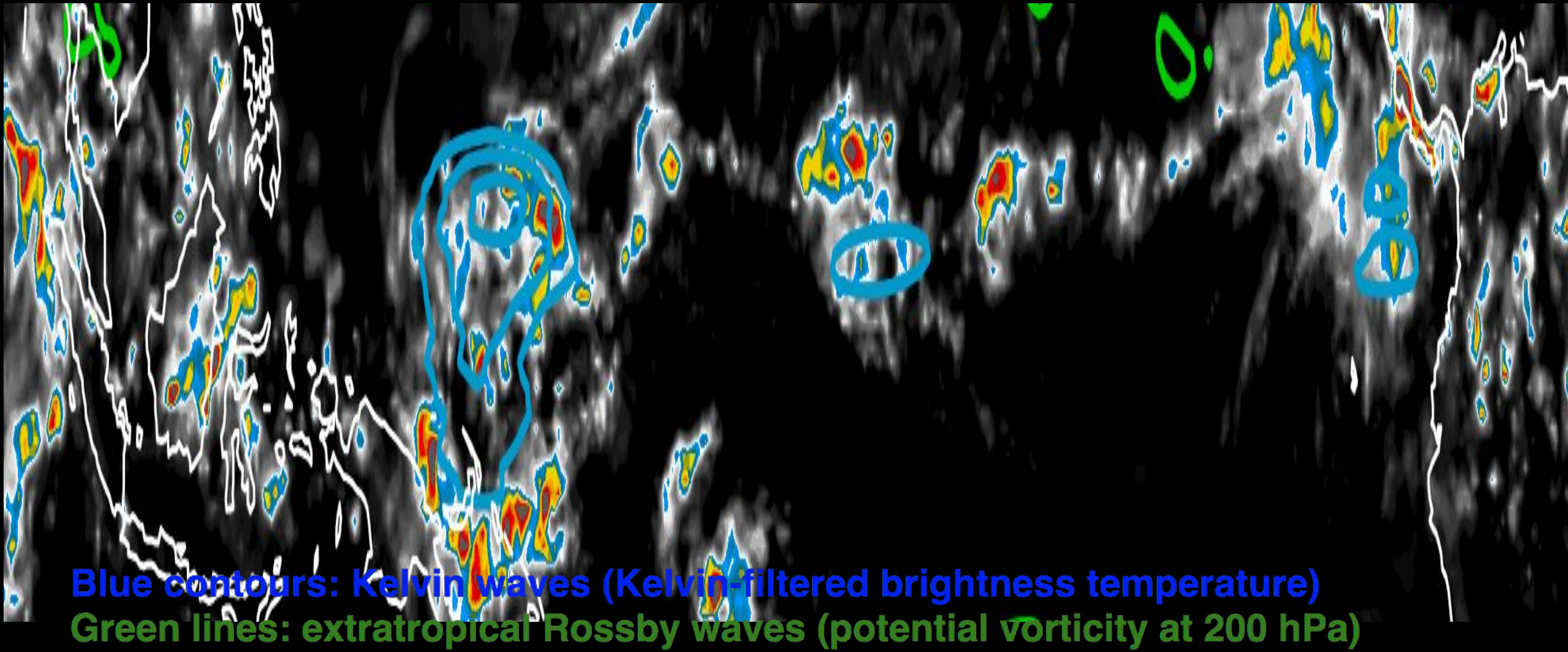
Addressing Tropical Variability and Convective Gray-Zone Representation in NOAA's Unified Forecast System

Lisa Bengtsson, NOAA ESRL PSL

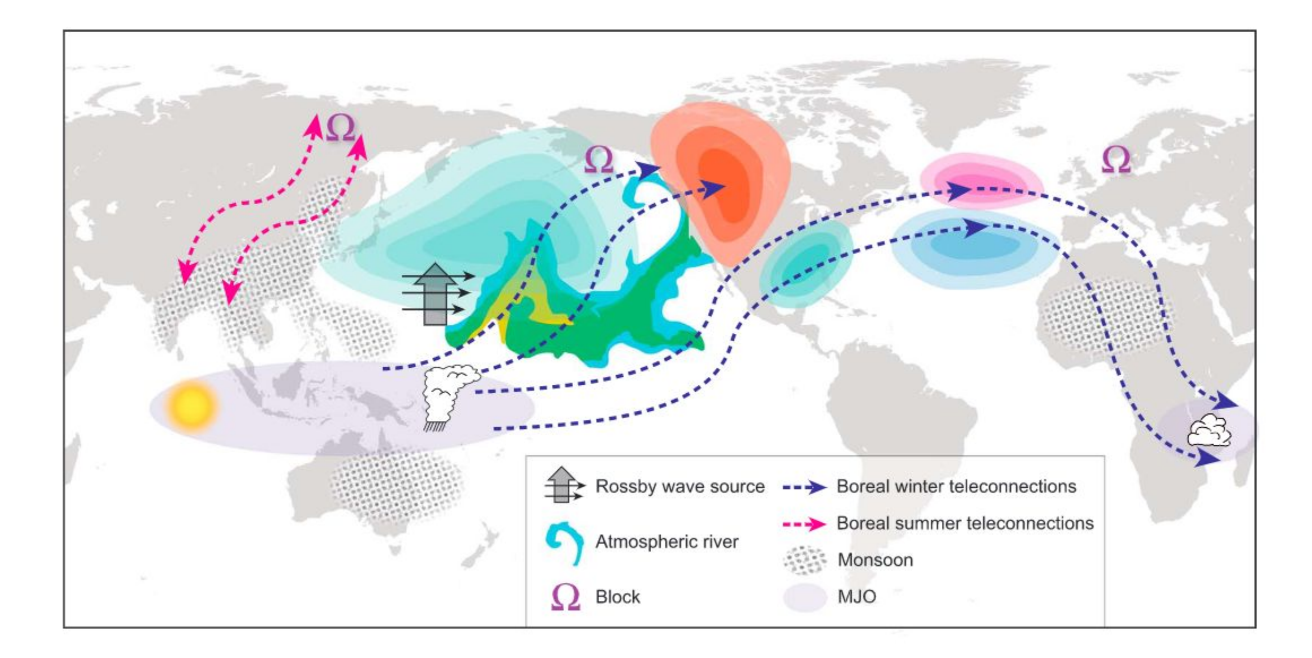
Acknowledgements:
PSL: *Juliana Dias, Maria Gehne, Stefan Tulich, Philip Pegion, Jeff Whitaker, George Kiladis, Sara Michelson, Cecile Penland, Jian-Wen Bao.*
EMC: *Jongil Han, Wei Li, Fanglin Yang*
ECMWF: *Peter Bechtold, Linus Magnusson*
RMI Belgium: *Luc Gerard*

Funding: California Department of Water Resources, NOAA UFS R2O, and NOAA IFAA FY19 Hurricane supplemental.



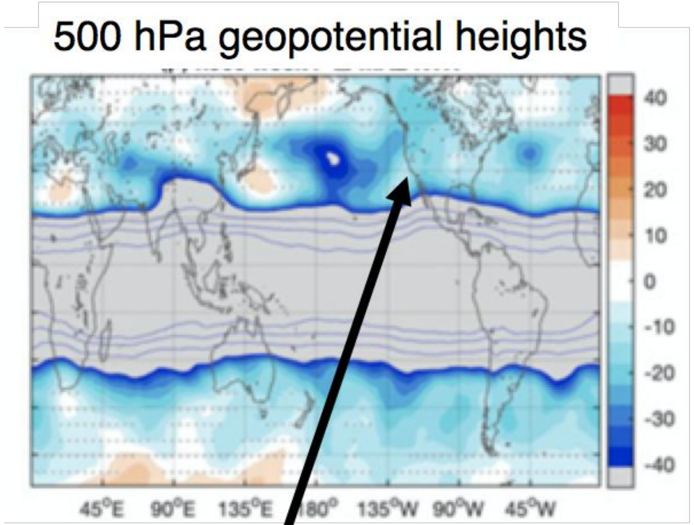
Animation from Yuan-Ming Cheng, PSL

Tropical convective variability has impacts on our ability to forecast weather and extremes in the mid-latitudes.

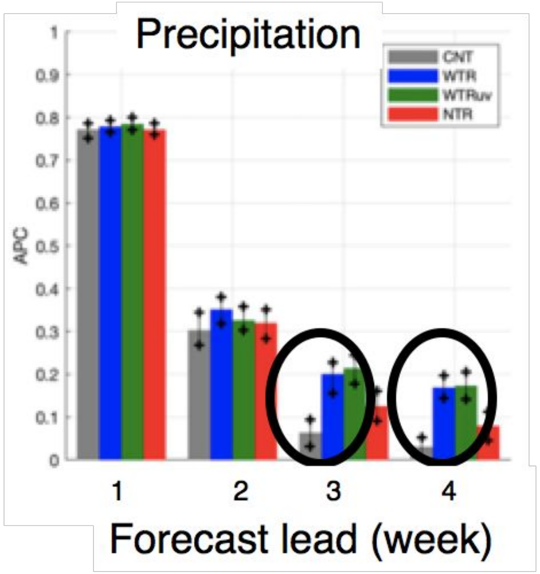


Stan et al. 2017

How much forecast skill can we gain in the mid-latitudes, if the representation of the tropics is “perfect”?



20~40% reduction of mean absolute error in Week 4



2~4 times larger anomaly pattern correlations in week 3 & 4

Dias et al, 2021

Convective parameterizations plays a key role for model representation of tropical variability.

Figure from ECMWF

For the UFS global application (GFS) I will show that the following aspects are important for the modelling of tropical space-time variability and precipitation frequency distribution:

- Moisture profile in the initial state
- Cloud depth - coupling to upper level dynamics
- Representation of convective organization feedbacks (memory)
- Moisture sensitivity in the convective closure
- Stochasticity

Editorial Type: Article

Convectively Coupled Equatorial Wave Simulations Using the ECMWF IFS and the NOAA GFS Cumulus Convection Schemes in the NOAA GFS Model

Lisa Bengtsson[1,2], Juliana Dias[1,2], Maria Gehne[1,2], Peter Bechtold[3], Jeffrey Whitaker[2], Jian-Wen Bao[2], Linus Magnusson[3], Sara Michelson[1,2], Philip Pegion[1,2], Stefan Tulich[1,2], and George N. Kiladis[2]

[1] CIRES, University of Colorado Boulder, Boulder, Colorado | [2] NOAA/Earth System Research Laboratory, Boulder, Colorado | [3] European Centre for Medium-Range Weather Forecasts, Reading, United Kingdom

View Less –

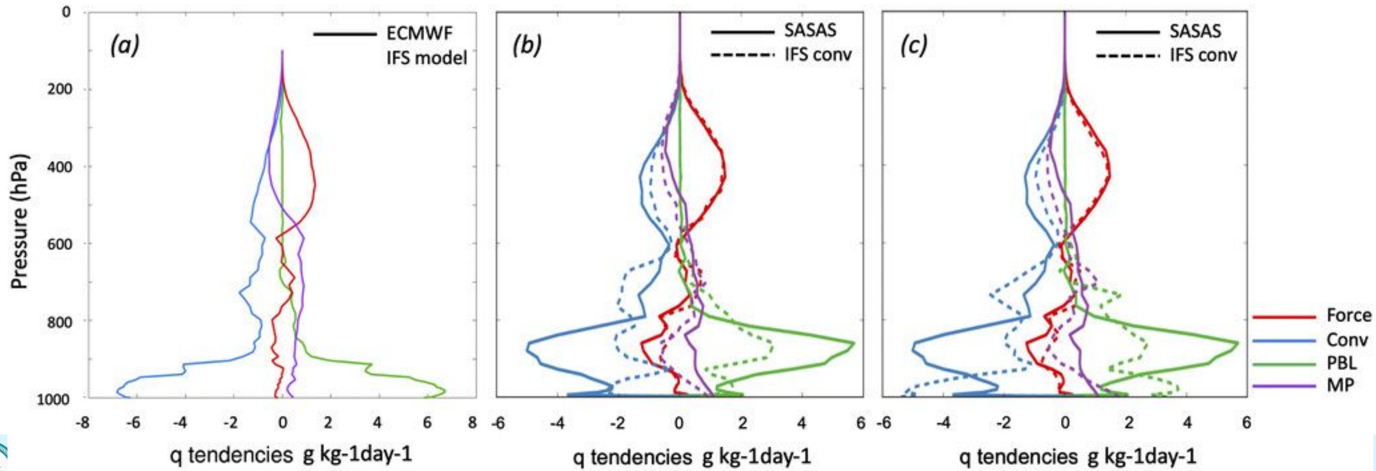
Print Publication: 01 Nov 2019

DOI: https://doi.org/10.1175/MWR-D-19-0195.1

Page(s): 4005–4025

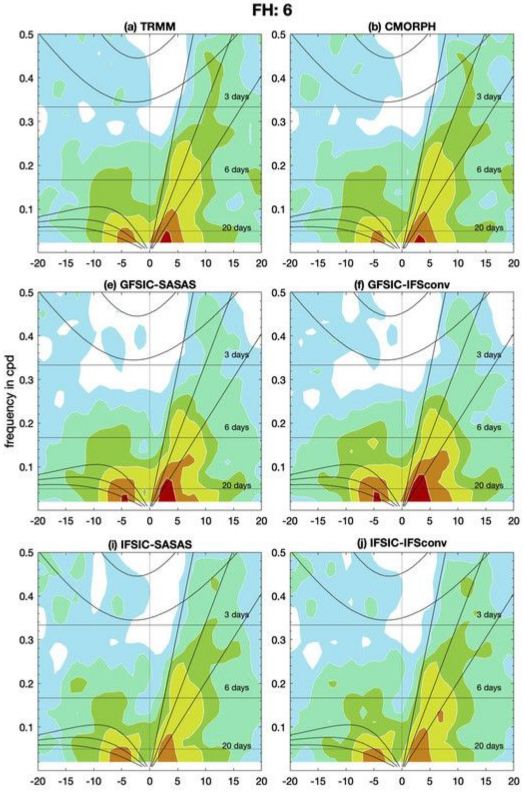
Implementation details

- Since physical processes interact with one another, it is not possible to "plug-and-play" one well tuned parameterization scheme into another physics suite, without carefully addressing how the various schemes interact.
- Integrating the ECMWF cumulus convection scheme with the other physics schemes in the GFS suite took about a year, and are mainly in regards to how convection and boundary layer mass-flux are unified, how convective clouds are seen by radiation, as well as how liquid water detrained to resolved clouds are handled.



Example; unifying PBL moist mass-flux and shallow convective mass-flux treatment (as is done in the ECMWF model).

Is it the initial condition or the convective parameterization that contributes to better tropical variability in the ECMWF model? (GFSv15)



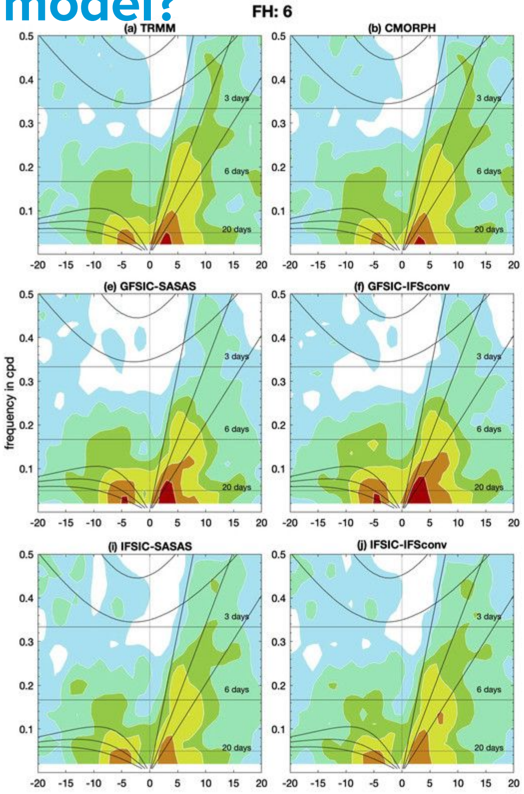
Observations

GFSv15 with GFS initial conditions

GFSv15 IFS initial conditions

GFS conv. IFS conv.

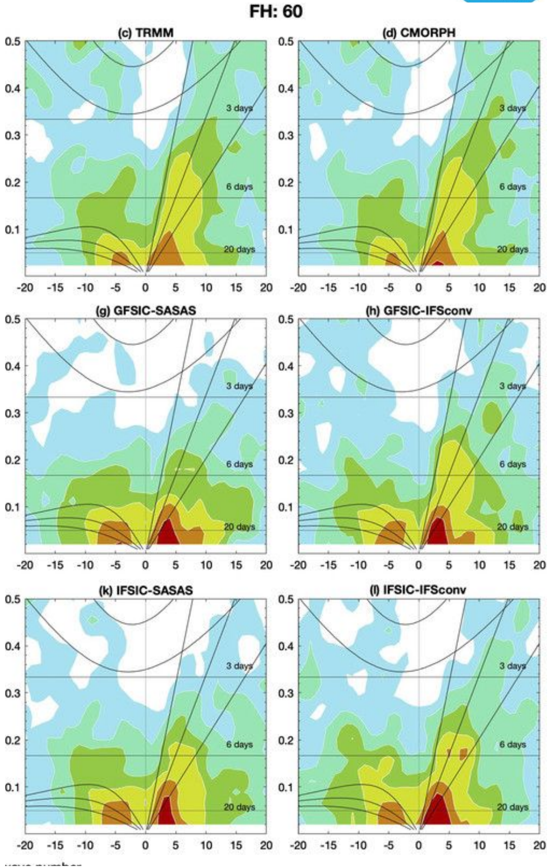
Is it the initial condition or the convective parameterization that contributes to better tropical variability in the ECMWF model?



Observations

GFSv15 with GFS initial conditions

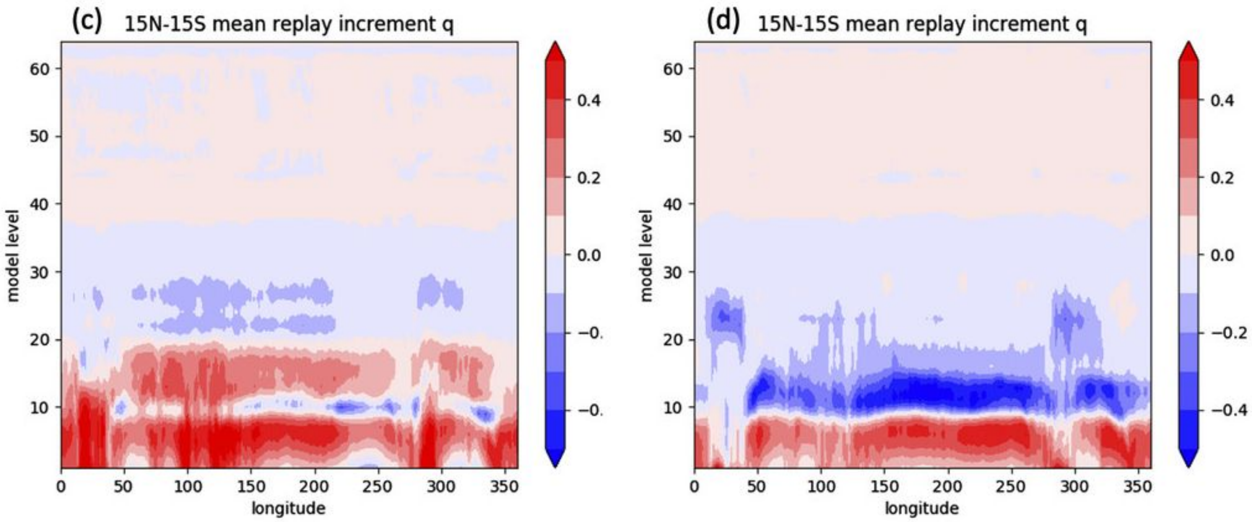
GFSv15 with IFS initial conditions



GFS conv. IFS conv.

GFS conv. IFS conv.

GFSv15 is too dry in the lower troposphere, and replacing the convection scheme does not change this picture in the lower boundary layer.

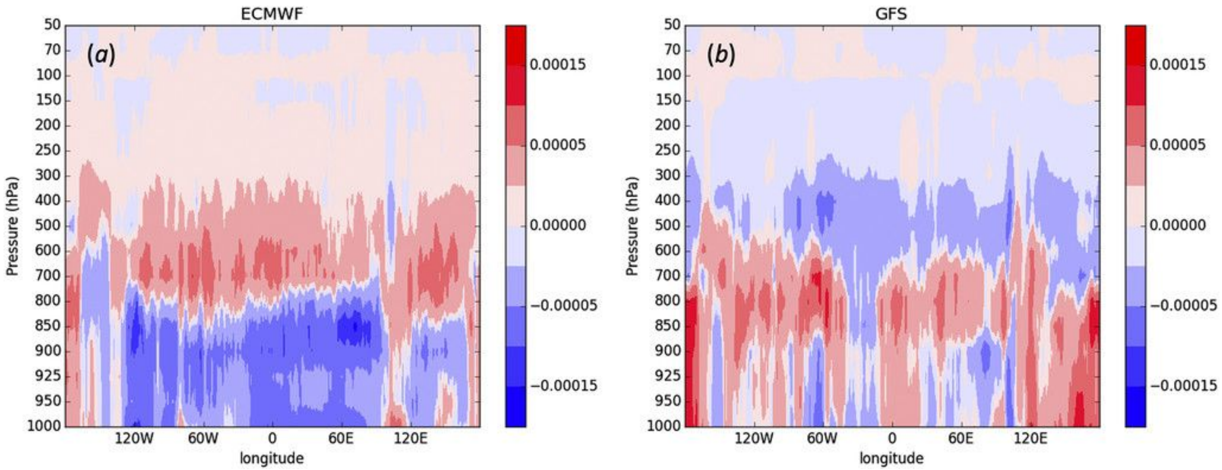


GFSv15 replayed to IFS analysis

GFSv15 with IFS convection replayed to IFS analysis

- Red areas indicate where the IFS analyses are moister than the 6 h forecast.

The ECMWF IFS analysis could be moister than the forecast due to differences in the use of humidity observations in the IFS data assimilation. Or the IFS model background (first guess) forecast used in the data assimilation is itself moister than the GFSv15 forecast model.

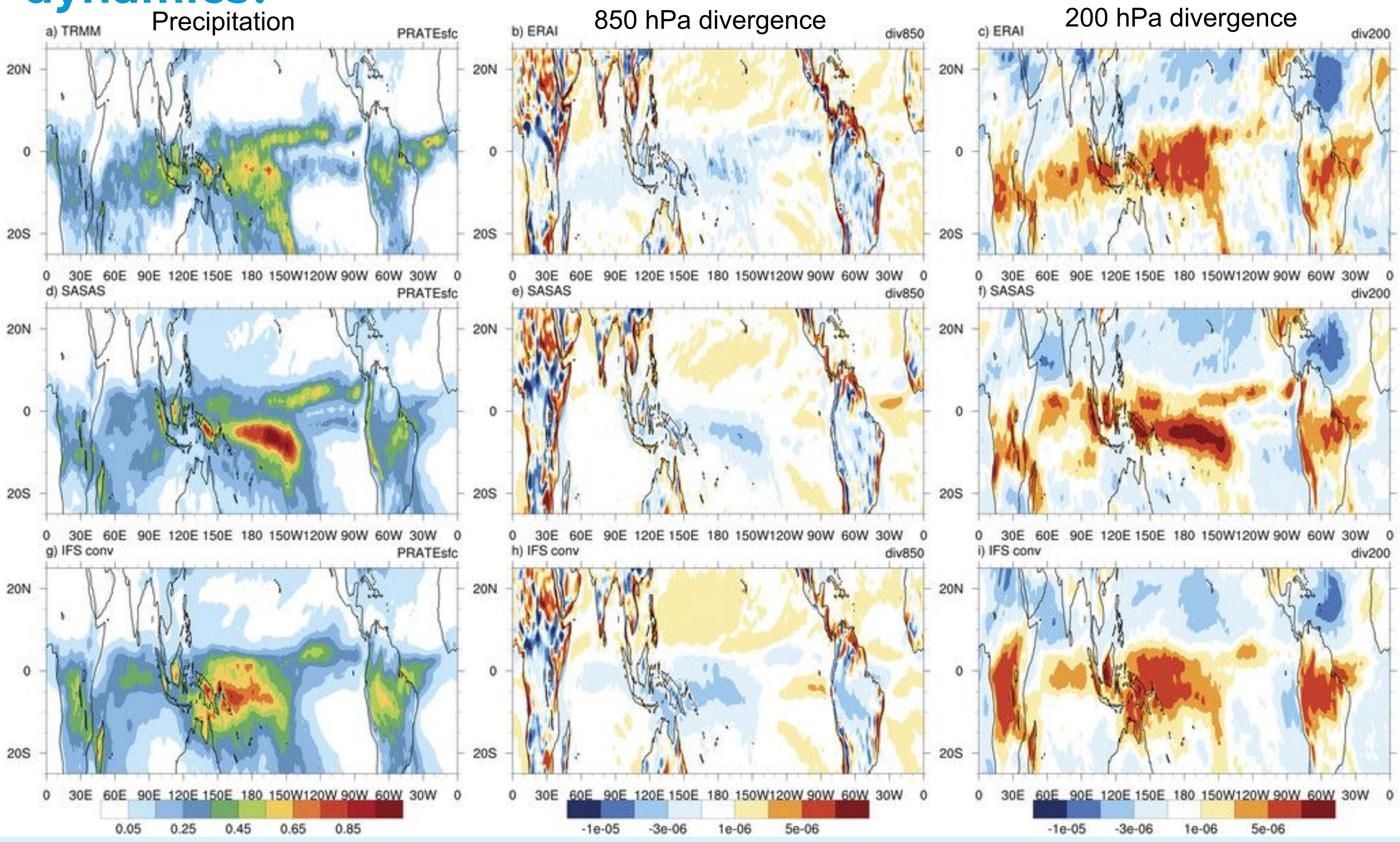


ECMWFv45r1 GFSv15

- ECMWF analysis is working to dry the tropical lower troposphere where the first guess forecast is too moist.
- Generally opposite in the GFS indicating that the analys is trying to moisten the lower troposphere, where the model tends to be too dry.

This suggests that the GFSv15 forecast is too dry, but other aspects of the physics are contributing to this in the PBL, such as differences in PBL physics, surface fluxes and cloud and precipitation microphysics.

How does the different convection schemes interact with the dynamics?

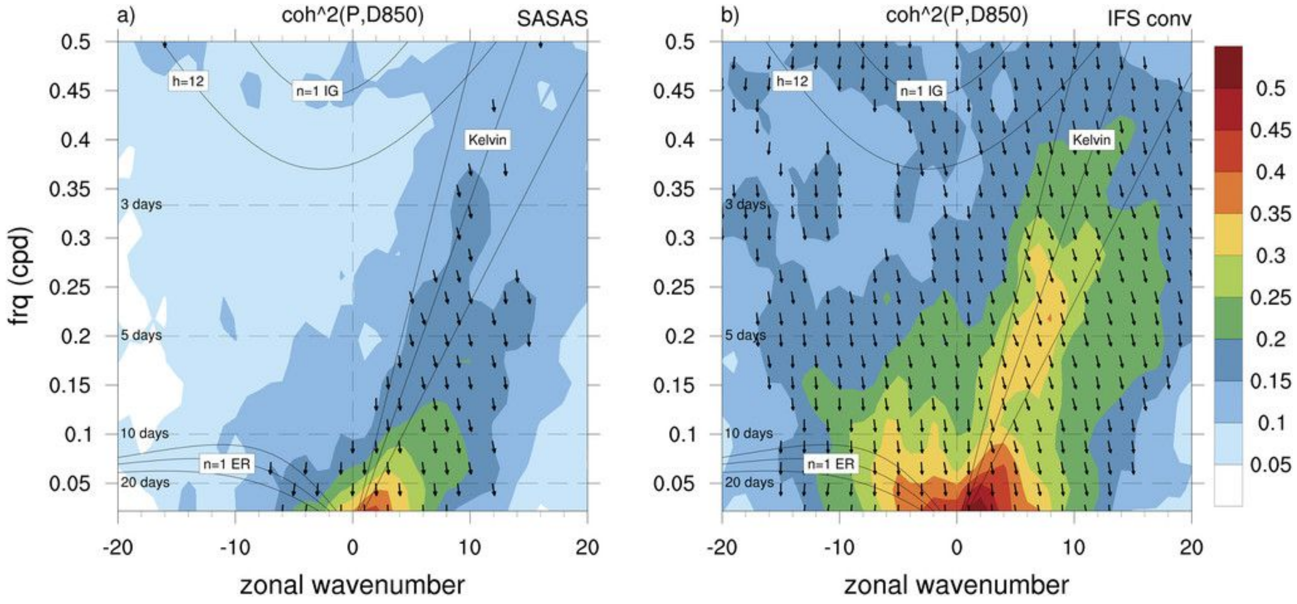


ERA interim

GFSv15

GFSv15
IFS conv

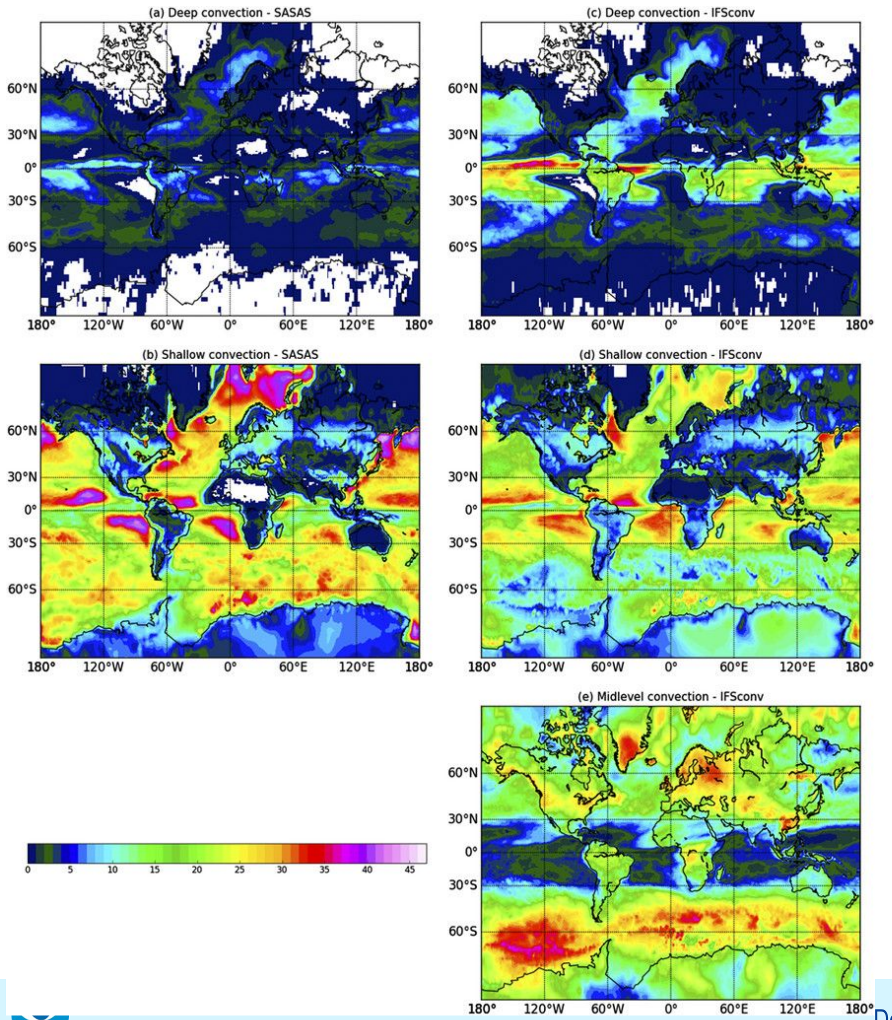
How does the different convection schemes interact with the dynamics?



GFSv15

GFSv15 +
IFS convection

Coherence between precip and divergence



Number of times convection is called varies substantially.

- IFS conv. calls deep convection much more frequently.
- saSAS calls shallow convection much more frequently.
- IFS conv. also triggers convection from “mid level” (elevated convection).

Deeper convection yields stronger interaction with the upper level dynamics fields.

JAMES | Journal of Advances in Modeling Earth Systems

Research Article | Open Access

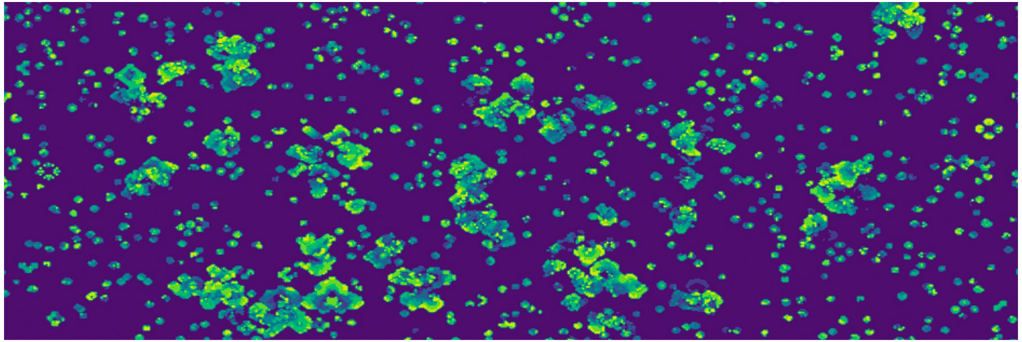
A Stochastic Parameterization of Organized Tropical Convection Using Cellular Automata for Global Forecasts in NOAA's Unified Forecast System

Lisa Bengtsson, Juliana Dias, Stefan Tulich, Maria Gehne, Jian-Wen Bao

See also: Bengtsson et al. 2011, 2013, 2016, 2019

Motivation for using cellular automata

1. Self-organization and birth-death processes suitable for modeling of organized physical systems - such as atmospheric convection.
2. Introduce 3D effects of convection which is generally modelled using a 1D plume model.
3. Stochastic representation of deep convection to address statistical fluctuations in cloud number or intensity.
4. For seasonal/climate prediction, stochastic cumulus convection can be viewed as a noise induced forcing.



Important considerations

1. Model forcing to the CA.
2. Evolution ruleset of the CA.
3. Time and space scales.
4. CA coupling to convection.

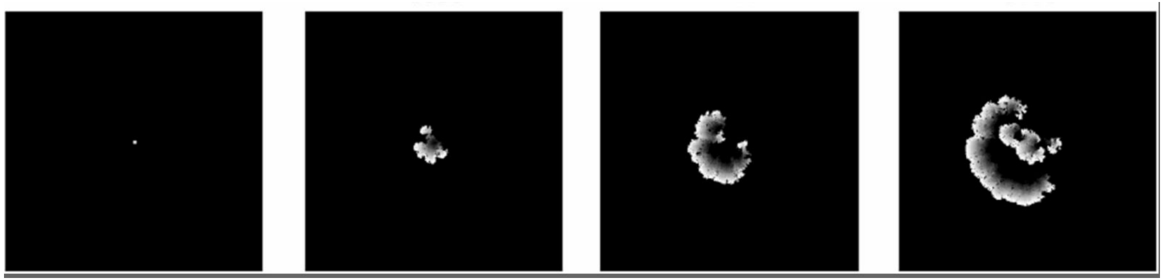
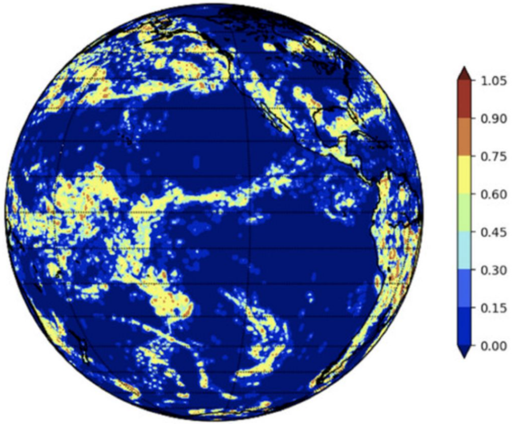
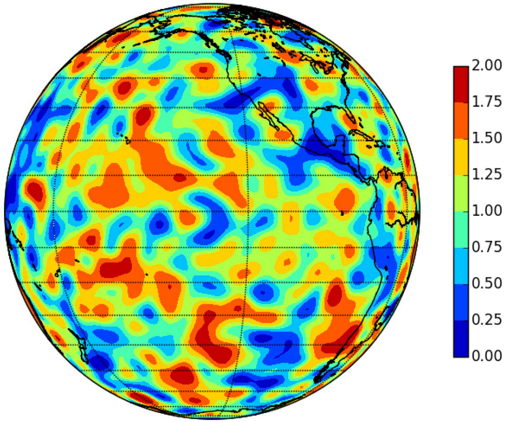


Figure by Martin Steinheimer, Astro control, Austria

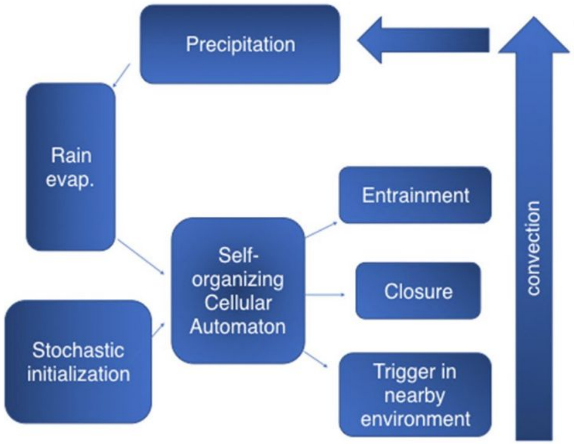


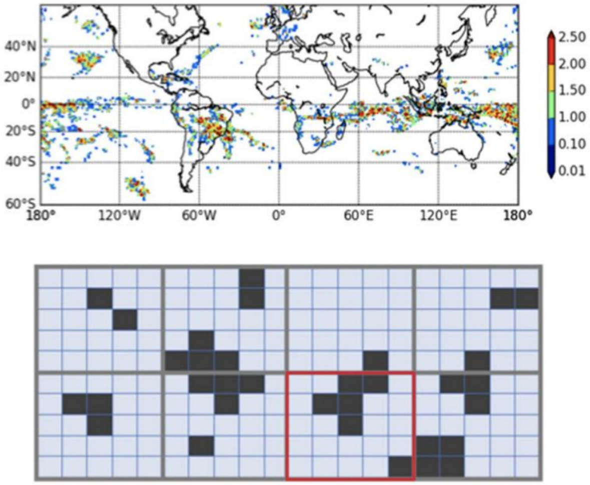


CA coupling to convection

Bulk mass-flux scheme

If bulk quantities are provided, we use the CA to parameterize convective sub-grid (and cross-grid) organization in terms of how the resolved flow would "feel" convection if more coherent structures were present on the subgrid.

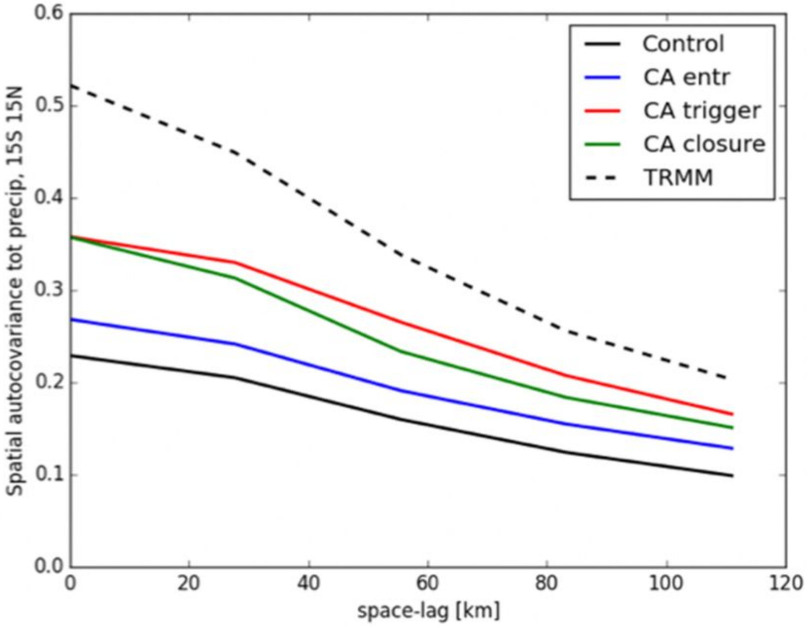




Flow chart adapted from Mapes and Neale, 2011 "org" scheme

Bengtsson et al. 2021

Spatial autocovariance of total precipitation - impact using cellular automata.



All of the organization feedback mechanisms provides enhanced spatial autocovariance of total precipitation on the common 25 km grid, which better matches the observed dataset on the same grid.

CA coupling to convection - example impact on Kelvin wave phase speed.

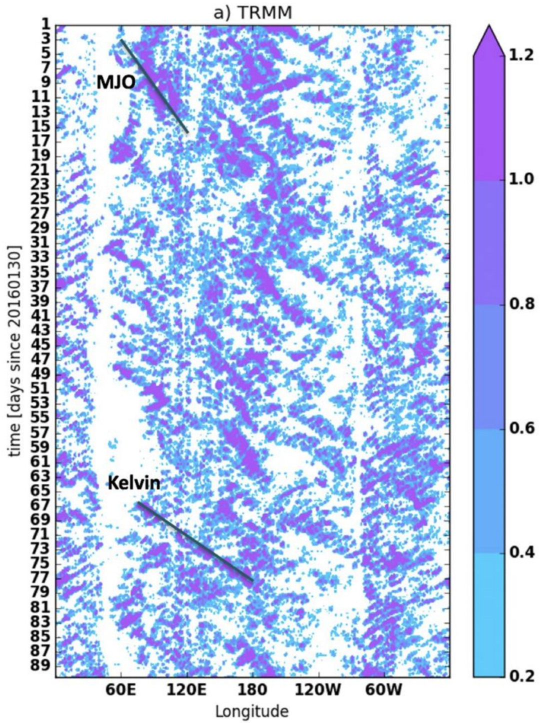
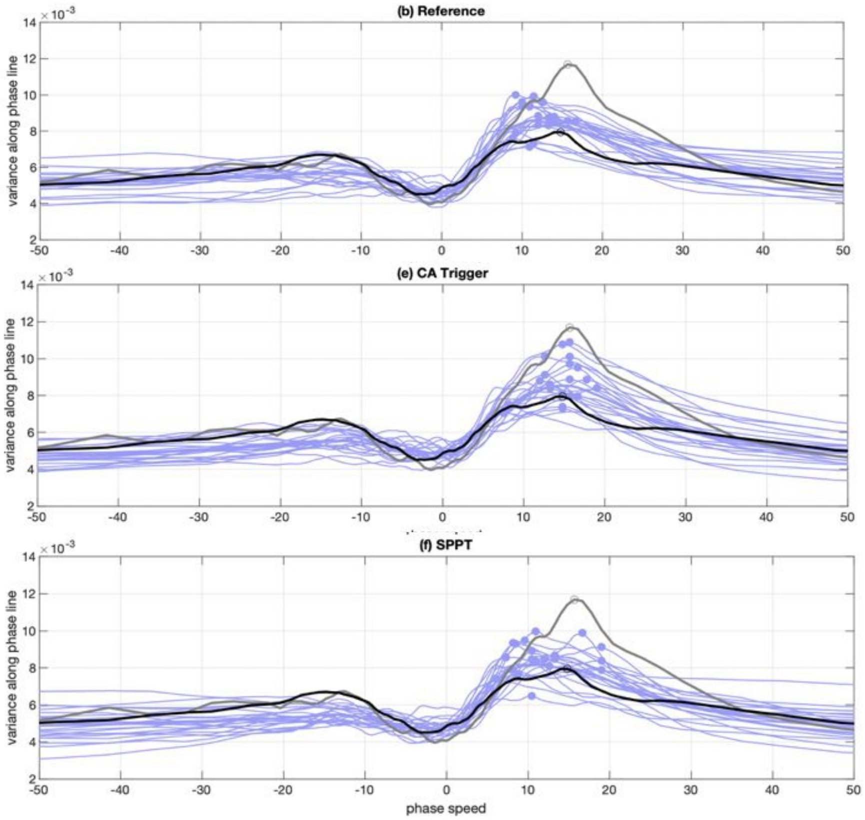


Figure 3. Observed (TRMM) Hovmöller diagram of precipitation (mm/h) for the period 20160130–20160429 between 5°S and 5°N. Lines indicate typical phase speeds associated with MJO (~7 m/s) and Kelvin wave (~15 m/s) propagation. TRMM, Tropical Rainfall Measuring Mission.



Why does enhanced subgrid organization enhance phase speed?

Changes in Normalized Gross Moist Stability (NGMS) has been shown to influence the Kelvin wave phase speed through interaction between latent heat release and with low level moisture convergence (e.g., Fuchs et al., 2012; Wang & Chen, 1989).

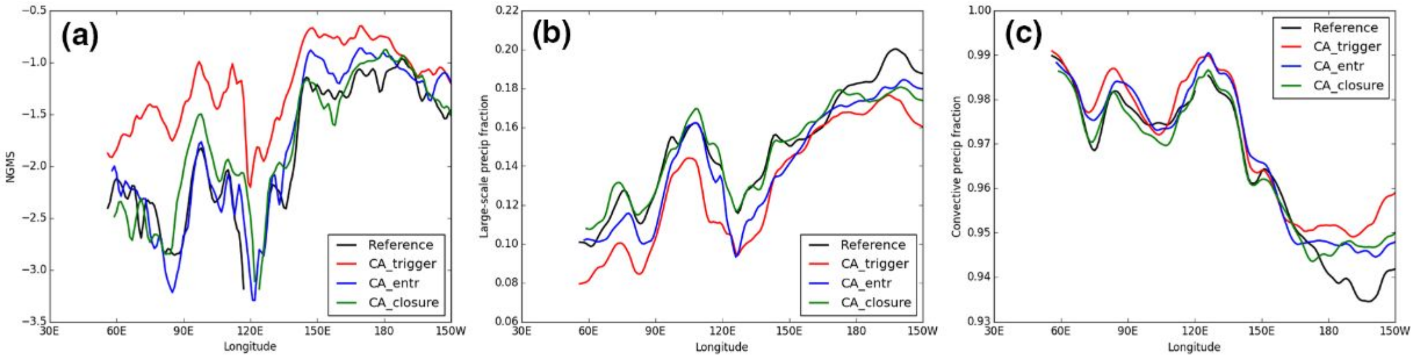


Figure 10. (a) Vertical component of Normalized Gross Moist Stability (NGMS). (b) Large-scale precipitation fraction, and (c) convective precipitation fraction. Variables have been latitudinally averaged over a chosen Indo-Pacific domain where climatological vertically integrated moisture convergence is positive following the methodology in Benedict et al. (2014).

A Model Framework for Stochastic Representation of Uncertainties Associated with Physical Processes in NOAA's Next Generation Global Prediction System (NGGPS)

LISA BENGTSSON,[a,b] JIAN-WEN BAO,[b] PHILIP PEGION,[a,b] CECILE PENLAND,[b]
SARA MICHELSON,[a,b] AND JEFFREY WHITAKER[b]

[a] *Cooperative Institute for Research in Environmental Sciences, University of Colorado Boulder, Boulder, Colorado*
[b] *NOAA/Earth System Research Laboratory, Boulder, Colorado*

(Manuscript received 5 July 2018, in final form 26 December 2018)

Use of cellular automata to model “plume” distribution

Spectral plume distribution

In this case the CA provides a distribution of ‘plume number’ and ‘plume size’.

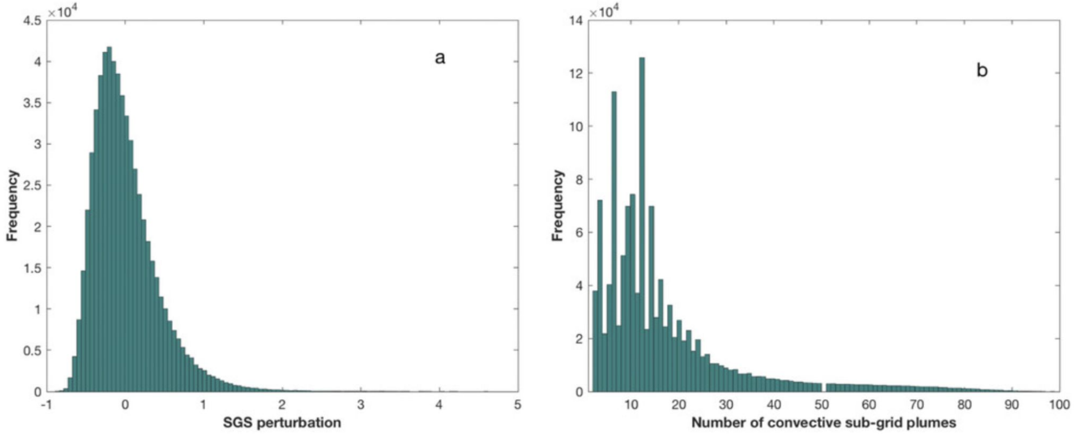
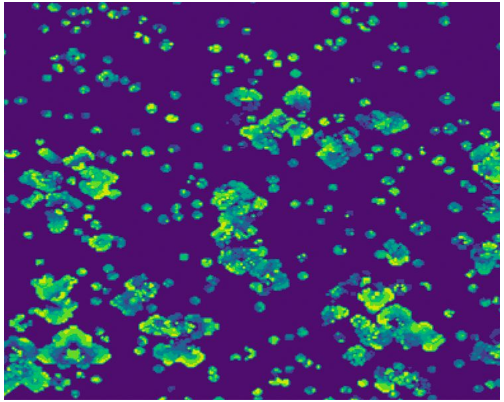


FIG. 2.

(a) SGS distribution and (b) distribution of convective subgrid plumes.

Citation: Monthly Weather Review 147, 3; 10.1175/MWR-D-18-0238.1

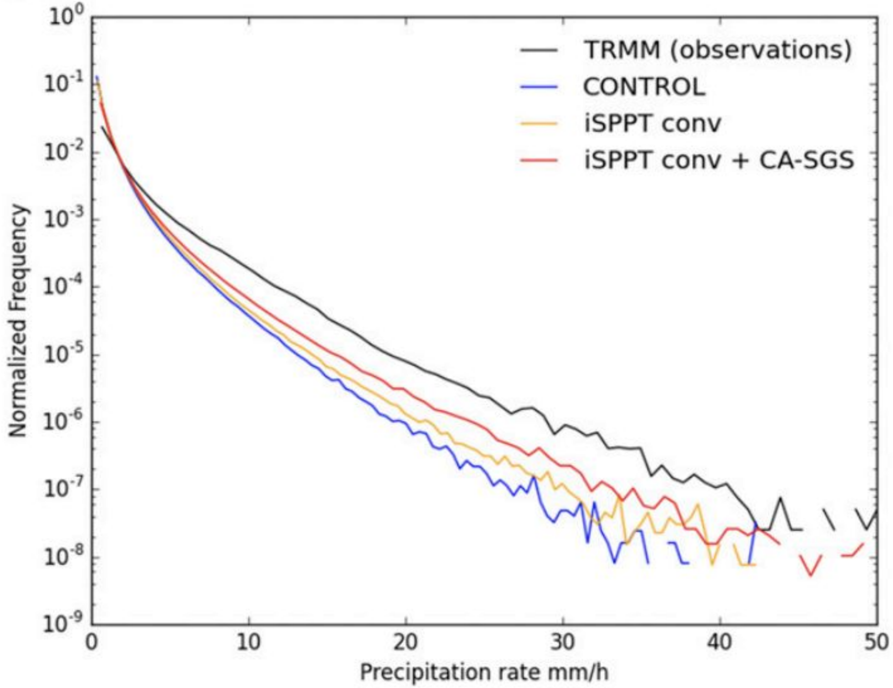


In this case, the CA is coupled with the Chikira and Sugiyama cumulus convection scheme to inform on plume number.

Bengtsson et al. 2019

Stochastic physics can help model the frequency distribution of precipitation

(a) 90 day, single stochastic forecast.



Cellular automata pattern used, Chikira & Sugiyama plume numbers are sampled from sub-grid “plumes”

Article Type: Research Article

A prognostic-stochastic and scale-adaptive cumulus convection closure for improved tropical variability and convective gray-zone representation in NOAA's Unified Forecast System (UFS).

Lisa Bengtsson[1], Luc Gerard[3], Jongil Han[4], Maria Gehne[1,2], Wei Li[5], and Juliana Dias[1]

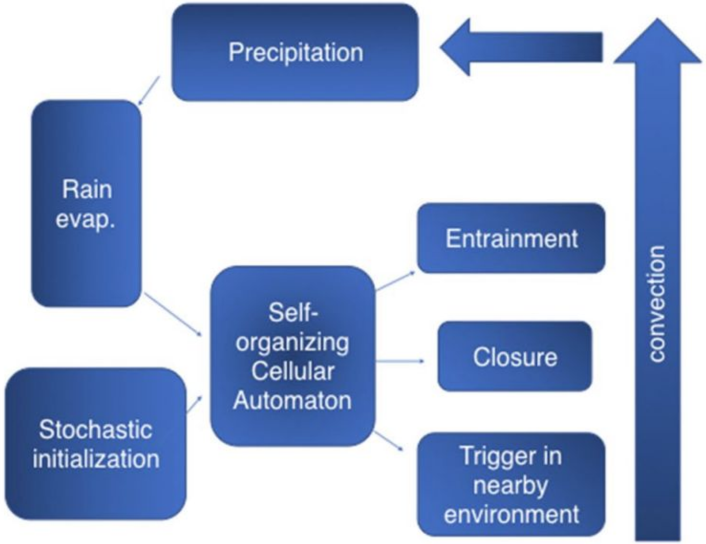
View More +

Published-online: 02 Sep 2022

DOI: https://doi.org/10.1175/MWR-D-22-0114.1

CA coupling to convection

Bulk mass-flux scheme



Flow chart from Bengtsson et al. 2021 adapted from Mapes and Neale, 2011 “org” scheme

Closure - More sub-grid organization would result in larger area fraction.

- In traditional cumulus convection schemes, it is assumed that the area coverage of all the cloud elements in a grid-box is much smaller than the grid-box itself. And area fraction is negligible.
- Instead, the average effect of the full ensemble of possible cloud elements in the grid box is in quasi-equilibrium with the resolved large-scale variables at any instant (steady-state assumption).
- Under this assumption the representation of “more organization” is associated with an increase in the mass-flux at cloud base.
- As we go to higher resolution this quasi-equilibrium assumption is not valid any longer.

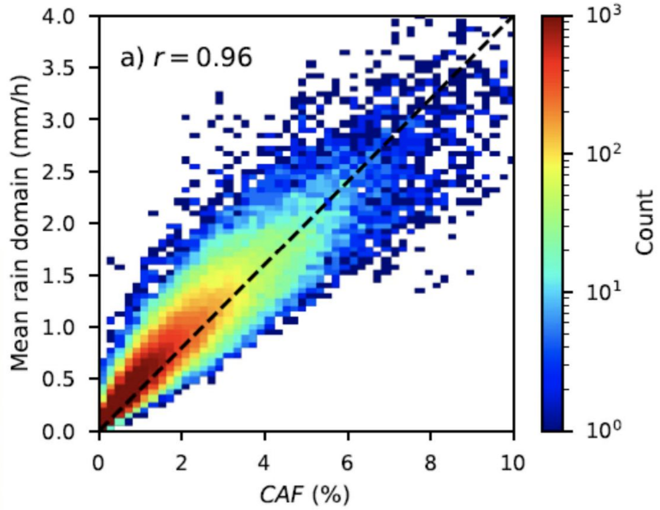
CA coupling to convection

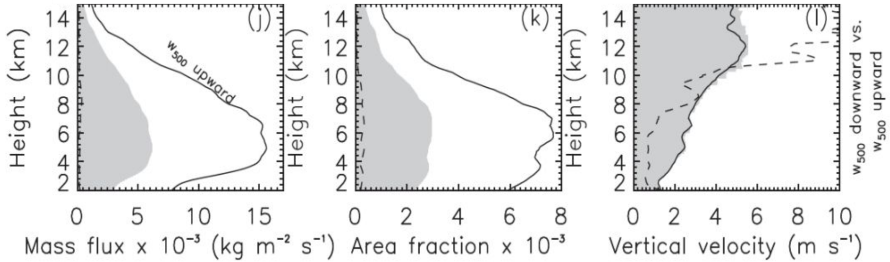
New prognostic-stochastic closure.

1) No longer assume negligible area fraction
2) Introduce prognostic equation for updraft area fraction based on a moisture budget equation (following Gerard and Geleyn 2005, Gerard et al. 2009.)
3) Let the CA enhance the area fraction in case of more sub-grid scale organization.

$$\frac{\partial \sigma_B}{\partial t} \int_{p_B}^{p_T} \xi(p)(h_u(p) - h_s(p)) \frac{dp}{g} = L \int_{p_B}^{p_T} \sigma_B \omega_u \xi(p) \frac{\partial q_{cond}}{g} + L \int_{p_B}^{p_T} MFC \frac{dp}{g}$$

Observational support for prognostic area fraction



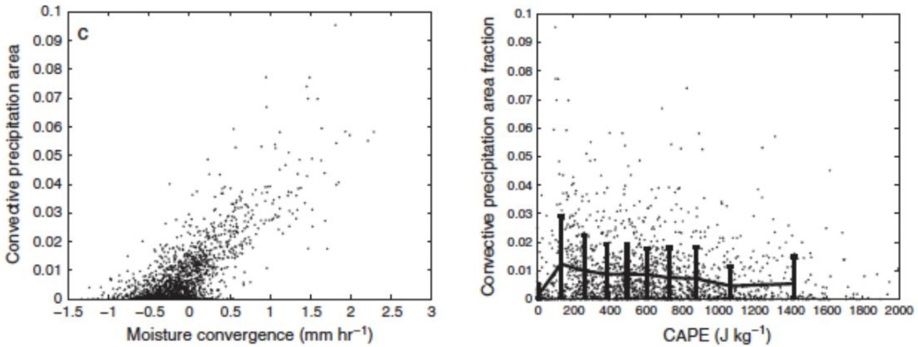


Vertically pointing radar observations from Darwin, Australia. Christian Jakob and colleagues at Monash University:

Kumar et al. 2016, Louf et al. 2019, Narsey et al. 2019

Observations (from Darwin) tells us:

1. There is a strong relationship between convective area fraction and tropical precipitation rate.
2. The vertical distribution of the massflux is mainly informed by the convective area fraction.
3. Convective area fraction has a closer relation to convergence (velocity, moisture) than CAPE.



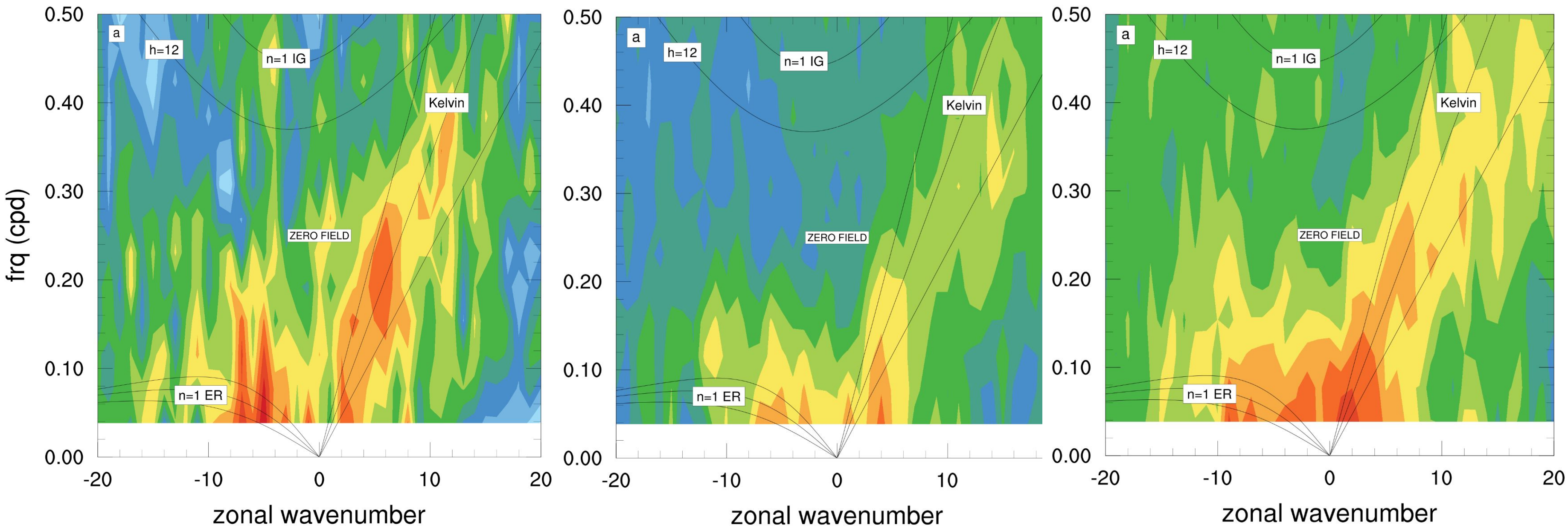
Davies et al, 2013, JGR

Moisture coupling to convection

- Idealized studies have demonstrated that moisture feedbacks are essential for CCEW initiation and propagation (Mapes et al. 2006).
- In particularly the MJO is improved when convection is made more sensitive to environmental moisture (e.g., Maloney and Hartmann 2001; Benedict and Randall 2009; Tulich and Mapes 2010; Hannah and Maloney 2011 and Kim et al. 2012).
- Furthermore, a recent study by Liu et al. (2021) indicates that the MJO prediction is largely improved if shallow convection is not activated until a time composite of moisture convergence over grid box turns to positive.
- Thus, we explore the impact of the prognostic-stochastic closure on CCEW and MJO prediction

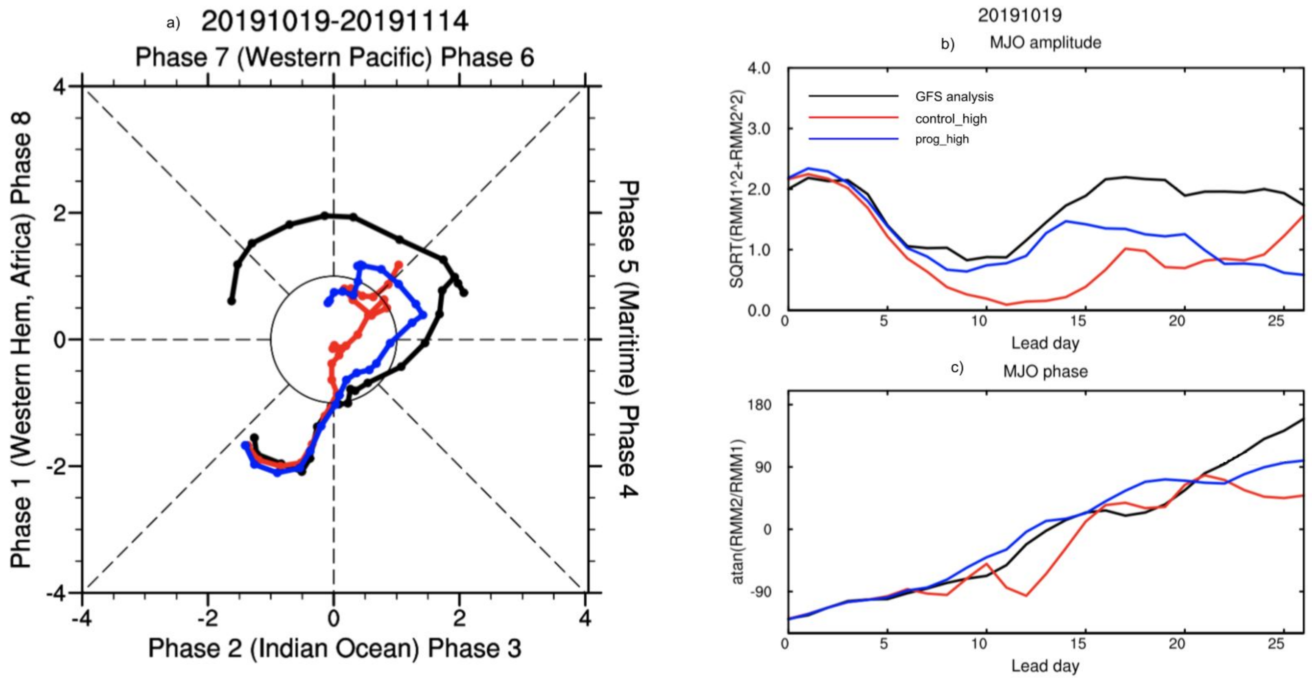
Coherence between low level moisture flux convergence and precipitation

a) ERA5 b) control GFSv16 c) prog closure



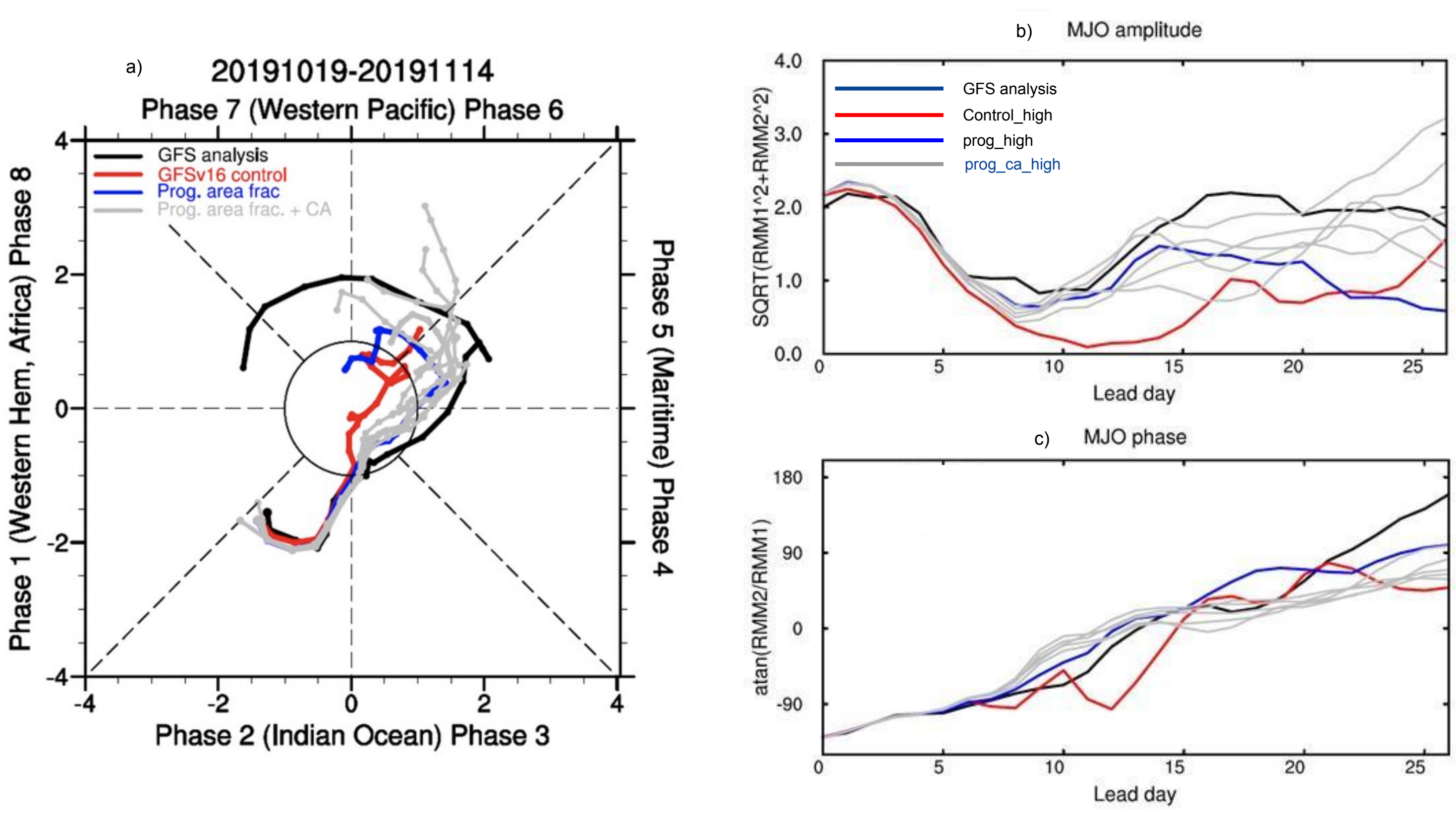
Figures from Maria Gehne, PSL

MJO statistics, impact of new closure



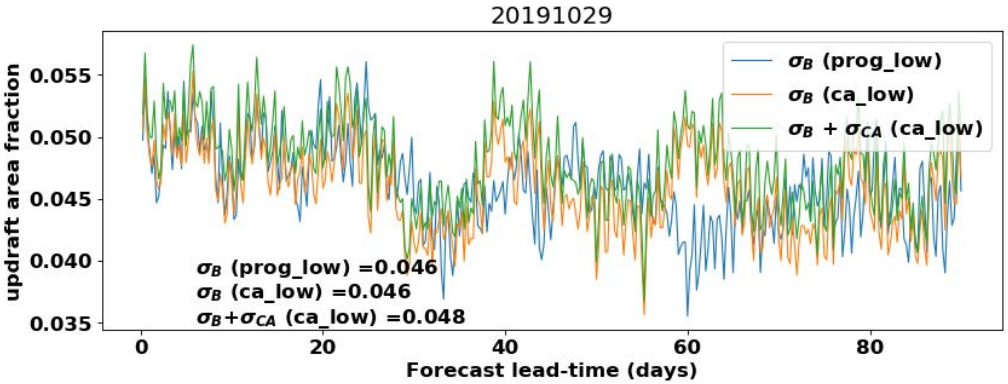
Figures from Wei Li, EMC

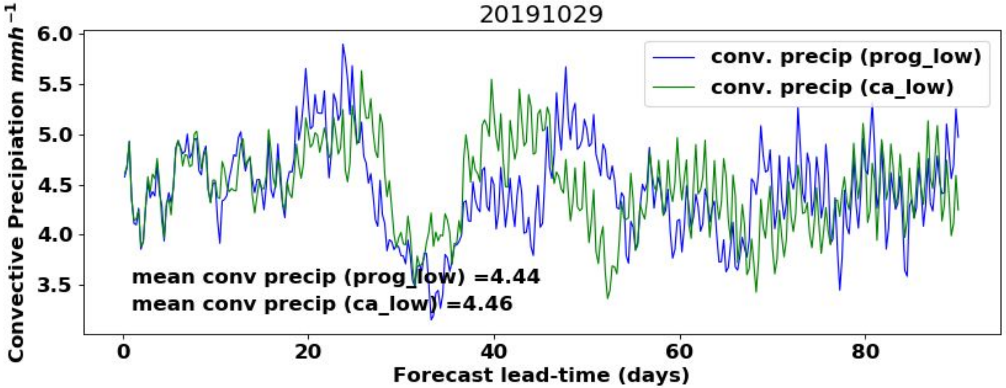
MJO statistics, impact of new closure - with CA



Figures from Wei Li, EMC

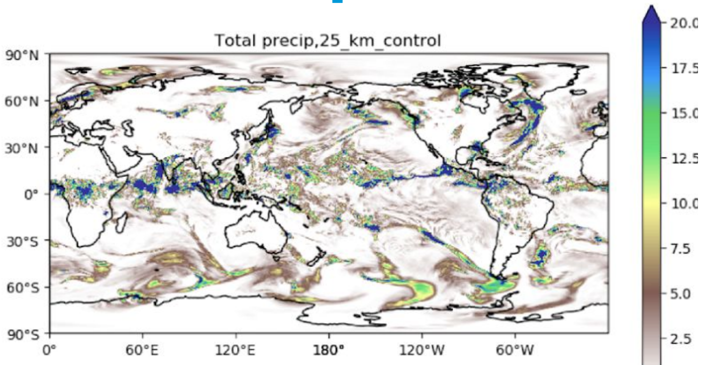
Can the impact of the CA in this case be viewed as a noise induced forcing, or do we see a systematic enhancement of sub-grid precipitation?



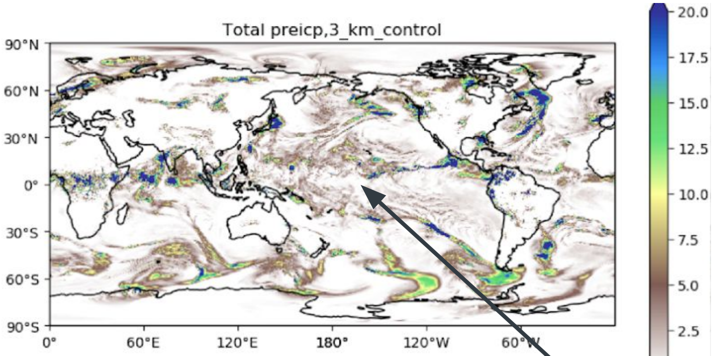


While the updraft area fraction is systematically enhanced due to sub-grid organization feedbacks given by the CA, the response in convective precipitation is not systematic.

Scale-adaptive considerations



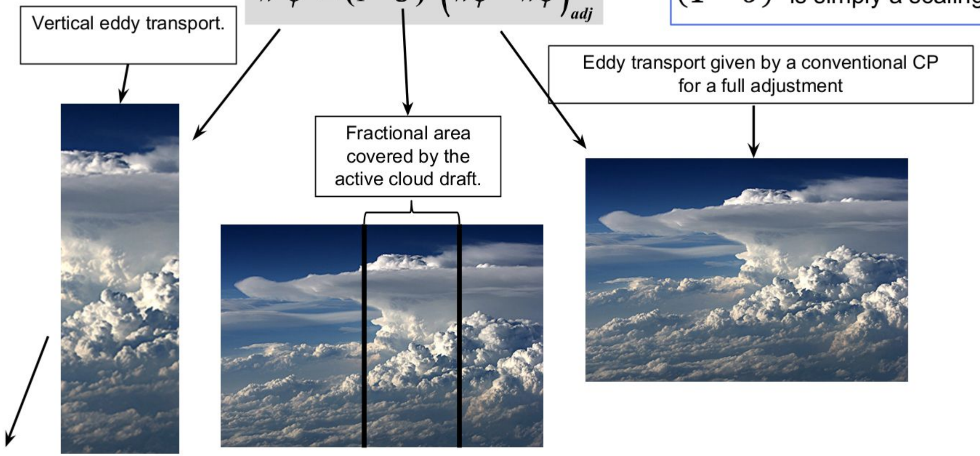
GFSv16 - 25 km resolution



GFSv16 - 3 km resolution

$$\overline{w'\phi'} = (1-\sigma)^2 \left(\overline{w\phi} - \bar{w}\bar{\phi}\right)_{adj}$$

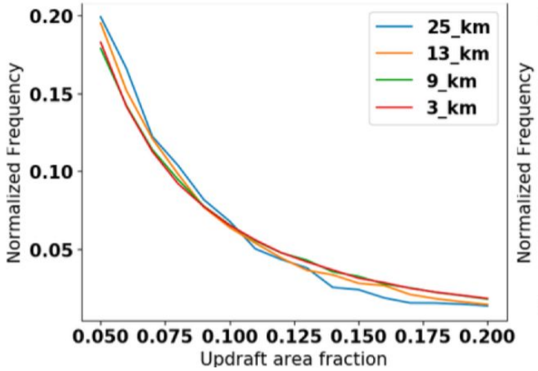
$(1-\sigma)^2$ is simply a scaling factor!

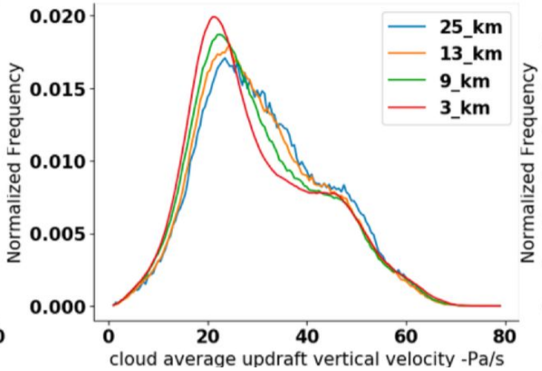


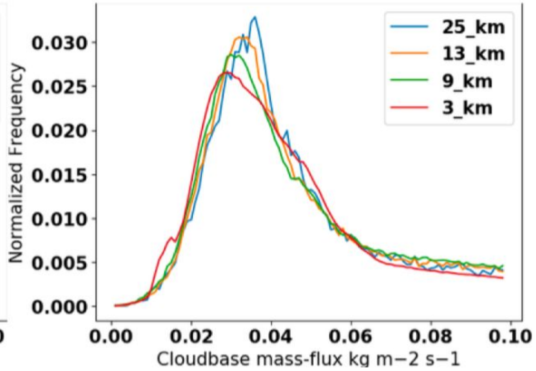
In weakly forced environments, resolved convection is not "picked up" by the dynamics, when subgrid fluxes are scaled down.

Arakawa and Wu, 2013
Image adapted from Georg Grell

Scale-adaptive considerations - the devil's in the details!







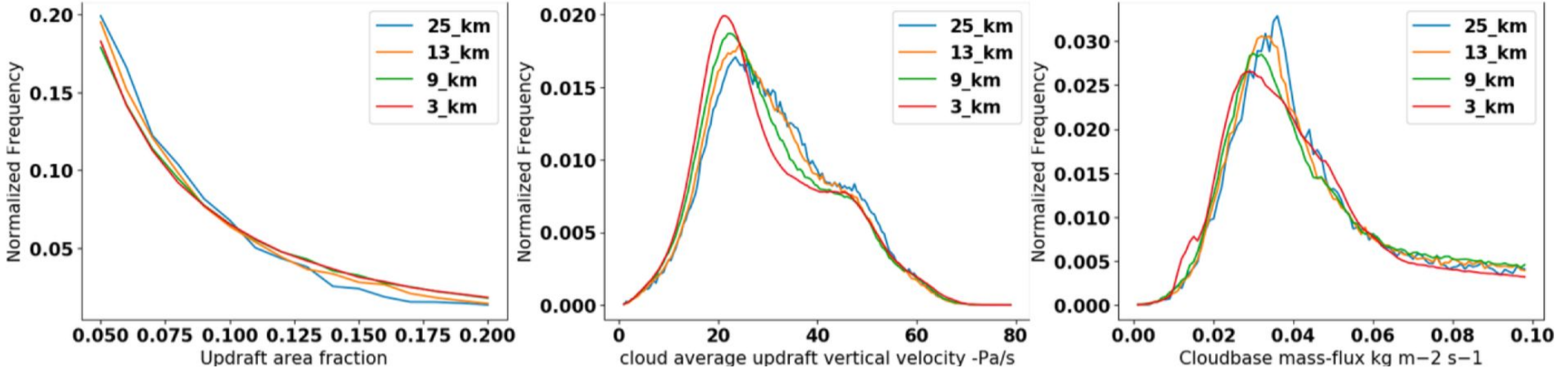
$$M_B = -(1.-\sigma_B)^2 \frac{\sigma_B \overline{\omega_u}}{g}$$

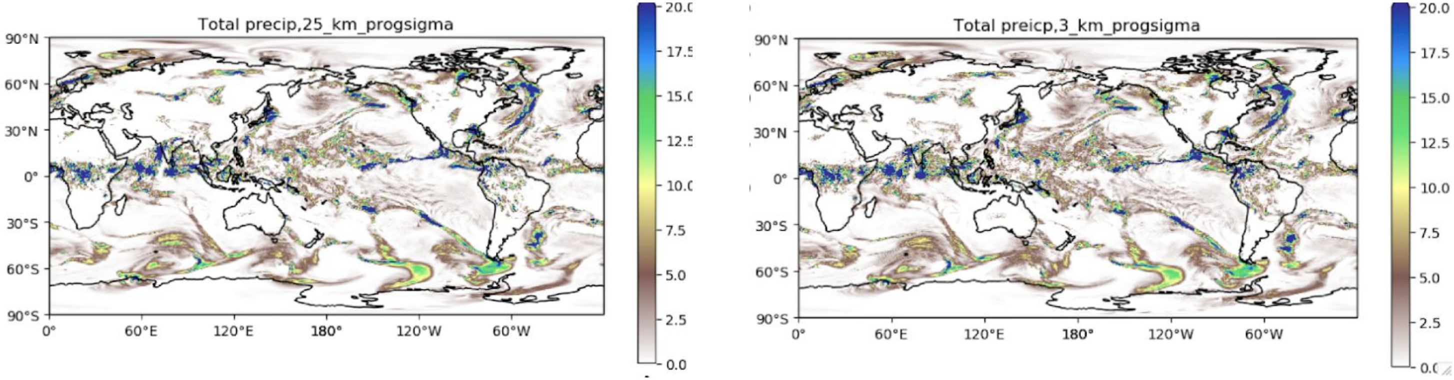
$$\frac{\partial \sigma_B}{\partial t} \int_{p_B}^{p_T} \xi(p)(h_u(p) - h_s(p)) \frac{dp}{g} = L \int_{p_B}^{p_T} \sigma_B \omega_u \xi(p) \frac{\partial q_{cond}}{g} + L \int_{p_B}^{p_T} MFC \frac{dp}{g}$$

$$\frac{\partial w_u^2}{\partial z} = -c_1 \varepsilon w_u^2 + c_2 B \qquad B = g(\theta_{v,u} - \overline{\theta_v})/\overline{\theta_v}$$

Bengtsson et al. 2022

Scale-adaptive considerations - new closure





Prog closure 25km

Prog closure 3km

Bengtsson et al. 2022

Summary

- A model's convection parameterization plays an important role for the representation of tropical variability. Specifically, for the Unified Forecast System (global application GFS) we find:
  - Cloud depth (shallow vs deep decision) plays an important role for the interaction with the dynamics, which in turn is important for the representation of tropical wave variability.
  - Convective organization feedbacks improves auto-correlation space/time scales (memory) and strengthens the interaction between sub-grid convection and the resolved dynamics.
  - Bringing moisture sensitivity to the closure, and introducing a prognostic (memory) evolution suggests an improved space-time spectra of moisture-precipitation coupling. This can have positive effects on MJO propagation, amplitude and phase as suggested by our case study.
  - Stochastic convection parameterization can improve the precipitation distribution and also enhance MJO propagation.

- Early results using a new prognostic closure shows improvements in scale adaptive behaviour of model precipitation across 25, 13, 9 and 3 km global UFS simulations.
  - Area fraction plays a role, but the updraft velocity is also scale-adaptive by design.

Vertical heating profile

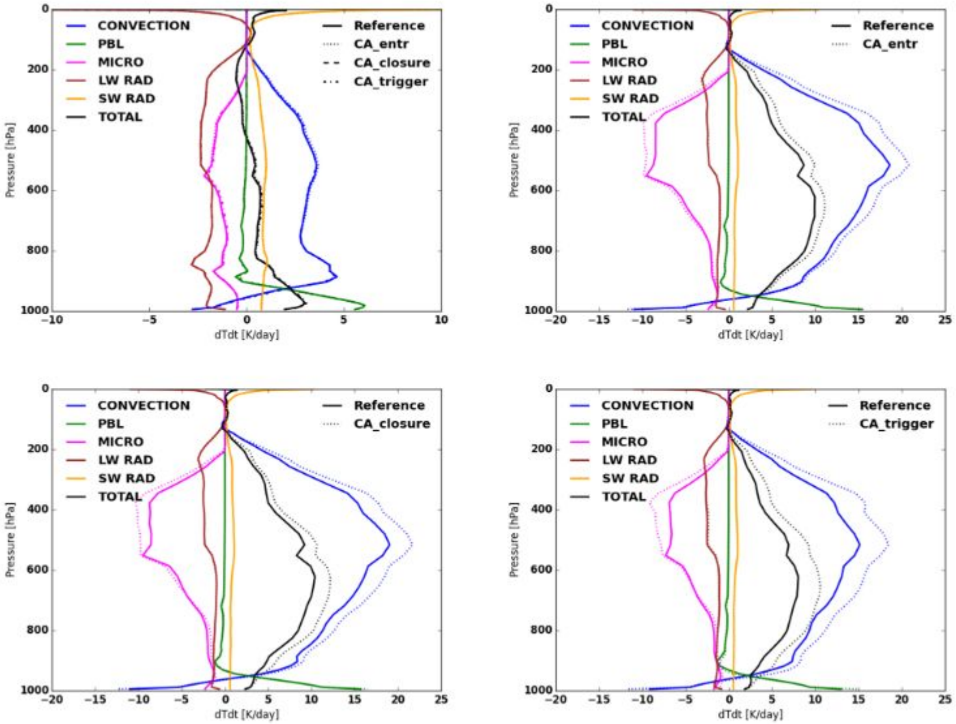


Figure 11. Vertical heating profiles from different physics parameterizations in the model. Top left: Averaged over the 90-day time period, and all longitude points between 5°S and 5°N. Top right and bottom row are averaged over the 90-day period for points 5°S and 5°N where the CA field in the model simulations has a maximum cluster size of at least eight individual CA cells for CA_entr, CA_closure and CA_trigger respectively. CA, cellular automata.