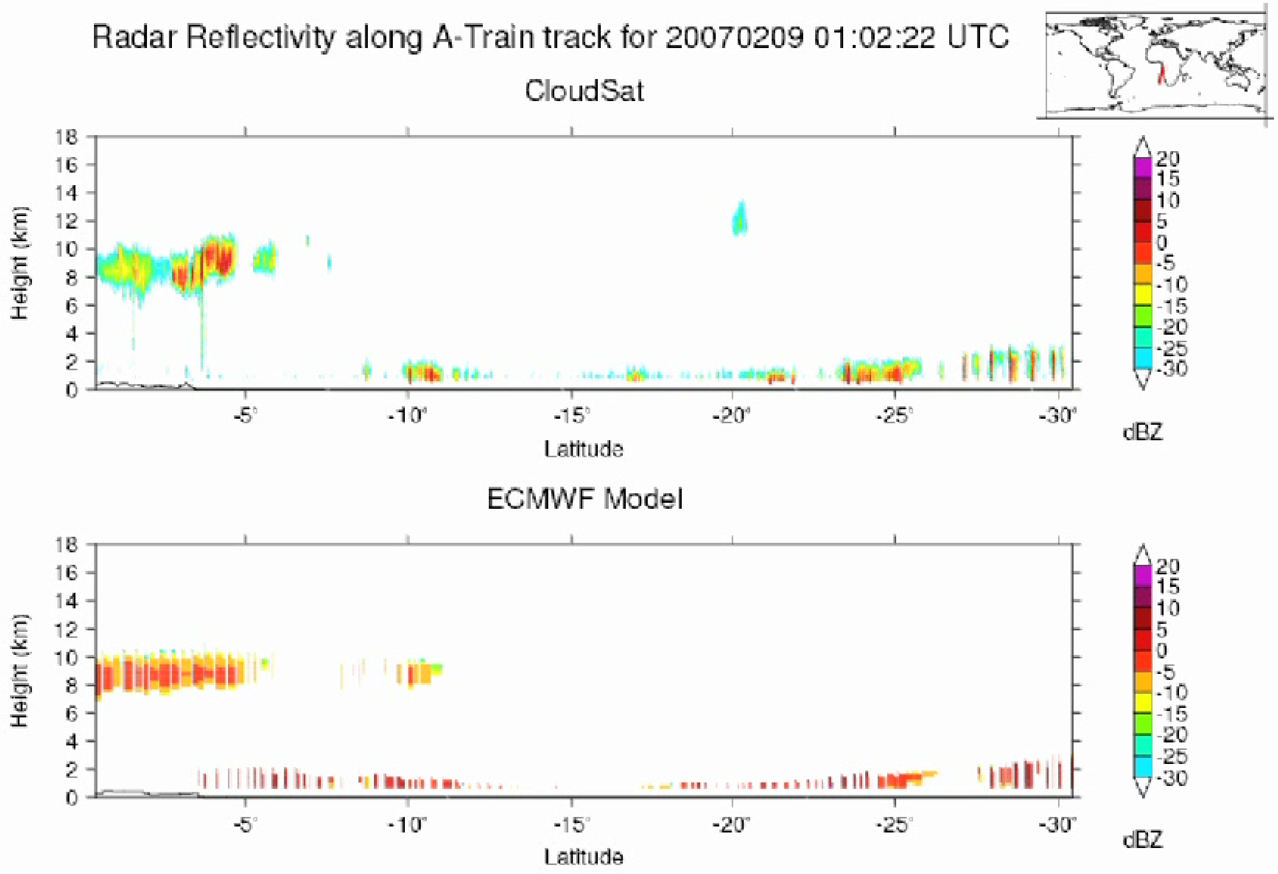
Diagnosing Model Systematic Error for Clouds and Precipitation

Richard Forbes (ECMWF)

With Thanks to Maike Ahlgrimm, Peter Bechtold, Martin Köhler and ECMWF colleagues, and Graeme Stephens (CSU), Julien Delanoë (Univ. Reading)

ECMWF Annual Seminar, Sep 2009

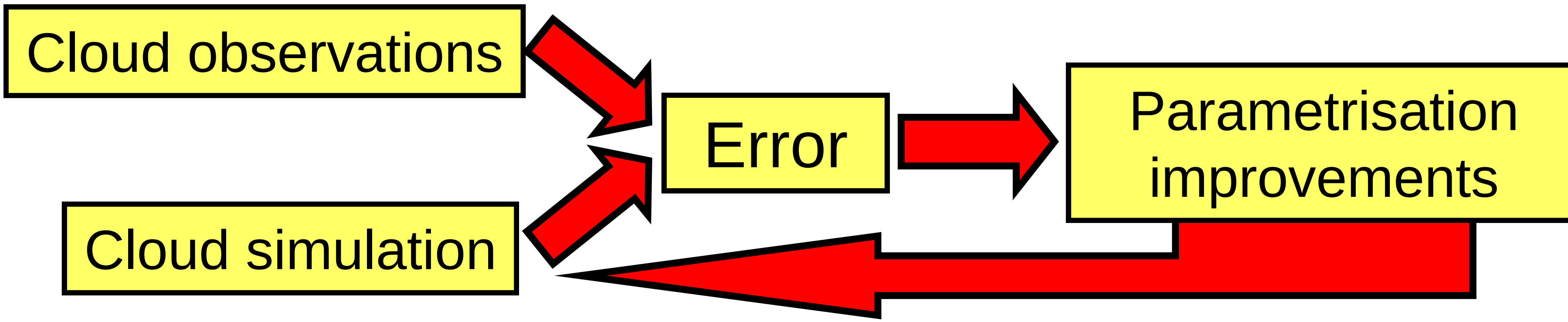
Diagnosing Model Systematic Error for Clouds and Precipitation



Richard Forbes (ECMWF)

With Thanks to Maike Ahlgrimm and ECMWF colleagues, Robin Hogan and Julien Delanoë (Univ. Reading), Graeme Stephens (CSU)

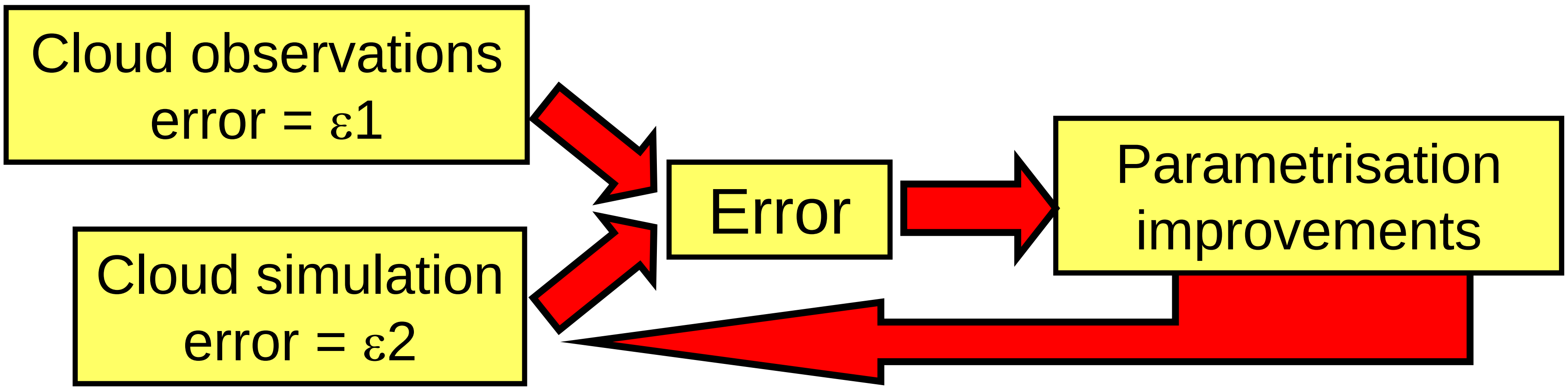
Cloud Validation: The issues



Sounds easy…..

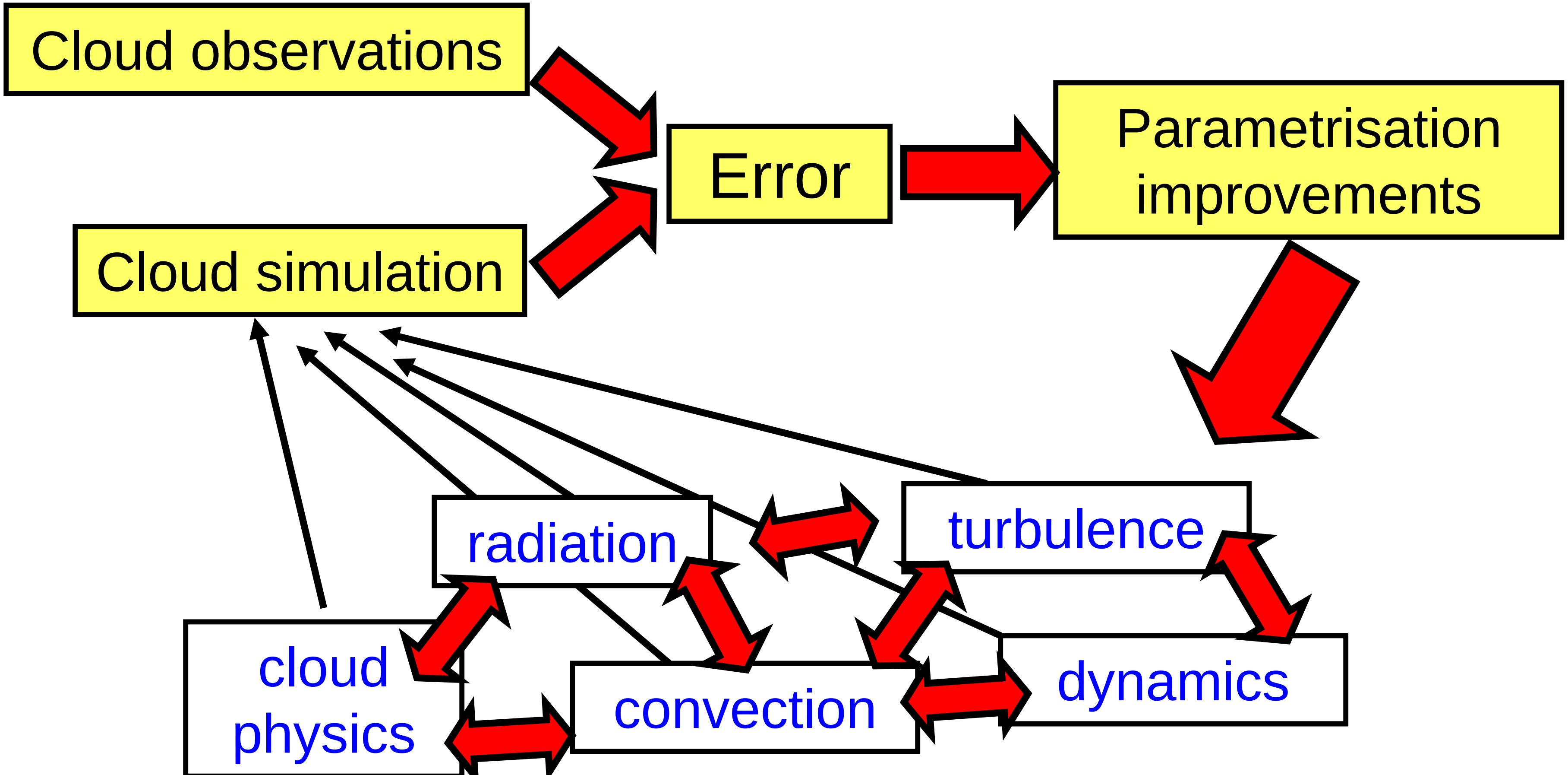
Cloud Validation: The problems

- How much of the 'error' derives from observations?

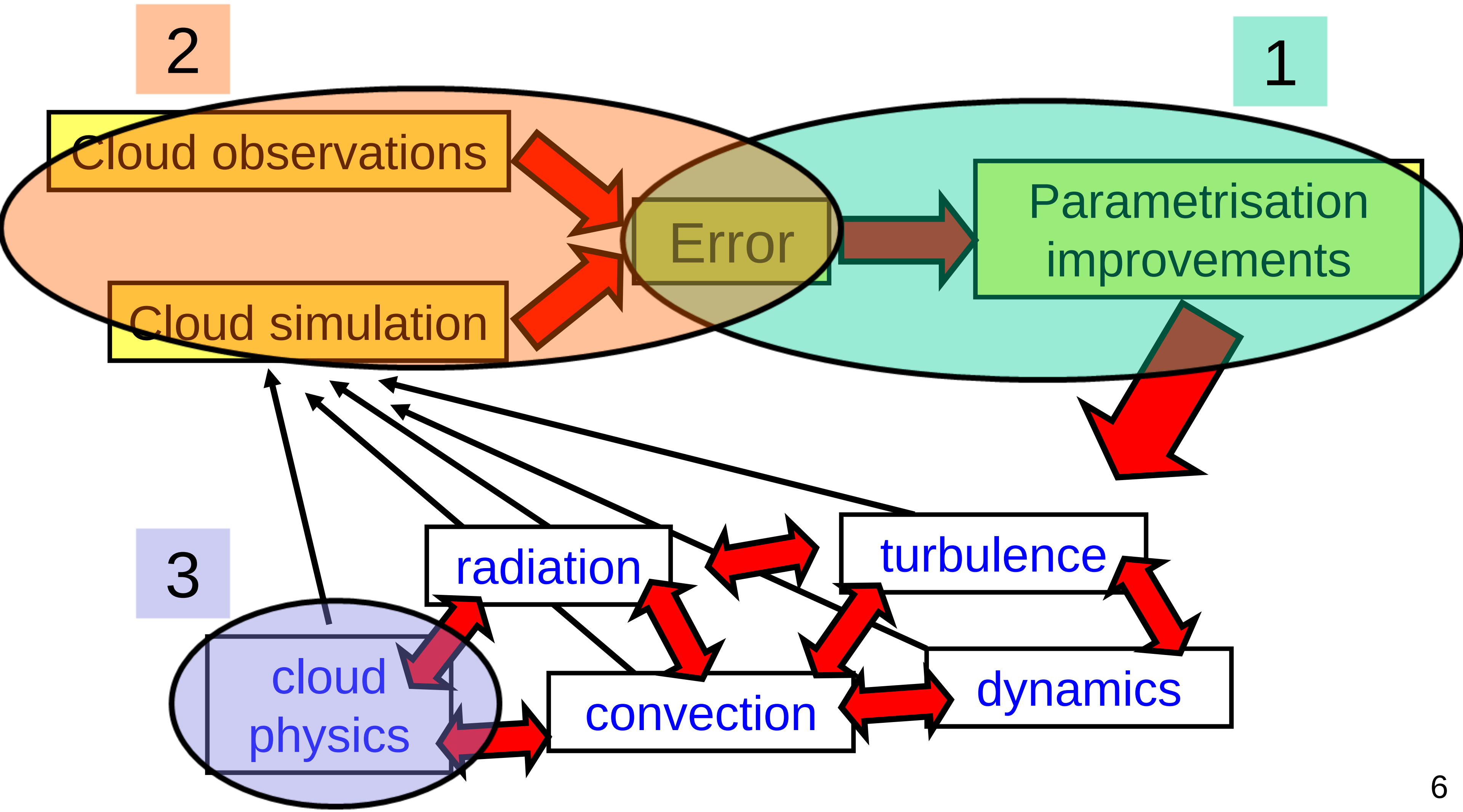


Cloud Validation: The problems

- Which Physics is responsible for the error?

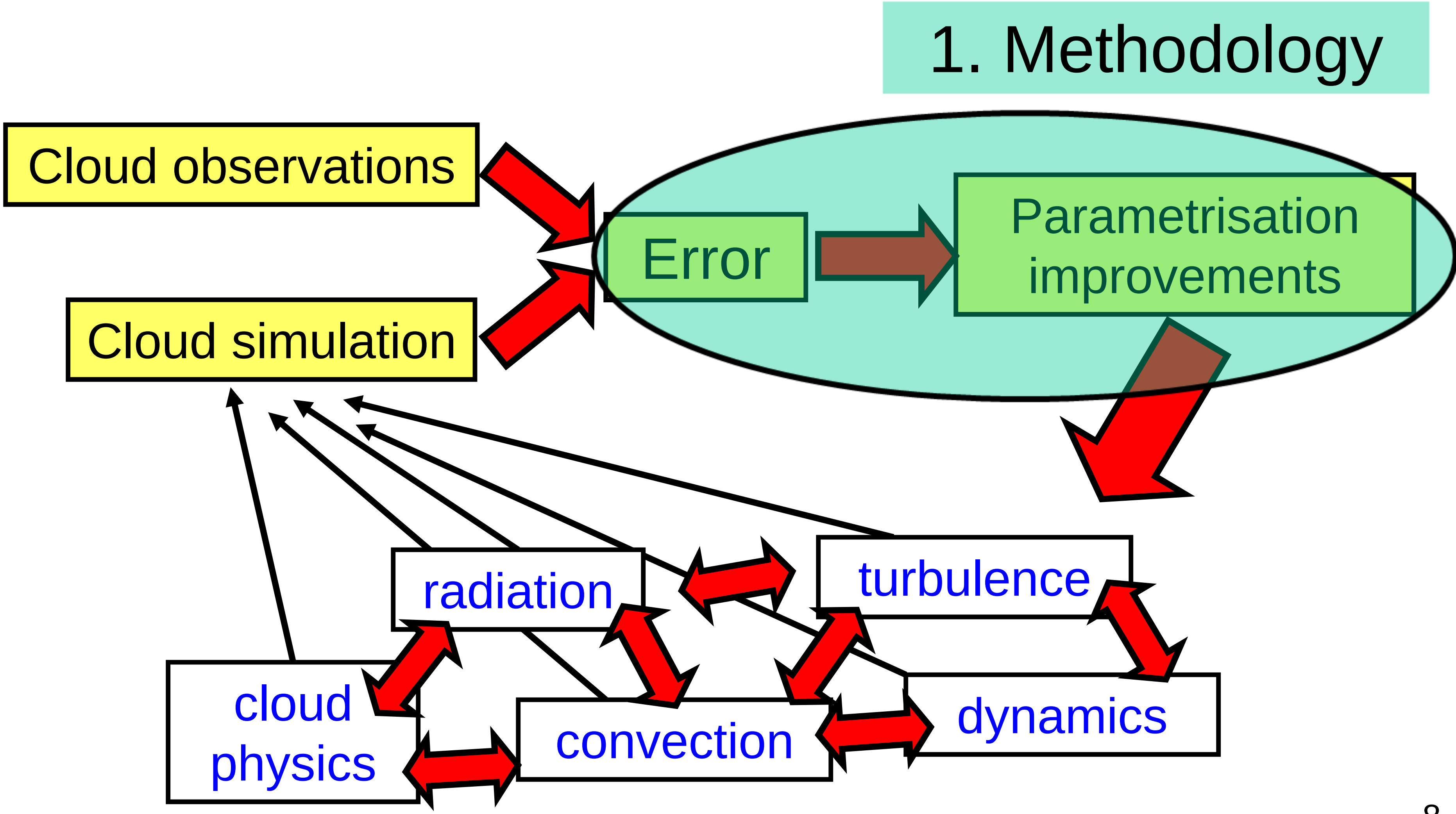


Cloud Validation: The problems

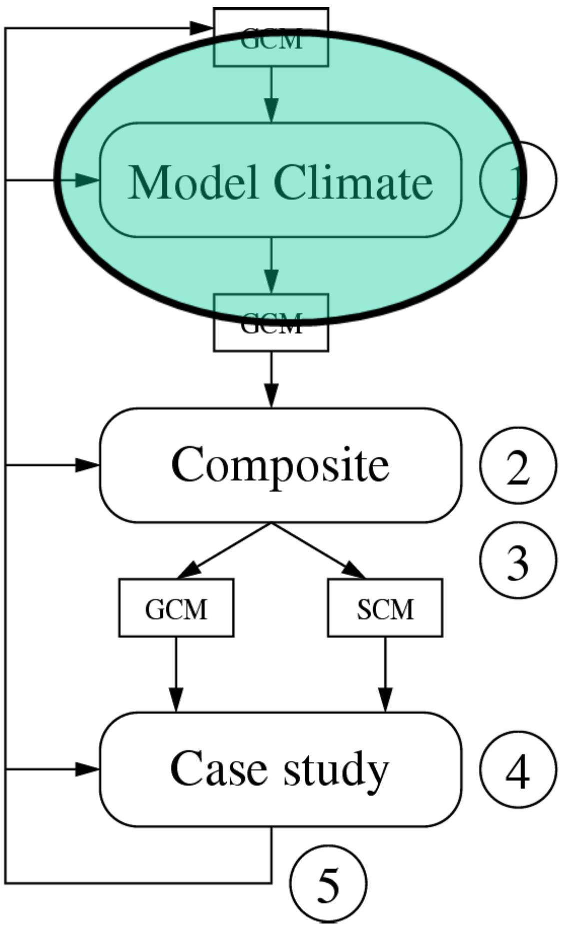


1. Methodology for diagnosing errors and improving parametrizations

Cloud Validation: The problems



A strategy for cloud parametrization evaluation



Step 1 : identify major problem areas

Step 2 : identify major problem regimes

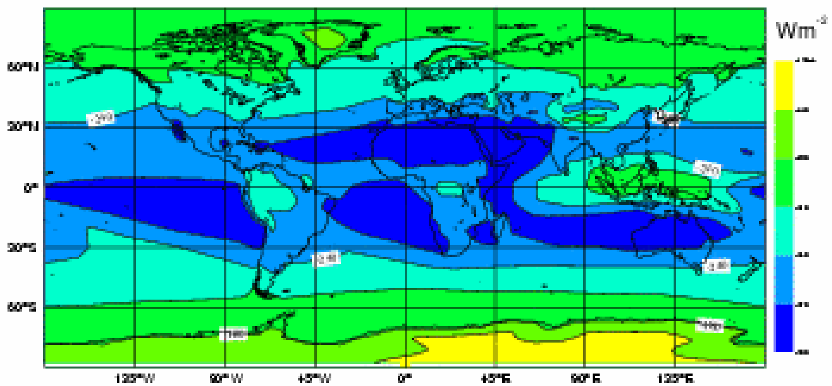
Step 3 : identify typical case

Step 4 : identify detailed problems

Step 5 : improve parametrization

C.Jakob

TOA lw ezzn Sep 2000 nmon=12 nens=4 Global Mean: -241 50S-50N Mean: -253

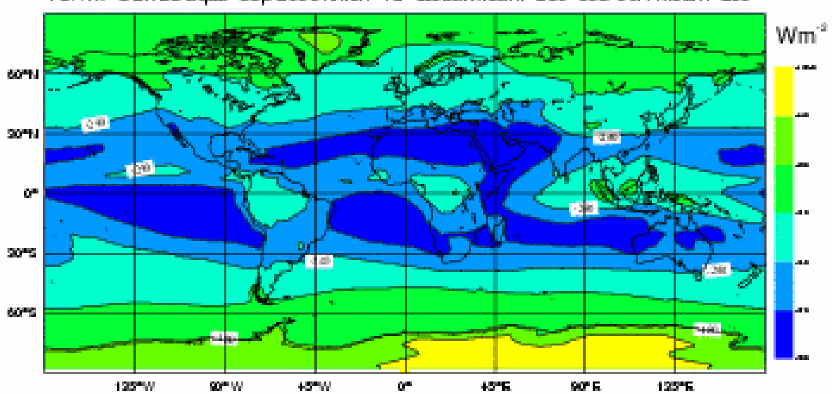


-150

-300

Model
T159
L91

TOA lw CERES aqua Sep 2000 nmon=12 Global Mean: -239 50S-50N Mean: -250



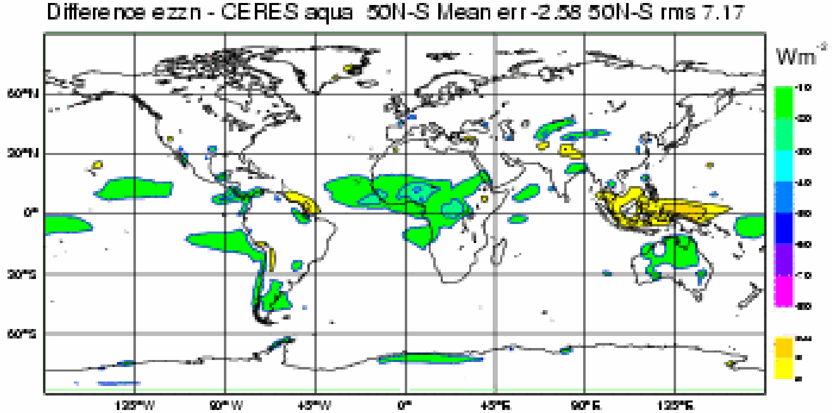
-150

-300

CERES

Top-of-atmos net LW radiation

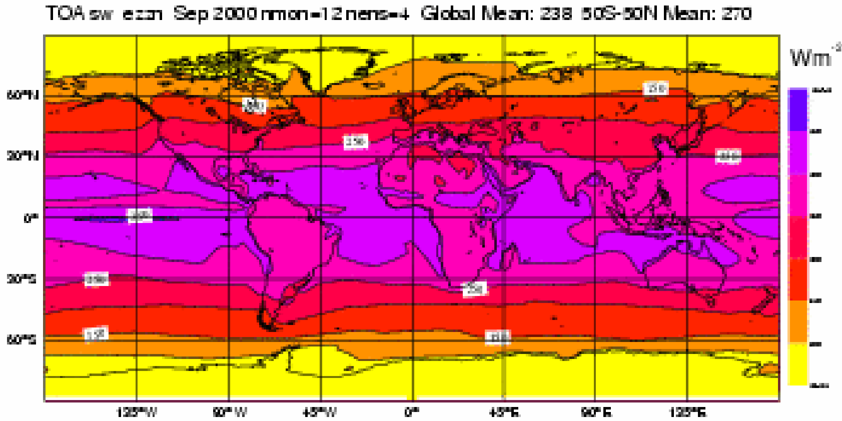
Difference ezzn - CERES aqua 50N-S Mean err -2.58 50N-S rms 7.17



too high

too low

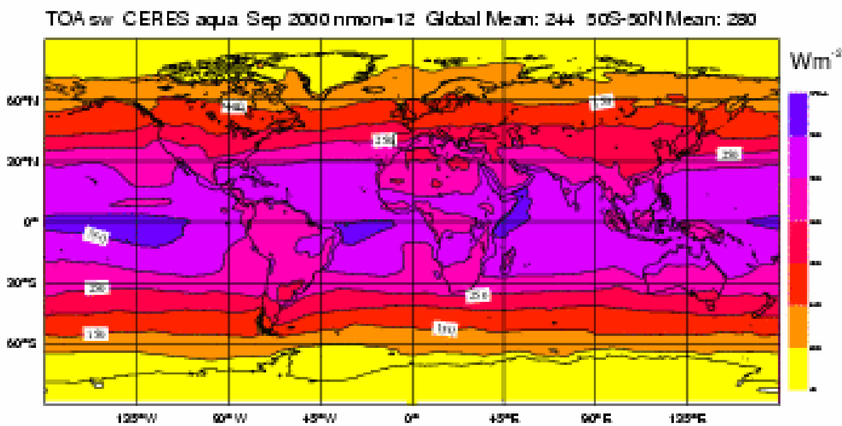
Difference



350

100

Model
T159
L91

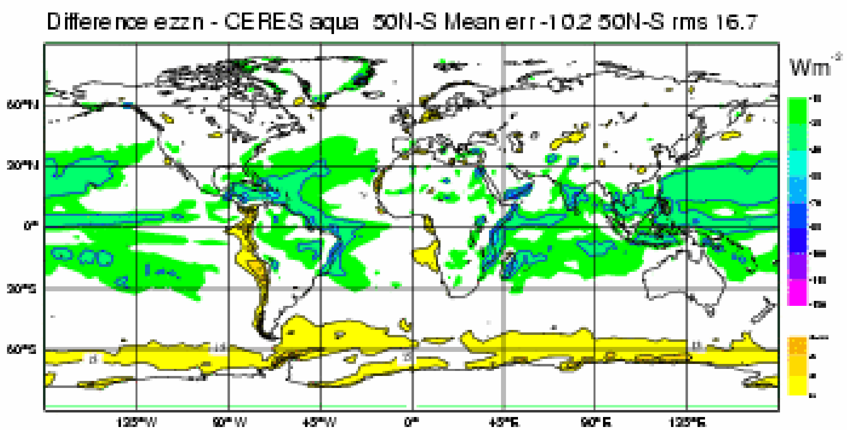


350

100

CERES

Top-of-atmos
net SW
radiation

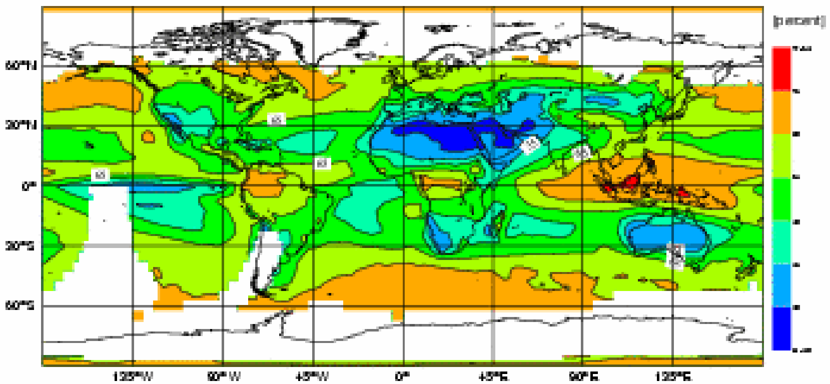


albedo
high

Difference

albedo low

Total Cloud Cover ezzn Sep 2000 nmon=12 nens=4 Global Mean: 63.1 50N-S Mean: 61.1

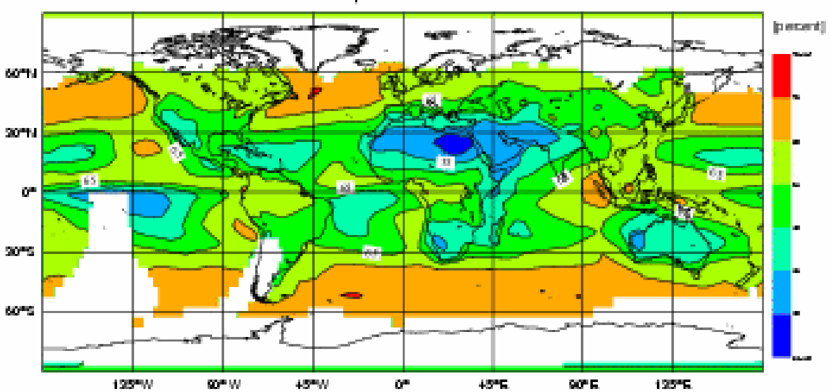


80

10

Model
T159
L91

Total Cloud Cover ISCCP Sep 2000 nmon=12 50N-S Mean: 62.2



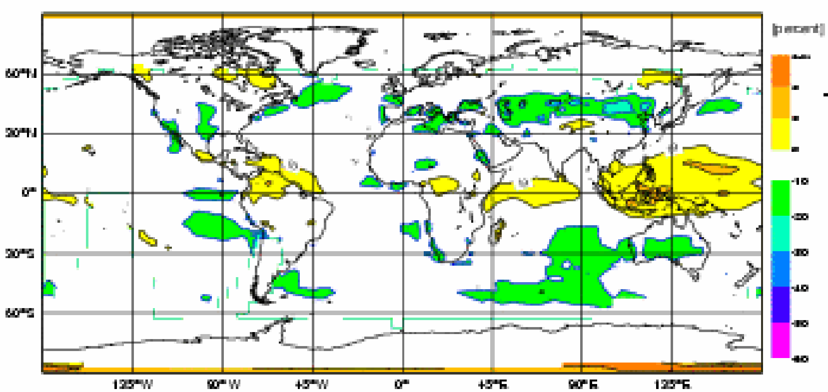
80

10

ISCCP

Total Cloud Cover (TCC)

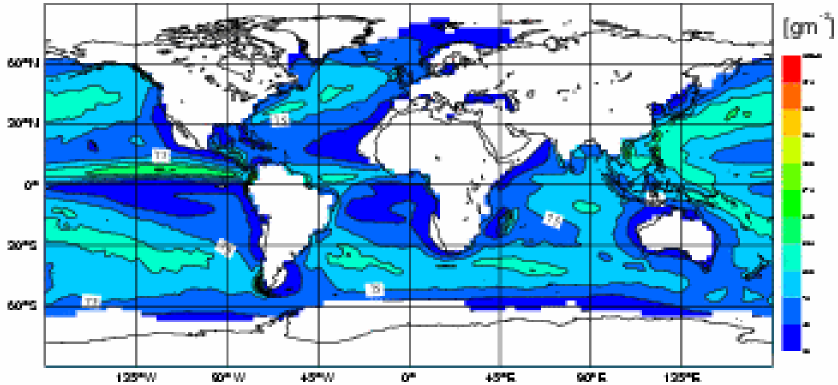
Difference ezzn - ISCCP 50N-S Mean err -1.1 50N-S rms 8.5



TCC high

TCC low

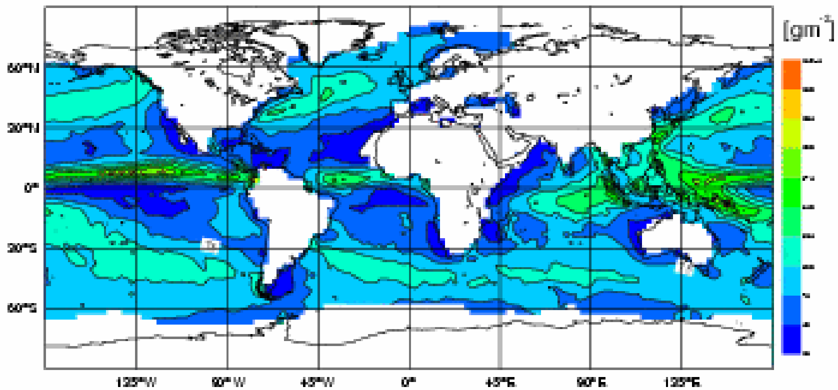
Difference



250

25

Model
T159
L91

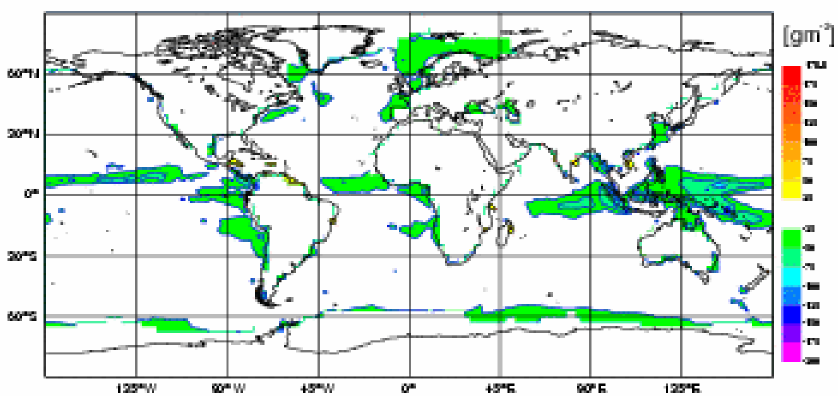


250

25

SSMI

Total Column Liquid Water (TCLW)



high

low

Difference

ECMWF Model Configurations

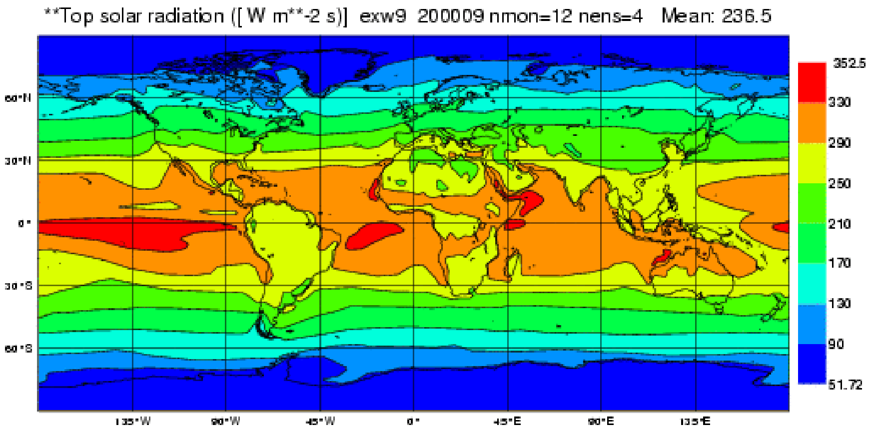
- ECMWF Global Atmospheric Model (IFS)
  - T159 (125km) Monthly and Seasonal Prediction, (+Model Testing)
  - T399 (50km) Ensemble Prediction System (EPS)
  - T511 (40km) Previous NWP
  - T799 (25km) Current Deterministic Global NWP 10 day f/c
  - T1279 (16km) NWP (soon!)
  - 62 and 91 levels in use
- Need a model with a “climate” that is robust to resolution.

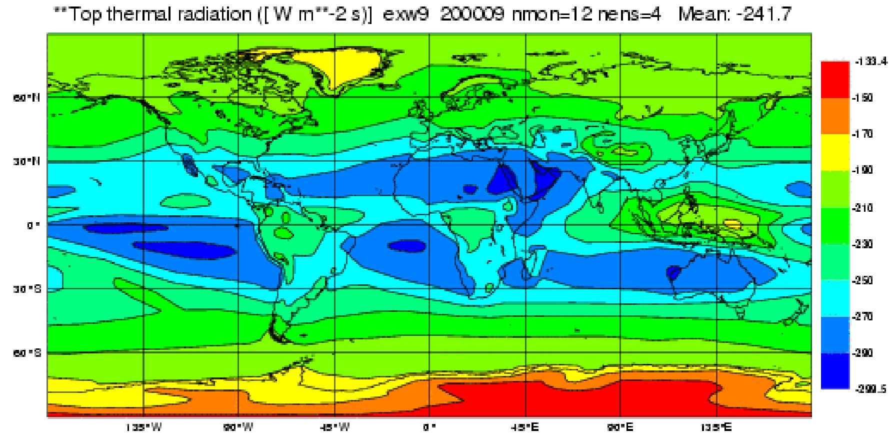
Clouds, Precipitation and Model Resolution

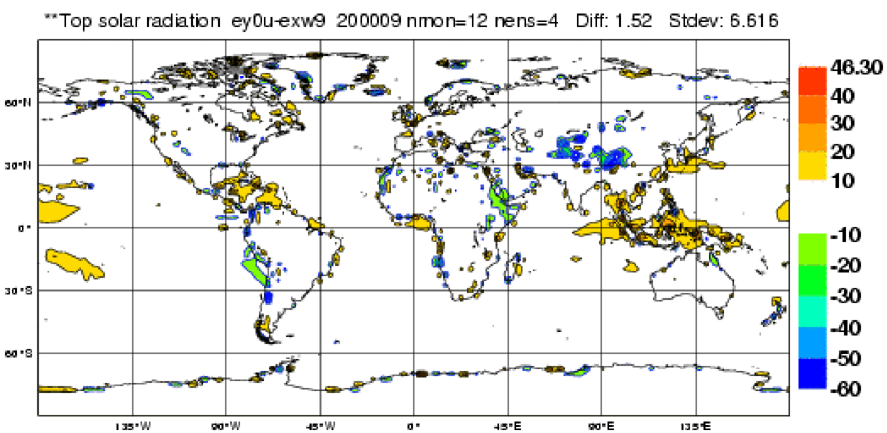
1. Choice and formulation of microphysical processes
   - As resolution increases, the range of scales of dynamical forcing increases. Non-linear microphysical processes can respond differently.
   - Parametrization schemes are based on time/space scale separation. As resolution increases, require change from diagnostic to prognostic variables.
2. Representation of sub-gridscale inhomogeneities
3. Numerical techniques for efficient implementation
   - Long timesteps used for computational efficiency.
   - Explicit vs implicit formulations.

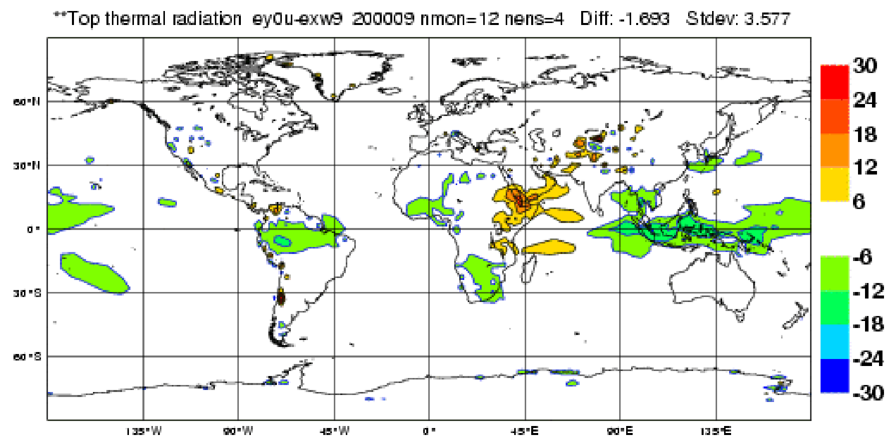
TOA Net Radiation (T511 vs T159)

Diagnosing Cloud Error, Forbes
ECMWF Seminar 2009







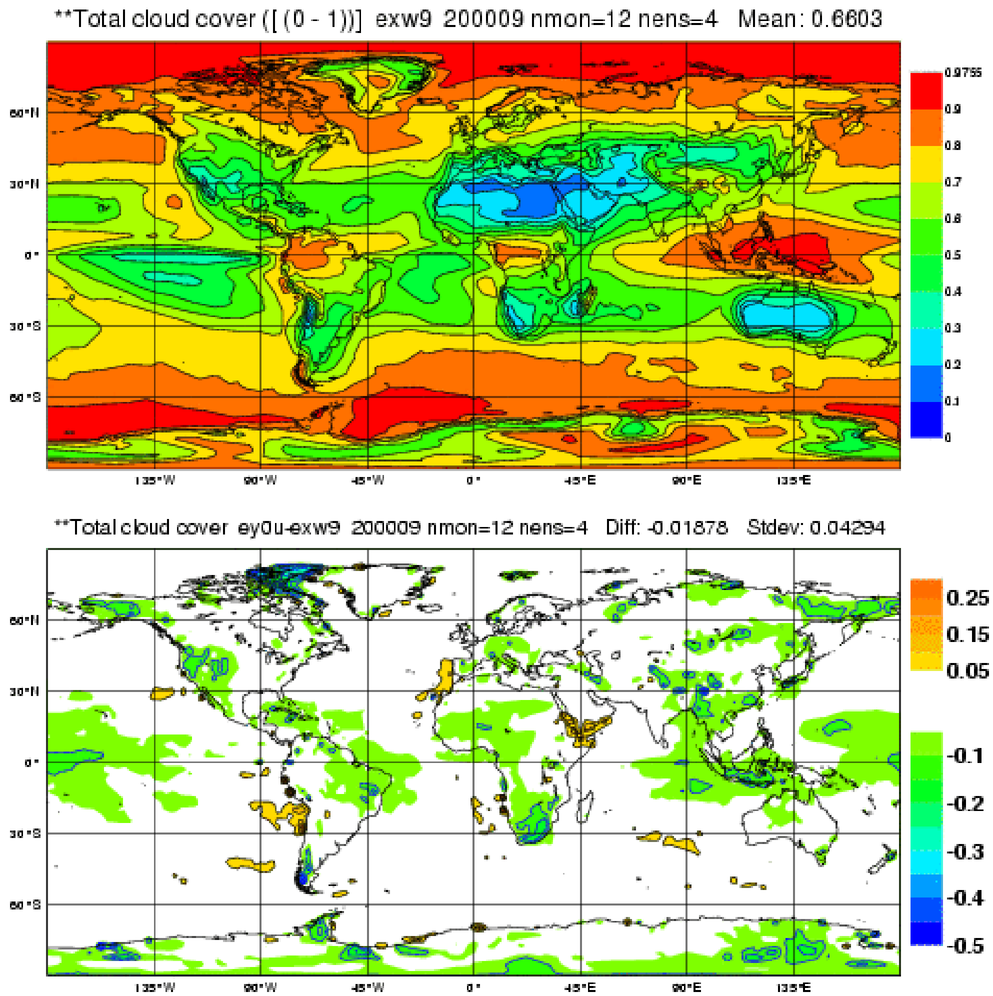


TOA Net SW

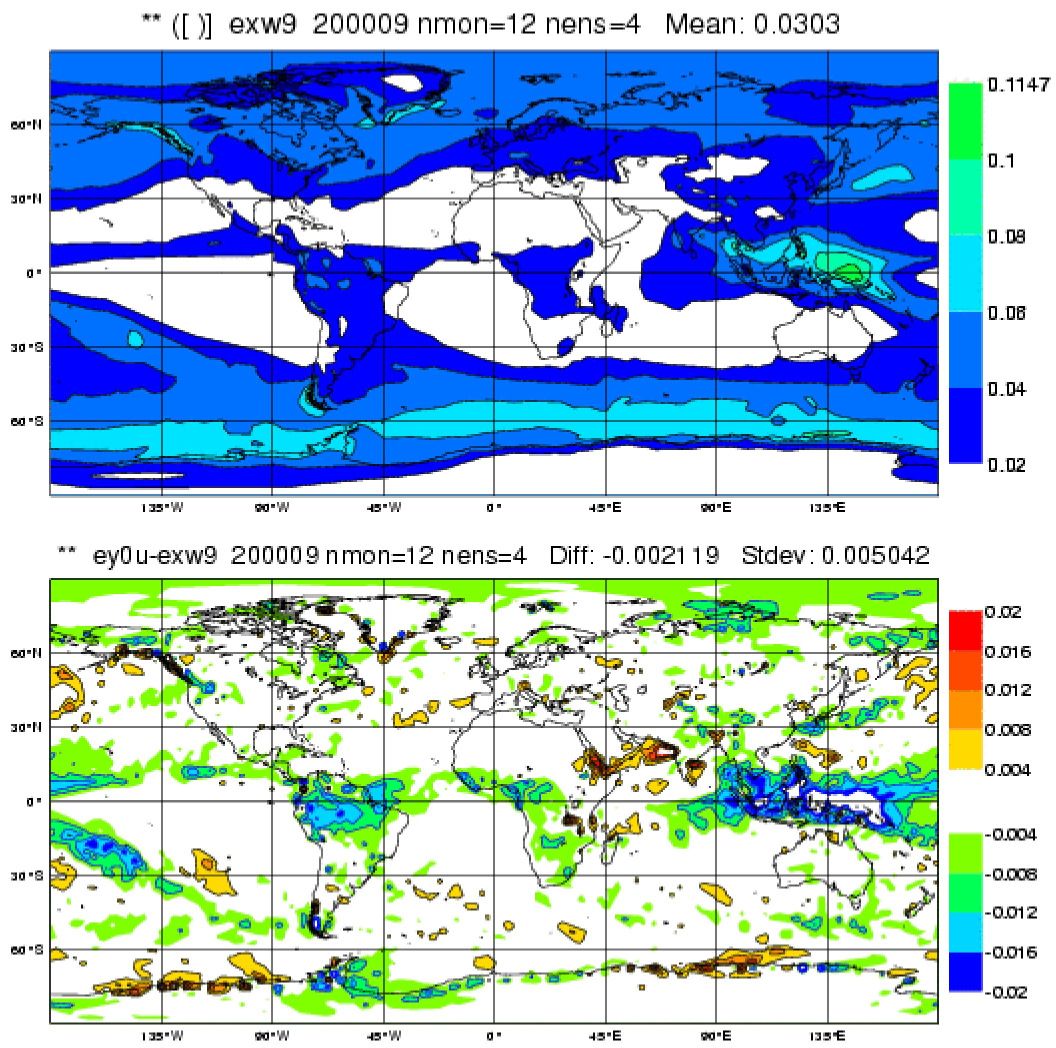
TOA Net LW

Sensitivity to resolution
Total Cloud Cover (T511 - T159)

Diagnosing Cloud Error, Forbes
ECMWF Seminar 2009



Sensitivity to resolution
Ice Water Content (T511 - T159)



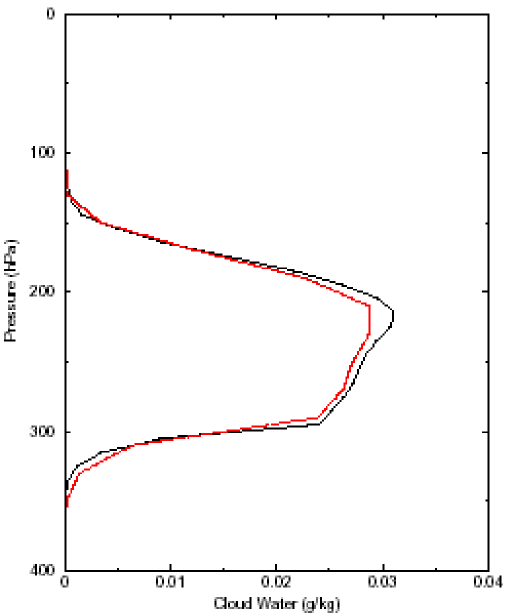
Vertical resolution sensitivity

Ice Sedimentation

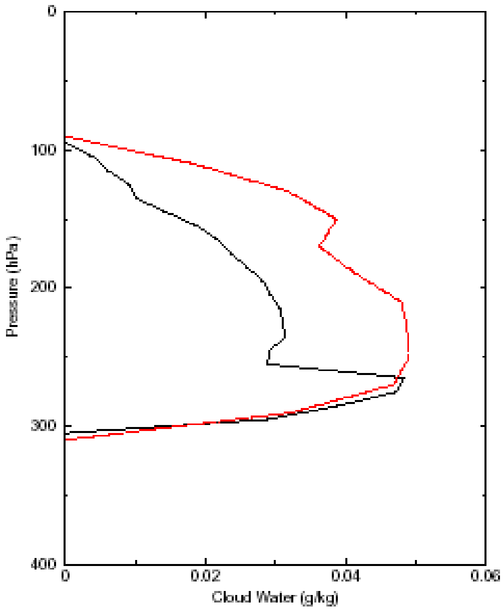
100 vs 50
layer resolution

- Forward-in-time upstream implicit solver.
- Small sensitivity to vertical resolution / timestep.

30r2 Scheme



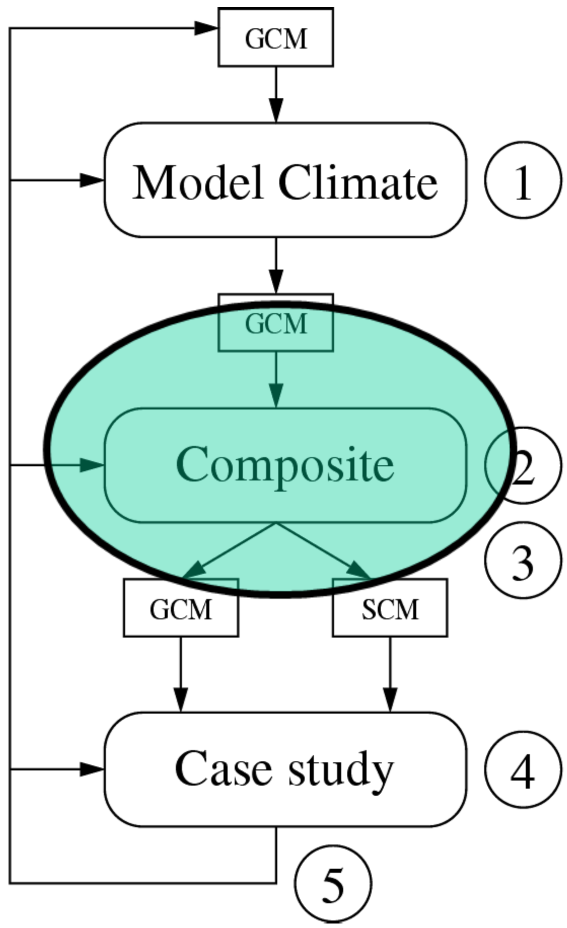
29r1 Scheme



- At earlier cycles, the problem was **much** worse.
- Caused by the “exact” solver of Tiedtke in combination with ice sedimentation acting as a proxy for autoconversion if ice fell into clear sky.

Adrian Tompkins

A strategy for cloud parametrization evaluation



Step 1 : identify major problem areas

Step 2 : identify major problem regimes

Step 3 : identify typical case

Step 4 : identify detailed problems

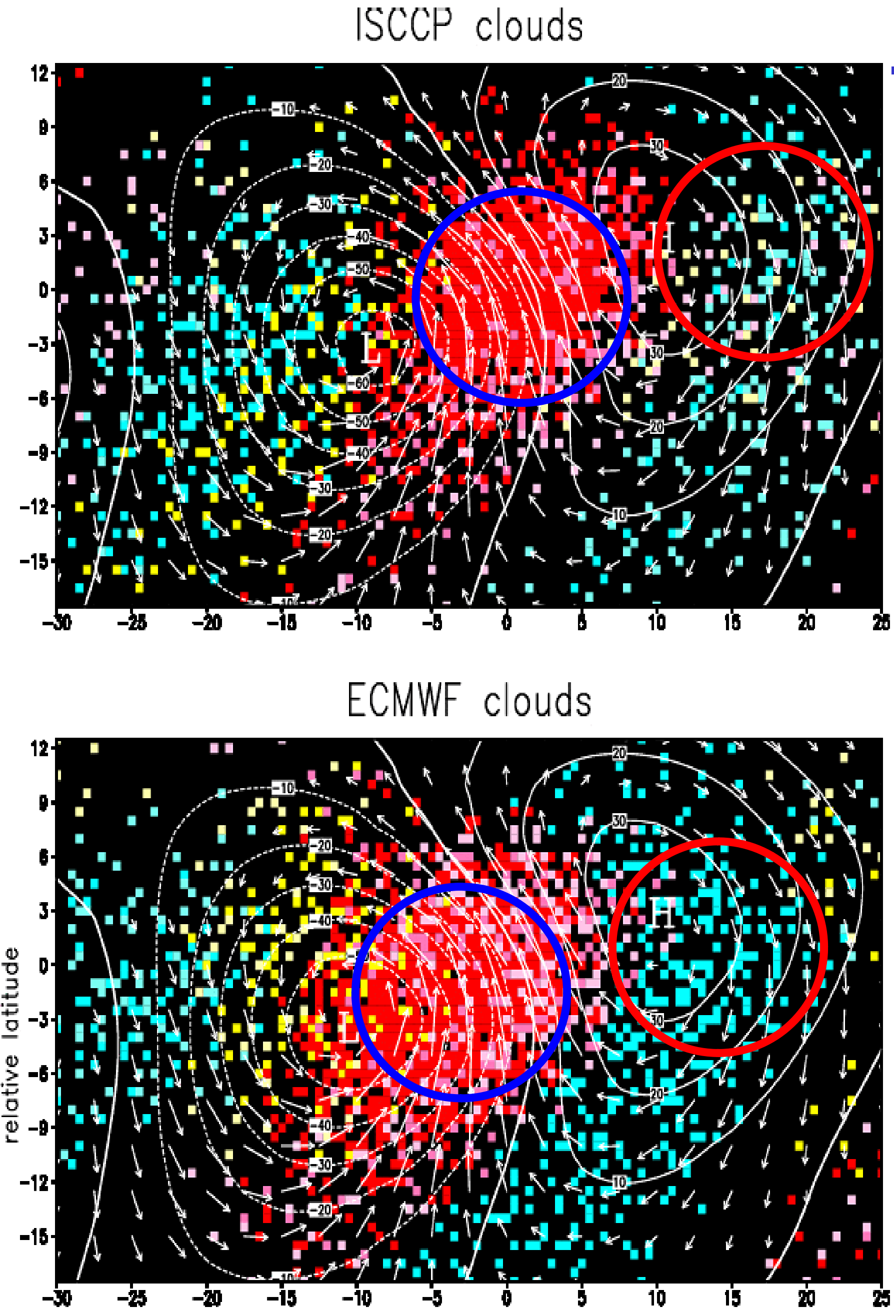
Step 5 : improve parametrization

C.Jakob

Isolating the source of error

- We want to isolate the sources of error. Focus on particular phenomena/regimes, e.g.
  - Extra tropical cyclones
  - Stratocumulus regions
- An individual case may not be conclusive: Is it typical?
- On the other hand general statistics may swamp this kind of system
- Can use compositing technique (extra-tropical cyclones)
- Focus on distinct regimes if can isolate (SCu, Trade Cumulus)

Composites – Extra-tropical cyclones



Overlay about 1000 cyclones, defined about a location of maximum optical thickness

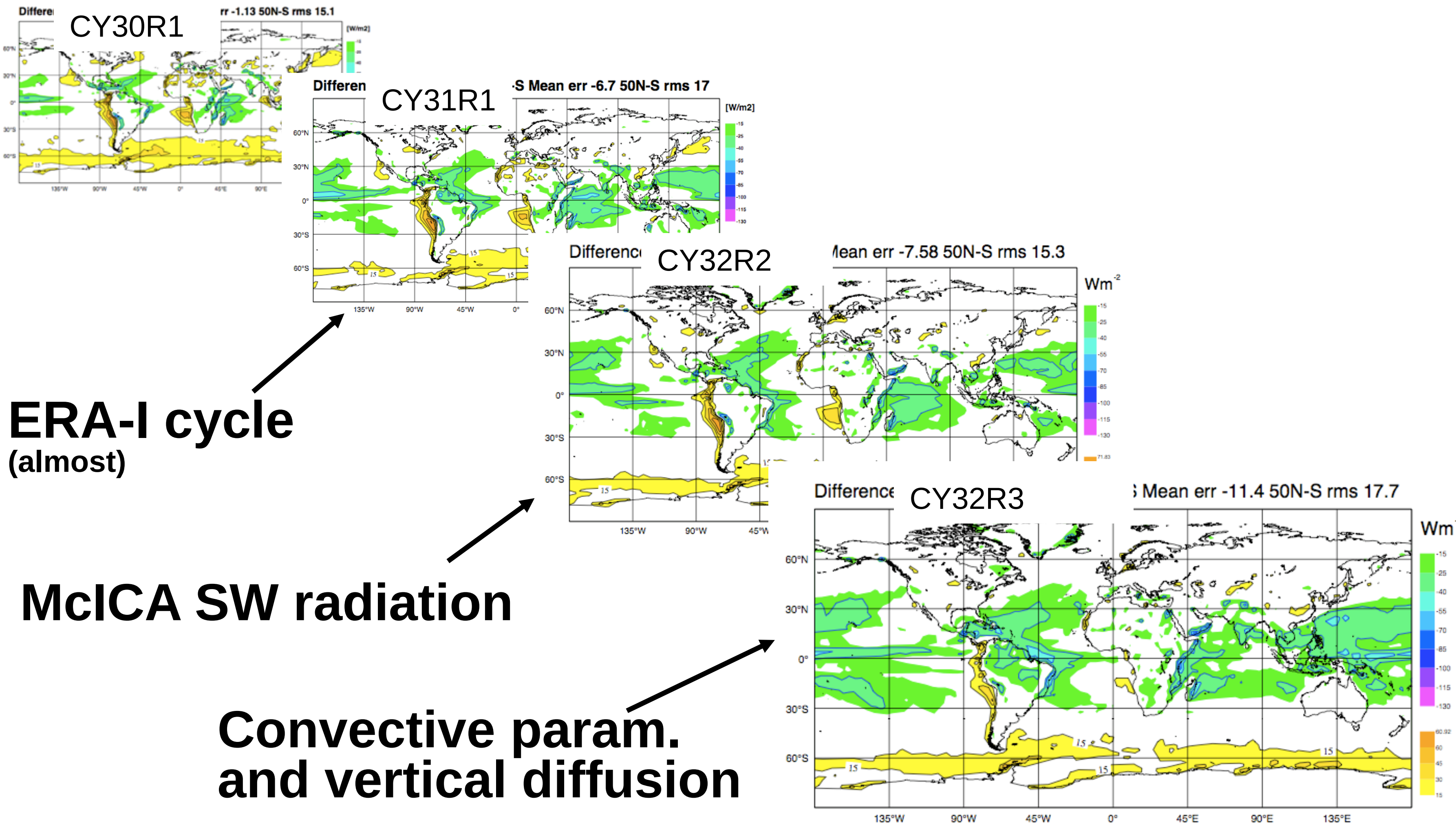
Plot predominant cloud types by looking at anomalies from 5-day average

- High Clouds too thin
- Low clouds too thick

High tops=Red, Mid tops=Yellow, Low tops=Blue

Klein and Jakob, 1999, MWR

Model Climate: Regime dependent error?



TOA net SW radiation vs. CERES:
Too much reflectance from TCu, not enough from Sc

Maike Ahlgrimm

Does the model have "correct" trade cumulus cloudiness?

Three aspects:

Cloud amount when present (AWP)

helps identify cloud type

Cloud frequency of occurrence (FOO)

with AWP gives total cloud cover

Radiative properties

radiative balance ultimately drives the system

Maike Ahlgrimm

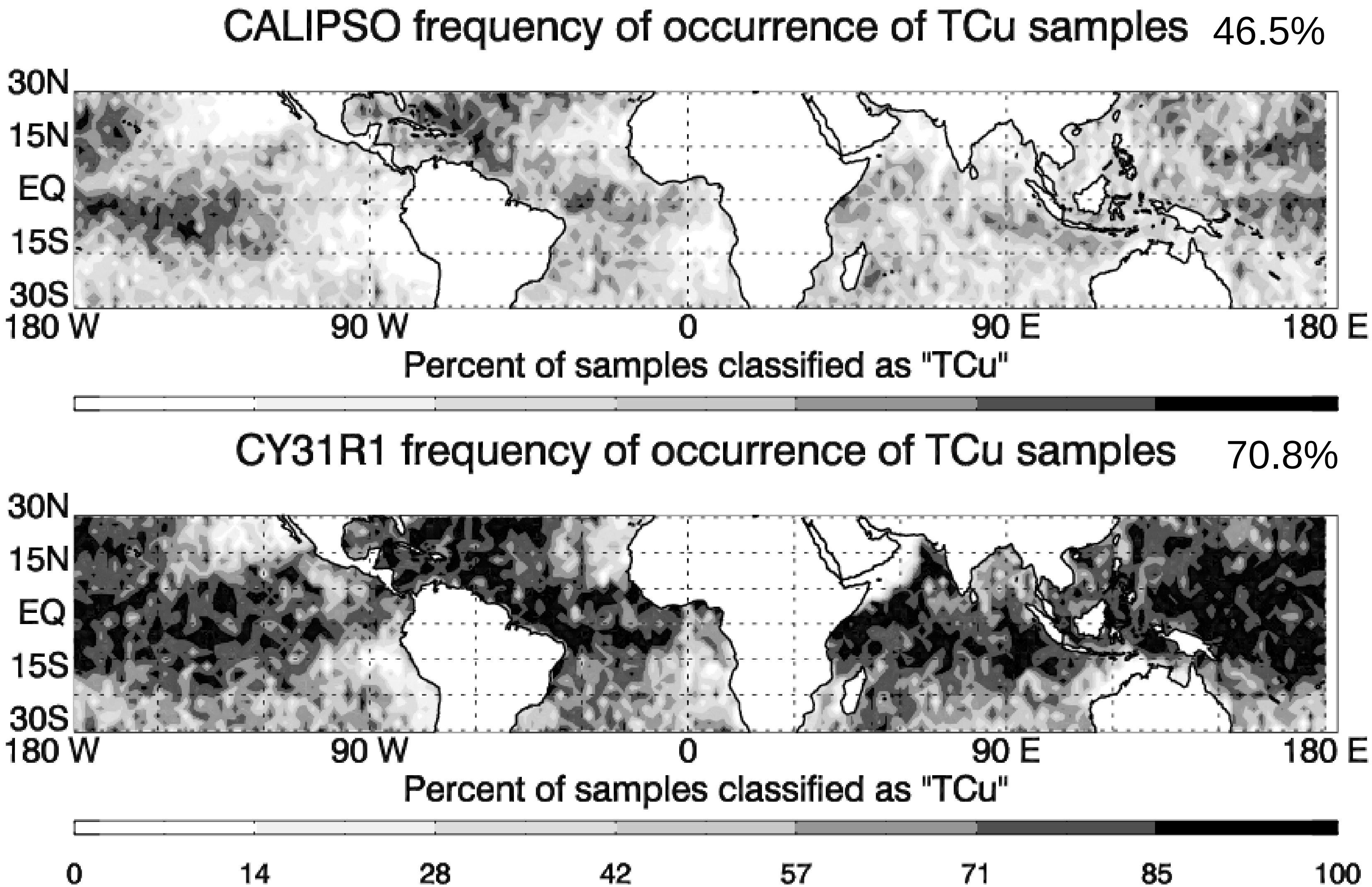
Isolating the Trade Cu Regime

Identify cloud samples as:

- with less than 50% cloud fraction
- cloud top below 4km
- over ocean
- between 30S and 30N

Maike Ahlgrimm

TCu frequency of occurrence (FOO)

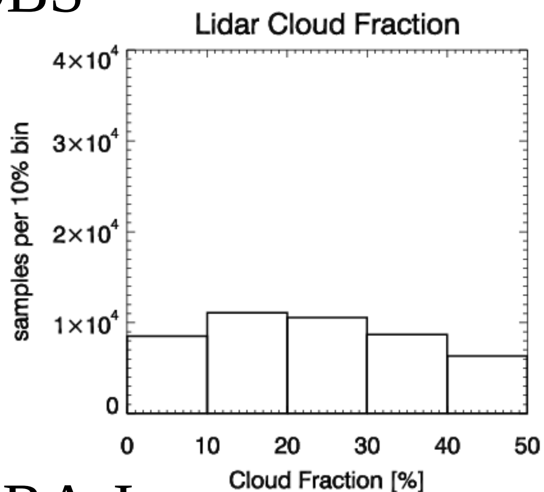


Model has TCu more frequently than observed

Maike Ahlgrimm

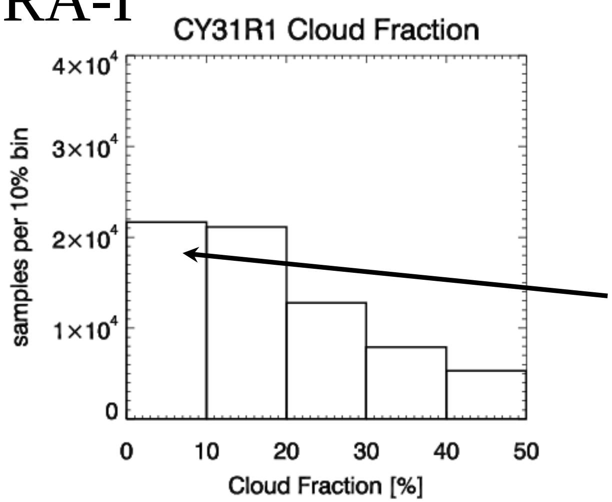
Cloud amount when present (AWP)

OBS



Cloud fraction is subject to representativity error. Observations have not been corrected!

ERA-I

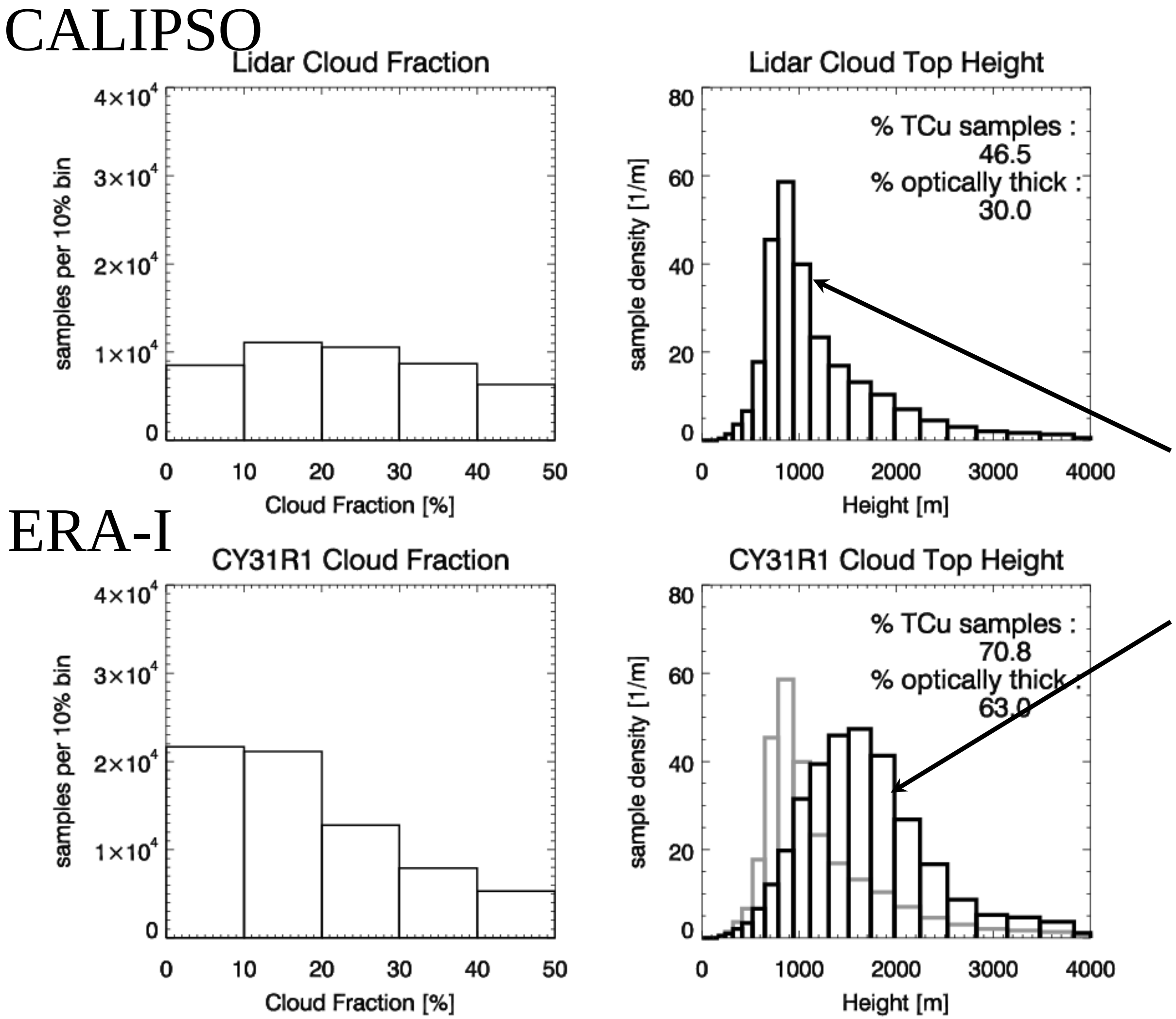


Most of the additional TCu samples have very small cloud fractions

Maike Ahlgrimm

Cloud top height

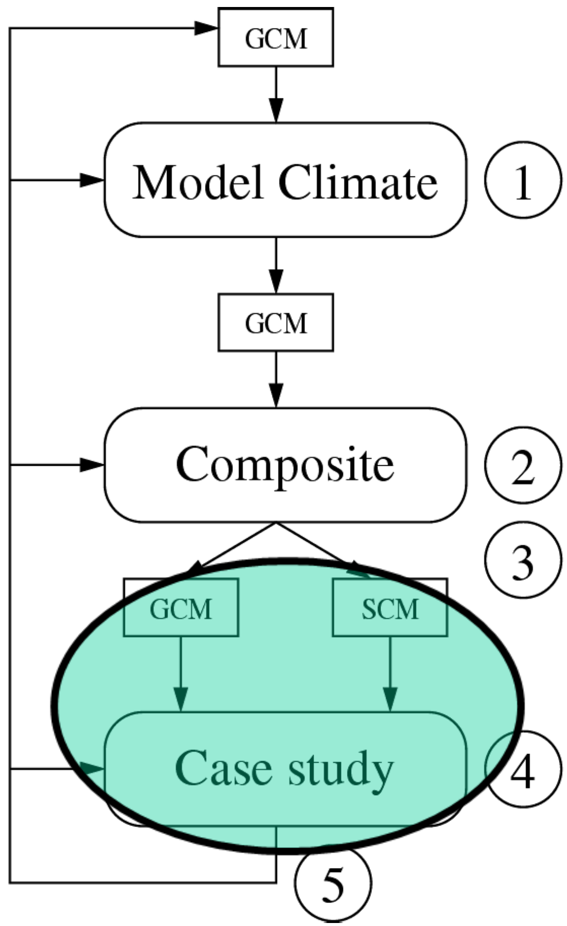
Skewed distribution with low peak: Majority of TCu clouds are very shallow, few grow deeper



Model clouds have higher cloud tops than observed

Maike Ahlgrimm

A strategy for cloud parametrization evaluation



Step 1 : identify major problem areas

Step 2 : identify major problem regimes

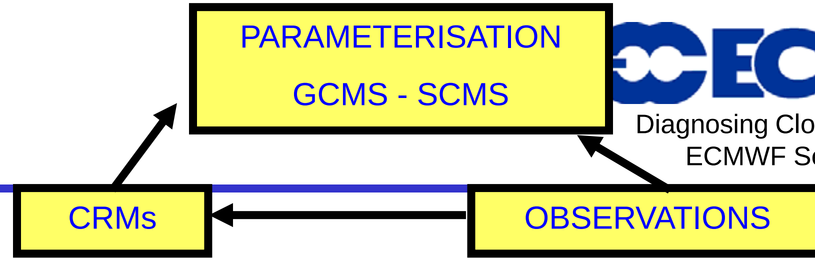
Step 3 : identify typical case

Step 4 : identify detailed problems

Step 5 : improve parametrization

C.Jakob

GCSS - GEWEX Cloud System Study



(Moncrieff et al. Bull. AMS 97)

Step 1 — Use observations to evaluate parameterizations of subgrid-scale processes in a CRM

Step 2 — Evaluate CRM results against observational datasets

Step 3 — Use CRM to simulate precipitating cloud systems forced by large-scale observations

Step 4 — Evaluate and improve SCMs by comparing to observations and CRM diagnostics

GCSS: Validation of CRMs

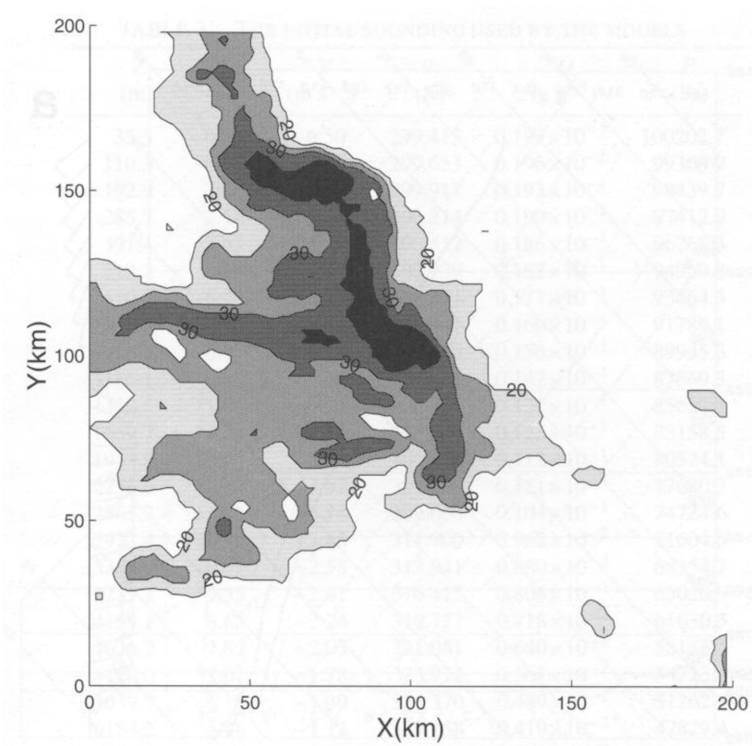
Redelsperger et al QJRMS 2000

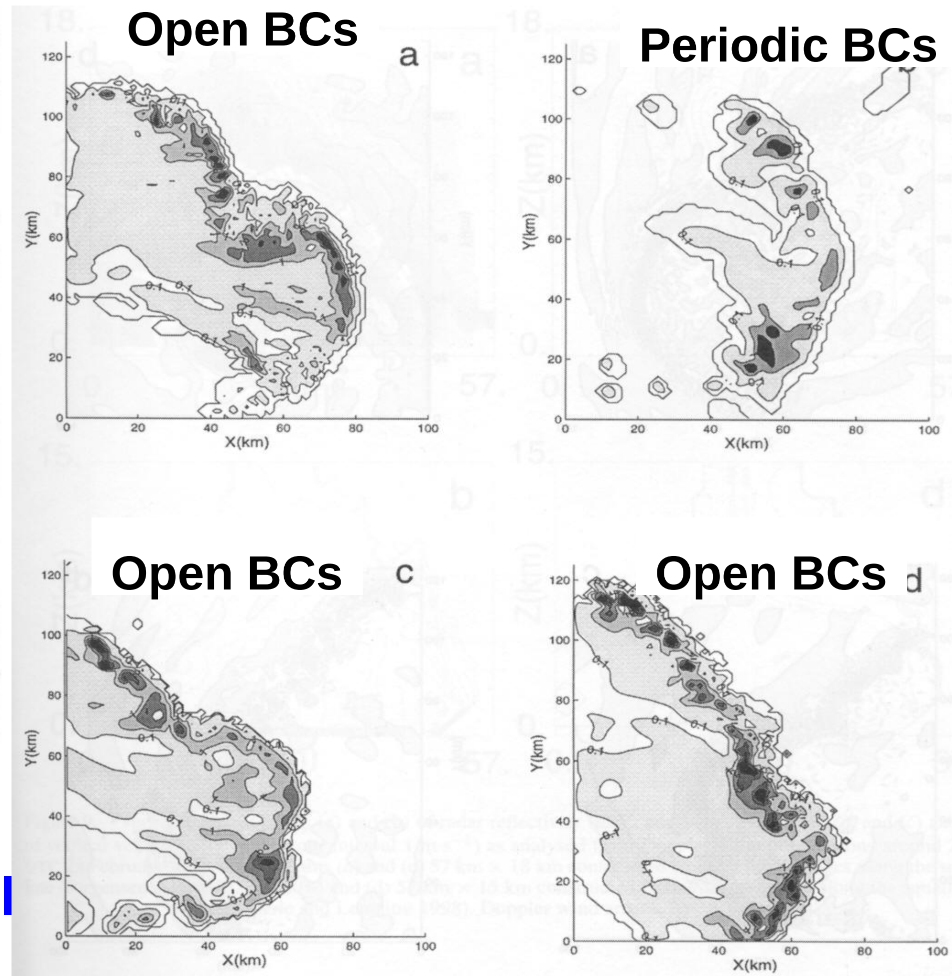
SQUALL LINE SIMULATIONS

Simulations from different models

(total hydrometeor content)

Observations - Radar





Conclude that only 3D models with ice and open BCs reproduce structure well

GCSS: Comparison of many SCMs with a CRM

Bechtold et al QJRMS 2000 SQUALL LINE SIMULATIONS

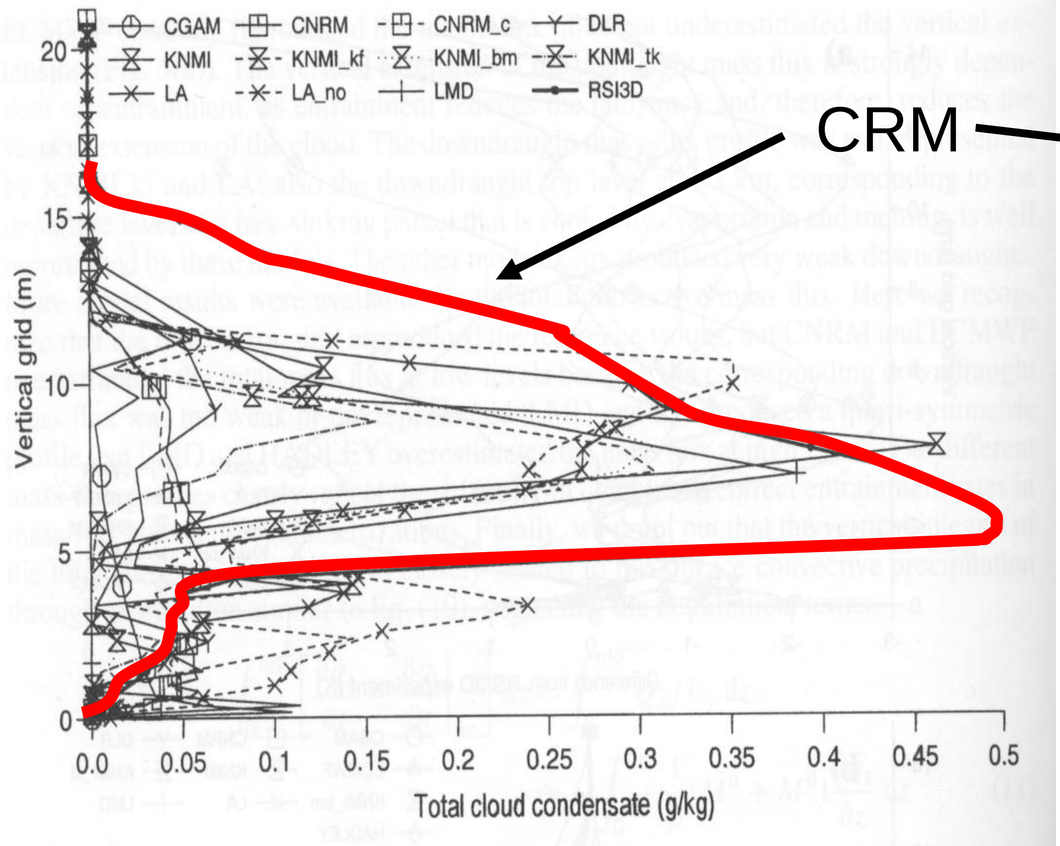
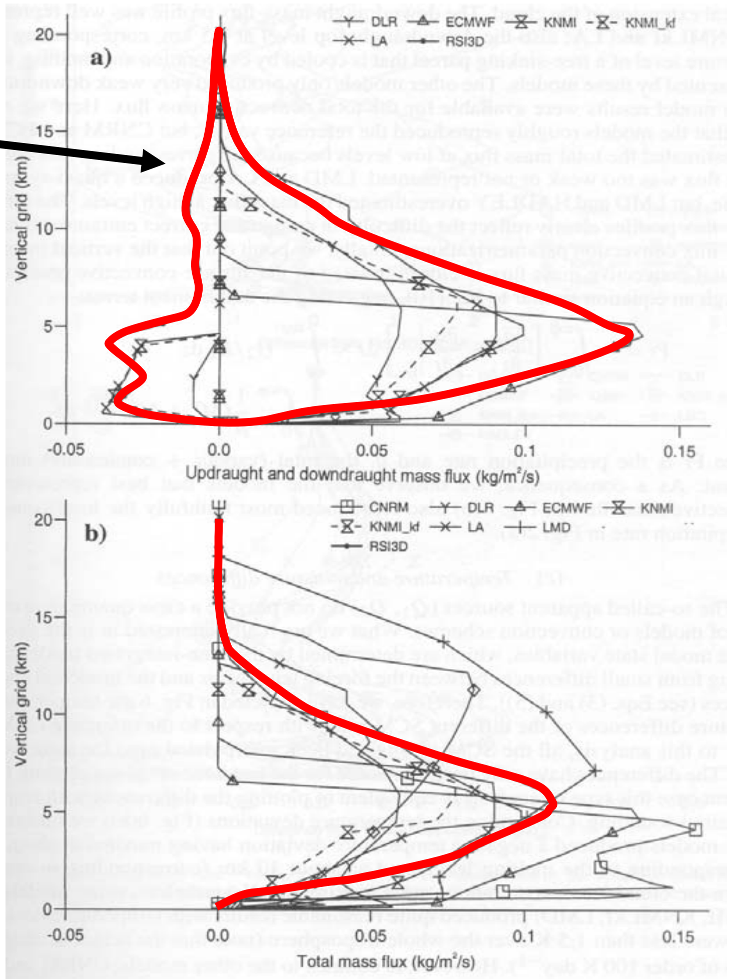


Figure 7. Vertical profiles of the total cloud condensate (liquid + solid) for simulations by different single-column models (see Tables 1 and 2 for explanations of the acronyms).



Summary

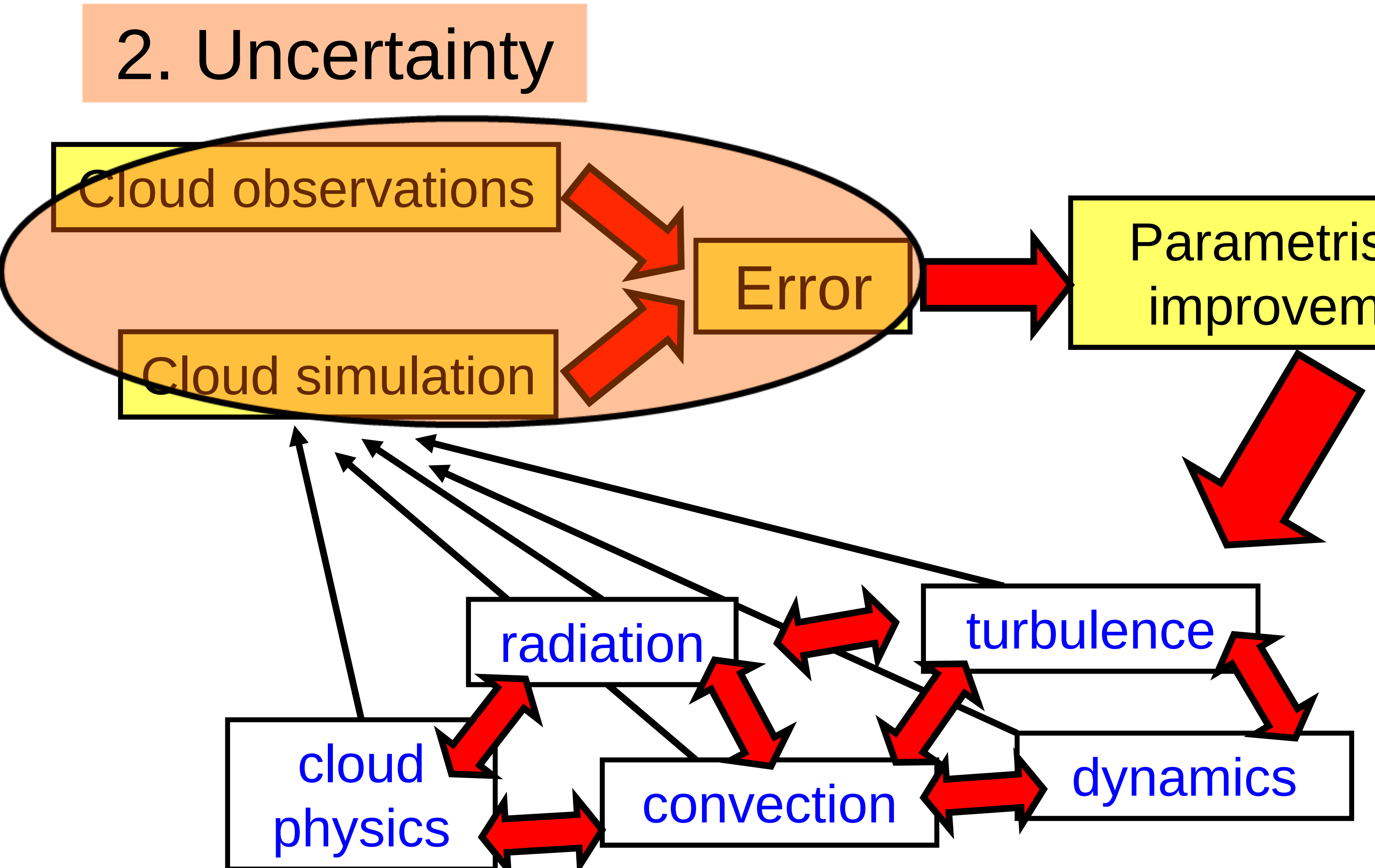
- Long term climatologies:
  - Climate systematic errors – we want to improve the basic state/climatology of the model
  - But which physics is responsible for the errors? Non-linear interactions.
  - Long term response vs. transient response.
  - We want to remove sensitivity to resolution = the parametrization problem!

- Isolating regimes: Composites and focus on geographical regions.

- Case studies
  - Detailed studies with Single Column Models, Cloud Resolving Models, NWP models
  - Easier to explore parameter space.
  - Are they representative? Do changes translate into global skill?

2. Comparing model and obs: Uncertainty and limitations

Cloud Validation: The problems



What is a cloud ?

What is a cloud ?

- Different observational instruments will detect different characteristics of clouds.
- A cloud from observations may be different to the representation in models

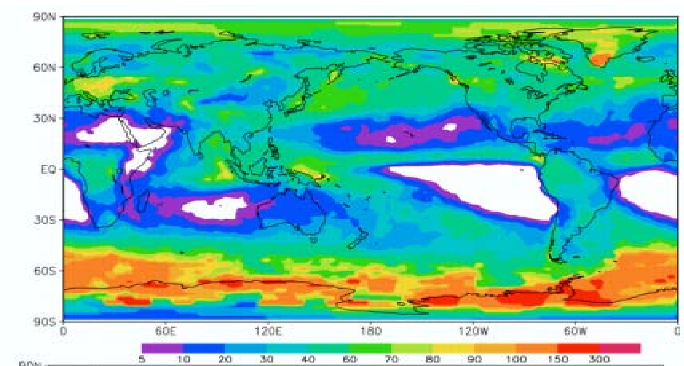
- ➢ Understanding the limitations of different instruments
- ➢ Benefit of observations from different sources
- ➢ Comparing like-with-like (physical quantity, resolution)

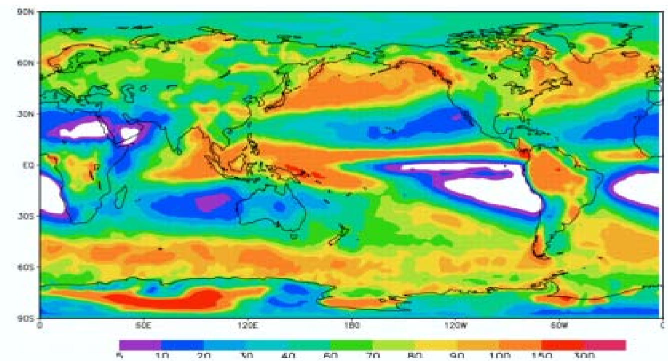
Verification

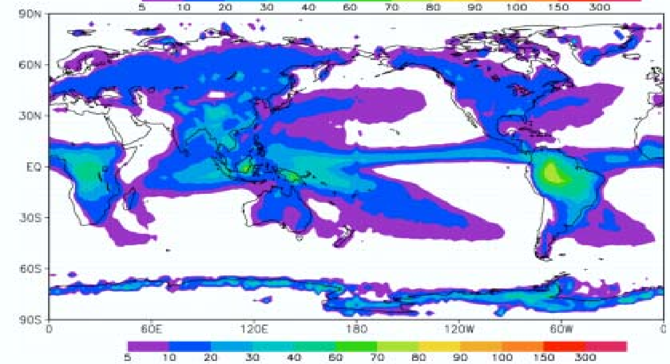
Annual average T159 Ice Water Path vs. Obs

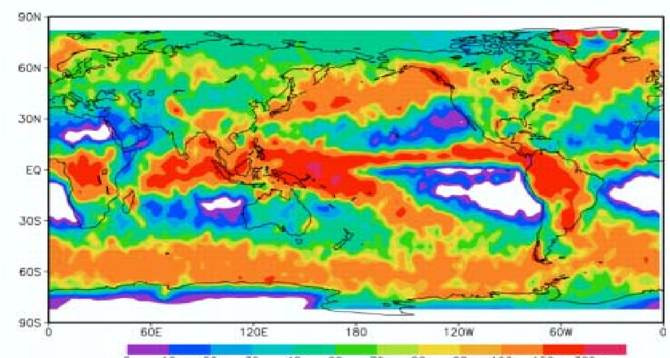
Widely varying estimates of IWP from different satellite datasets!

From Waliser et al. (2009), JGR

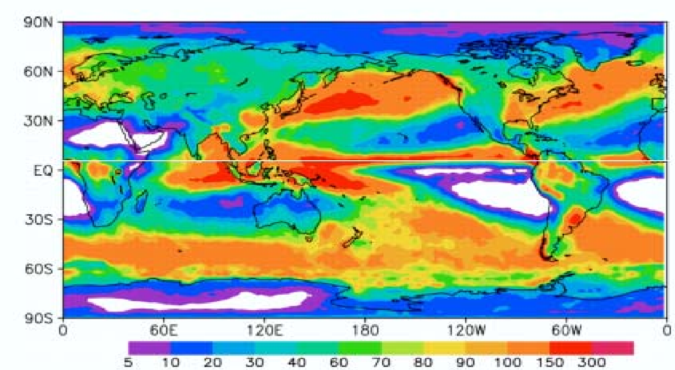


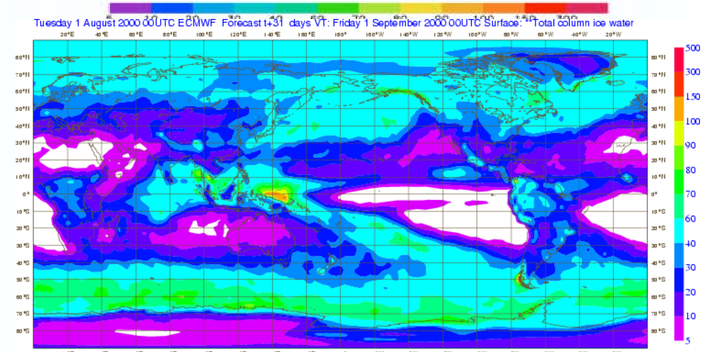






CloudSat (From Waliser et al 2009)



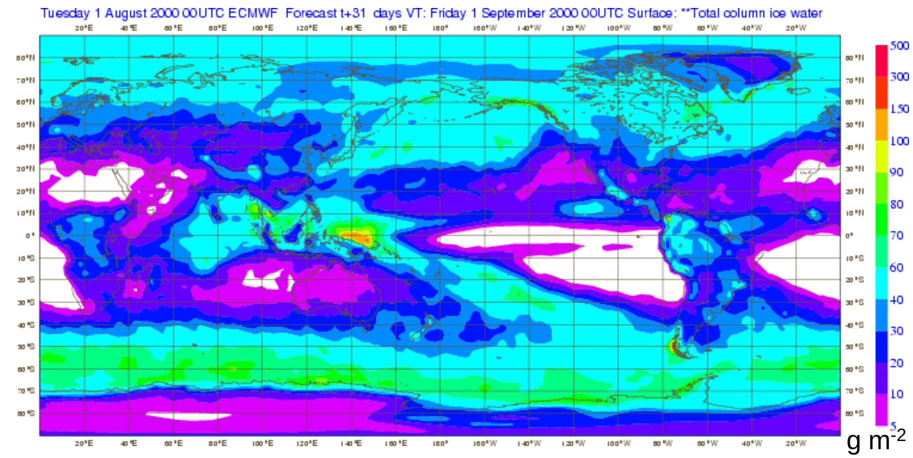


Current ECMWF model IWP

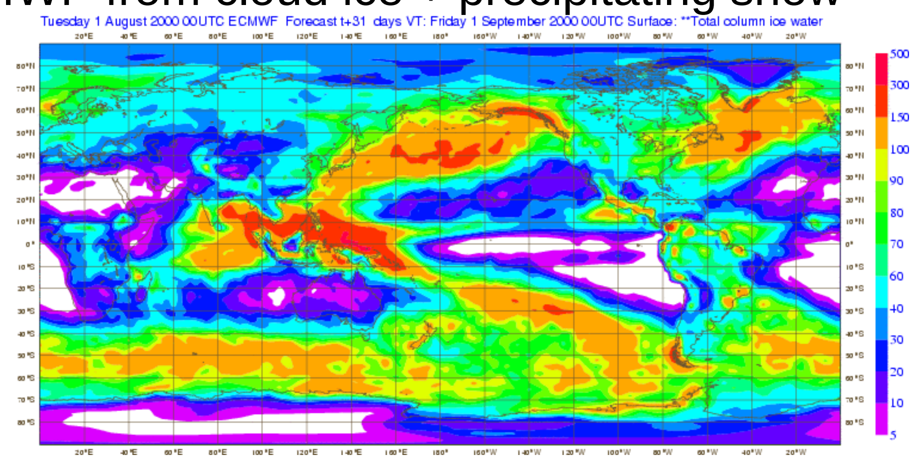
New 5 prognostic cloud microphysics
Ice vs. Snow

Model Ice Water Path (IWP)
(1 year climate)

IWP from prognostic cloud ice variable

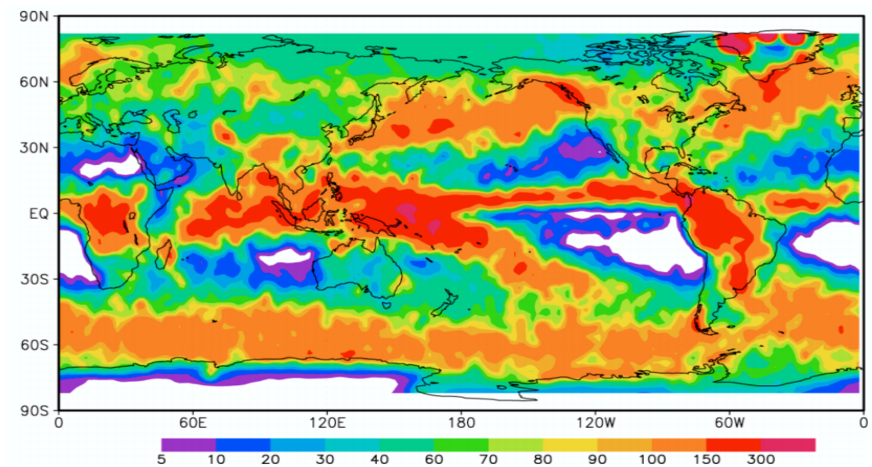


IWP from cloud ice + precipitating snow

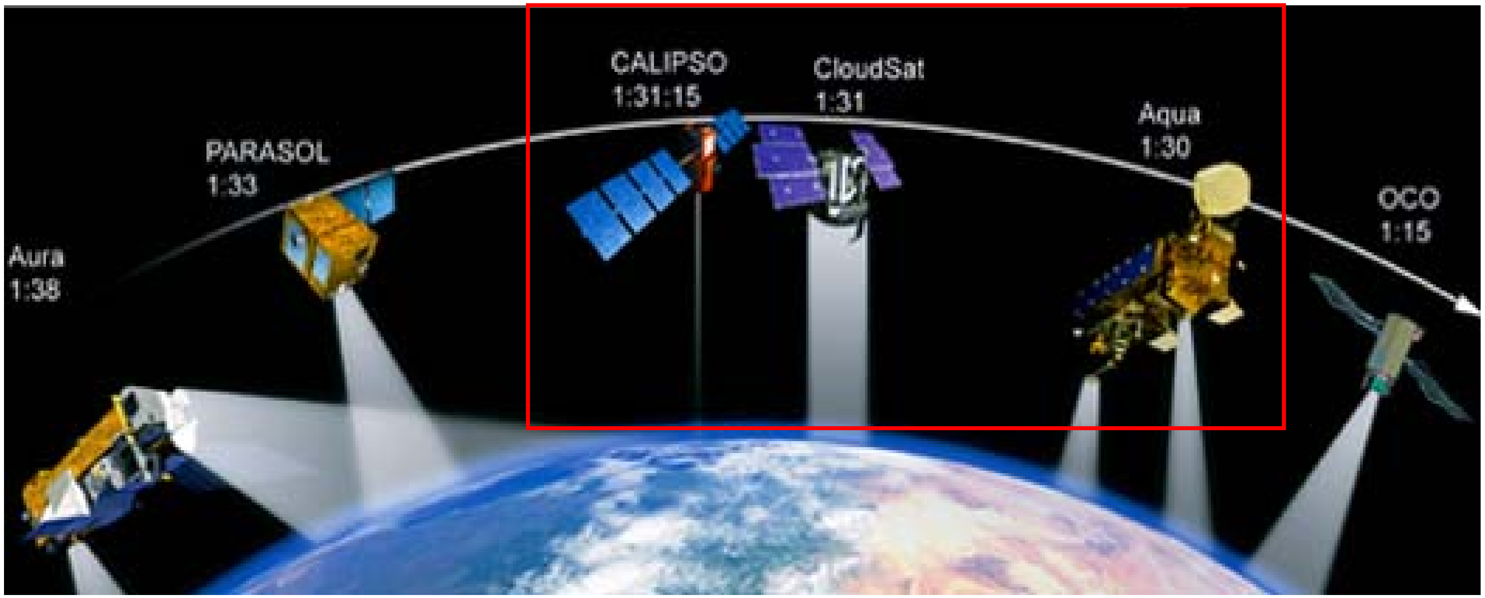


Observed Ice Water Path (IWP)

CloudSat 1 year climatology



A-Train: 28th April 2006

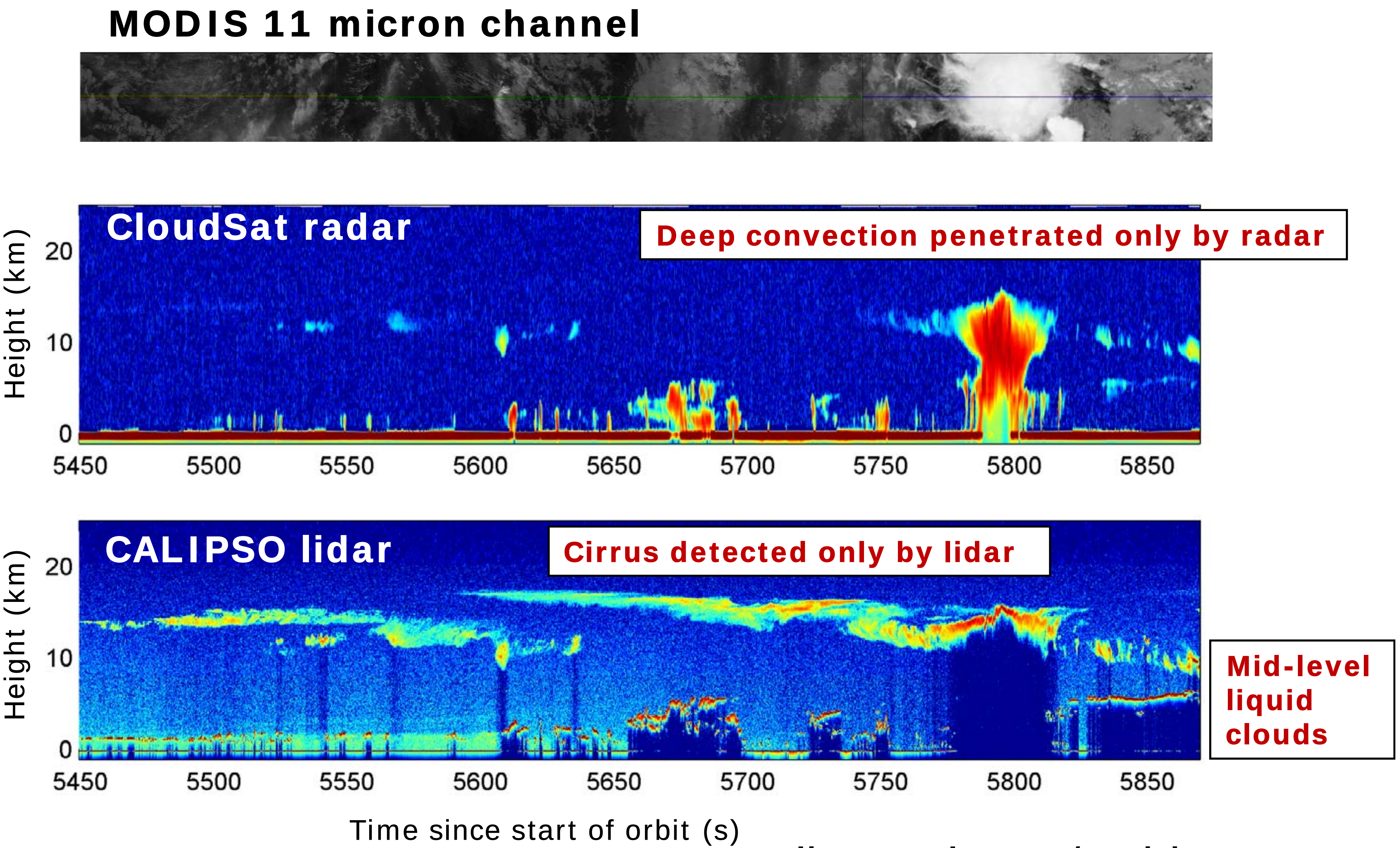


CloudSat: Cloud profiler radar 94GHz
CALIPSO: Cloud profiler lidar 532, 1064nm + Infra Red Imager
AQUA: radiometers MODIS, AIRS, CERES, AMSR-E

Global coverage:
Radar :2.5 km along track X 1.2 km across track / 500m =>250m
Lidar: 333 m / 30 m
Our merged product: CloudSat footprint/vertical resolution 60m

Julien Delanoë/Robin Hogan

Example of mid-Pacific convection

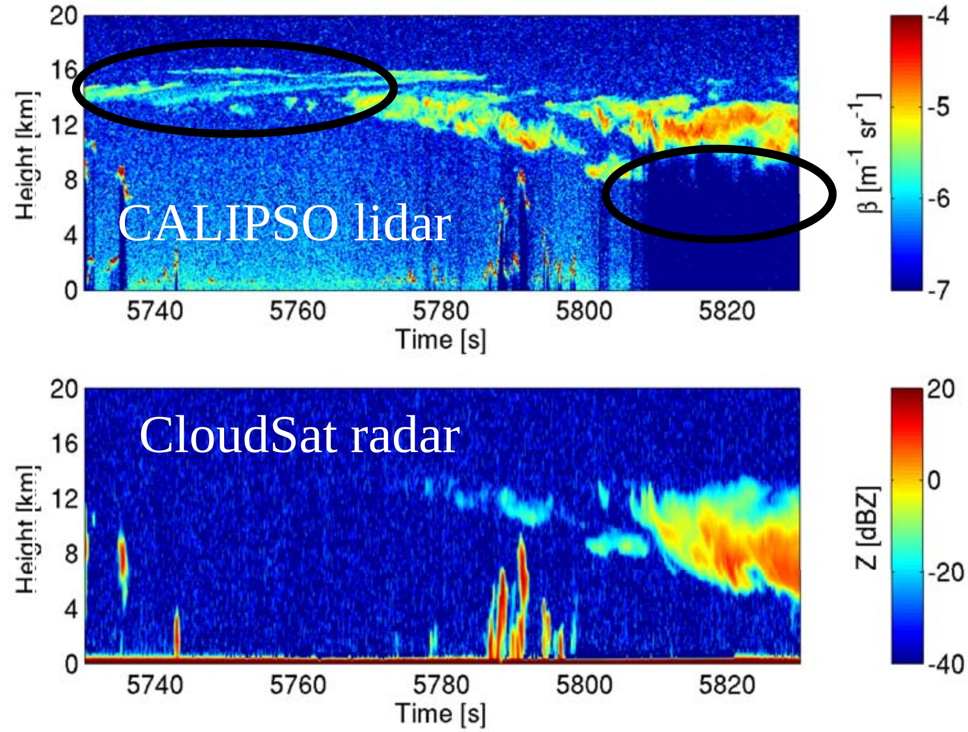


Julien Delanoë/Robin Hogan

Why combine radar, lidar and radiometers?

Radar $Z \propto D^6$, lidar $\beta' \propto D^2$ so the combination provides particle size

- *Lidar:* sensitive to particle concentration, can be extinguished
- *Radar:* very sensitive to the particle size, not very sensitivity to liquid clouds and small ice particles



Radiances ensure that the retrieved profiles can be used for radiative transfer studies

- *Single channel:* information on extinction near cloud top
- *Pair of channels:* ice particle size information near cloud top

We use "unified" variational scheme to retrieve ice cloud properties, thin and thick ice clouds

Delanoë and Hogan 2008, JGR (doi:10.1029/2007JD009000)

Julien Delanoë/Robin Hogan

Formulation of the retrieval scheme

*We know the **observations** (instrument measurements) and we would like to know **cloud properties** : visible extinction, Ice water content, effective radius…*

- Observation vector
  - Elements may be missing
- State vector (which we want to retrieve)

$$\mathbf{y} = \begin{pmatrix} \ln \beta'_1 \\ \vdots \\ \ln \beta'_n \\ Z_1 \\ \vdots \\ Z_m \\ I_{11\mu m} \\ \Delta I_{8.7-12.0\mu m} \end{pmatrix}$$

- $\ln \beta'_1 \ldots \ln \beta'_n$: Attenuated lidar backscatter profile
- $Z_1 \ldots Z_m$: Radar reflectivity factor profile
- $I_{11\mu m}$: Infrared radiance
- $\Delta I_{8.7-12.0\mu m}$: Radiance difference

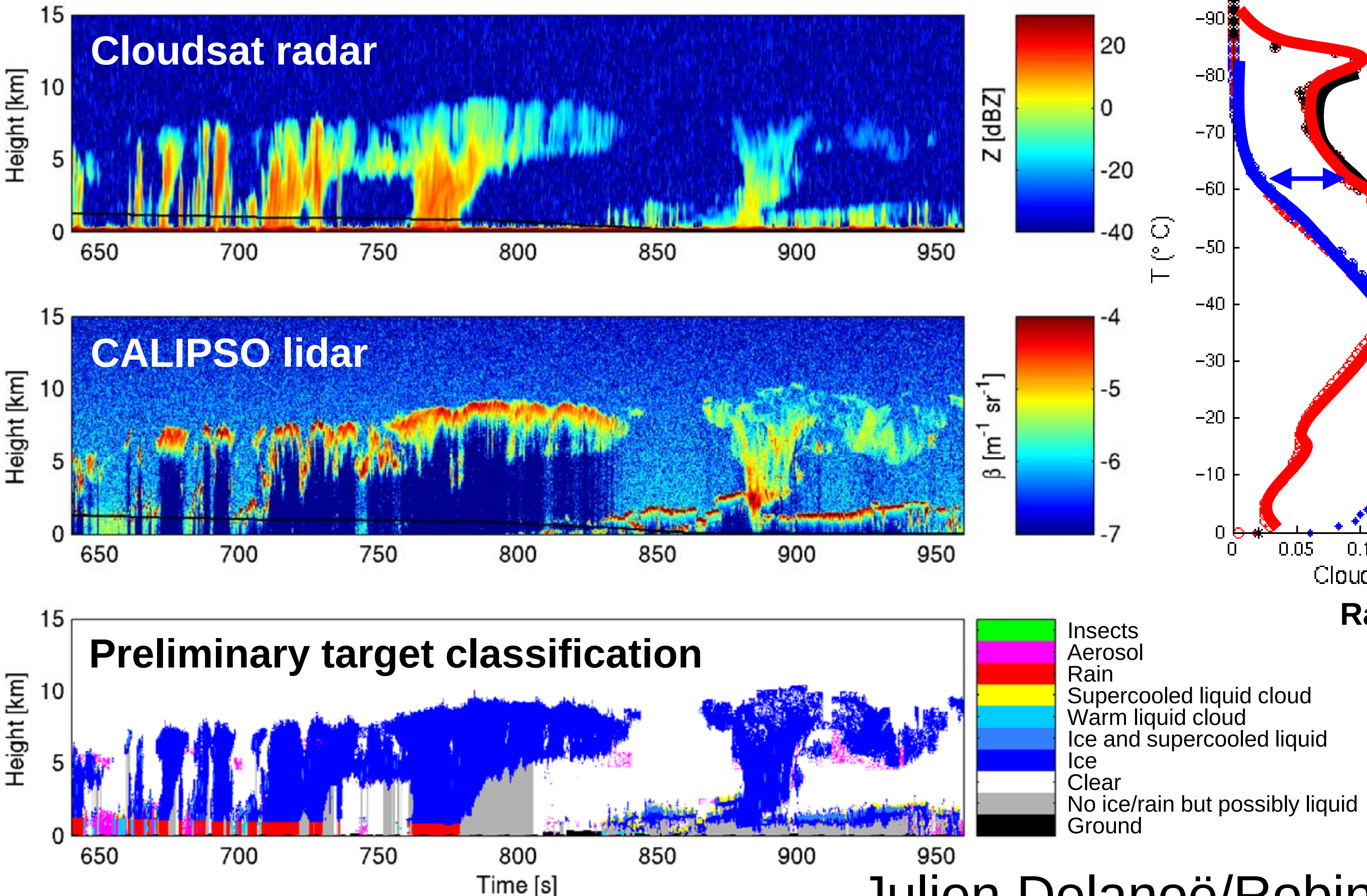
$$\mathbf{x} = \begin{pmatrix} \ln \alpha_1^{\mathrm{ice}} \\ \vdots \\ \ln \alpha_n \\ \ln N_{01}^{\mathrm{ice}} \\ \vdots \\ \ln N_{0n}^{\mathrm{ice}} \\ S \end{pmatrix}$$

- $\ln \alpha_1^{\mathrm{ice}} \ldots \ln \alpha_n$: Ice visible extinction coefficient profile
- $\ln N_{01}^{\mathrm{ice}} \ldots \ln N_{0n}^{\mathrm{ice}}$: Ice normalized number conc. profile
- S: Extinction/backscatter ratio for ice

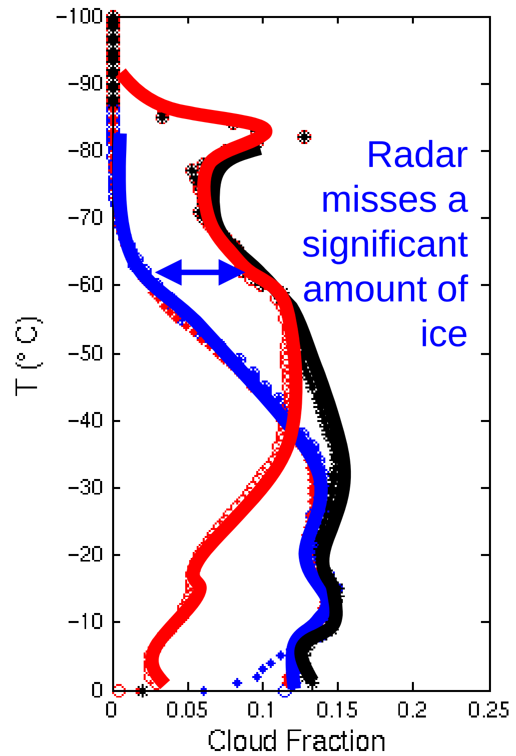
Iterative process: compare predicted observations and measurements, with an **a-priori** and **measurement errors** as a constraint

Julien Delanoë/Robin Hogan

Combining radar and lidar…



Global-mean cloud fraction



Radar and lidar
Radar only
Lidar only

Julien Delanoë/Robin Hogan

Frequency of occurrence of IWC vs temperature

IWC increases with temperature:

- but spread over 2 to 3 orders of magnitude at low temperatures
  - reach 5 orders of magnitude close to 0° C

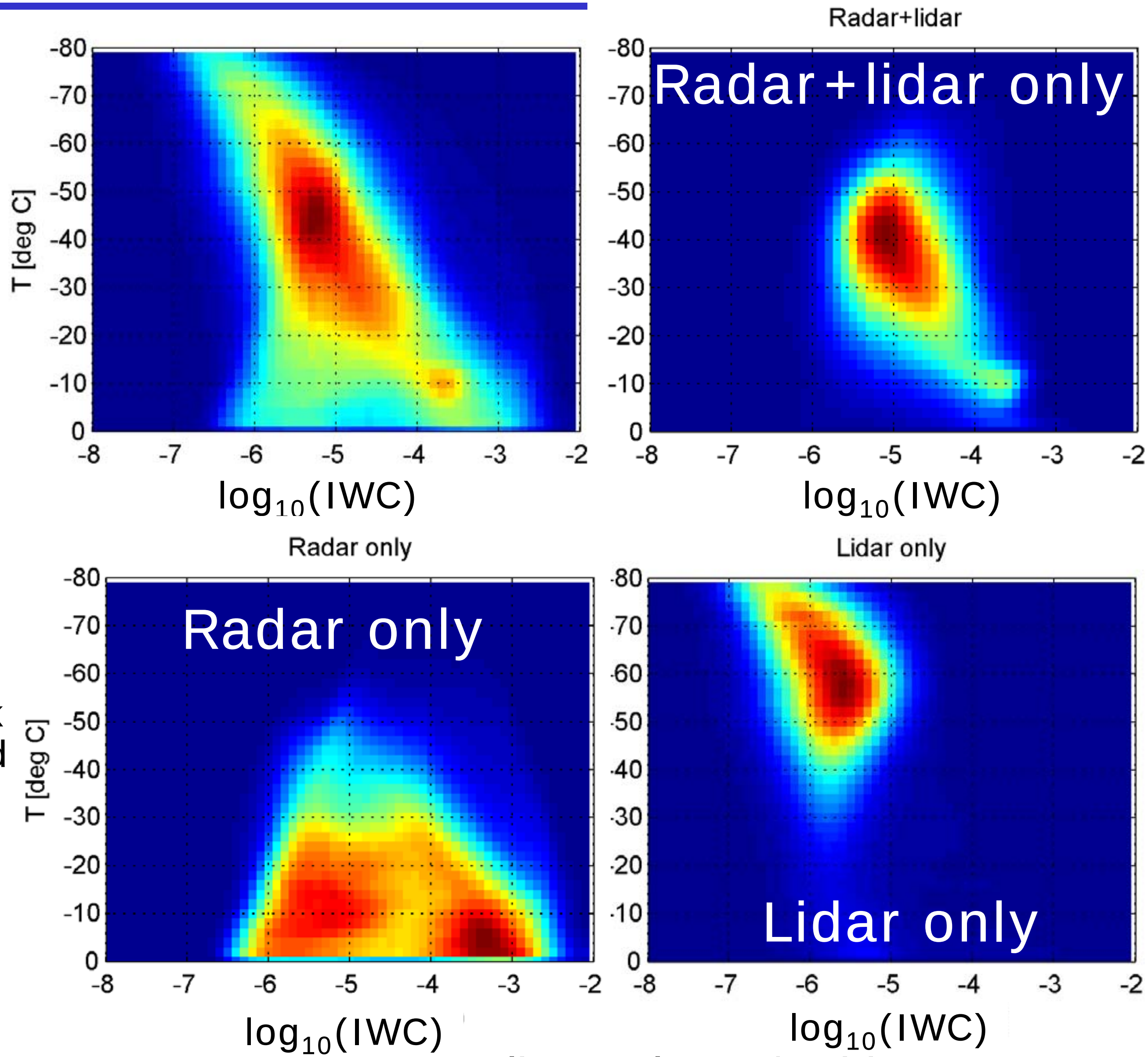
Advantage of the algorithm:

Deep ice clouds: radar

Thin ice clouds: lidar

When radar and lidar work well together very good confidence in the retrievals

⇒ Obvious complementarity radar-lidar



Julien Delanoë/Robin Hogan

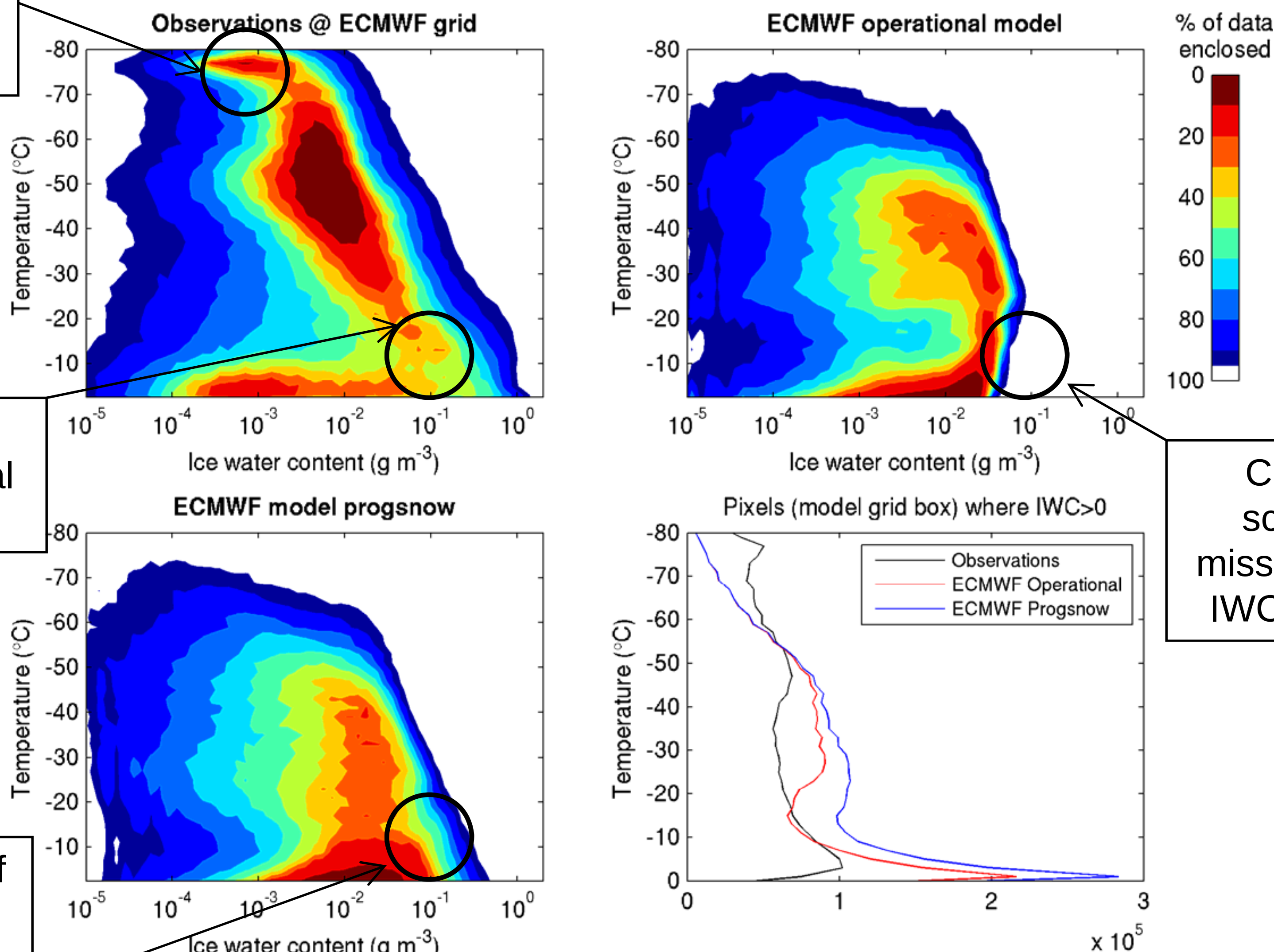
CloudSat/CALIPSO Model Verification

GLOBAL Ice Water Content vs. T distributions

Diagnosing Cloud Error, Forbes
ECMWF Seminar 2009

Specular reflection ?

Changes to IWC retrieval result

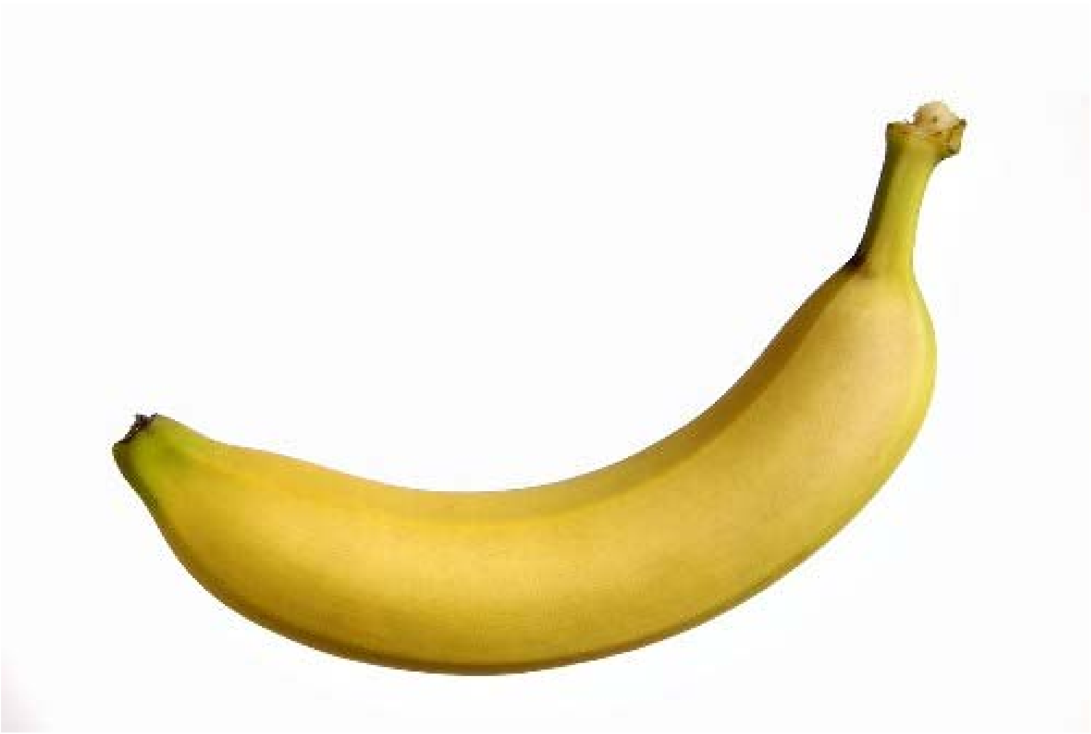


Current scheme misses larger IWC (snow)

Distribution of IWC in new scheme is improved

(In collaboration with Delanoë and Hogan, Reading Univ.)

When comparing a model with observations, we need to compare like-with-like

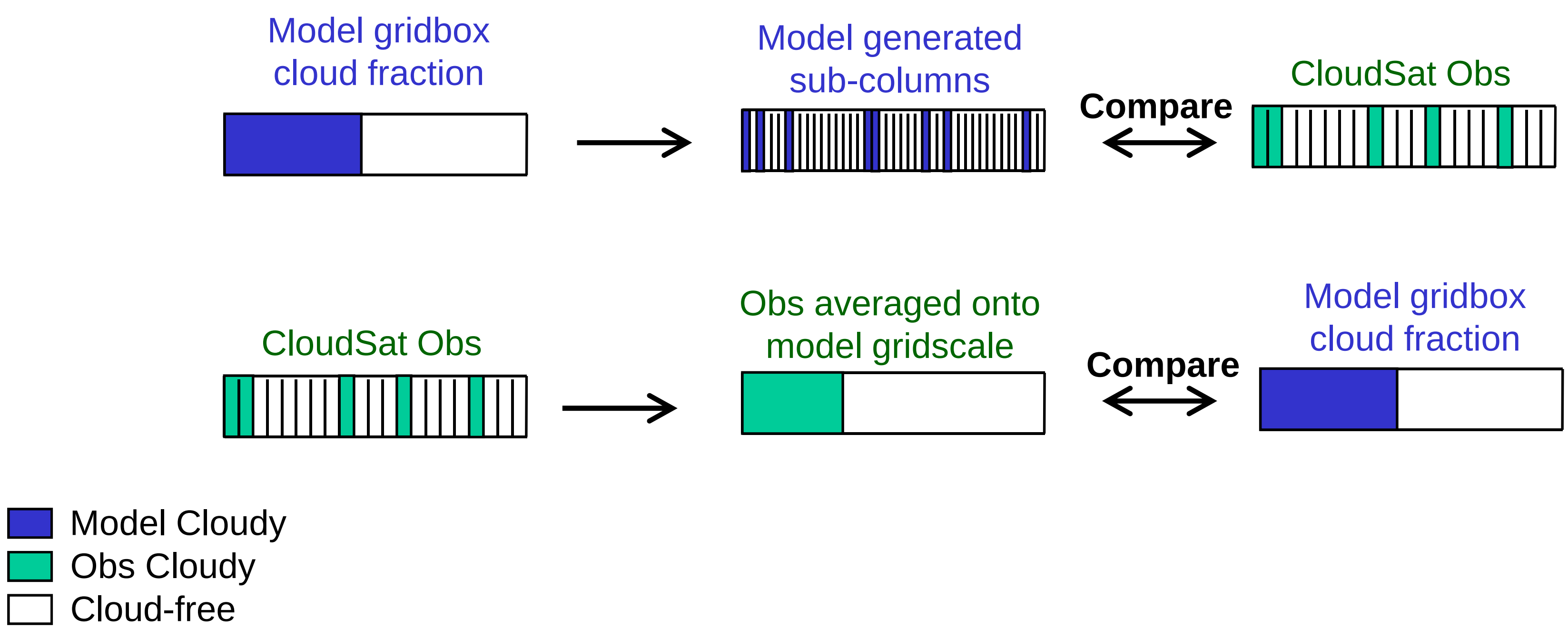


Spatial resolution mis-match

- Need to address mismatch in spatial scales in model (50 km) and obs (1 km)
- Sub-grid variability is predicted by the IFS model in terms of a cloud fraction and assumes a vertical overlap.
- Either:

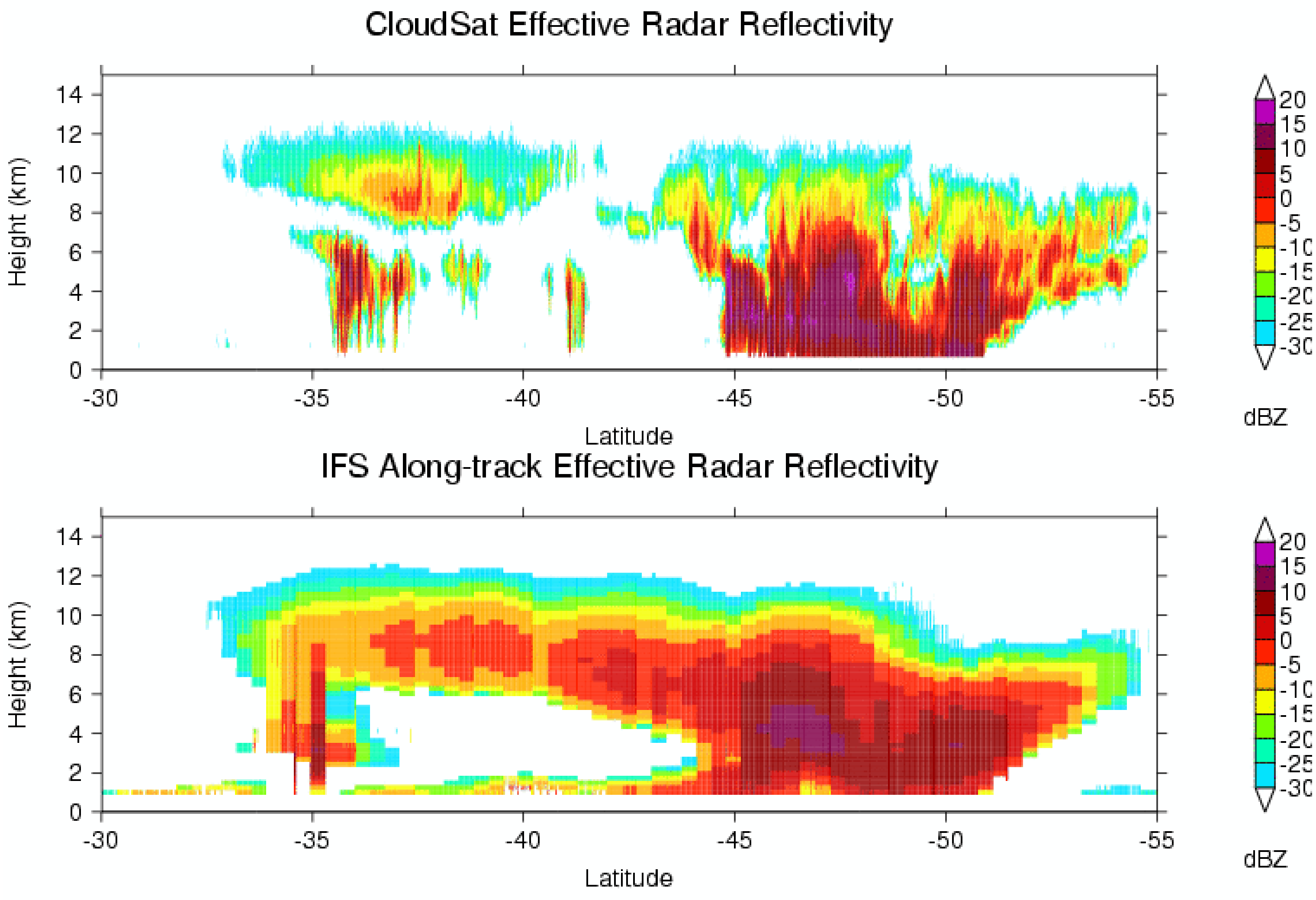
  (1) Average obs to model representative spatial scale

  (2) Statistically represent model sub-gridscale variability using a Monte-Carlo multi-independent column approach.

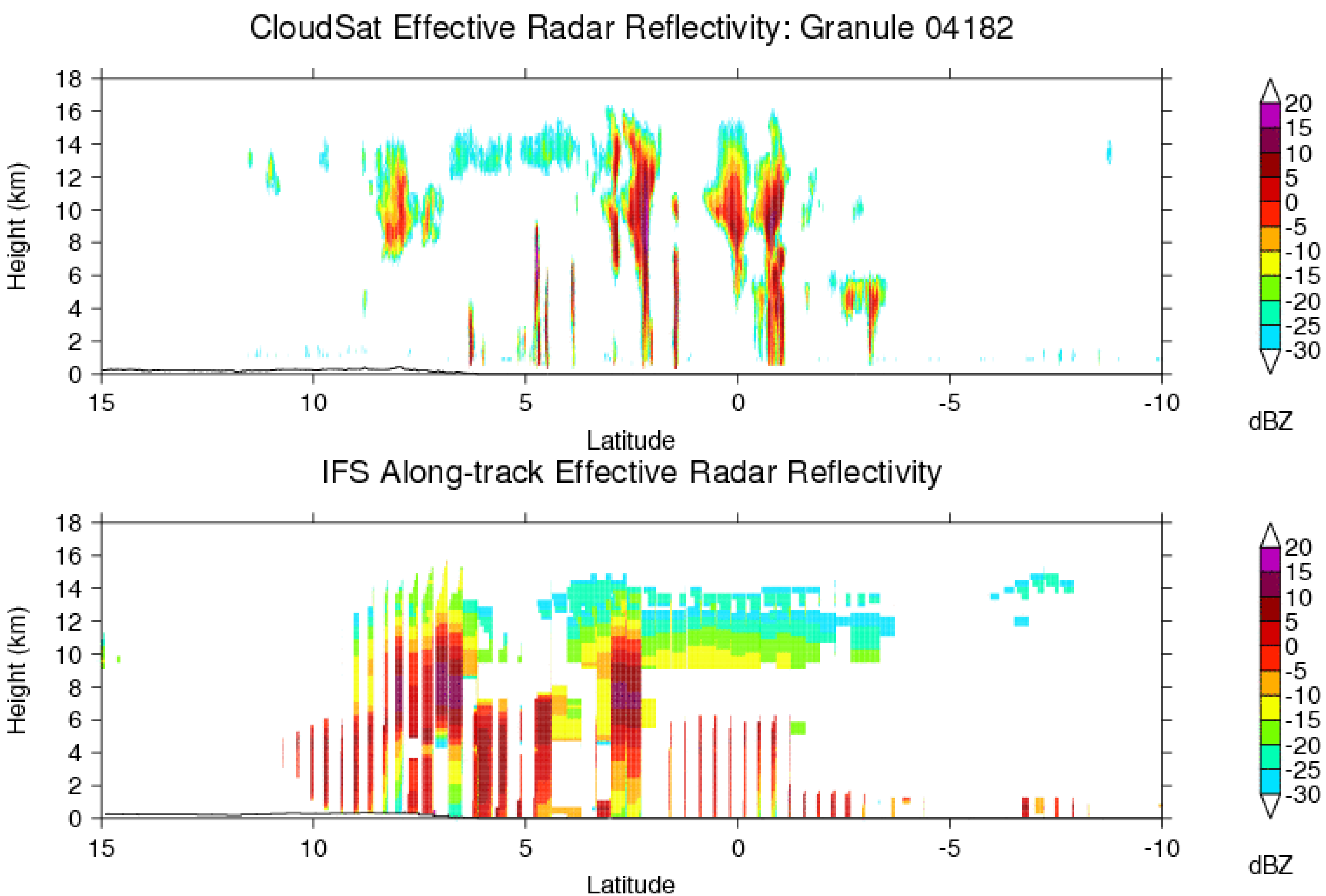


MODEL to OBSERVATION

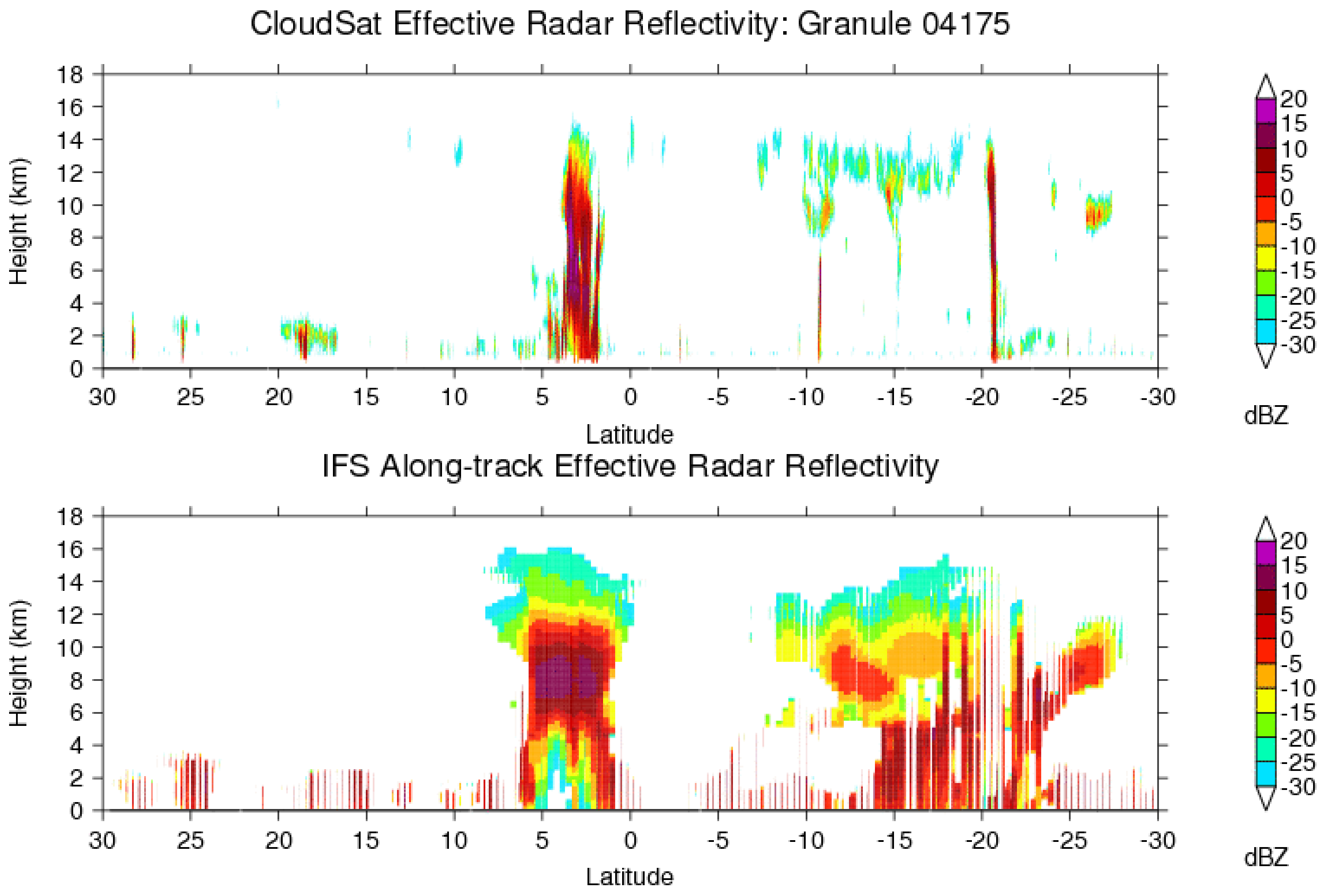
Radar Reflectivity: Cross-section through a mid-latitude front



Radar Reflectivity
Cross-section through tropical convection



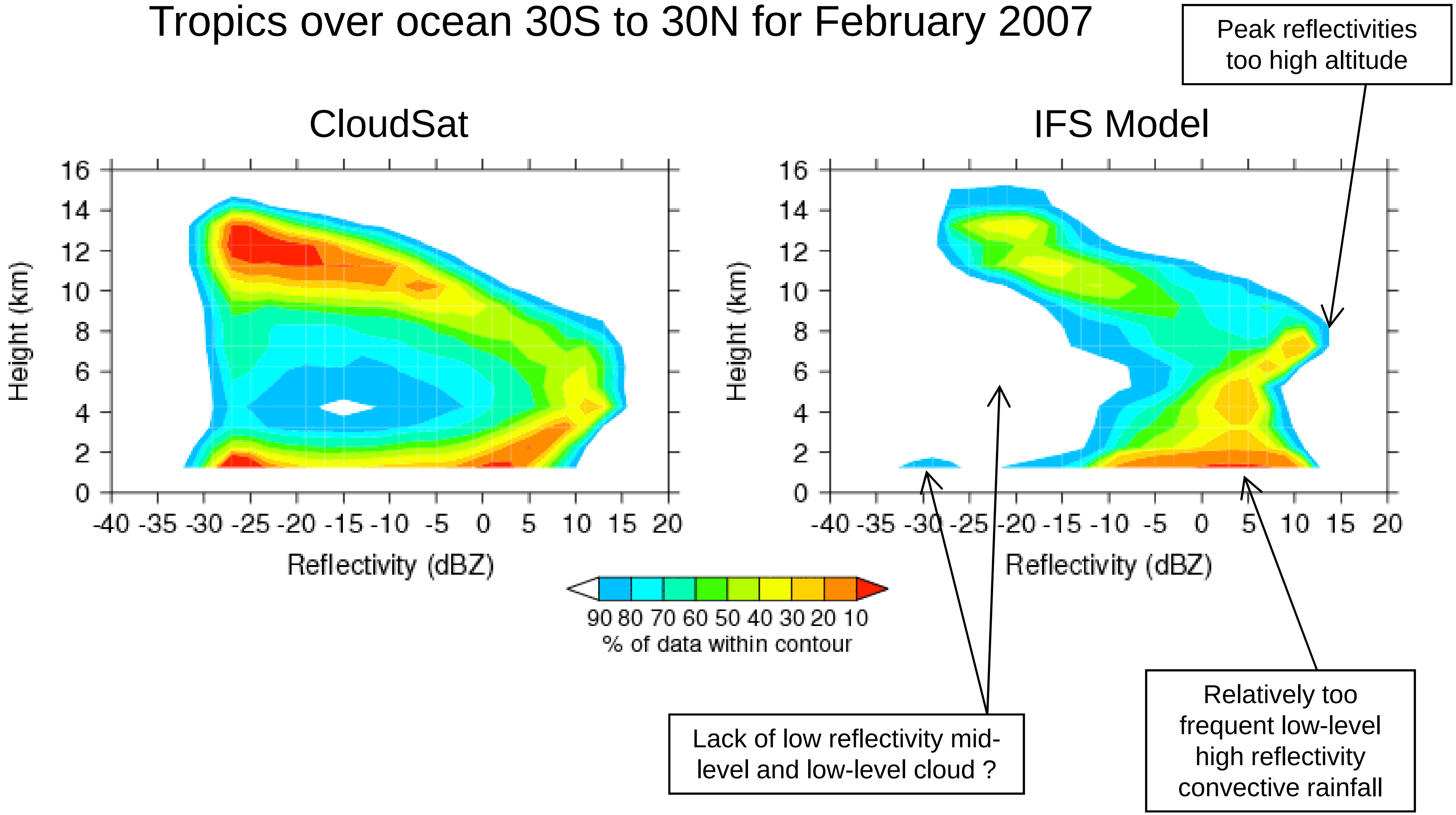
Radar Reflectivity
Cross-section through tropical convection



Radar Reflectivity Statistics

Radar Reflectivity vs. Height
Relative Frequency of Occurrence

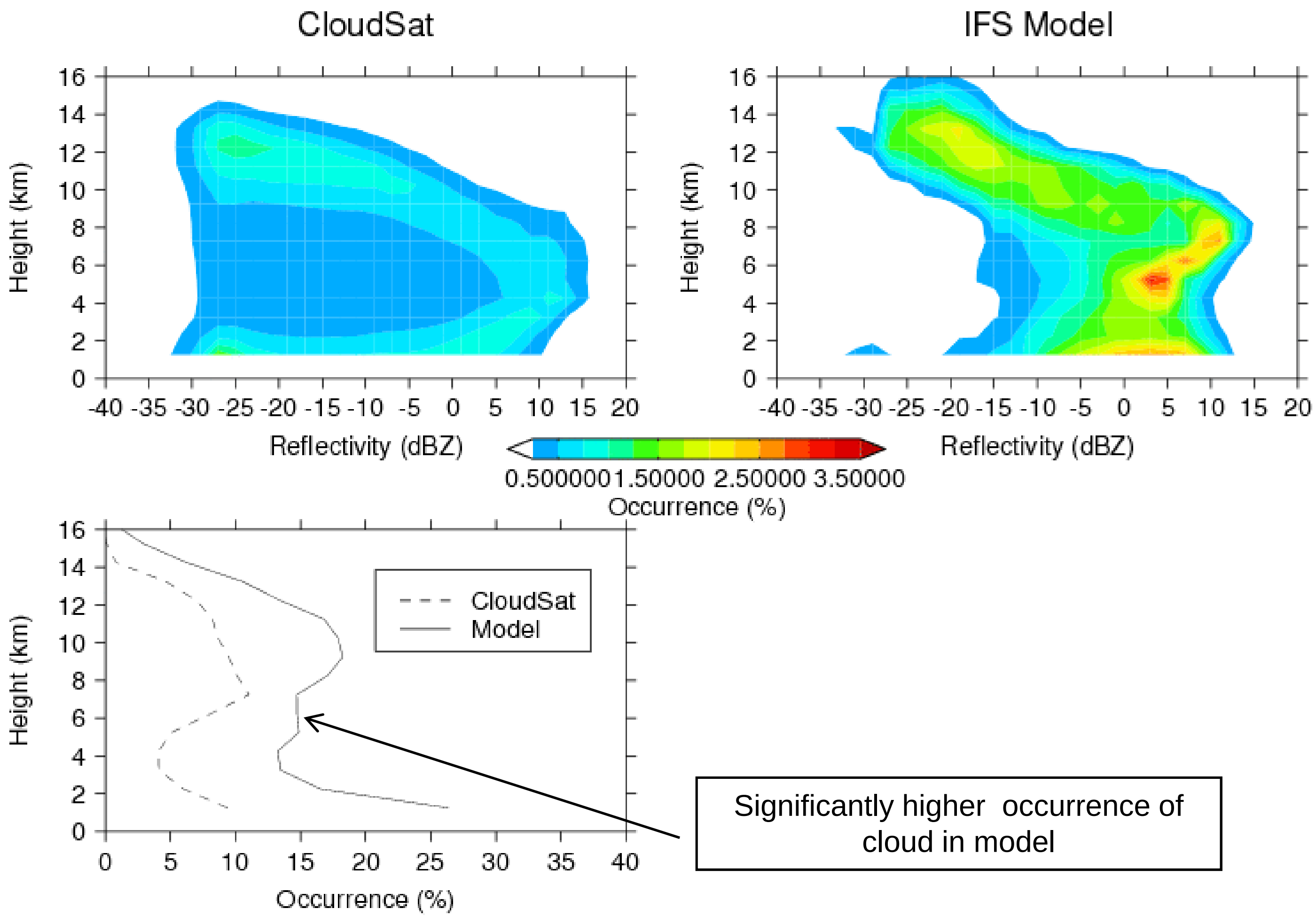
Tropics over ocean 30S to 30N for February 2007



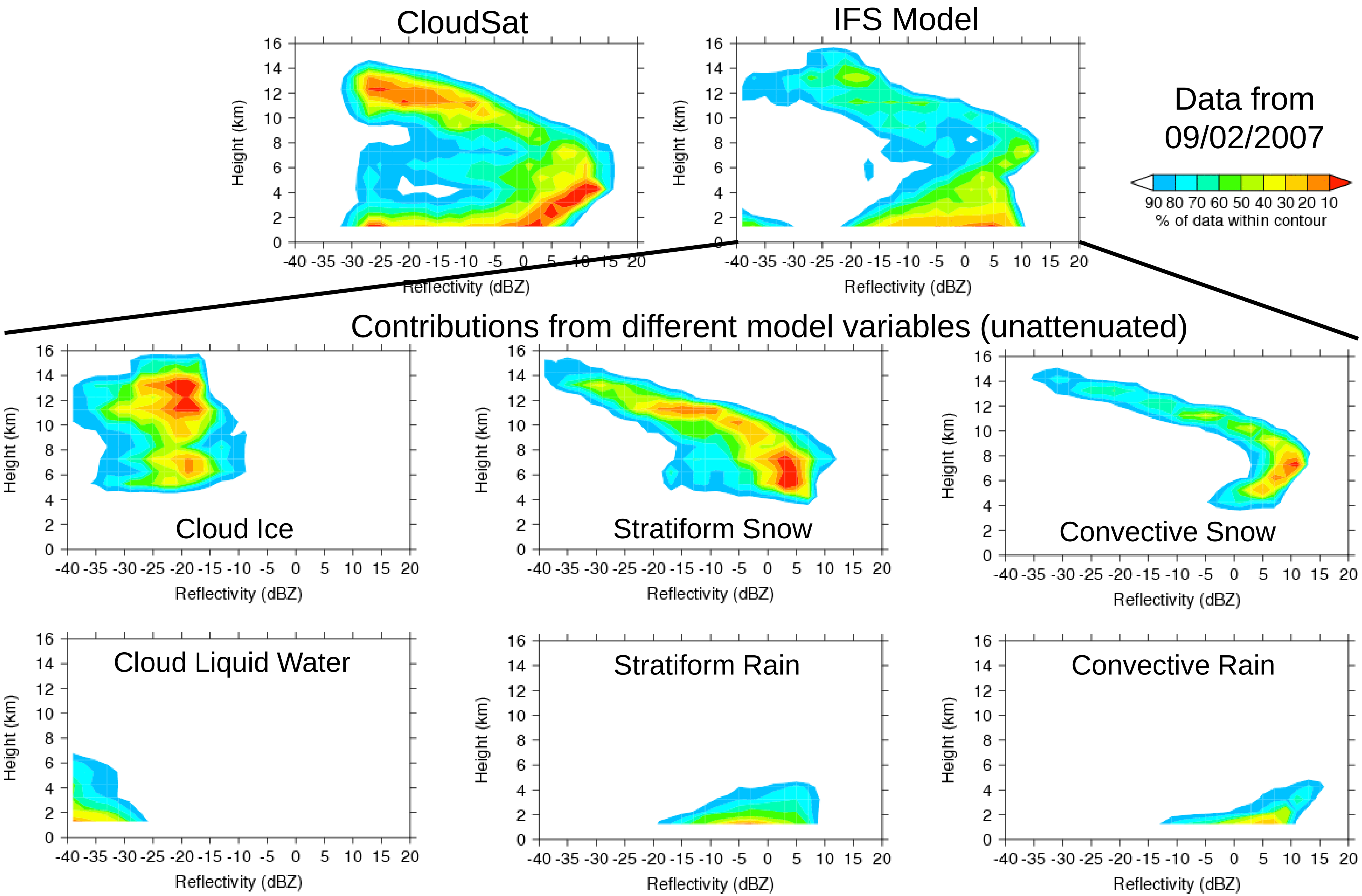
Radar Reflectivity Statistics

STATISTICS: Frequency of occurrence (Radar Reflectivity vs. Height)

Tropics over ocean 30S to 30N for February 2007



Radar Reflectivity PDF
Contributions from cloud/precip (tropics)



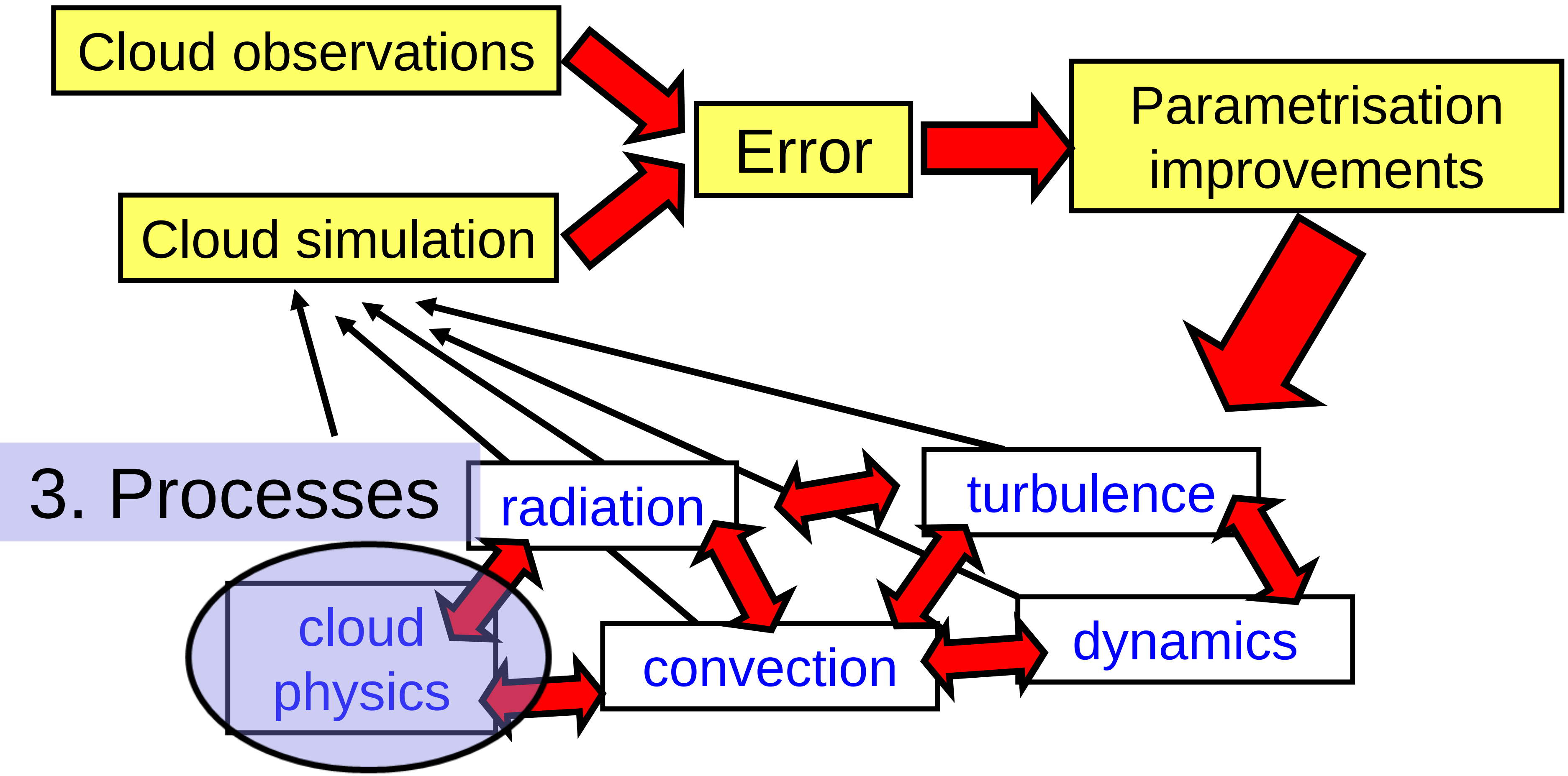
Data from 09/02/2007

Summary

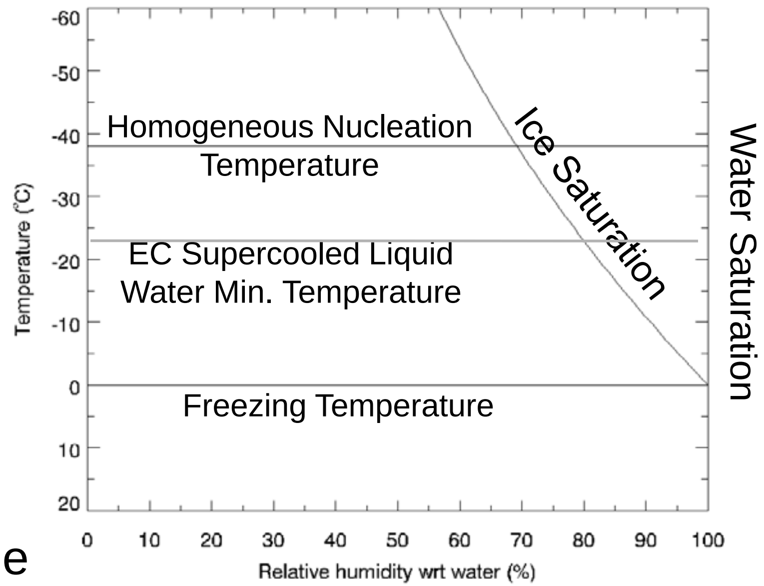
- Limitations and uncertainty:
  - Observations have limitations, provide a partial picture.
  - We need to know the error characteristics (including systematic errors). But we don't always know this!
- Synergy:
  - Different observation sources have different strengths and weaknesses Make the most of this complementary information (e.g. CloudSat, CALIPSO, MODIS)
- Need to compare like-with-like
  - Compare in "model-space", or "obs space"
  - Assumptions required for both
  - Spatial and temporal resolution differences
- Diagnose model problems from different angles
  - Retrieval of model variables from observations ("obs-to-model"), e.g. IWC
  - Forward modelling of observed variables ("model-to-obs"), e.g. Z
  - Different approaches help to diagnose model problems

3. Understanding Physical Processes

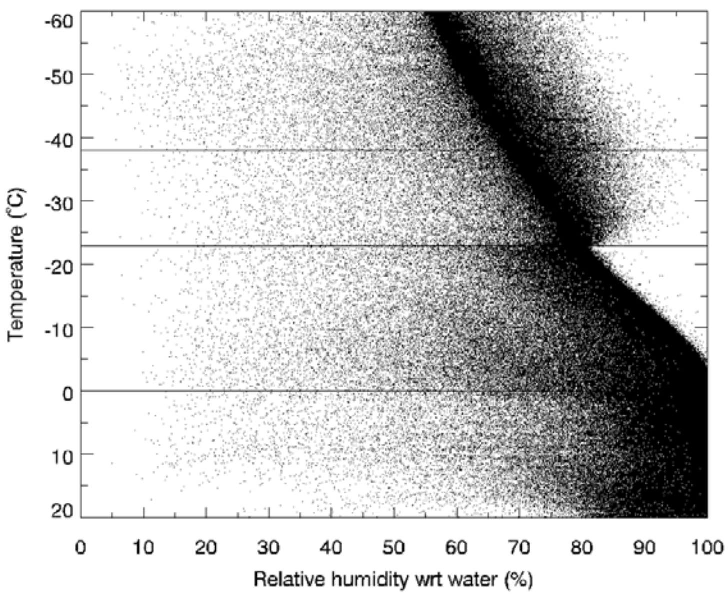
Cloud Validation: The problems



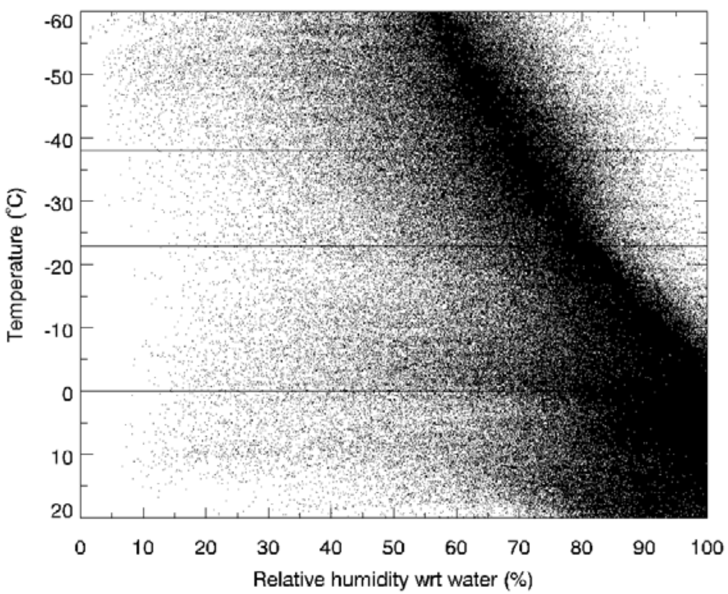
Temperature vs. Relative Humidity



Current EC cloud scheme

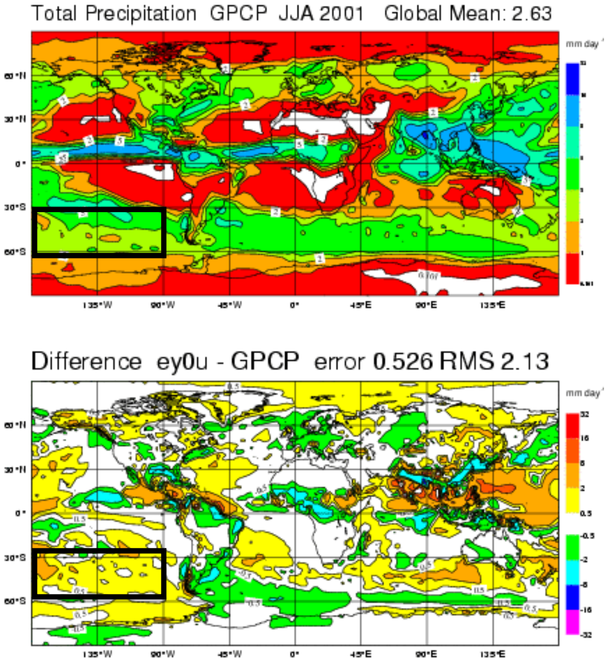


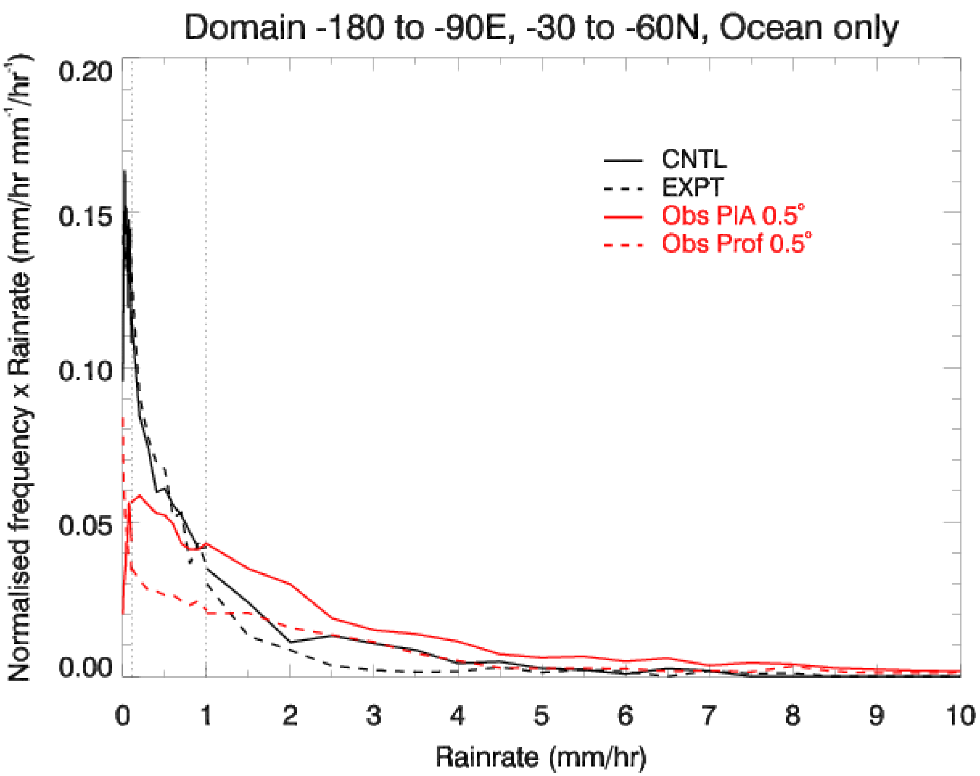
New EC cloud scheme



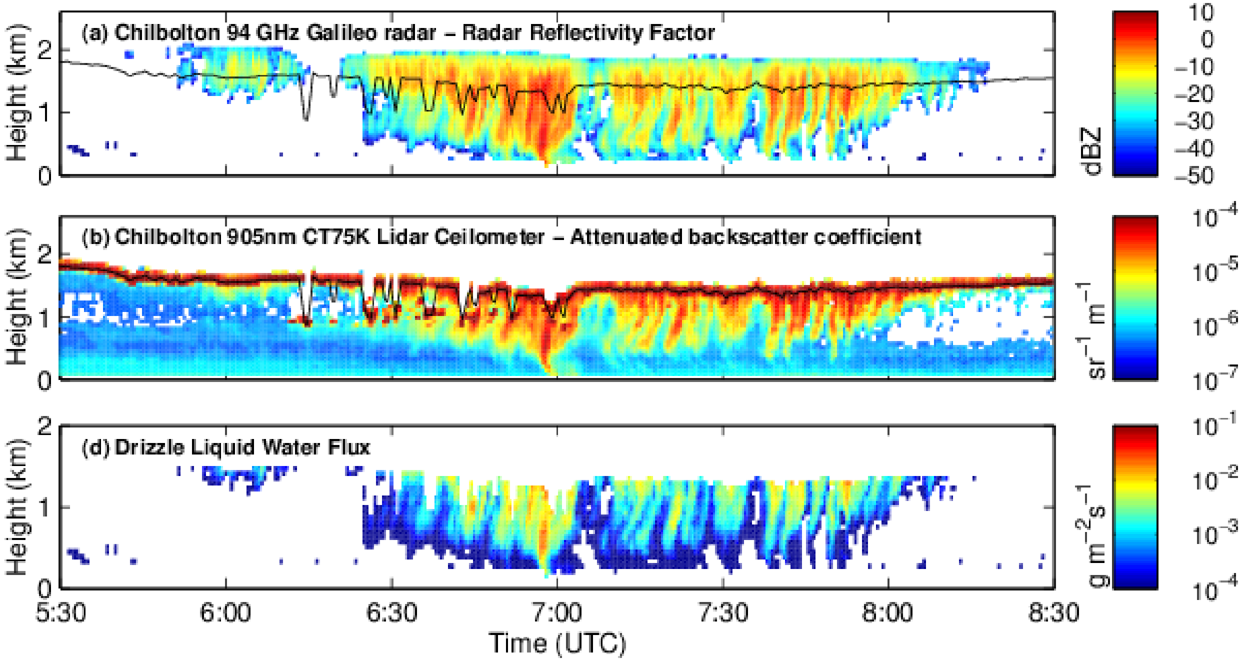
Precipitation validation with CloudSat

(in collaboration with Graeme Stephens)





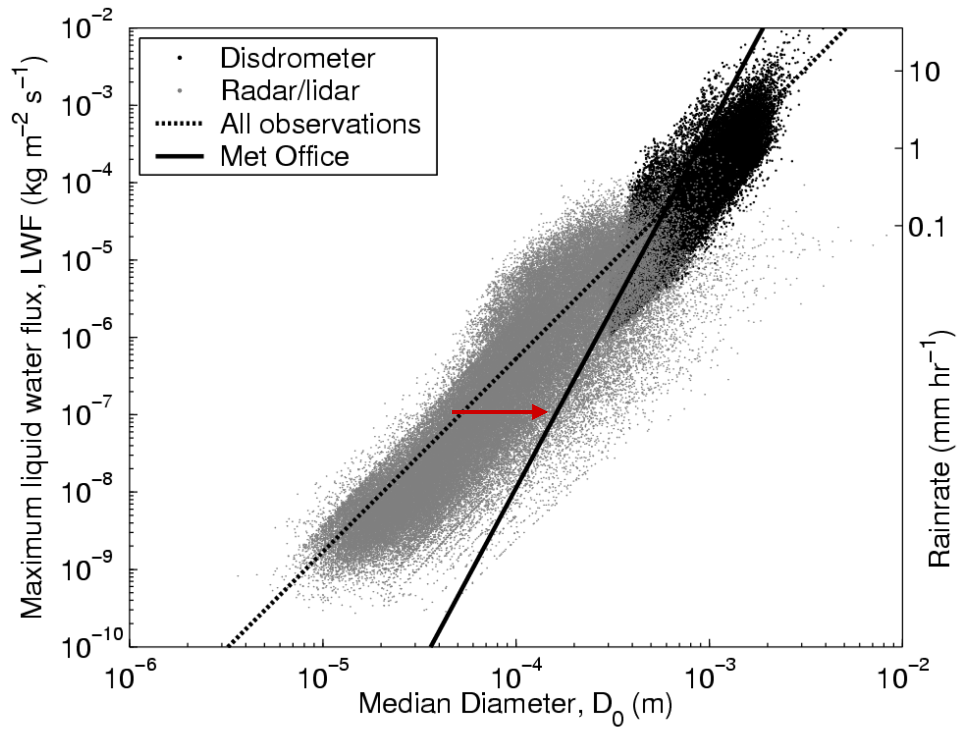
- Model overestimates frequency of low precipitation rates (< 1 mm/hr)
- Model underestimates frequency of high precipitation rates (> 5 mm/hr?) (but representativity?)
- Still an issue of uncertainty in the obs – work in progress.



- Radar and lidar used to derive drizzle rate below stratocumulus
- Important for cloud lifetime in climate models

O'Connor et al. (2005)

- Met Office uses Marshall-Palmer distribution for all rain
  - Observations show that this tends to *overestimate* drop size in the lower rain rates
- Most models (e.g. ECMWF) have no explicit raindrop size distribution

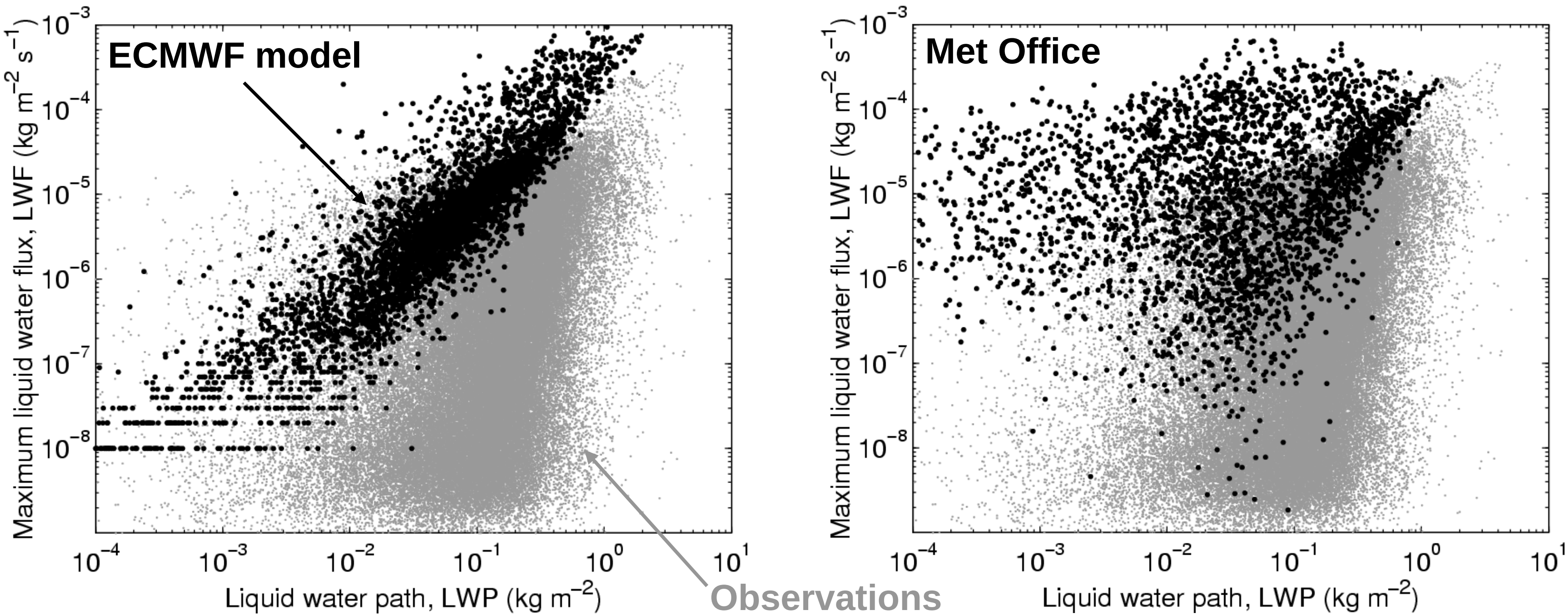


From Robin Hogan

Drizzle
1-year comparison with models

Diagnosing Cloud Error, Forbes
ECMWF Seminar 2009

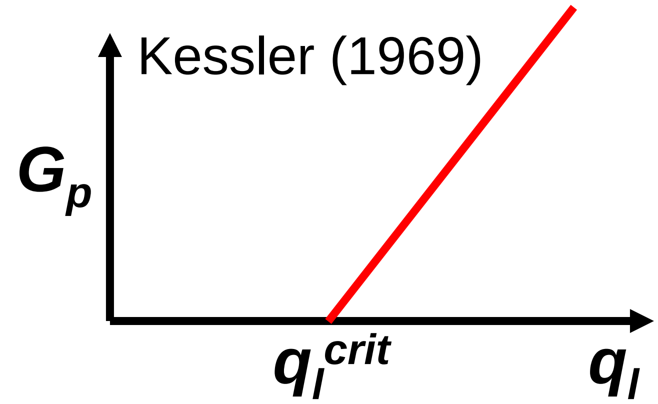
- ECMWF, Met Office and Meteo-France overestimate drizzle rate
  - Problem with auto-conversion and/or accretion rates?
- Larger drops in model fall faster so too many reach surface rather than evaporating: drying effect on boundary layer?



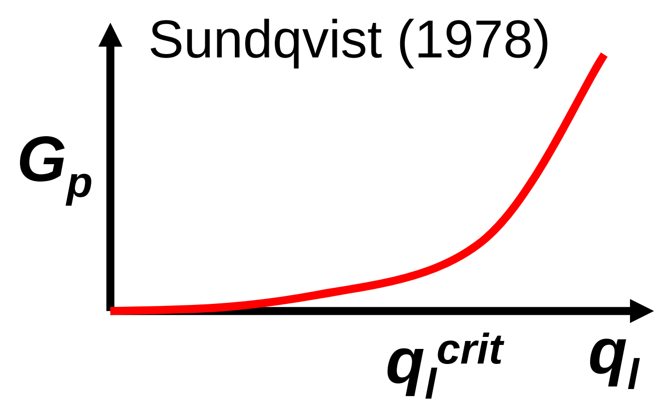
From Ewan O'Connor, Robin Hogan (Reading Univ.)

Warm-rain processes

- Autoconversion – conversion of cloud droplets to raindrops



- Accretion – sweep out of cloud droplets by rain
- Evaporation – below cloud base



Process-validation with CloudSat: Autoconversion/accretion

The observables

Z_e: layer-mean radar reflectivity

$$R_e = \frac{3}{2}\frac{1}{\rho_w}\frac{LWP(\text{AMSR-E})}{\tau_c(\text{MODIS})}$$

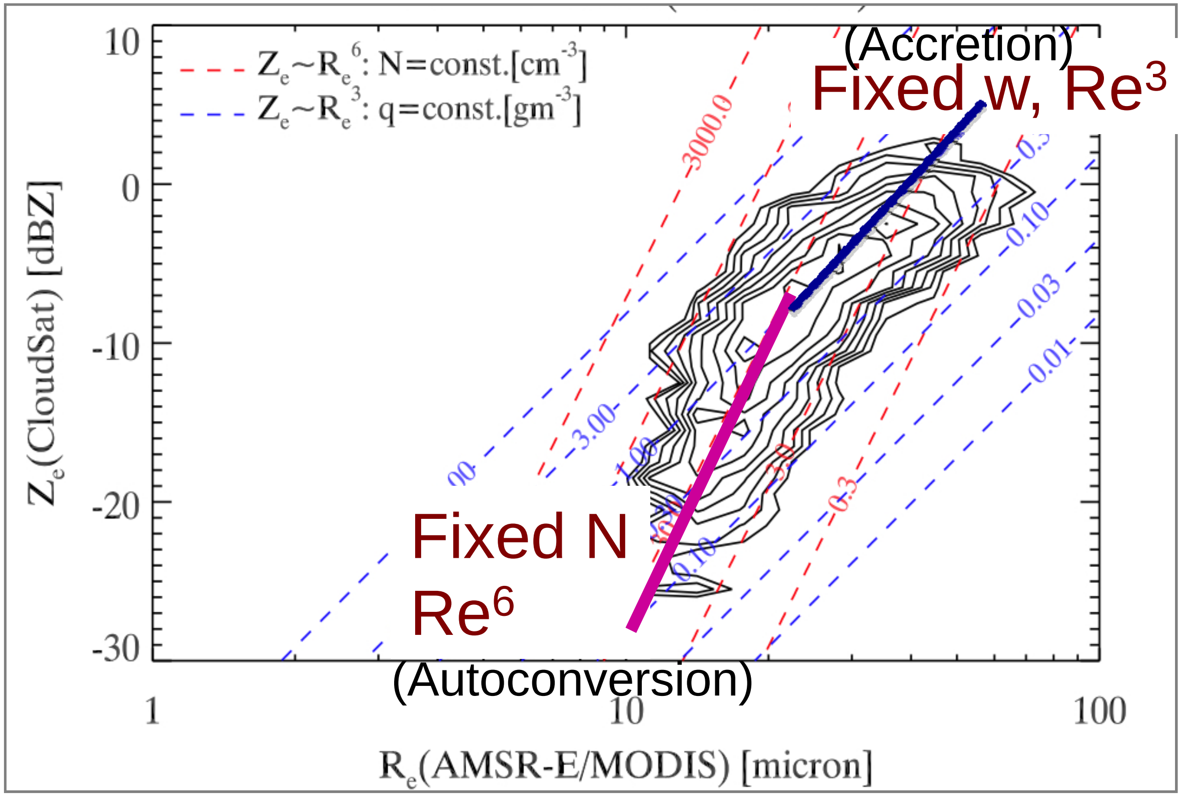
Masunaga et al., 2002a,b
Matsui et al., 2004

The relationships

$$Z_e \approx 64 N R_e^{\,6}$$

$$Z_e \approx \frac{48}{\pi \rho_w}(w) R_e^{\,3}$$

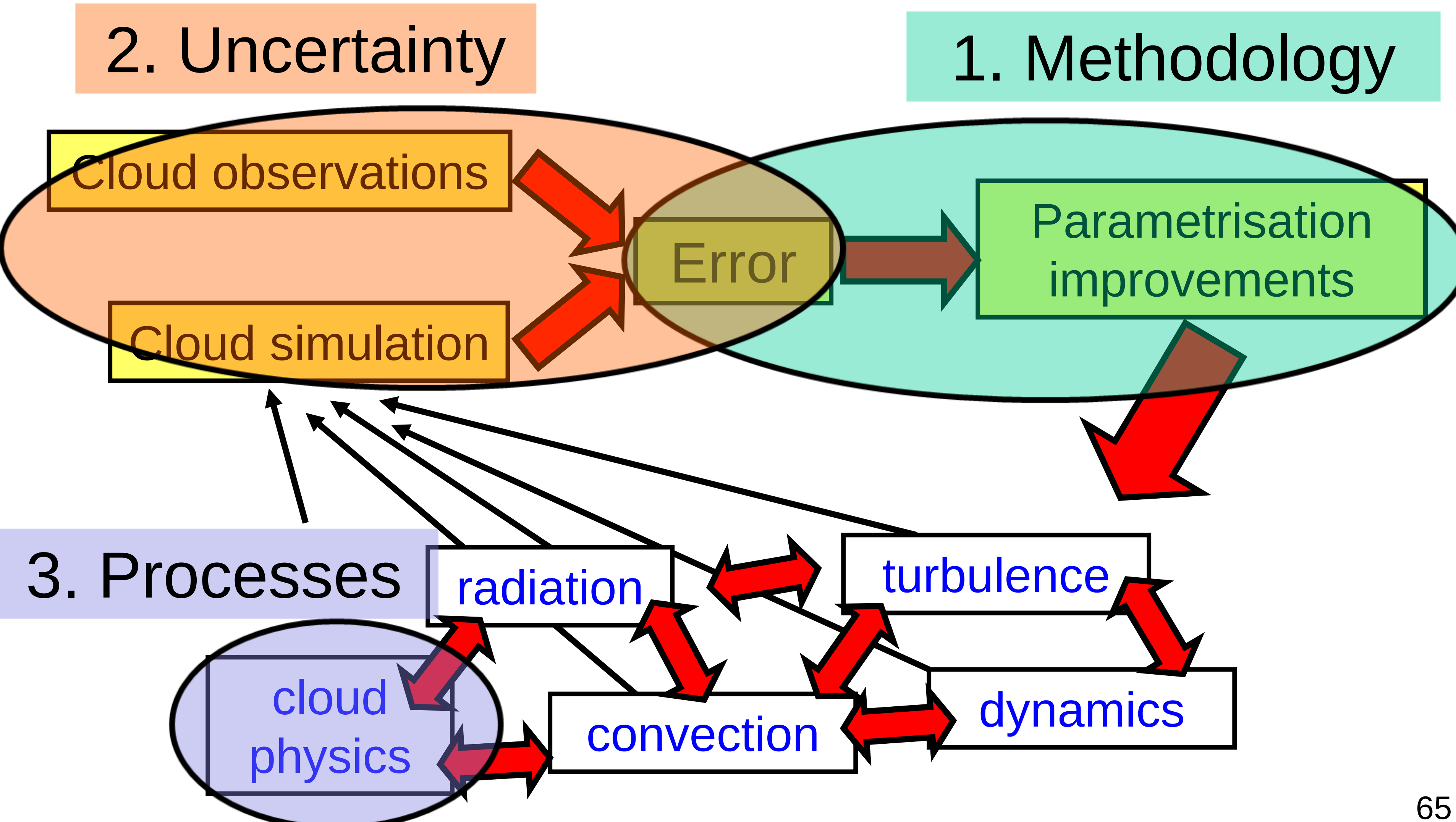
Suzuki and Stephens, 2008



From Graeme Stephens

Summary

Cloud Validation: The problems



Summary

1. **Methodology**

   Different approaches to verification (climate statistics, case studies, composites), resolution

2. **Comparing model and obs: Uncertainty and limitations**

   Need to **understand the limitations** of observational data.

   Different techniques (model-to-obs, obs-to-model) and a **range of observations** are required to validate and improve cloud parametrizations.

3. **Processes**

   Can observations be used to test model's **physical relationships** between variables and to understand physical processes.