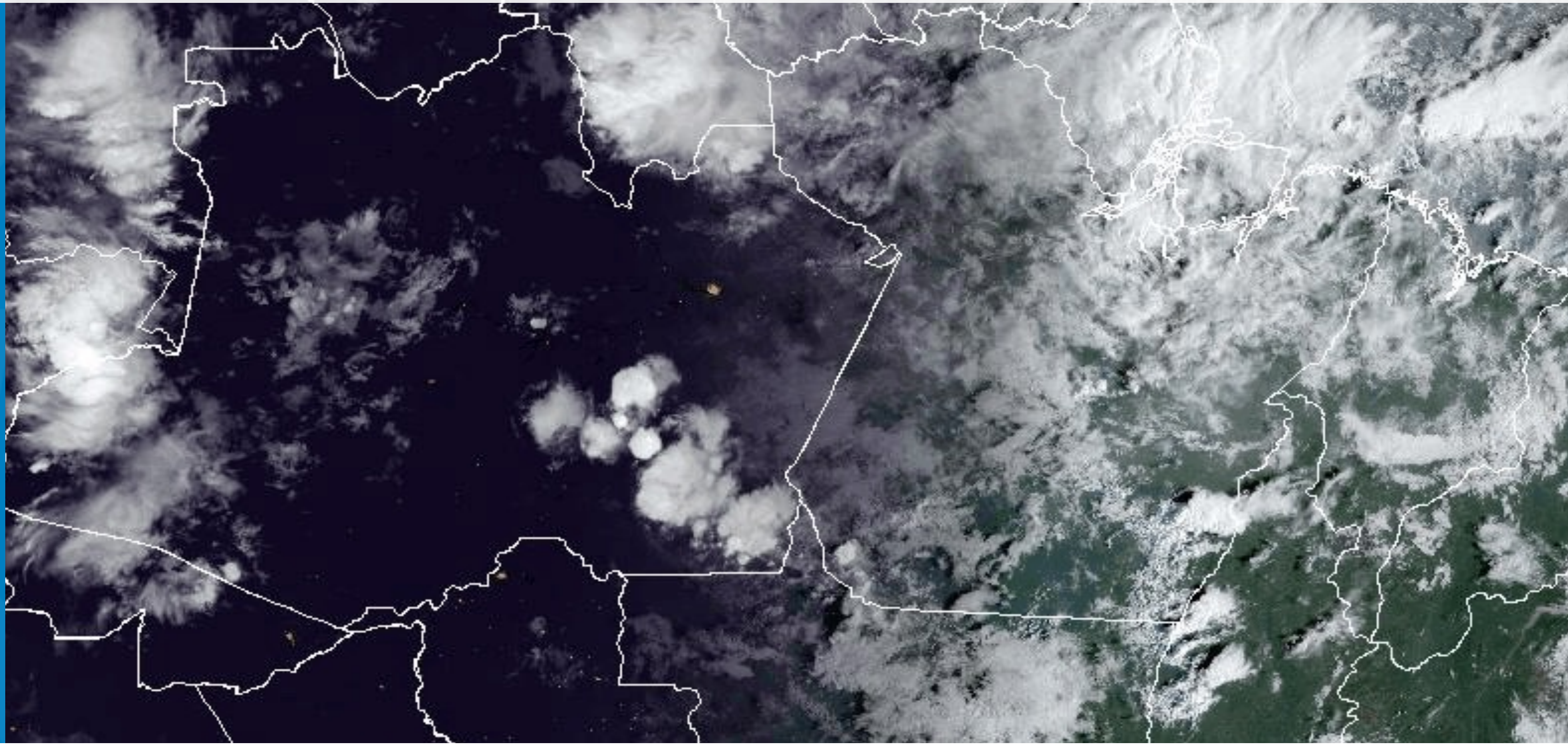
MINISTÉRIO DA CIÊNCIA, TECNOLOGIA E INOVAÇÕES
INSTITUTO NACIONAL DE PESQUISAS ESPACIAIS

Global Systems Laboratory
Oceanic and Atmospheric Research

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



Saulo R. Freitas

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

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For citation, refer to : Freitas et al (JAMES, 2023)

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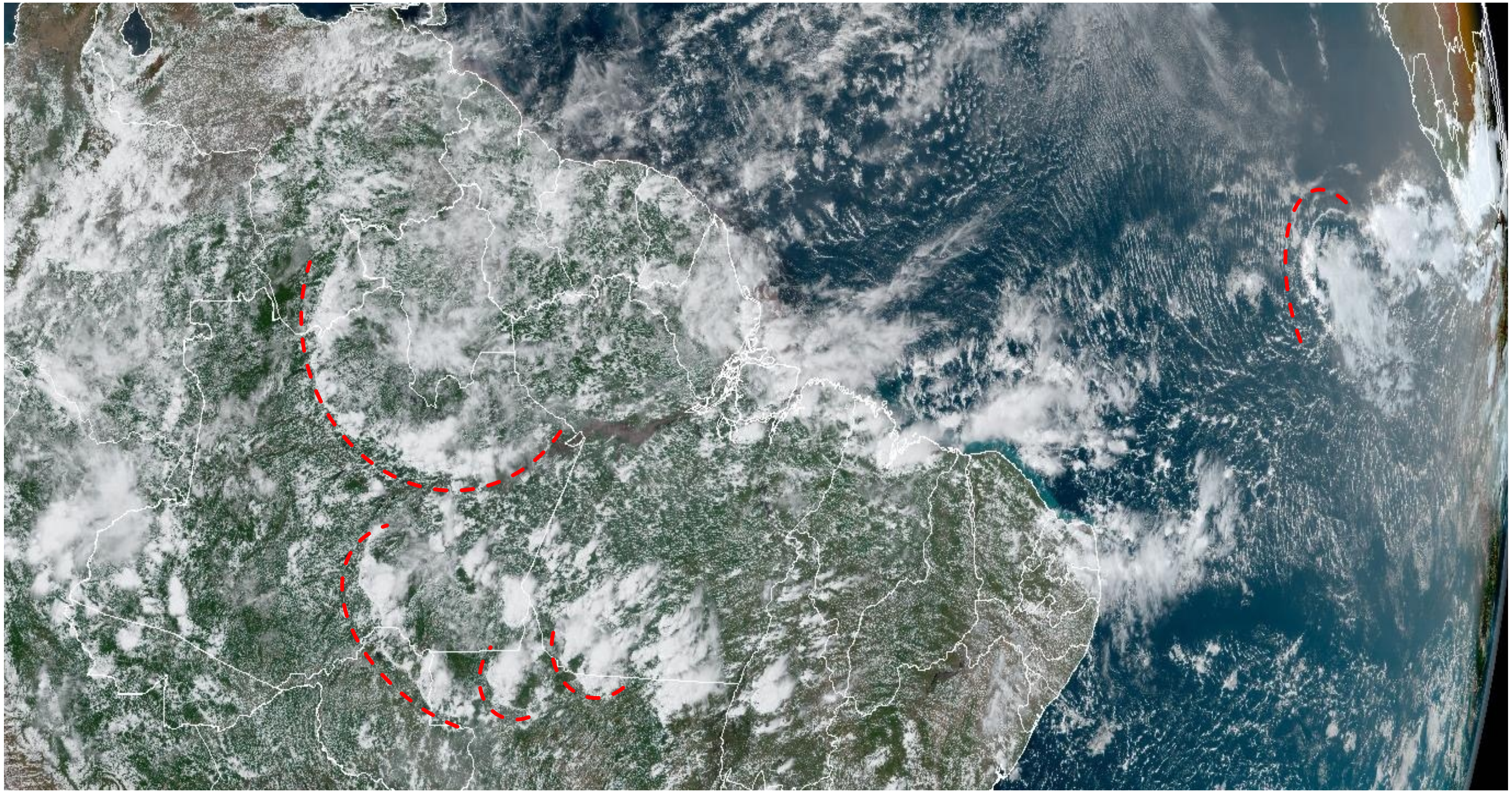
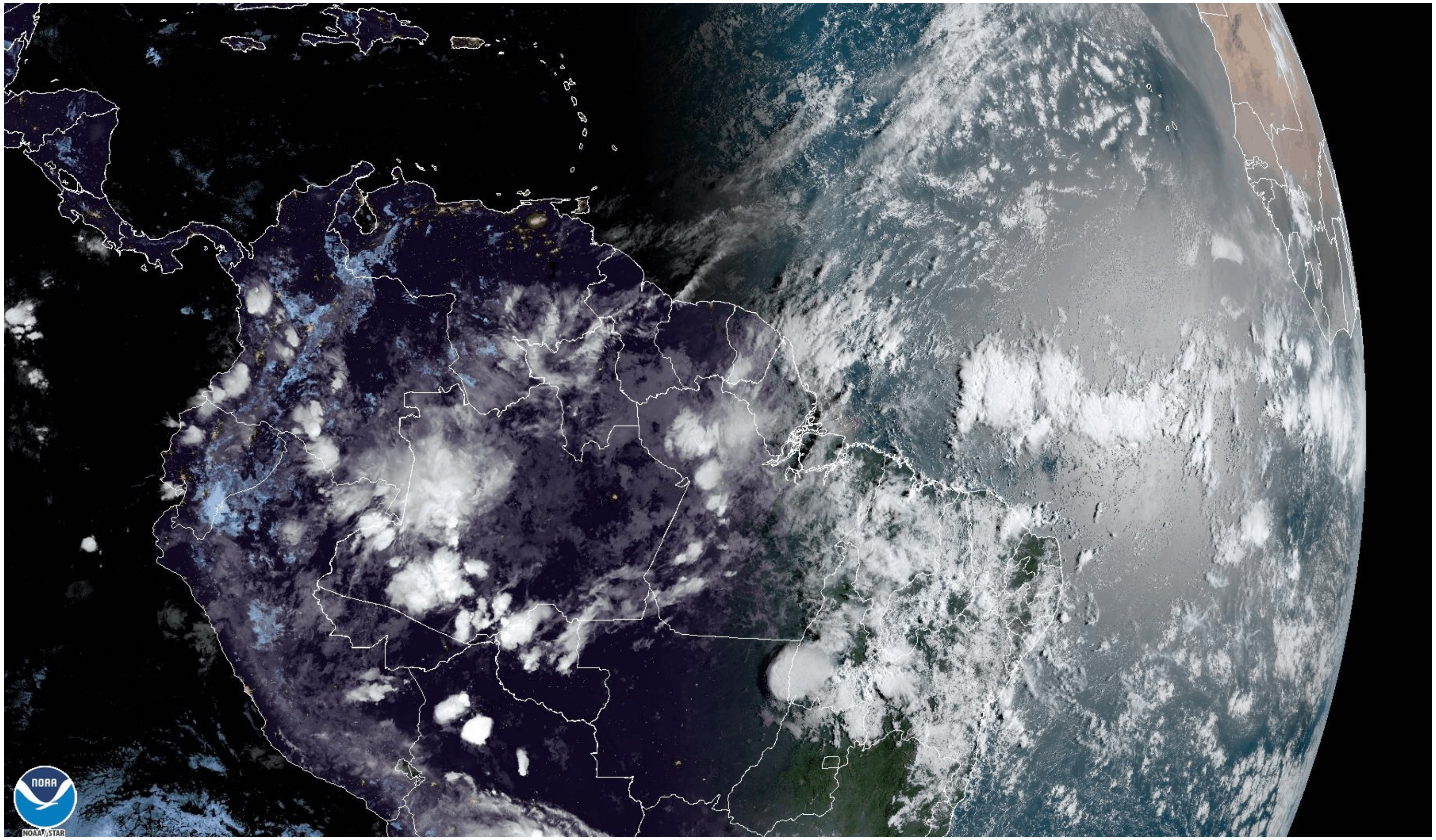
Squall lines propagation and associated cold-pools over Amazonia

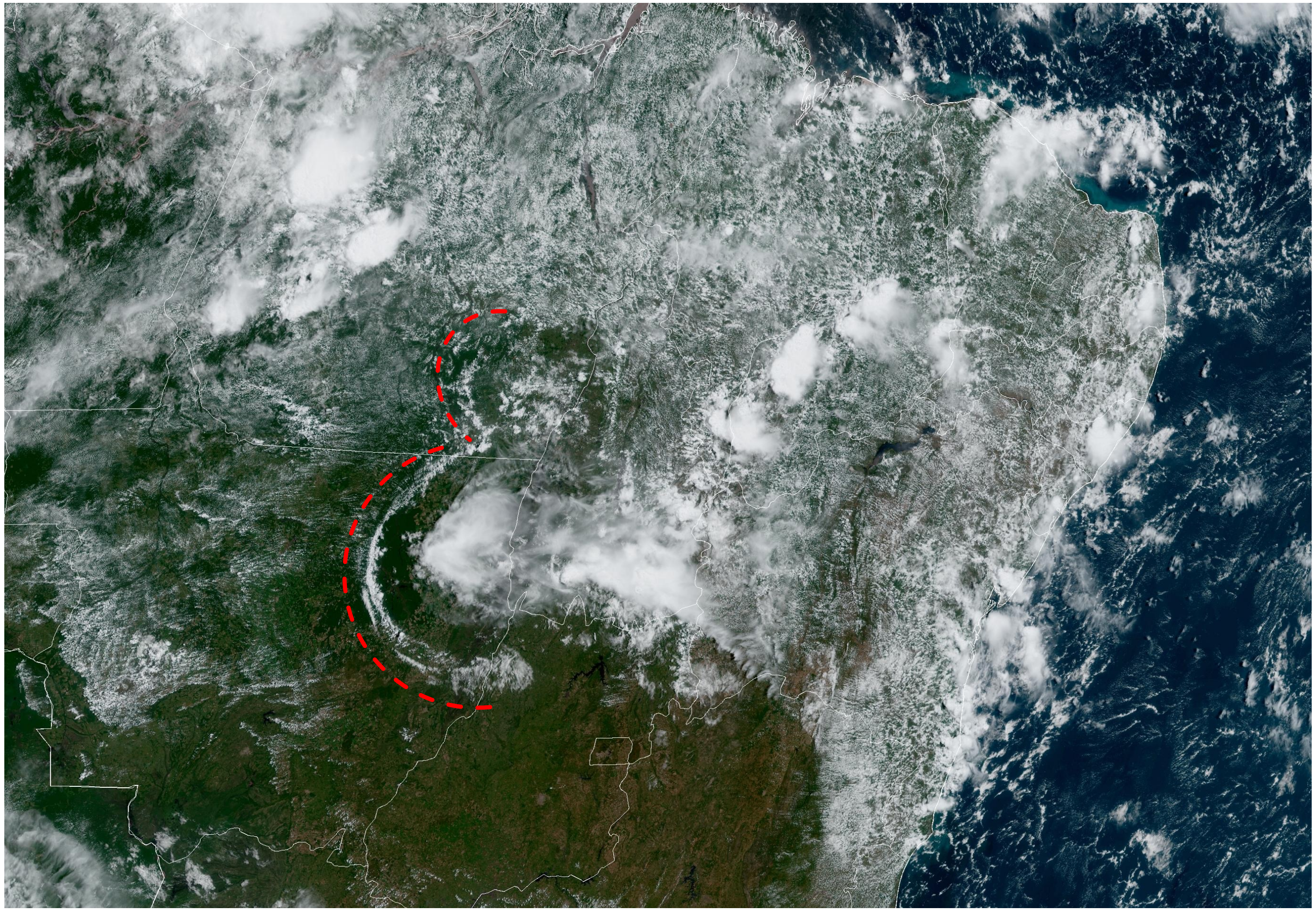


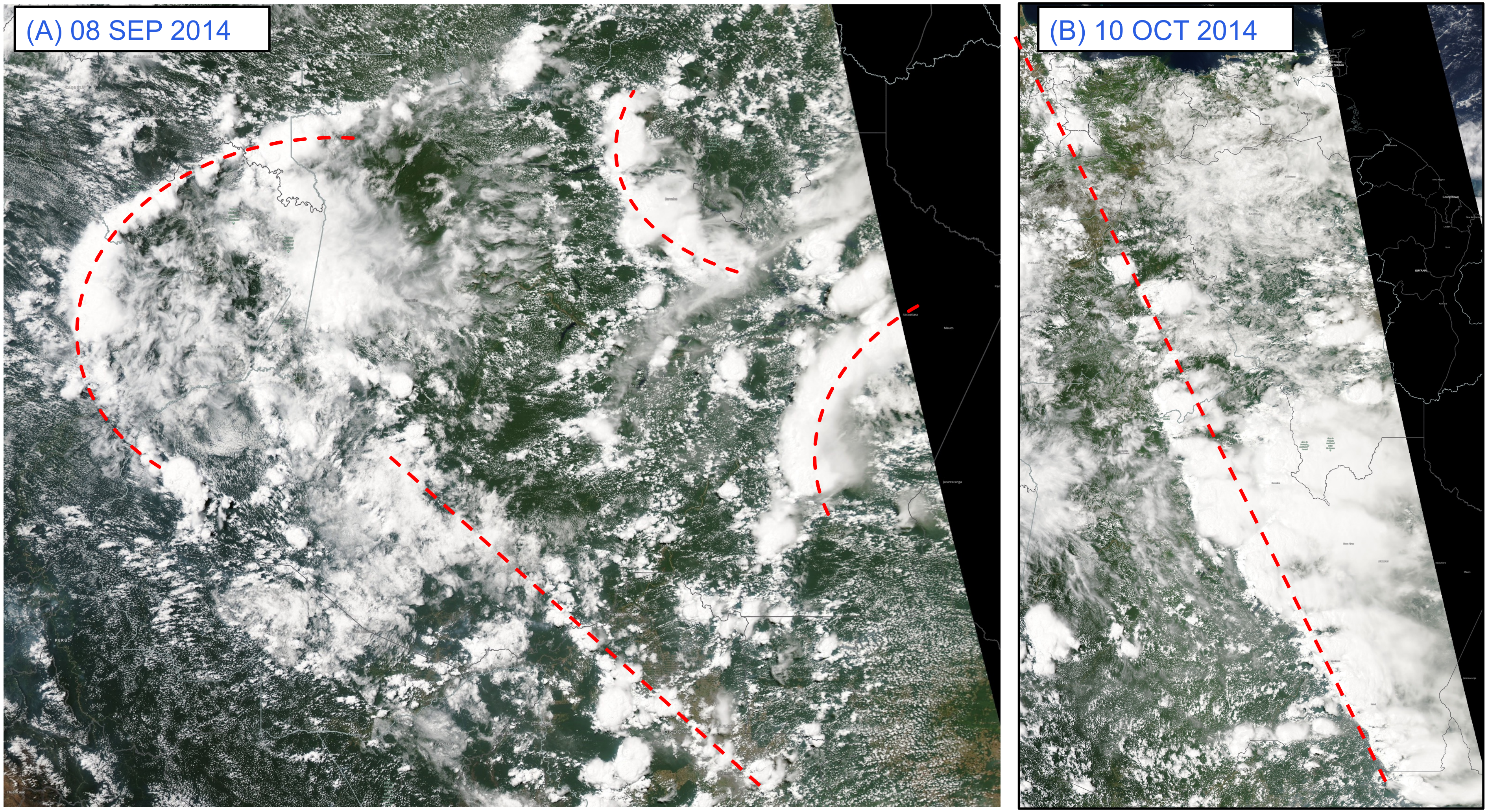
Cold Pools over the central part of Brazil



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

Cold Pools over the central part of Brazil





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

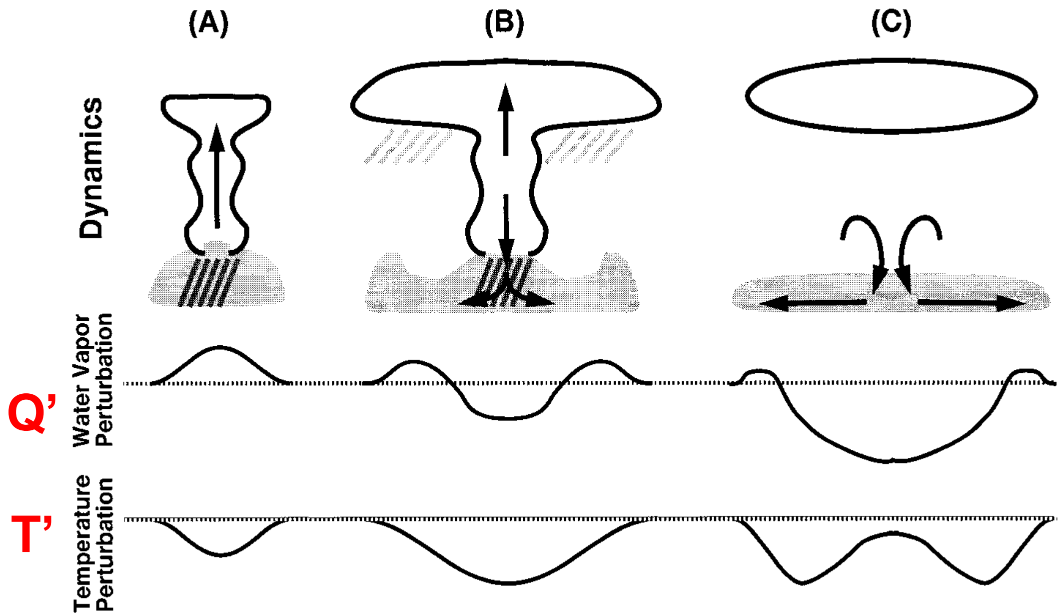
Motivation

Including representation of cold-pools 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.
- …

1 - Some Previous Studies.

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 for development of new convective cells.

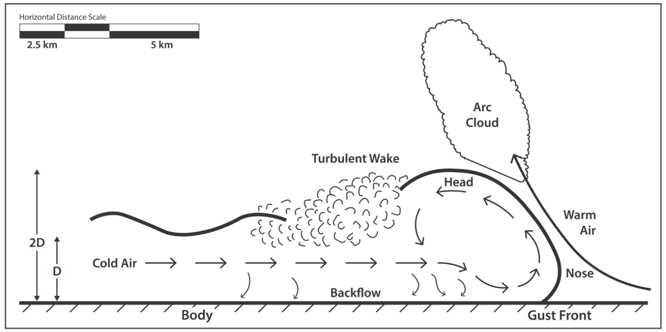


FIG. 1. Conceptual model of a density current. *D* is the height of the cooler air far behind the head of the density current. Adapted from Droegemeier and Wilhelmson (1987).

Geophysical Research Letters

RESEARCH LETTER
10.1002/2015GL063227

Mechanisms for convection triggering by cold pools

Giuseppe Torri[1], Zhiming Kuang[1,2], and Yang Tian[1]

Two mechanisms:

- At the surface mechanical lifting is needed for parcels to start ascending.
- With the kinetic energy and the total buoyancy they reach the convective inhibition layer.
- In this region, the effects of the thermodynamic forcing become manifest: because the parcels left the surface from areas of high moisture content reach their LFC more easily.

Journal of Advances in Modeling Earth Systems

RESEARCH ARTICLE
10.1002/2014MS000384

Special Section:
The 2011-12 Indian Ocean Field Campaign: Atmospheric-Oceanic Processes and MJO Initiation

Mechanisms of convective cloud organization by cold pools over tropical warm ocean during the AMIE/DYNAMO field campaign

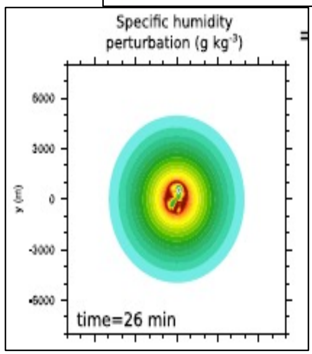
Zhe Feng[1], Samson Hagos[1], Angela K. Rowe[2], Casey D. Burleyson[1], Matus N. Martini[1], and Simon P. de Szoeke[3]

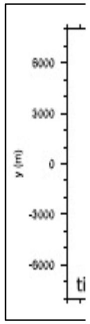
Geophysical Research Lett

RESEARCH LETTER
10.1002/2015GL065623

The origin of water vapor rings in tropical oceanic cold pools

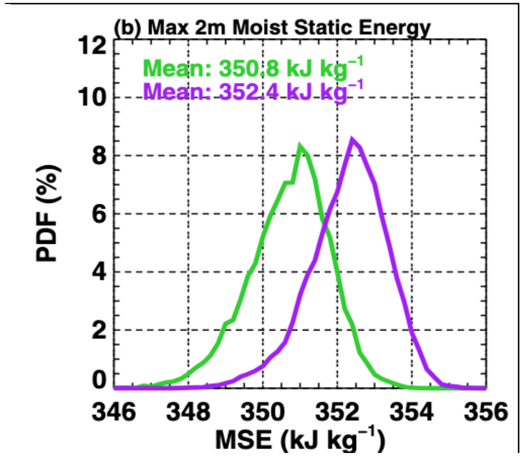
Wolfgang Lang





Environment at the edge of cold pools is clearly more favorable for new convection:

- in contrast to the cold pool centers, the temperature depressions along the edges are less than -1 C.
- moist static energy is on average 1600 J/kg higher along the edges.
- CAPE is higher
- CIN is lower

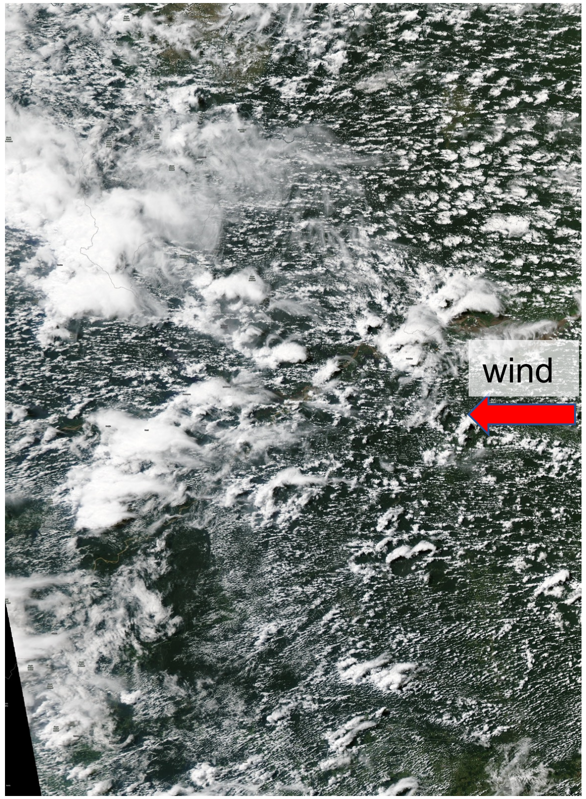


- the LCL is on average lower on the edges compared to the center.

2 - Cloud-Resolving Simulations to Support the Parameterization Design.

Cloud-resolving simulations over the Amazon Basin

- Model BRAMS (Freitas et al., 2017 GMD)
- 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)
- Microphysics: hybrid single and double moment (Thompson and Eidhammer, 2014)
- Radiation : RRTMG (short- and long-wave)
- Surface scheme : LEAF-3 (Walko et al., 2000)



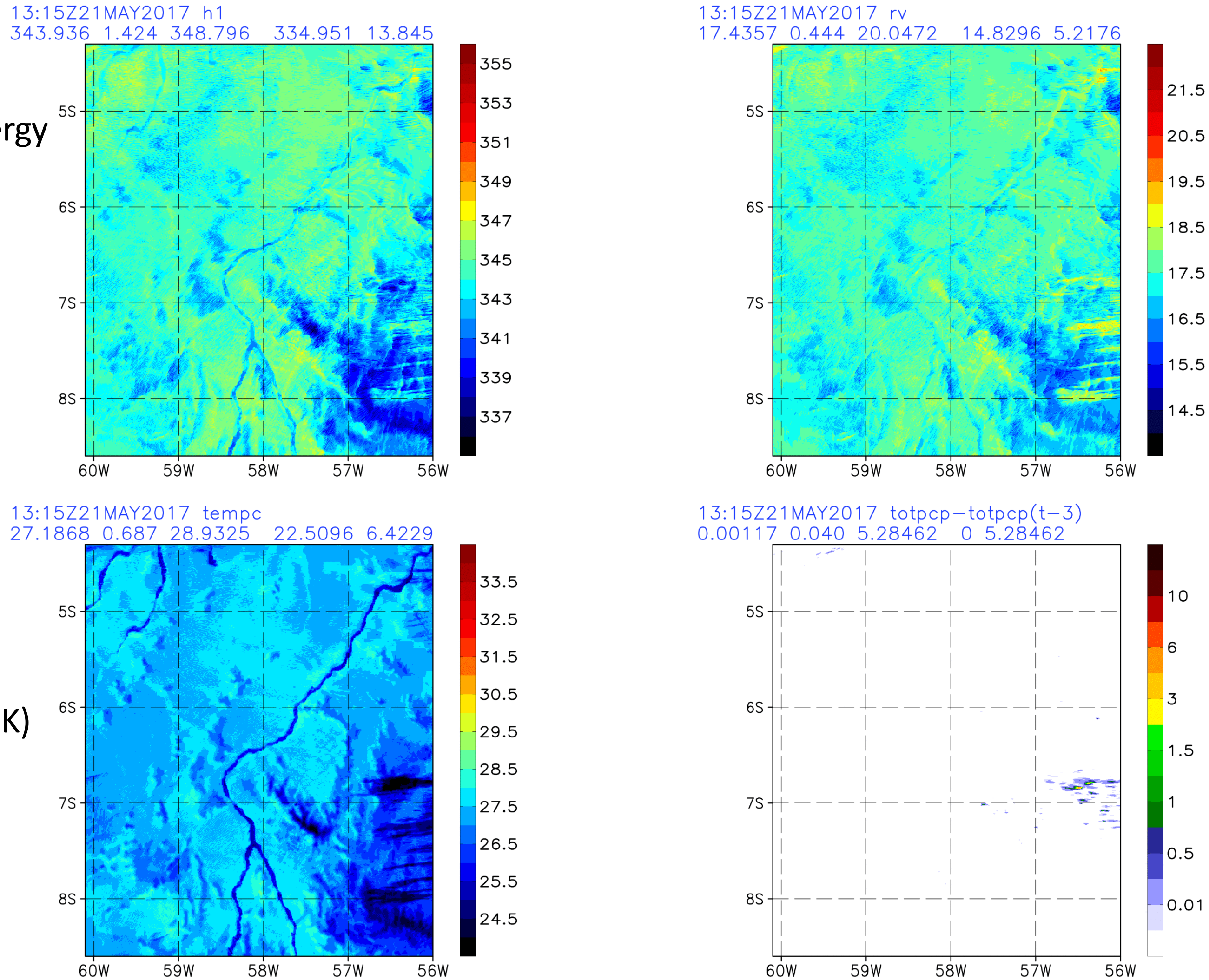
MODIS visible image
1:30 PM MAY 2017

Simulation day

Cloud-resolving simulations over the Amazon Basin

Moist Static Energy (MSE/c_p, K)

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



Temperature (K)

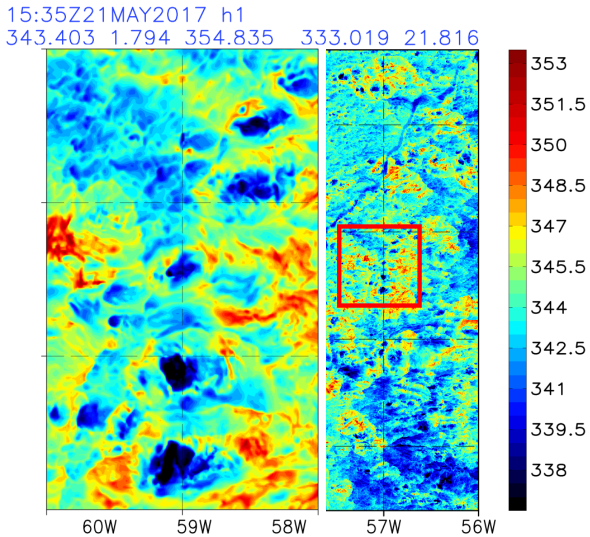
15mn accum. precipitation (mm)

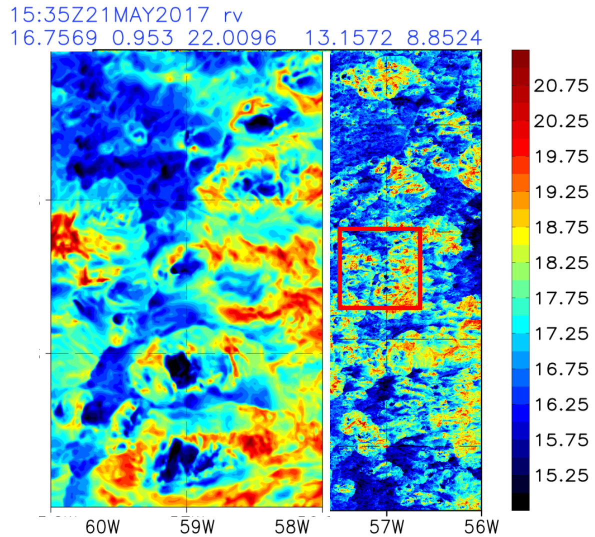
Freitas et al. (in prep.)

21 MAY 2017 – 13:00 to 20:00 UTC

Cloud-resolving simulations over the Amazon Basin

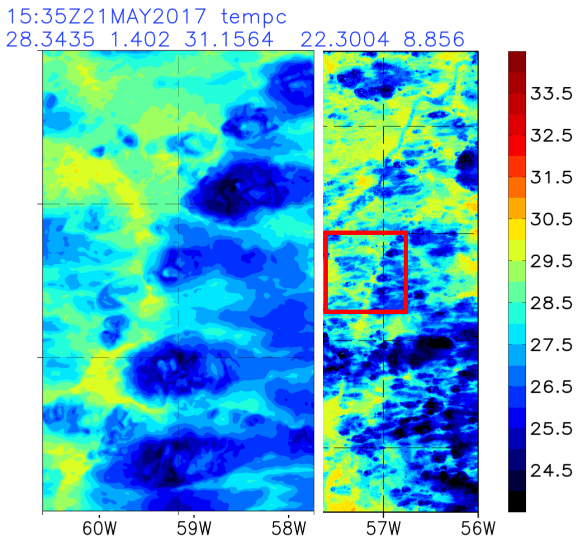
MSE/c_p (K)

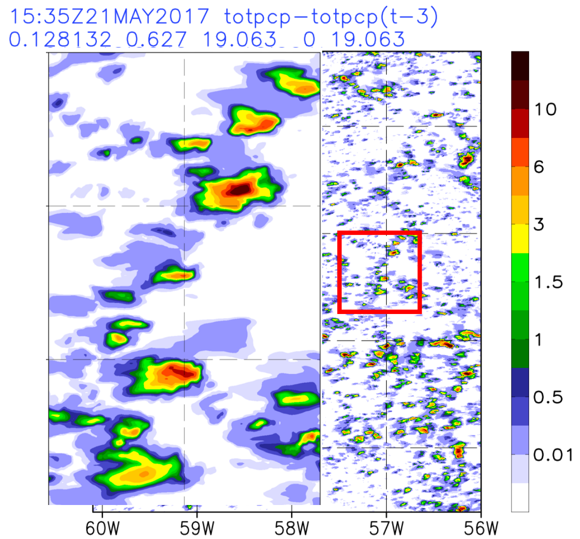




Water vapor mixing ratio ($g\ kg^{-1}$)

Temperature (K)

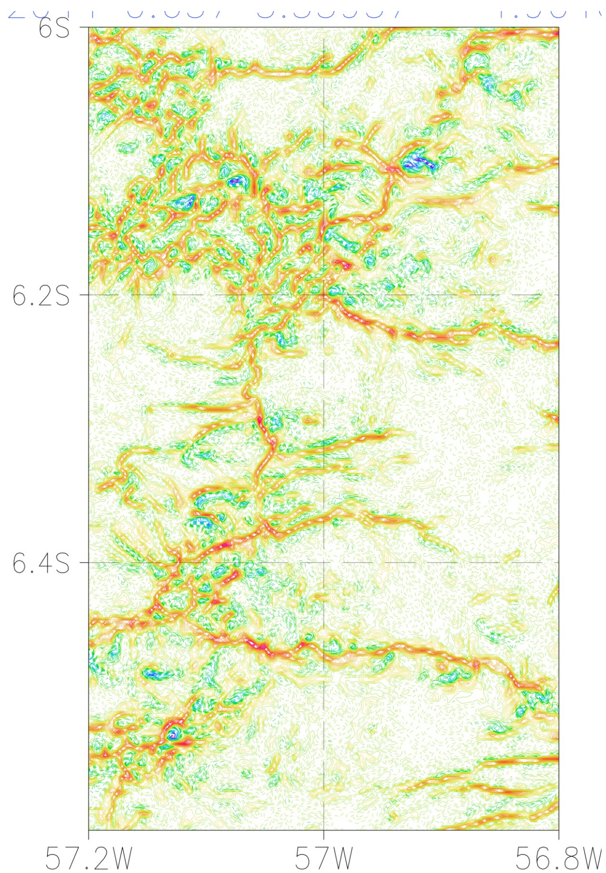




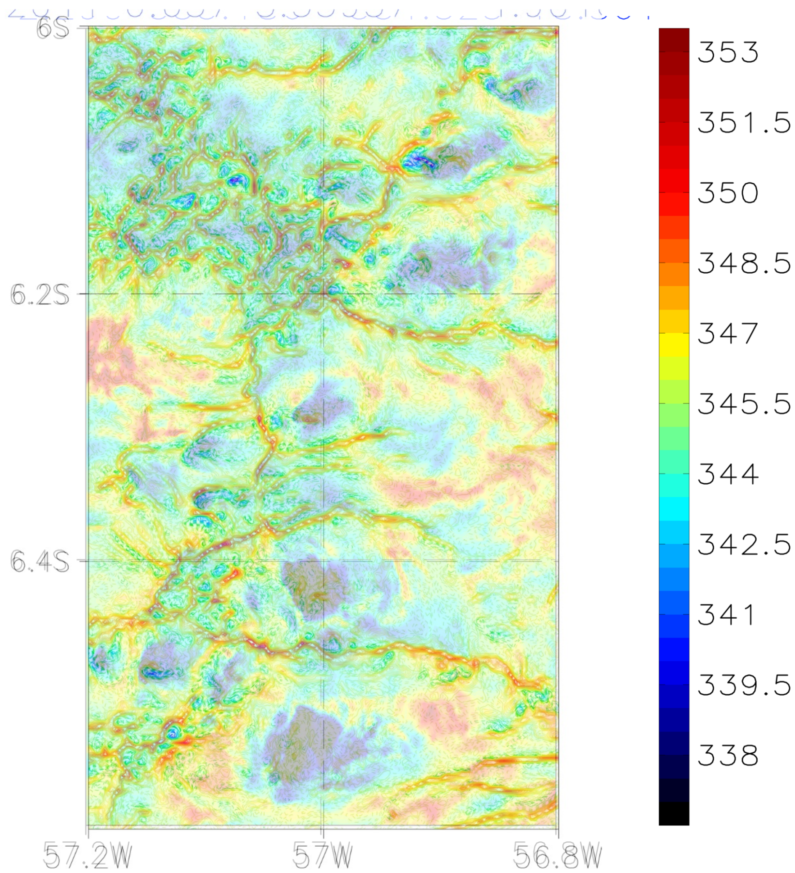
15mn accum. precipitation (mm)

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)

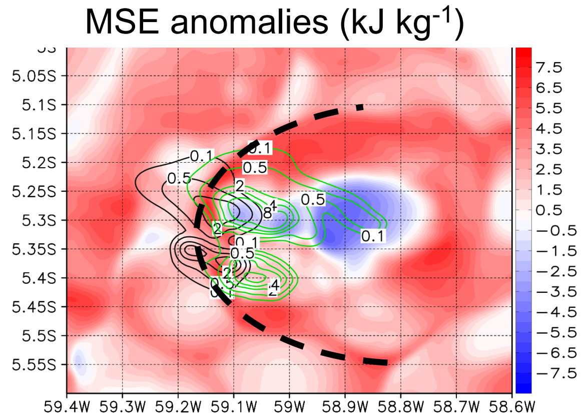
Discriminating regions at the edges and inside the cold pools

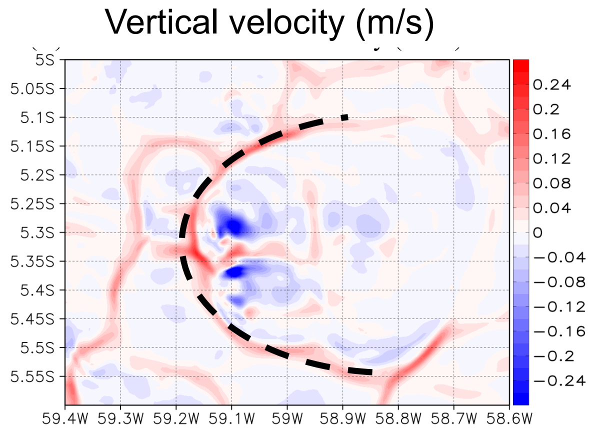
1) if W > 0.1 m/s + subsequent 30mn precipitation is > 4 mm

=> region of positive MSE anomalies or the region of the 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.

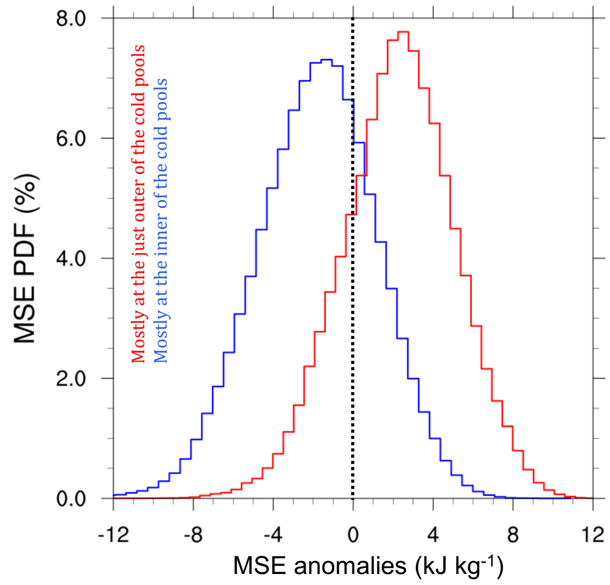




PDFs for the MSE anomalies:

Red : just outer 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

Table 1. Statistical indicators of the MSE anomalies PDF

Similar to Feng et al (2014) over tropical ocean

3 - A proposed parameterization.

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

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

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

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:

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

Freitas et al. (2023, JAMES, under review)

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

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

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

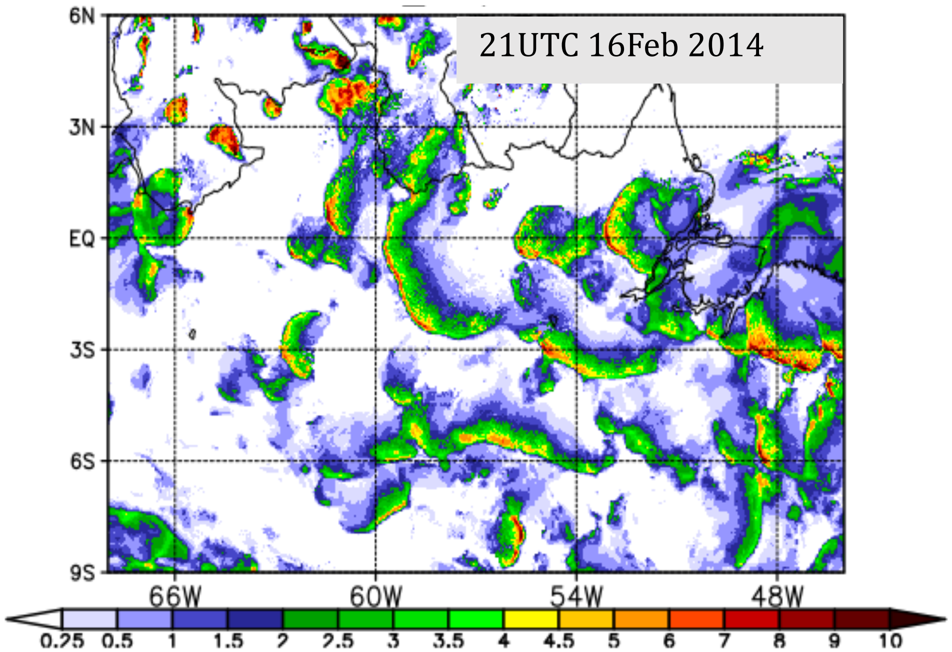
2-d advection

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 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).

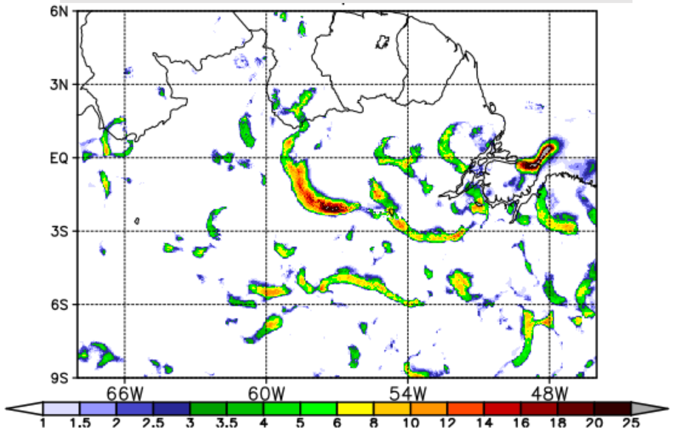
2nd Effect: optional trigger function based on the kinetic energy ($E_k = \frac{1}{2} W_{gf}^2$) of the air parcels at the leading edge of the gust front. In this case, deep convection is allowed in a model column if

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

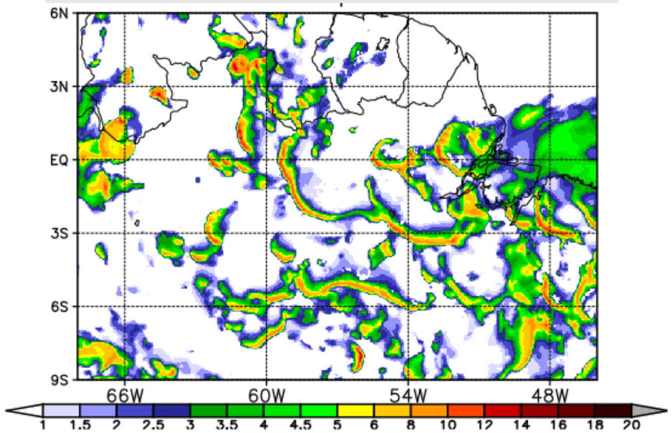
GF (Grell and Freitas ACP 2014; Freitas et al. JAMES 2018, GMD 2021)

Results using BRAMS model with Grell-Freitas CP

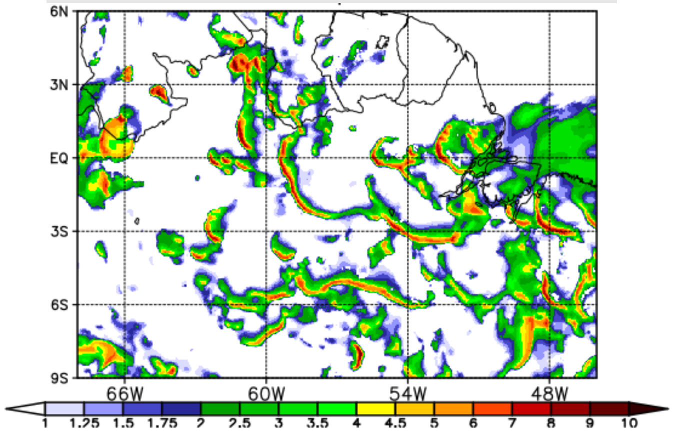
1-hourly precipitation rate (mm/h)



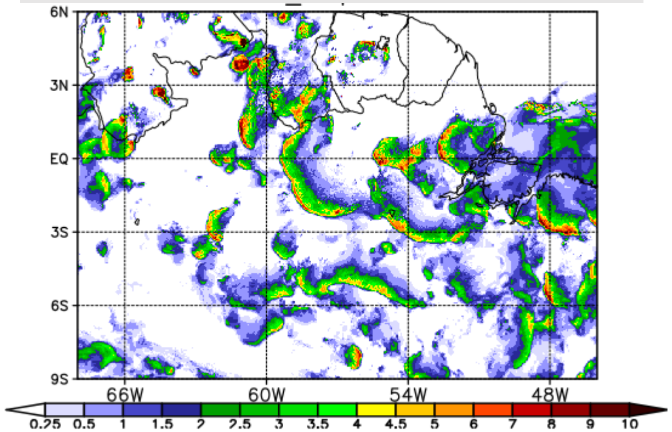
Gust front speed (m/s)



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



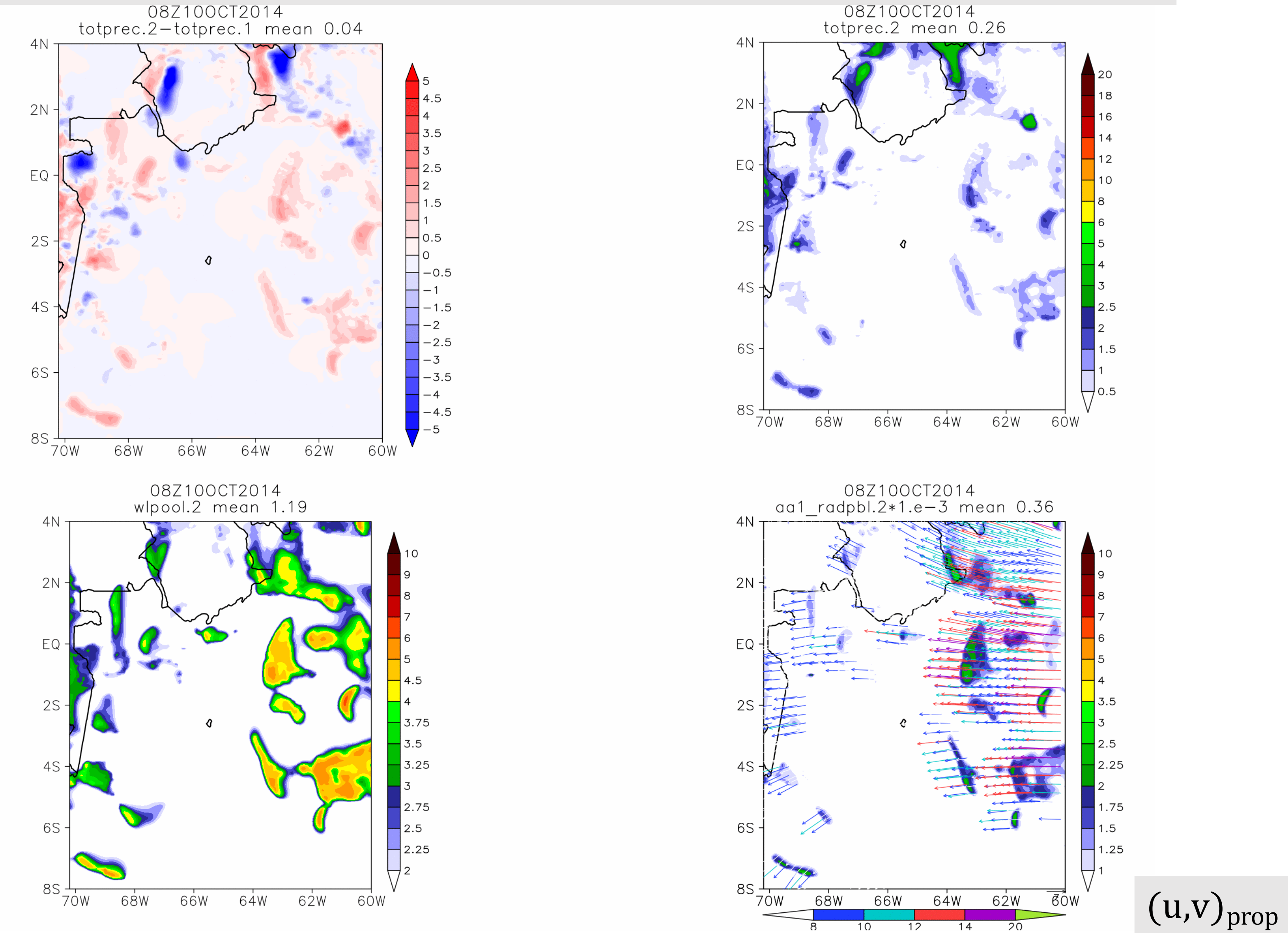
Near surface buoyancy-excess (kJ/kg)



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

Results from BRAMS @ 8km

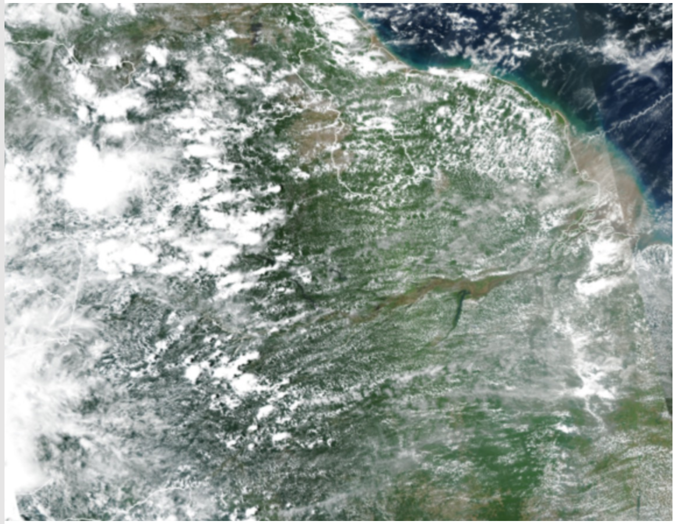
Precipitation rate (cold-pool – control) (mm/h) Precipitation rate (cold-pold)



Max vertical velocity at the edge of the cold-pool (m/s) Near surface buoyancy-excess (kJ/kg)

GoAmazon Simulations with the BRAMS model

- Model BRAMS (Freitas et al. 2017 GMD)
- 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, Rodrigues et al. 2020)
- PBL Parameterization: M&Y 2.5 (Mellor & Yamada 1982)
- Monotonic advection for scalars (Freitas et al. 2011)
- Microphysics: WSM 5-class single moment (Hong et al. 2004)
- Convection Parameterization: GF (Grell and Freitas 2014; Freitas et al. 2018, 2021)
- Radiation : RRTMG (short- and long-wave, Iacono et al. 2000)
- Surface scheme : JULES (Moreira et al. 2013)

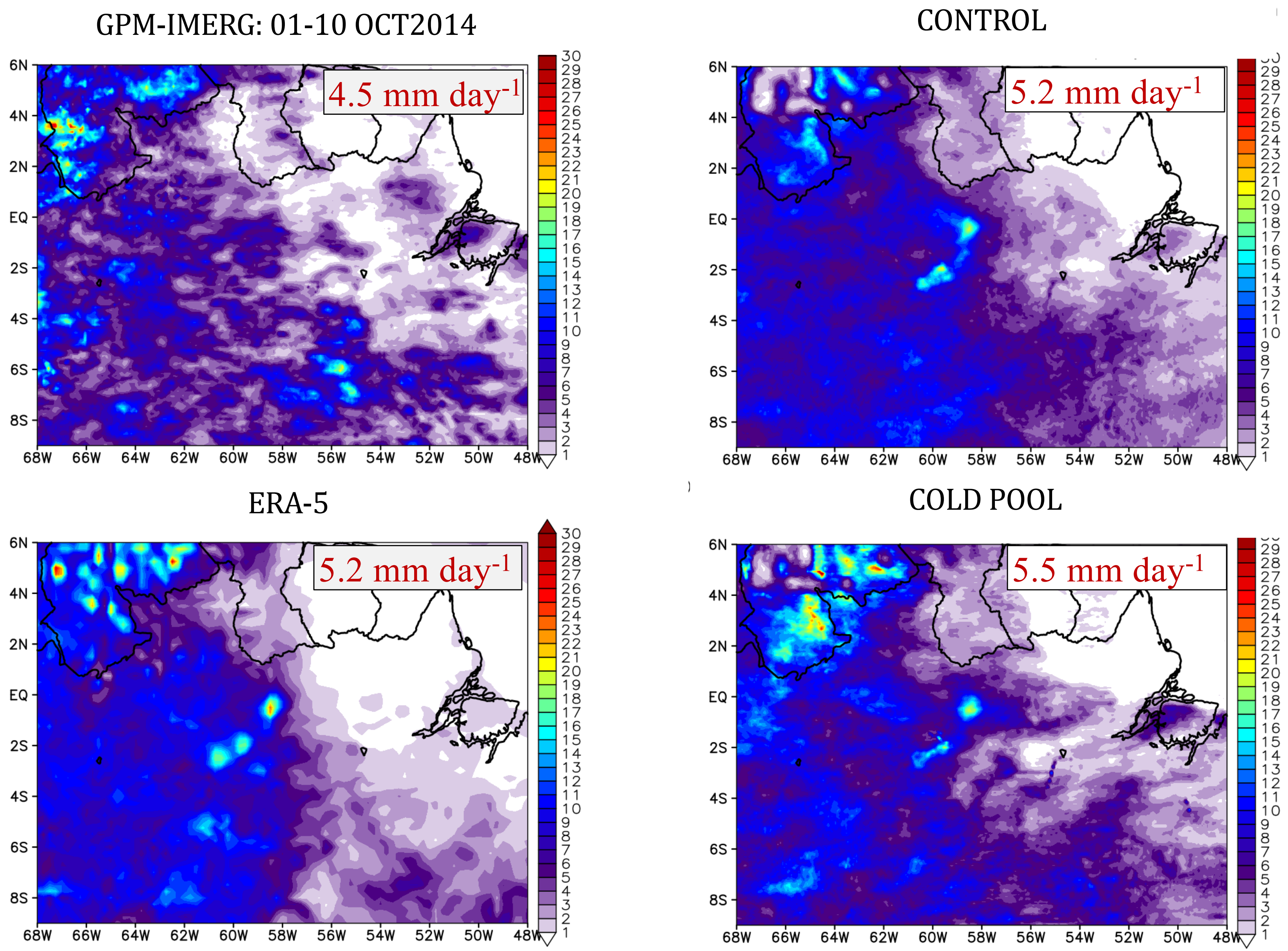


Model Domain

- 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)

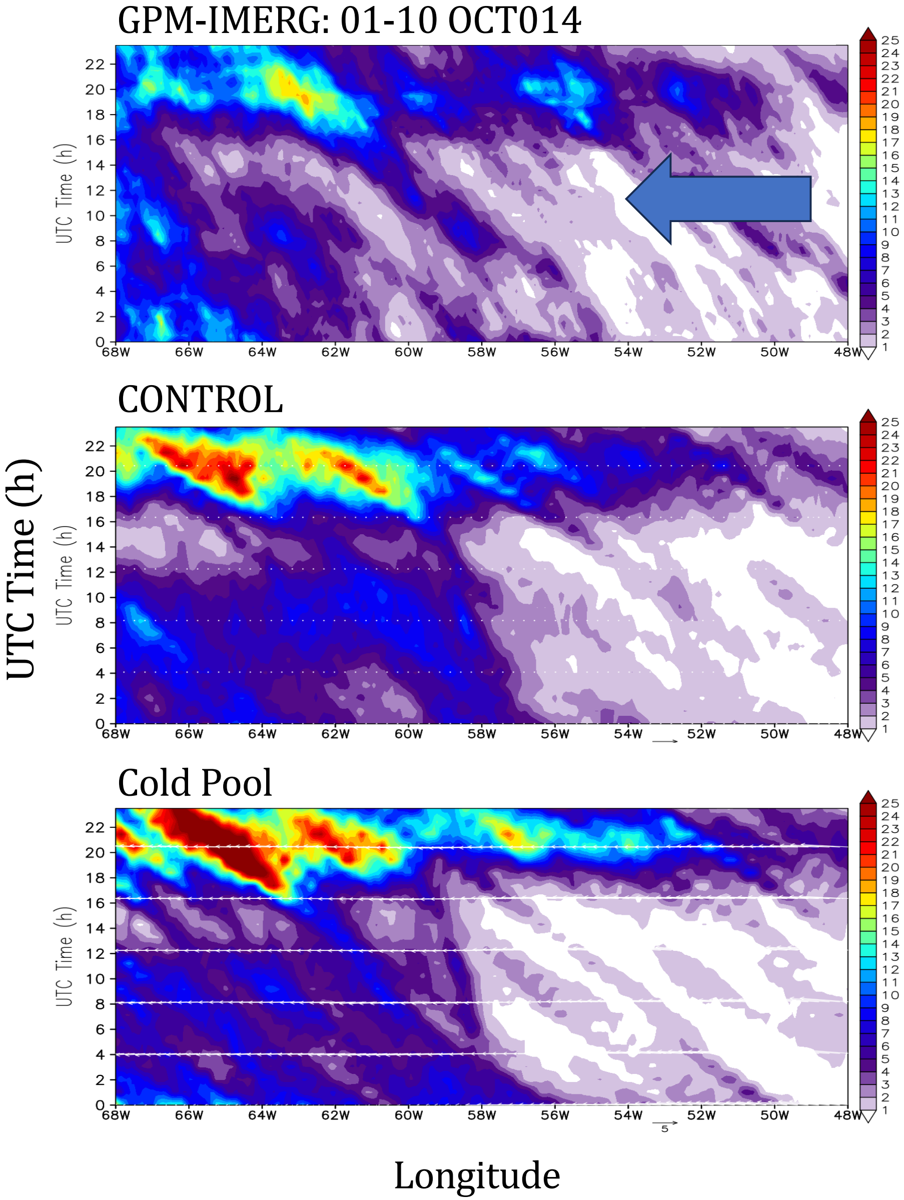
- Experiments GoAmazon
- IOP1_1: 15-24 Feb 2014 – wet season
- IOP2_1: 01-10 SEP 2014 - dry season
- IOP2_4: 01-10 Oct 2014 - transition
- Total analyzed days: 30

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

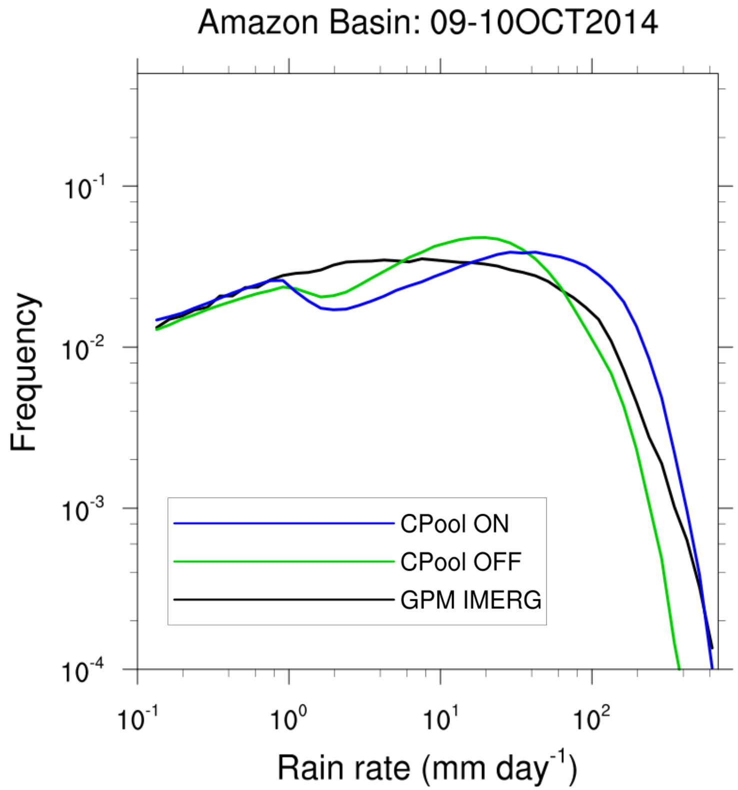


10 days average

Impacts on Storm's Propagation



Effects on the Intensity of the Storms

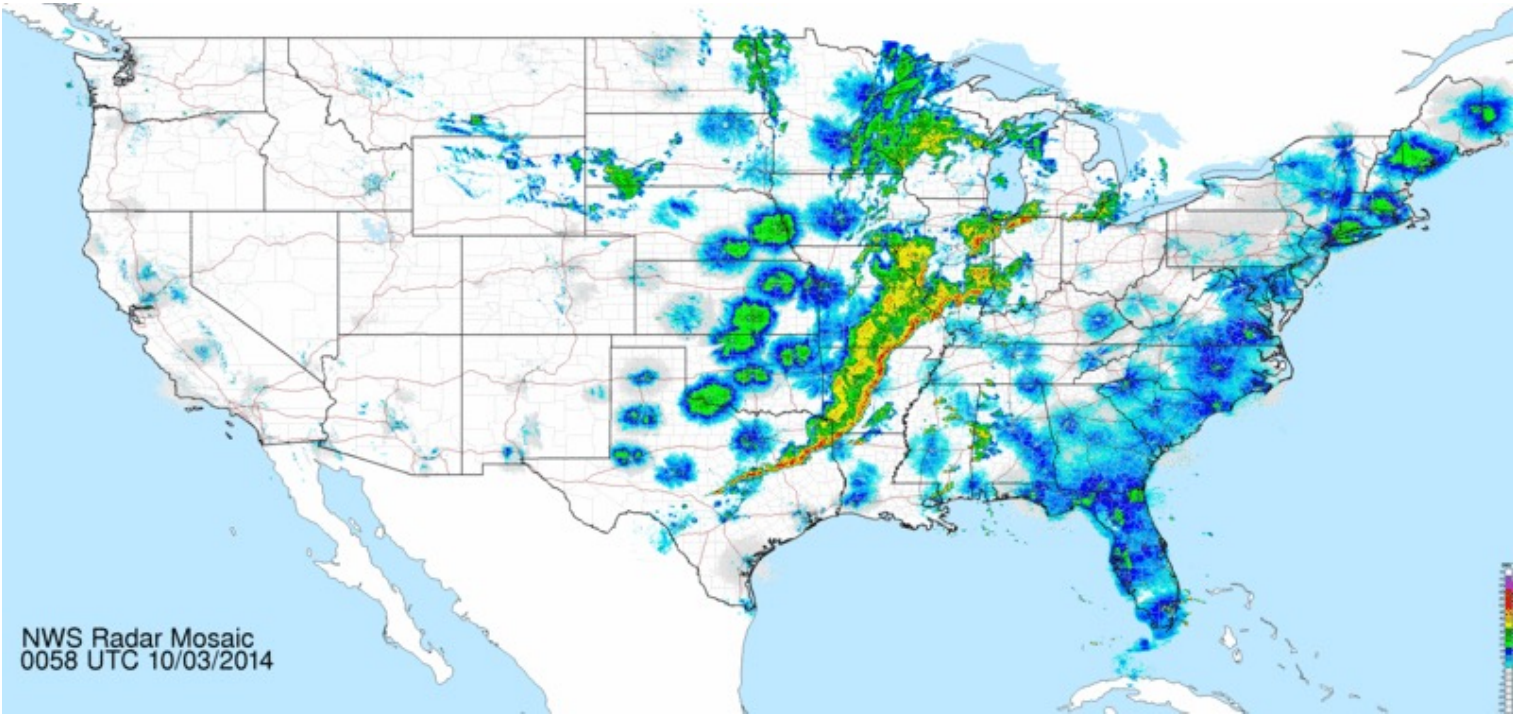


4 - Mesoscale Convective Systems Case Studies.

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

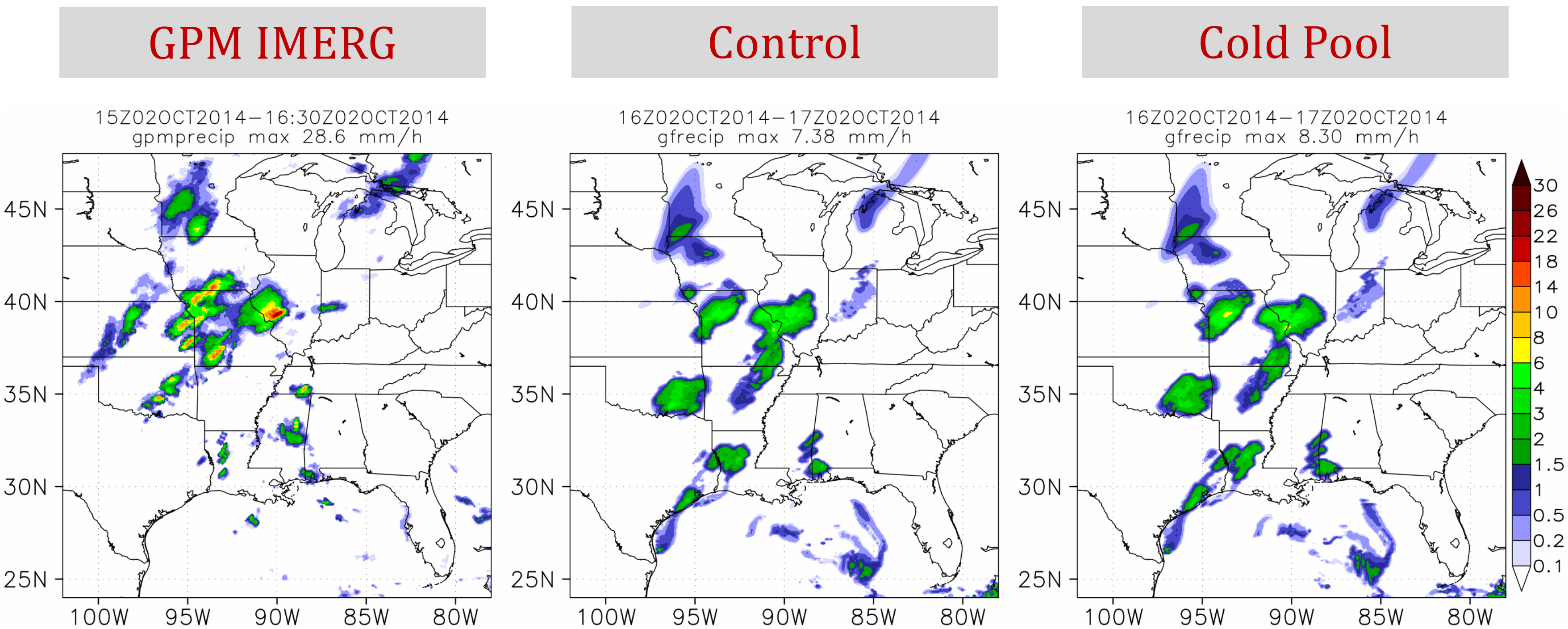
“1,200-Mile-Long Line of Storms Batters Central U.S. on Thursday Night”



02-03 October 2014

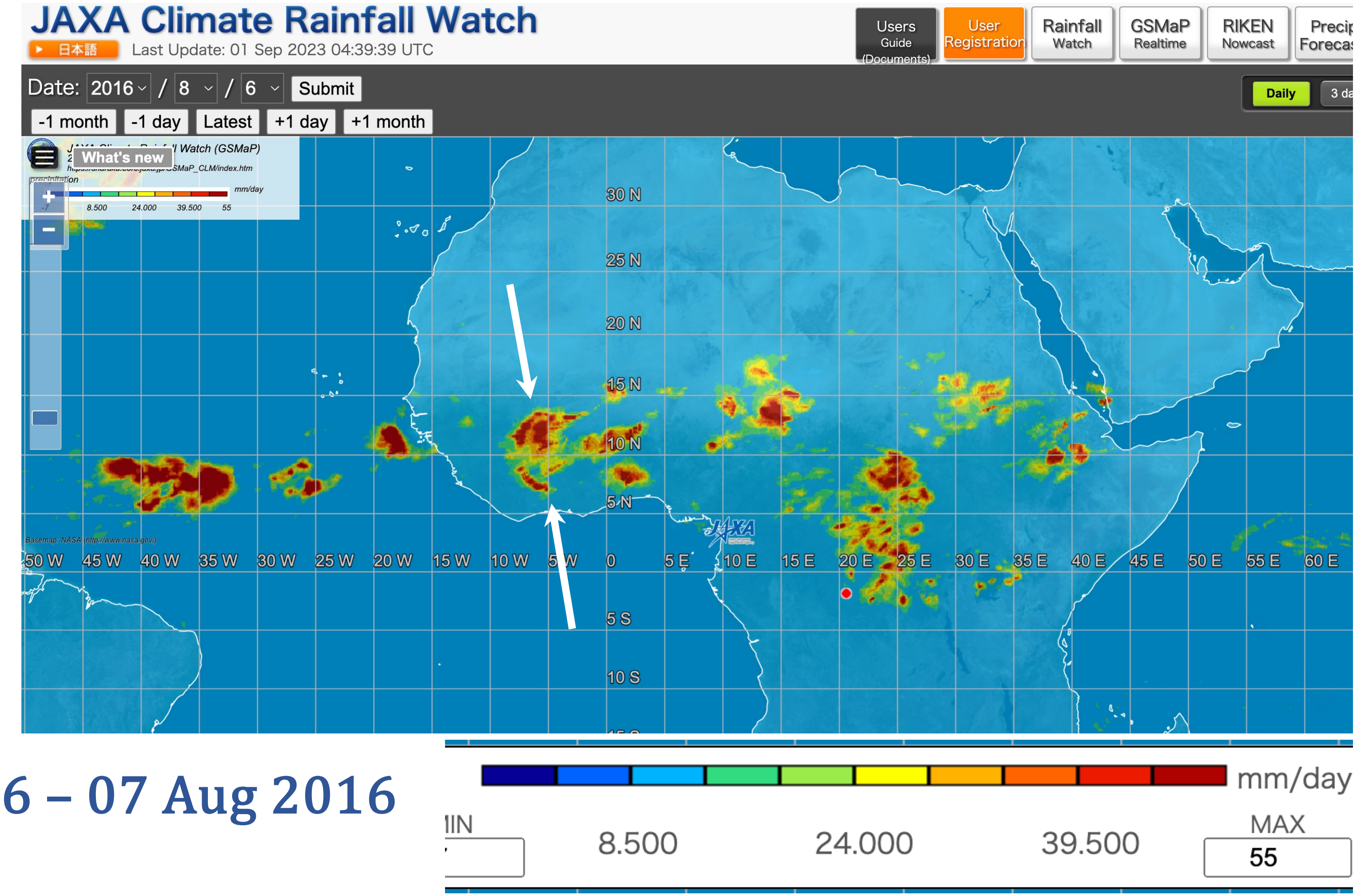
https://thevane.gawker.com/1-200-mile-long-line-of-storms-batters-central-u-s-on-1641956485

MCS over the CONUS



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

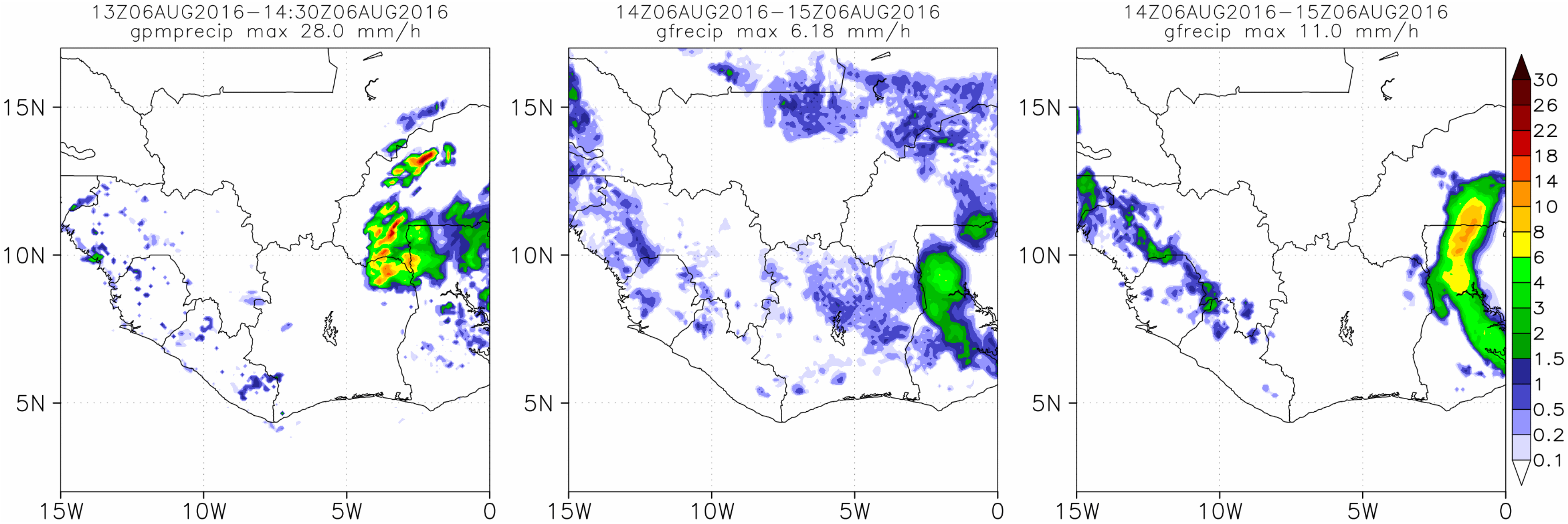
MCS over Western Africa



06 – 07 Aug 2016

MCS over Western Africa

GPM IMERG	Control	Cold Pool

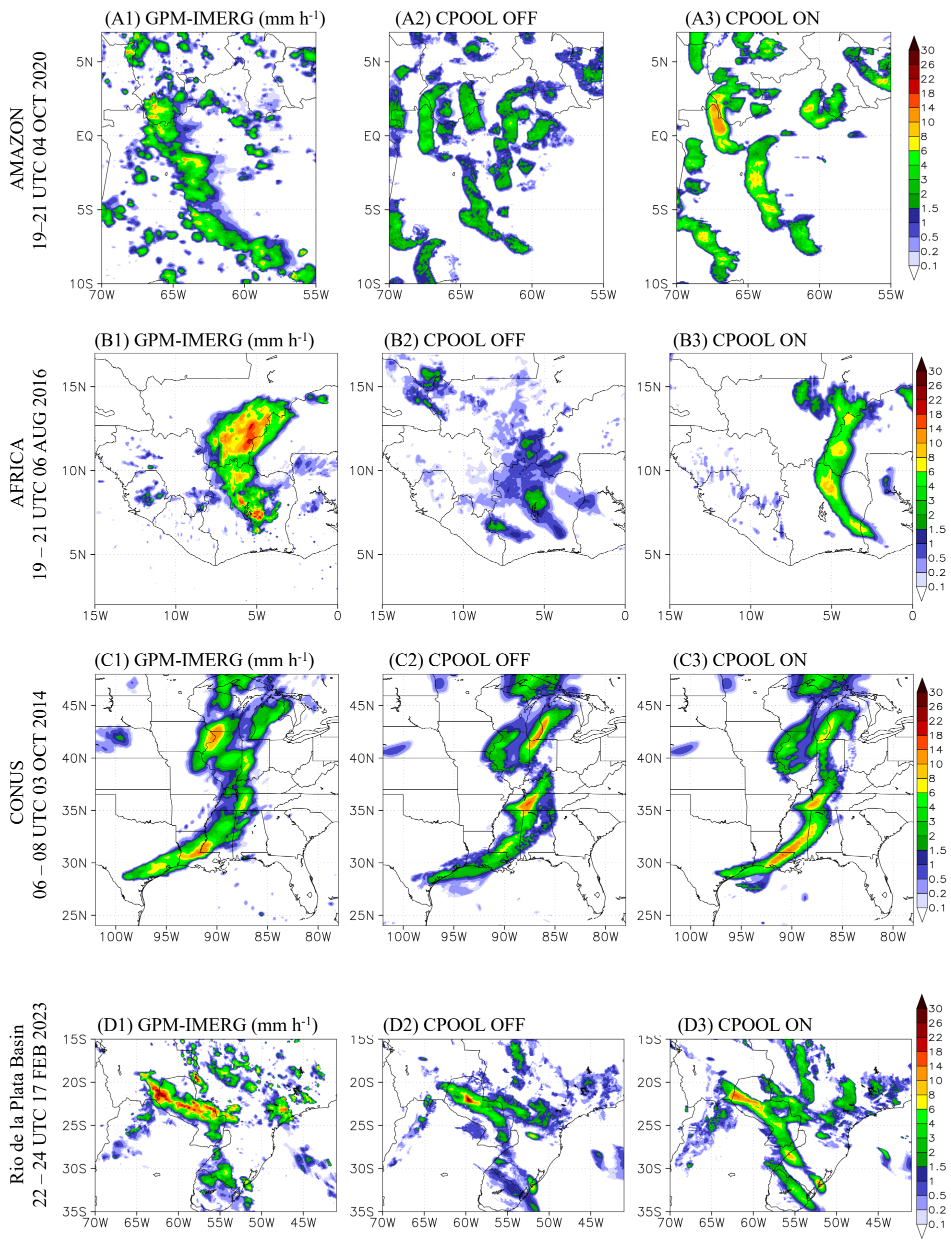


2-h Accumulated Precipitation (mm h^{-1})

Four MCS Case Studies

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

GPM IMERG



5 – Summary and Plans for the Future

- A parameterization for interplays between cold pools, wind shear, and mesoscale convective systems for low resolution GCMs.
- 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).

- Future work will implement this new scheme in the Brazilian MONAN Earth System model as well as NOAA's UFS global modeling system (Georg Grell and Haiqin Li).
- More details and evaluation will appear in Freitas et al. (2023, under review JAMES)

- Thanks for your attention!
- Questions?