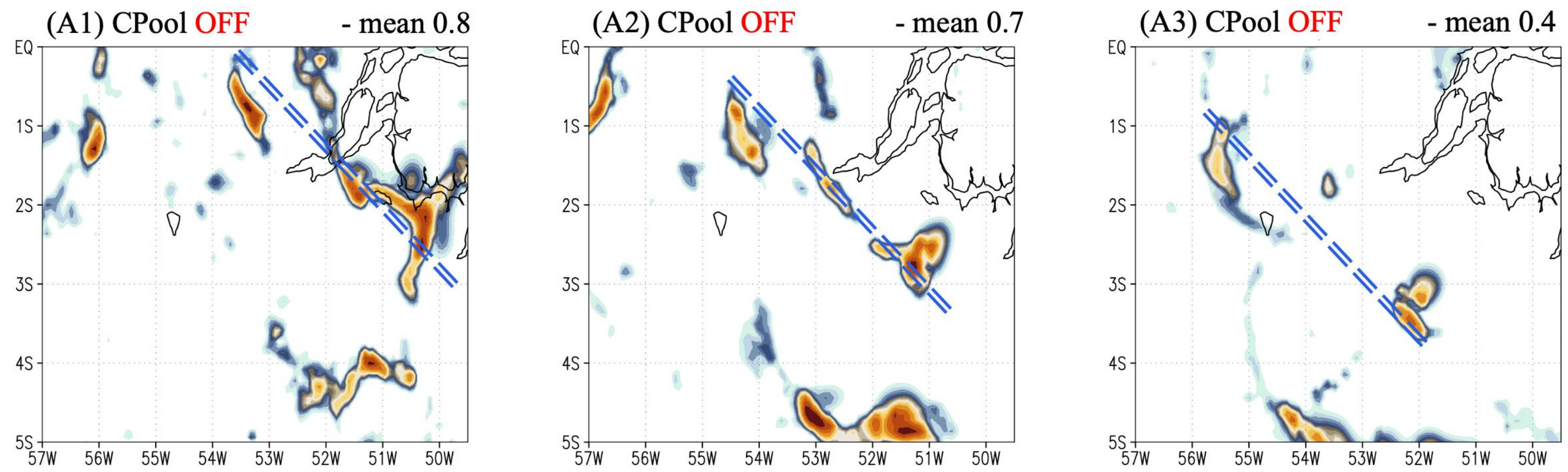
Example of Impact on organization and propagation



Propagation direction

20 UTC 19 FEB 2014

22 UTC 19 FEB 2014

00 UTC 20 FEB 2014

Time

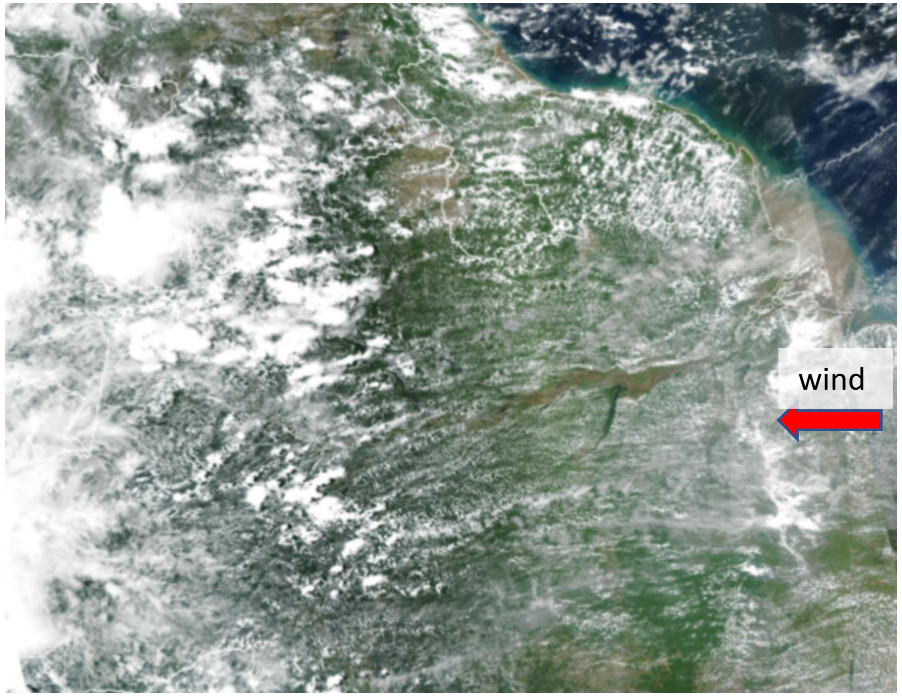
GoAmazon simulations with the BRAMS model

BRAMS model	Freitas et al. (GMD 2017)
Spatial resolution	• Horizontal: 8 km x 8 km covering 2800 x 2200 km^2 over the Amazon basin • Vertical: 90 m – 750 m, top at 20km
Dynamic core	Non-hydrostatic, Boussinesq compressible (Cotton et al., 2001)
Time integration	Runge-Kutta 3rd order, 3rd and 5th order advection operators (Wicker and Skamarock, 2002)
PBL Parameterization	M&Y 2.5 (Mellor & Yamada 1982)
Monotonic advection for scalars	Freitas et al. (2011)
Cloud microphysics	WSM 5-class single moment (Hong et al. 2004)
Convection Parameterization	Grell and Freitas (2014); Freitas et al. (2018, 2021, 2024)
Radiation	RRTMG (short- and long-wave, Iacono et al. 2000)
Surface scheme	JULES (Moreira et al. 2013)

Initial and boundary conditions, and strategies

- ERA-5 Reanalysis (0.25 x 0.25 degree) – 3hourly
- U, V, T, Rv, geopotential height, soil moisture and soil temperature
- Lateral and top nudging: Newtonian relaxation
- 10 days with 48 hours forecast (free runs, forecast mode)
- Results analyzed using only the 2nd forecast day (1st fcst day is discarded)

Model Domain



Experiments GoAmazon

- IOP1_1: 15-24 Feb 2014 – wet season
- IOP2_1: 01-10 SEP 2014 - dry season
- IOP2_4: 01-10 Oct 2014 - transition
- Total analyzed days: 30

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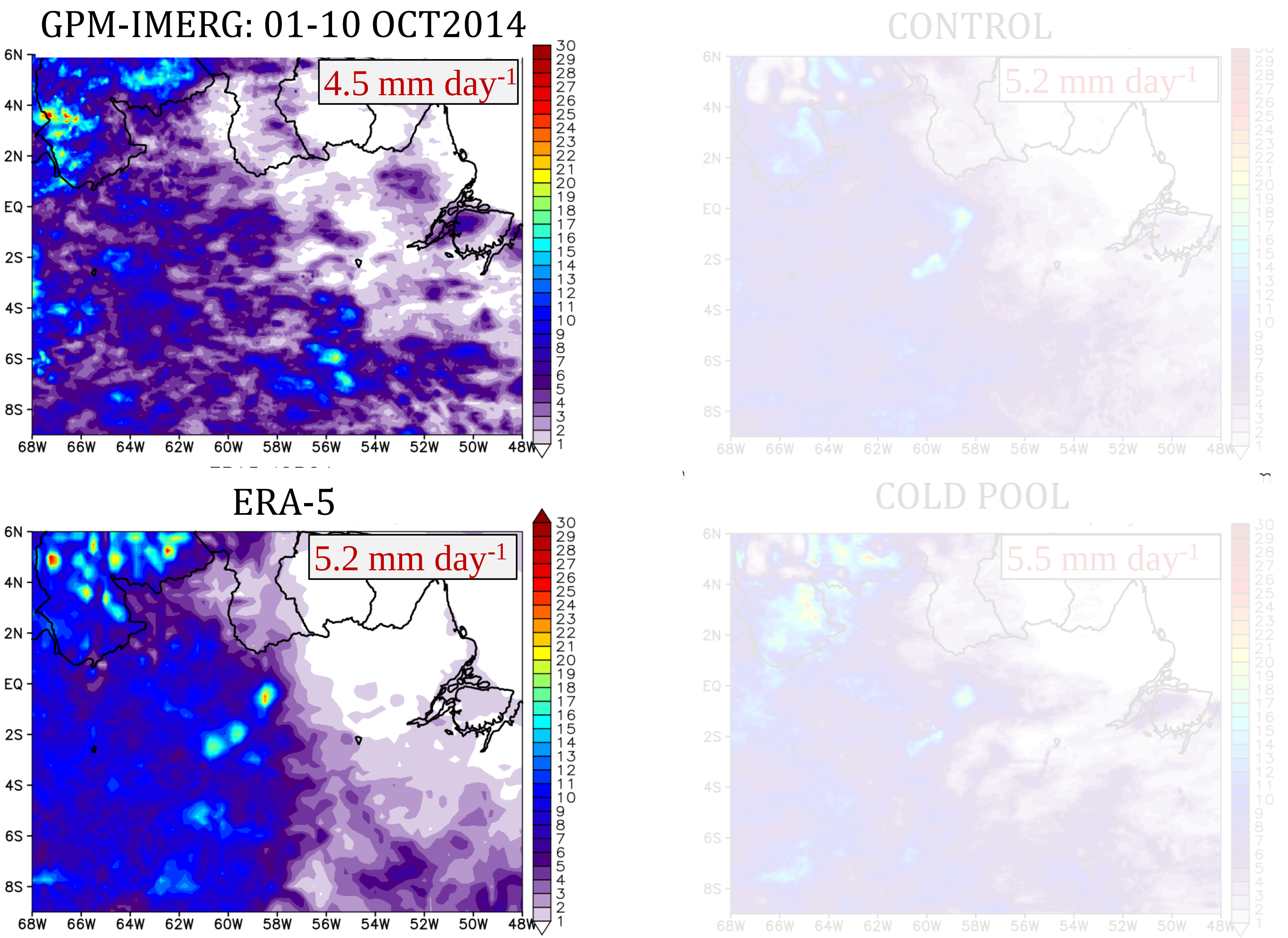
Effects on the Mean Precipitation – Transition to dry-to-wet season



10 days average

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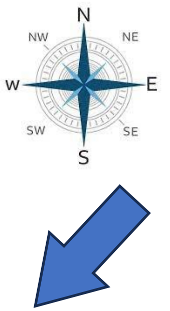
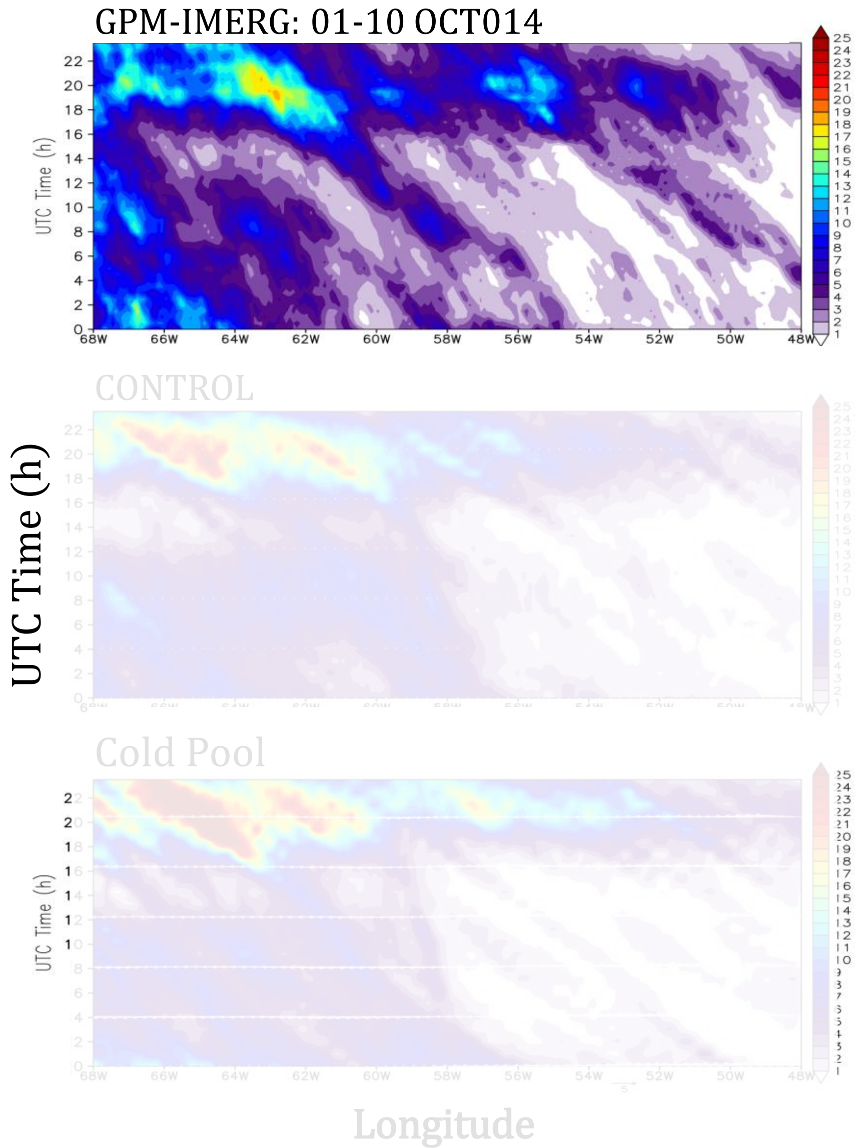
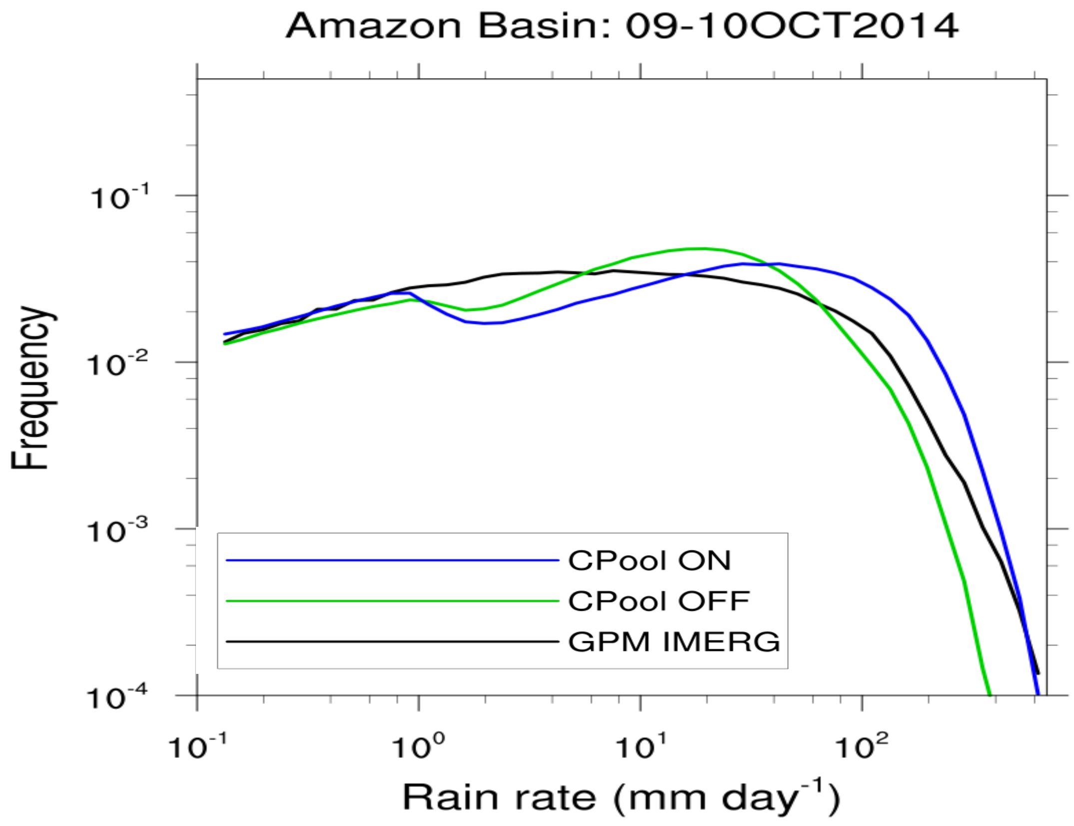
Impacts on Storm's Propagation





Effects on the Intensity of the Storms

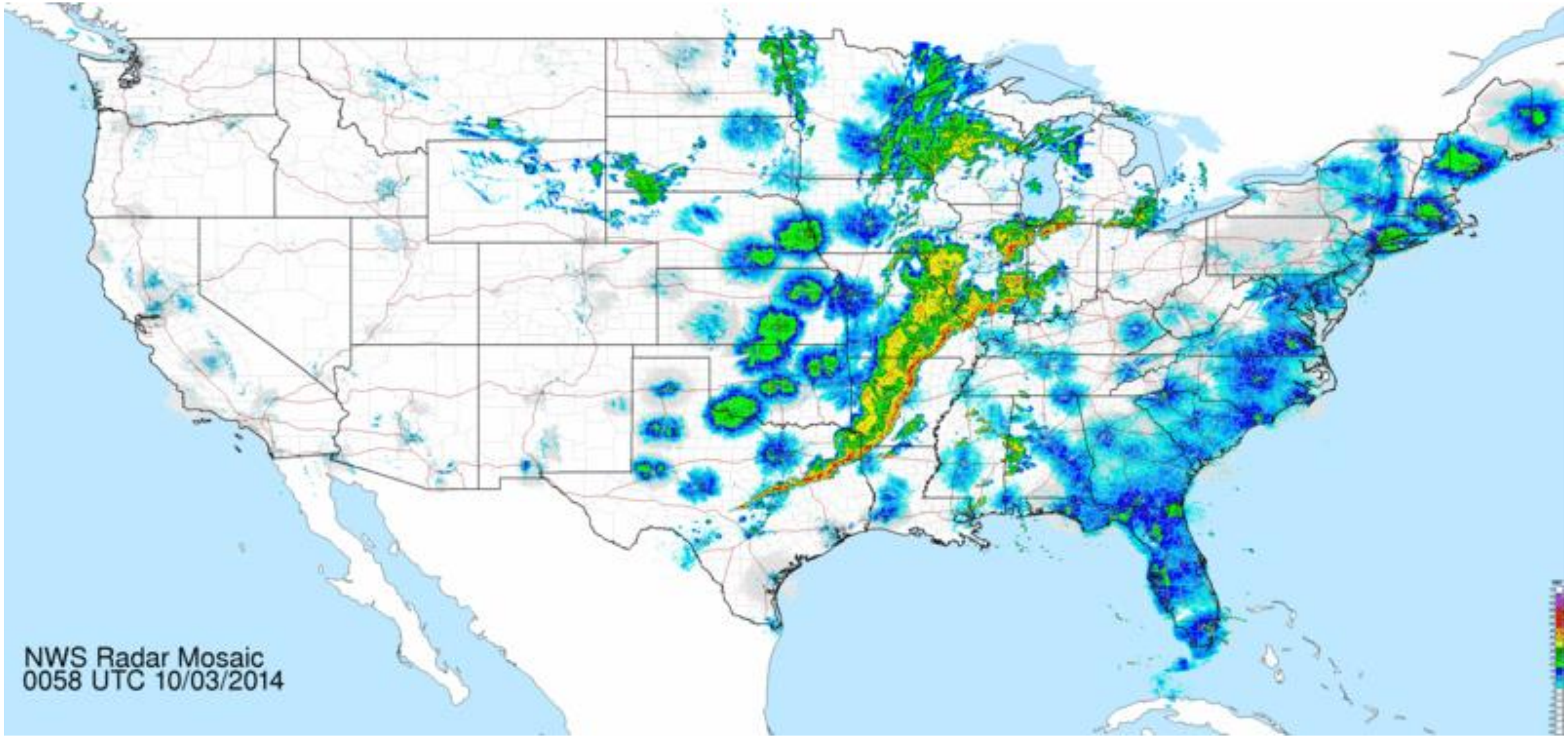


4 - Mesoscale Convective Systems Case Studies.

Mesoscale Convective Systems
Case Studies

Region	Time of start - Integration length	Model grid spacing
Amazon Basin	12UTC 04 OCT 2020 48 hours	H: 8 km x 8 km V: 90 m – 750m
Equatorial Africa	00UTC 06 AUG 2016 48 hours	H: 12 km x 12 km V: 90 m – 750 m
CONUS	12UTC 02 OCT 2014 48 hours	H: 12 km x 12 km V: 70 m – 750m
Rio de la Plata Basin	12UTC 15 FEB 2023 48 hours	H: 10 km x 10 km V: 90 m – 600m

“1,200-Mile-Long Line of Storms Batters Central U.S. on Thursday Night”



02-03 October 2014

https://thevane.gawker.com/1-200-mile-long-line-of-storms-batters-central-u-s-on-1641956485

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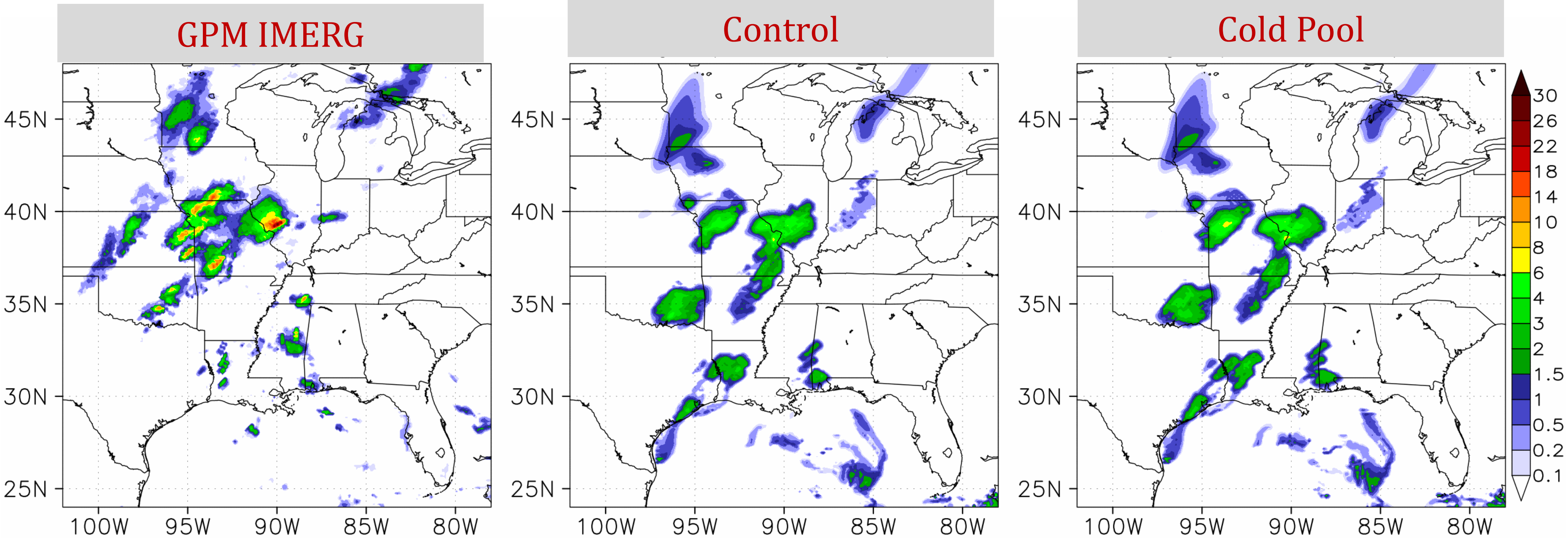
MCS over the CONUS



2-h Accumulated Precipitation (mm h^{-1})

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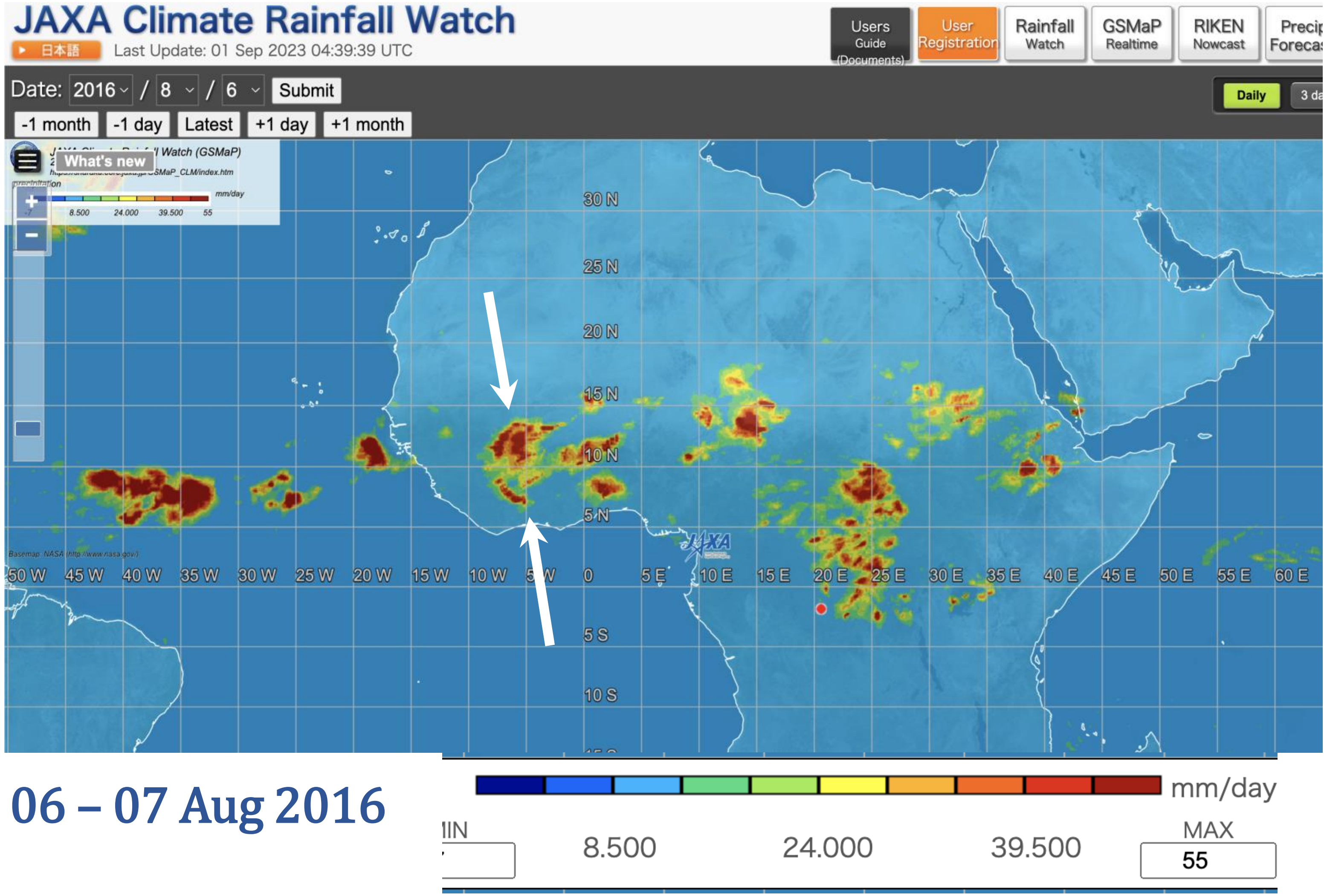
MCS over Western Africa



06 – 07 Aug 2016

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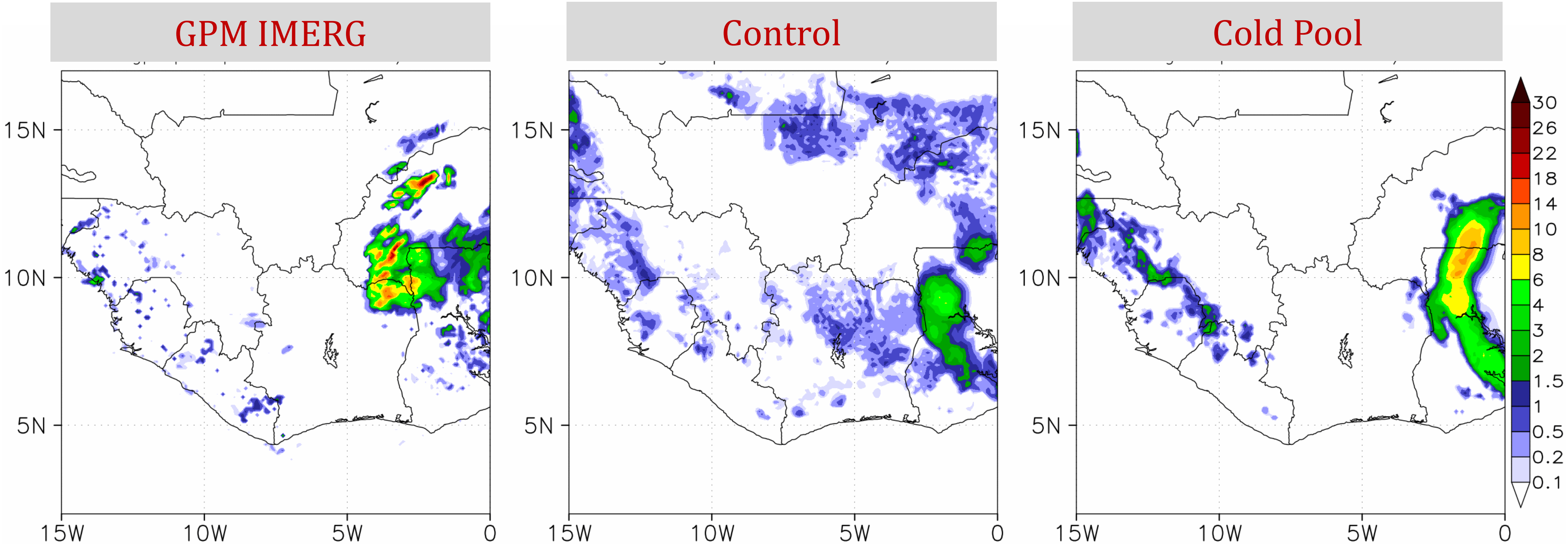
MCS over Western Africa



2-h Accumulated Precipitation (mm h^{-1})

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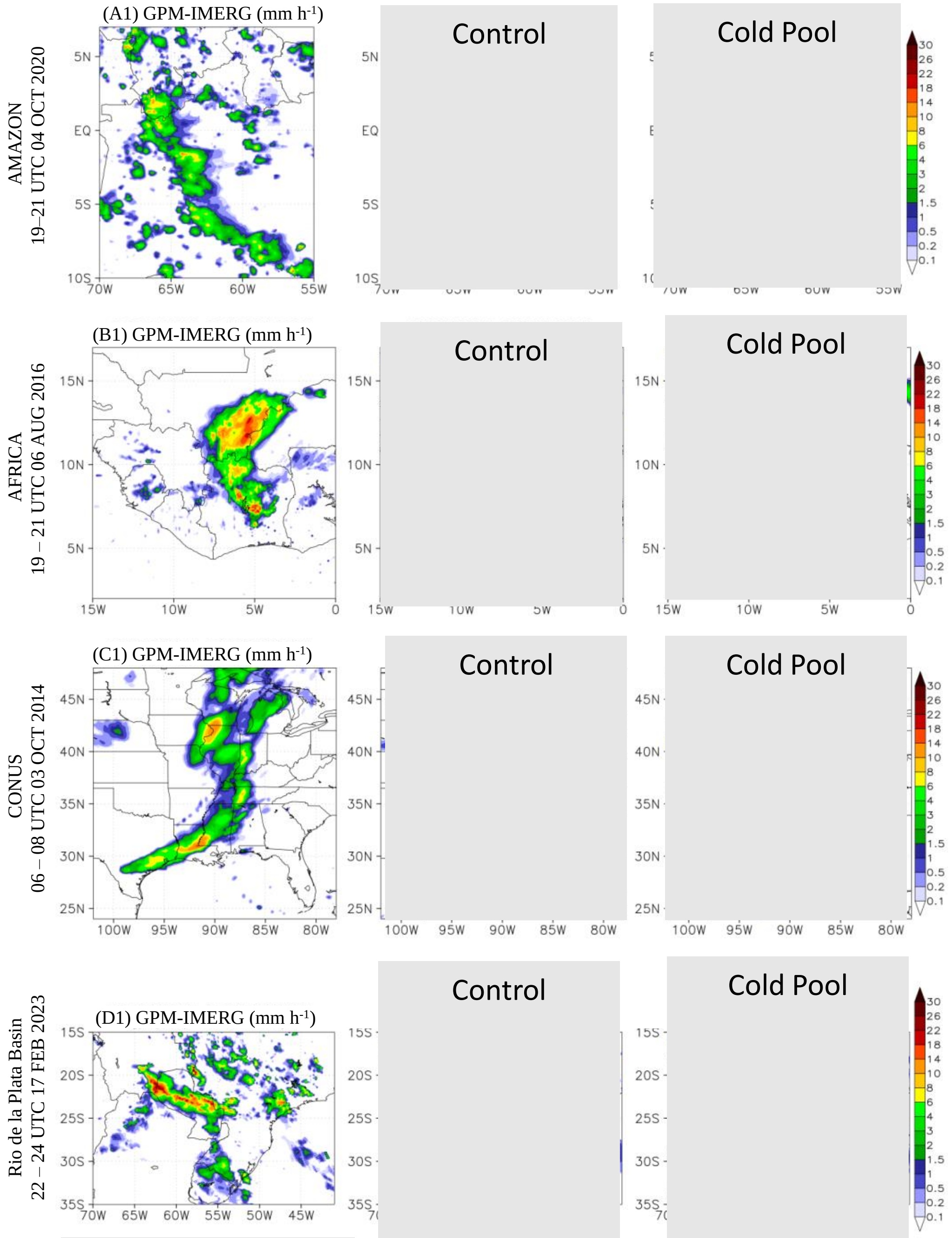
Four MCS Case Studies

2-h Accumulated Precipitation
(mm h^{-1})



GPM IMERG

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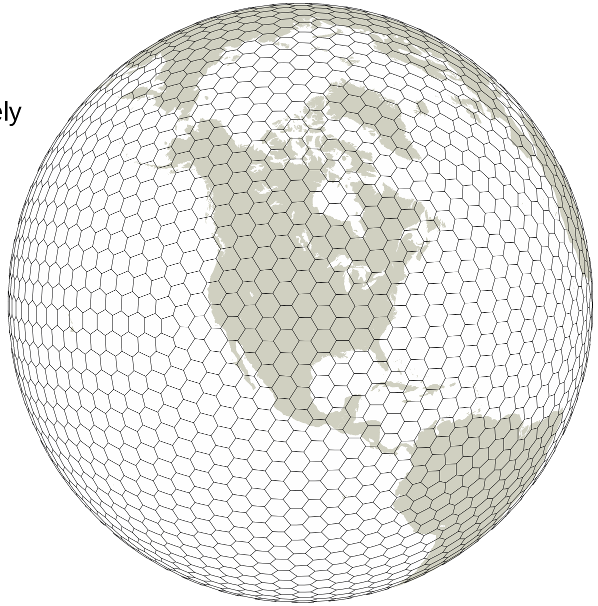
Global scale simulations with the MPAS/MONAN model

MPAS model	
Spatial resolution	• Horizontal: various (240 to 15km) • Vertical: 55 levels, top at ~ 35 km
Dynamic core/ time integration/ advection	• Fully-compressible, non-hydrostatic dynamics • Split-explicit Runge-Kutta time integration • Exact conservation of dry-air mass and scalar mass • Positive-definite and monotonic transport options
PBL Parameterization	MYNN
Cloud microphysics	WSM 6-class single moment (Hong et al. 2004)
Cloud fraction	Chaboureau and Bechtold (2002)
Radiation	RRTMG (short- and long-wave, Iacono et al. 2000)
Surface scheme	NOAH
Convection Parameterization	• Updated GF scheme (Grell and Freitas , 2014; Freitas et al. 2018, 2021, 2024) • Deep and shallow modes

MPAS
Unstructured Voronoi
(hexagonal) grid

- Good scaling on massively parallel computers
- No pole problems



Initial condition and strategies

- GFS (0.25 x 0.25 degree)
- U, V, T, Rv, geopotential height, soil moisture and soil temperature, SST
- 10 days (free runs, forecast mode)

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MPAS Model for Prediction Across Scales

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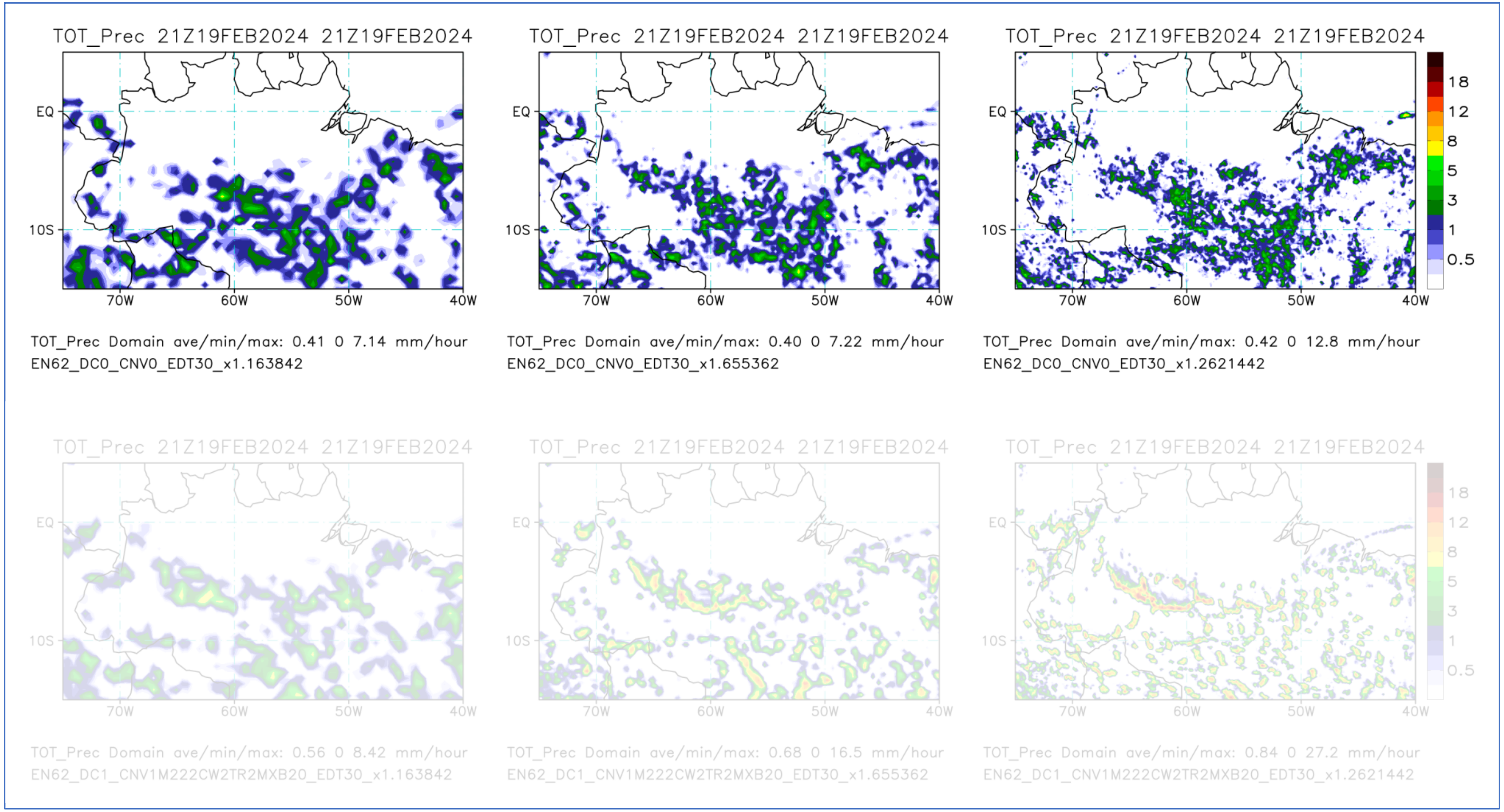
Helps organization in low resolution GCM configuration

Control

Cold Pool



60 km | 30 km | 15 km

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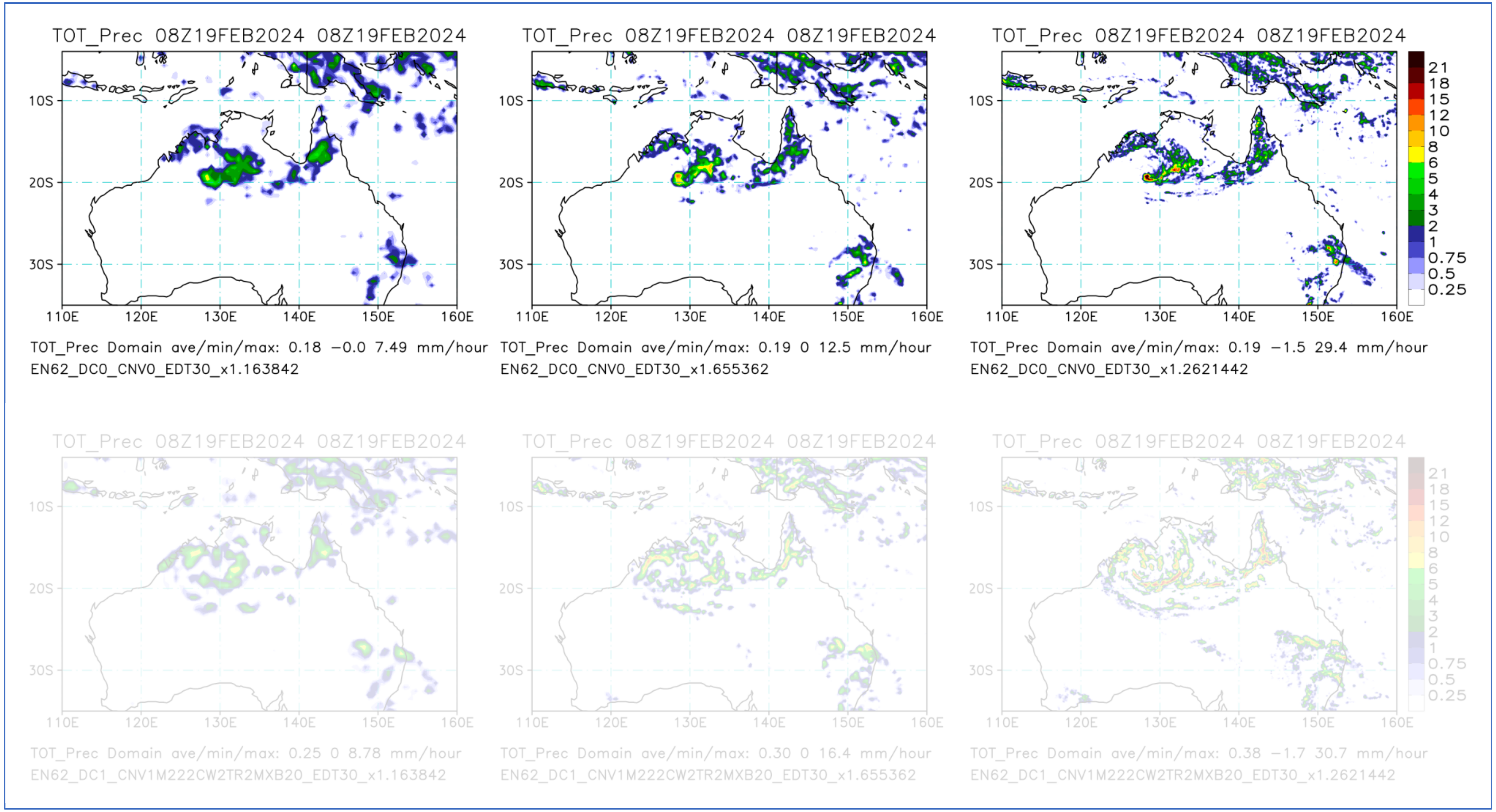
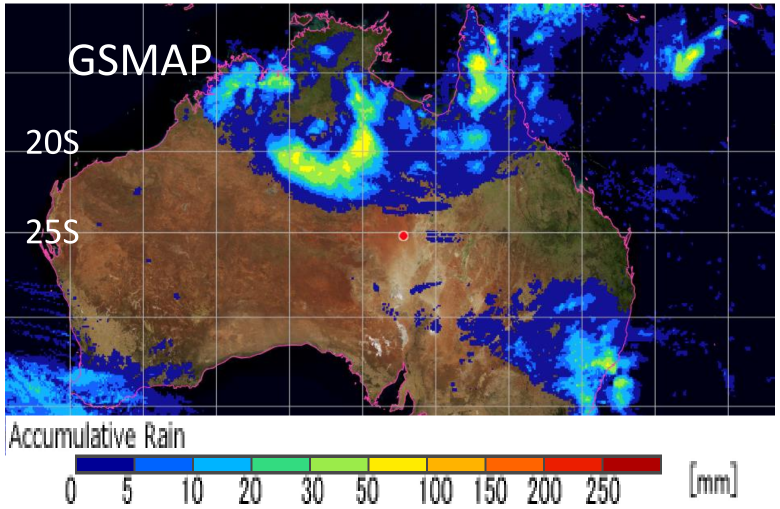
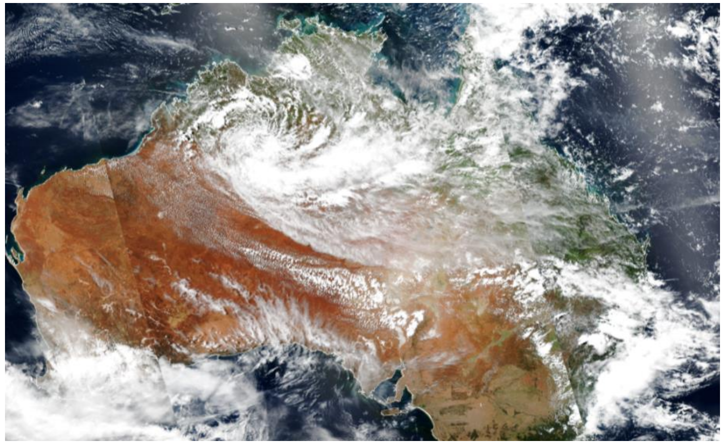
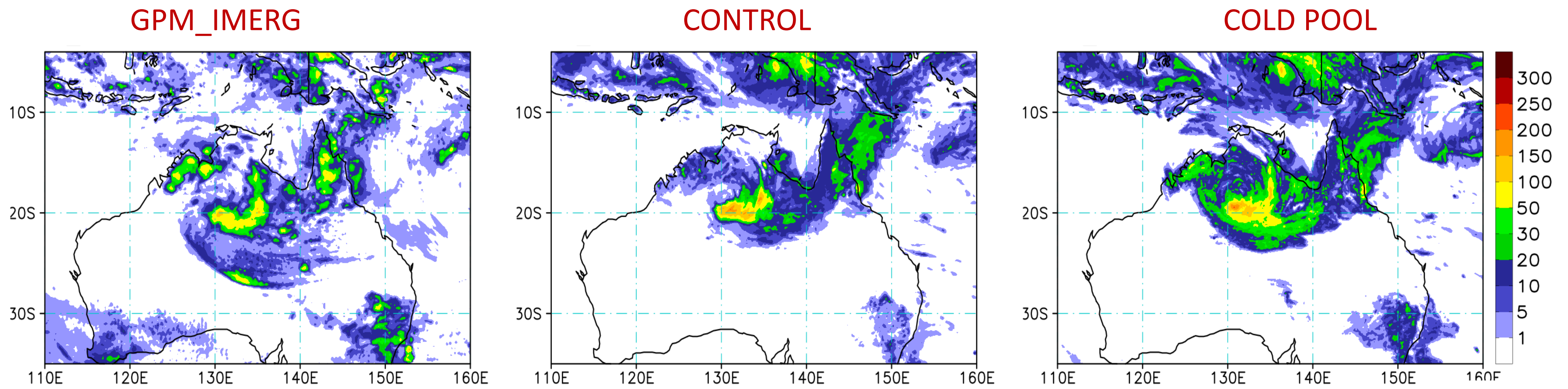


60 km | 30 km | 15 km

Tropical Cyclone Lincoln – Australia Feb 2024







GPM_IMERG Domain ave/min/max: 4.17 0 167. mm/hour
monan_GLB_3B-HHR-L.MS.MRG.3IMERG.20240218_19

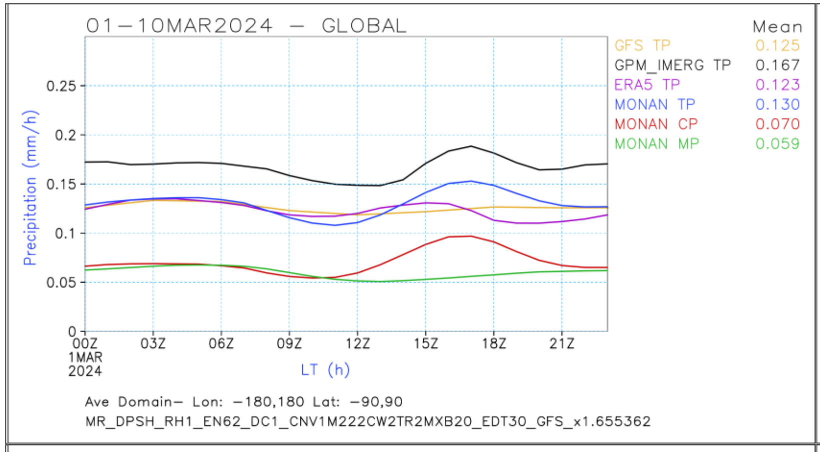
TOT_Prec Domain ave/min/max: 4.02 −9.1 216. mm/hour
EN62_DC0_CNV0_EDT30_x1.2621442

TOT_Prec Domain ave/min/max: 5.88 −3.1 211.
EN62_DC1_CNV1M222CW2TR2MXB20_EDT30_x1.2621442

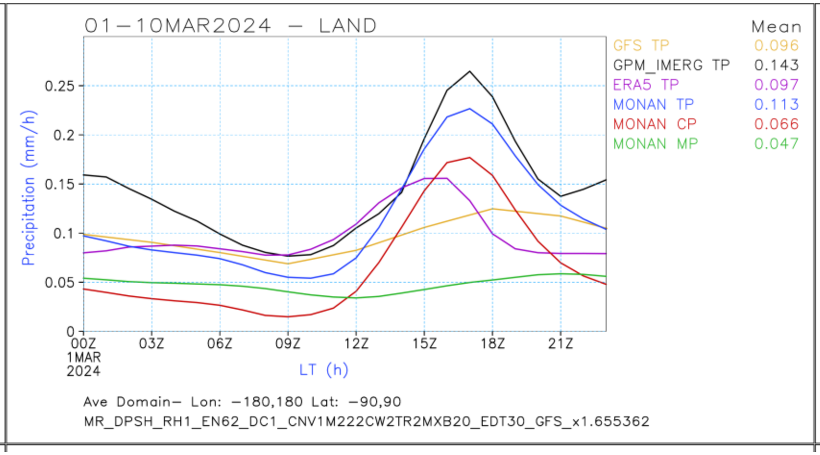
Prec 00Z18-00Z19 Feb

Impact on the diurnal cycle of the precipitation

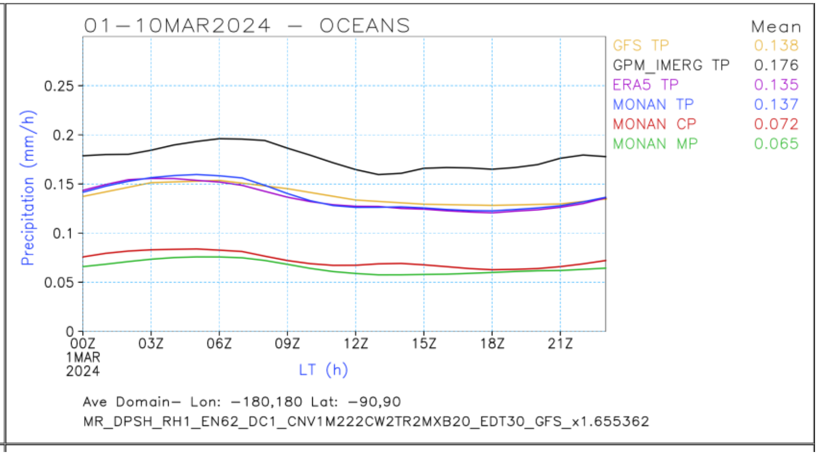
Global



Land



Oceans



GFS TP
GPM_IMERG TP
ERA5 TP
MONAN TP
MONAN CP
MONAN MP

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MPAS Model for Prediction Across Scales

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Summary and Plans for the Future

- A parameterization for interplays between cold pools, wind shear, and mesoscale convective systems for low-resolution GRCMs.
- The parameterization improves the organization, longevity, propagation, and severity simulation of MCS in the Amazon Basin and over a set of contrasting continental regions and environments.

- Room for additional features include:
  - Environmental entrainment rate response to cloud organization.
  - Playing a role in shaping the development of shallow and congestus plumes near the area enclosing the cold pool.
  - Direct interaction between the surface and the gust front.
  - The slope angle of the cold pool head could be based on the balance of low-level wind shear and gust front propagation speed (RKW theory).

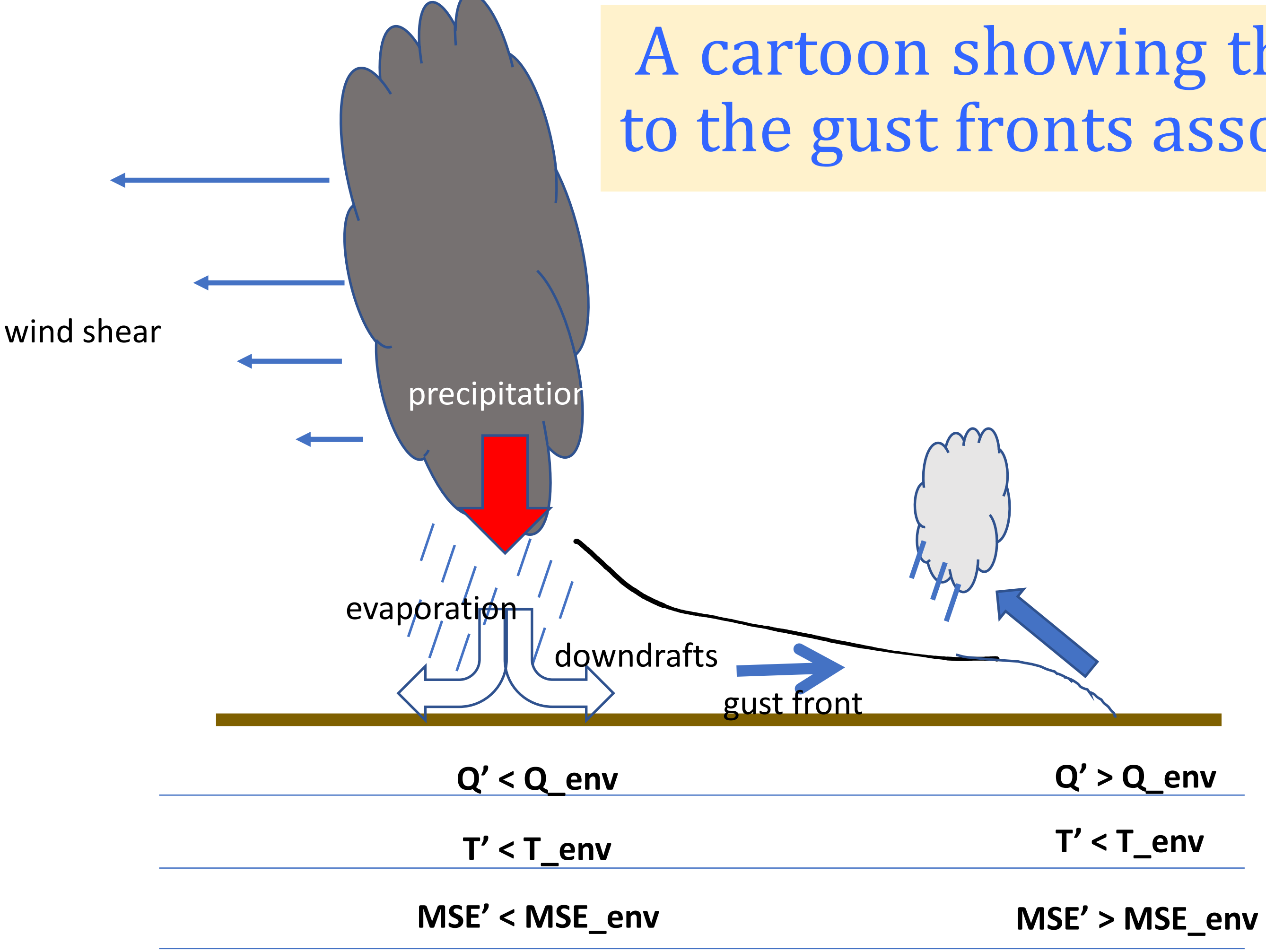
Thanks for your attention!

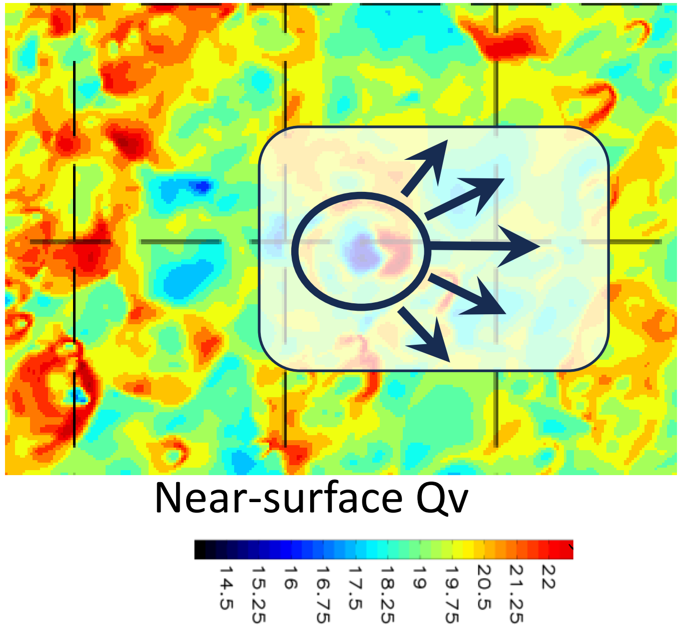
Questions?

This framework should work within different mass-flux convection schemes as well.

Contact me if you have any interest in implementing it into your model: saulo.freitas@inpe.br

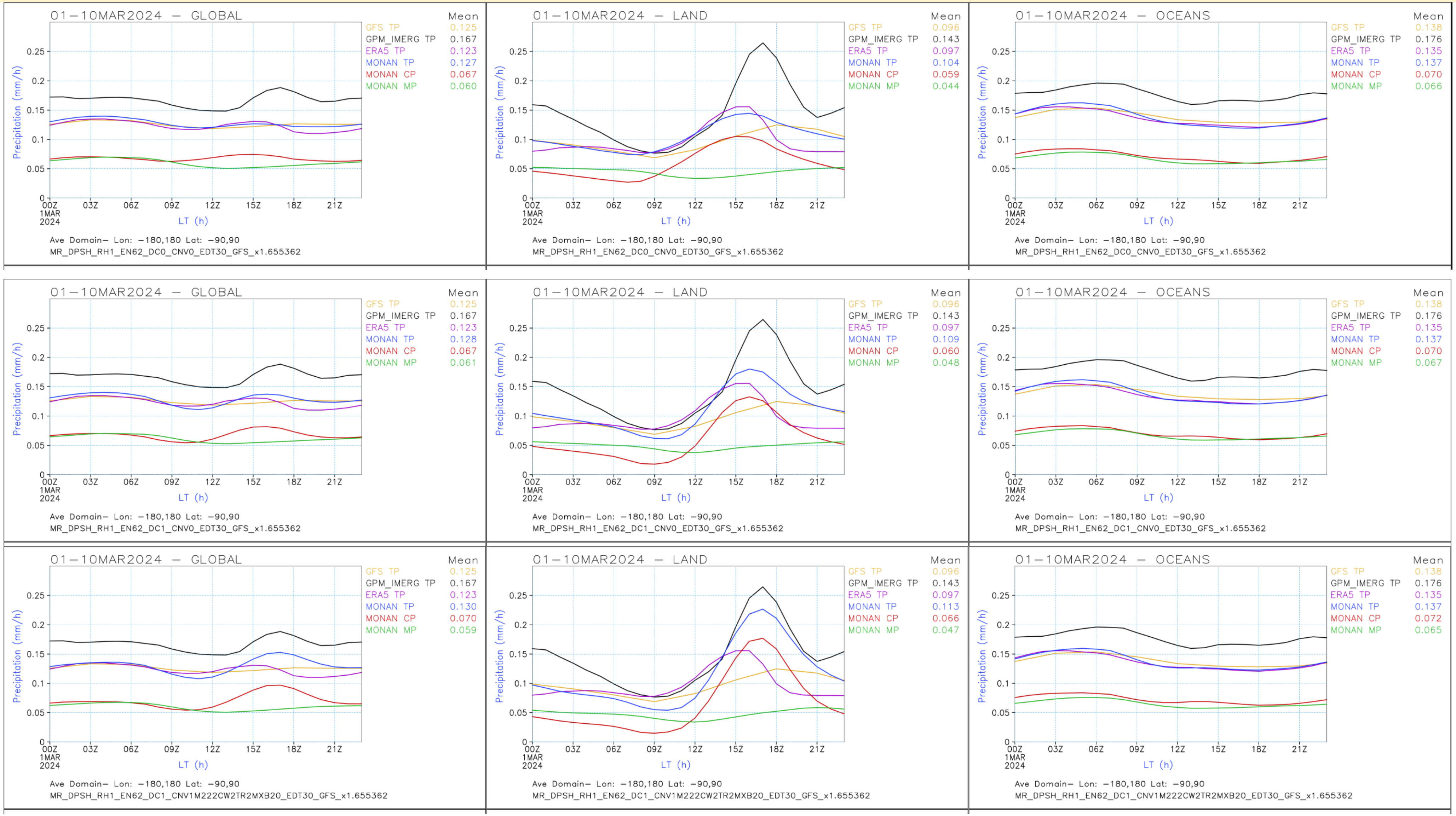
A cartoon showing the initiation of new convection due to the gust fronts associated with cold pools.





Near-surface Qv

Tropical Cyclone Lincoln – Australia Feb 2024



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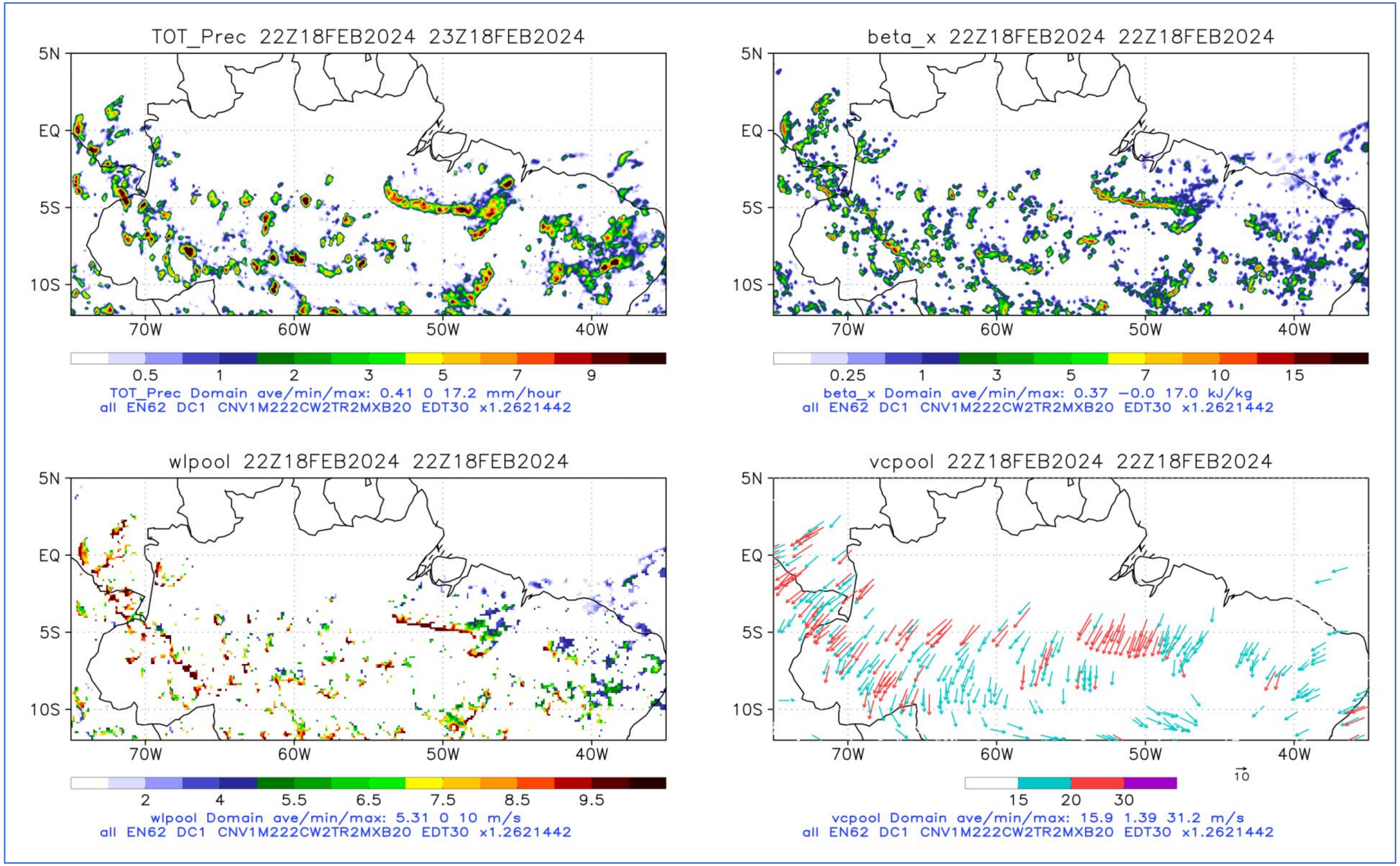
Results using MPAS/MONAN model



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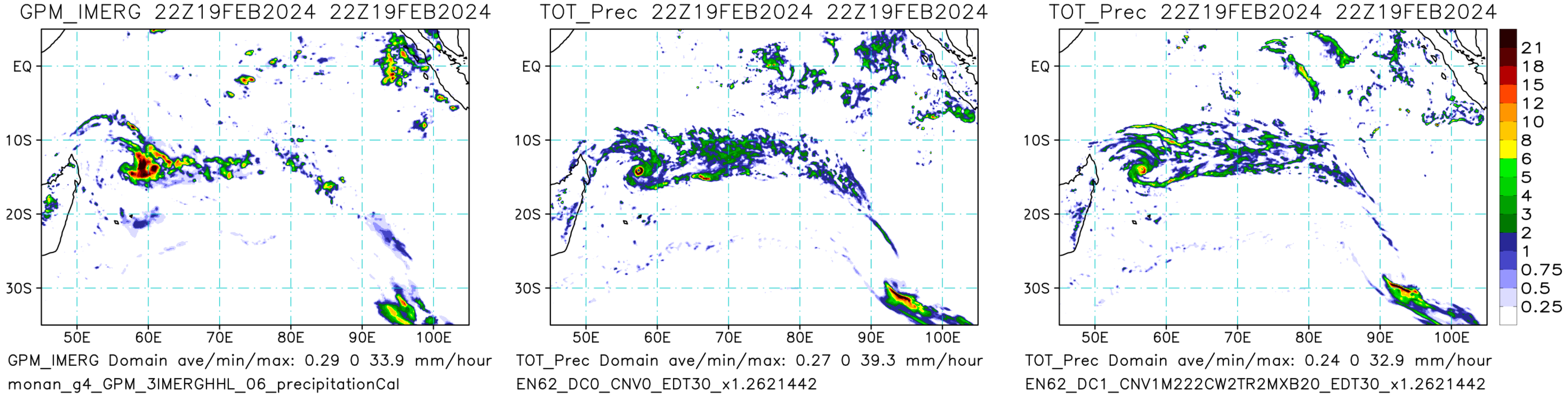
GPM_IMERG | CONTROL | COLD POOL



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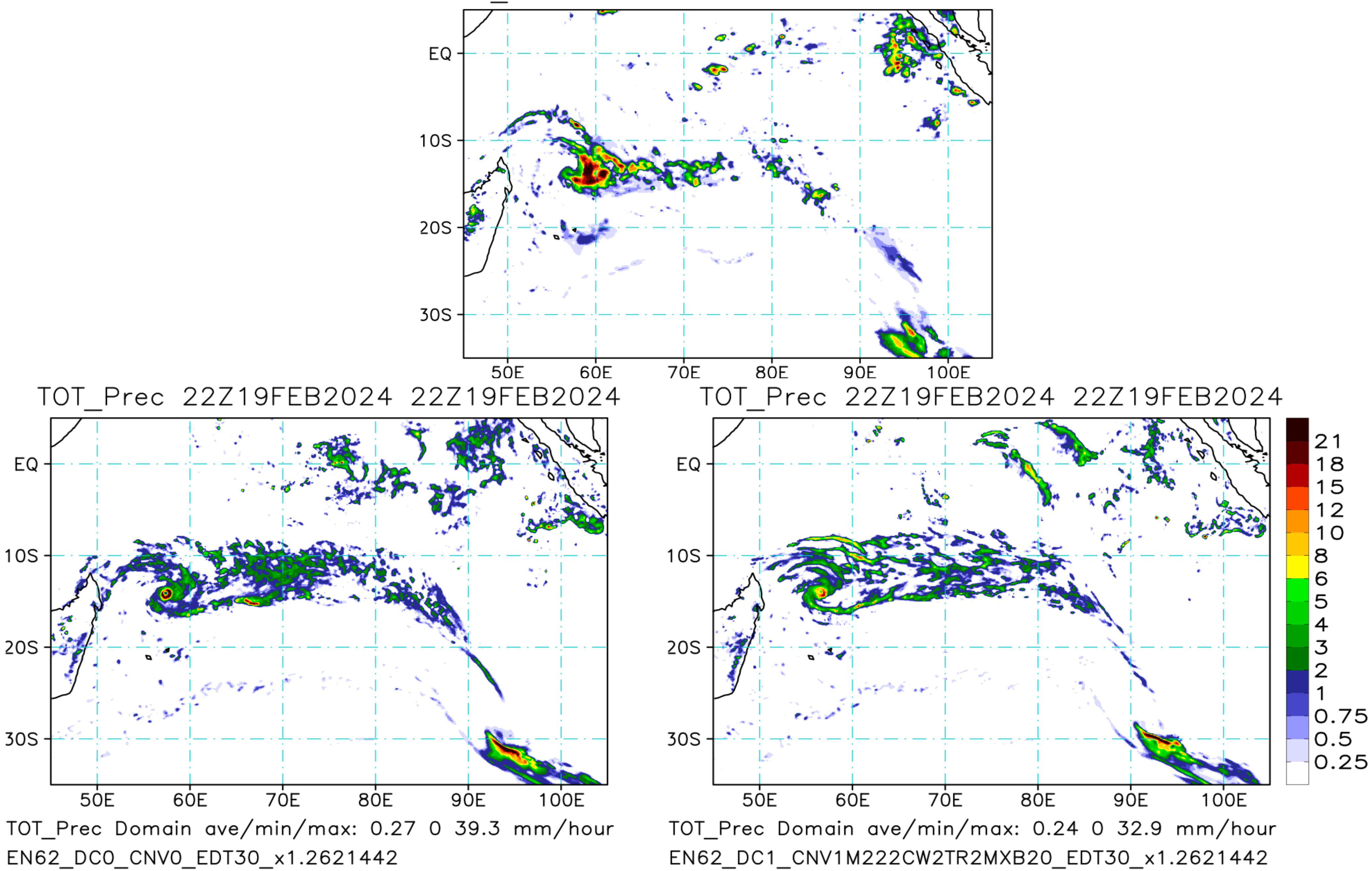

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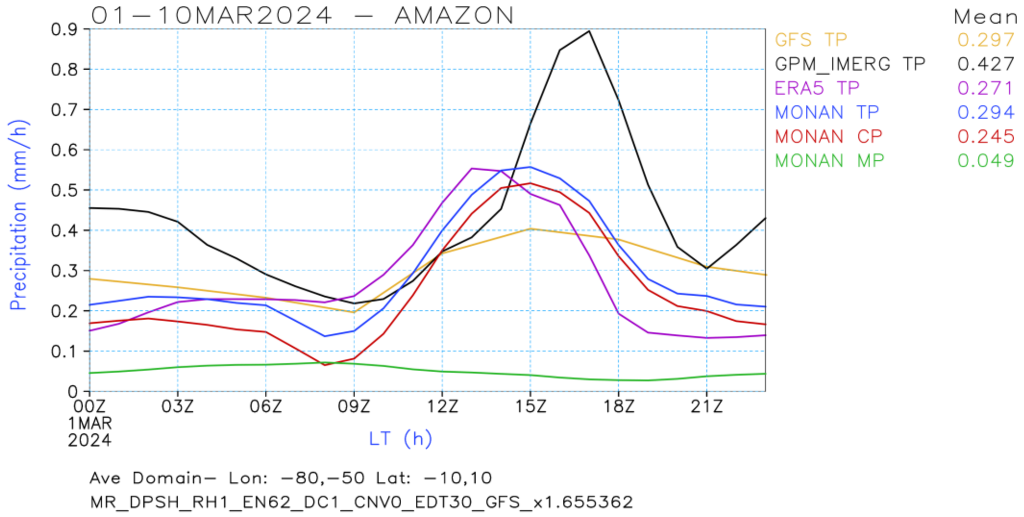

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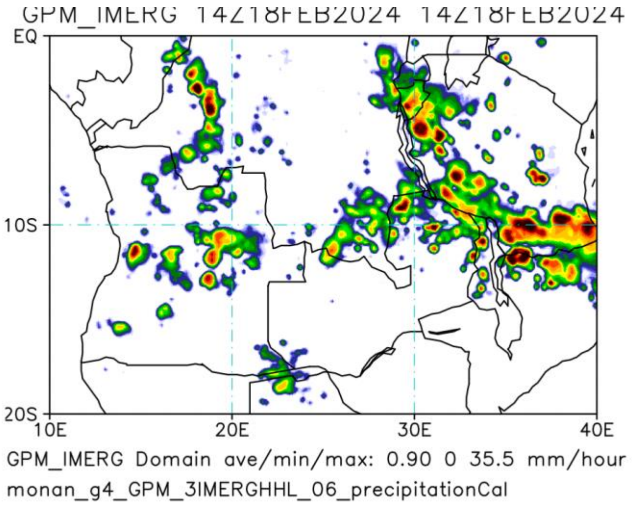
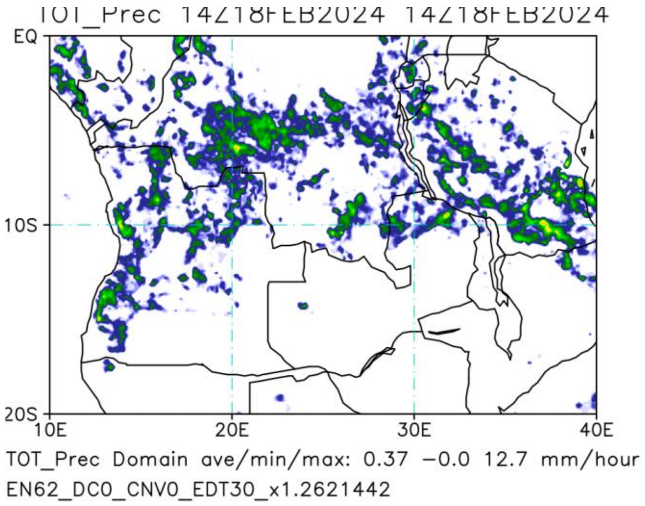
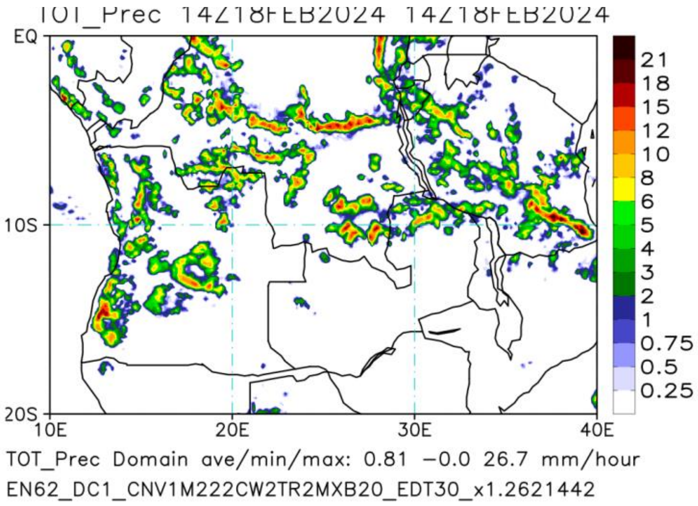
GPM_IMERG



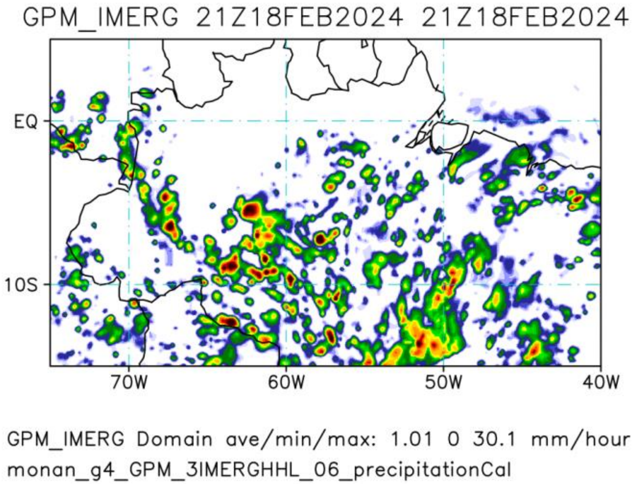
CONTROL



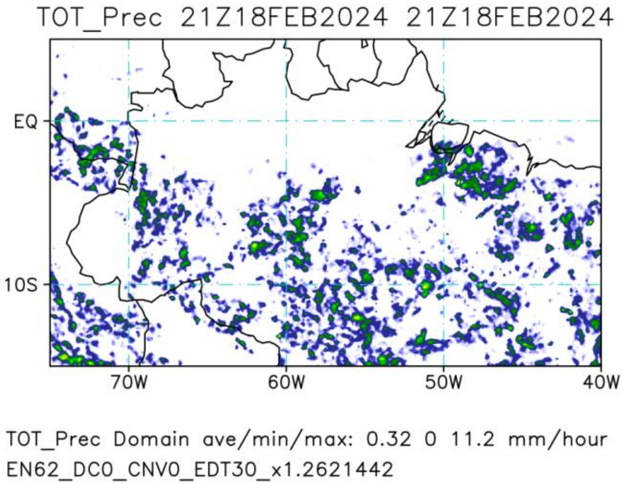
COLD POOL



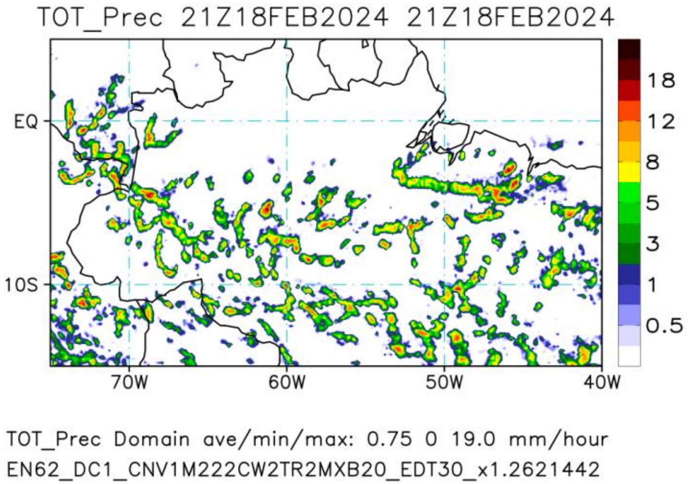
GPM_IMERG



CONTROL



COLD POOL



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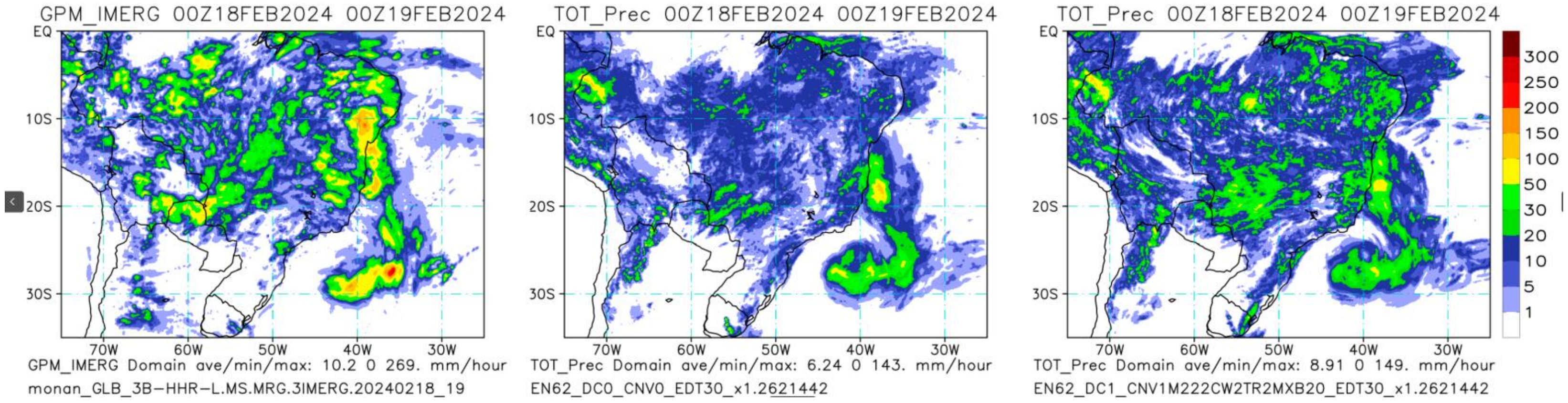

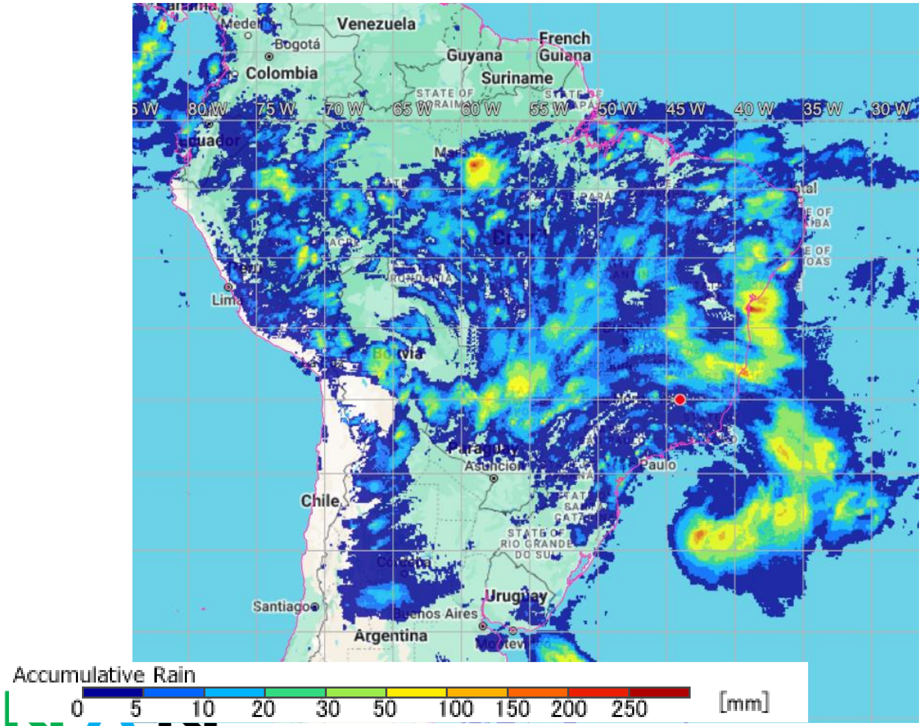

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