Next Generation Climate Models

Bjorn Stevens

MAX-PLANCK-GESELLSCHAFT
Max-Planck-Institut
für Meteorologie

Sometimes we apply the same name to very different things

i.e., 'climate models'

A semi-empirical climate model (Budyko, 1969)

On the basis of these data relating to each month for 260 stations an empirical formula was derived

$$I = a + BT - (a_1 + B_1 T)n \qquad (1)$$

where I = outgoing radiation in kcal/cm² month,

T = temperatu

surface in

n = cloudiness

For mean annual conditions, the equation of the heat balance of the Earth-atmosphere system has the following form:

$$Q(1 - \alpha) - I = A \qquad (2)$$

where Q = solar radiation coming to the outer boundary of the atmosphere;

α = albedo;

A = gain or loss of heat as a result of the atmosphere and

tion, including

phase water tra

The result of the above comparison in Fig. 2 from which it follows tha responding dependence can be expres form of equation

$$A = \beta(T - T_p) \qquad (3)$$

where $\beta = 0.235$ kcal/cm² month degree

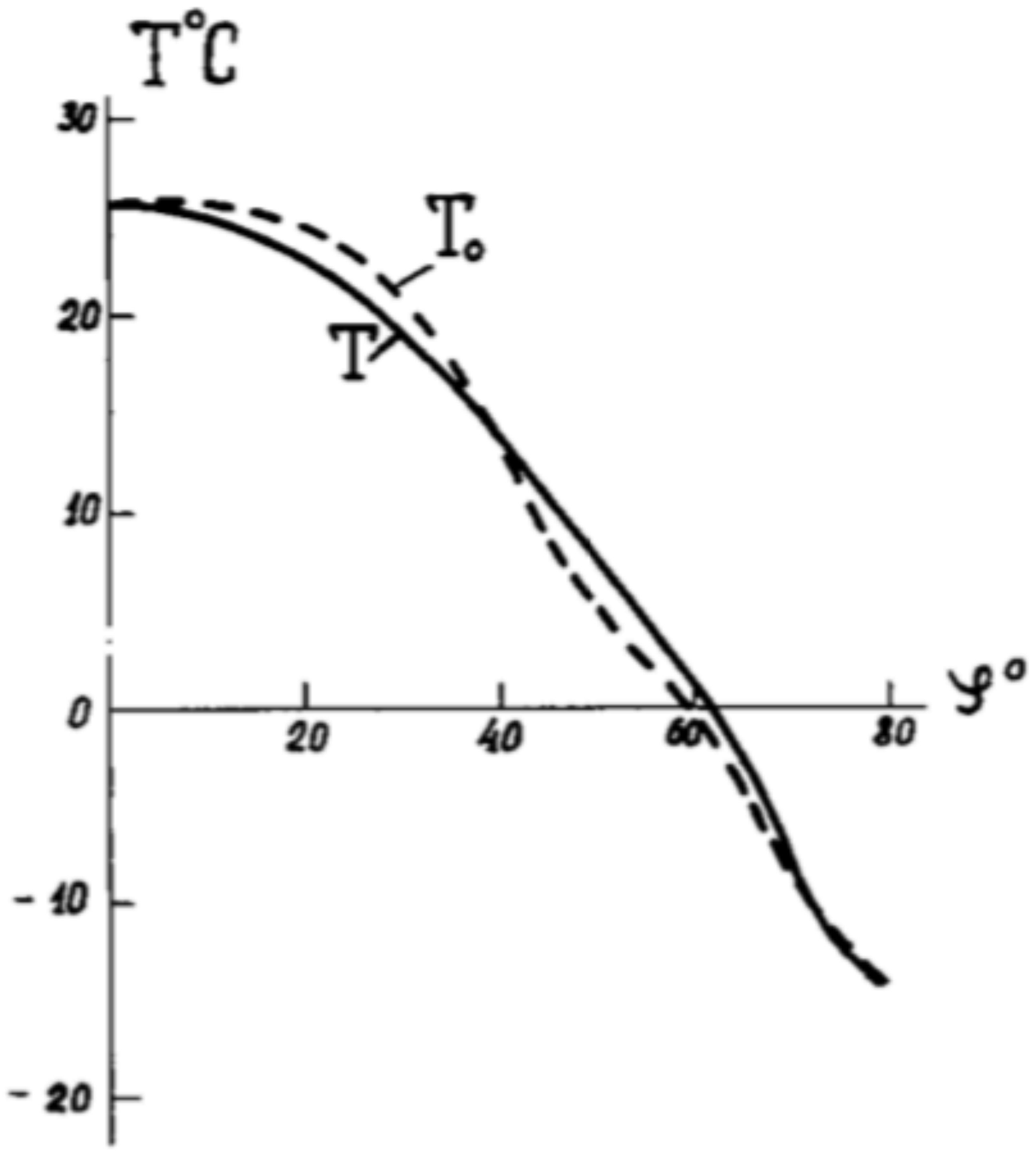
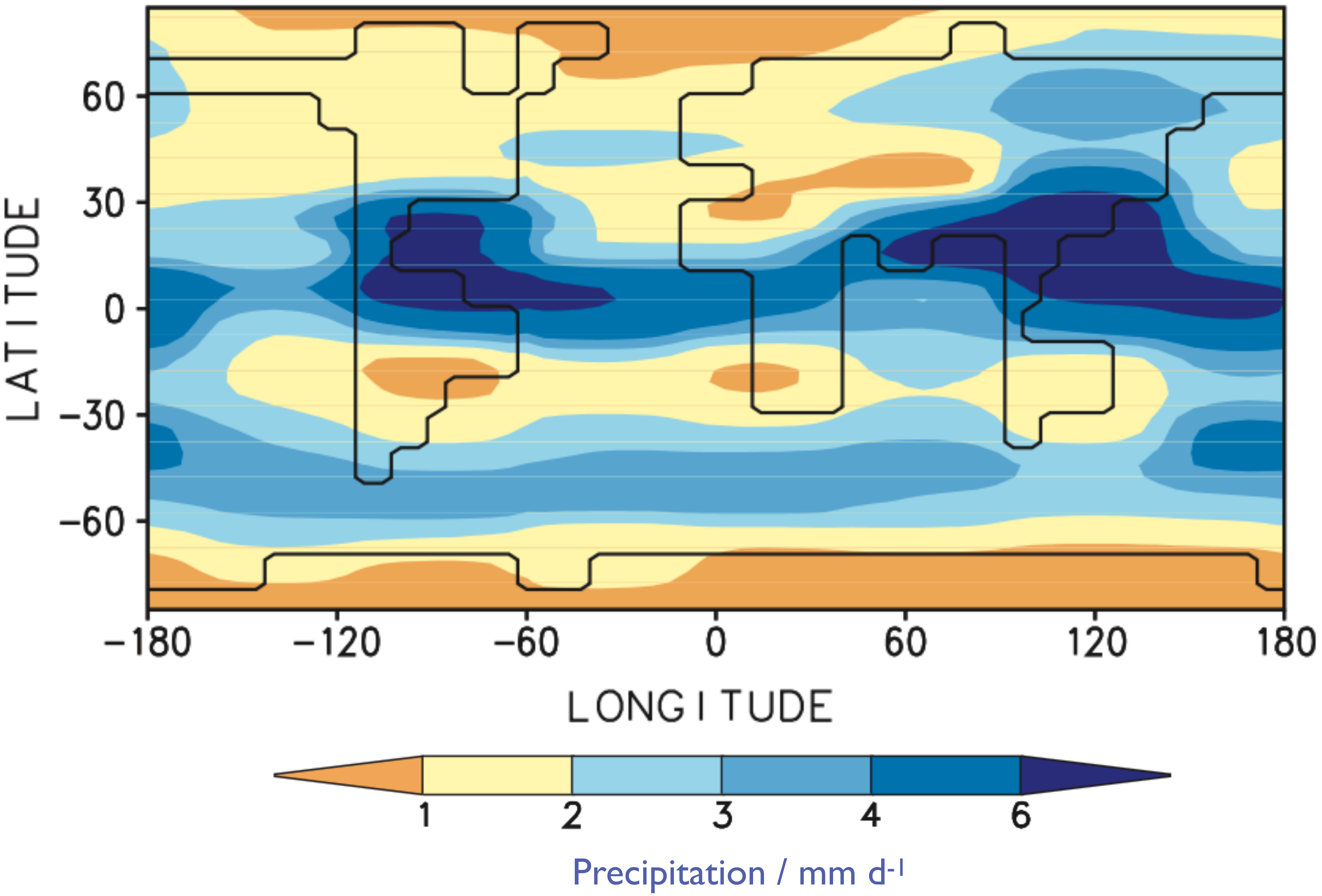


Fig. 3. The average latitudinal temperature distribution.

A more elaborate version of Budyko's model (CLIMBER, PIK)



A big leap …

In constructing a dynamical model of the atmosphere for the purpose of accounting for the features of the general circulation, two obvious courses present themselves:

(i) to treat transient dynamics of the large-scale motions explicitly and then to calculate the statistical-mechanics of the evolutions,

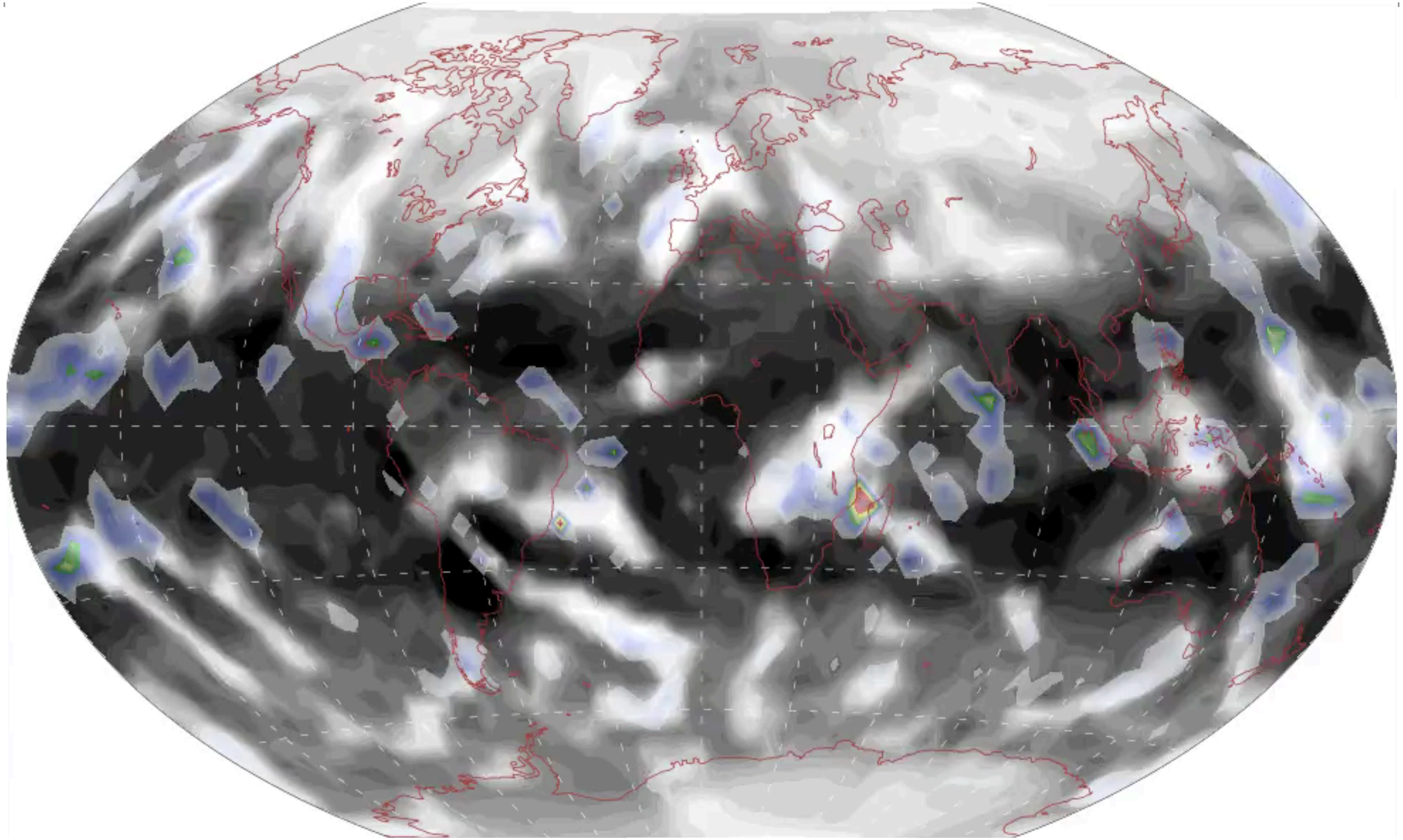
or

(ii) to treat the large-scale motions as turbulence which is somehow related to the mean properties of the flow.

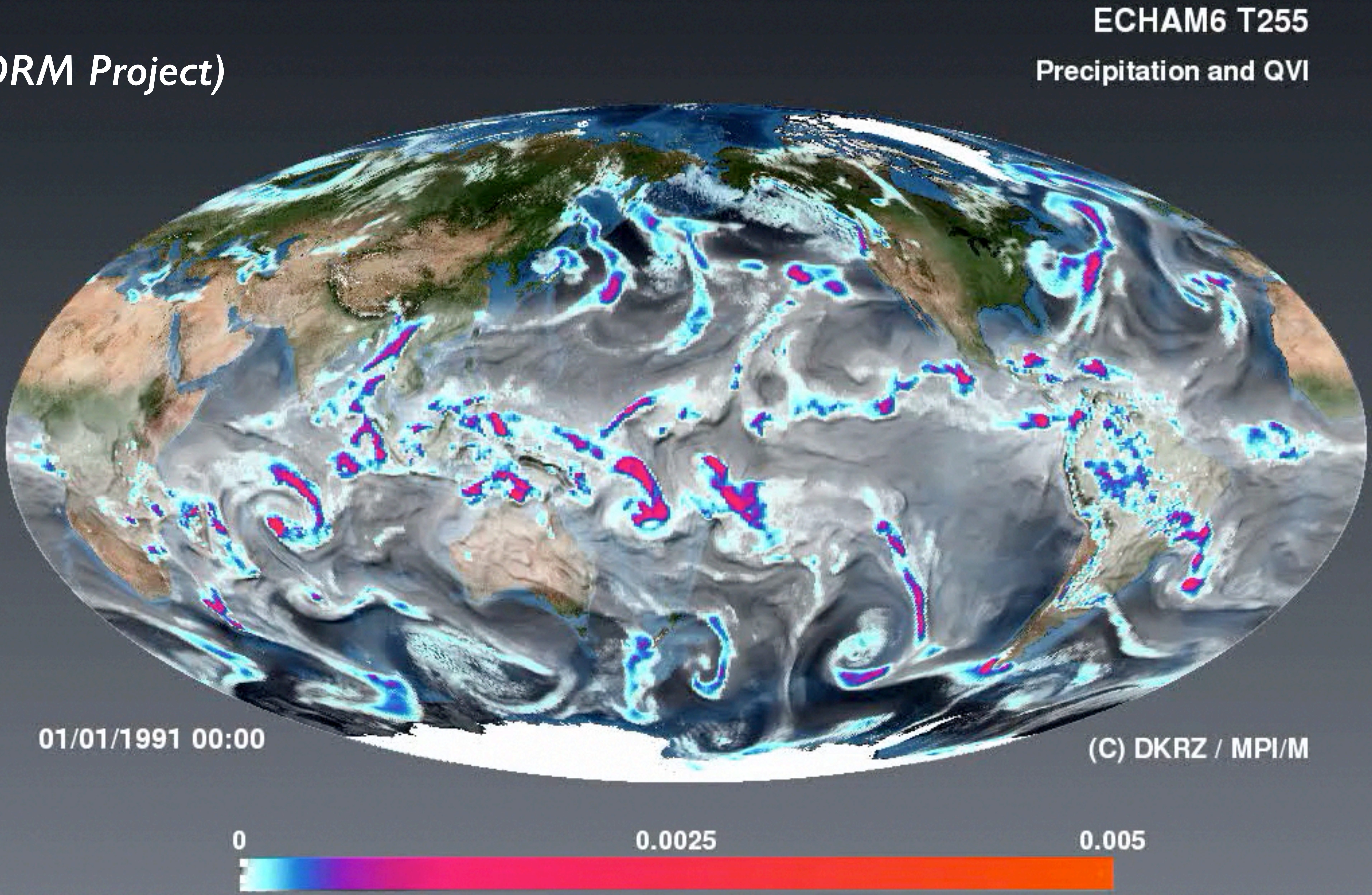
The latter course has a natural appeal following the successful application of such techniques by Prandtl and von Kármán to small-scale motions through analogy to kinetic theory. The application to large-scale cyclones and anticyclones has been suggested by Defant [11] and from time to time attempts have been made, e.g., by Berson [4] and others. In fact, it is employed implicitly by Namias [34] in operational 5- and 30-day forecasts by techniques which thus far have evaded quantitative formulation. More recently some success has been attained in theoretical studies, e.g., Thompson [57]. The still incomplete understanding of the statistical-dynamics of large-scale baroclinic transient motions in terms of the mean flow and particularly the maintenance of the westerlies by the non-linear transfer of perturbation energy leaves course (i) as the painful alternative. One would hope however that this explicit approach would ultimately contribute to the formulation of a "turbulence" theory. The advent of high speed computing machines and the parallel development of techniques of short range numerical prediction permit reducing the turbulence threshold from cyclone-scale to a characteristic length of a few hundred kilometers—a horizontal scale for which the eddy transport in the direction of the mean gradient is assumed to be valid, i.e., the grid scale lies within an inertial sub-range.

Smagorinsky, *MWR* (1963)

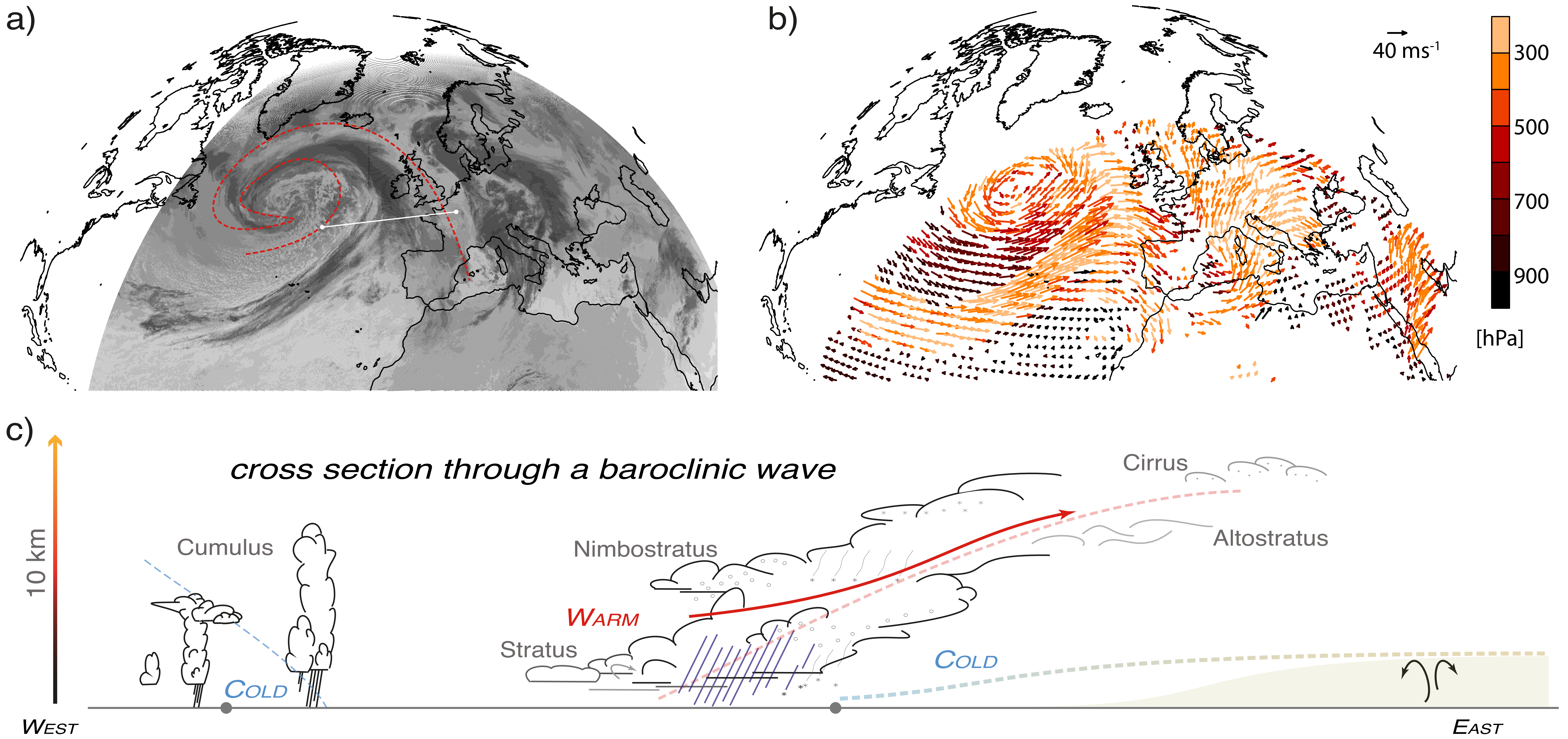
PalMOD (MPI, ECHAM T31)



MPI (STORM Project)

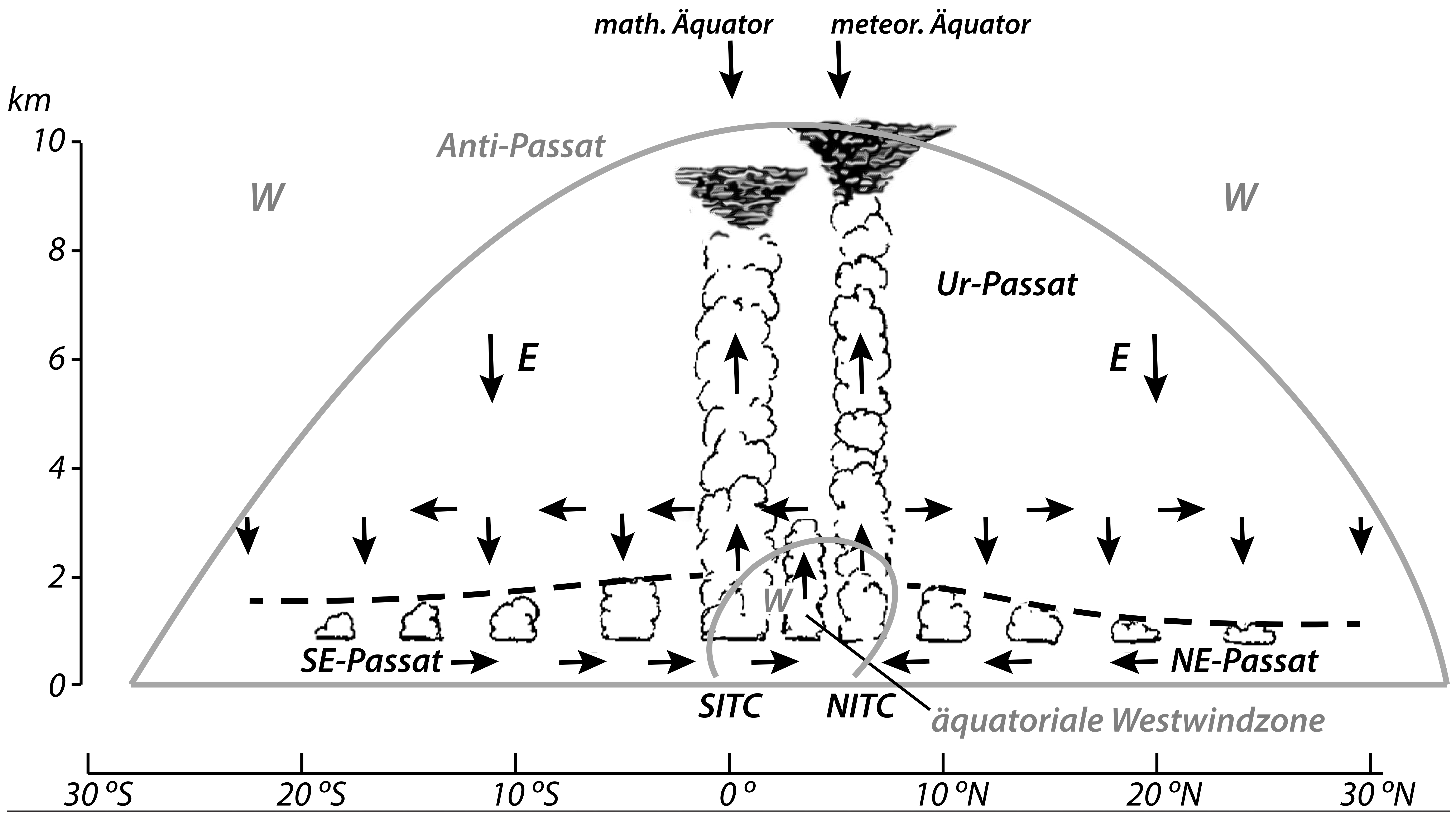


Mid latitude eddies



… large scale and quasi two dimensional

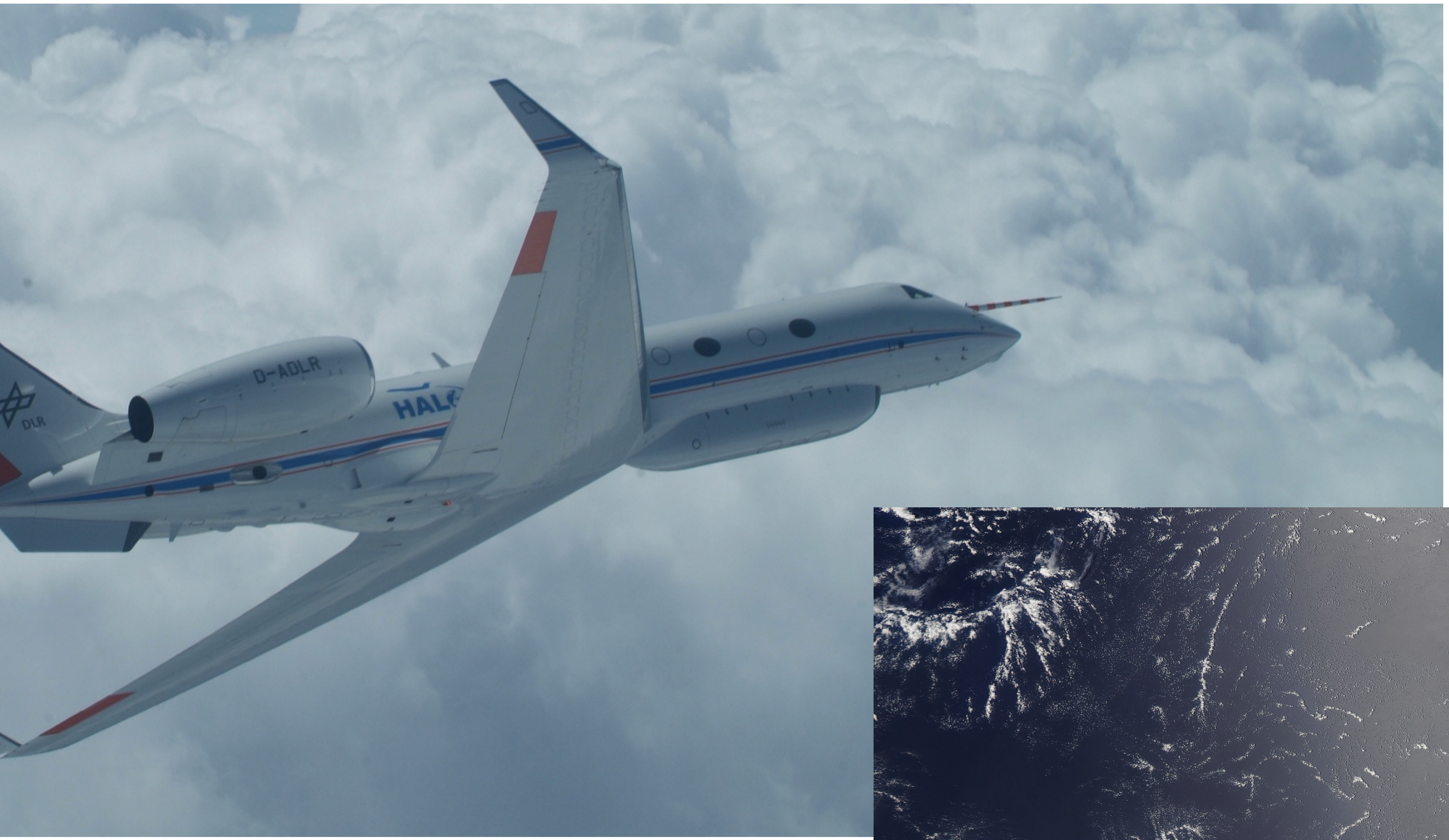
The Atlantic ITCZ as schematized by Flohn

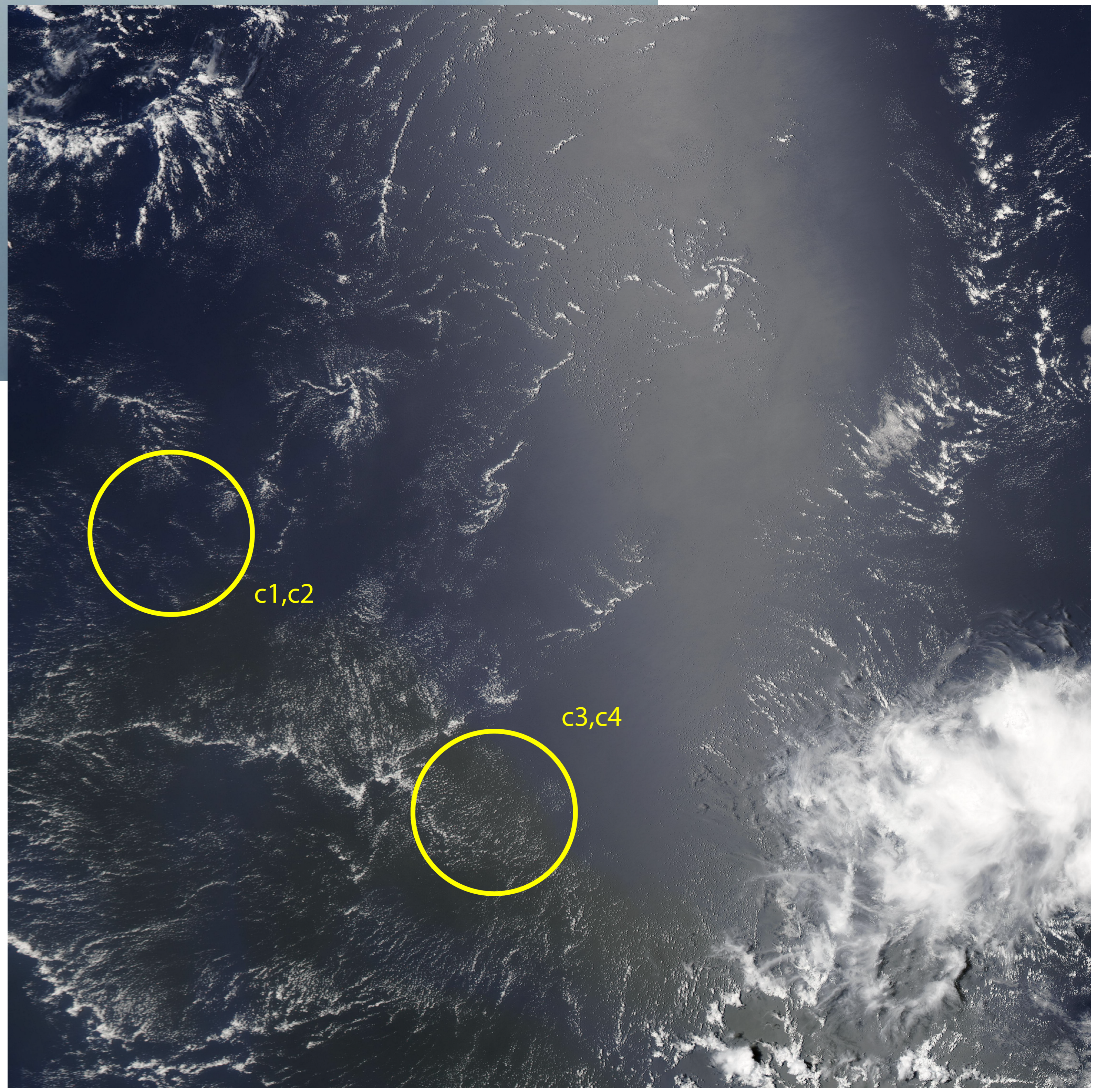


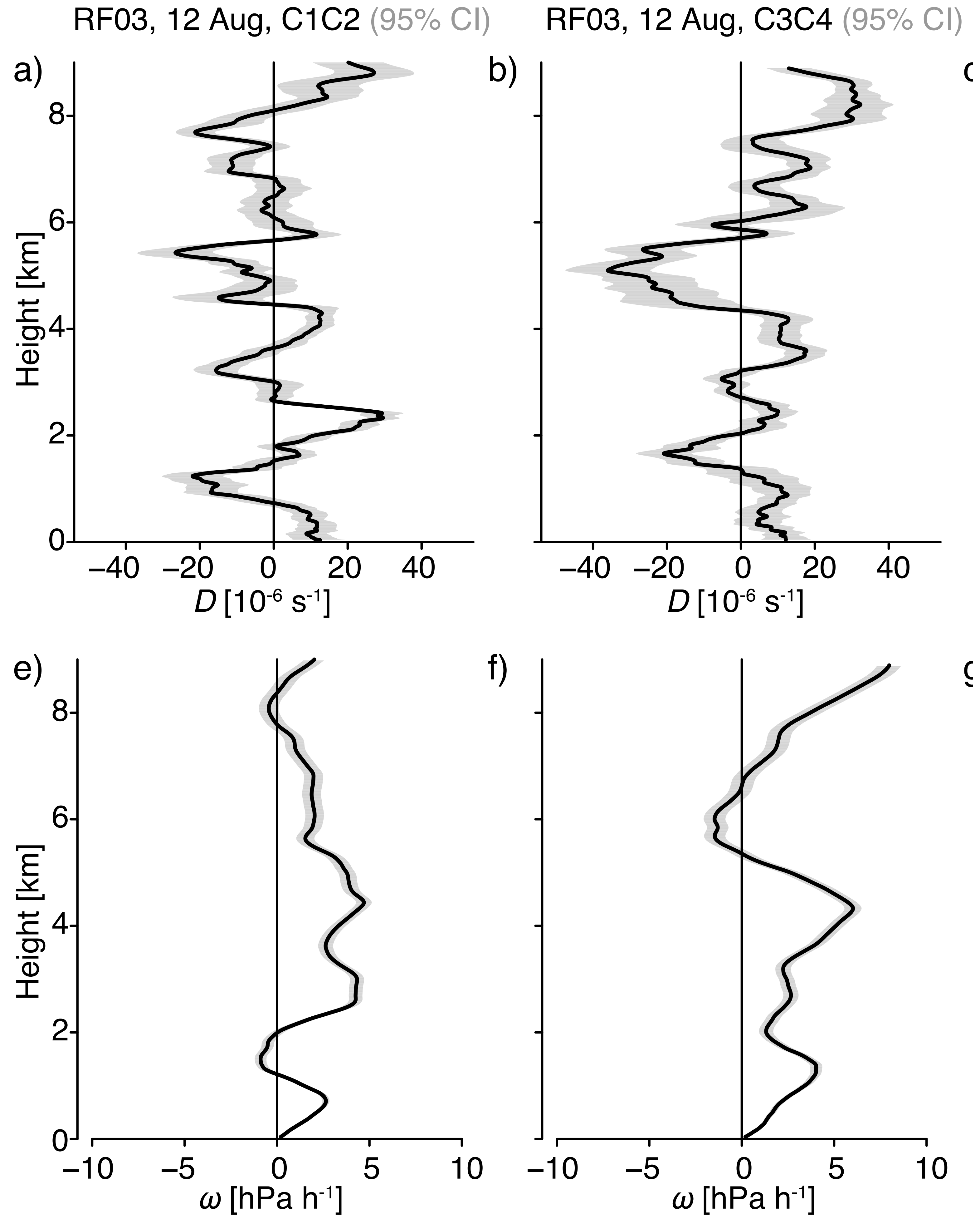
… inherently small-scale and three dimensional

H. Flohn, *Archiv Für Meteorologie, Geophysik Und Bioklimatologie Serie B,* (1951)

First measurements of mean vertical motion in the tropics



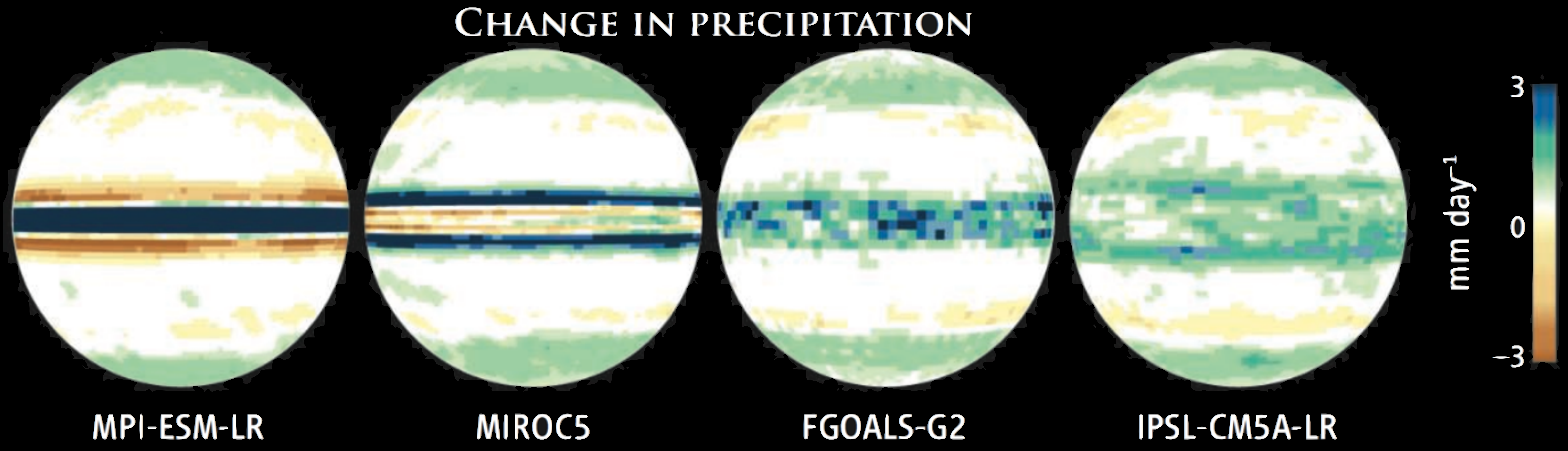




… tropical wave trap, rich spectrum of motions are coupled diabatically

Bony and Stevens *J. Atmos Sci.* (2019)

Large uncertainties in the representation of tropical rainfall

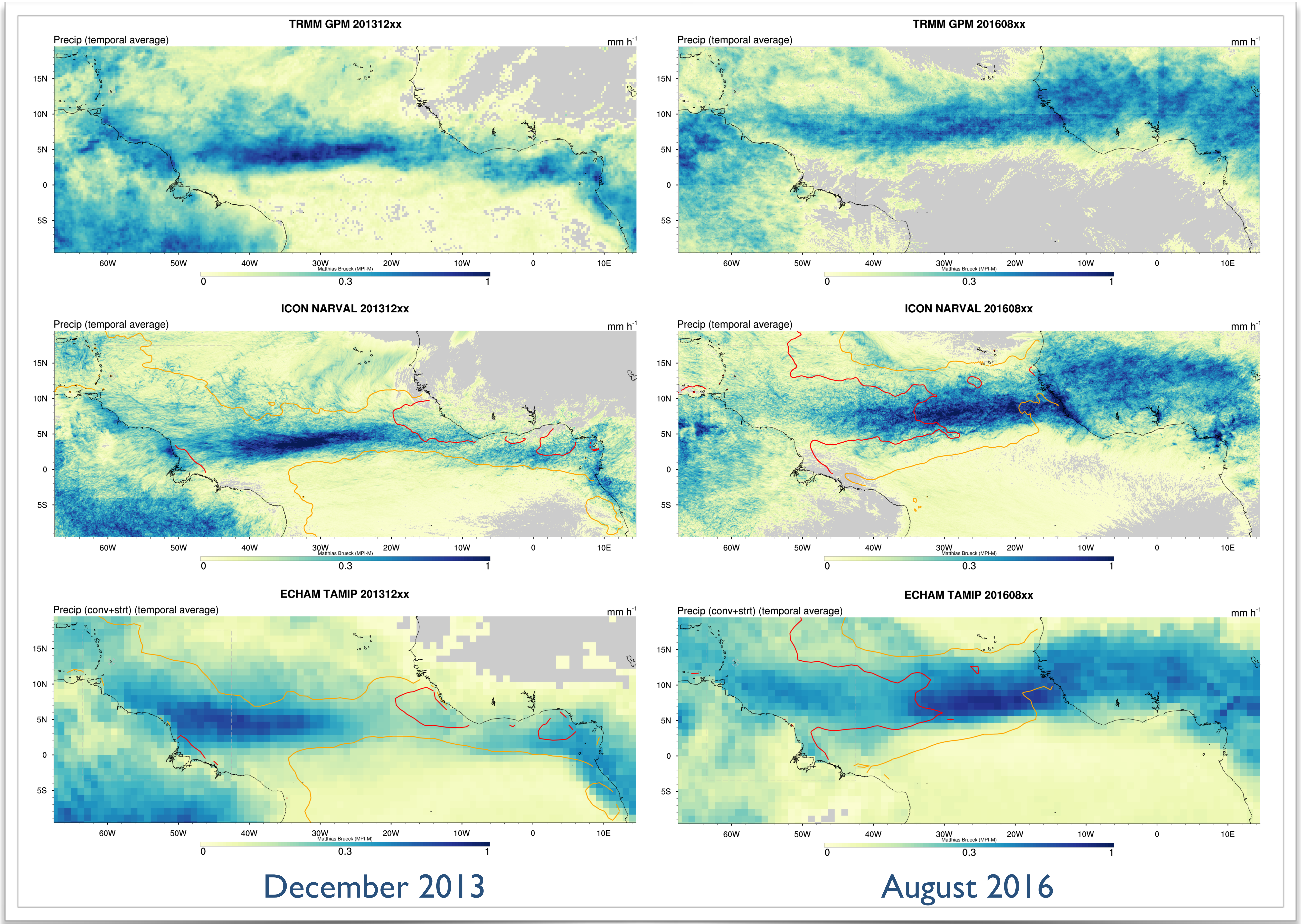


Stevens and Bony, *Science* (2013)

Remarks

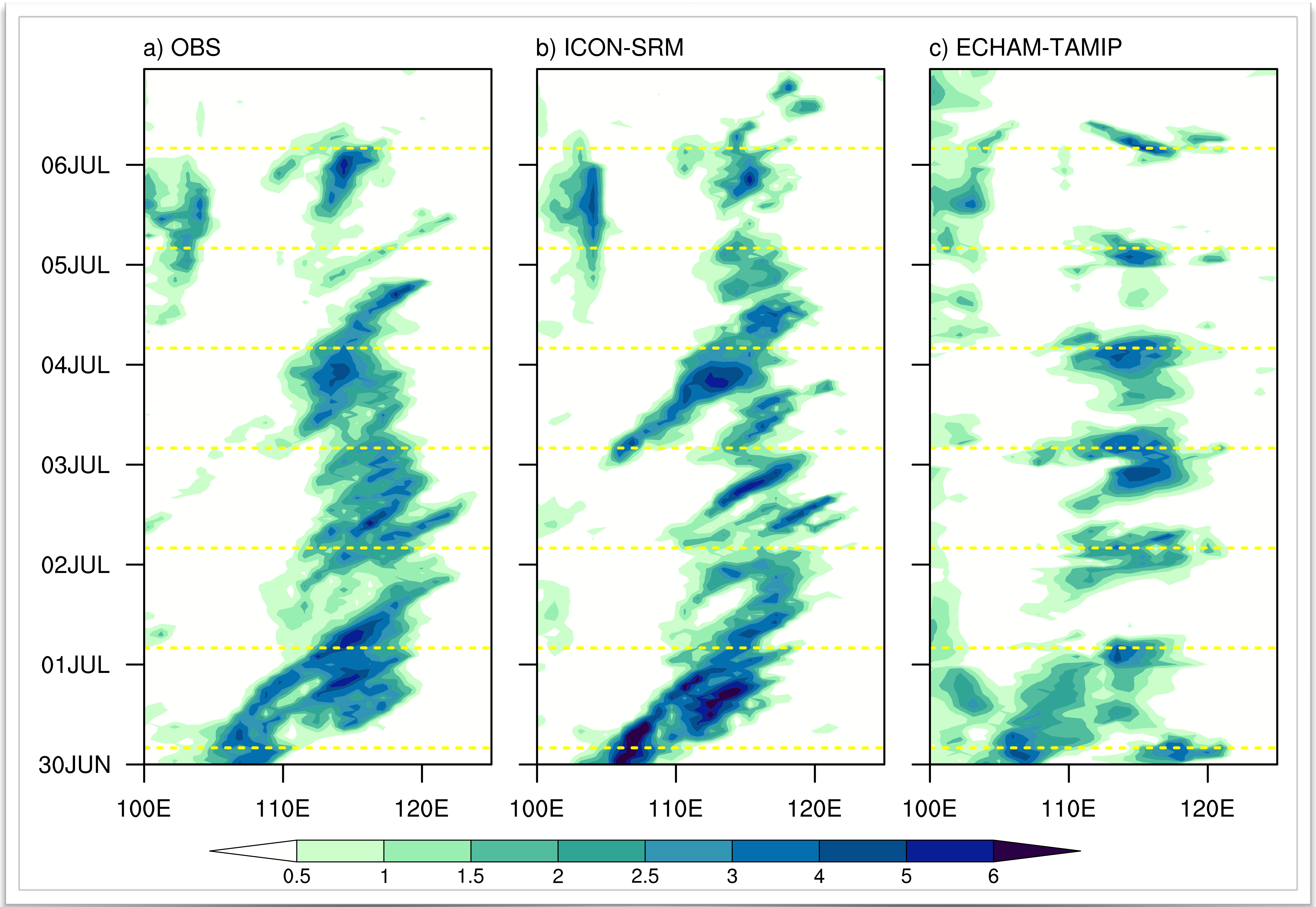
- The type of climate models that many people associate with adjectives such as "sophisticated", "complex", "comprehensive", "physically based" distinguish themselves from yet simpler models through their ability to resolve the physics of quasi two dimensional mid-latitude eddies and planetary waves, and thus represent important coupling pathways within the atmosphere — and to some extent the ocean.
- The vertical coupling among layers in such models remains, however, semi-empirical, and unsatisfactory.
- In the tropics the diabatic processes expressed in this coupling cannot be externalized from the circulation. The necessity of doing so in "comprehensive" climate models has been shown to underpin large systematic errors in the tropics, but also in other regimes where vertical coupling is important,

Improved spatial distribution of precipitation over the Atlantic



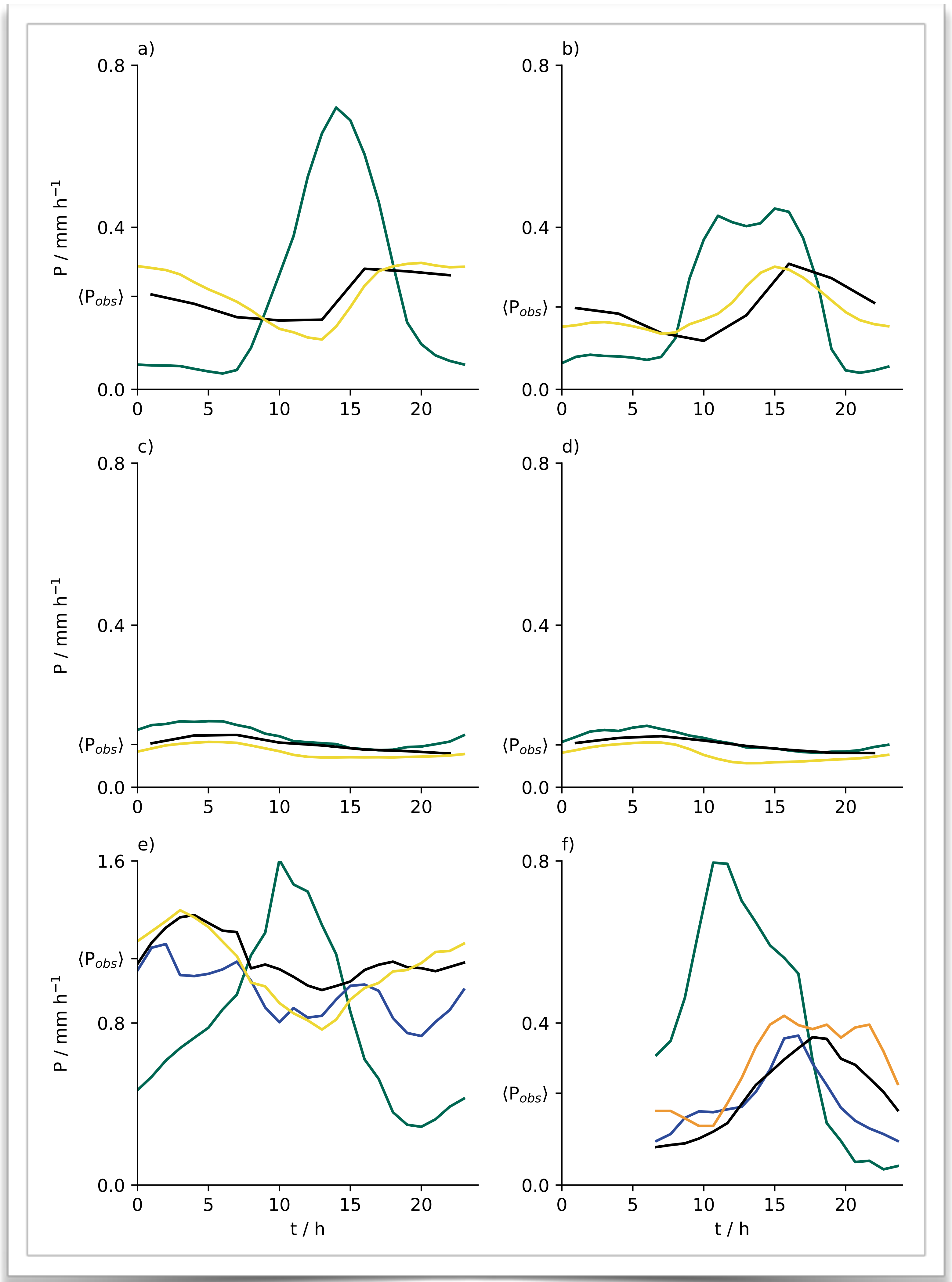
Matthias Brueck

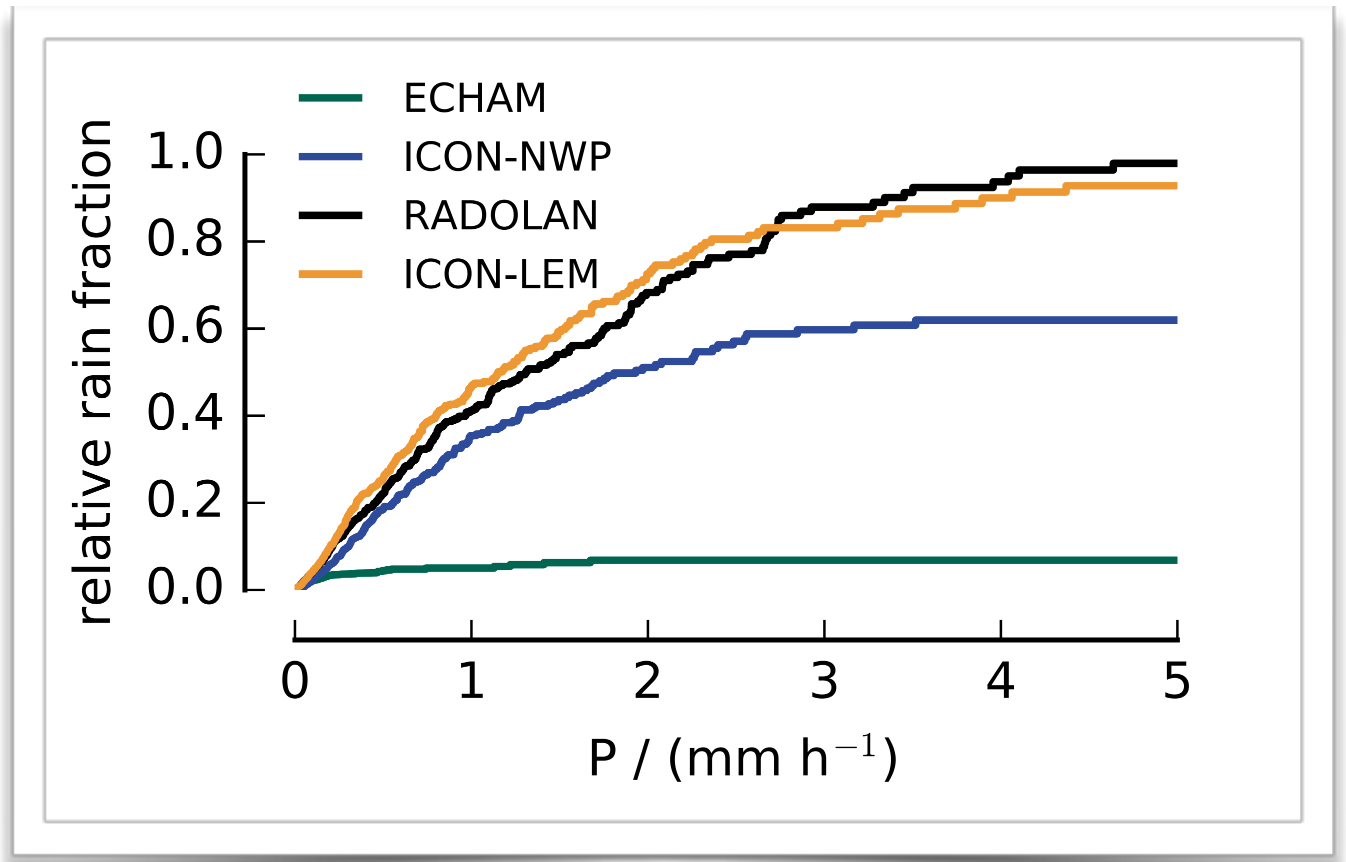
Better organized features over SE Asia (China)



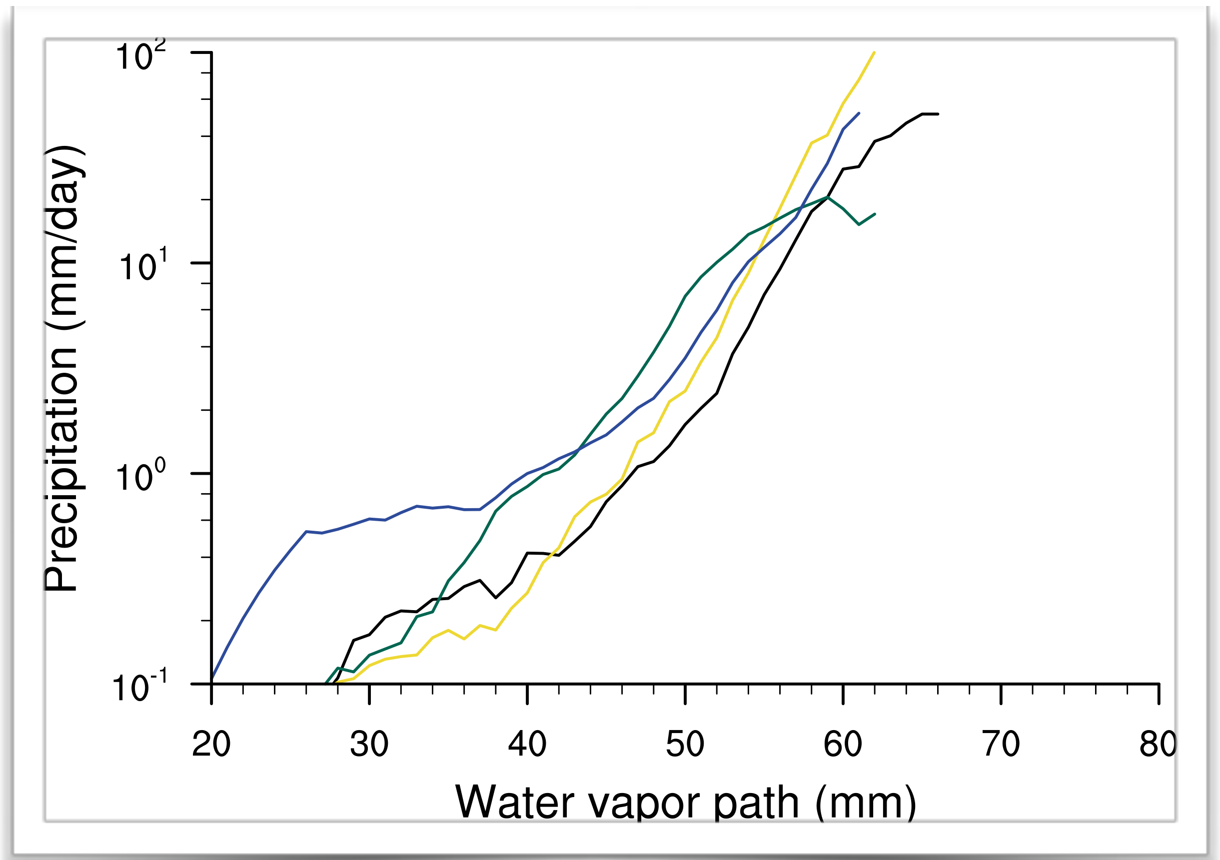
Puxi Li

Improved diurnal cycle over all regions, especially at night



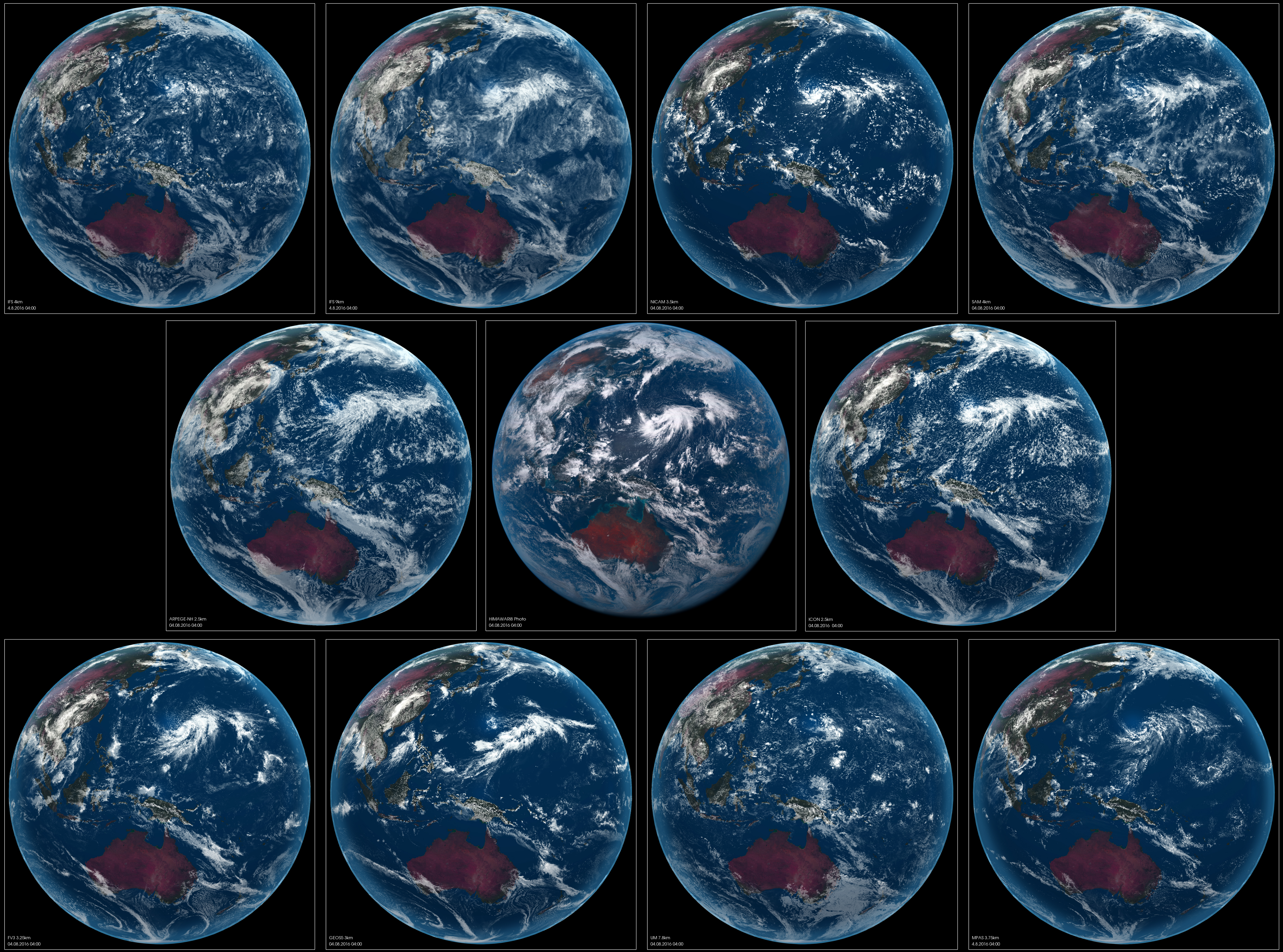


'Cumulative' distribution

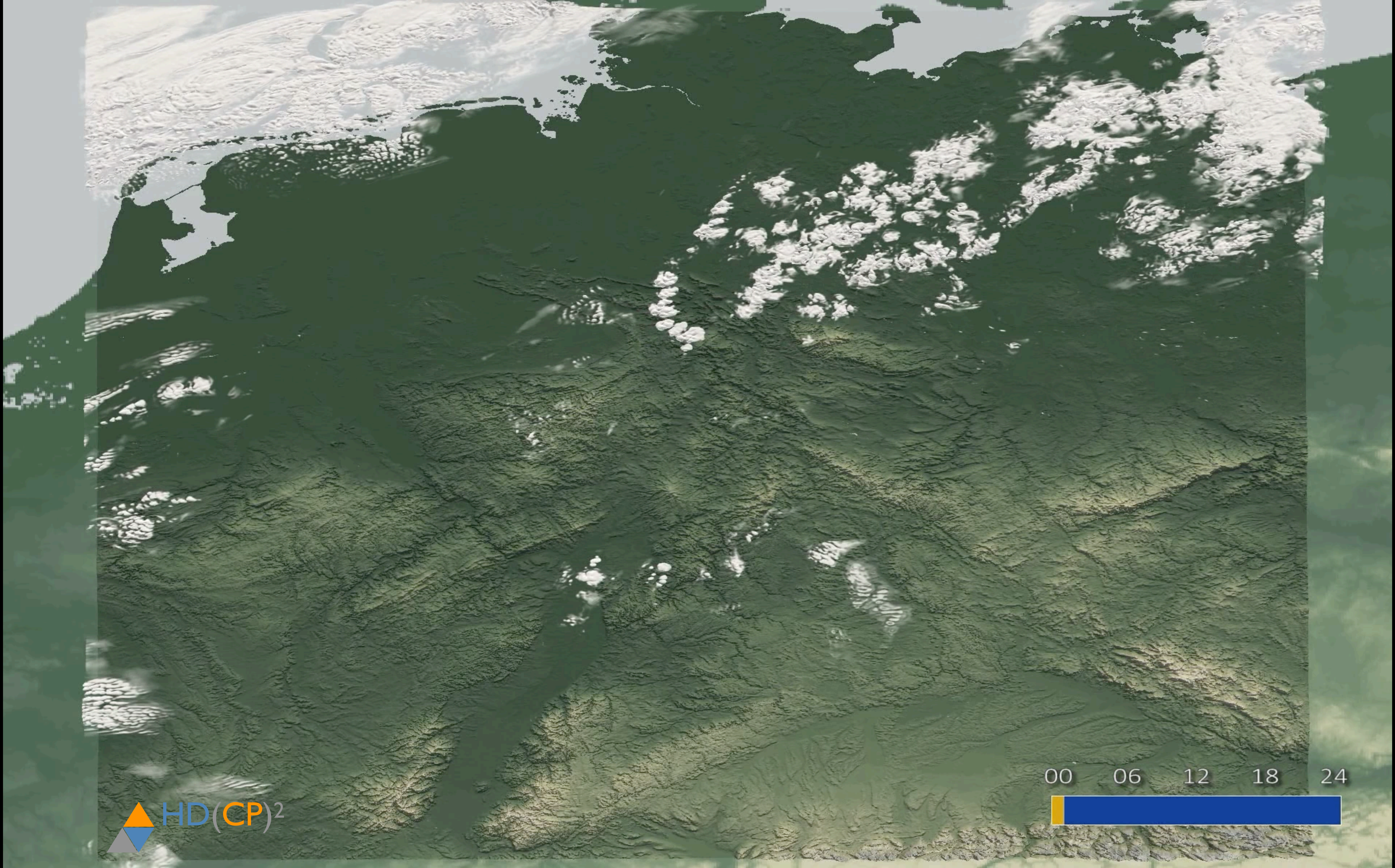


Precipitation pick-up with WVP

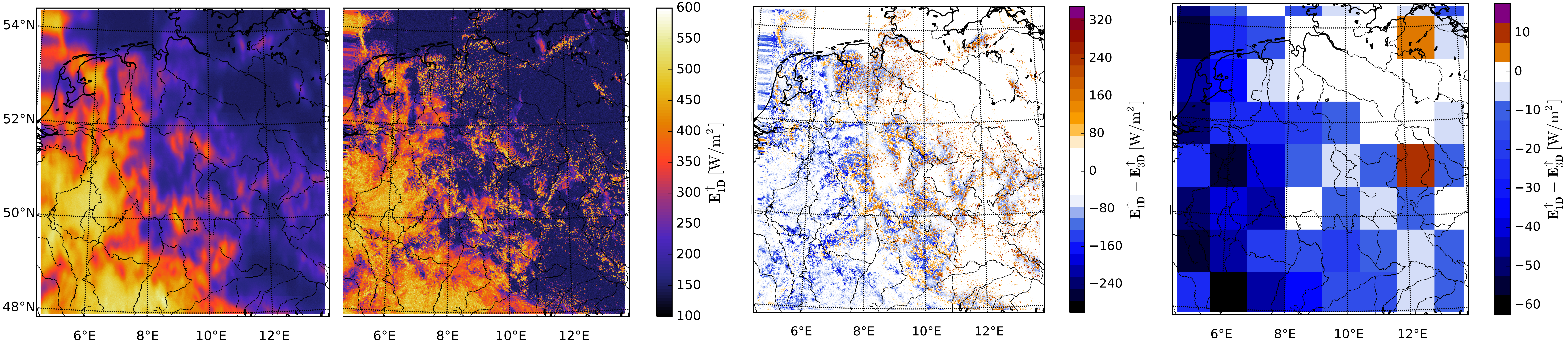
Karsten Peters, Puxi Li, Fabian Senf (diurnal cycle plot);
Fabian Senf (Relative rain fraction for night time rain); Cathy Hohenegger (Precipitation - WVP distribution)


IFS 4km
4.8.2016 04:00
IFS 9km
4.8.2016 04:00
NICAM 3.5km
04.08.2016 04:00
SAM 4km
04.08.2016 04:00
ARPEGE-NH 2.5km
04.08.2016 04:00
HIMAWARI8 Photo
04.08.2016 04:00
ICON 2.5km
04.08.2016 04:00
FV3 3.25km
04.08.2016 04:00
GEOS5 3km
04.08.2016 04:00
UM 7.8km
04.08.2016 04:00
MPAS 3.75km
4.8.2016 04:00


IFS 9km
4.8.2016 04:00
NICAM 3.5km
04.08.2016 04:00
SAM 4km
04.08.2016 04:00
HIMAWARI8 Photo
04.08.2016 04:00
ICON 2.5km
04.08.2016 04:00

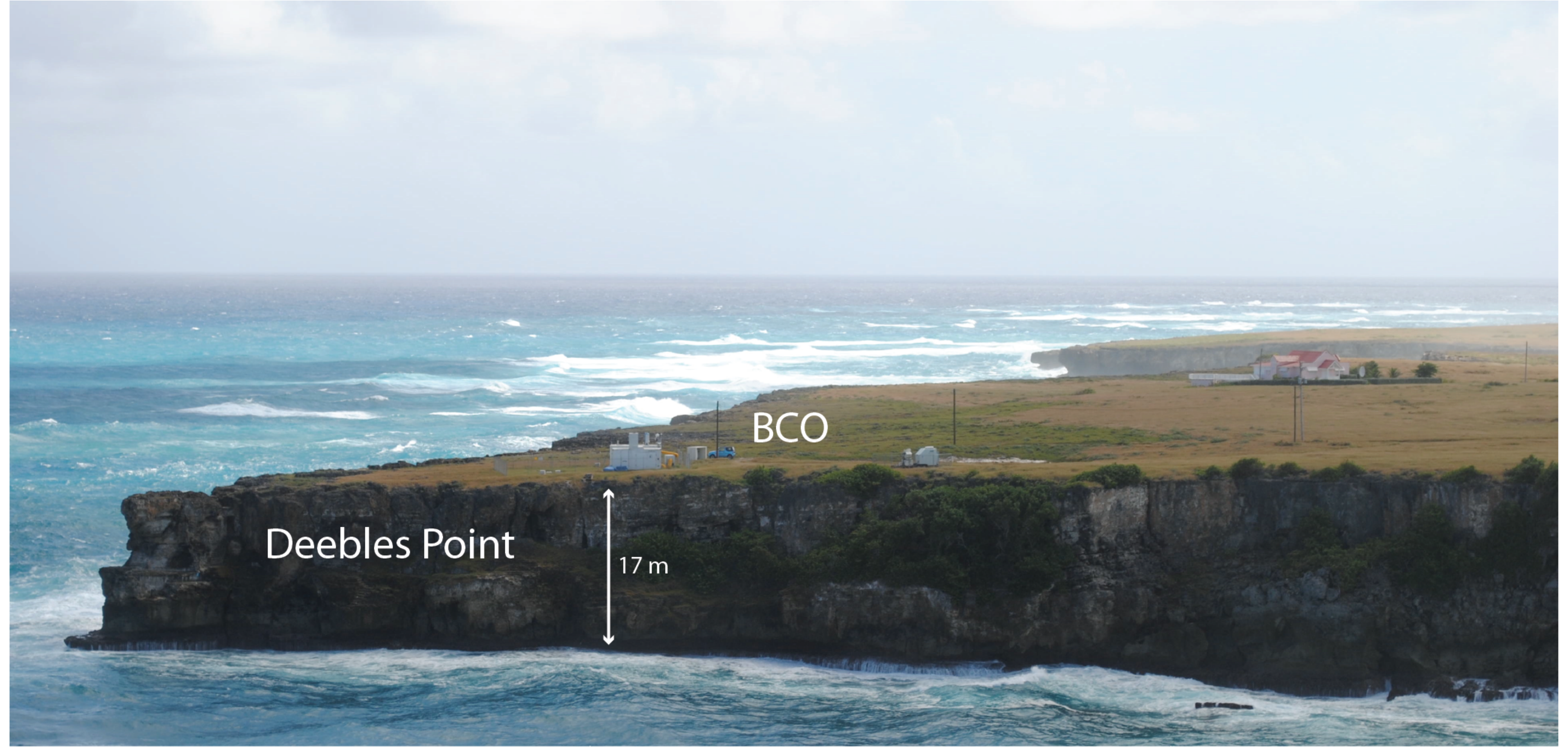

00 06 12 18 24
HD(CP)2

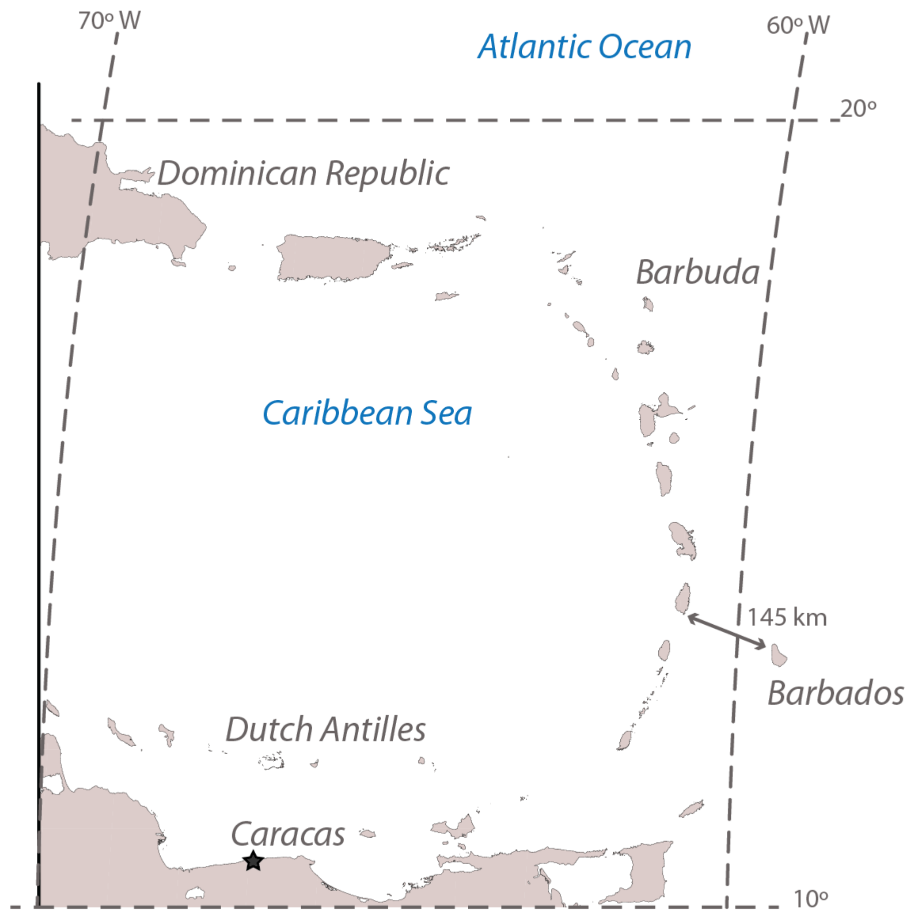
Three dimensional radiation biases

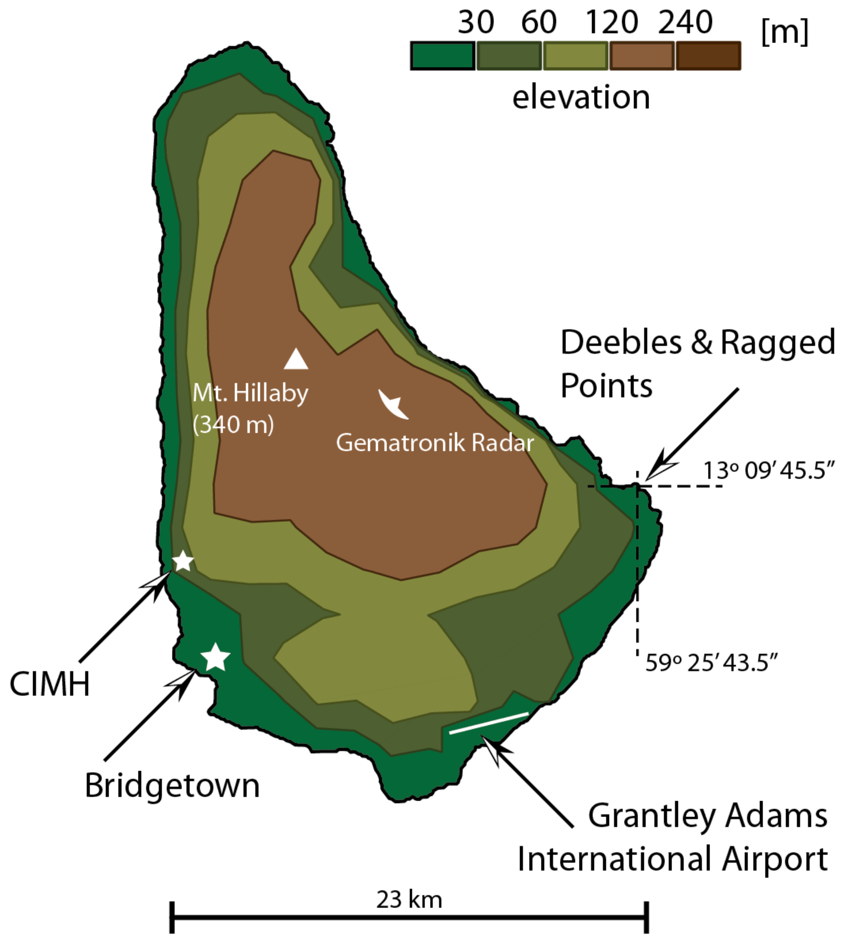


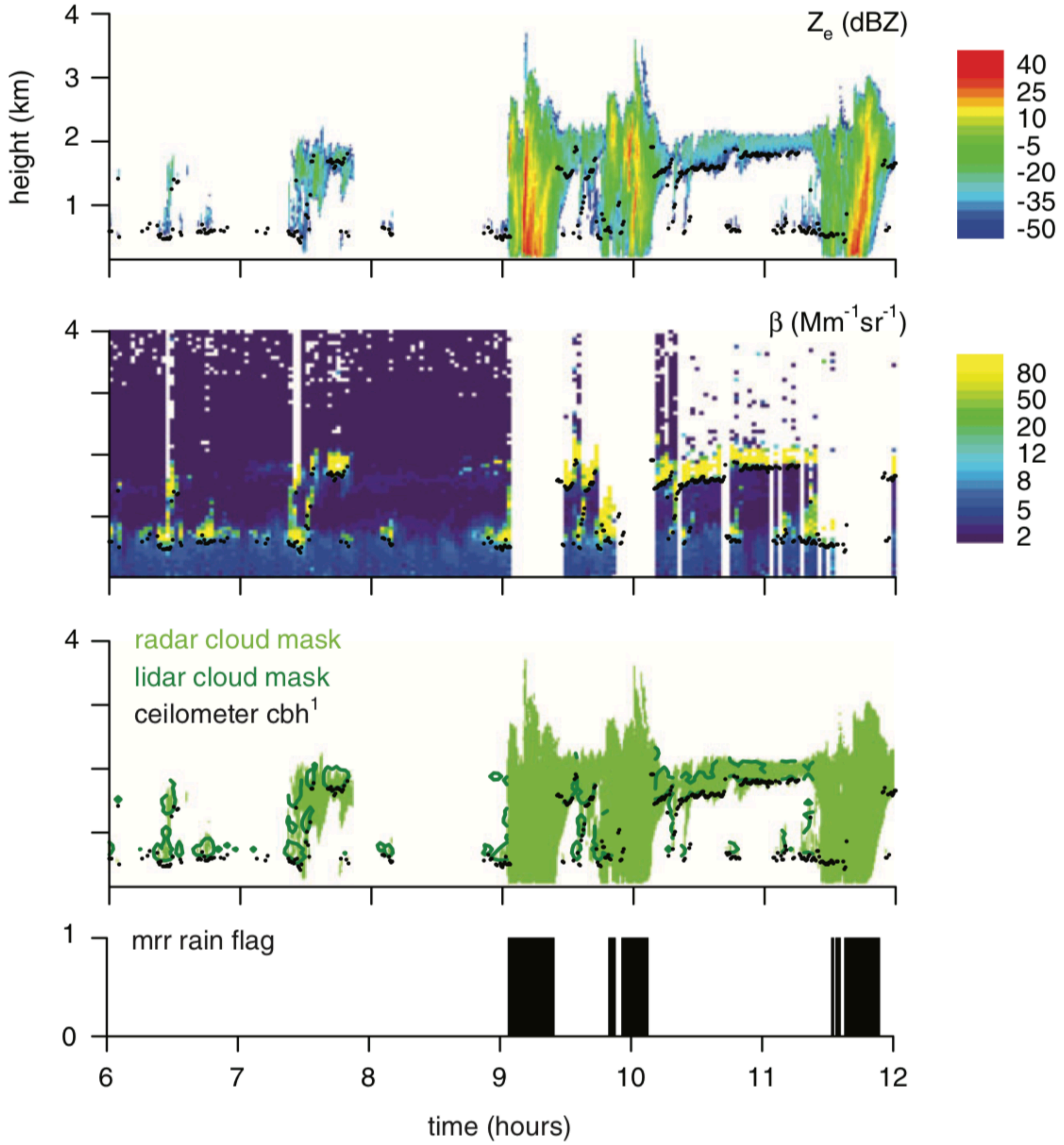
Analysis by C. Klinger, F. Jakub (B. Mayer lab, LMU)

Fields of shallow cumulus over Barbados



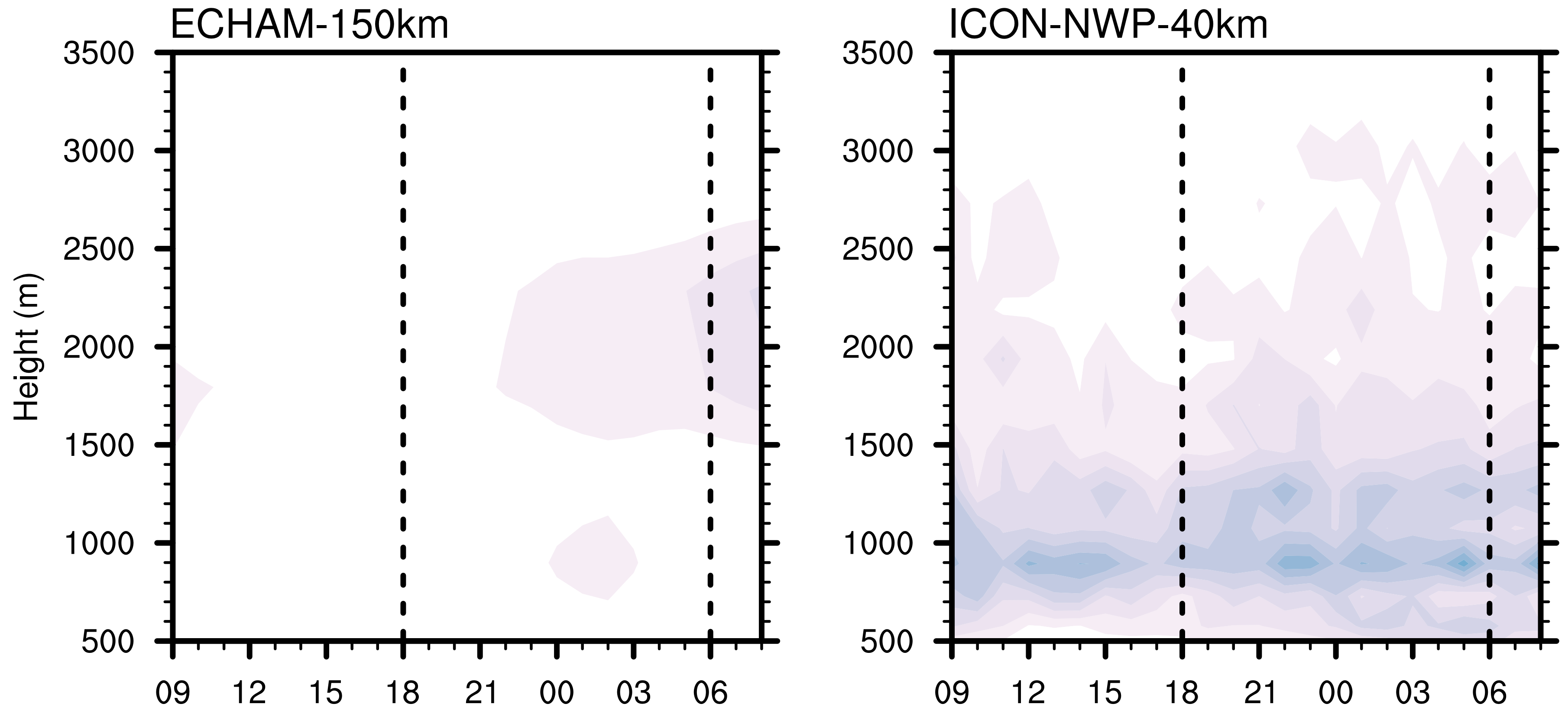






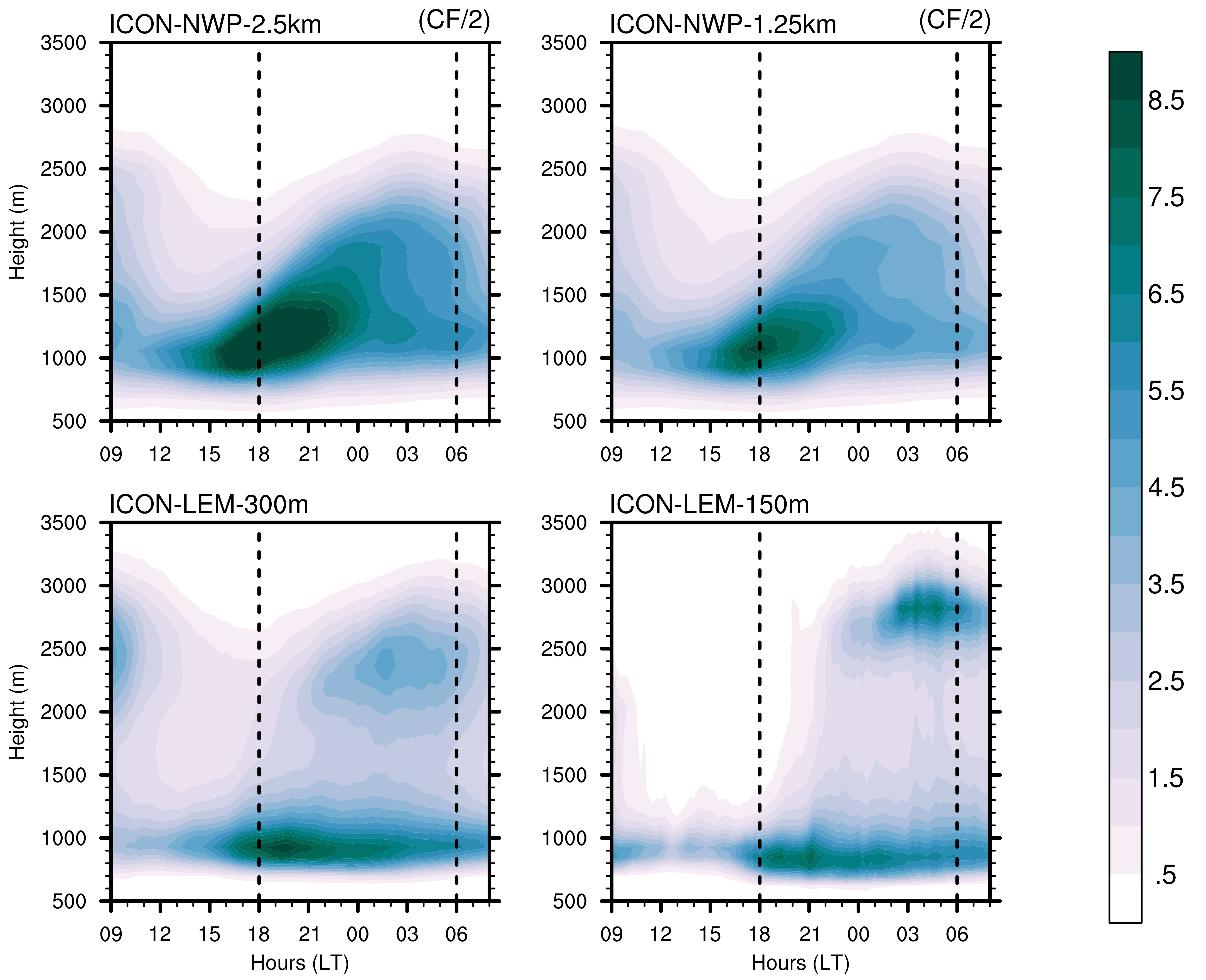
Nuijens et al., Q. J. Roy. Meteor. Soc.(2014)

As seen in simulations



Parameterized Convection

Storm Resolving Model (Δx = 2.5 km)



Large Eddy Model (Δx = O(100 m))

Analysis by Jessica Vial

How well does detailed microphysics constrain simulations?

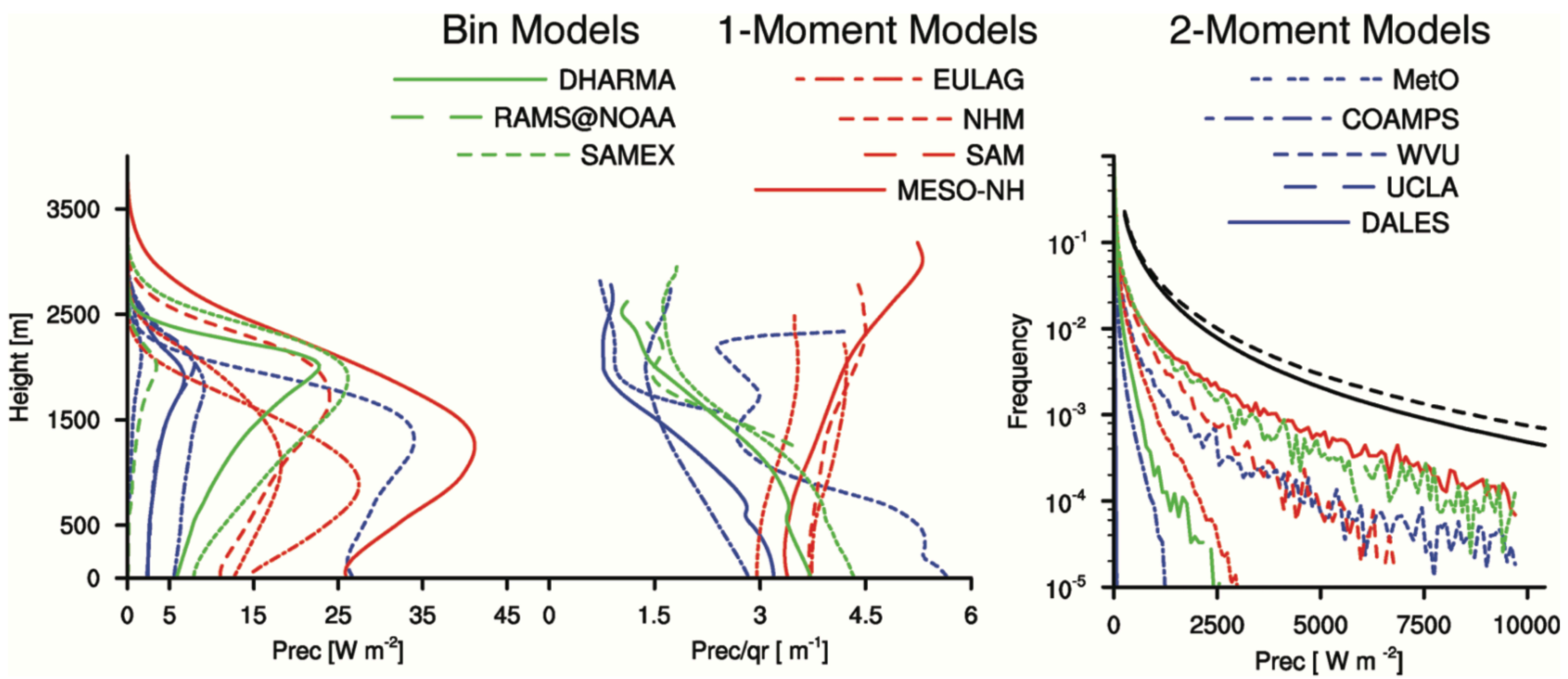


Figure 6. Precipitation flux profile (upper-left); 'bulk' fall velocity (upper-right); histograms of surface rain rates as a function of intensity (for last hour only, bottom right). In the rain-rate histograms the black lines denote the SPol data converted using either the TRMM (solid) or RICO (dashed) reflectivity vs rain-rate relationship. Lines are otherwise colored following the degrees of freedom available for the microphysical scheme, green for bin, blue for two moment and red for one moment schemes (note because of an output diagnostic problem the UCLA-LES is not included in the 'bulk' fall velocity plot).

… unlike the case for improved representations of the fluid dynamics, improved microphysics shows less evidence of convergence to a single solution.

vanZanten et al., *J. Adv. Model. Earth Syst.* (2011)

A new quality of model with each leap

Each leap is an enormous challenge, solves a fundamental problem, and focuses intellectual effort where it can be most effective.

Concluding Remarks

- There are many flavors of climate models.
- We are on the cusp of a major leap in our ability to link the behavior of the climate to basic physical principles.
- This transformation will solve some, but not all, important problems. The ones it does not solve are the ones we should be focusing on.
- Present day 'sophisticated' and 'comprehensive' climate models will still play an important role in our science, but loose a bit of their authority and no longer need be applied to problems for which they are poorly suited.