Future direction of physics development for the UFS

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UFS R2O physics development team vision

In 2019 we were asked to provide a plan for UFS Research to Operations (UFSR2O) for years 1 and 2, including a 5-10 year vision:

"(1) to address the physics improvement needed for the GFSv17 (and GEFS v13) implementation, and (2) to start developing an advanced moist physics suite that will be implemented in the UFS through a unified effort across the MRW and SRW deterministic and stochastic physics development teams."

In the first two years, most of the effort was spent on contributions to the GFSv17 and GEFSv13 physics suite.

With the reduced funding from UFSR2O, and the limited NOAA funding for lower readiness level research, we have found ourselves a bit distraught and concerned for the continued effort.

Our long term vision - Unification

Figure from ECMWF

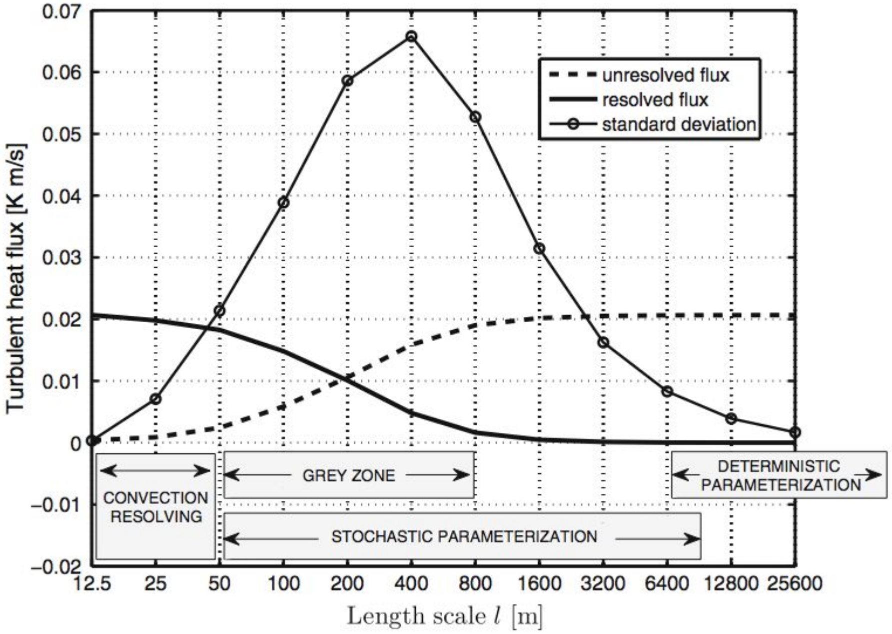
1) Move away from an either/or approach of shallow/deep convection. Introduce prognostic evolution and improve transition from shallow to deep cumulus convection.

2) Unify mass-flux representation between dry PBL plumes, shallow moist PBL plumes, shallow and deep moist cumulus convective plumes.

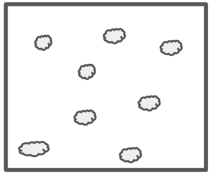
3) Unify clouds through prognostic cloud fraction description, where any sub-grid process leading to cloud formation is a source term to the unified cloud cover.

4) Unify clouds (fraction, cloud optical properties) between cloud microphysics, aerosols and radiation schemes. Introduce a 2 moment cloud microphysics scheme.

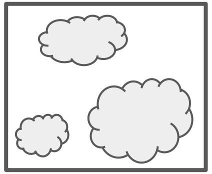
Our long term vision - scale adaptive and grey-zone considerations



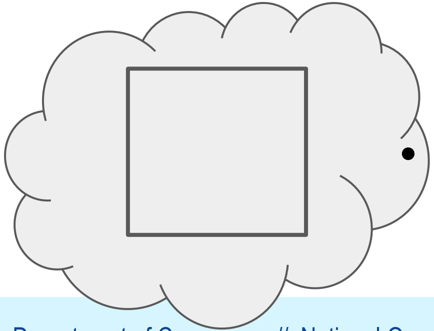
Dorrestijn, J., *et al.* (2013), example for shallow cu.



- **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**

A two-moment cloud microphysics scheme in GFS as a starting-point

- Thompson-Eidhammer 2-moment cloud microphysics scheme was selected to be used in GFSv17 as a starting point for the “unified suite” as it would:

  1) introduce the possibility of coupling to aerosols by having a prognostic evolution of both mass and number concentration.

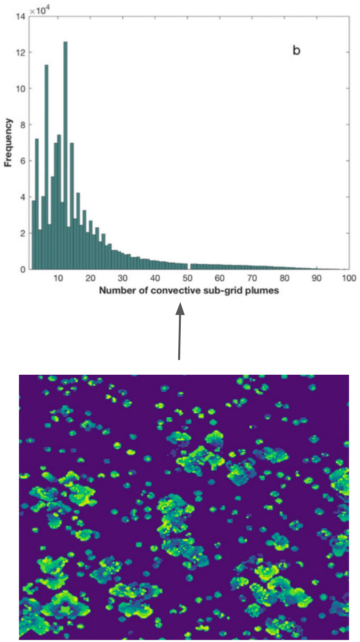
  2) unify the cloud microphysics schemes used across UFS applications (RRFS and GFS).

- A huge effort by many developers across NOAA and NCAR made it possible to include the scheme in the UFS global coupled prototypes, as issues with numerical instability and coupling to radiation had to be addressed (e.g. Ruiyu Sun, Jongil Han, Songyou Hong, Anning Chen, Eric Aligo, Jili Dong, Greg Thompson, Jian-Wen Bao, Fanglin Yang…)

A new prognostic-stochastic cumulus closure has been developed.

In an effort to represent cumulus convection at grey-zone resolutions, and to address prognostic evolution and stochastic effects, a “prognostic-stochastic” cumulus convection closure has been developed and tested in the GFS.

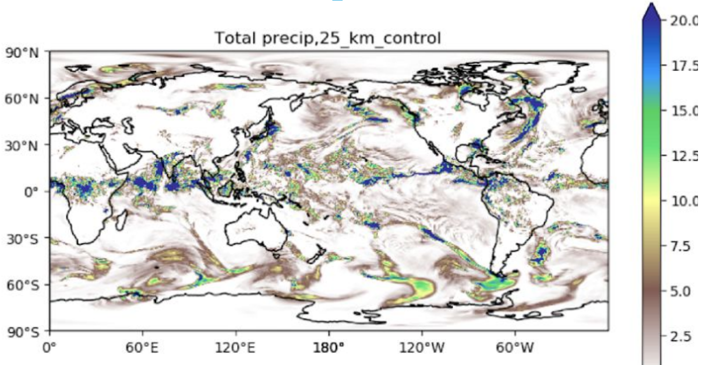
1. ***No longer assume negligible area fraction in cumulus parameterization***. Introduce a physical equation for the area fraction - bring moisture sensitivity to the closure.
2. ***No longer assume steady state and statistical equilibrium with large scale flow***. Prognostic evolution - provides memory of the moisture convergence.
3. ***Add stochastic term*** based on self-organizing **cellular automata** for 3D convective organization feedbacks, and stochasticity.



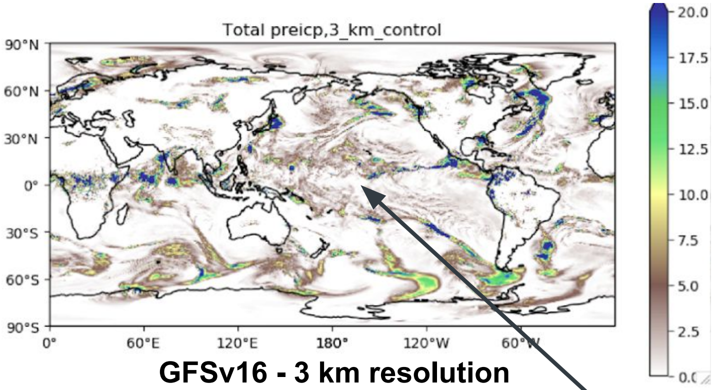
$$\frac{\partial \sigma_B}{\partial t}\int_{p_B}^{p_T} \xi(p)\left(h_u(p) - h_s(p)\right)\frac{dp}{g} = L\int_{p_B}^{p_T} \sigma_B \omega_u \xi(p)\frac{\partial q_{cond}}{g} + L\int_{p_B}^{p_T} MFC\frac{dp}{g}$$

Bengtsson et al. 2022

Scale-adaptive considerations



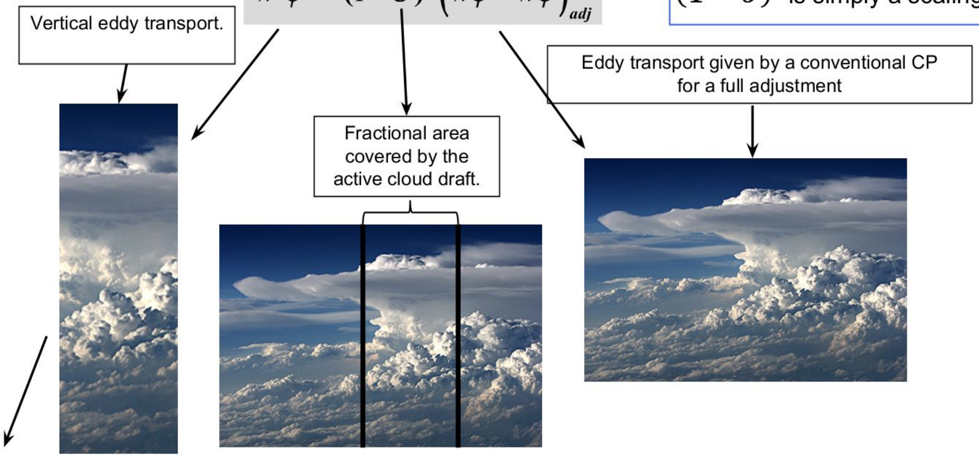
GFSv16 - 25 km resolution



GFSv16 - 3 km resolution

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

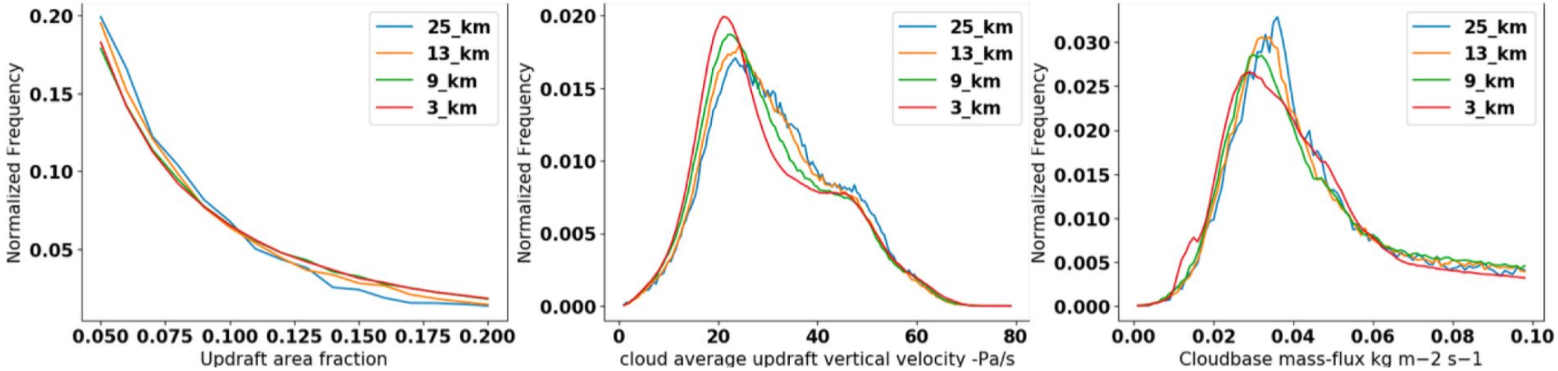
$(1-\sigma)^2$ is simply a scaling factor!



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!



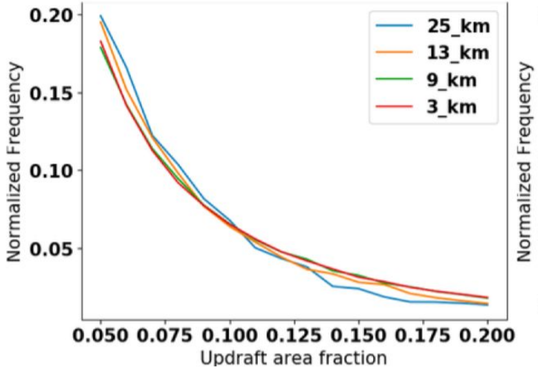
$$M_B = -(1. - \sigma_B)^2 \frac{\sigma_B \overline{\omega_u}}{g}$$

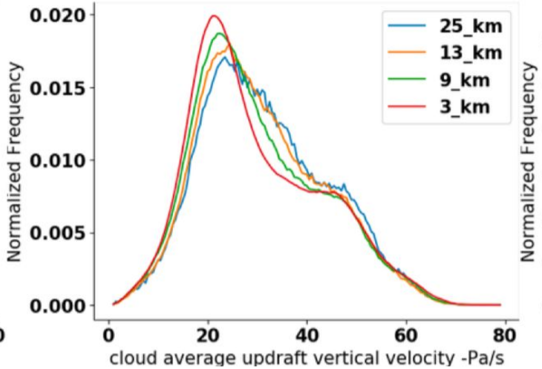
$$\frac{\partial \sigma_B}{\partial t} \int_{p_B}^{p_T} \xi(p)(h_u(p) - h_s(p)) \frac{dp}{g} = L \int_{p_B}^{p_T} \sigma_B \omega_u \xi(p) \frac{\partial q_{cond}}{g} + L \int_{p_B}^{p_T} MFC \frac{dp}{g}$$

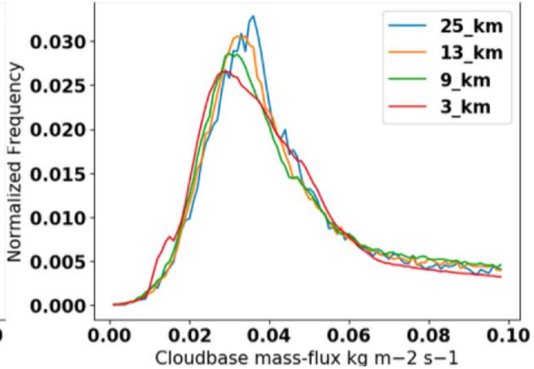
$$\frac{\partial w_u^2}{\partial z} = -c_1 \varepsilon w_u^2 + c_2 B \qquad B = g(\theta_{v,u} - \overline{\theta_v})/\overline{\theta_v}$$

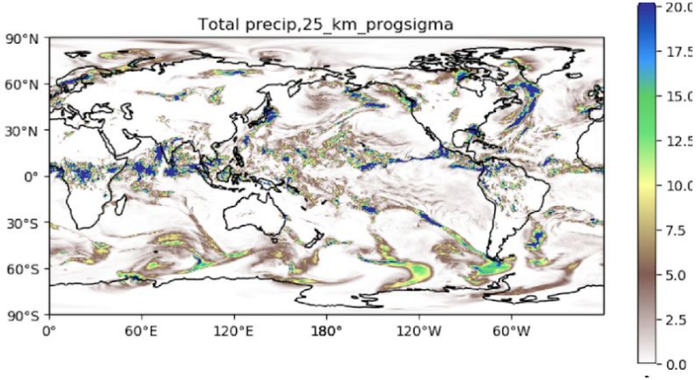
Bengtsson et al. 2022

Scale-adaptive considerations - new closure

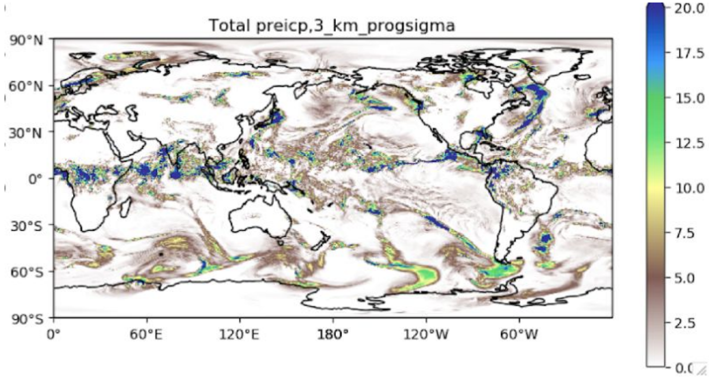








Prog closure 25km



Prog closure 3km

Bengtsson et al. 2022

Development of a new prognostic cloud scheme for unified moist-turbulent physics is underway!

Joseph Olson GSL, Grant Firl CIRES/GSL

Prognostic equations for cloud fraction (qa) and cloud species (ql, qi, and qs)

$$\frac{\partial q_x}{\partial t} = \left.\frac{\partial q_x}{\partial t}\right|_{adv} + \left.\frac{\partial q_x}{\partial t}\right|_{conv} + \left.\frac{\partial q_x}{\partial t}\right|_{vdiff} + \left.\frac{\partial q_x}{\partial t}\right|_{ls} + \left.\frac{\partial q_x}{\partial t}\right|_{eros} + \left.\frac{\partial q_x}{\partial t}\right|_{micro}$$

Processes contributed from each component work to regulate unified cloud fields:

Adv: advection
Conv: convection schemes
Vdiff: boundary layer scheme
Ls: large-scale processes
Eros: erosion
Micro: microphysics scheme

- Begin **implementation of GFDL's/IFS's prognostic cloud scheme into the ufs-weather-model/CCPP**
- Couple to Thompson microphysics, all PBL and convection schemes
- **This unifies the subgrid-scale (SGS) clouds and resolved-scale clouds, extending full thermodynamics and consistent handling of cloud species to all SGS clouds.**
- **Unifies how different cloud sources are passed to radiation**.
- For some model configurations, this allows us to drop 3 3D arrays used for SGS clouds

Unified mass-flux and seamless transition from shallow to deep convection.

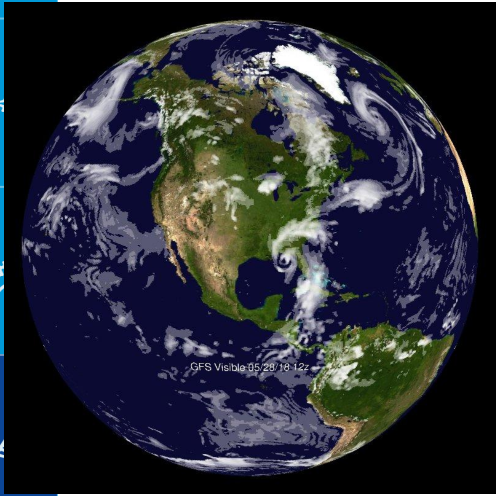
- Scientifically we are in agreement that we should avoid compartmentalization of process descriptions as much as possible, and unify the mass-flux descriptions when appropriate.

- Practically, it is challenging to realize, as there are several PBL and convection schemes under development within *ufs-weather-model/ccpp* simultaneously.

- It should be noted that there are physics parameterizations available that addresses these concepts, examples include (but are not limited to) SHOC (Bogenschutz and Krueger, 2013) and UNICON (Park, 2015).

- The challenge of transferring SHOC to NCEP operations demonstrates the need for continuous funding, and the need for the developers (experts) to be part of the integration with other schemes, data assimilation, coupling to other earth components etc.

Current R2O procedure



Operational GFSv17

UFSR2O physics development team

CCPP

EMC, PSL, GSL CSL, NSSL, ARL, NESDIS

CIRES

U.S. NAVAL RESEARCH LABORATORY

NOAA

GFDL

NCAR UCAR

DTC

In a large organization such as NOAA (and wider community), the task of unification of a suite becomes difficult as schemes can be contributed in a modular fashion by individual contributors. It is important to have a conceptual framework in mind as physics is not plug-and-play.

Unifying innovations in forecasting capabilities: A request for a research grade UFS from the physics and chemistry community

Why do we think a research grade UFS is a good option

1. To gain understanding in processes that are important for weather, climate, air quality predictions **on all scales**
2. To be able to improve representation of processes that are important for operational forecasting **on all scales**
3. It will get a wider community more involved
4. Research using (3) will help improving operational forecasting

What should be included in a research grade UFS?

1. Physics and Atmospheric Composition parameterizations and modules/models to study complex physics/chemistry interaction processes (see also **poster by Rebecca Schwantes et al**.).
2. Ability to run in Large Eddy Simulation mode
3. A simple version (depending on application) of UFS to be able to do model development efficiently

What is necessary to maintain a research grade UFS?

- **Consistent master repository;** this may be the most difficult task, since operational versions as well as R2O traffic should not be disturbed - may require significant software engineering involvement
- User friendliness and user support - including live user documents

How does our vision fit in with the international community?

UK met-office (Keith Williams):

*Our key priorities are development of a **scale-aware convection scheme** and **double moment cloud microphysics schemes.** As part of this, we also want to **unify the moist physics in our global and regional model configurations.** With a scale-aware convection scheme planned to be used across all [applications/scales], the intention is to **fully unify the system.***

*Another area of focus is development of the **aerosol scheme**, in particular developing solutions for NWP use. We also want to look at **stochastic physics** and put this more centrally in the development of parametrizations.*

Finally, we're collaborating with a hydrology research centre in the UK to develop a new hydrology scheme (surface, rivers and groundwater) for the land model.

How does our vision fit in with the international community?

Env-Canada (Ron McTaggart-Cowan):

1. *We're working on incremental changes to the connections between the PBL scheme and shallow convection that will hopefully allow for some* ***unification around an EDMF-based 1.5-order PBL scheme.***

2. *Increase efforts towards* ***scale-awareness in deep convection*** *(we currently use K-F even in our 2.5 km system). Over the next few years we're planning to work on improvements in grey-zone convection (likely still parameterized, but relaxing some of the QE et al assumptions).*

3. *Develop a fractional-cloud version of the P3 microphysics scheme (two-moment rain and single ice category) that will make the scheme applicable for any resolution. This work will also require assessment of the scheme's behaviour at global scales.*

How does our vision fit in with the international community?

ECMWF (Richard Forbes):

…one relatively new area of development is to ***get the global model physics ready for kilometre-scale resolutions (1-5km), which includes the grey-zone for convection.*** *This includes improvements to the parametrizations of convection and turbulent mixing processes (probably still some role for deep convection parametrization at these resolutions, explore prognostic TKE scheme, possibly 3D turbulence for the higher resolutions) for microphysics (graupel, explore double-moment), and developments for improved seamlessness across spatial scales (gravity wave drag, 3D radiation,…).*

The second area of development is continuing the ***expansion of the Earth system modelling approach, including aerosols*** *(improved climatologies or prognostic, perhaps lower-resolution grid), and hydrological models as well as continuing improvements to land surface, ocean and sea-ice models (including higher resolution).*

Concluding remarks

- Our vision is well aligned with the international community. If we do not consider the aspects discussed here, we risk falling behind other centers when the global model resolution enters the sub 10 km range.
- A 1-2 year turnaround time between operational cycles is very short when it comes to including new innovations. Support is needed for lower readiness level both in terms of funding and pre-operational testing environment.
- Community involvement (e.g. university contributions of individual schemes) offers opportunity, but it also puts additional strains on coordination and the focused effort needed to have a well integrated physics suite for operations.