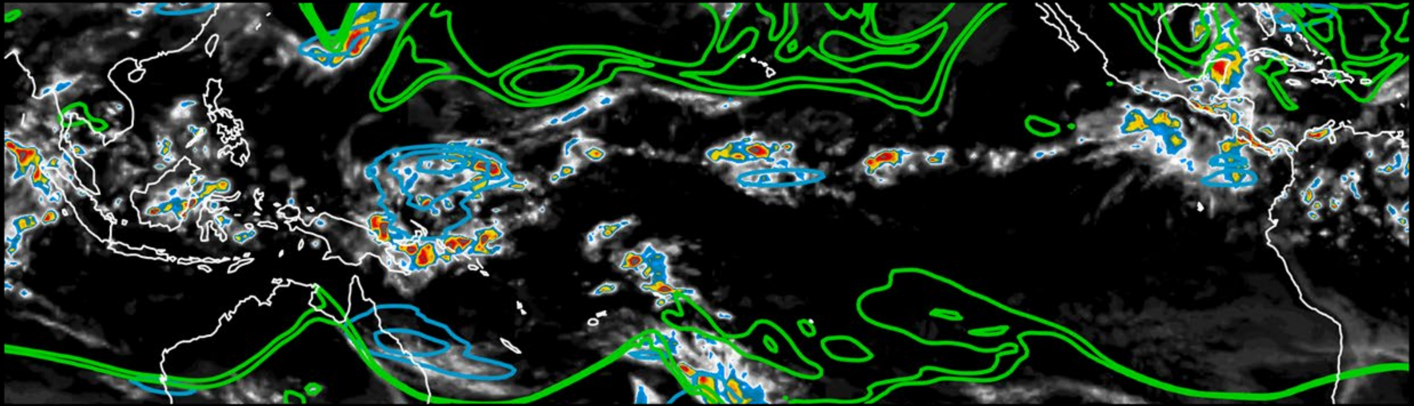
A prognostic-stochastic and scale-adaptive cumulus convection closure for improved tropical variability and convective gray-zone representation in NOAA's Unified Forecast System (UFS)

Lisa Bengtsson, NOAA ESRL PSL

Acknowledgements:
NOAA ESRL PSL: *Juliana Dias, Maria Gehne, Stefan Tulich, Cecile Penland, Jian-Wen Bao.*
NOAA NCEP EMC: *Jongil Han, Wei Li, Fanglin Yang*
RMI Belgium: *Luc Gerard*

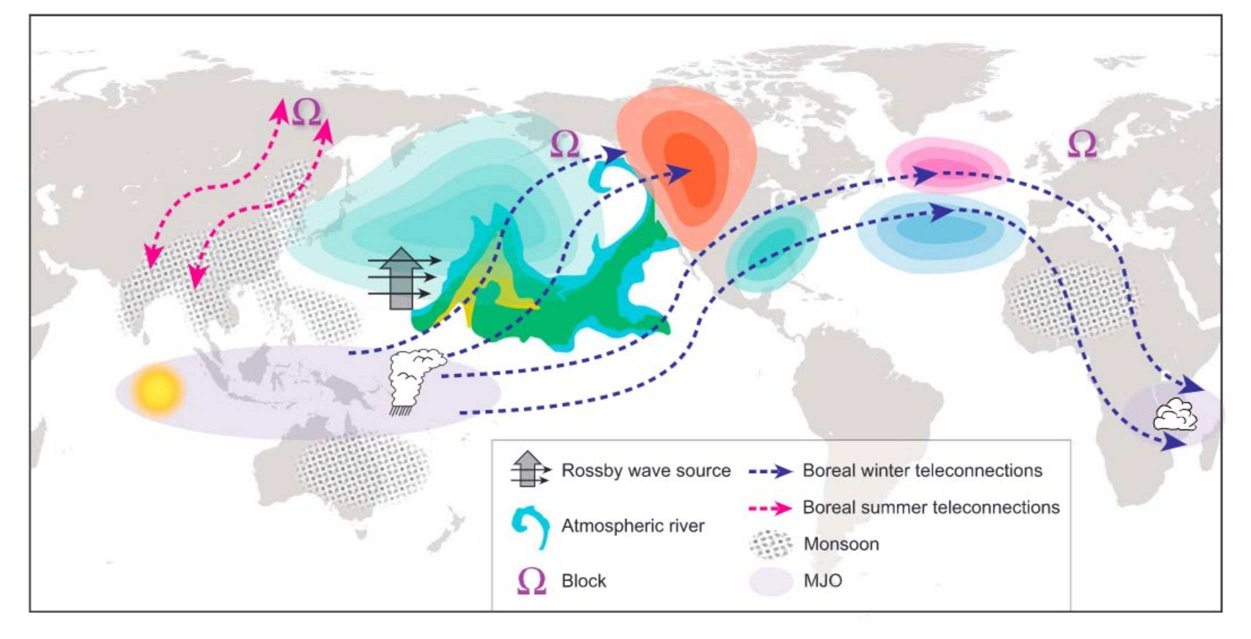


Blue contours: Kelvin waves (Kelvin-filtered brightness temperature)

Green lines: extratropical Rossby waves (potential vorticity at 200 hPa)

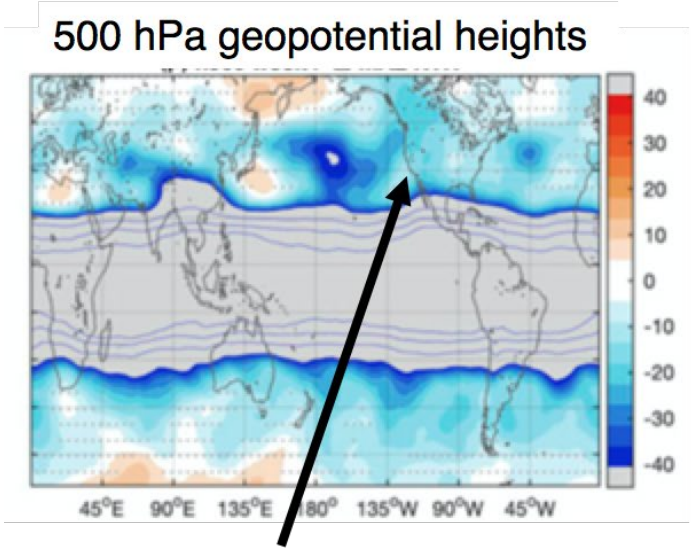
Animation from Yuan-Ming Cheng, PSL

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

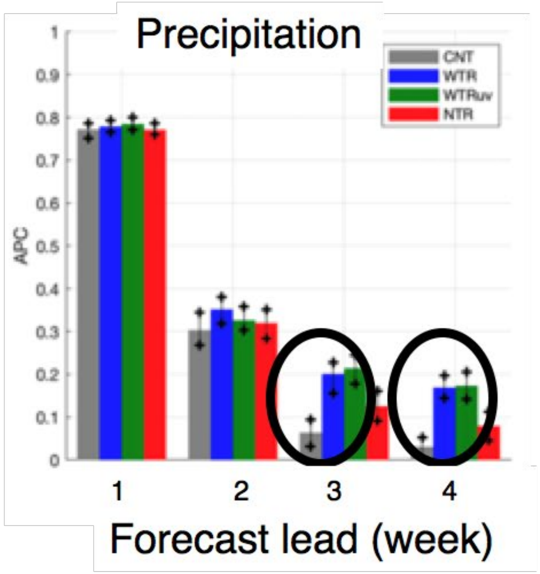


Stan et al. 2017

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):

-Parameterization of convective organization feedbacks improves auto-correlation space/time scales (memory) and strengthens the interaction between sub-grid convection and the resolved dynamics.

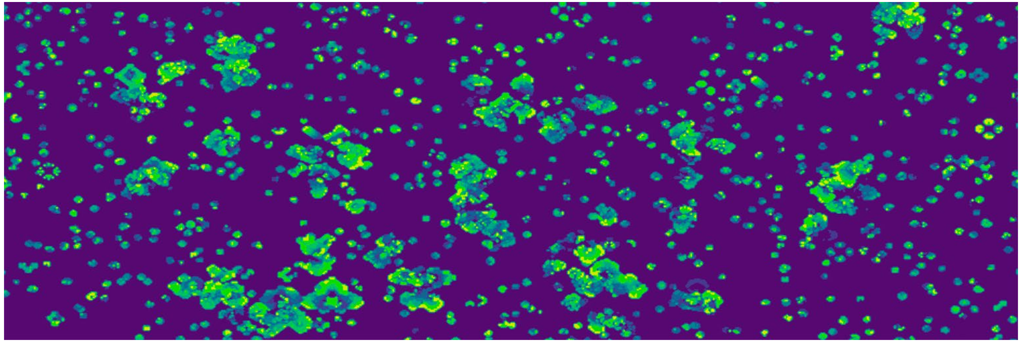
-Bringing moisture sensitivity to the closure, and introducing a prognostic (memory) evolution suggests an improved space-time spectra of moisture-precipitation coupling. This can have positive effects on MJO propagation, amplitude and phase, as suggested by our case study.

-Stochastic convection parameterization can enhance MJO propagation through noise induced forcing.

-Describing the cloud-base mass-flux as a product between area fraction and updraft velocity provides a scale adaptive closure.

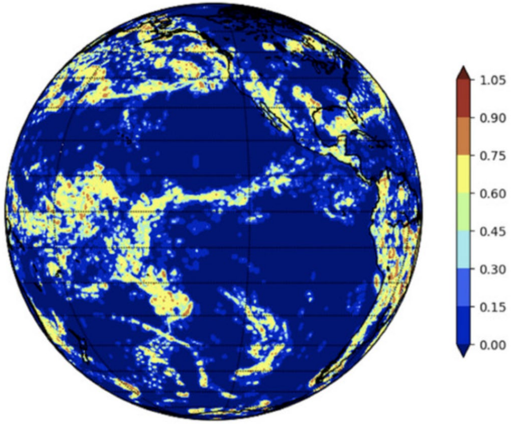
Parameterization of convective organization feedbacks using cellular automata

1. Self-organization and birth-death processes are suitable for modeling of organized physical systems - such as atmospheric convection.
2. Neighbouring gridbox information introduce 3D effects in 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 (sub-grid variability).
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.



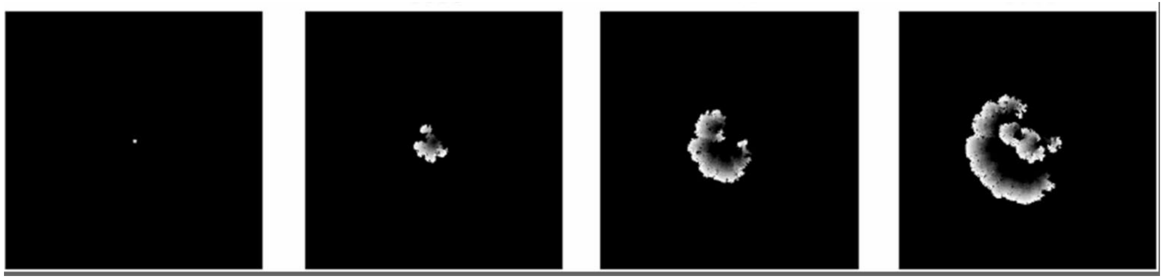
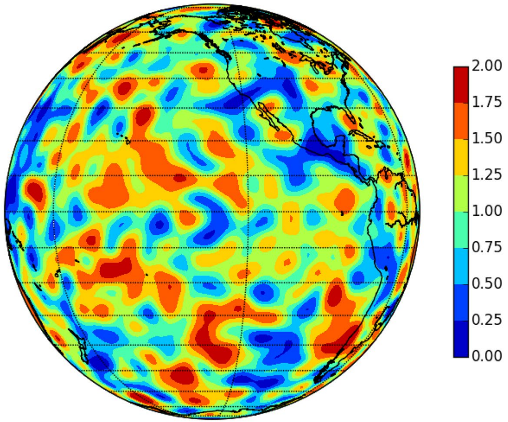


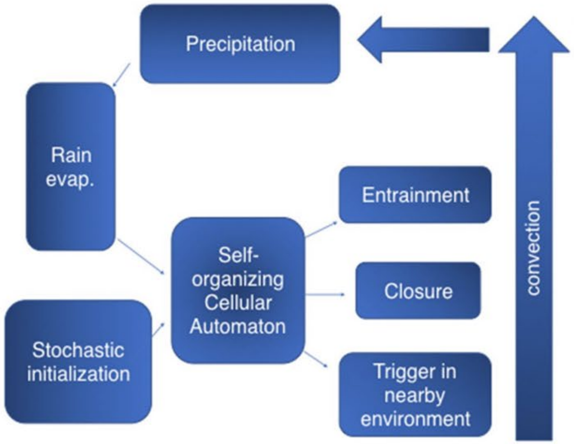
Figure by Martin Steinheimer, Astro control, Austria



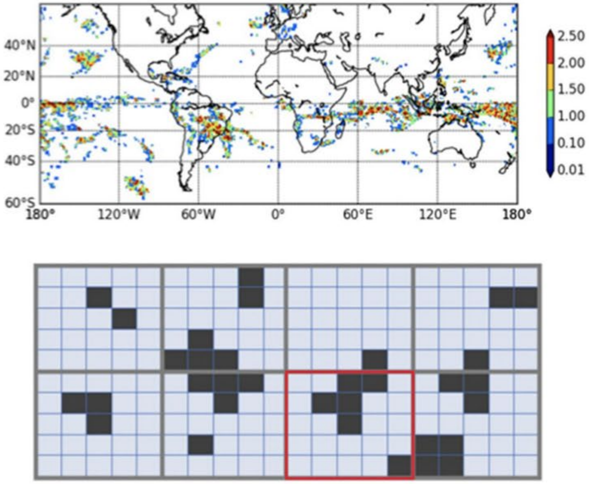
CA coupling to convection

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.

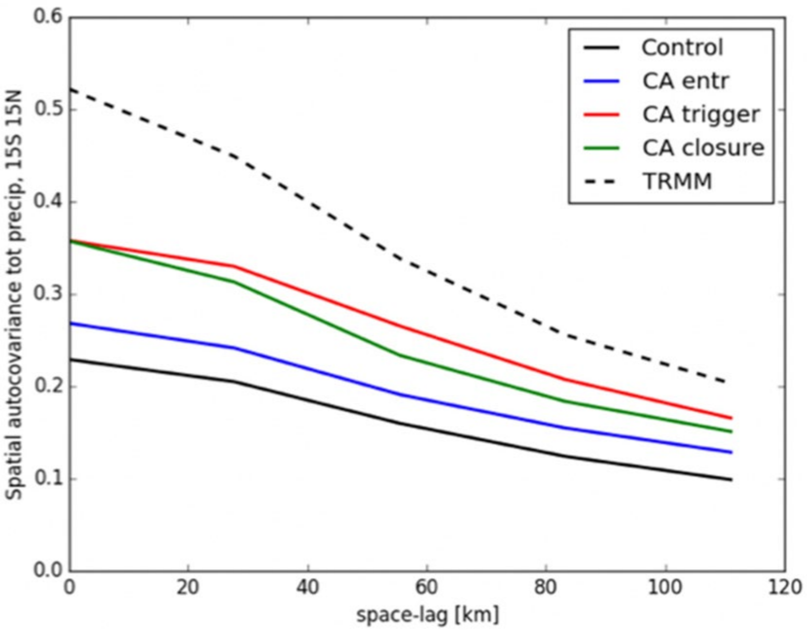


Flow chart adapted from Mapes and Neale, 2011 “org” scheme



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.

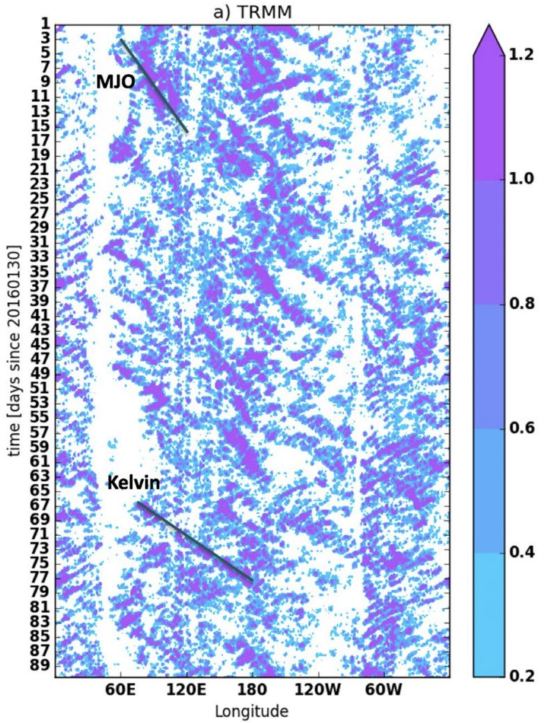
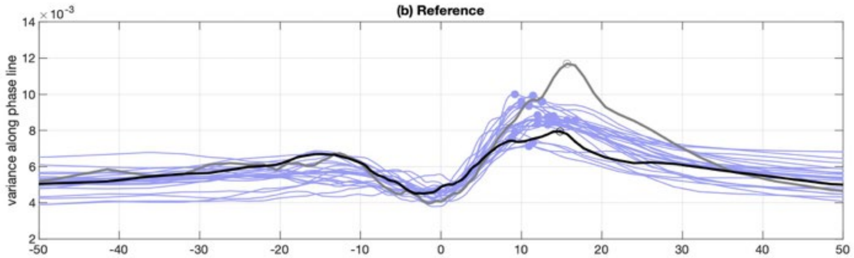
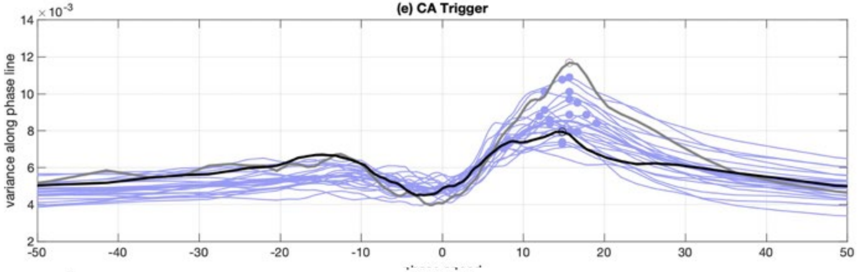
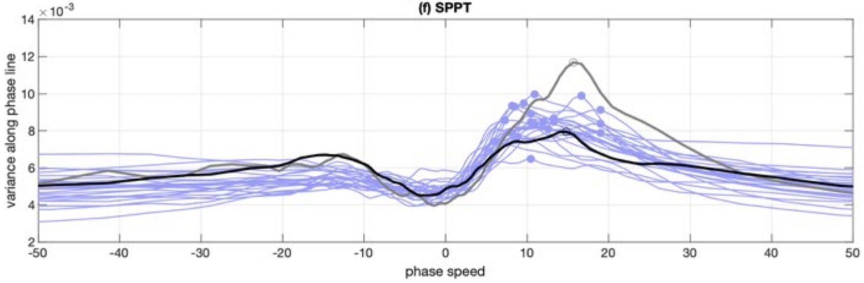


Figure 3. Observed (TRMM) Hovmöller diagram of precipitation (mm/h) for the period 20160130–20160429 between 5°S and 5°N. Lines indicate typical phase speeds associated with MJO (~7 m/s) and Kelvin wave (~15 m/s) propagation. TRMM, Tropical Rainfall Measuring Mission.

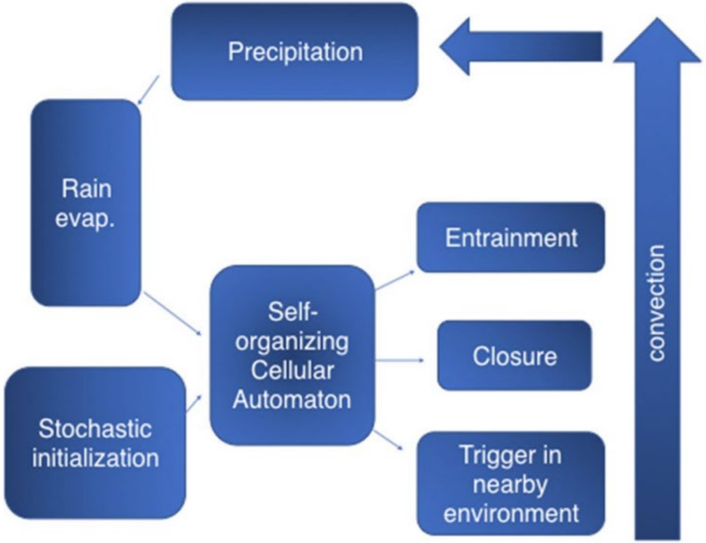

(b) Reference


(e) CA Trigger


(f) SPPT

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.

- However, in traditional cumulus convection schemes, under the quasi-equilibrium assumption, area fraction is assumed negligible.
- As we go to higher resolution this quasi-equilibrium assumption is not valid any longer, as convection can consume a considerable part of the grid-box.

CA coupling to convection

New prognostic-stochastic closure.

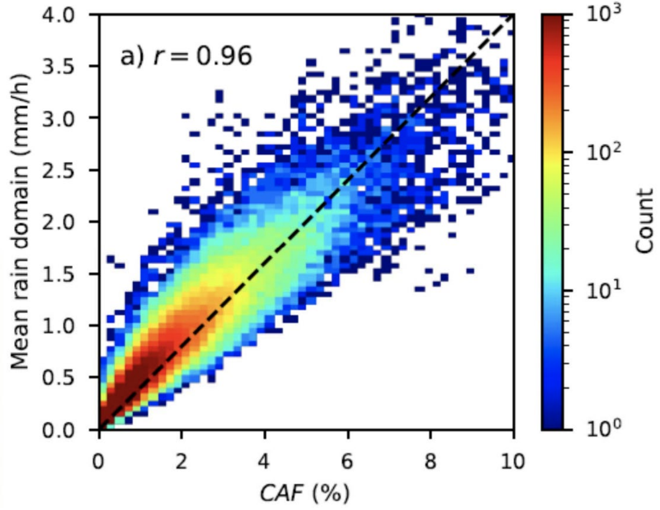
1) No longer assume negligible area fraction - need to come up with a value for it.
2) Introduce prognostic equation for updraft area fraction based on a moisture budget equation (following Gerard and Geleyn 2005, Gerard et al. 2009.)
3) Let the CA enhance the area fraction in case of more sub-grid scale organization.
4) While area fraction increases in regions of enhanced moisture flux convergence, and sub-grid organization by the CA, at higher resolution the resolved motions take over, and the parameterized cloud-base mass-flux should be reduced. For this purpose we apply a scaling to the mass-flux following Arakawa and Wu (2013), but using the prognostic area fraction outlined below.

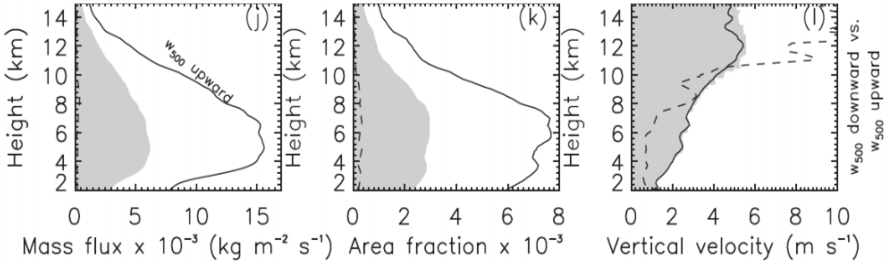
$$\frac{\partial\sigma_B}{\partial t}\int_{p_B}^{p_T}\xi(p)(h_u(p)-h_s(p))\frac{dp}{g} = L\int_{p_B}^{p_T}\sigma_B\omega_u\xi(p)\frac{\partial q_{cond}}{g} + L\int_{p_B}^{p_T}MFC\frac{dp}{g}$$

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

$$\frac{\partial w_u^2}{\partial z} = -c_1\varepsilon w_u^2 + c_2 B$$

Some observational support for prognostic area fraction



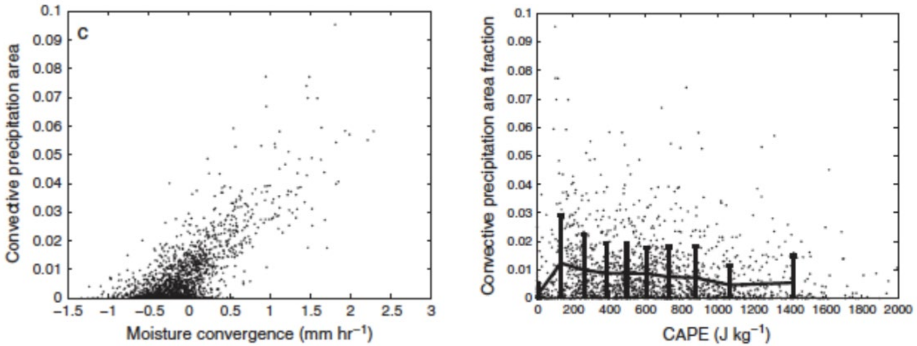


Vertically pointing radar observations from Darwin, Australia. Christian Jakob and colleagues at Monash University:

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.

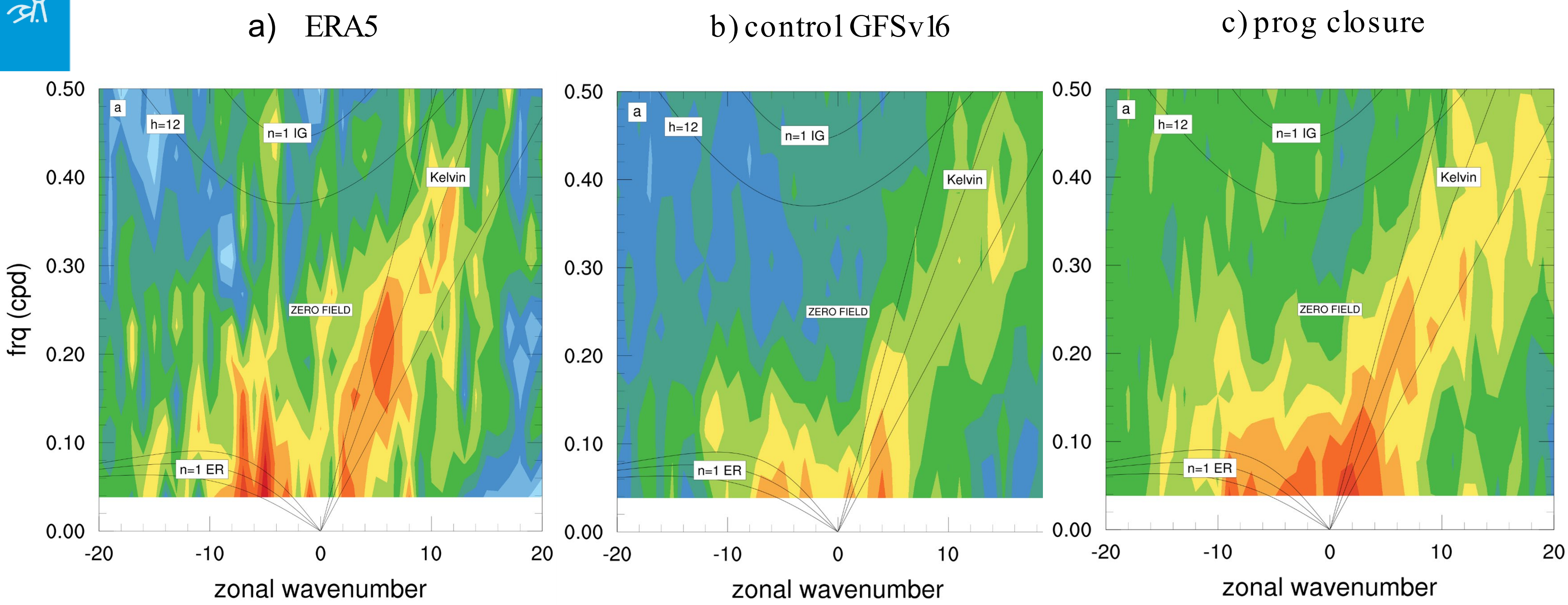


Davies et al, 2013, JGR

Moisture coupling to convection

- Idealized studies have demonstrated that moisture feedbacks are essential for CCEW initiation and propagation (Mapes et al. 2006, Maloney and Hartmann 2001; Benedict and Randall 2009; Tulich and Mapes 2010; Hannah and Maloney 2011 and Kim et al. 2012, Bechtold et al. 2008)
- Thus, we here explore the impact of the prognostic-stochastic closure, as cast as a moisture budget equation, on CCEW and MJO prediction

Coherence between low level moisture flux convergence and precipitation



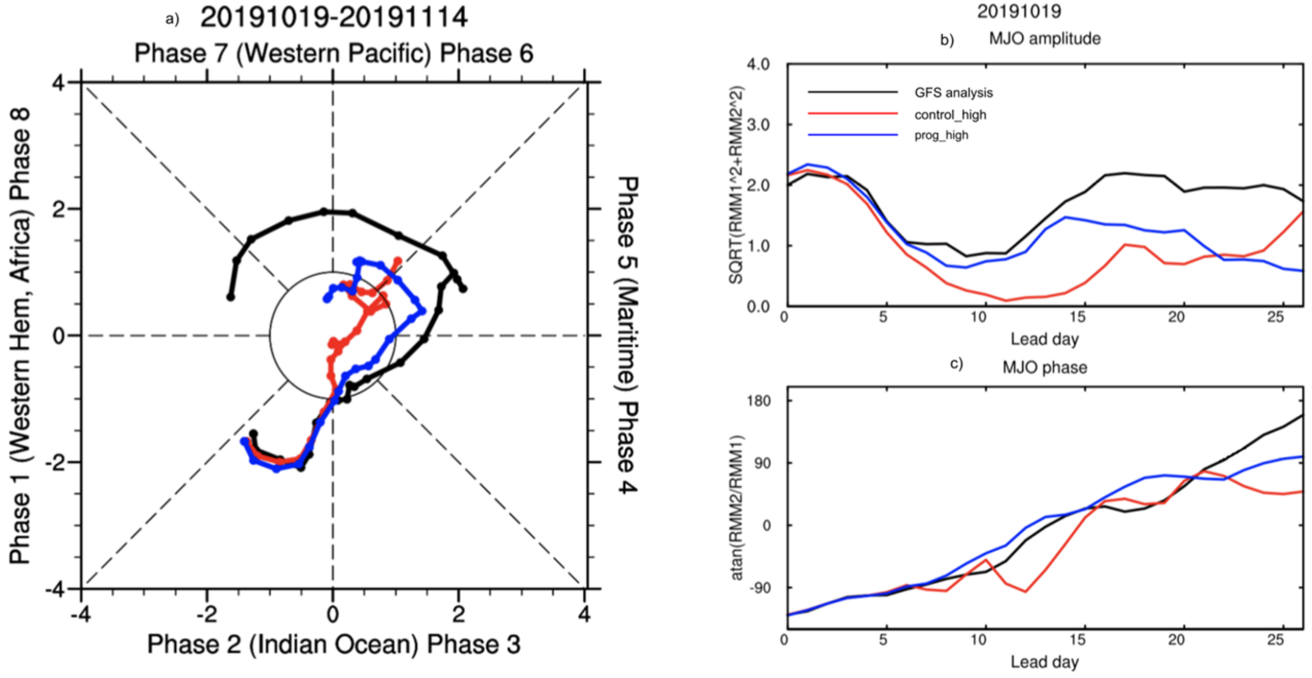
a) ERA5

b) control GFSv16

c) prog closure

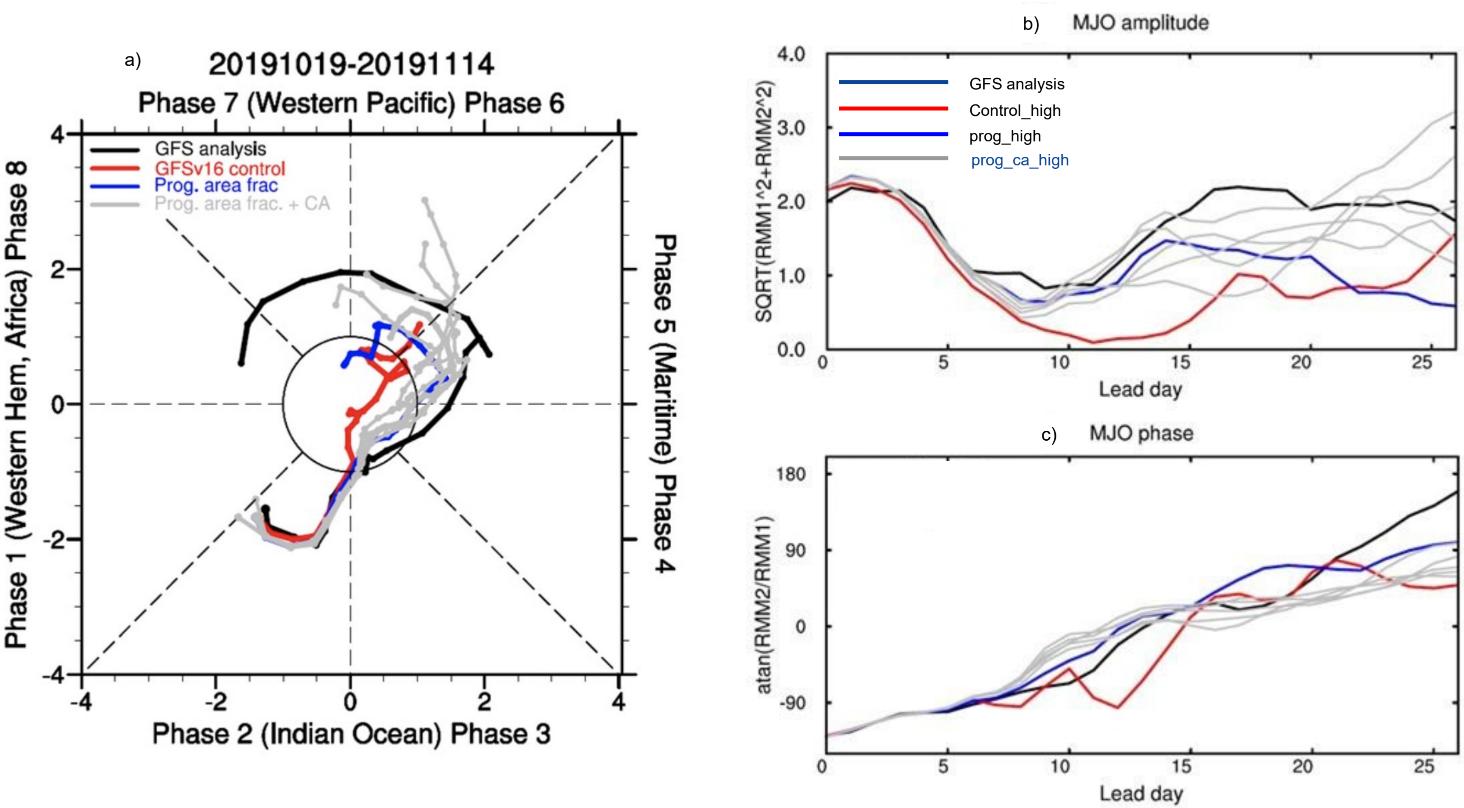
Figures from Maria Gehne, PSL

MJO statistics, impact of new closure



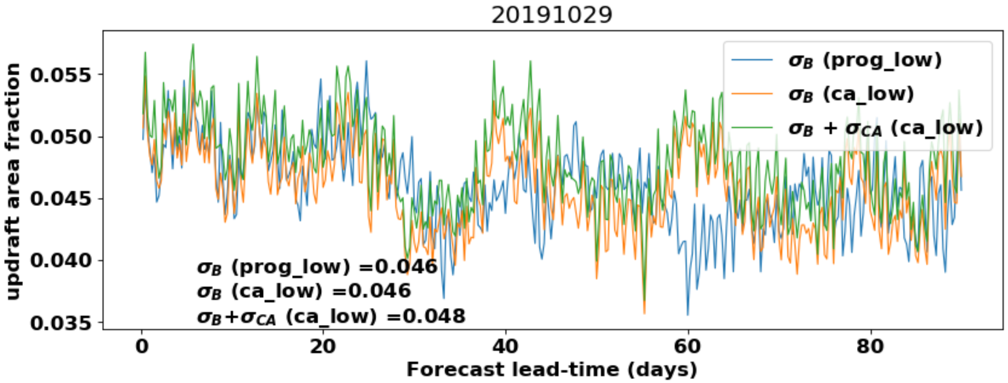
Figures from Wei Li, EMC

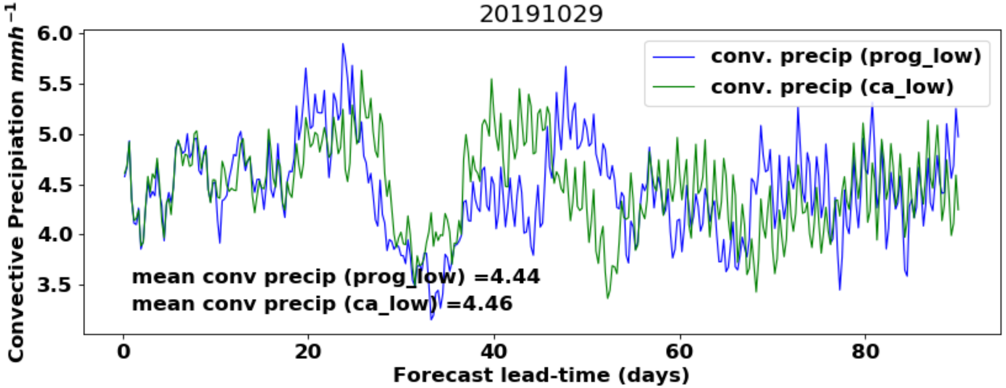
MJO statistics, impact of new closure - with CA



Figures from Wei Li, EMC

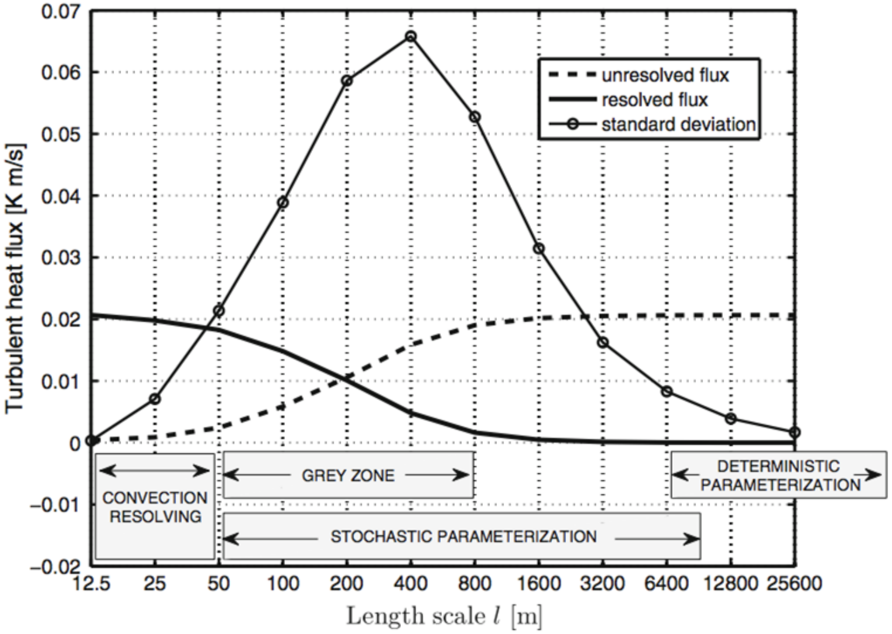
Can the impact of the CA in this case be viewed as a noise induced forcing, or do we see a systematic shift in precipitation time-series?



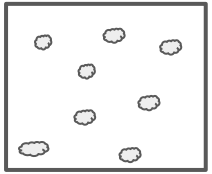


While the updraft area fraction is systematically enhanced due to sub-grid organization feedbacks given by the CA, the response in convective precipitation is not systematic.

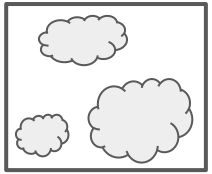
Scale adaptive and grey-zone considerations



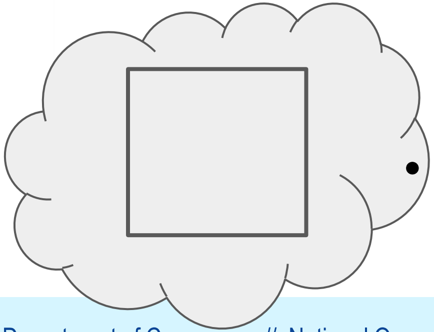
Dorrestijn, J., *et al.* (2013), example for shallow cu.



- **Convective area fraction is assumed negligible. Assume that all convective cloud motions in a grid-box can be represented in a statistical sense, under a steady state assumption.**

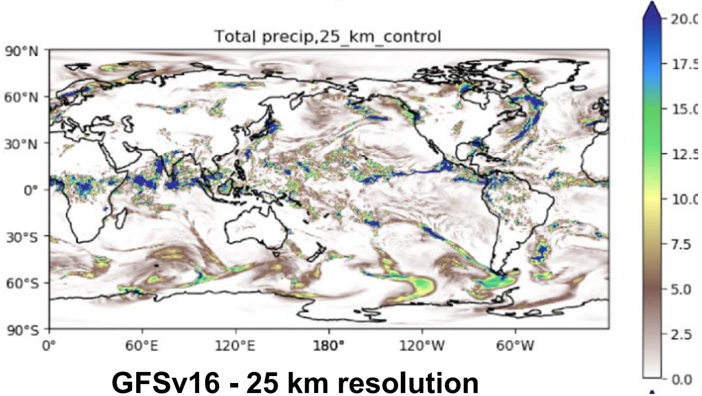


- **No longer assume negligible area fraction. Standard deviation of fluxes is large. Stochastically sample plume number and plume size.**

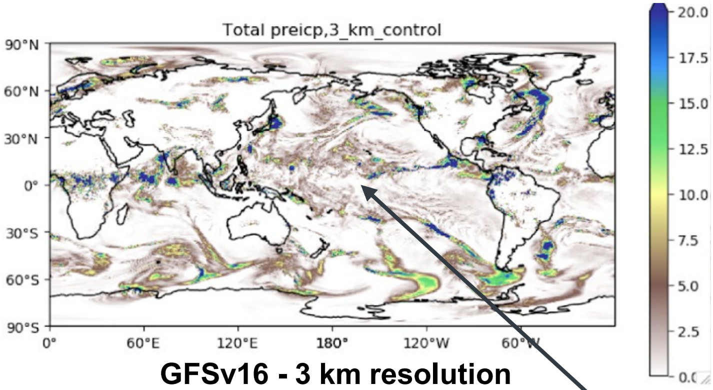


- **Convection is fully resolved**

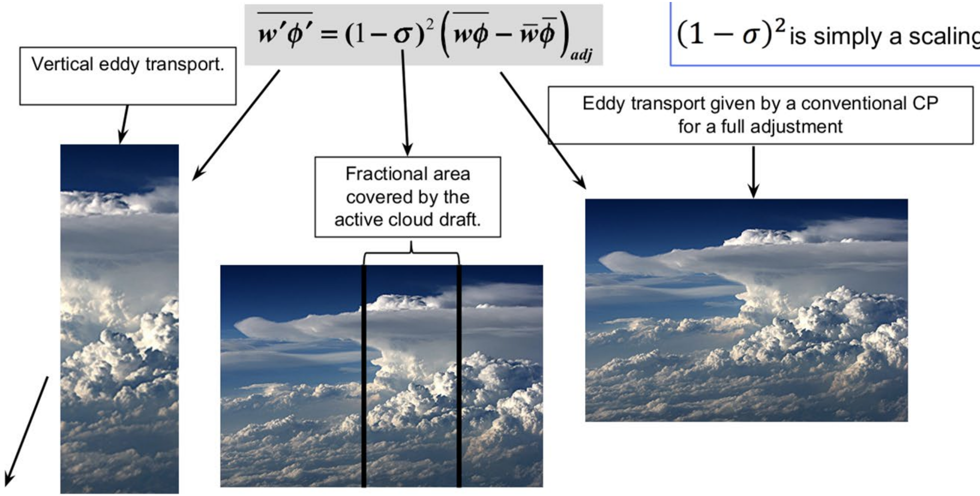
Scale-adaptive considerations



GFSv16 - 25 km resolution



GFSv16 - 3 km resolution



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

Vertical eddy transport.

Fractional area covered by the active cloud draft.

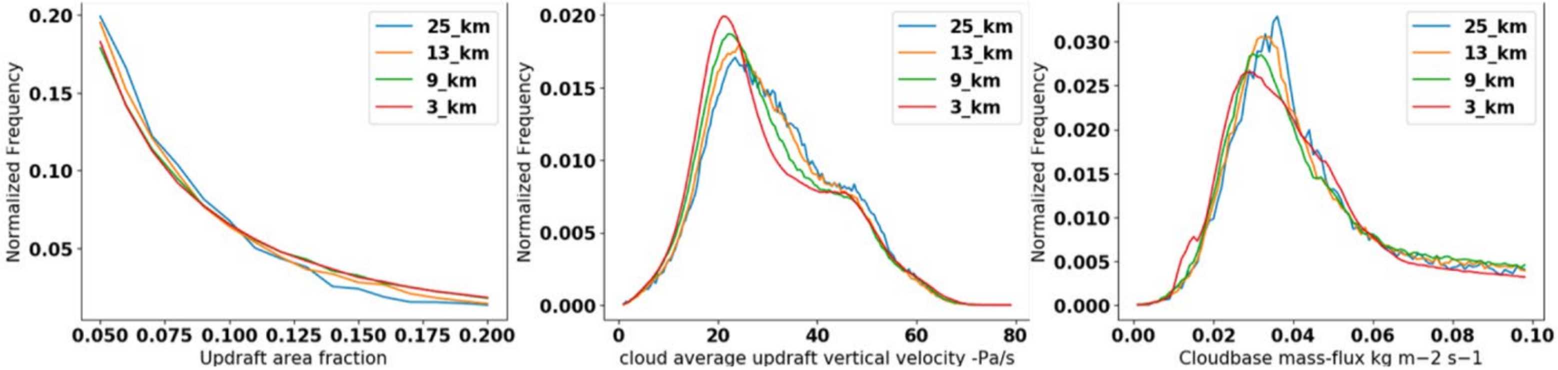
Eddy transport given by a conventional CP for a full adjustment

$(1-\sigma)^2$ 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!



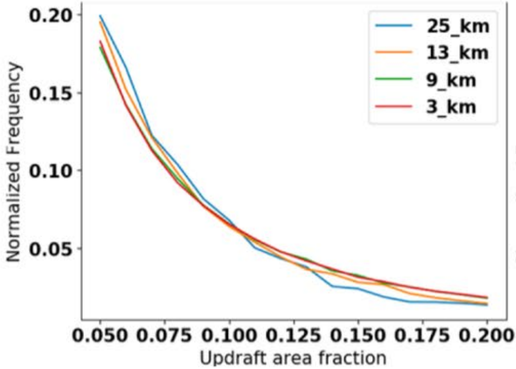
$$M_B = -(1.-\sigma_B)^2 \frac{\sigma_B \overline{\omega_u}}{g}$$

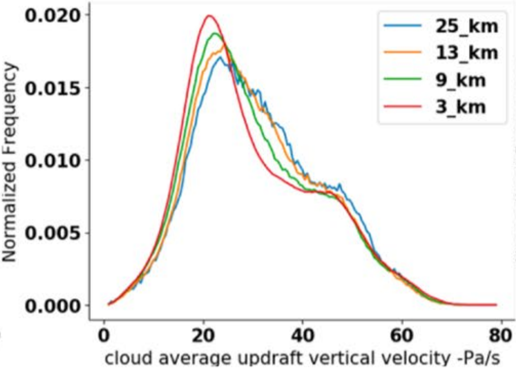
$$\frac{\partial \sigma_B}{\partial t} \int_{p}^{p_T} \xi(p)(h_u(p) - h_s(p)) \frac{dp}{g} = L \int_{p_B}^{p_T} \sigma_B \omega_u \xi(p) \frac{\partial q_{cond}}{g} + L \int_{p_B}^{p_T} MFC \frac{dp}{g}$$

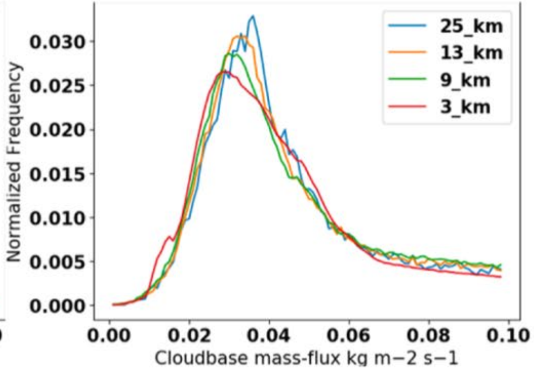
$$\frac{\partial w_u^2}{\partial z} = -c_1 \varepsilon w_u^2 + c_2 B \qquad B = g(\theta_{v,u} - \overline{\theta_v})/\overline{\theta_v}$$

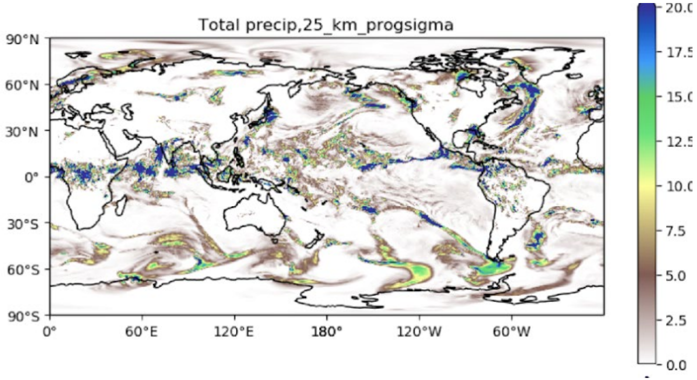
Bengtsson et al. 2022

Scale-adaptive considerations - new closure

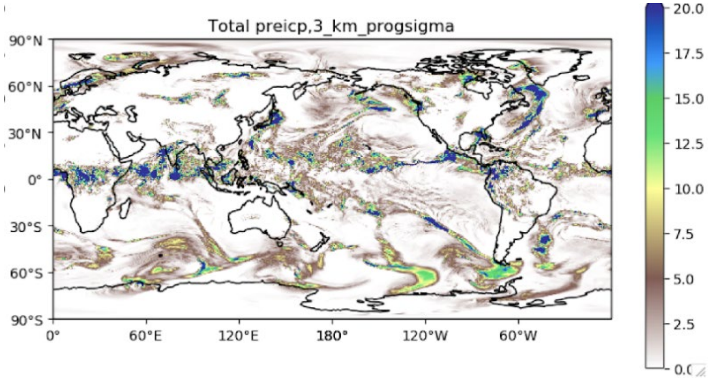








Prog closure 25km



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:
    - 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.

- 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.