1) Comparisons of convectively coupled equatorial wave simulations using the ECMWF IFS and the NOAA GFS cumulus convection schemes in the NOAA GFS model

2) A stochastic approach to cumulus convection parameterization using cellular automata.

Lisa Bengtsson

CIRES and NOAA-ESRL-PSD (FMD)

Collaborators

Jian-Wen Bao (PSD/FMD), Peter Bechtold (ECMWF), Juliana Dias (PSD/AOP), Sherrie Frederick (PSD/FMD), Maria Gehne (PSD/AOP), George Kiladis (PSD/AOP), Linus Magnusson (ECMWF), Sara Michelson (PSD/FMD), Philip Pegion (PSD/FMD), Cecile Penland (PSD/DMI), Stefan Tulich (PSD/AOP), Jeffrey Whitaker (PSD/FMD).

Motivation

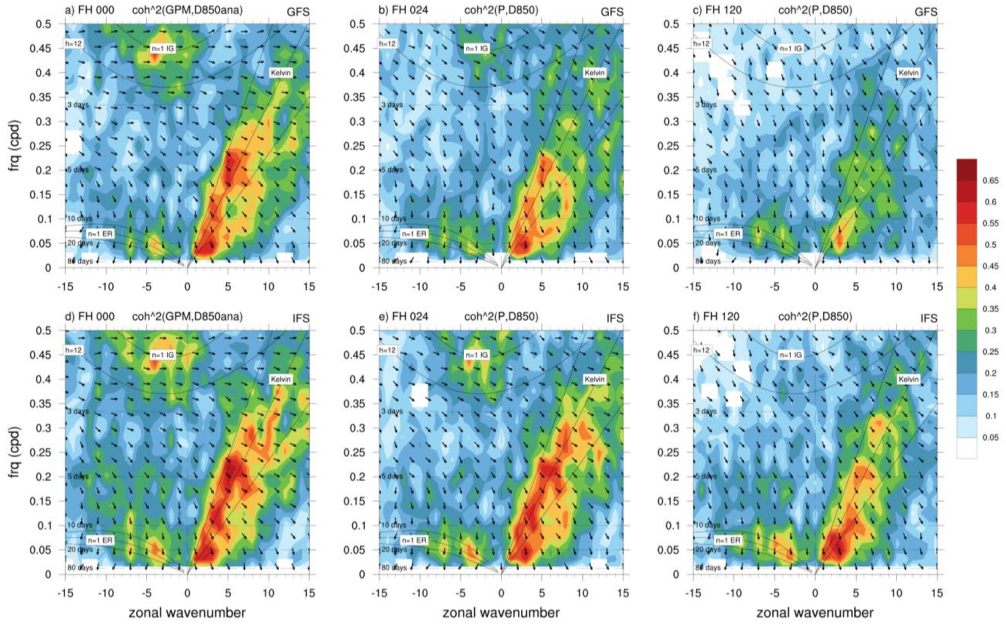
Tropical variability ECMWF IFS vs GFS (Dias et al. 2018):

“It is shown that while tropical variability is too weak in both models, the IFS model is more skillful in propagating tropical waves for longer lead times.”

0 h 24 h 120 h

GFS

IFS



Implementation of the ECMWF IFS convection scheme into NOAA GFS.

- **GFS v. 15.0.0** – First version of the GFS that uses the FV3-dynamical core.
  - **GFDL-microphysics** *(Lin et al. (1983), Chen and Lin (2011) and, Chen and Lin (2013))*
  - **PBL - First order turbulent transport scheme** *(Han and Pan, 2011 and Han, 2015)*. ("hybrid" Eddy Diffusion Mass Flux (EDMF) approach where the mixing by eddy diffusion is modeled using a counter gradient closure *(Troen and Mahrt, 1986 and Hong and Pan, 1996)*, and the mixing by dry convective plumes is modeled using a mass-flux profile following *Siebesma et al. 2007*.)
  - **Shallow and deep cumulus convection**: Scale Aware Simplified Arakawa-Schubert (SASAS) *(Arakawa and Schubert (1974), Pan and Wu (1995), Han and Pan (2011) and Han et al. (2018))*
- **IFS cumulus convection** scheme from IFS cycle 45r1. *Tiedtke (1988), Gregory et al. 2000, Bechtold et al. 2008 and 2014, IFS cycle 45r1 documentation.*
- **Model setup**: C384 (~25 km), 65 vertical levels, "cold start" from GFS and IFS initial conditions.
- **Time periods:** seasonal forecasts 90 days, weather forecasts 5 days, replay forecasts 6 hours.

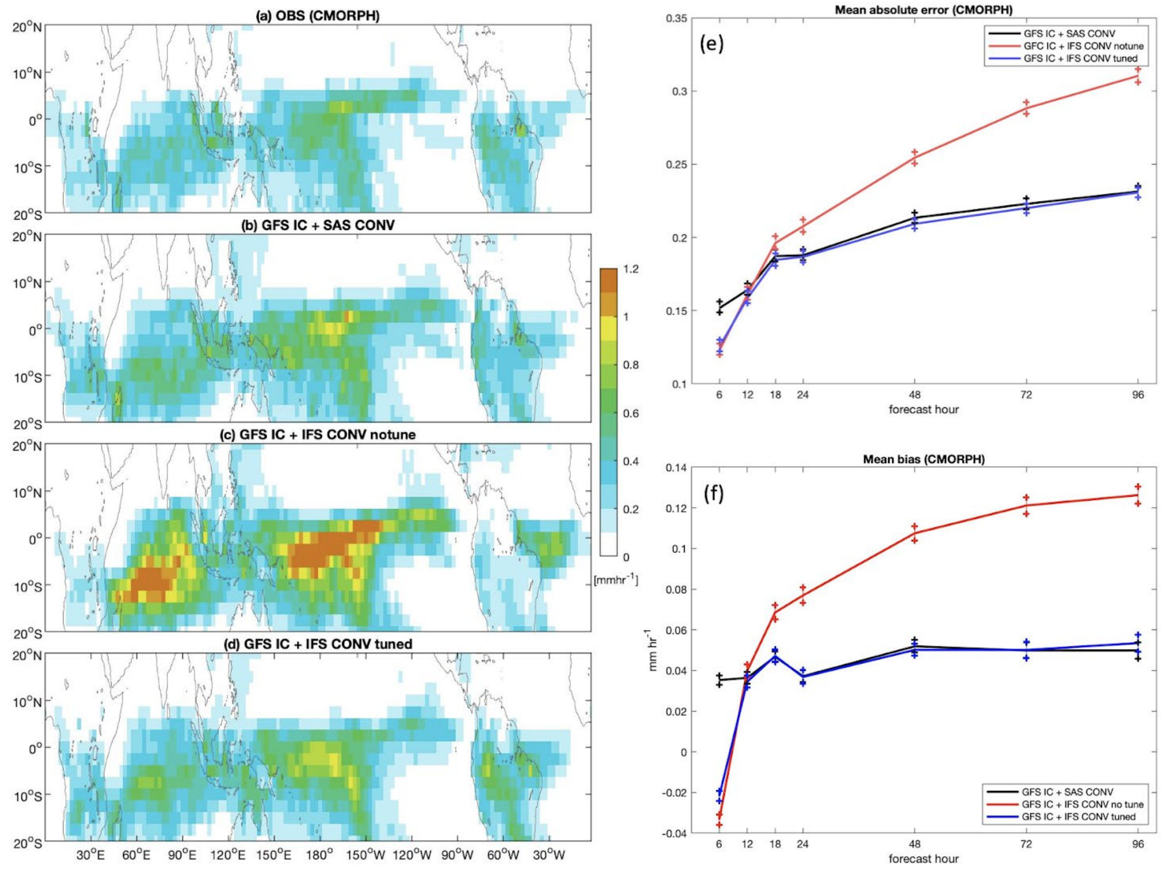
Implementation of the IFS convection scheme

OBS

CONTROL

IFS conv "as is"

IFS conv after addressing physics interactions

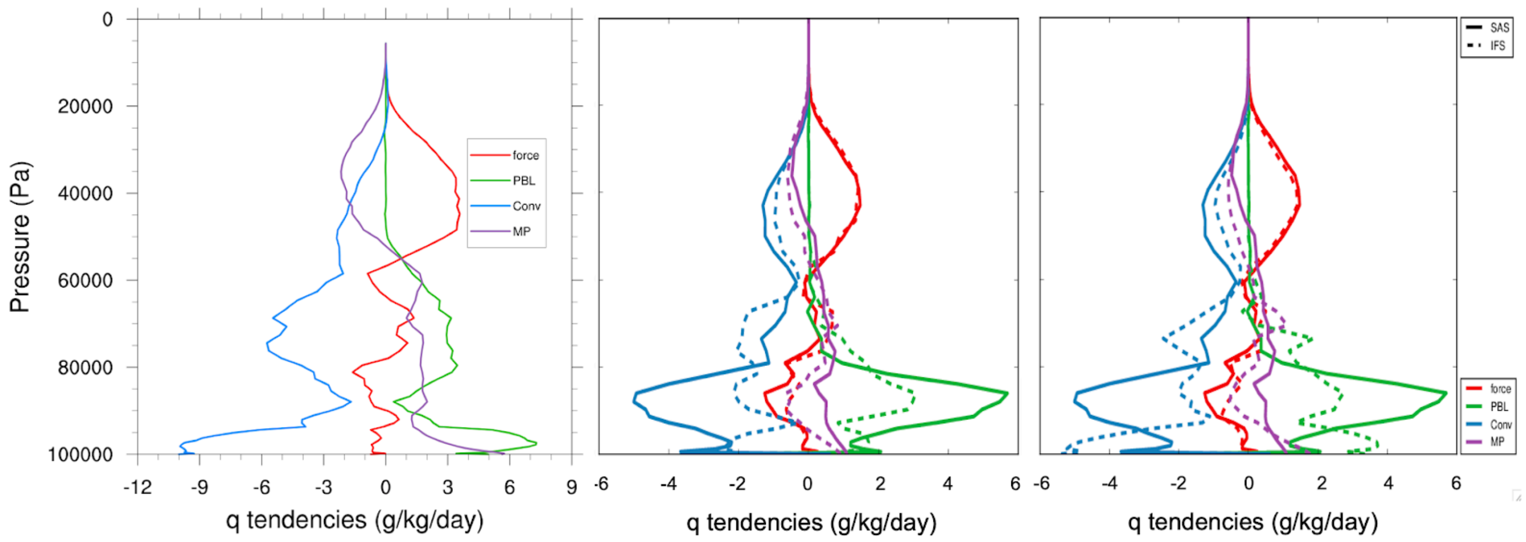


- How do we ensure that the IFS convection scheme behaves as "expected" in GFS?
- How do we eliminate model drifts and introduction of a increased/reduced precipitation bias?

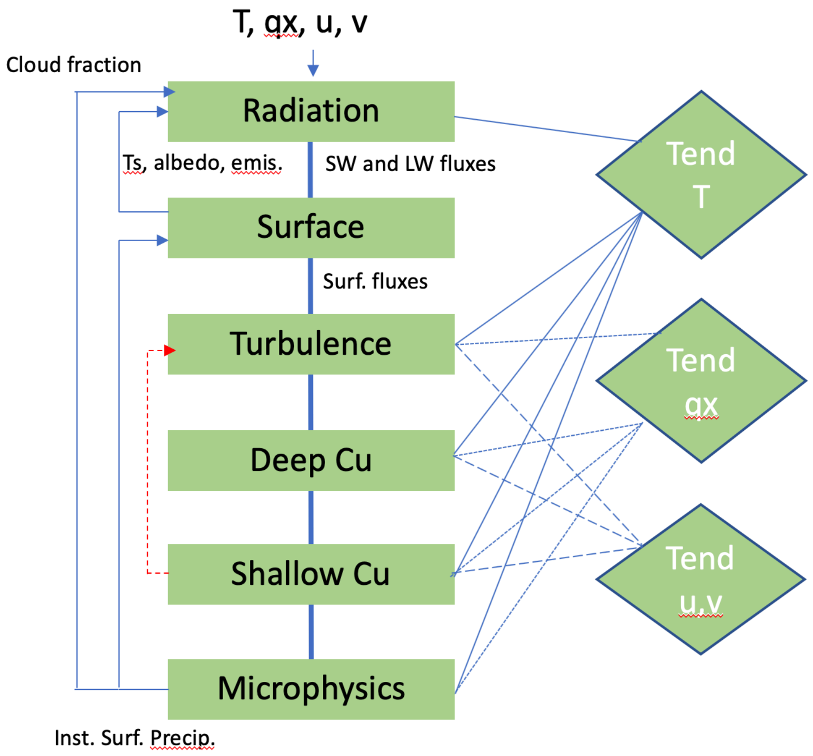
Plots from Juliana Dias, PSD

Idealized case study in a single column framework.

TWP-ICE case, specific humidity tendencies g/kg/day



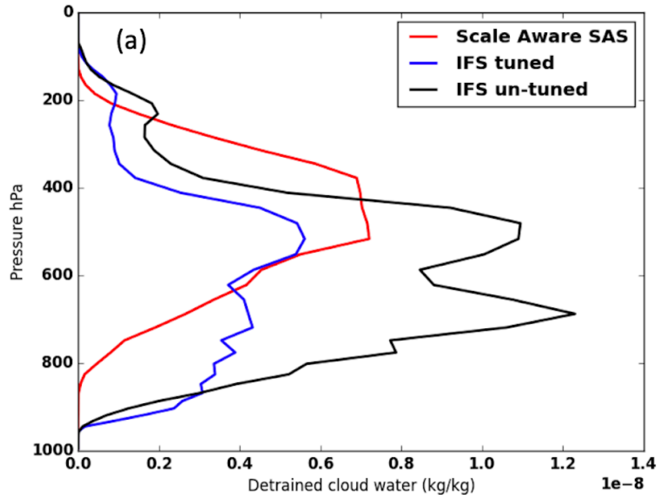
GFS physics time-step (“roughly”)



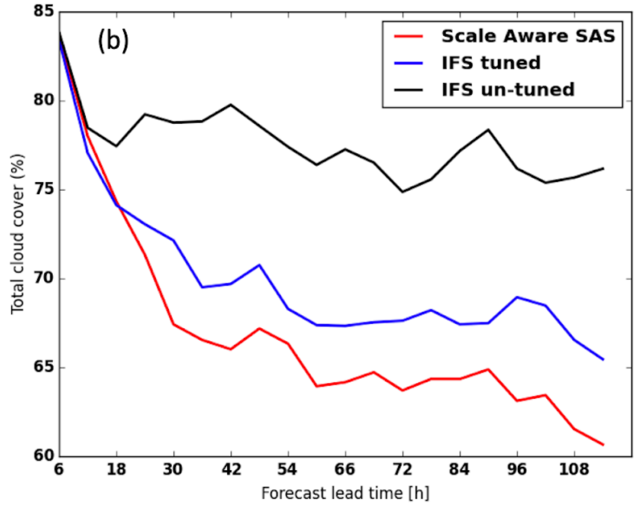
Data from Peter Bechtold, ECMWF. Plotted by Sara Michelson, PSD. Single column model and analysis plots from GMTB (Grant Firl)

Interaction between convective clouds, resolved clouds and radiation.

Detrained cloud condensate profile 20S to 20N.



Averaged total cloud cover (%). 20S to 20N



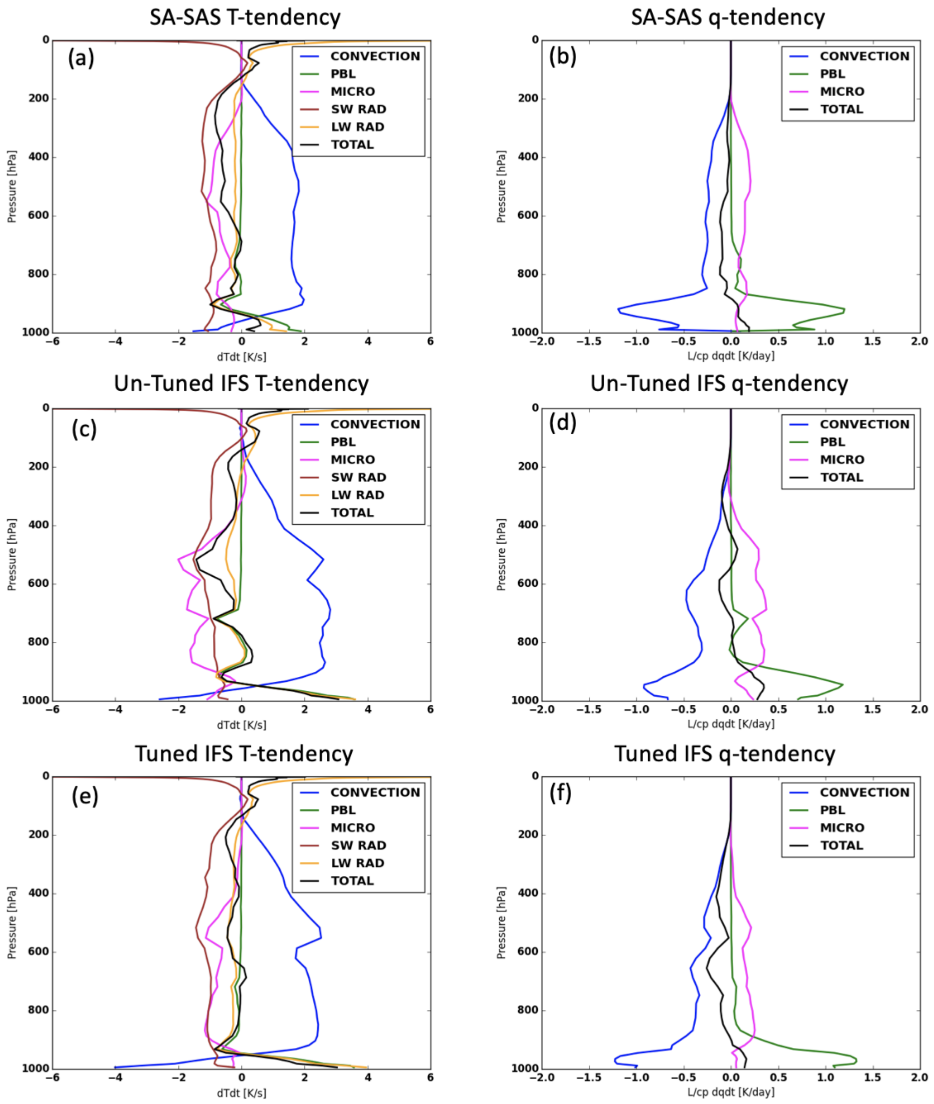
1. Increase the amount of convective cloud that is converted into convective rain.
2. Remove additional suspended cloud liquid seen by radiation (through optical properties of the cloud).

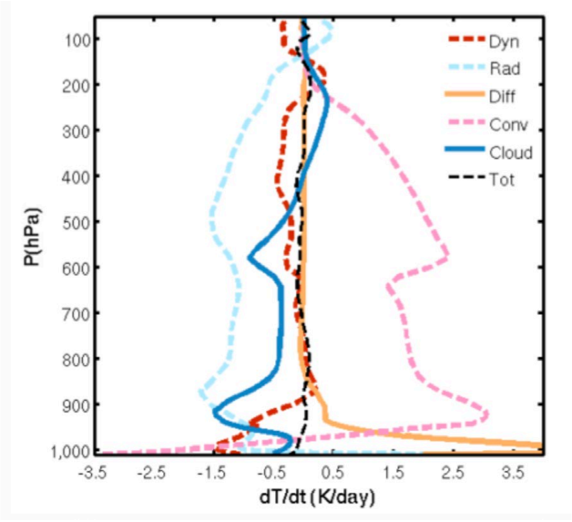
Mean physics tendencies in 3D simulations

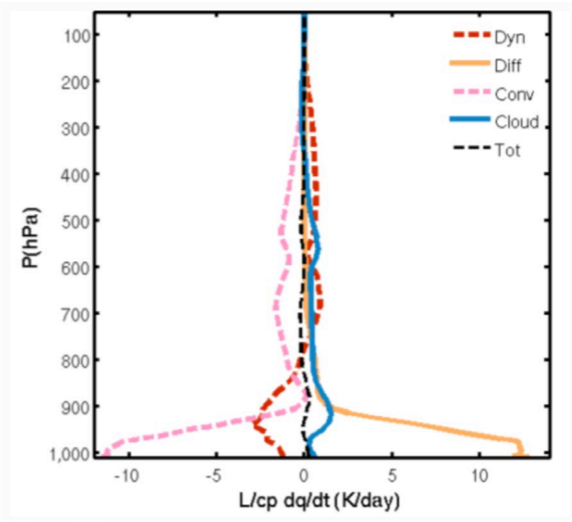
CONTROL

IFS conv “as is”

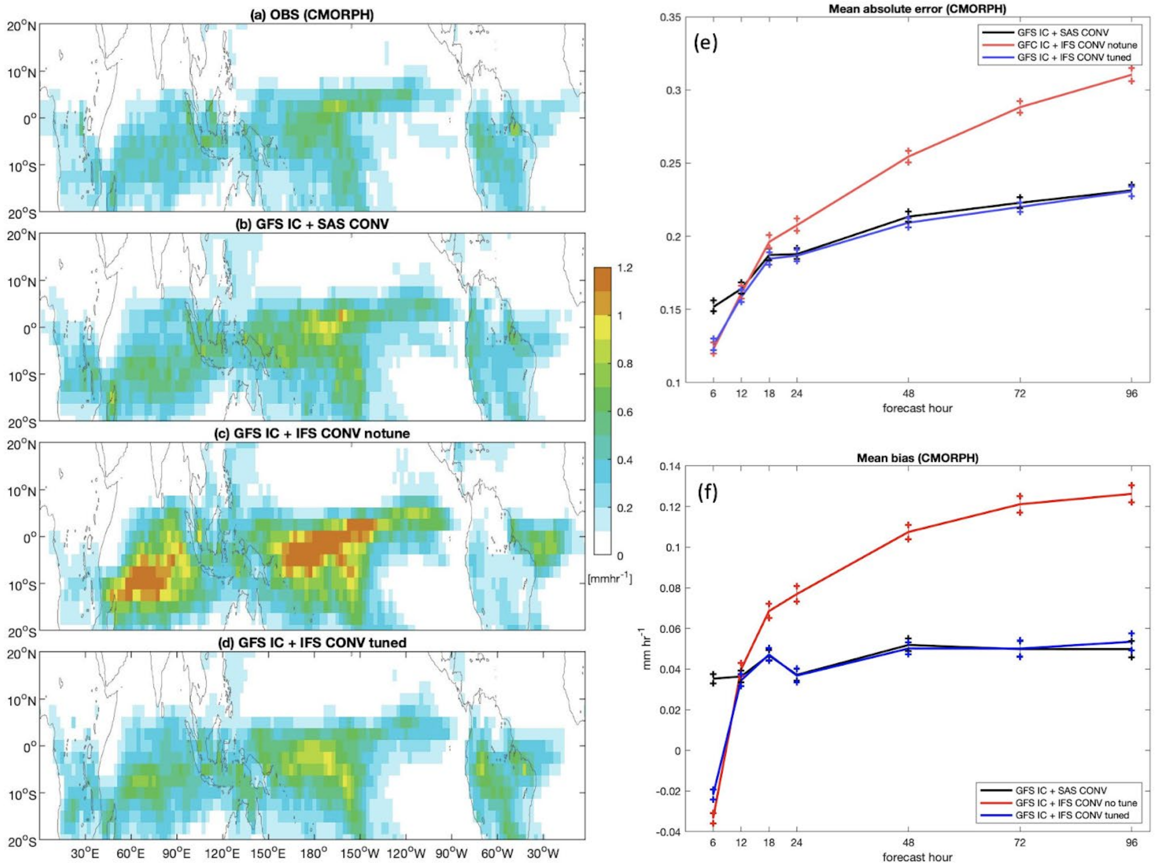
IFS conv updated







Implementation of the IFS convection scheme



- How do we ensure that the IFS convection scheme behaves as “expected” in GFS?
- How do we eliminate model drifts and introduction of a increased/reduced precipitation bias?

Plots from Juliana Dias, PSD

(Sub)seasonal runs (90-days)

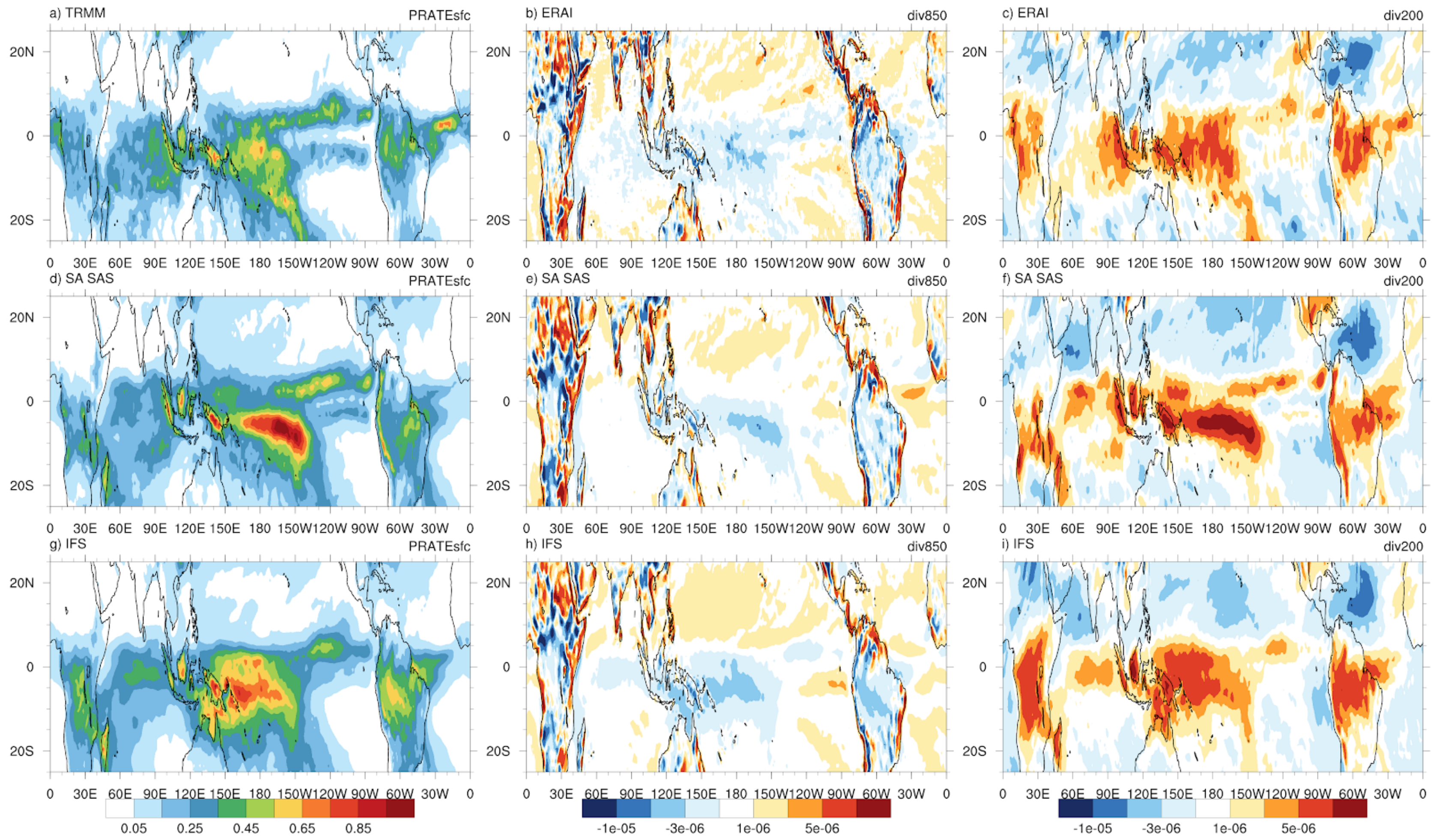
Impact on tropical variability and convective organization.

Mean state maps for seasonal runs divergence 850, 200 hPa and surface precip

OBS

CONTROL

IFS conv



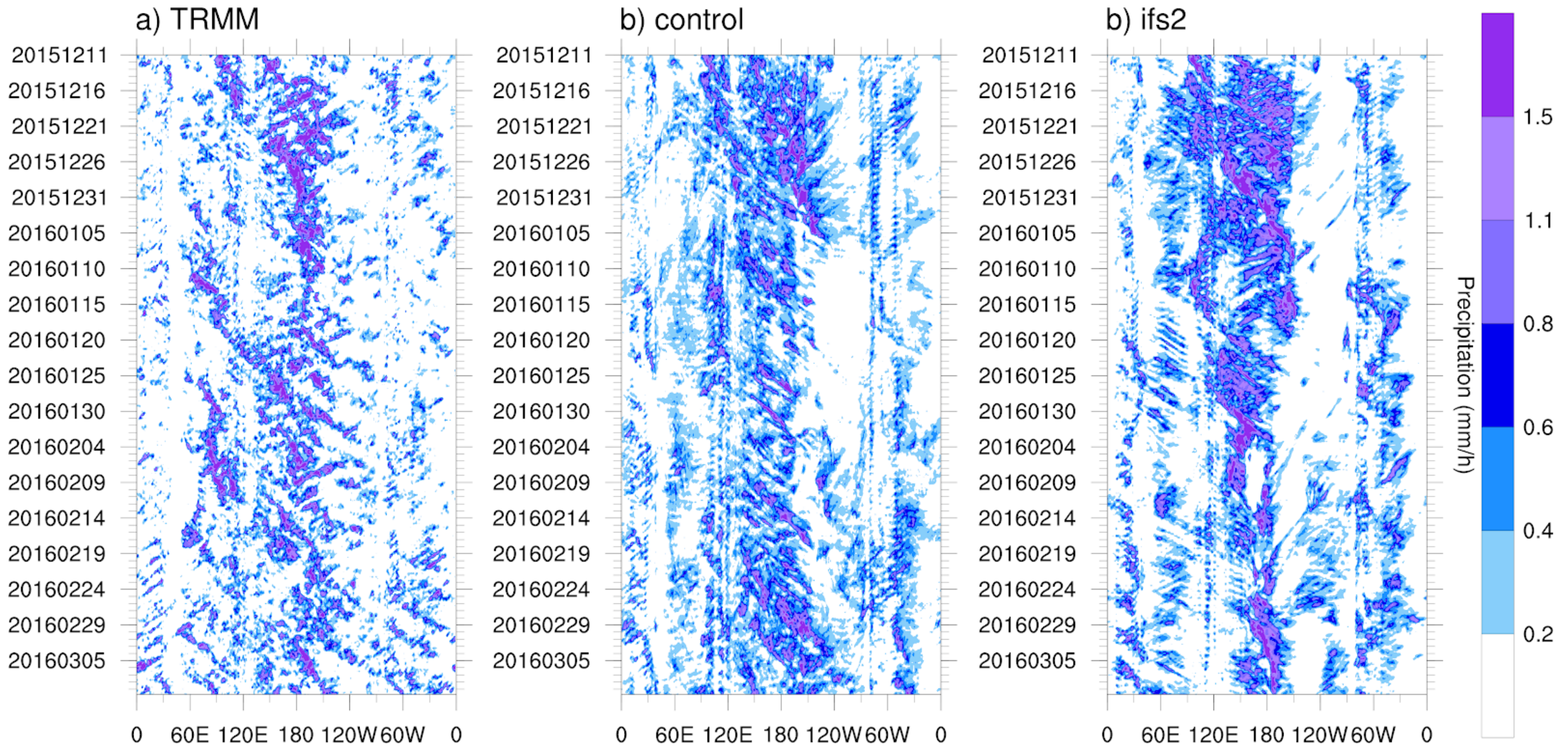
PRECIP

Div 850 hPa

Div 200 hPa

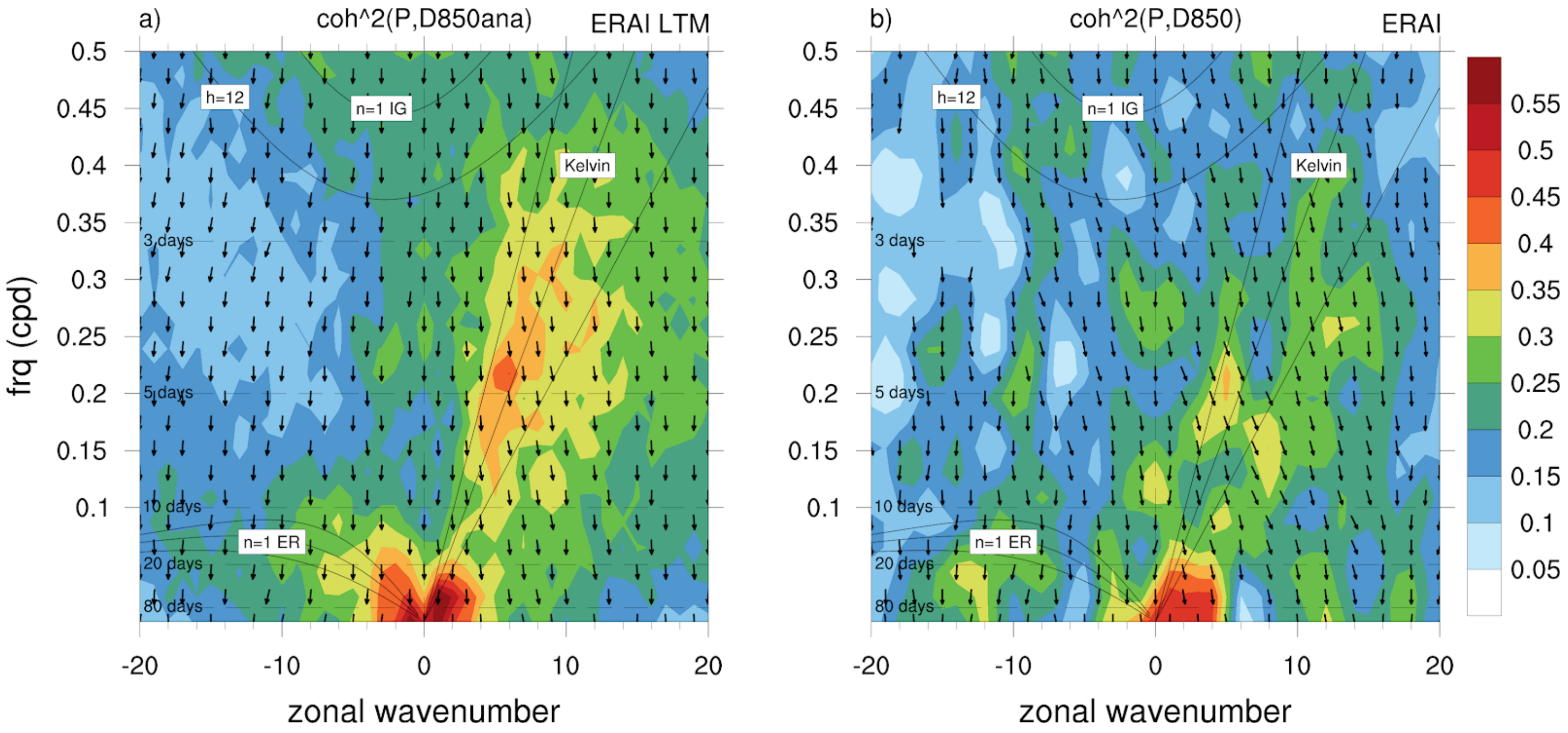
Plots by Maria Gehne, PSD

Hovmöller diagrams



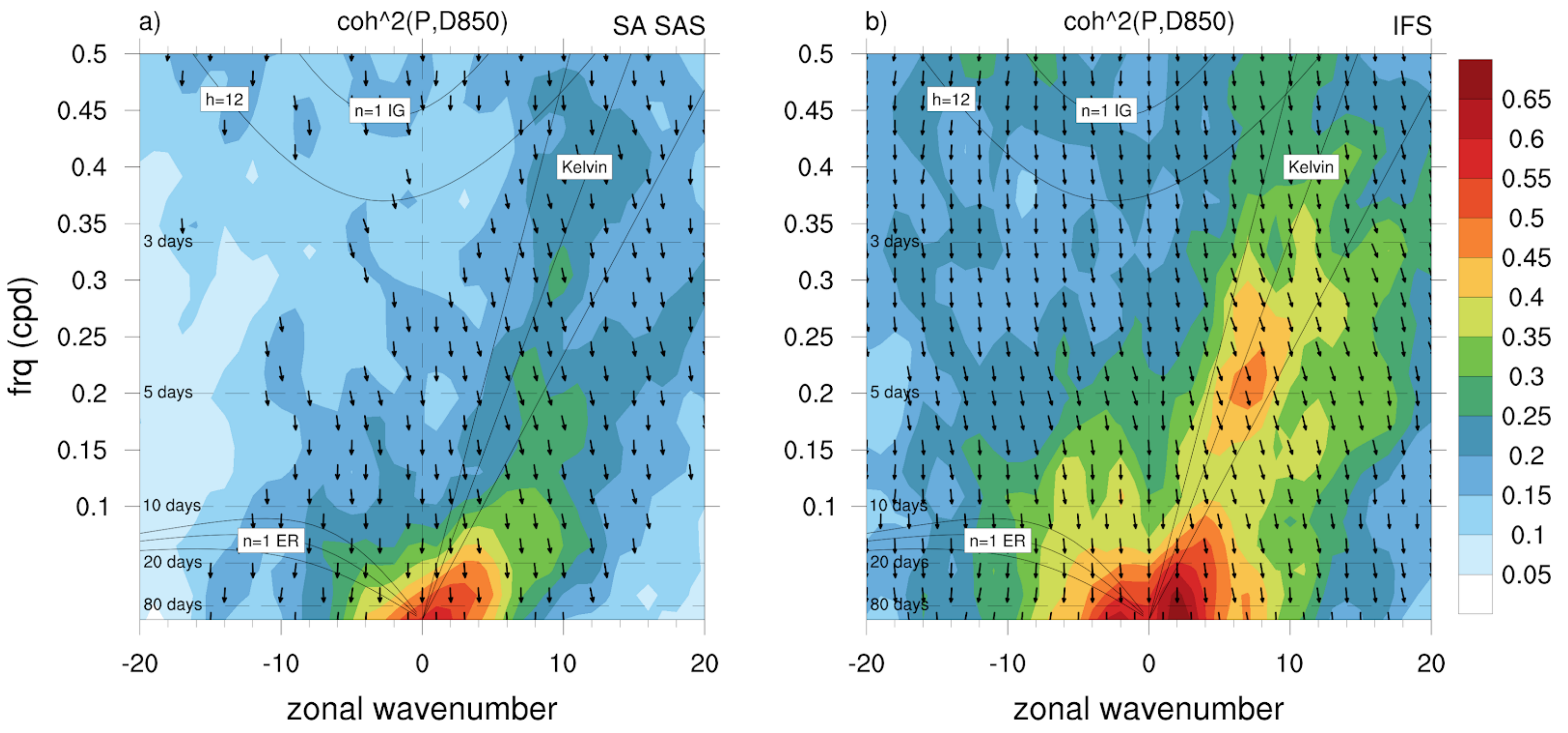
Plots by Maria Gehne, PSD

Coherence between divergence at 850hPa and surface precipitation. Climate and seasonal re-analysis (ERAI) data.



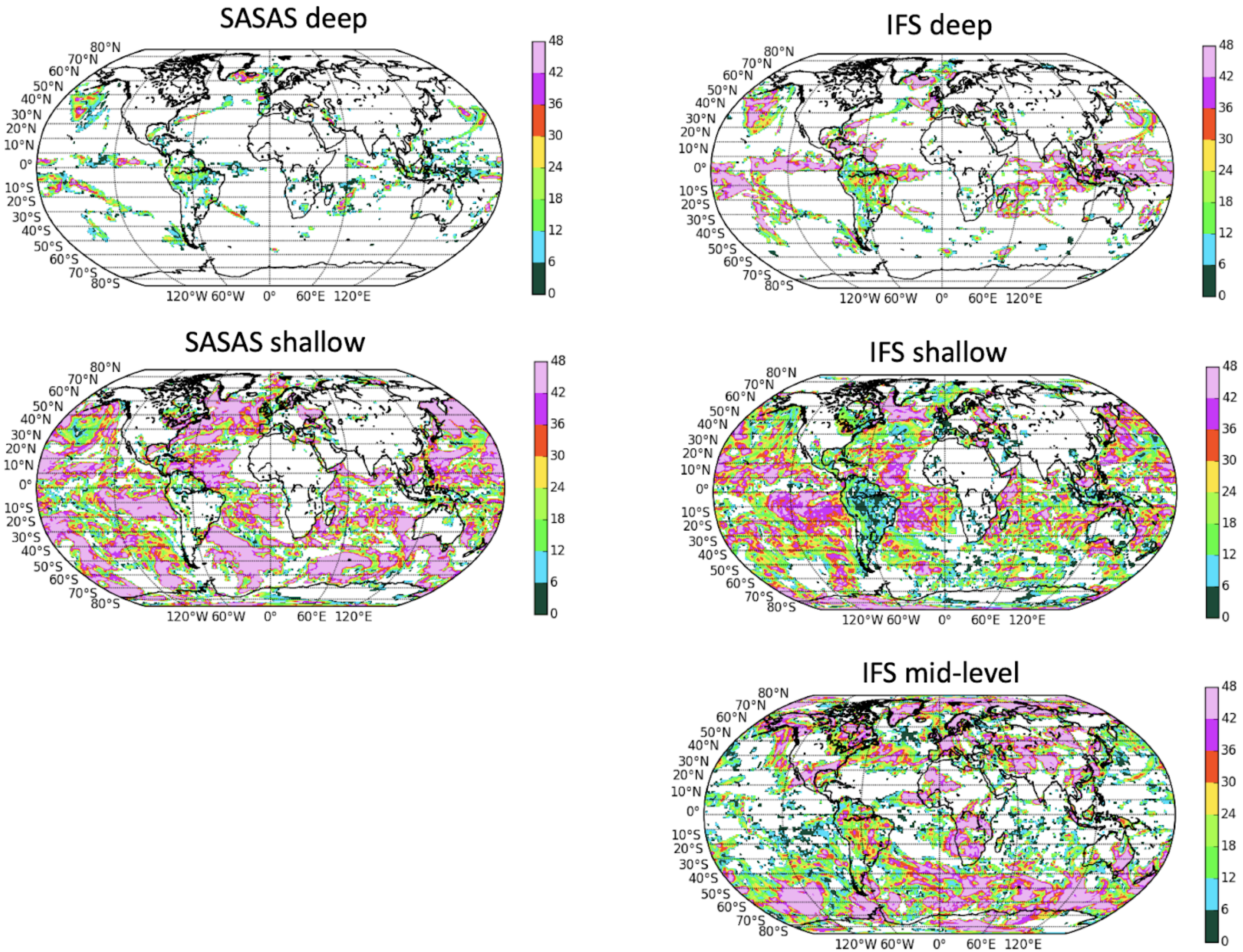
Plots by Maria Gehne, PSD

IFS convection scheme has much more coherence between divergence at 850 hPa and surface precip compared with SASAS.



Plots by Maria Gehne, PSD

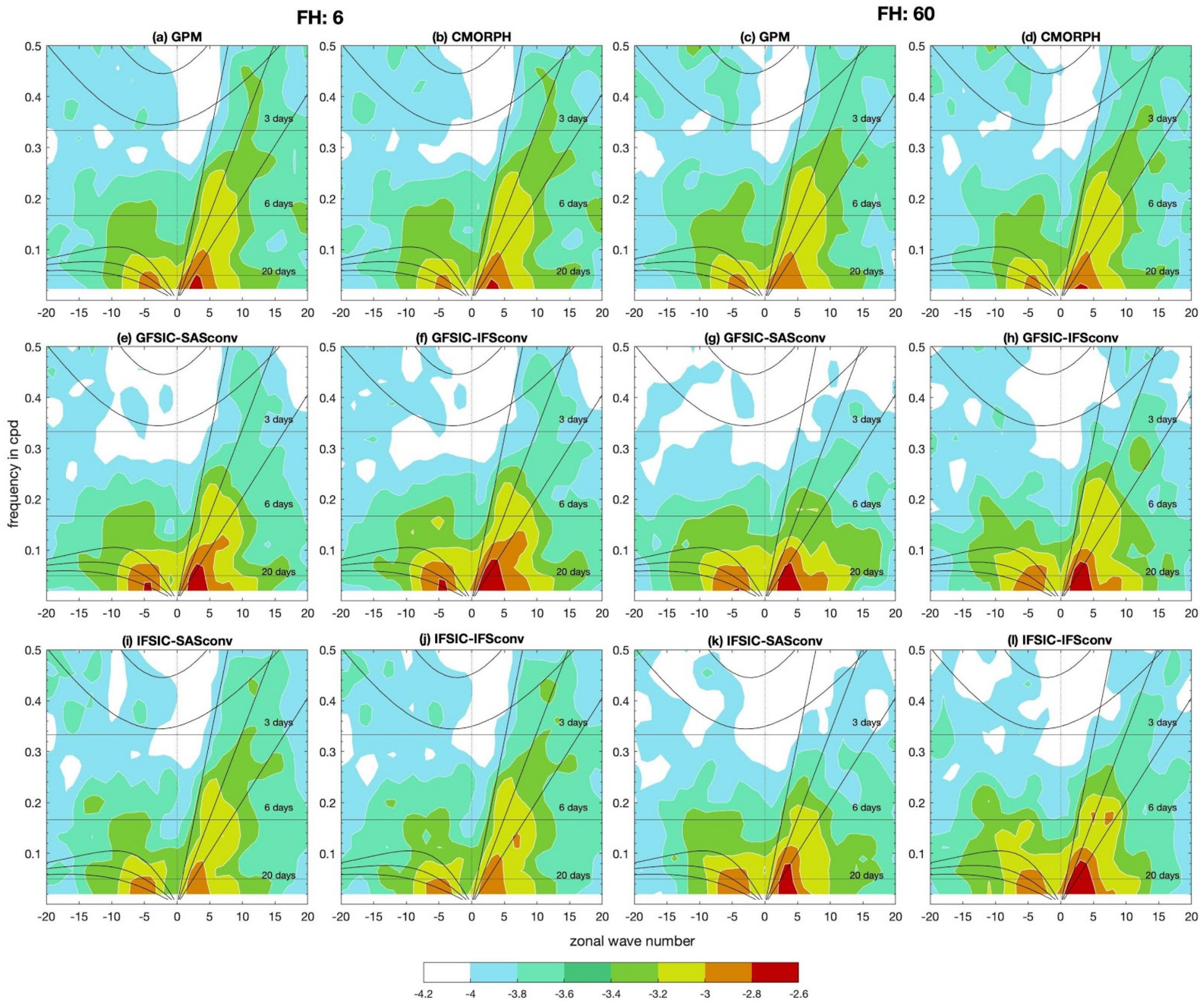
Triggering frequency of different convective modes



Weather forecasts (5 day lead time)

Relative impact of initial state vs updated physics on tropical variability.

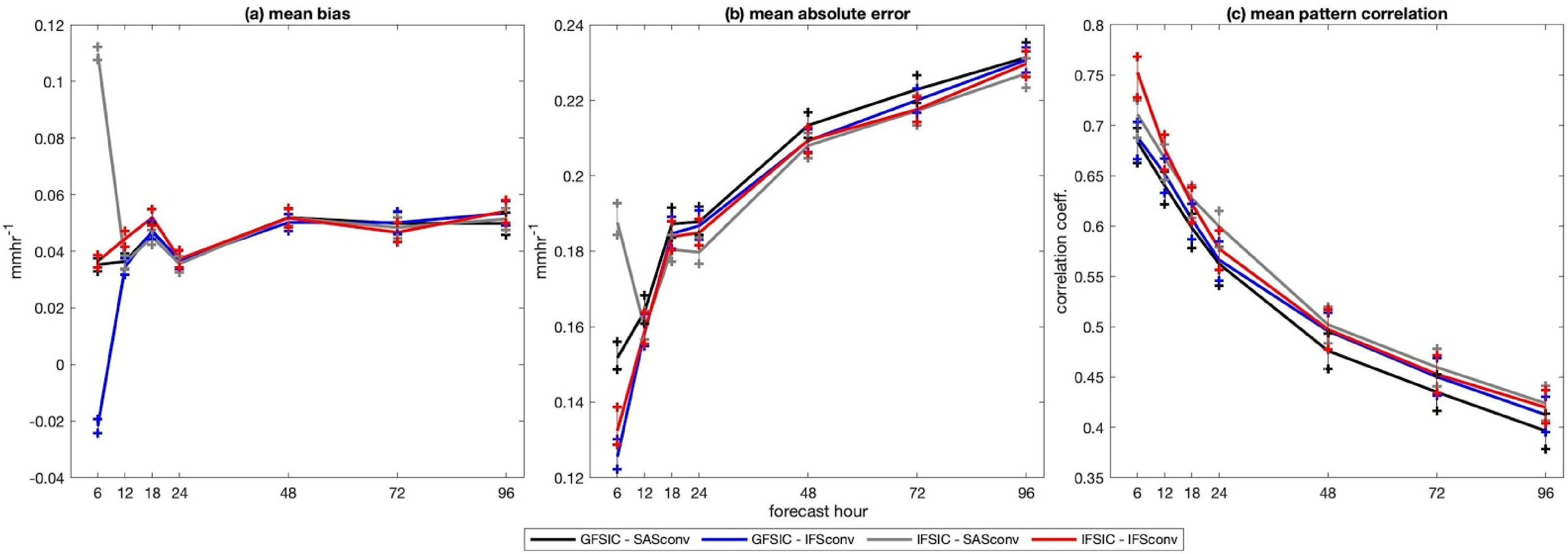
Wheeler and Kiladis – 99 diagrams.



- IFS initial conditions yields a much improved spectra at FH 6.
- IFS cumulus convection improves the Kelvin waves at longer lead times.

Plots by Juliana Dias, PSD

Quantitative precipitation estimates



Plots by Juliana Dias, PSD

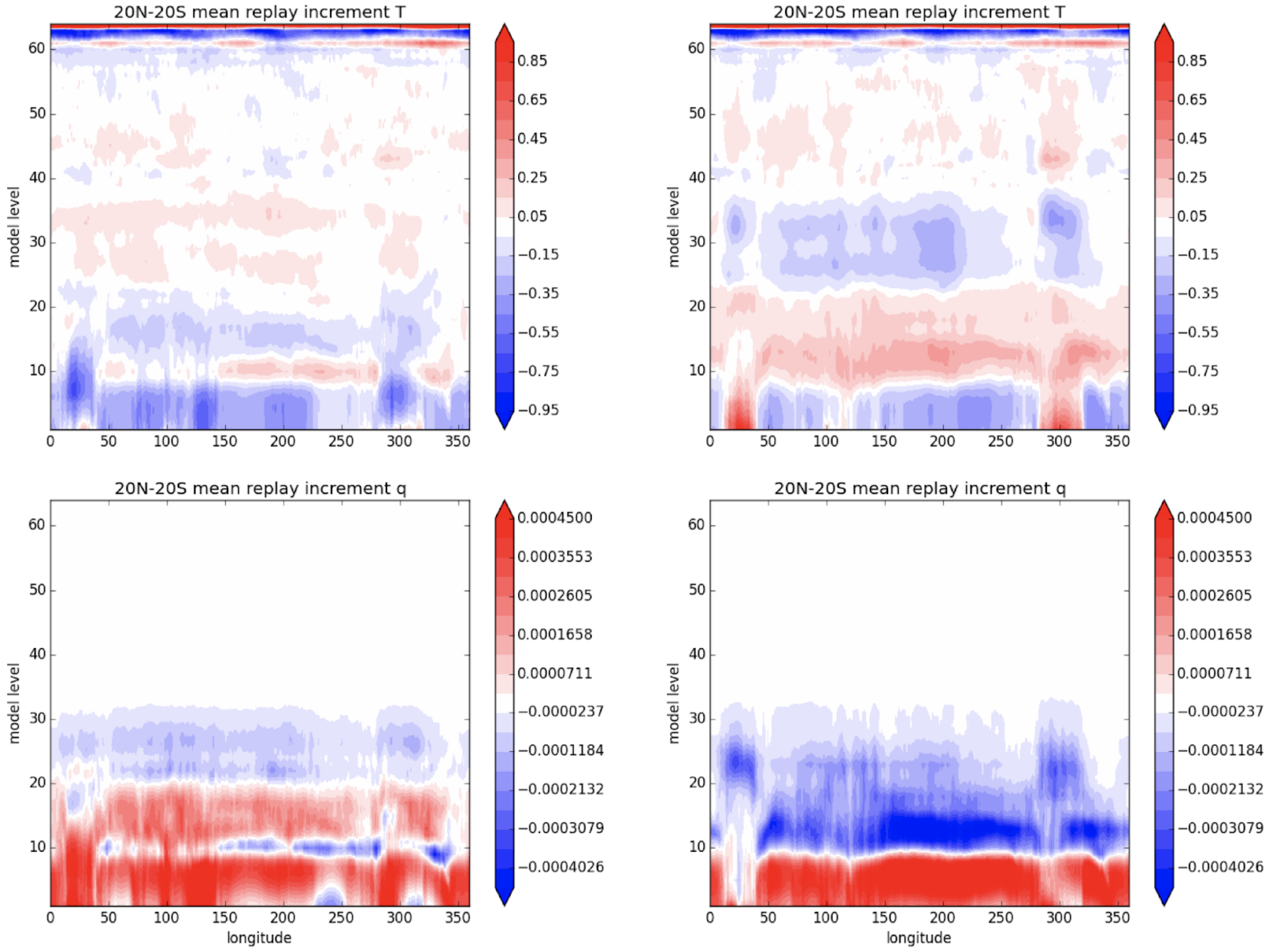
Analysis increments from replay runs. Do we get closer to the IFS analysis in the tropics?

SASAS

IFSconv

T

q



- Replay to IFS analysis. Compute analysis increments (analysis – forecast)
- Red: Analysis is warmer/moister than the first guess forecast.
- Blue: Analysis is colder/dryer than the first guess forecast.

- IFS analysis is moister than the forecast in the PBL.
- The IFS convection scheme yields a forecast that is moister and and cooler in a layer above 925 hPa - 850 hPa.

Computed and plotted by Jeffrey Whitaker (PSD).

Main conclusions from using ECMWF IFS convection in NOAA GFS.

- Consistent treatment between PBL and convection is necessary in order to reproduce the tendency profiles from the IFS model.
- The GFS model has a strong drying from convection at ~925 hPa not seen in the IFS analysis (replay increments), nor in the convective tendencies from the IFS model.
- The IFS convection scheme produces much more organized convection in the tropics, and tends to generate tropical waves that propagate more coherently than the GFS in its standard configuration, and has better simulated interaction between low level convergence and precipitation.
- The IFS convection scheme triggers deep convection to a much larger extent than the SASAS scheme, whereas the SASAS scheme triggers shallow convection more frequently.
- The IFS convection scheme moistens the PBL to a much larger extent than the SASAS scheme.

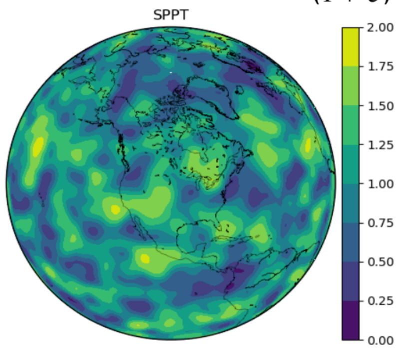
A stochastic approach to cumulus convection parameterization using cellular automata.

Stochastic physics

An example: the SPPT scheme

$$Total\ Physics\ Tendency = (1+\hat{e})\sum_{i=1}^{N}(Individual\ Physics\ Tendecy)_i$$

$(1+\hat{e})$

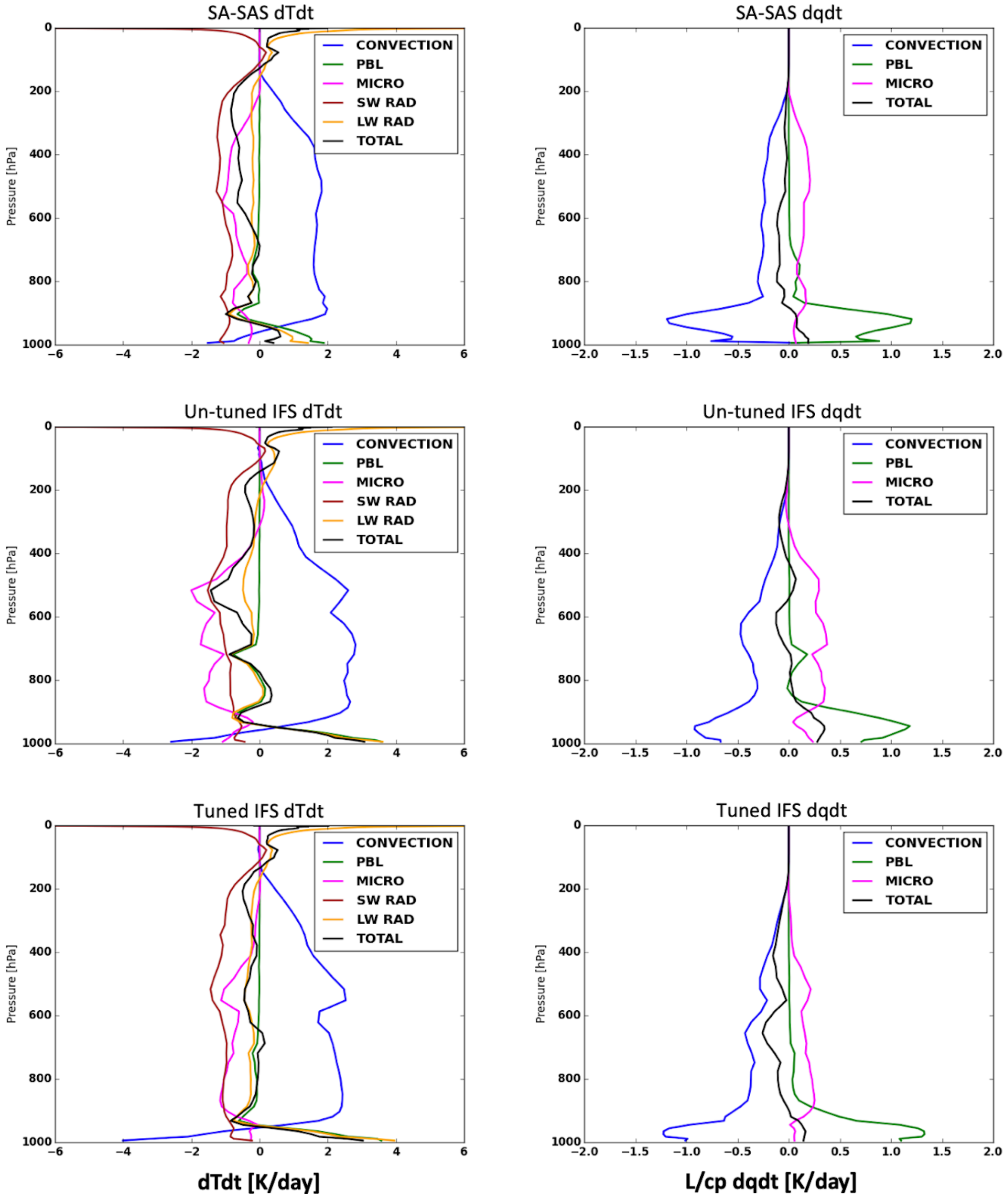


N = 5 in the GEFS:

1. Radiation
2. Surface fluxes
3. Turbulent mixing and gravity wave drag
4. Convection
5. Microphysics

Physics tendencies of four variables are randomly perturbed:
U, V, T, q

The random perturbation is invariant vertically but tapered in the boundary layer and stratosphere



Stochastic physics

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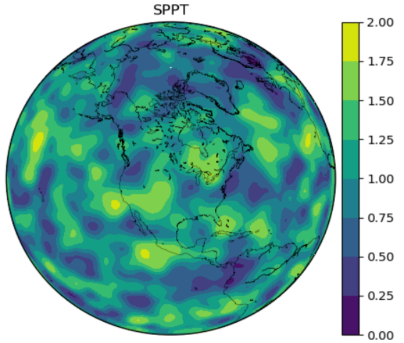

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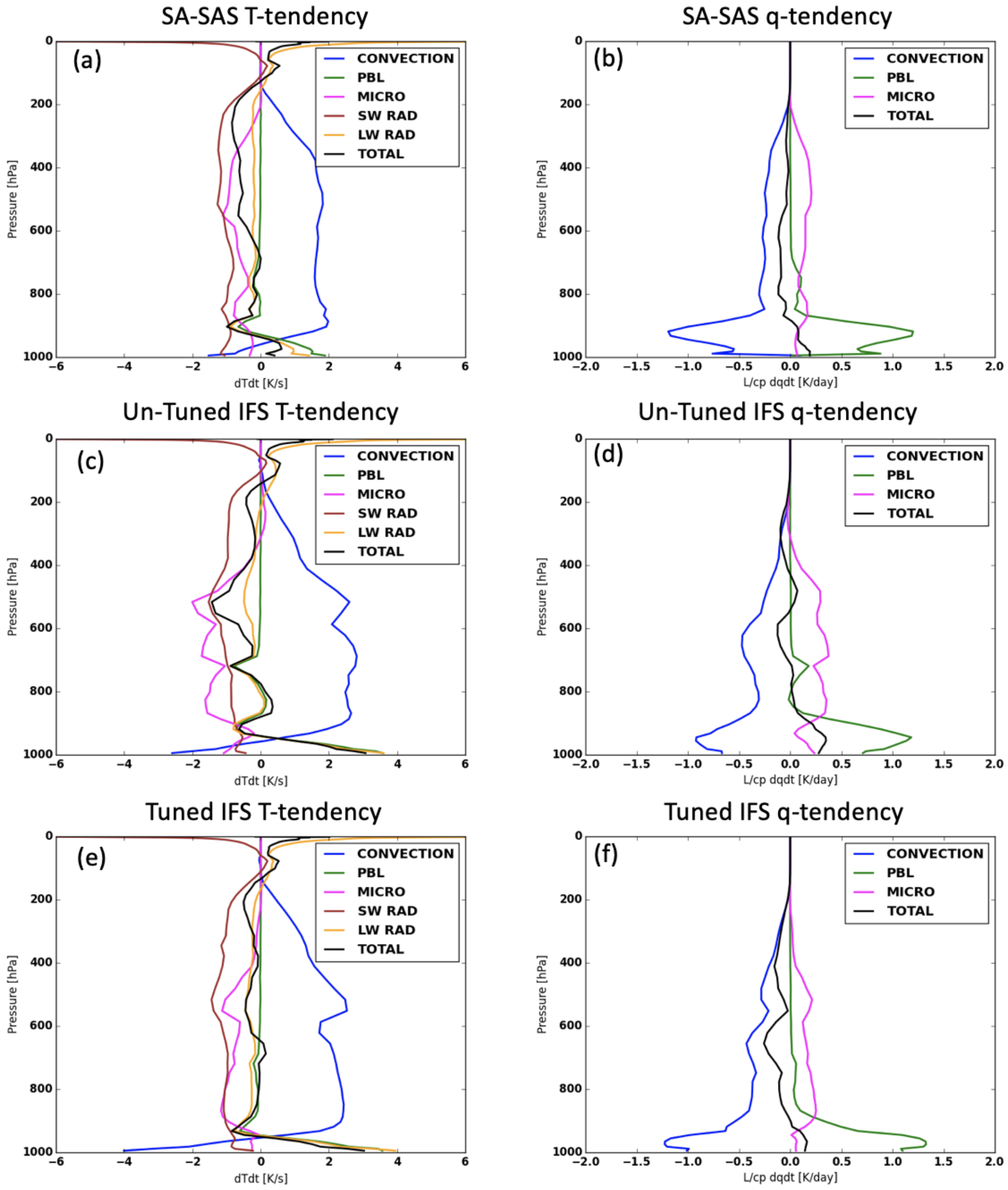
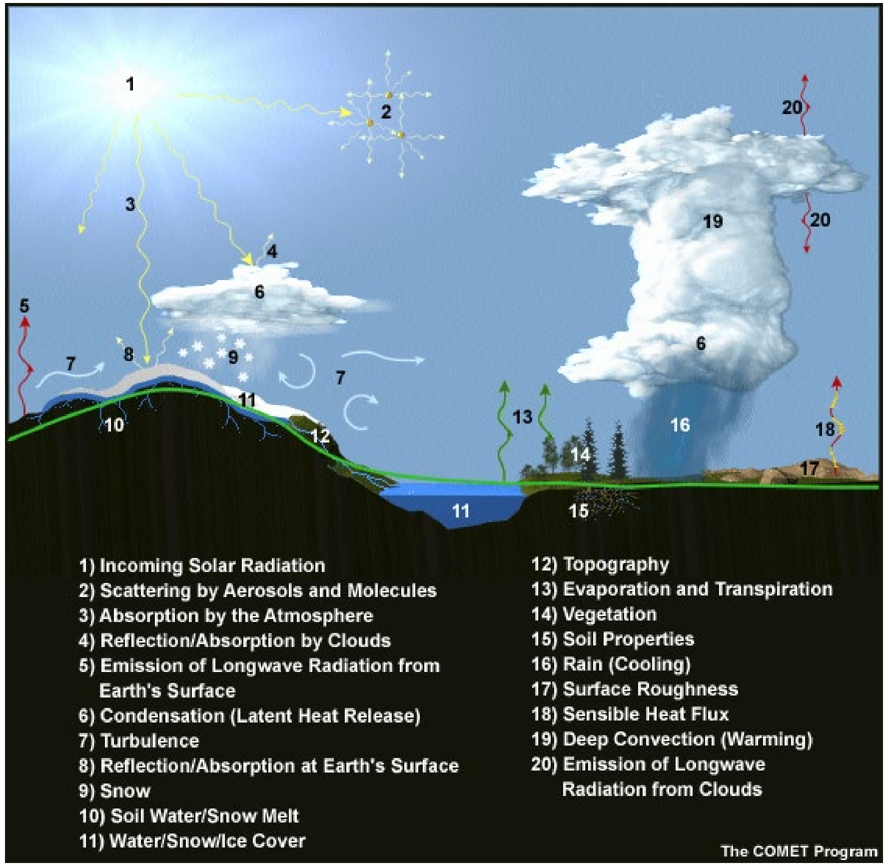


The roles of physics parameterization



dT/dt

1) To influence the total evolution of the resolved model equations (Source/Sink forcing terms).

2) There is “weather” on the sub-grid scale which is of interest for the forecast meteorologist; strato-cumulus clouds, fog, rain/snow, convective mixing, boundary layer mixing (stability) etc.

“A-priori” parameter/process perturbations

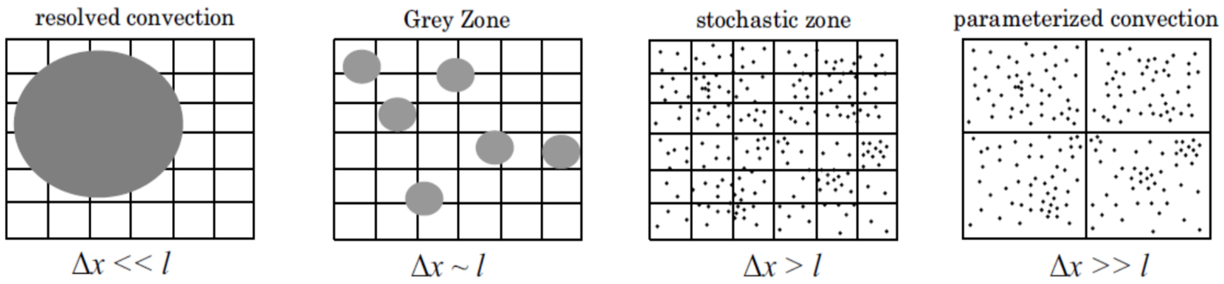
- Idea is to vary the values of some important parameters within the parameterizations schemes, recognizing that these may not be well constrained, using ”expert elicitation” – an educated guess.
  - Fixed values
  - Randomly sampled
- Assumed a single “correct” value exists but it is not known.
- Klocke et al, 2011, Knight et al, 2007, Murphy et al, 2004, Yang and Arritt (2002) (Seasonal forecasting), Grell and Dévényi (2002) 12-hour forecasts.

“A-priori” parameter/process perturbations

- A variant of the multi-parameter approach that has been used in NWP ensemble context is to allow parameters to vary randomly during a simulation.
- First developed for UK Met Office MO-GREPS (Arribas, 2004, Bowler et al. 2008, 2009, Baker et al. 2014) using an 1st order auto-regression function (AR1) for temporal correlations.
- Also tested in the ECMWF model with addition of spatial correlations using AR1 (Ollinaho et al. 2013). (referred to as SPP – already adapted by many regional models).

Uncertainty arising from taking space-time averages

In the mass-flux approach: Within a given area we find a finite number of deep convective clouds.



At higher resolution the grid-boxes might contain one cloud on average, but any particular grid-box area may very likely contain no clouds, one cloud, or several.

If the expected number of deep convective clouds is insufficient to produce a steady response for a given forcing, then a stochastic parameterization may be appropriate.

ECMWF/WWRP Workshop: Model Uncertainty, Reading, 11-15 April 2016

From Jesse Dorrestijn

Parameterization of Atmospheric Convection. Volume 2: Current Issues and New Theories. Plant and Yano 2015

Sub-grid fluctuations

In order to compute the fluctuations arising from averaging a field of convective clouds over a finite region, a statistical mechanics approach was used in Craig and Cohen, 2006.

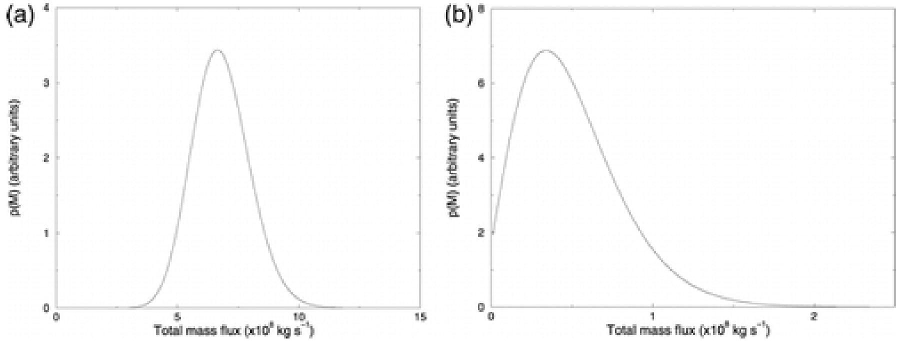
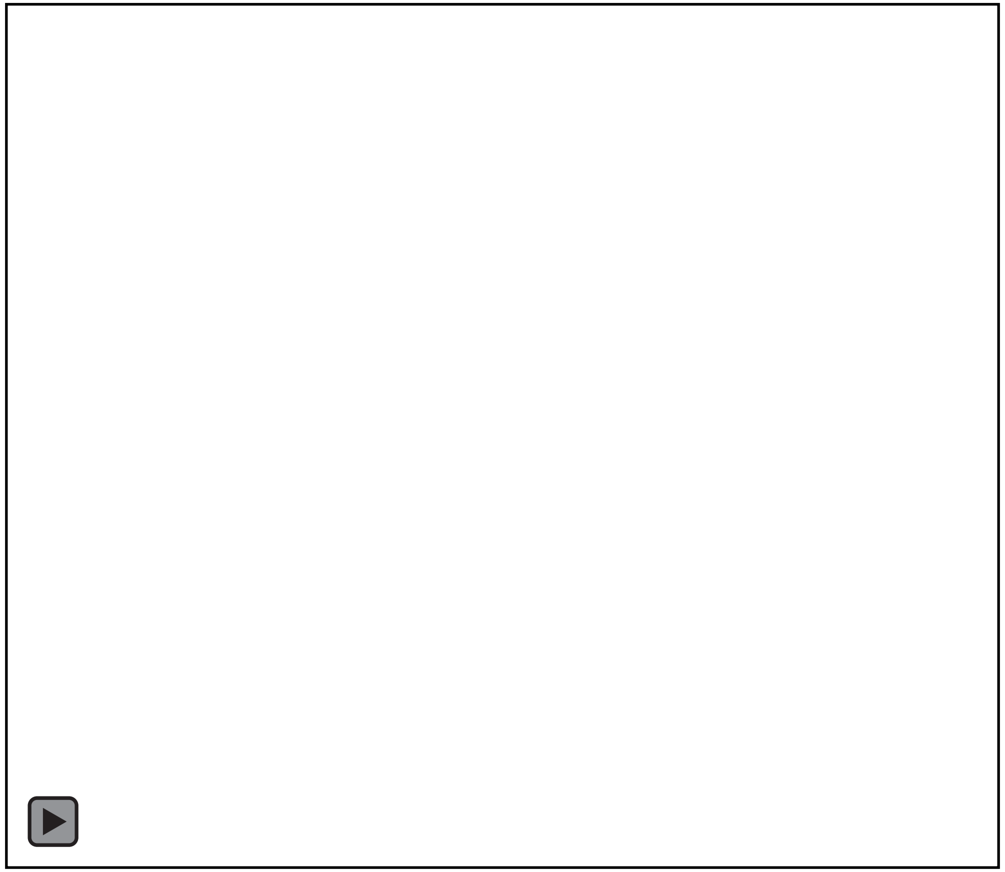


Fig. 2. Craig and Cohen, 2006. Theoretical probability distributions of total mass flux, p(M): (a) N = 68; (b) N= 5;

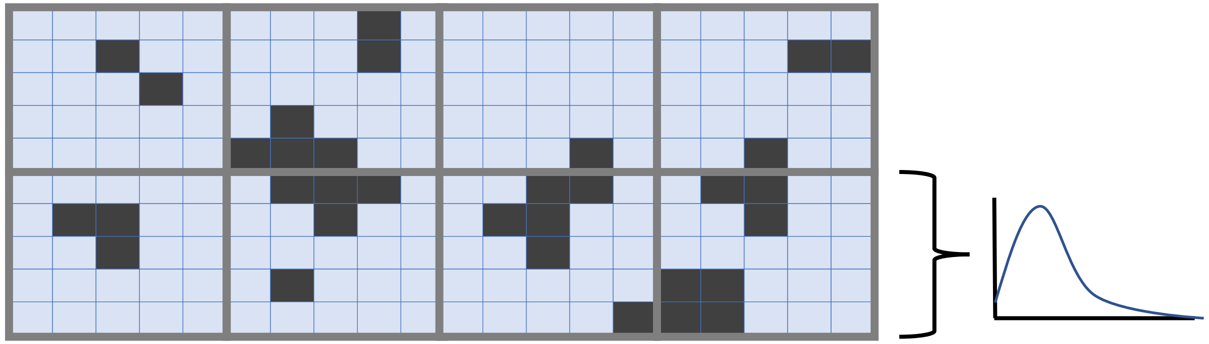
It was demonstrated that the distribution of cloud number within a given area follows that of a Poisson distribution, and that the theoretical predictions are in agreement with equilibrium cloud resolving model simulations (Craig and Cohen, 2006, Cohen and Craig, 2006, Plant and Craig 2008).

Stochastic “birth/death” processes for modeling convective plume distribution and sub-grid cloud models

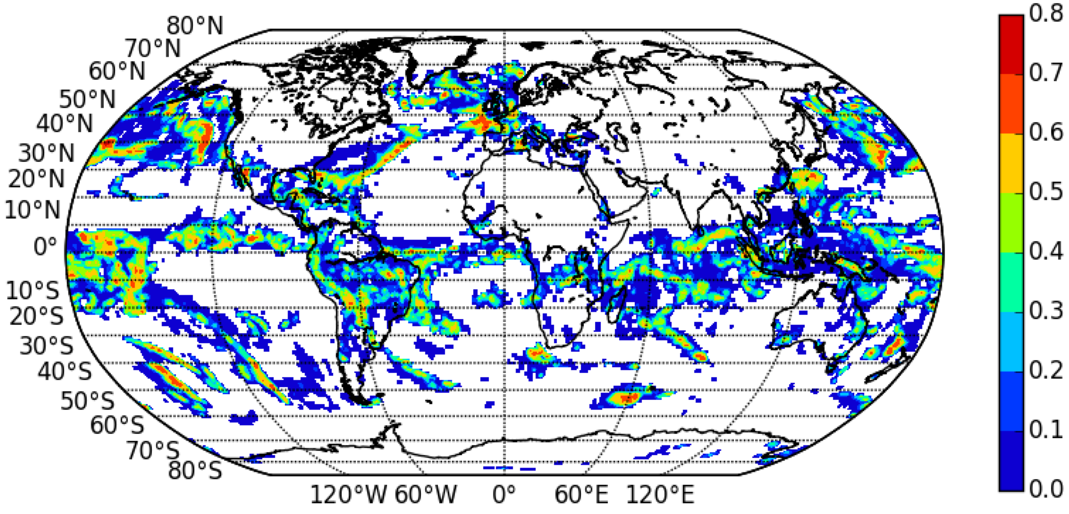
Plant (2012), Hagos et al. 2018, Khoudier et al, 2010, Dorrestijn et al. 2013, 2015, 2016, Gottwald et al. 2016, Frenkel et al, 2012, 2013, Bengtsson et al. 2011, 2013, 2016, 2019.



Cellular Automaton (CA) in FV3

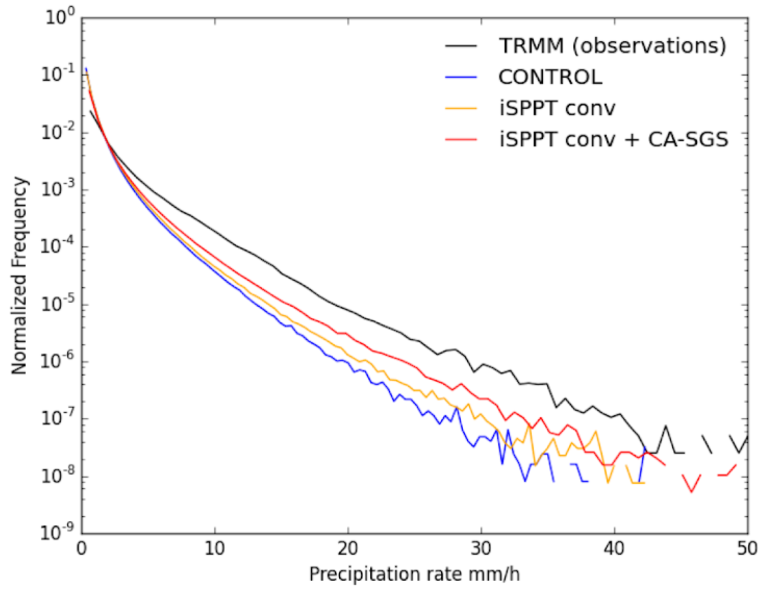


- Condition the cellular automaton on a skewed sub-grid distribution of updraft vertical velocity, and CAPE.
- Run at higher resolution than the NWP grid.
- Coarse grain back to NWP grid.



Chikira Sugiyama – stochastic number of plumes (Bengtsson et al. 2019)

- Count the number of sub-grid plumes modelled by the cellular automaton. Let this number modify the number of plumes in each grid-box modelled in the Chikira and Sugiyama convection scheme.



Bengtsson, L., J. Bao, P. Pegion, C. Penland, S. Michelson, and J. Whitaker, 2019: A Model Framework for Stochastic Representation of Uncertainties Associated with Physical Processes in NOAA's Next Generation Global Prediction System (NGGPS). *Mon. Wea. Rev.*, **147**, 893–911

Prognostic and stochastic closure (Bengtsson et al. 2013) in the Gerard et al. 2009 scheme.

$$M_u = -\sigma_u \frac{\omega_u^*}{g}$$

Mass-flux

$$\frac{\partial \omega_u^*}{\partial t} = B + E\omega_u^{*2} - A\frac{\partial \omega_u^{*2}}{\partial p}$$

Updraft vertical
Velocity relative its
environment

$$\frac{\partial \sigma_u}{\partial t}\int (h_u - \overline{h})\,\frac{dp}{g} = L\int \sigma_u \omega_u^* \frac{\delta q_{ca}}{g} + \alpha_{cvg} L \int CVGQ\frac{dp}{g} + \frac{\sigma_{CA} - \sigma_u}{\tau} * (\int (h_u - \overline{h})\,\frac{dp}{g})$$

Convective updraft area fraction

Specific humidity converted to cloud water (sink)

Moisture convergence (source)

Stochastic cellular automaton term (source or sink)

Introduction of a prognostic and stochastic cumulus convection closure in GFS(FV3).

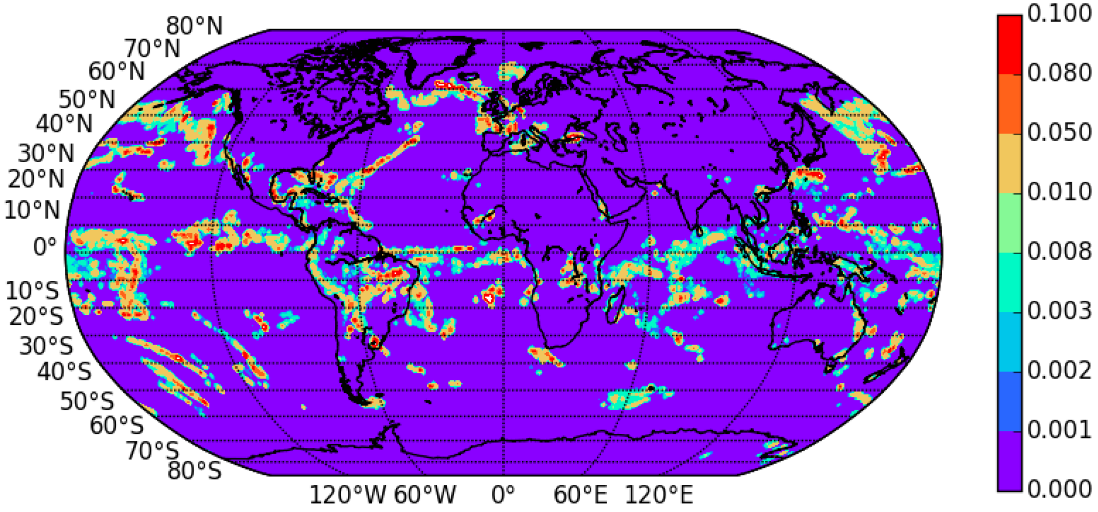
Han et al. 2018 introduced a closure based on the diagnostic updraft vertical velocity for high resolution simulations with SASAS:

Mb = 0.03*Wc*rho

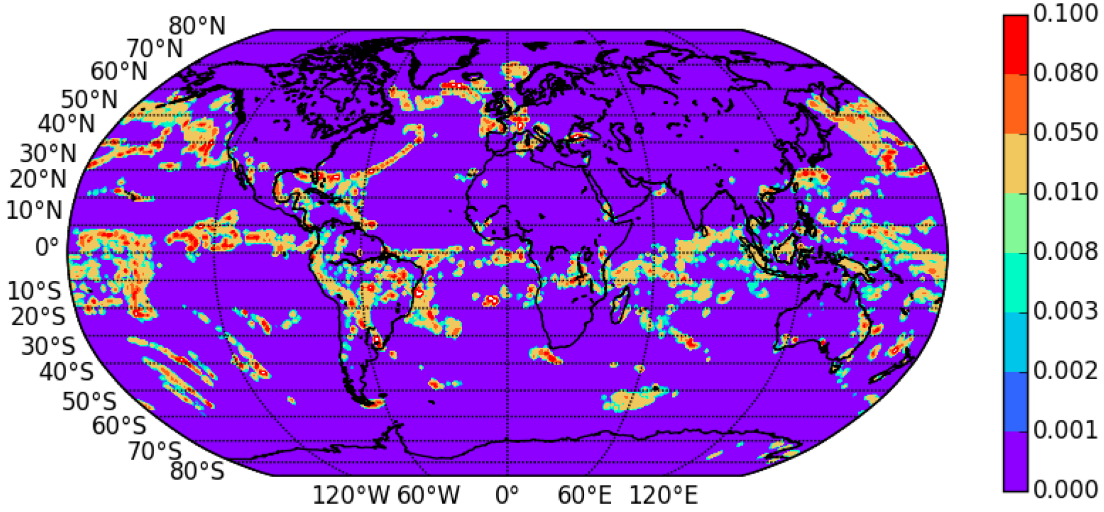
1) Replace constant “0.03” with prognostic sigma from Gerard et al. 2009.
2) Introduce cellular automaton modified sigma from Bengtsson et al. 2013 to address; **lateral communication**, **stochasticity** and **memory**.

Prognostic (and stochastic) updraft area fraction in SASAS in GFS(FV3)

$$\frac{\partial \sigma_u}{\partial t}\int (h_u-\overline{h})\,\frac{dp}{g} = L\int \sigma_u \omega_u^* \frac{\delta q_{ca}}{g} + \alpha_{cvg} L \int CVGQ \frac{dp}{g} + \frac{\sigma_{CA}-\sigma_u}{\tau} * \left(\int (h_u-\overline{h})\,\frac{dp}{g}\right)$$

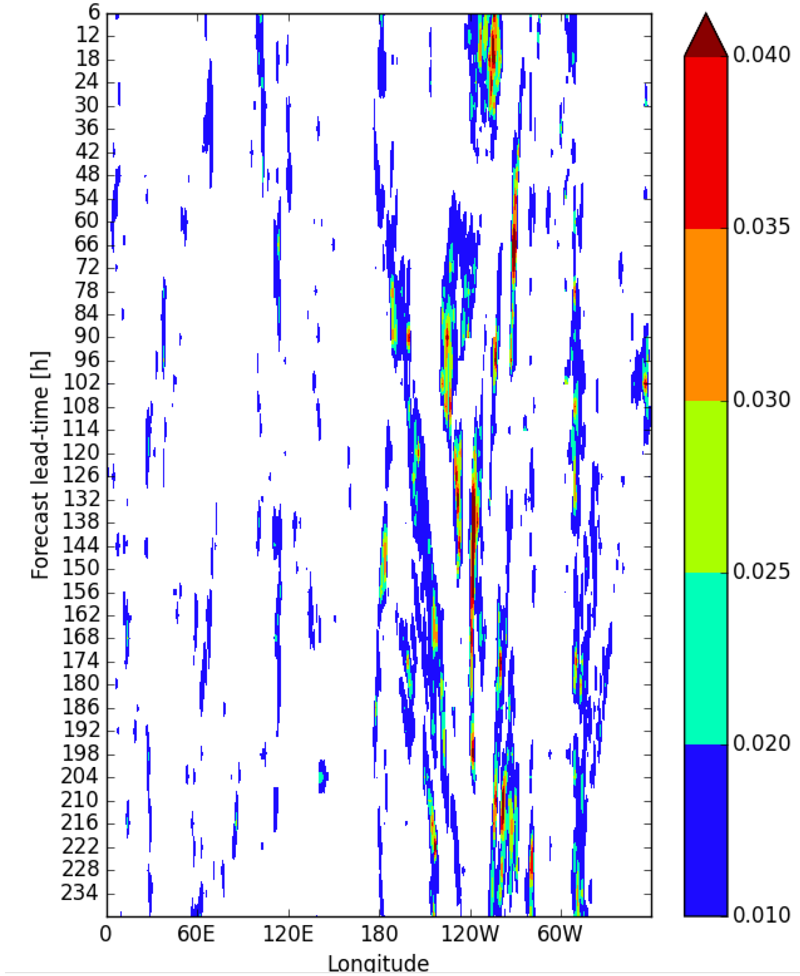


Prognostic advected area fraction (Gerard et al. 2009)

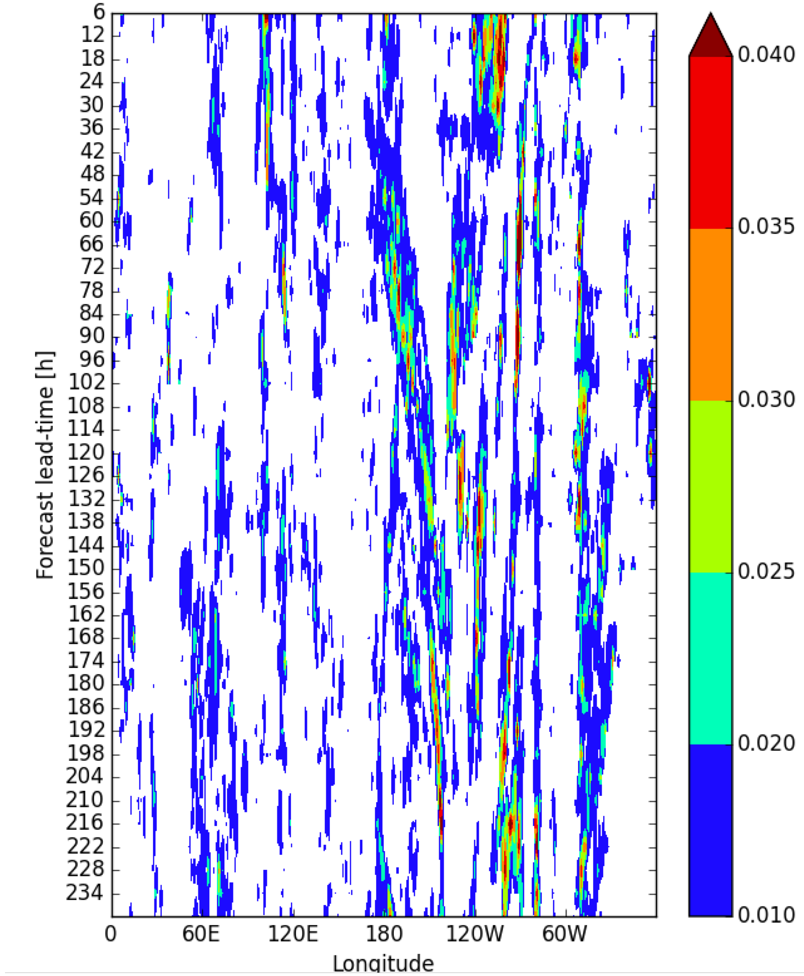


Prognostic advected area fraction plus CA term

Hovmöller diagrams of updraft area fraction with/without CA extension



Prognostic advected area fraction (Gerard et al. 2009)



Prognostic advected area fraction plus CA term

Future outlook

- Further explore impact of cellular automaton closure on convective organization and propagation in the GFS.
- Test "scale-awareness" of prognostic sigma at different resolutions.
- Explore impact on ensemble spread/skill.
- How to address dynamical memory in stochastic parameterizations (a whole other seminar!).