On cellular automata in stochastic convective parameterizations over the years - feats and defeats

Lisa Bengtsson, CIRES and NOAA ESRL PSL

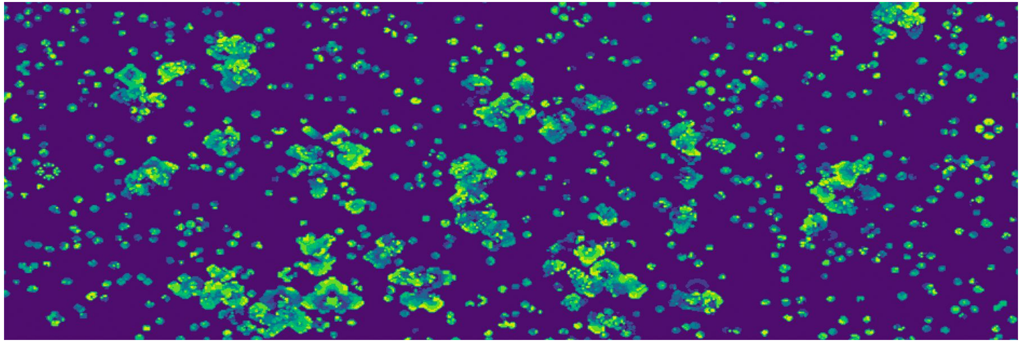
Acknowledgement to collaborators over the years

HIRLAM/ALADIN/ECMWF/Univ. Oxford - Jean-Francois Geleyn, Luc Gerard, Martin Steinheimer, Filip Vana, Peter Bechtold, Ulf Andrae, Heiner Körnich, Inger-Lise Frogner, Tim Palmer, Judith Berner, Glenn Shutts, Erland Källén, Hannah Christensen.

NOAA ESRL PSL /NOAA NCEP EMC /NOAA GFDL and CIRES - Jian-Wen Bao, Rusty Benson, Philip Pegion, Cecile Penland, Stefan Tulich, Jongil Han, Maria Gehne, Wei Li, Juliana Dias

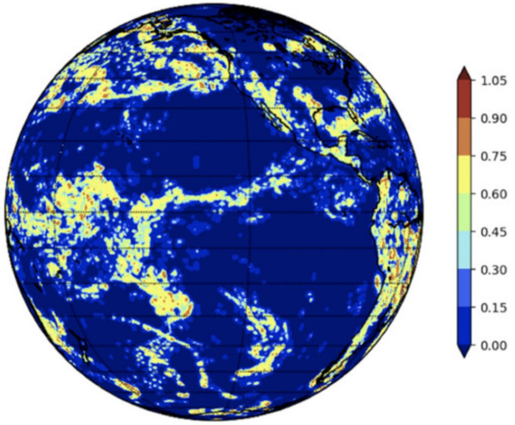
Motivation

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 predictions, stochastic cumulus convection can be viewed as a noise induced forcing to larger scale predictable waves.



Important considerations

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



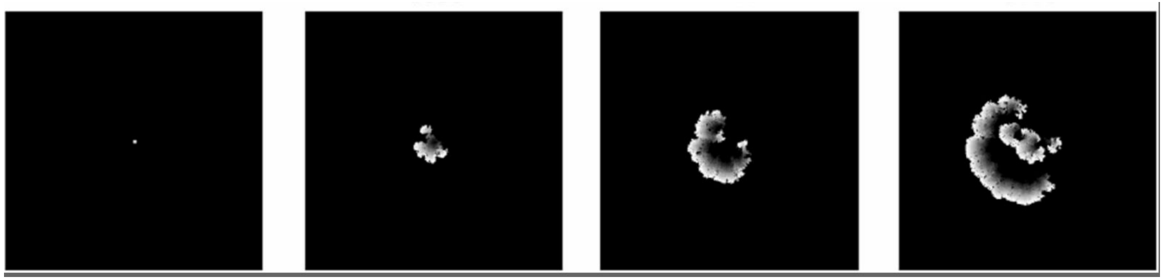
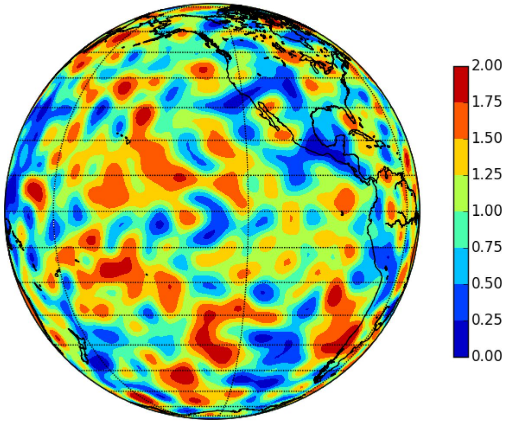


Figure by Martin Steinheimer, Astro control, Austria



CA coupling to convection

Spectral plume distribution (Chikira & Sugiyama cumulus conv)

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

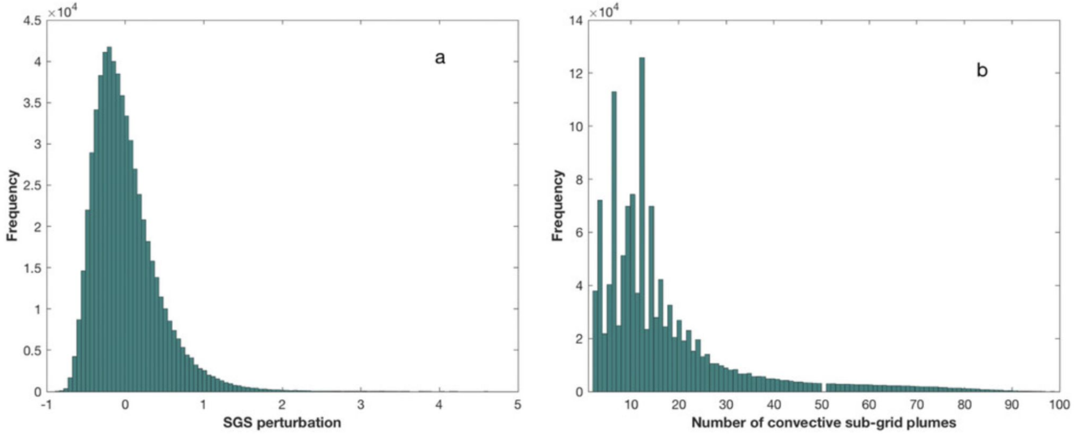
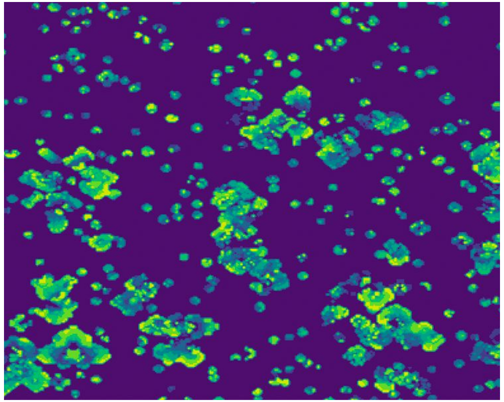


FIG. 2.

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

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

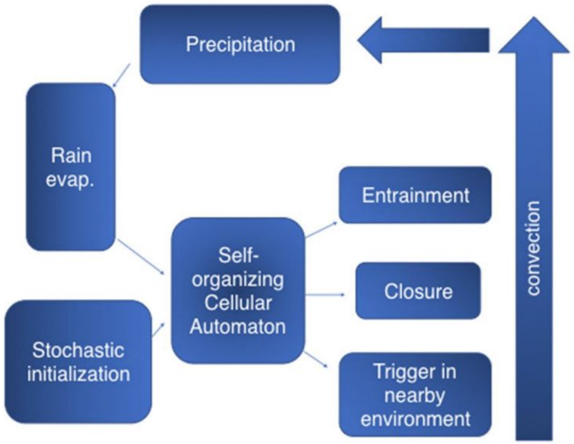


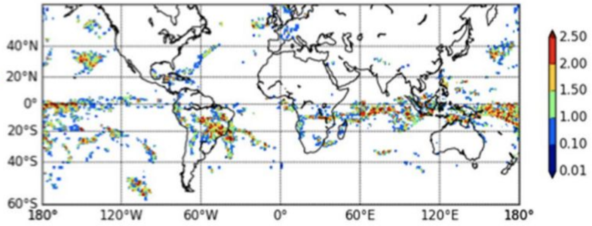
Bengtsson et al. 2019

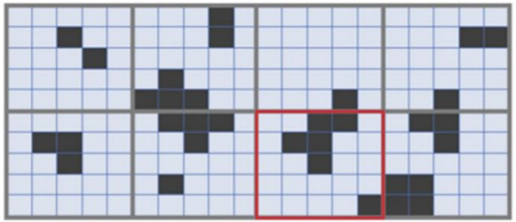
CA coupling to convection

Bulk mass-flux scheme

If bulk quantities are provided, we instead 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 from Bengtsson et al. 2021 adapted from Mapes and Neale, 2011 "org" scheme

Bengtsson et al. 2021

CA coupling to convection - example impact convective initiation

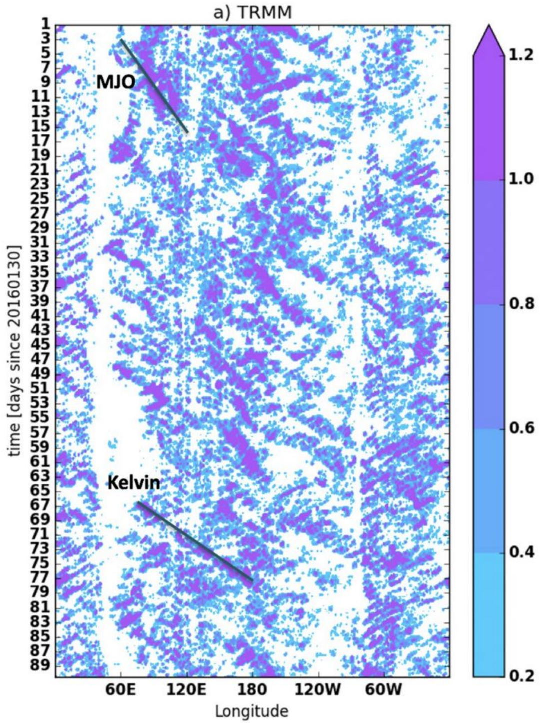
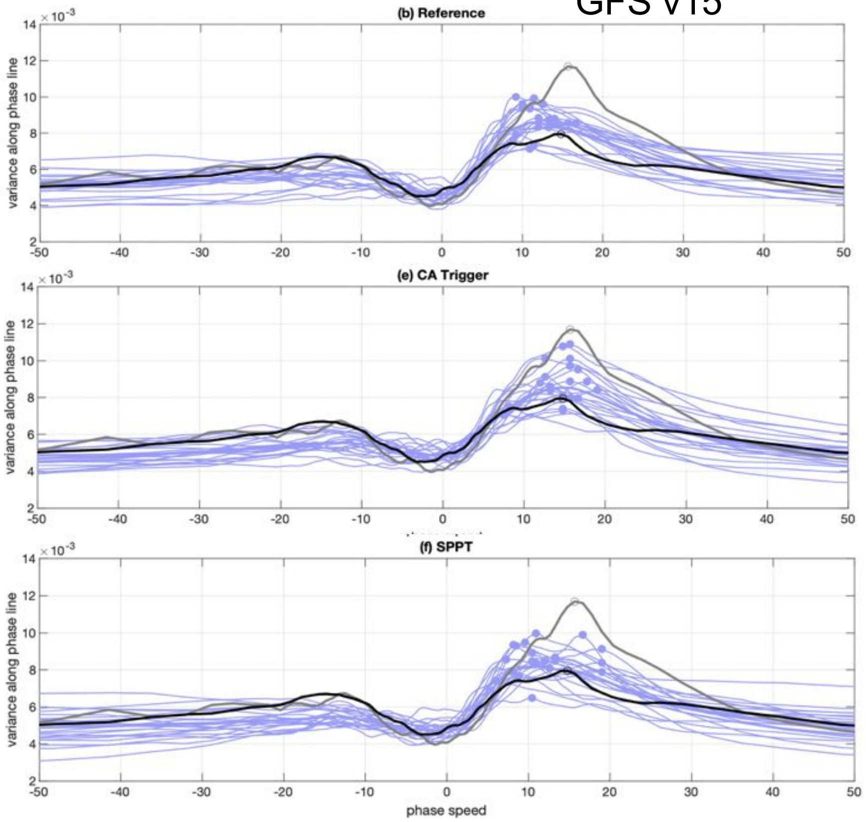


Figure 3. Observed (TRMM) Hovmöller diagram of precipitation (mm/h) for the period 20160130–20160429 between 5°S and 5°N. Lines indicate typical phase speeds associated with MJO (~7 m/s) and Kelvin wave (~15 m/s) propagation. TRMM, Tropical Rainfall Measuring Mission.

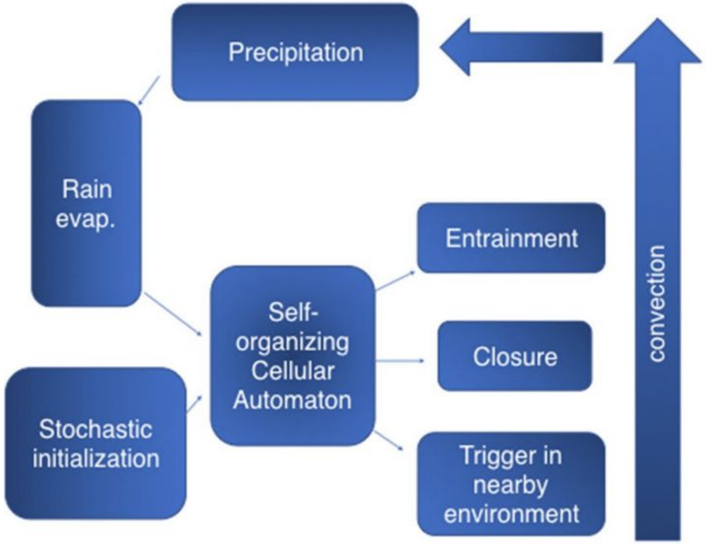
GFS v15



Figures from Maria Gehne and Juliana Dias, NOAA ESRL, PSL

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

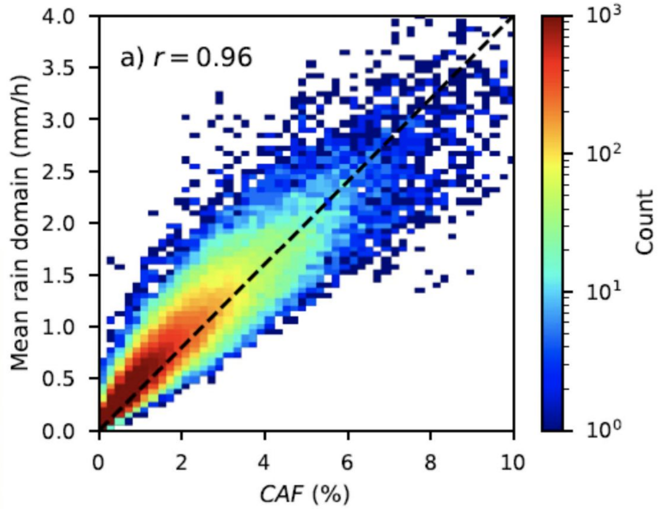
New prognostic-stochastic closure.

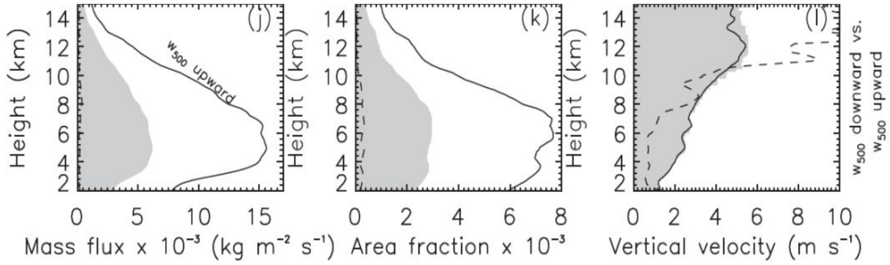
1) No longer assume negligible area fraction
2) Introduce prognostic equation for updraft area fraction based on a moisture budget equation (following Gerard and Geleyn 2005, Gerard et al. 2009.)
3) Let the CA enhance the area fraction in case of more sub-grid scale organization. Add CA stochastic forcing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

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

Important, the full closure is: $M_B = -(1. - \sigma_B)^2 \frac{\sigma_B \omega_u}{g}$

Observational support for prognostic area fraction cast as a moisture budget

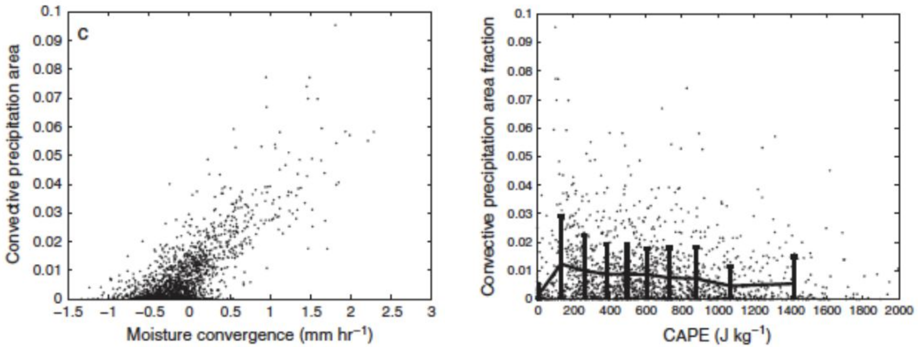




Vertically pointing radar observations from Darwin, Australia. Christian Jakob and colleagues at Monash University:
Kumar et al. 2016, Louf et al. 2019, Narsey et al. 2019

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.

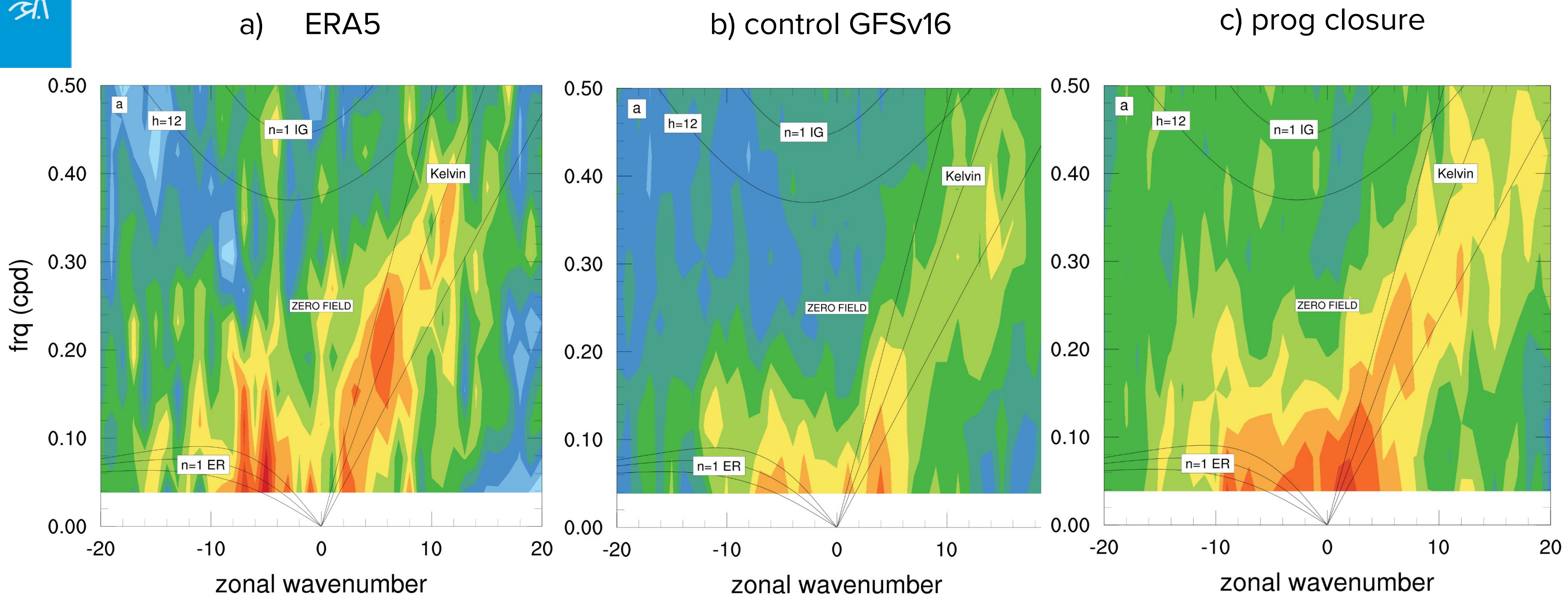


Davies et al, 2013, JGR

Moisture coupling to convection important for prediction of Convectively Coupled Equatorial Waves (CCEW)

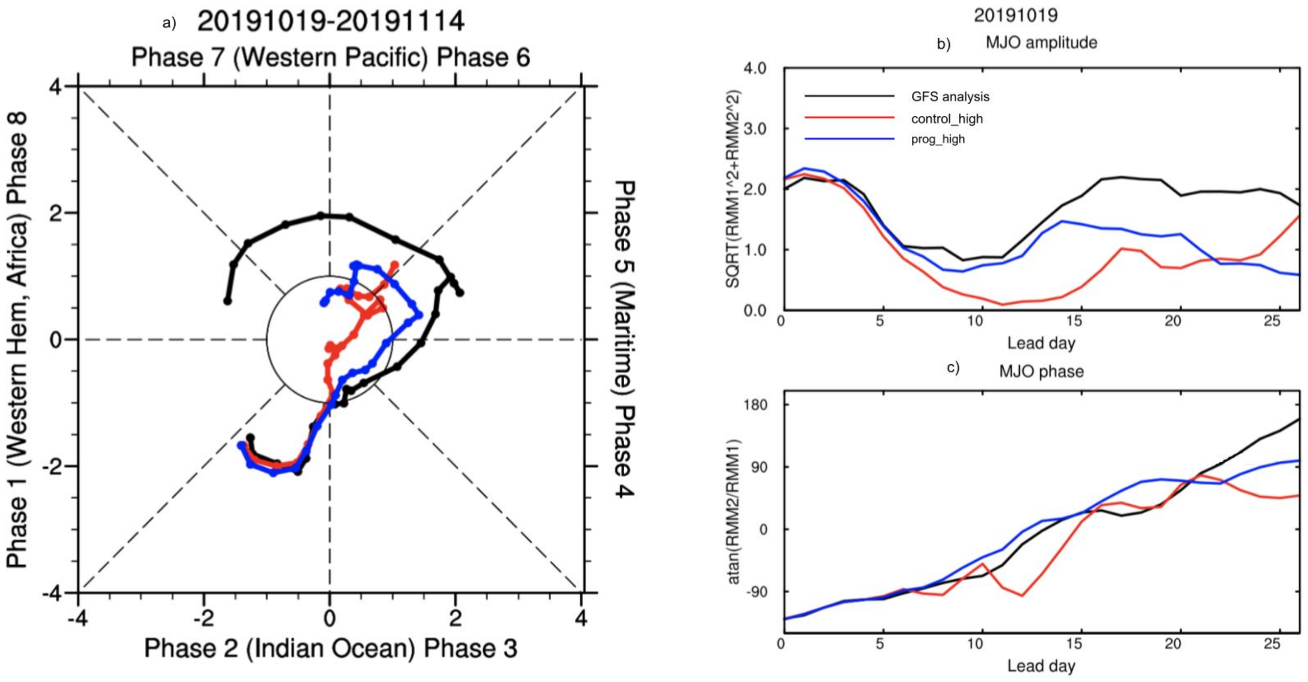
- Idealized studies have demonstrated that moisture feedbacks are essential for CCEW initiation and propagation (Mapes et al. 2006).
- In particularly the MJO is improved when convection is made more sensitive to environmental moisture (e.g., Maloney and Hartmann 2001; Benedict and Randall 2009; Tulich 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 used in the GFS deep and shallow convection schemes on CCEW and MJO prediction

Coherence between low level moisture flux convergence and precipitation



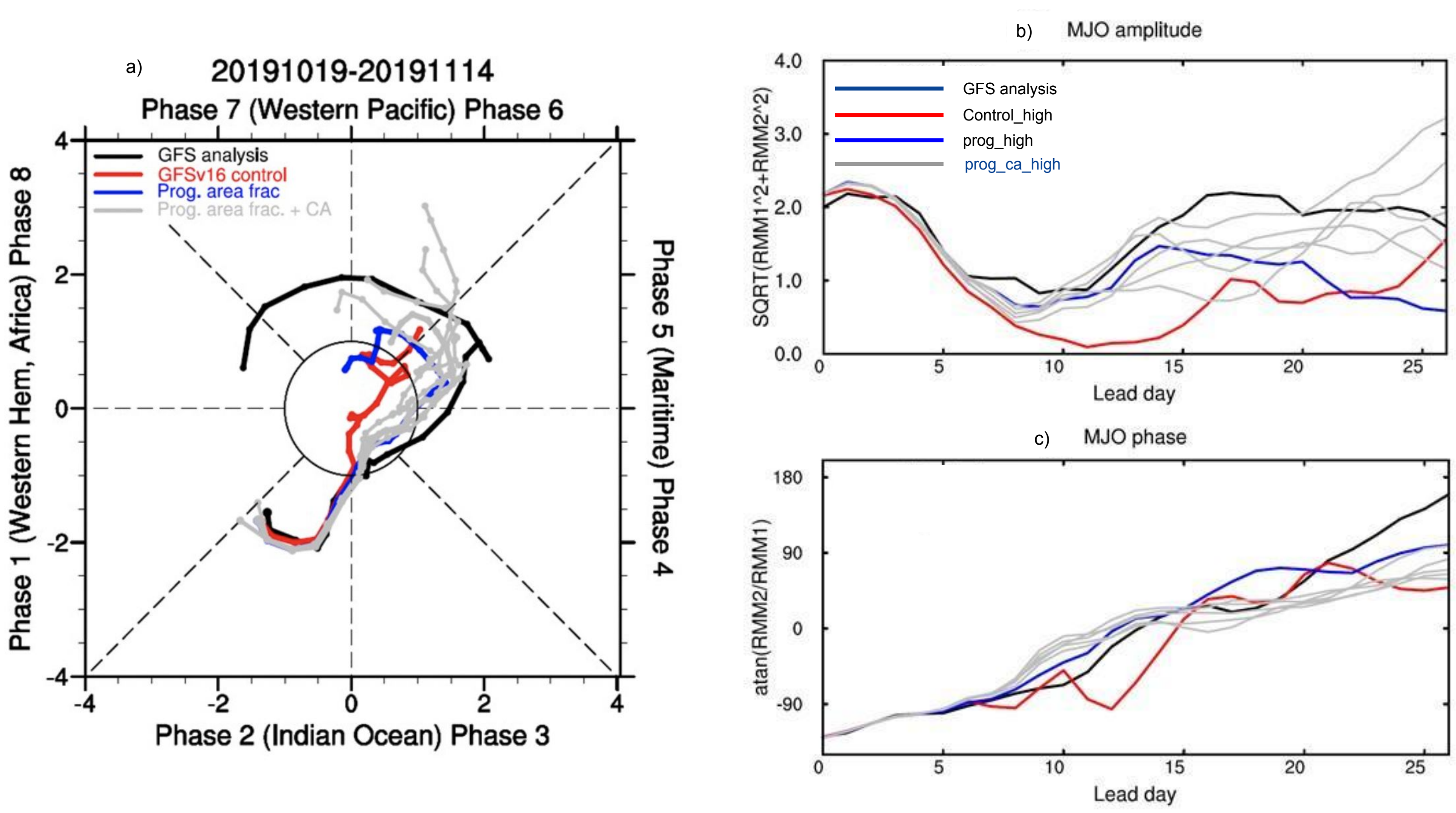
Figures from Maria Gehne, PSL

MJO statistics, impact of new closure



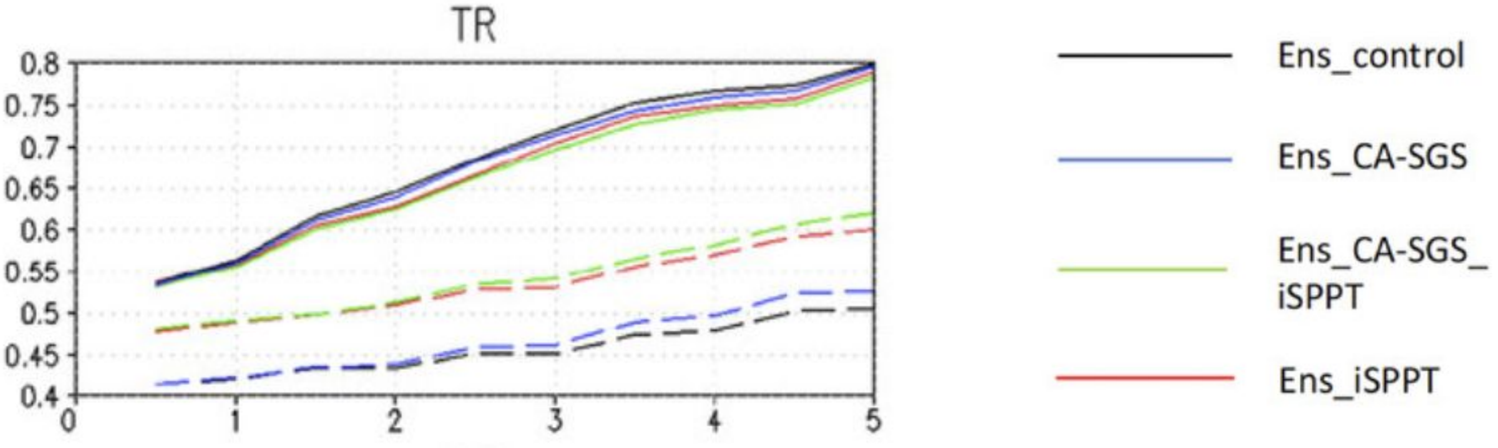
Figures from Wei Li, EMC

MJO statistics, impact of new closure - with CA



Figures from Wei Li, EMC

Ensemble spread and upscale propagation of uncertainty



Lead time, days

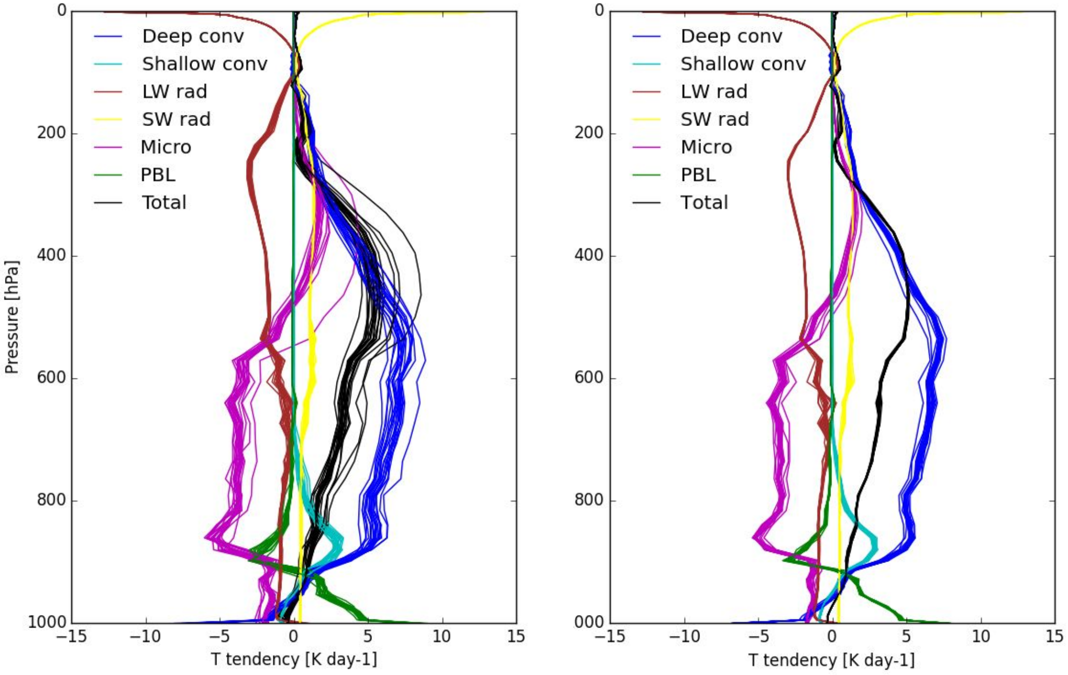
850 hpa Temperature spread / standard dev. error

From Bengtsson et al. 2019

Uncertainty growth - sampling strategy for stochastic representation in single column model.

SPPT on total tendency

SPP inside physics



Local perturbations are inefficient at producing ensemble spread in the total tendency due to compensating processes in other parts of the physics.

SPPT/SPP is only correlated in time, since we are here using a single column model for the analysis.

CCPP/SCM

Uncertainty growth - sampling strategy for stochastic representation

In Bengtsson et al. 2019, we discuss the importance of dynamical memory in uncertainty representation in NWP models, in the light of describing stochastic processes through the theory of Nonequilibrium Statistical Mechanics.

We use the Mori-Zwanzig formalism as the first principle, to connect subgrid uncertainty to the resolved dynamics.

$$(\partial\delta\boldsymbol{x}/\partial t)_{subgrid} = [dynamical\ memory] + [stochastic\ perturbation\ of\ subgrid\ process(es)]$$

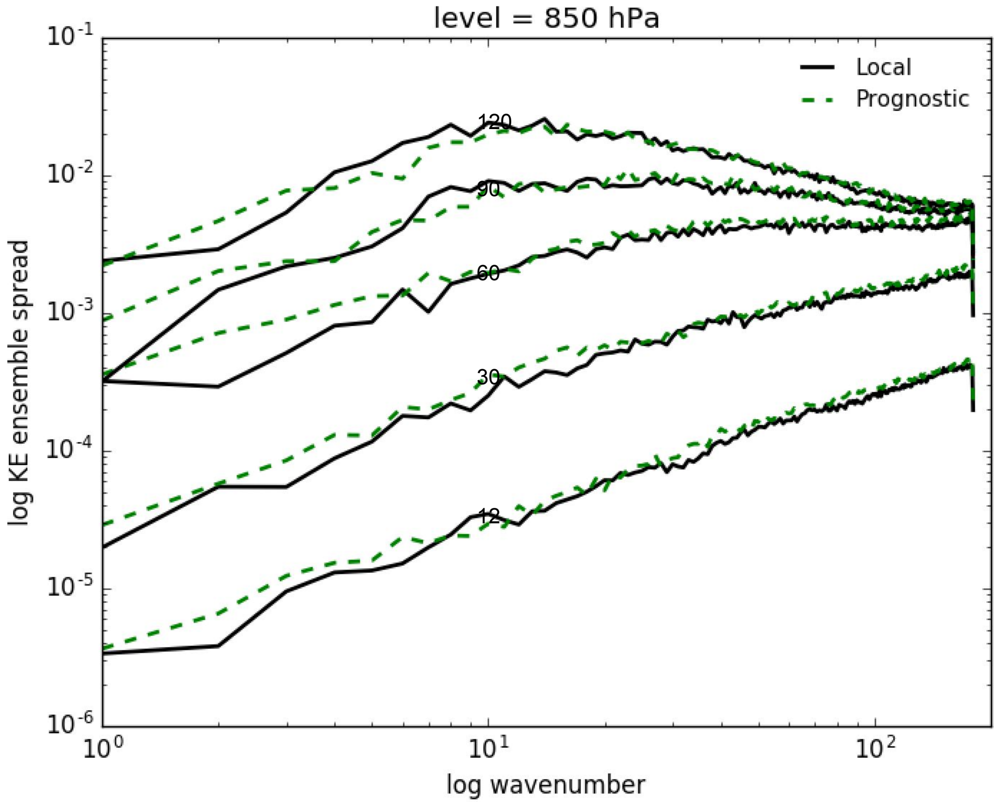
It is not a new idea, but a way to provide a theoretical background for stochastic physics parameterizations in NWP models, in fact, this is what has been implemented in stochastic backscatter schemes (e.g. Berner et al. 2008 and Shutts 2015).

Uncertainty growth - sampling strategy for stochastic representation

- The Mori-Zwanzig formalism is a theoretical principle, it does not provide a specific solution (e.g how to sample and represent uncertainty in sub-grid physics), nor a specific representation of the memory term.

- In ESRL PSL, we are working on specific PDF models, and memory representation, following this principal, to account for physics uncertainties at process level. (Jian-Wen Bao and others).

Prognostic-stochastic closure vs local perturbation



To some extent, the prognostic-stochastic equation of the updraft area fraction follows the idea of memory in the perturbation itself (MZ formalism).

——— CA used to locally perturb diagnostic updraft area fraction.

——— CA term in prognostic-stochastic closure equation.

In this case the "memory" is represented by advection.

Some concluding remarks

1. Using cellular automata in convection parameterization has been proven beneficial for enhancing convection-dynamic coupling (organization/memory), and a positive impact can be seen in the prediction of convectively coupled equatorial waves, and meso-scale convective organization. The use of cellular automata in the UFS is currently slated for operations in 2024 in both the deterministic and ensemble versions of GFSv17/GEFSv13.

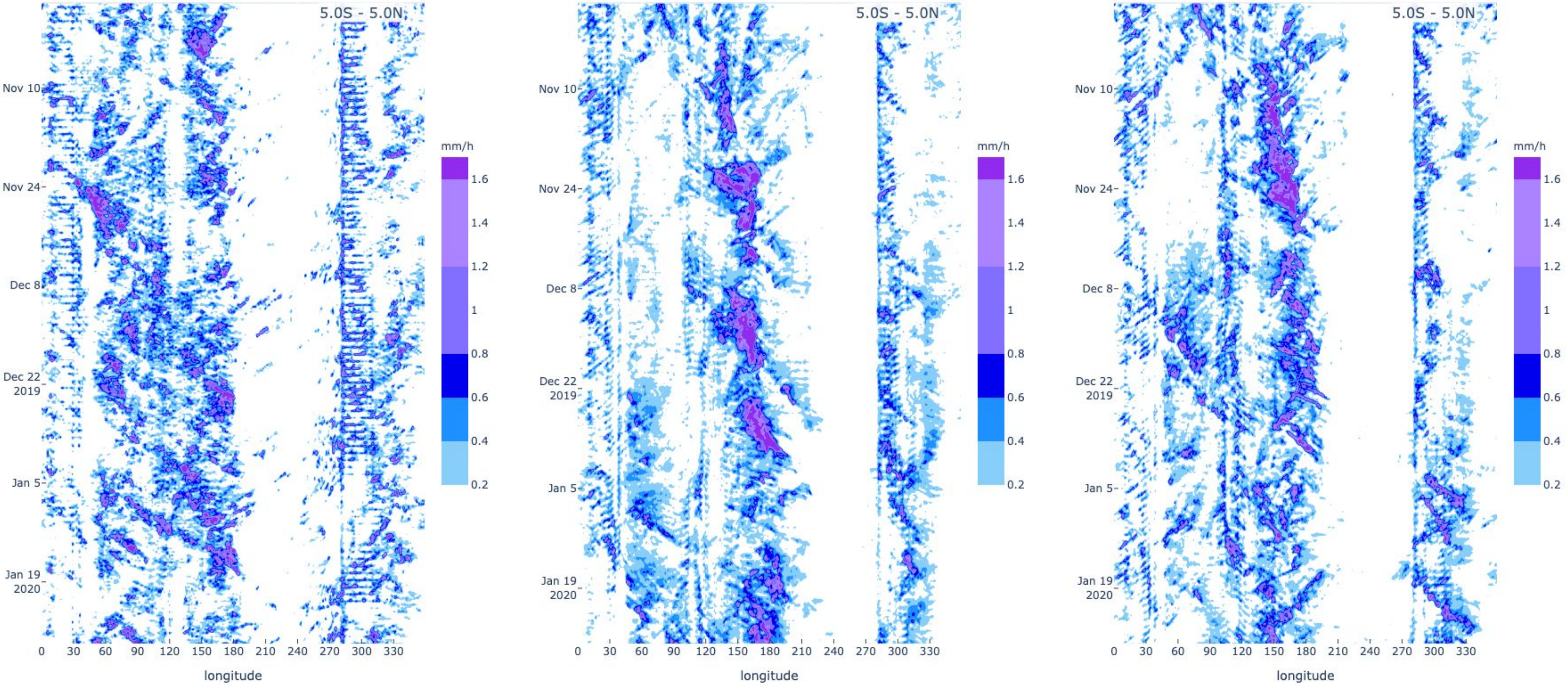
2. While the CA exhibits some correlated space-time scales (compared to white noise), the scales do not seem large enough to propagate uncertainty upscale to achieve the same spread as can be given by large scale SPPT perturbations. We are exploring if using the prognostic-stochastic closure, or propagating the perturbed quantity itself, can enhance upscare error growth.

Extra slides

a) ERA5

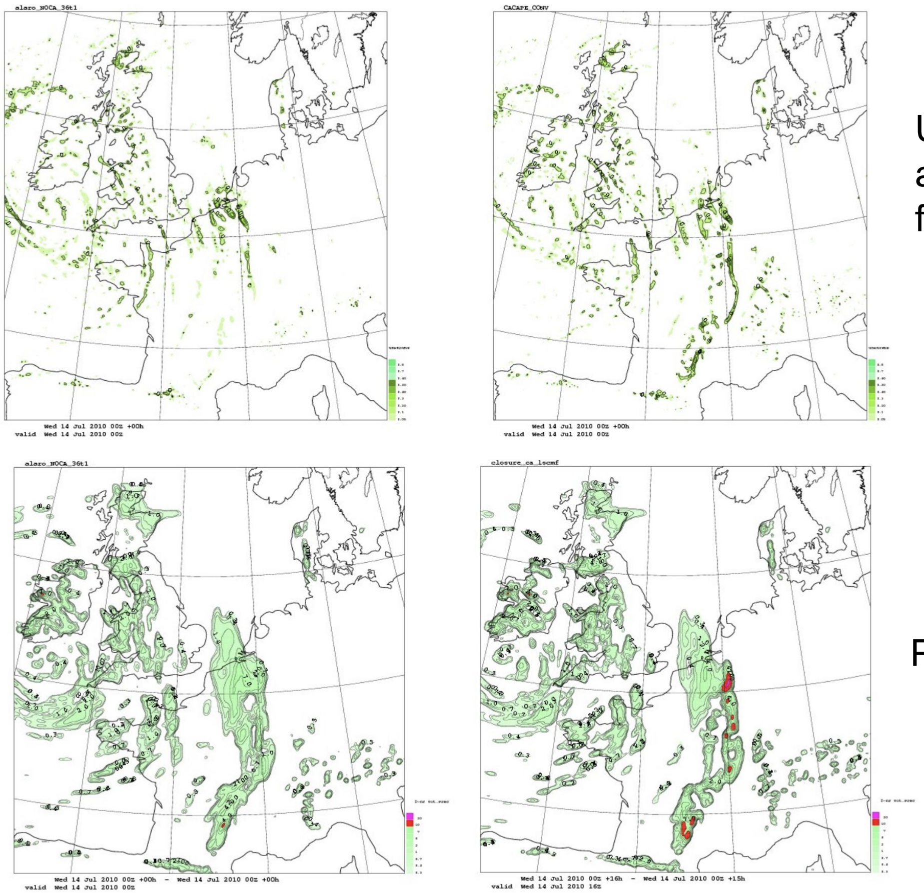
b) control GFSv16

c) prognostic closure



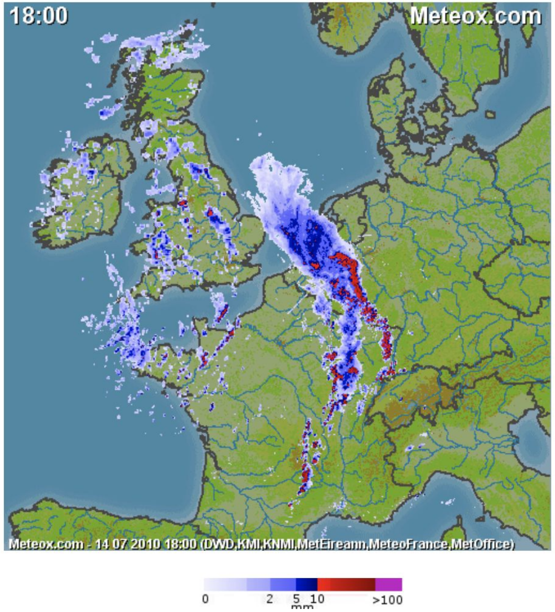
Figures from Maria Gehne, PSL

Similar approach, different scales (ALARO 5km res.)



Updraft area fraction

Precipitation



Bengtsson et al. 2013