Model Evaluation:
Clouds and the Boundary Layer

ECMWF training course

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Maike Ahlgrimm

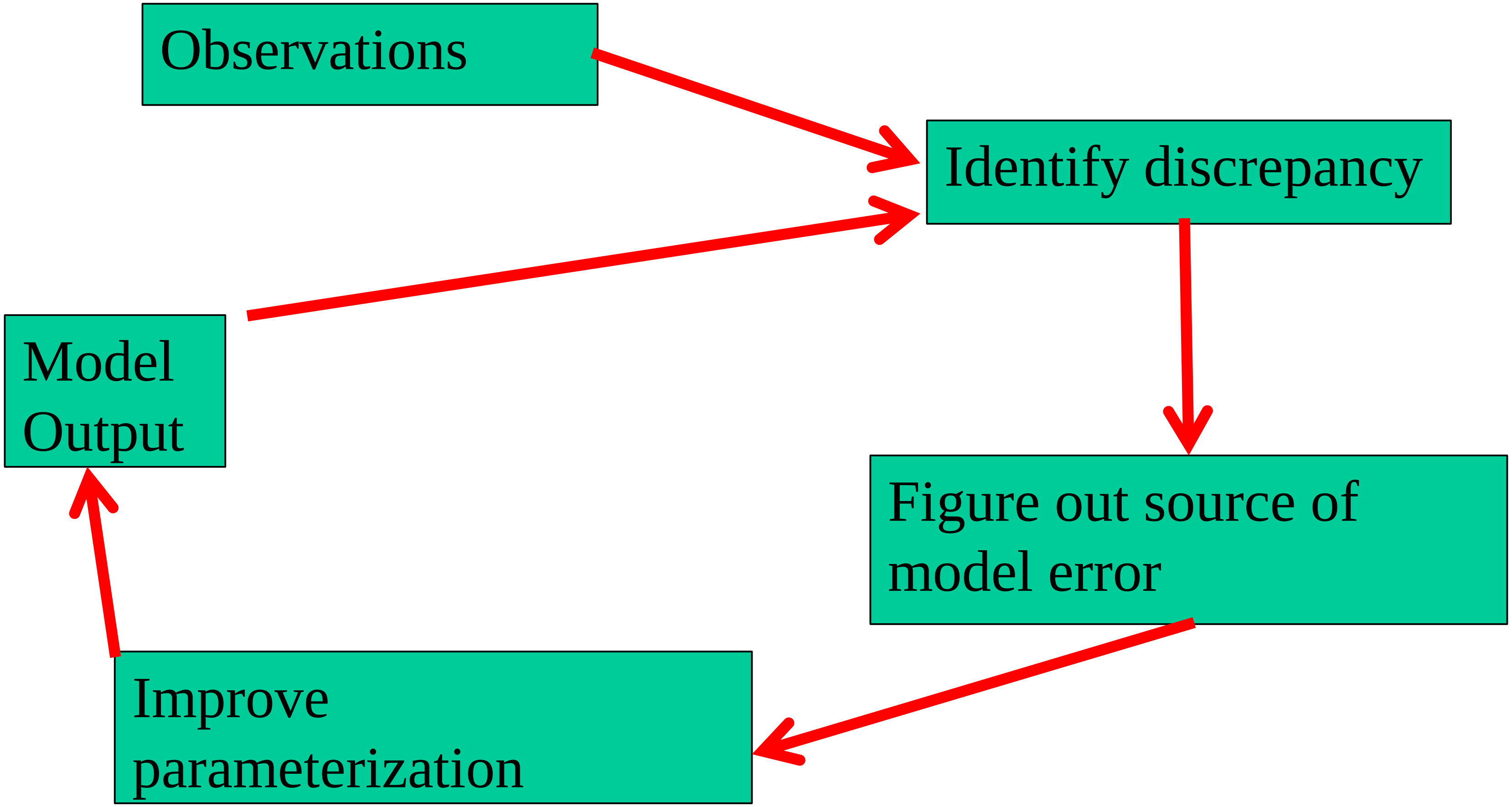
Aim of this lecture

- To give an overview of:
  - Evaluation strategies, with particular focus on methodologies that will help with parameterization development
  - Observation types for BL and cloud evaluation
  - Limitations of model evaluation due to uncertainties and differences in observed and modelled quantities
- By the end of this session you should be able to:
  - Identify data sources and products suitable for cloud and BL verification
  - Recognize the strengths and limitations of the verification strategies discussed
  - Choose a suitable verification method to investigate model errors in boundary layer height, transport, cloud occurrence and properties.

Overview

1. General strategy for model evaluation
2. Clouds
    1. Process-oriented evaluation
    2. Observations and their uncertainties
3. Boundary Layer
    1. Which aspects of the BL can we evaluate?
    2. What does each aspect tell us about the BL?
    3. Observations and their advantages and limitations

General strategy for model evaluation and improvement



Observations

Identify discrepancy

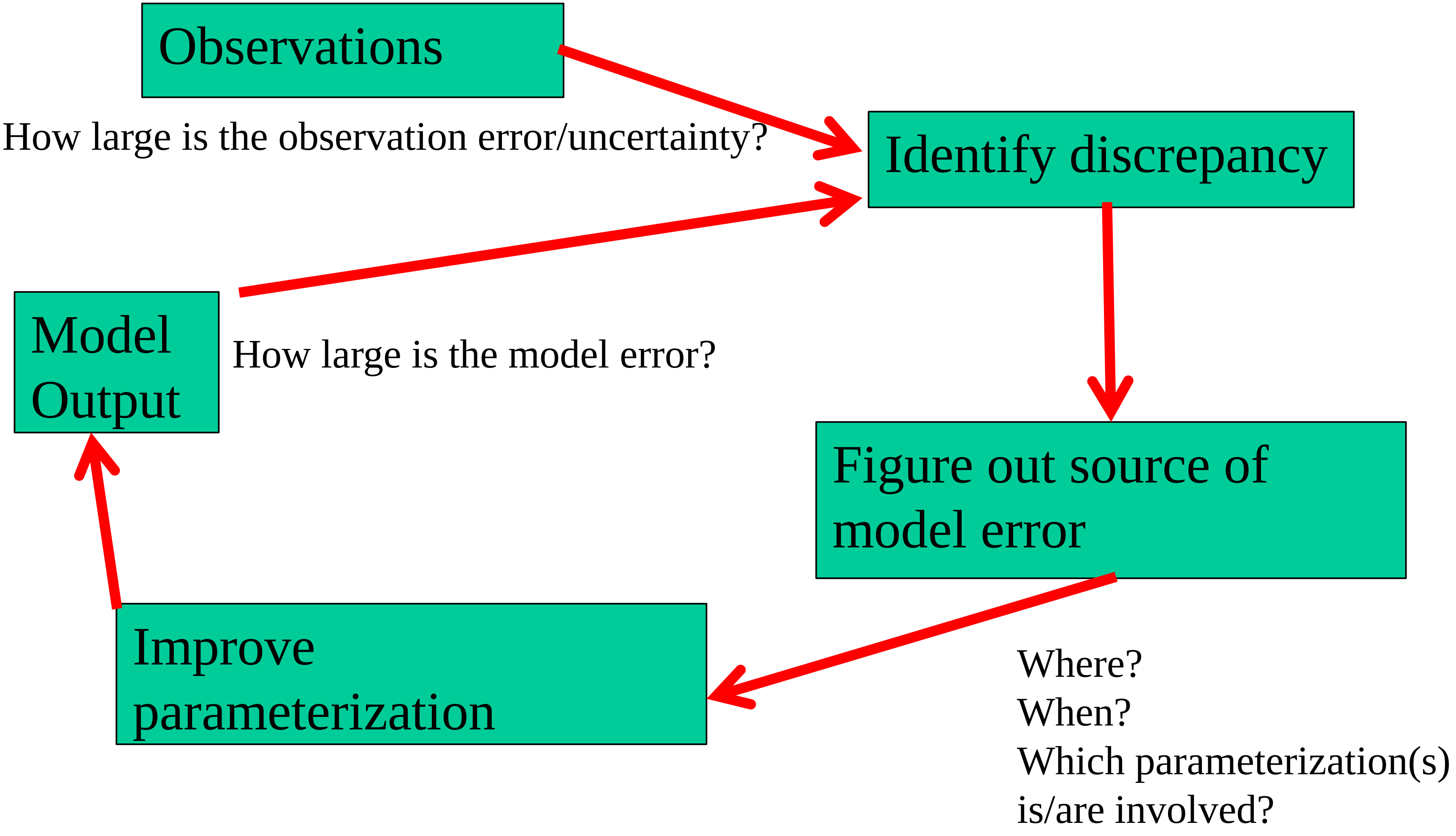
Model Output

Figure out source of model error

Improve parameterization

Conceptually simple, but the devil is in the detail!

General strategy for model evaluation and improvement



Observations

How large is the observation error/uncertainty?

Identify discrepancy

Model Output

How large is the model error?

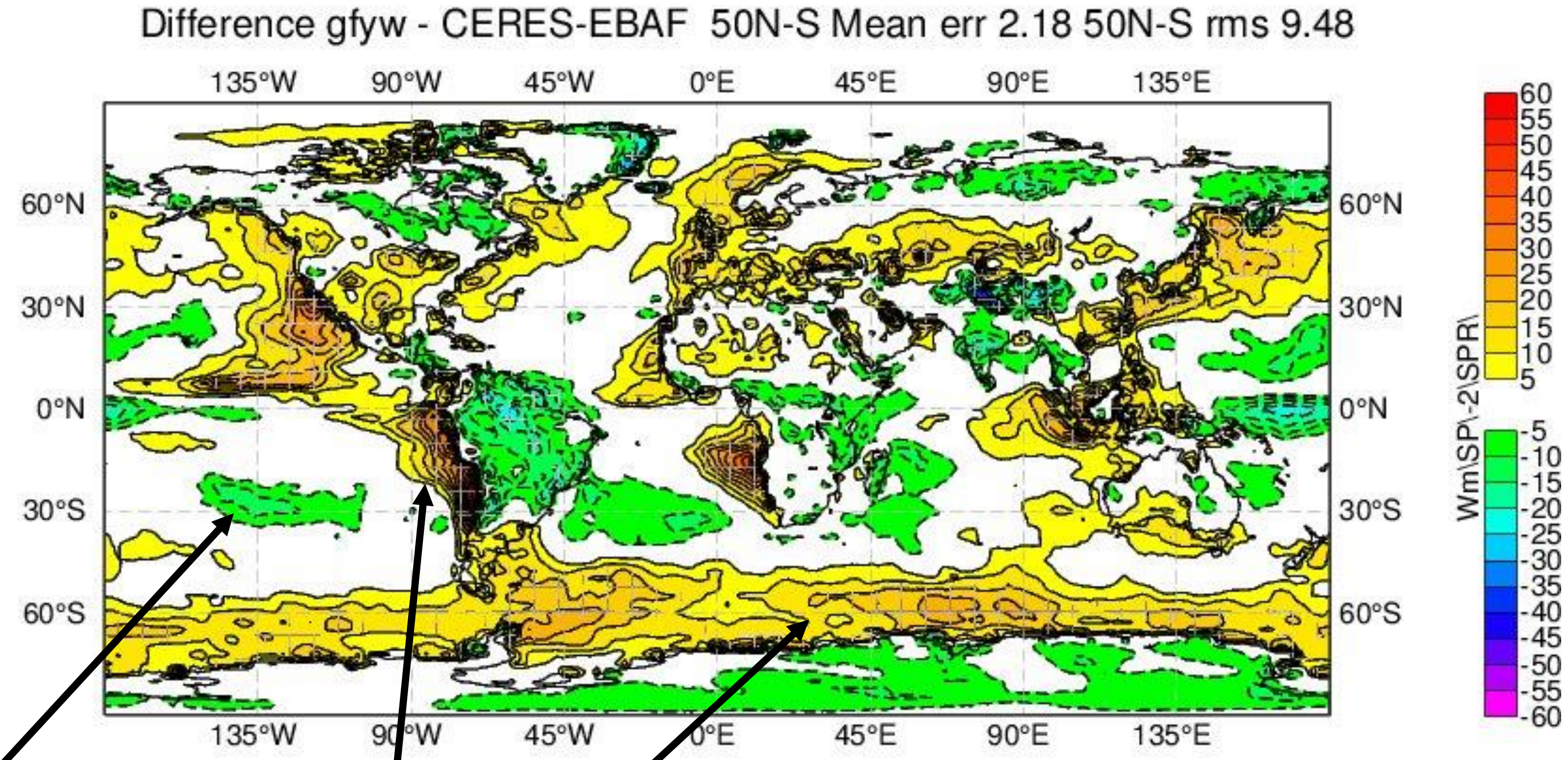
Figure out source of model error

Improve parameterization

Where?
When?
Which parameterization(s) is/are involved?

Process-oriented evaluation – why?

TOA broadband SW radiation shows pattern of systematic error



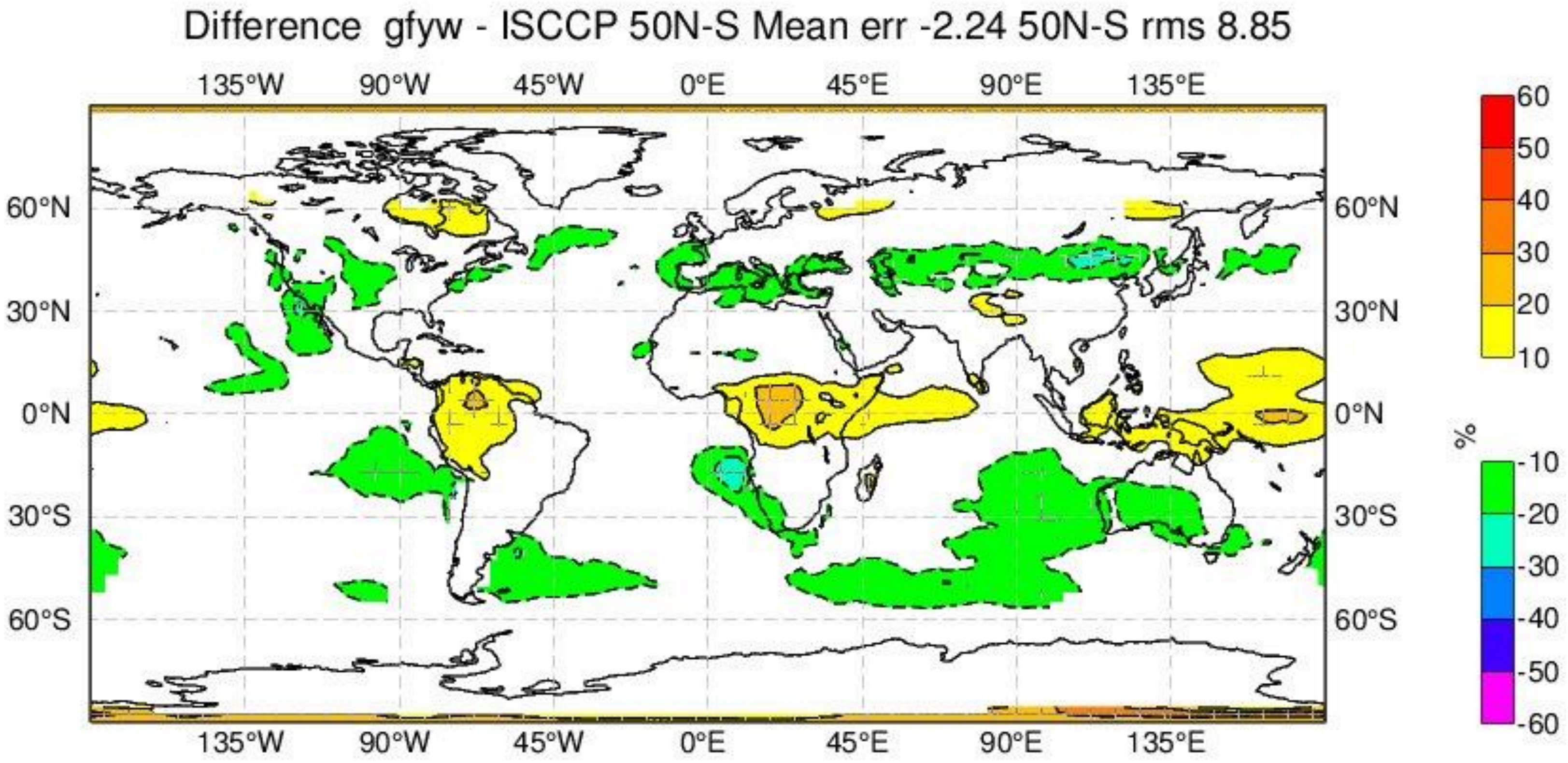
Too bright,
cloud too reflective

Or maybe surface albedo?

What is causing these errors?

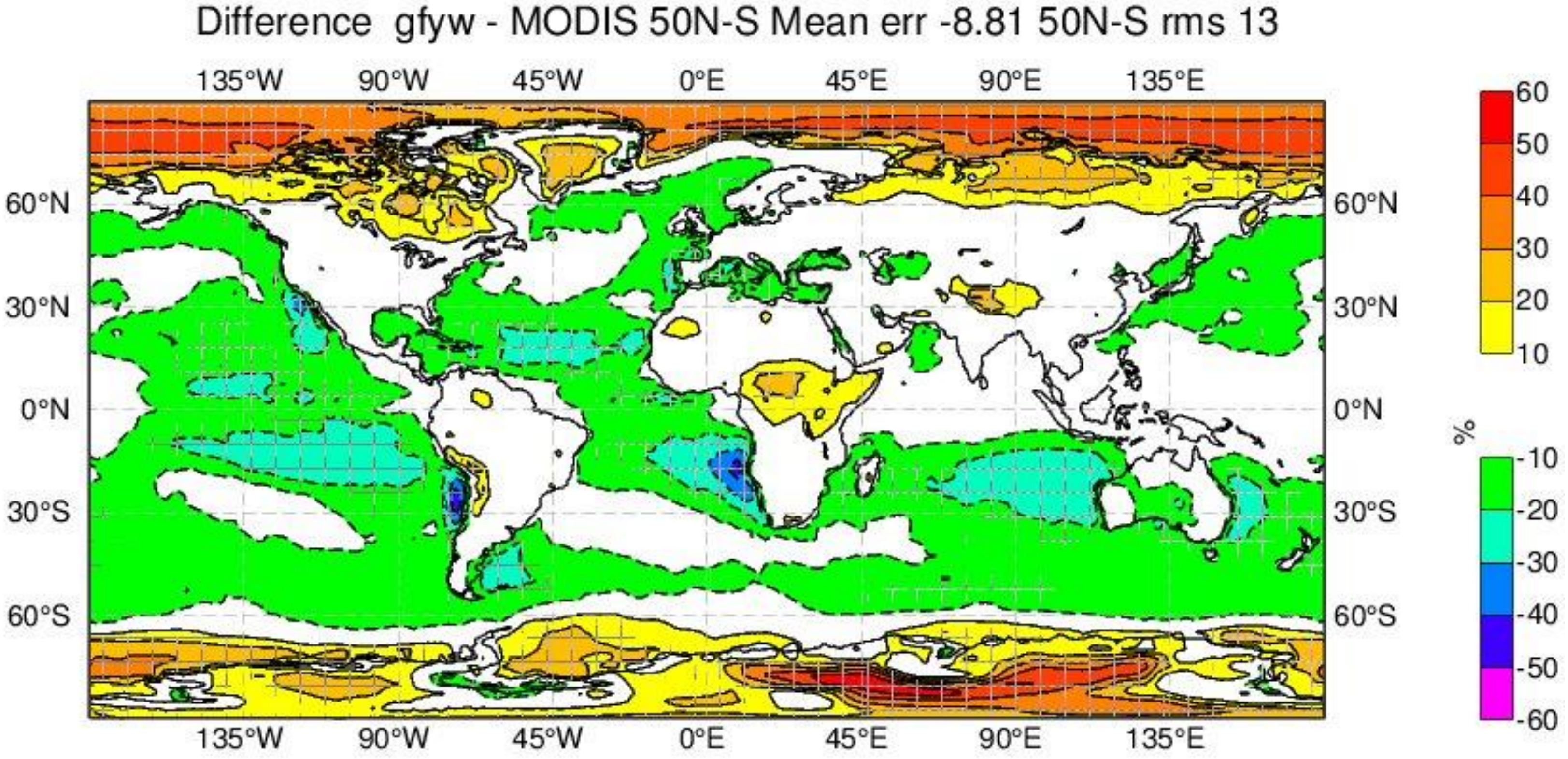
Too dark, clouds don’t reflect enough

Total cloud cover bias - ISCCP



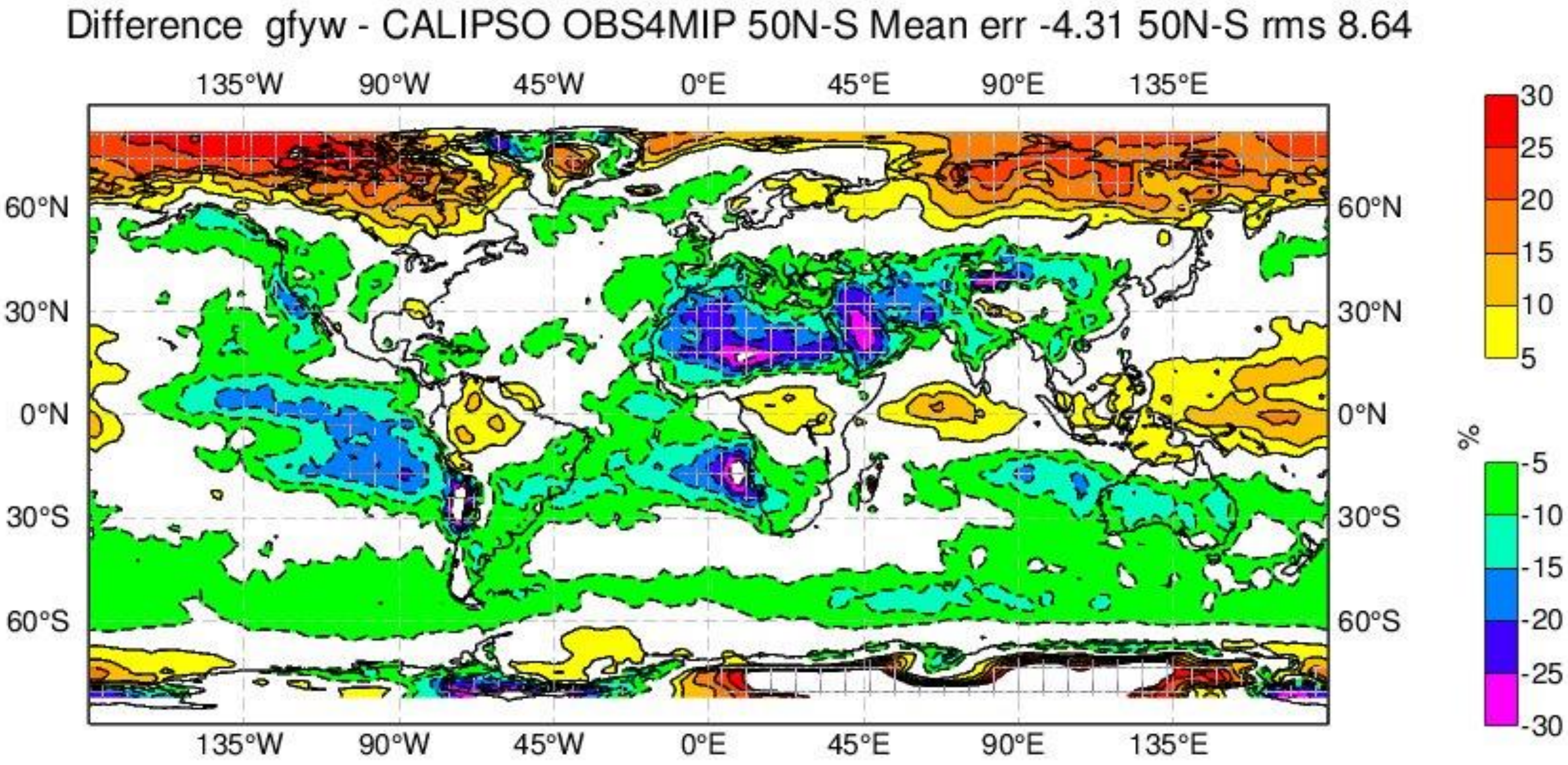
Traditional cloud product based on brightness temperatures – not bad, right?

Total cloud cover bias - MODIS



Total cloud cover from MODIS

Total cloud cover bias - CALIPSO

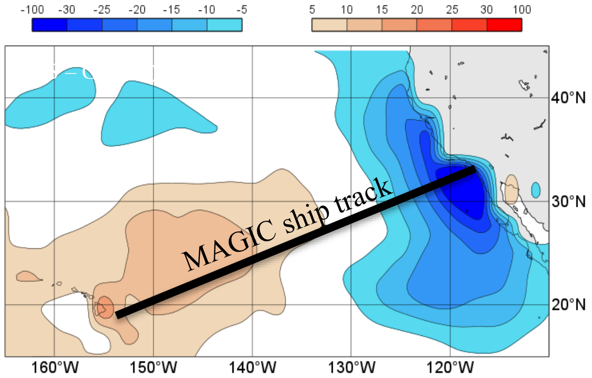


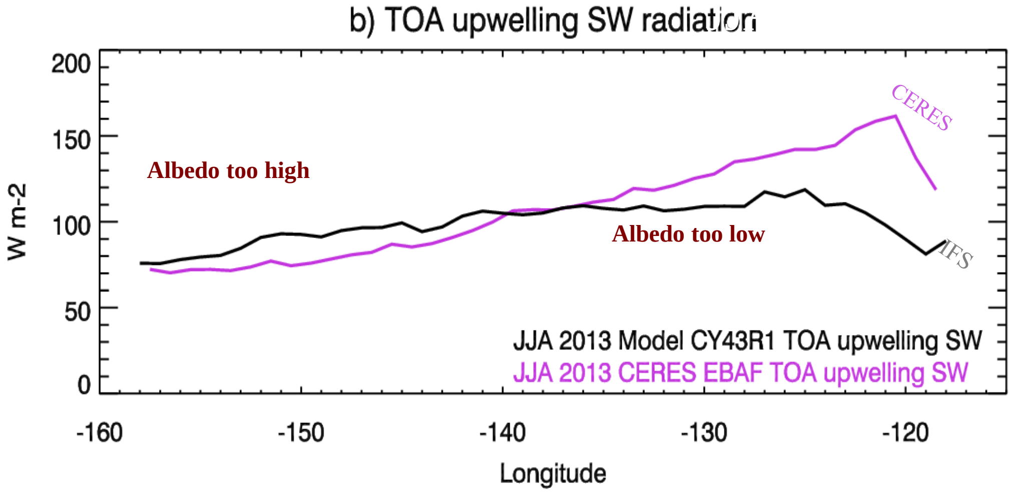
Total cloud cover from CALIPSO

How to disentangle contributions to model bias?

- Short-term forecast vs. climate runs
    - Close to observed state
    - Limit interactions, look for causality
    - Initial tendencies
- Compositing of long-term data by regime/type/bias growth
    - CAUSES
    - Shallow cloud in the IFS
- Educated guess/Case studies
    - Cold sector of cyclones

Typical marine BL SW bias found in short-term (12-36 hour) forecasts as well as climate





IFS albedo too high in trades

IFS albedo too low in stratocumulus

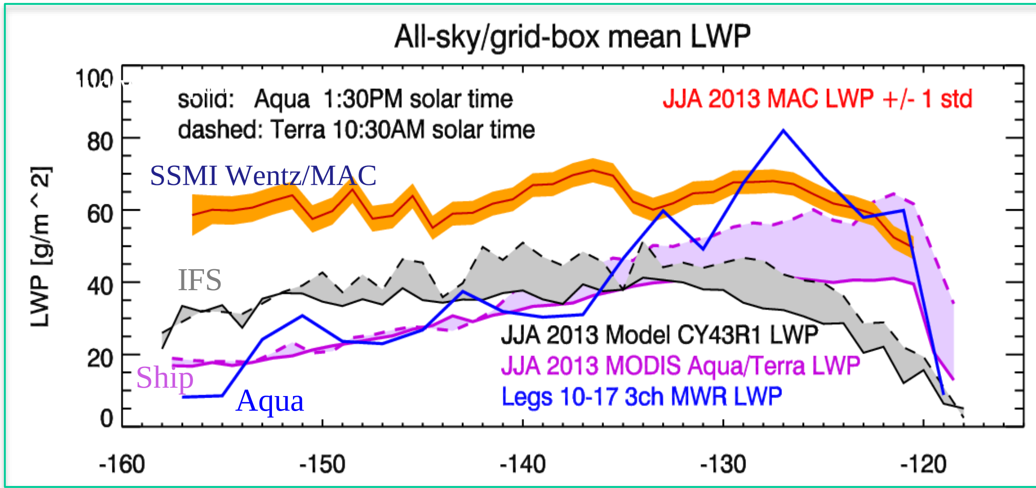
Potential contributors:

- Cloud fraction
- (Gridbox-mean) condensate amount
- Effective radius
- Heterogeneity assumption
- Cloud (vertical) overlap
- 3D radiative effects

Beware the diurnal cycle! Cloud fraction ok in Cu, too low near coast

Ahlgrimm, Forbes, Hogan, Sandu; JAMES (2018)

LWP – too high or too low?



IFS LWP too low vs widely used satellite microwave retrievals *(Painemal et al 2016)*

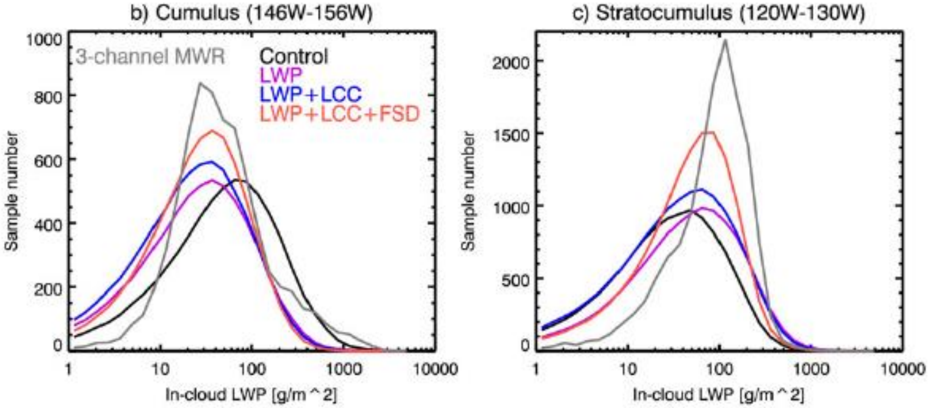
..but IFS LWP too high versus ship MWR and MODIS !

All-sky LWP not that helpful a measure – strongly influenced by high-end tail of LWP distribution, which is poorly constrained.

It's the distribution of in-cloud LWP that counts! (for SW rad)

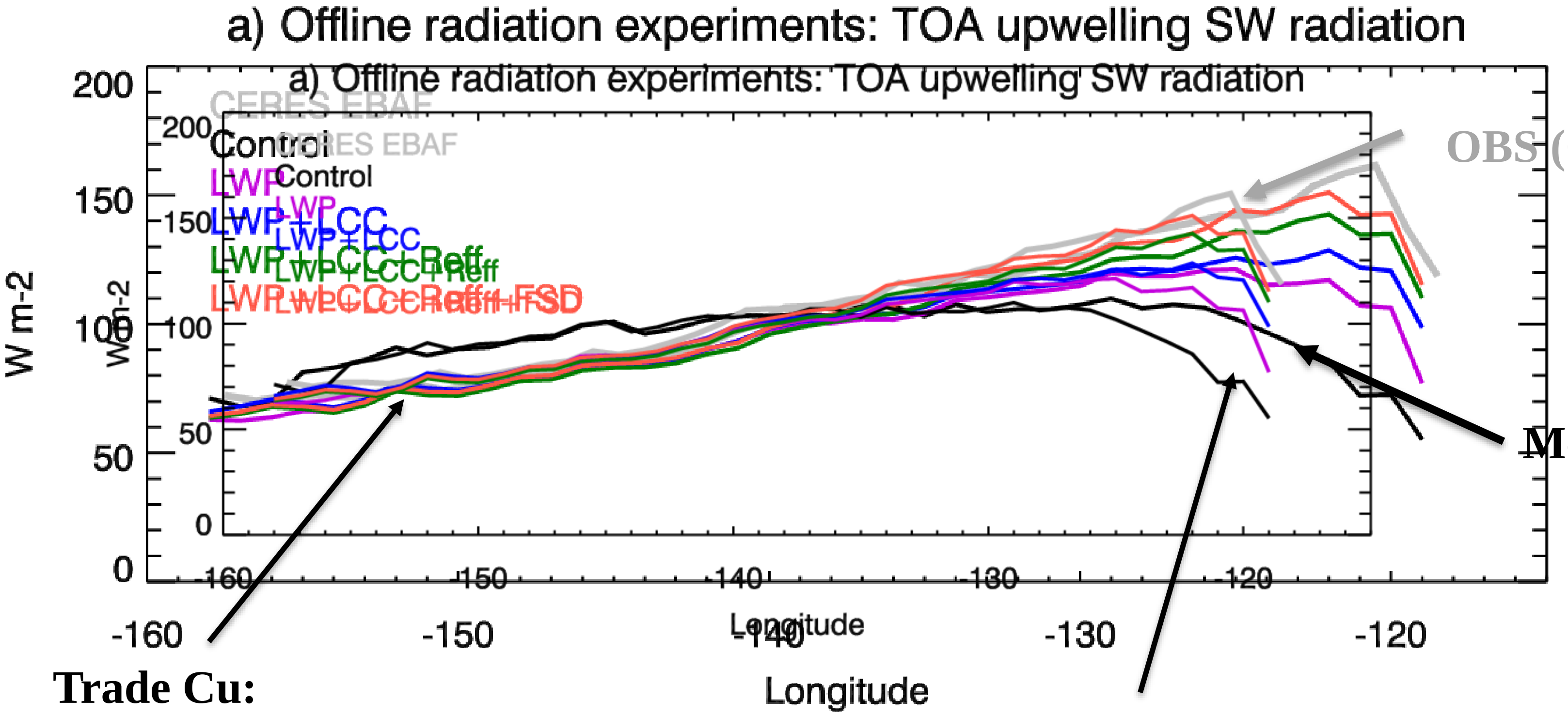
Distribution can be shifted by changing

- Gridbox-mean condensate amount
- Cloud fraction
- Heterogeneity assumption



Ahlgrimm, Forbes, Hogan, Sandu; JAMES (2018)

TOA SW radiation from ECRAD offline experiments



OBS (CERES-EBA

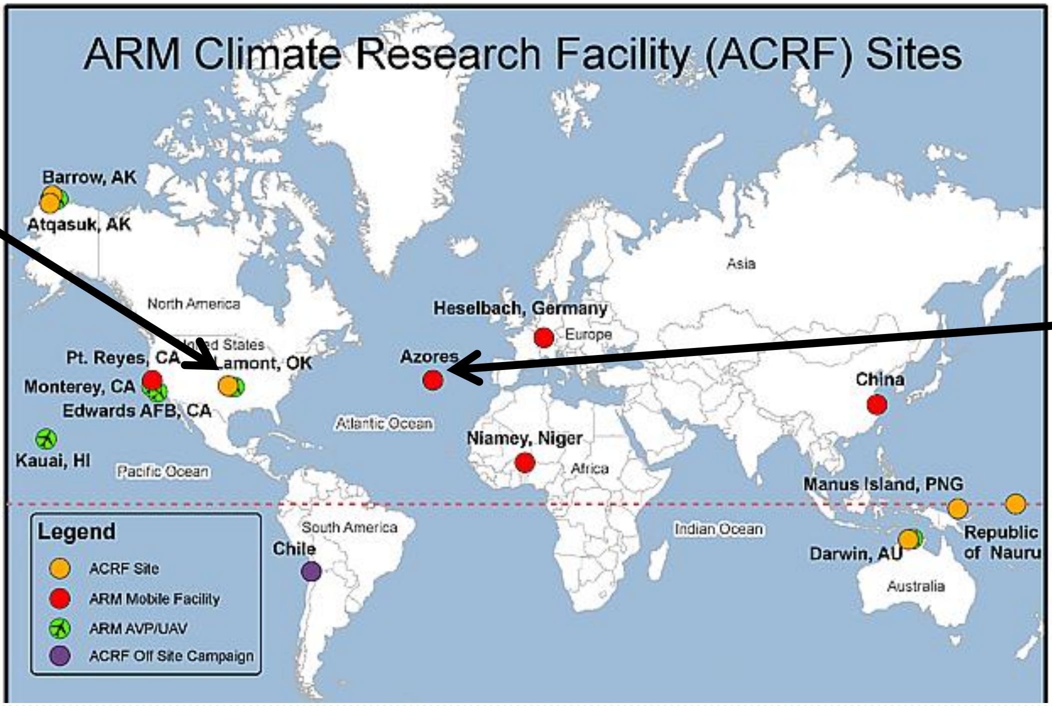
Model (control)

Trade Cu:
Greatest impact from reducing LWP
Cloud fraction, Reff and heterogeneity already ok (but also less impact from microphysical changes due to lower LCC)

Stratocumulus:
Cloud fraction and LWP explain about 60% of SW bias
Reff and heterogeneity also need to improve

This exercise helps to prioritise

Compositing of long-term data records



Global ARM and Cloudnet observation sites

devcloudnet.fmi.fi
www.arm.gov

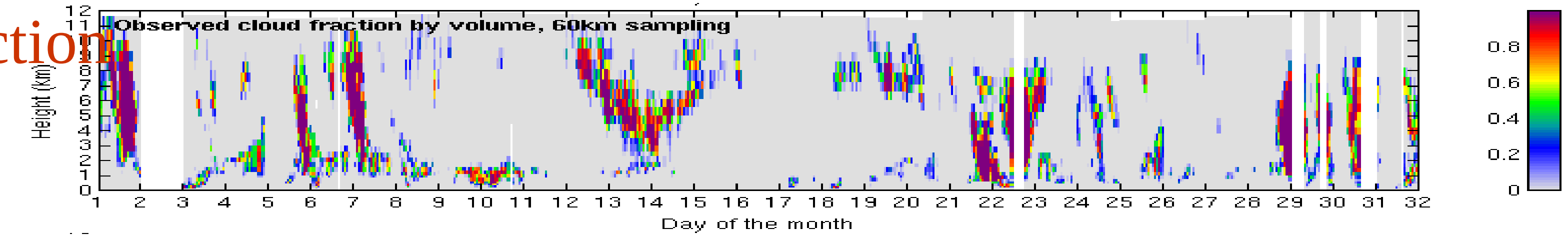
Chilbolton, UK
51.1445 North 1.4370 West
Operated by RCRU, RAL.

SIRTA, Palaiseau (Paris), France
48.713 North 2.204 Est
Operated by CNRS/IPSL

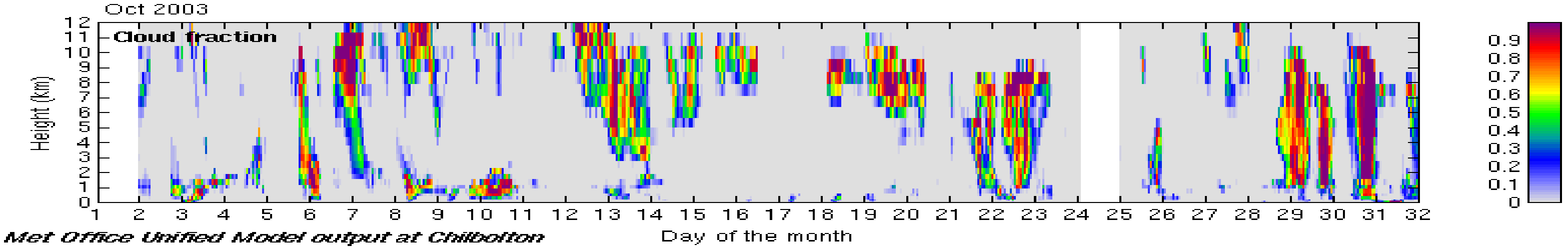
Cabauw, The Netherlands
51.971 North 4.927 Est
Operated by KNMI

Cloud fraction

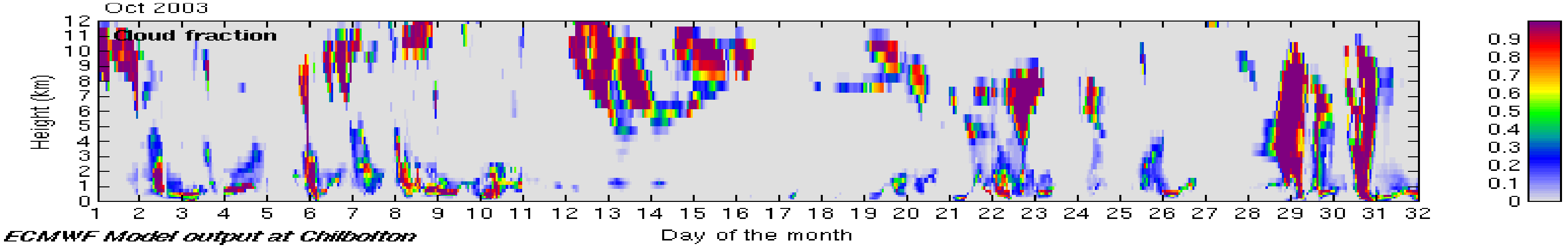
Chilbolton
Observations



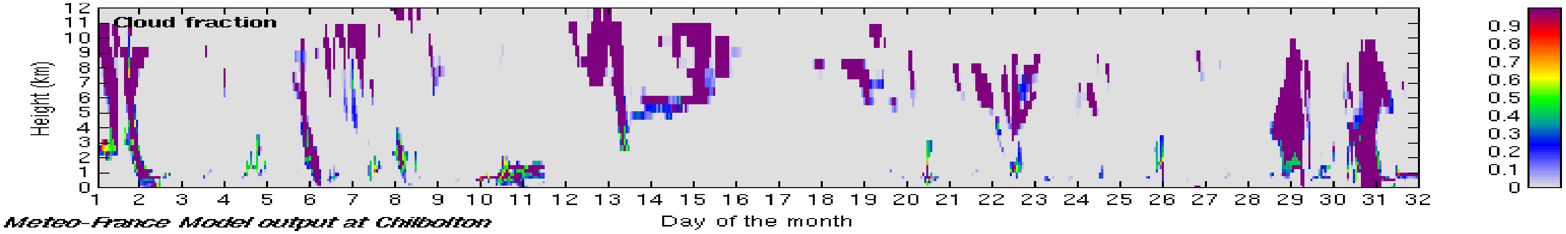
Met Office
Mesoscale
Model



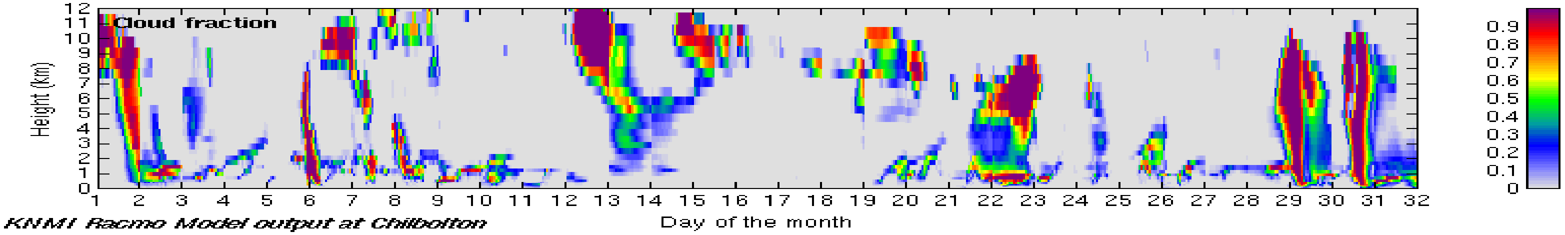
ECMWF
Global Model



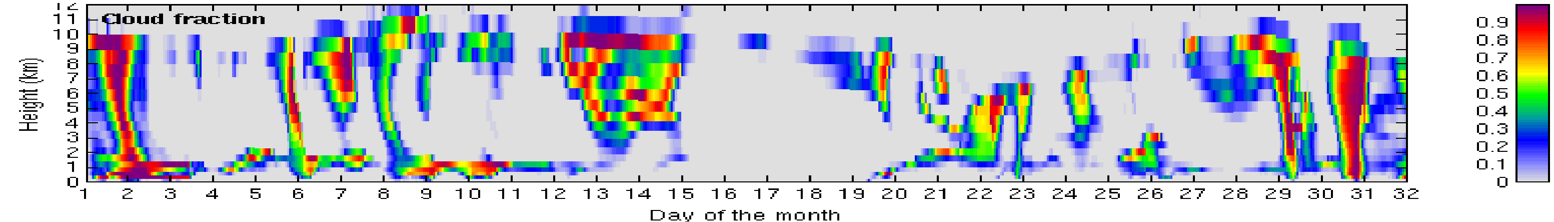
Meteo-France
ARPEGE Model



KNMI
RACMO Model

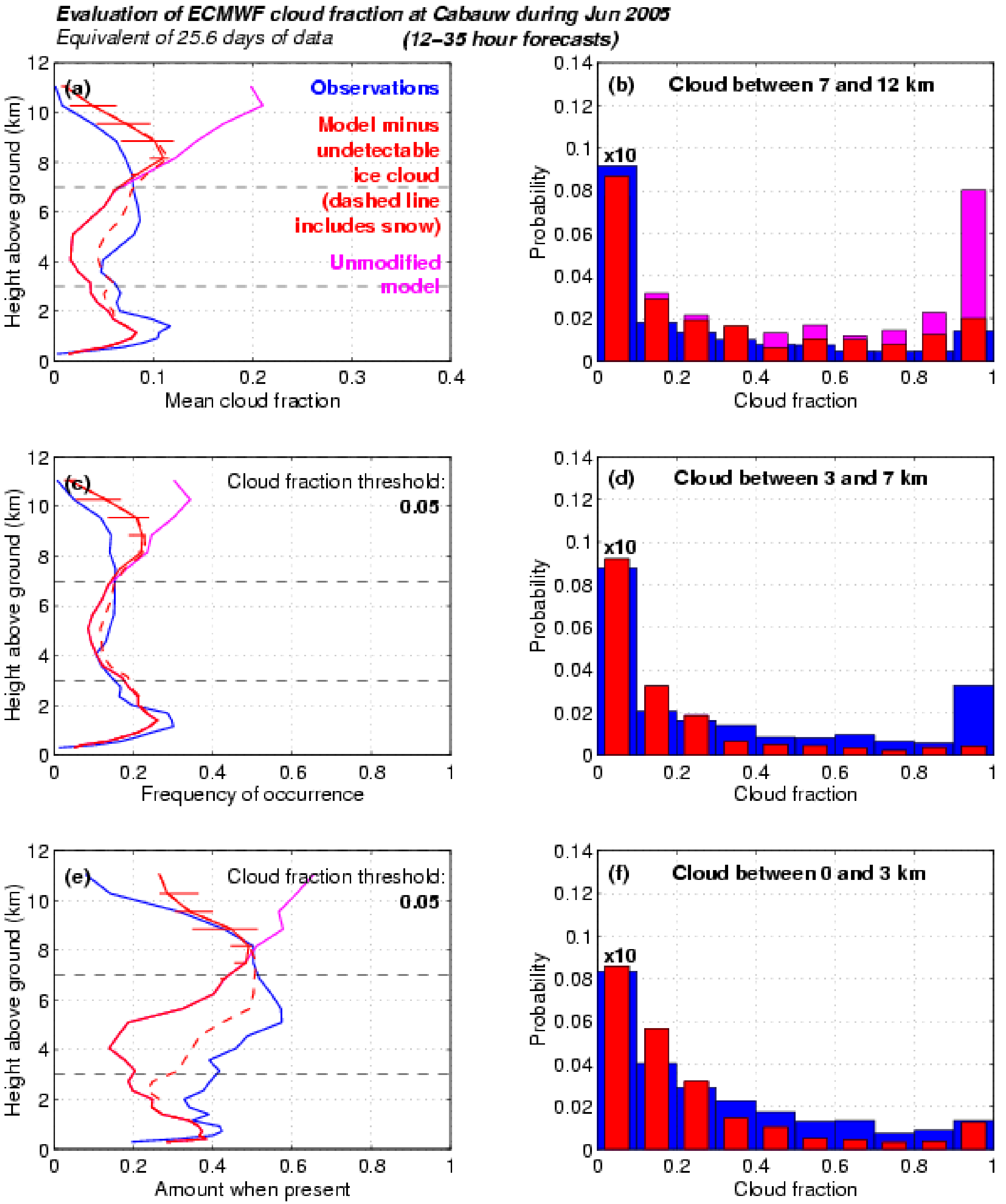


Swedish RCA
model



Statistical evaluation:
CloudNet Example

- In addition to standard quicklooks, longer-term statistics are available.
- This example is for ECMWF cloud cover during June 2005.
- Includes pre-processing to account for radar attenuation and snow.
- See devcloudnet.fmi.fi for more details and examples!



“Smart” compositing: let the bias tell you what is important

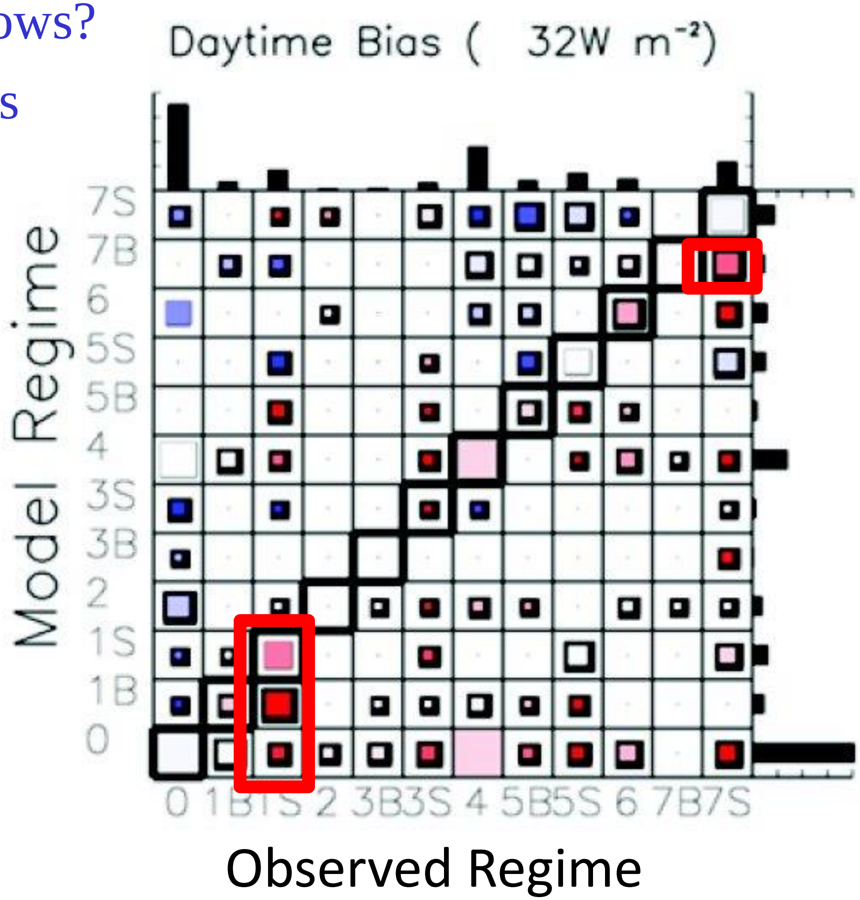
Which cloud type/regime contributes most to the radiation bias?

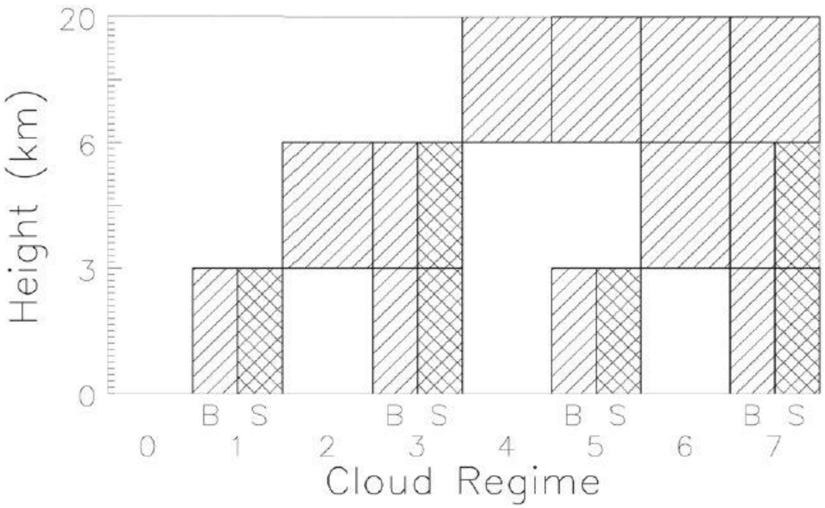
CAUSES project: What contributes to the 2m temperature bias over North America?

Is there a net radiation error when the bias grows?

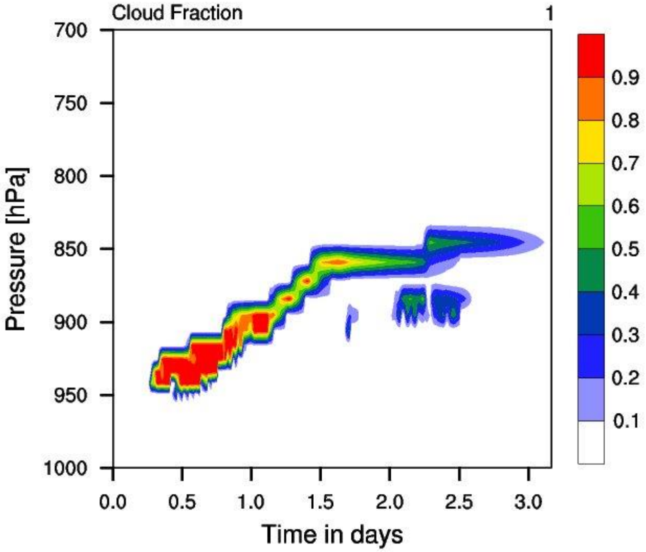
If so, what clouds are associated with that bias growth?

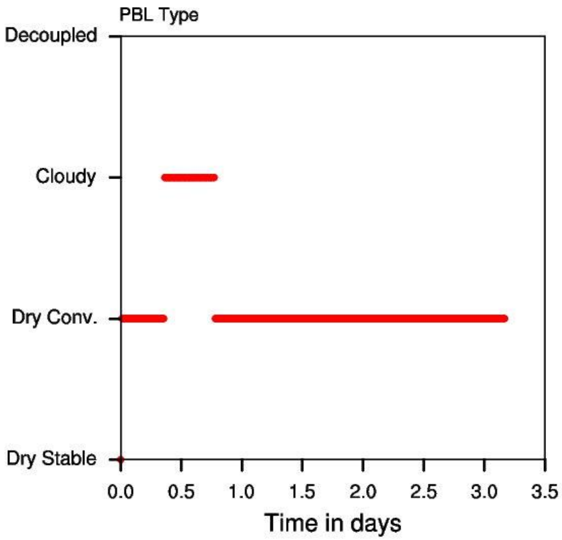
Size: frequency
Colour: bias magnitude

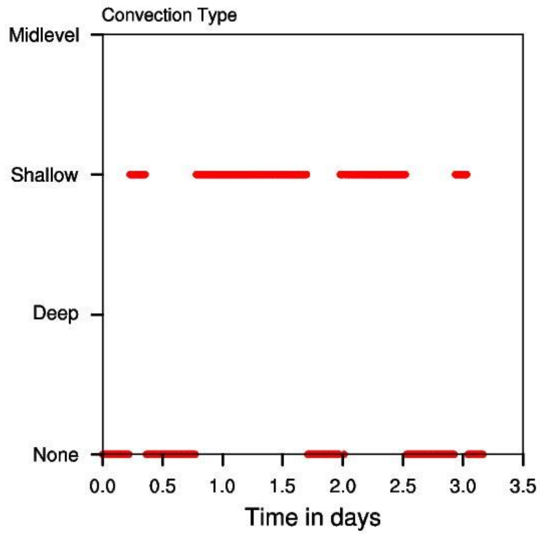


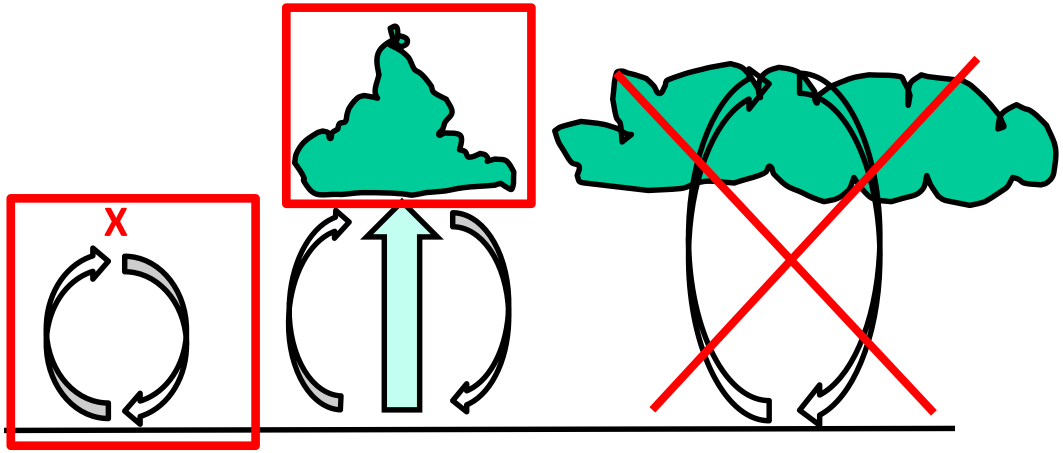


What does the BL and shallow Cu parameterization do?









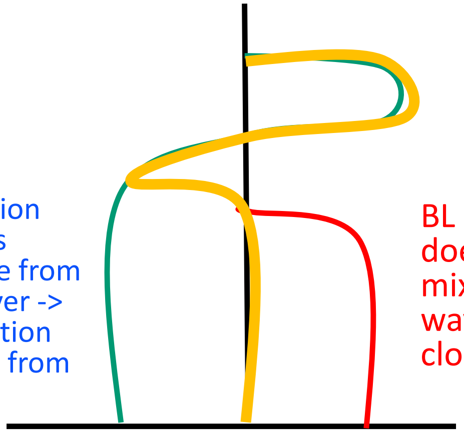
BL parcel rarely reaches LCL

shallow conv scheme active anyway

Sc type rare

Test parcel ascent

Convection removes moisture from a dry layer -> evaporation of cloud from below



BL scheme doesn’t mix all the way to cloud base

Moisture tendency

The shallow cloud problem has contributions from many interacting and partially compensating processes!

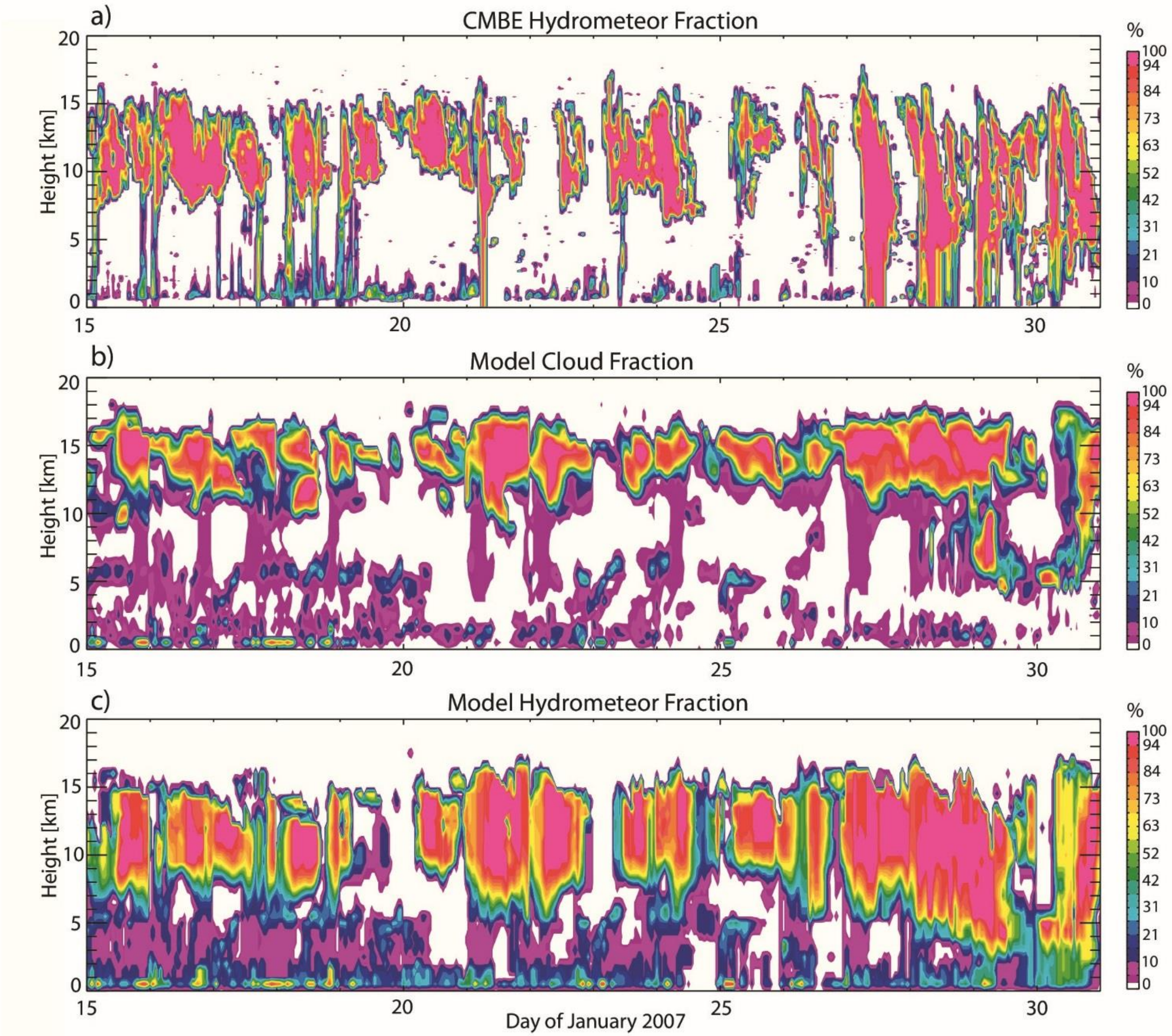
Error contributions from:

- Triggering of shallow convection/stratocumulus scheme
- Water amount in clouds
- Representation of cloud heterogeneity (or lack thereof)
- Unrealistic autoconversion/accretion and evaporation rates
- Error in effective radius

Observation types and uncertainties

- What is a cloud? It’s all (or mostly) electromagnetic radiation…
  - brightness temp
  - radar reflectivity
  - backscatter
  - sensitivity threshold
- How accurately can we measure this quantity?
  - Observation error/uncertainty
  - Conditional sampling (e.g. viewing geometry, instrument shut off)
  - Signal attenuation, noise from other stuff (insects, aerosol)
- How well does this quantity compare to variables predicted by the model?
  - Retrieval error
  - Forward model error

Cloud ice – what is it?



Whatever the ground-based radar detects.

Only suspended cloud ice?

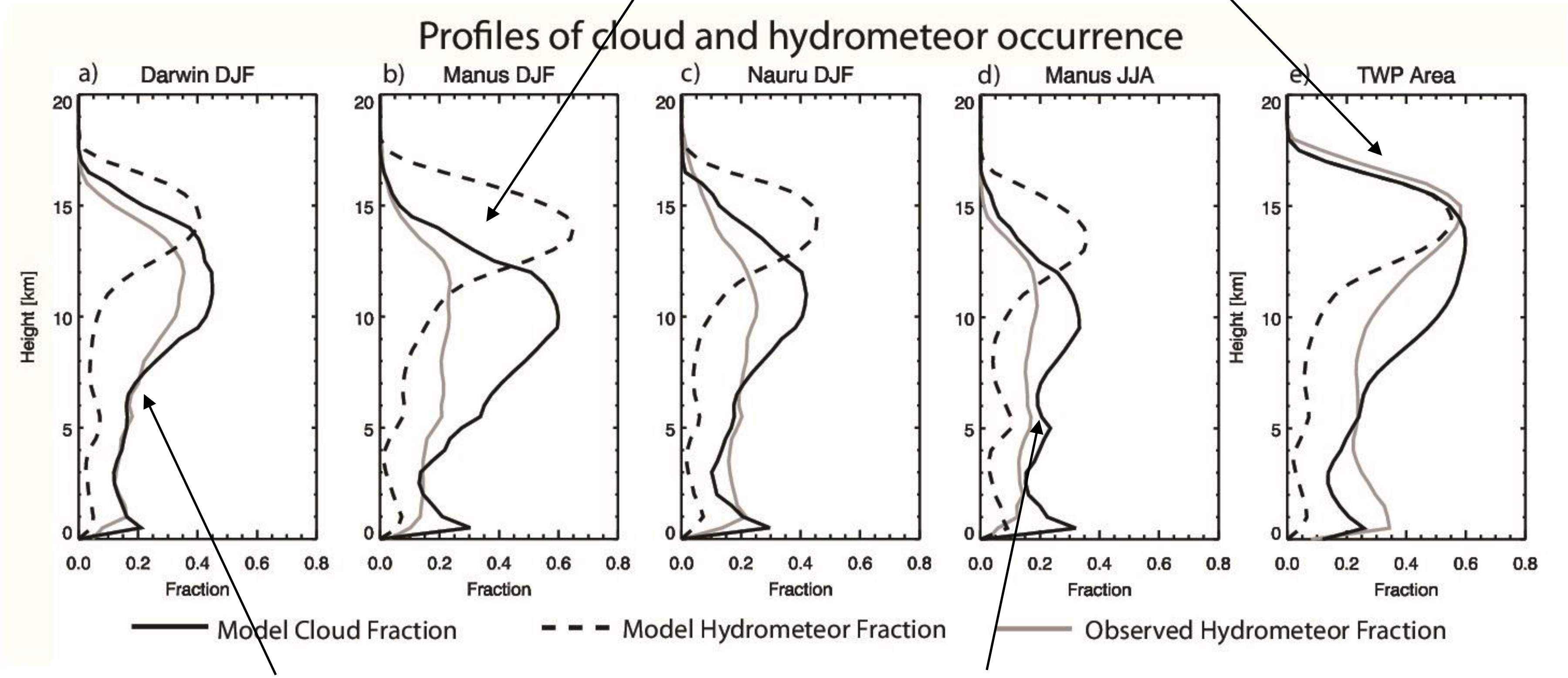
Cloud ice and precipitating snow?

What is the precipitation fraction?

TWP ICE, Darwin, Jan 2007

Ice cloud occurrence – we’re still mostly guessing!

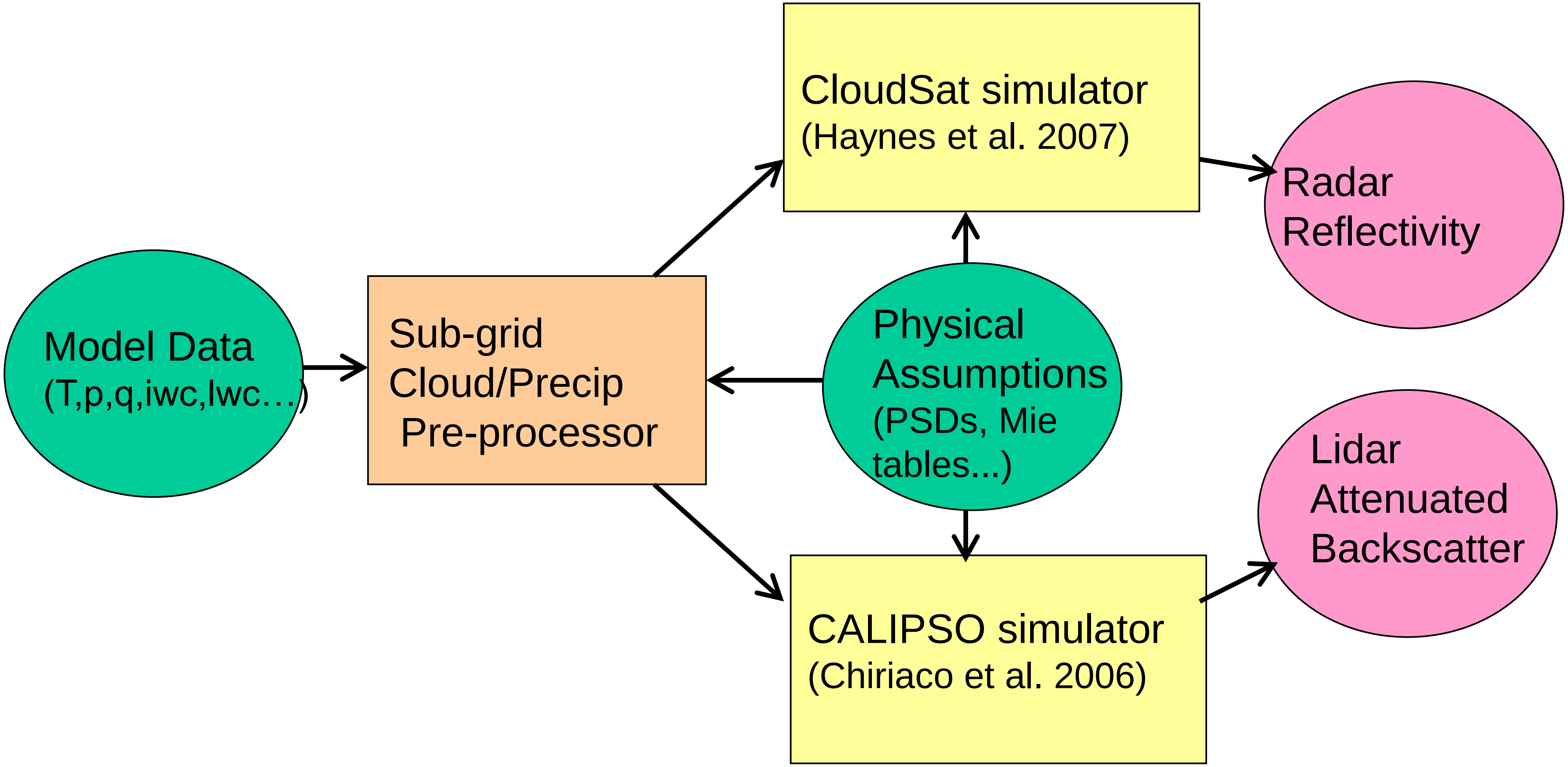
How much high cloud is missed?



Is the model really missing “mid-level cloud”?

Or should we rephrase: Can we constrain mid-level cloud amount? How good are the assumptions about precip fraction?

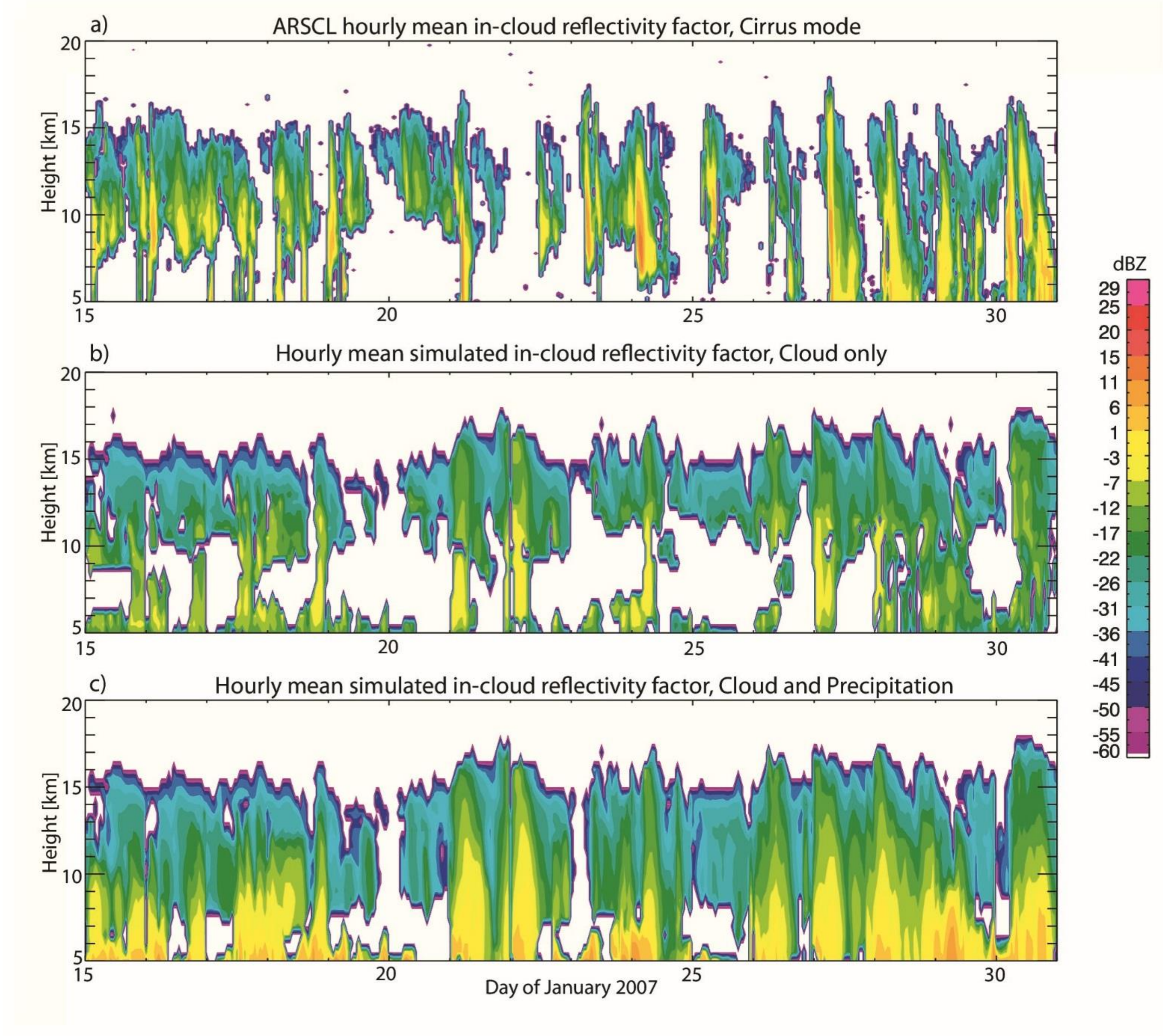
Simulating Observations CFMIP COSP radar/lidar simulator



http://cfmip.metoffice.com

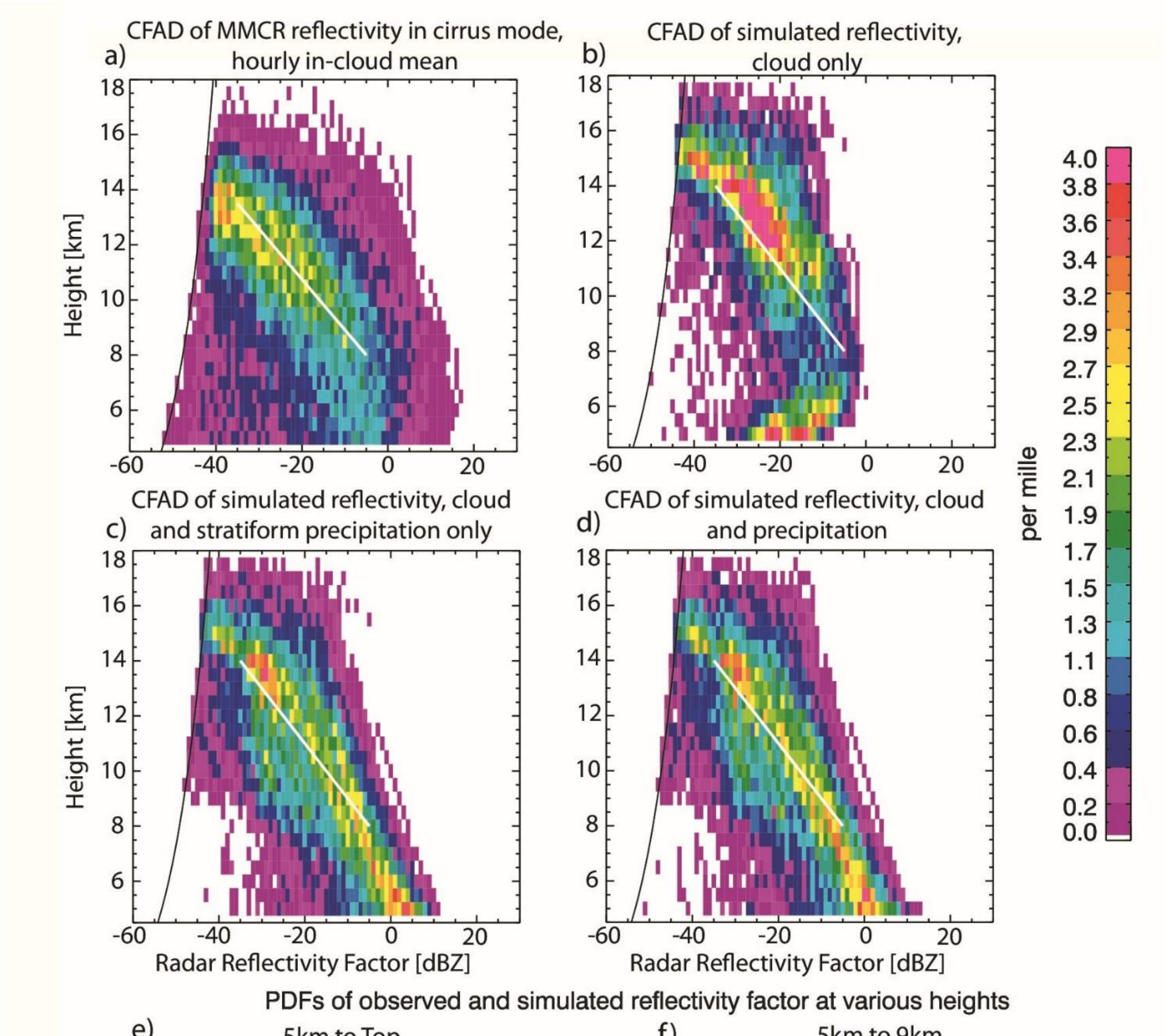
Note: COSP now has many more satellite simulators

Ice clouds: simulated reflectivity

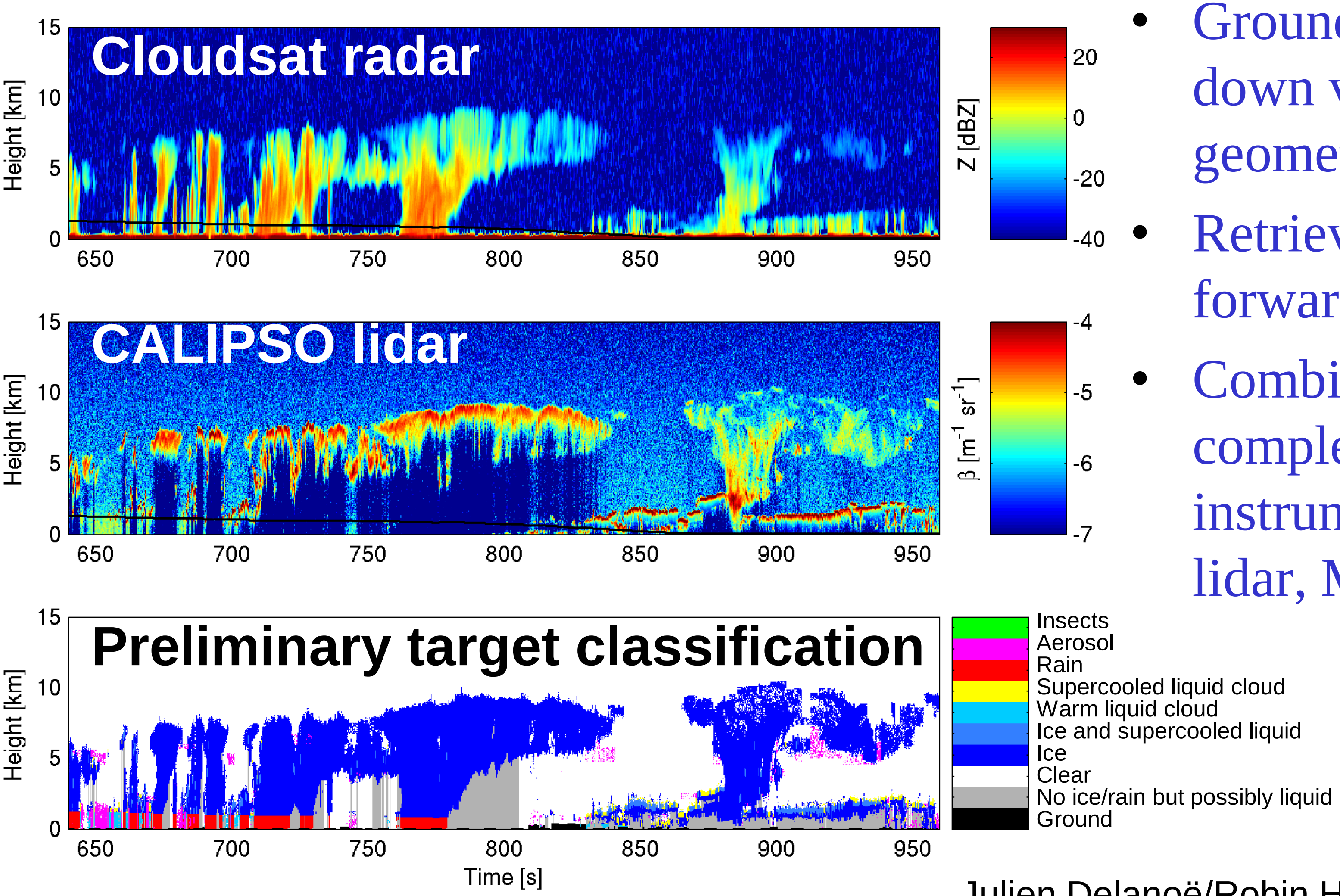


Precipitation introduces high dBZ values in simulated reflectivity

Ice clouds: simulated reflectivity CFADs



Consider all angles, and instrument synergy



- Ground-up and top-down viewing geometry
- Retrievals and forward models
- Combine complementary instruments (radar, lidar, MWR)

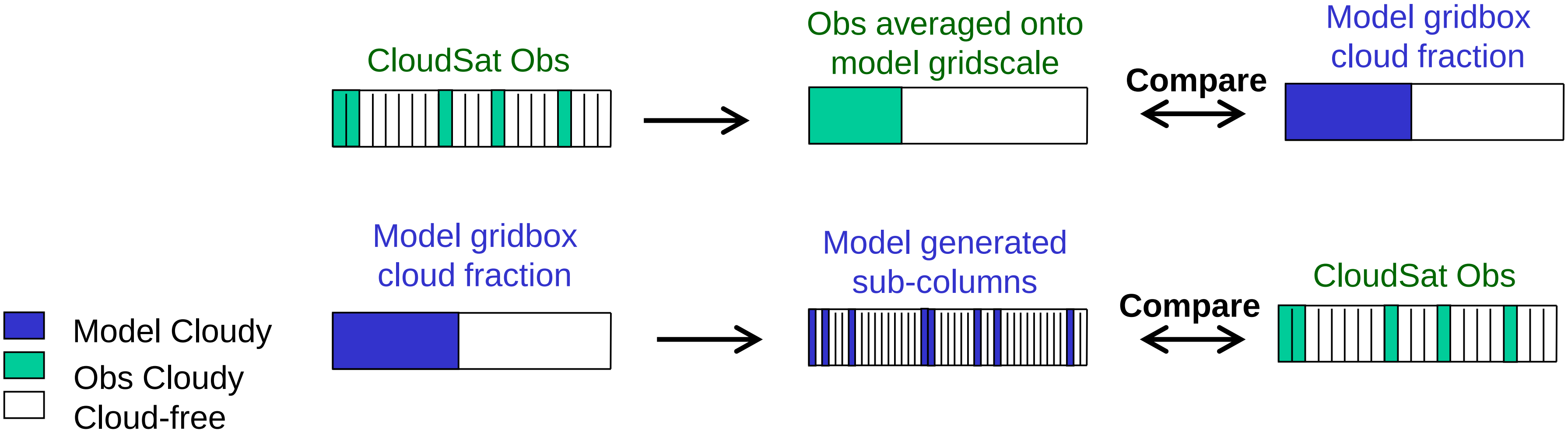
Julien Delanoë/Robin Hogan 2010

Representativity

- Need to address mismatch in spatial scales in model (50 km) and obs (1 km)
- Along-track/temporal variability vs. 3D spatial variability
- 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.



CloudSat Obs → Obs averaged onto model gridscale ⟷ **Compare** ⟷ Model gridbox cloud fraction

Model gridbox cloud fraction → Model generated sub-columns ⟷ **Compare** ⟷ CloudSat Obs

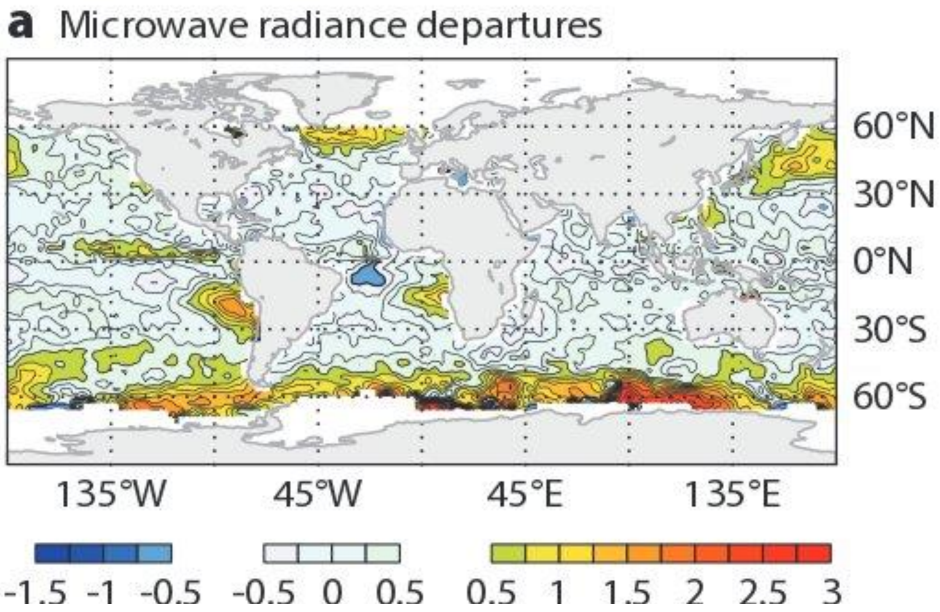
🟦 Model Cloudy

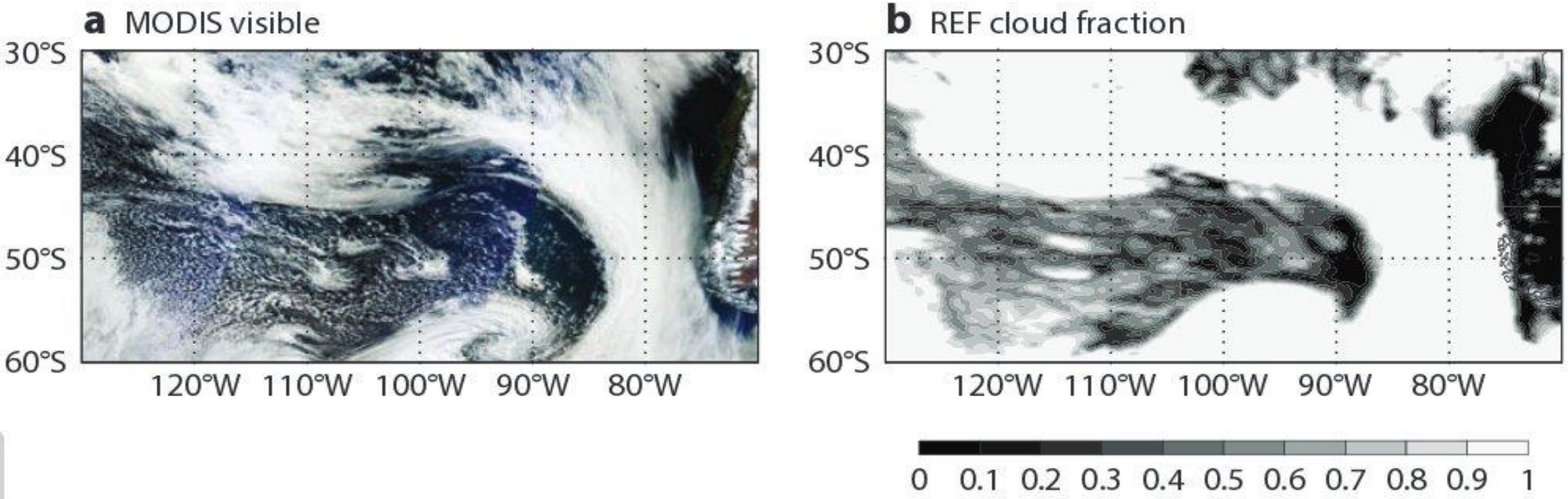
🟩 Obs Cloudy

⬜ Cloud-free

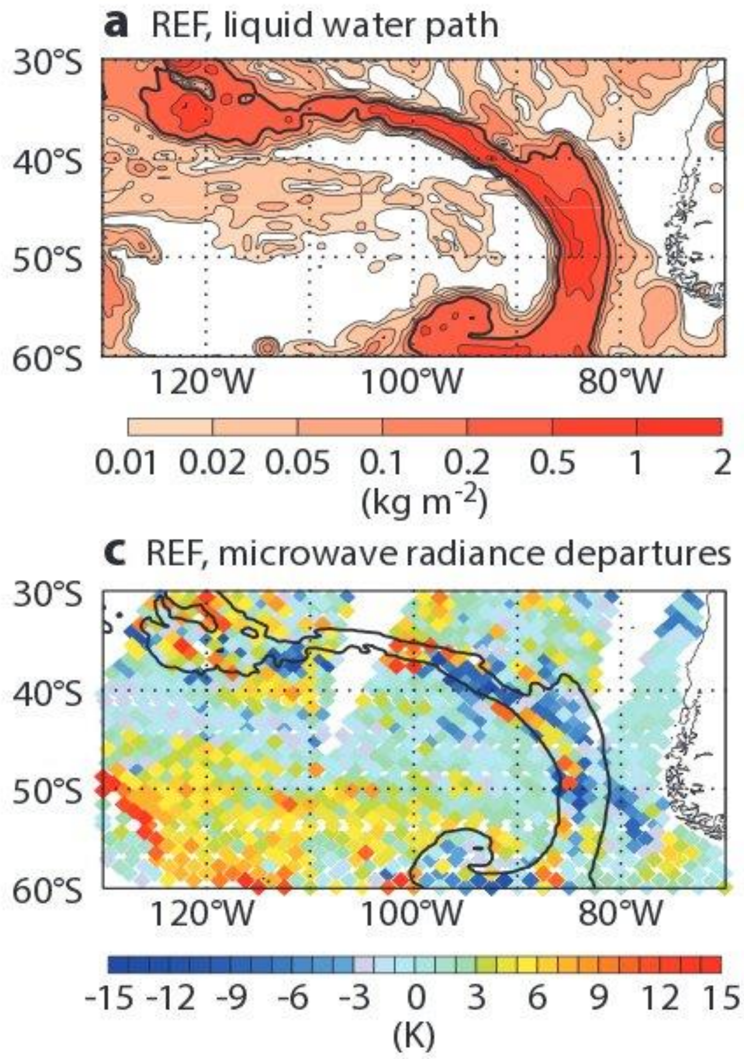
Case study: Cold sector cyclones

- First-guess departures suggest lack of liquid
- Educated guess: cold sector of cyclones not well represented





Case study: Cold sector cyclones

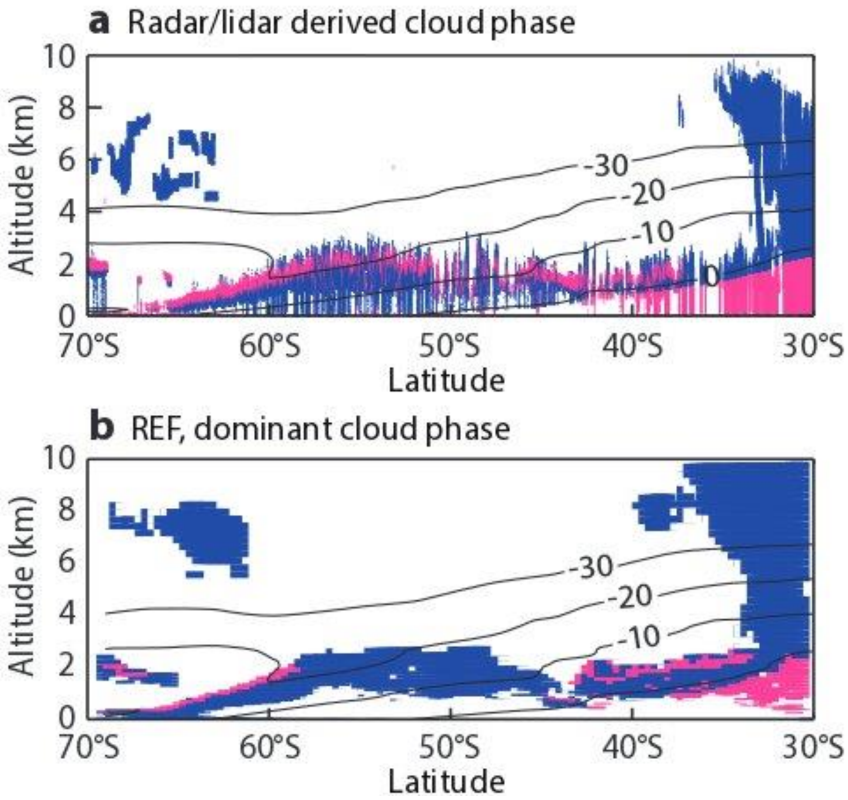


Liquid concentrated in frontal system

Very little liquid in cold sector of cyclone

This area corresponds to the greatest FG departures for microwave radiances

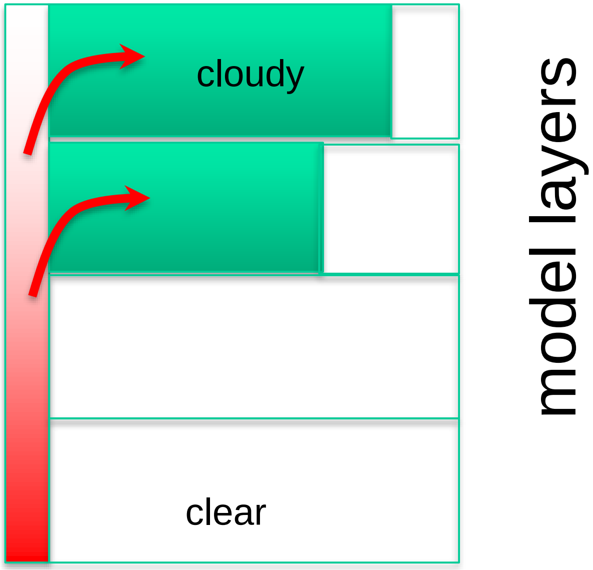
Case study: Cold sector cyclones



liquid

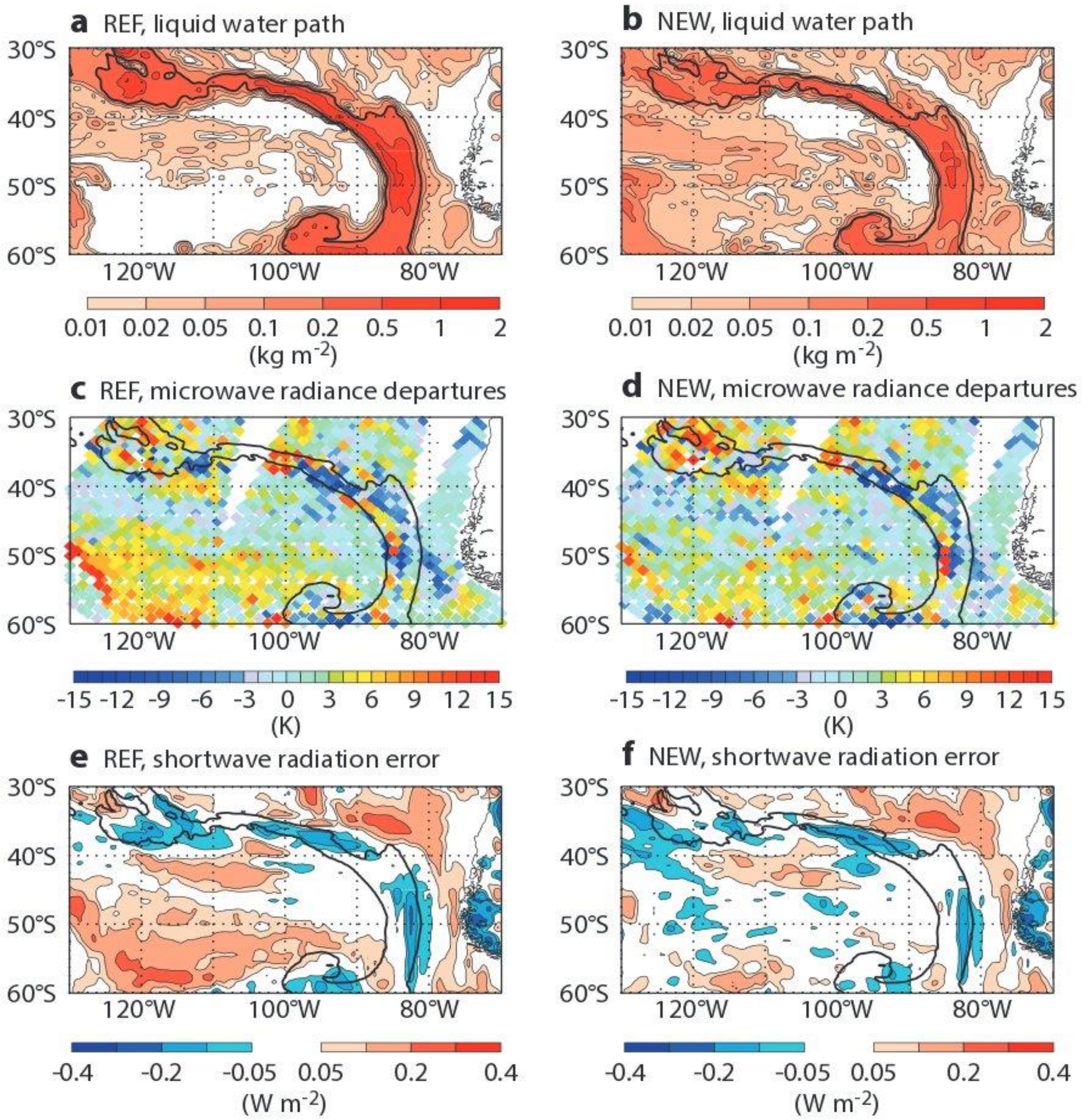
frozen

Supporting evidence: CALIPSO track across the area indicates supercooled liquid near the top of clouds, which is missing in the model



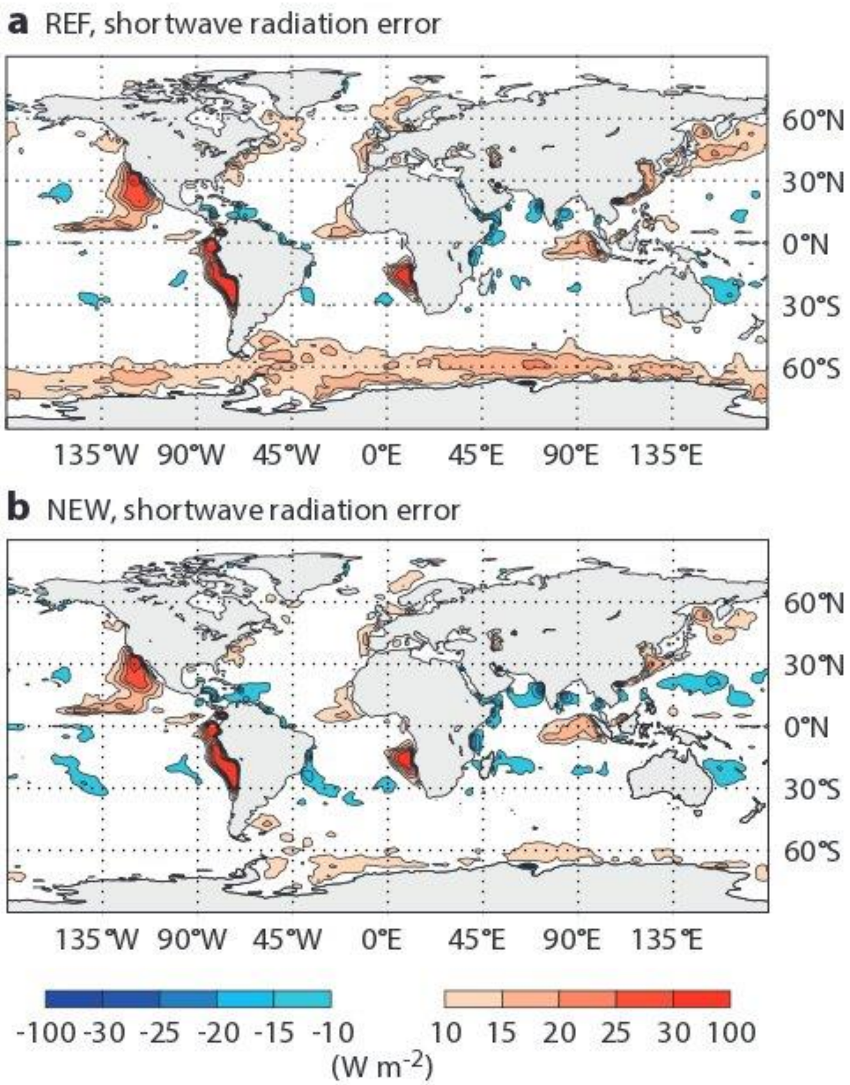
temperature dependent phase partitioning

Case study: Cold sector cyclones



Problem and (partial) solution:
The phase of the condensate detrained by the convection scheme is determined based on ambient temperature, and was only producing ice. This phase determination has been revised now.

Case study: Cold sector cyclones



Shortwave radiation bias in the Southern Ocean has been improved substantially!

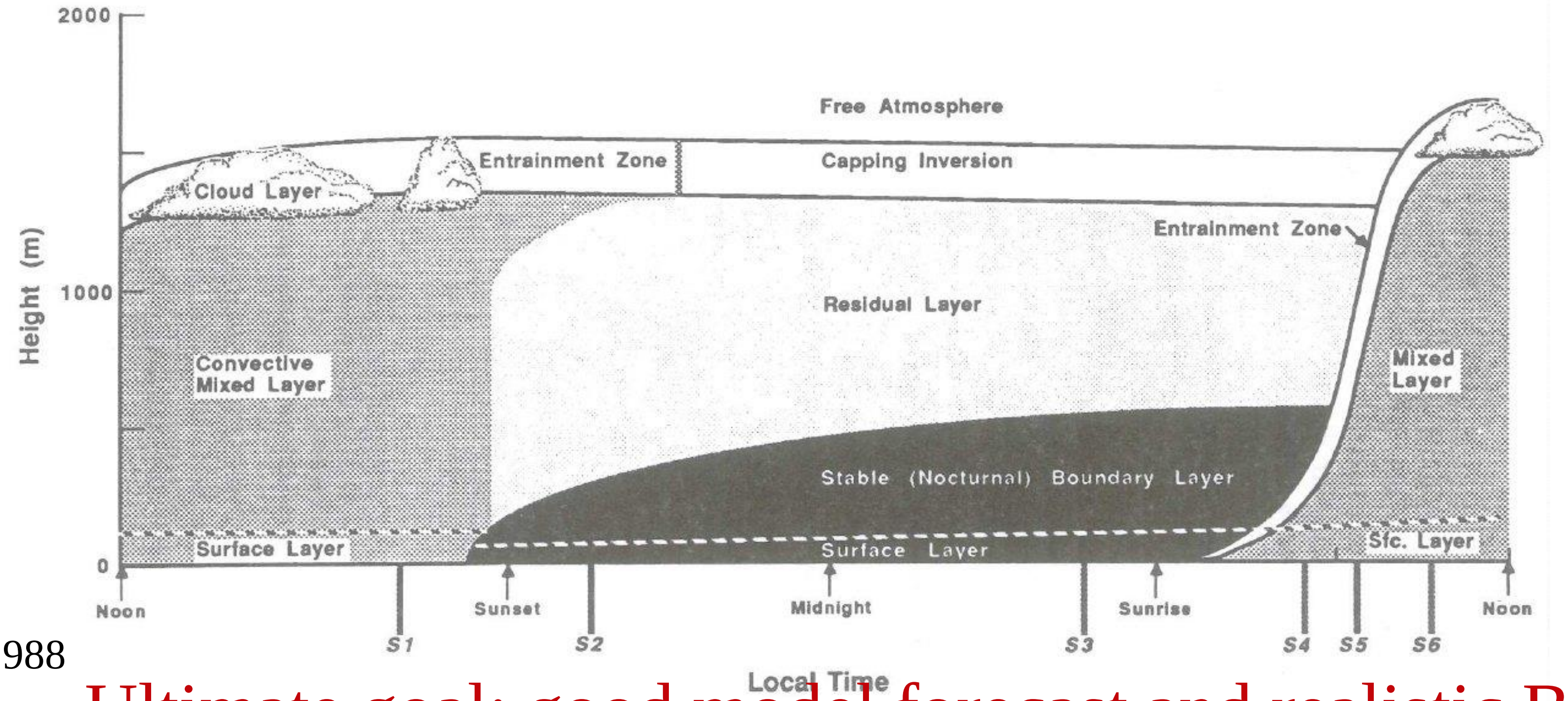
See ECMWF newsletter 146 for full article

Boundary Layer Evaluation

What does the BL parameterization do?

Attempts to integrate effects of small scale turbulent motion on prognostic variables at grid resolution.

Turbulence transports temperature, moisture and momentum (+tracers).



Stull 1988

Ultimate goal: good model forecast and realistic BL

Which aspect of the BL can we evaluate?

2m temp/humidity

we live here!
proxy for M-L T/q

10m winds

roughness length,
surface type

depth of BL

good bulk measure
of transport

structure of BL (profiles of temp, moisture, velocity)

BL type

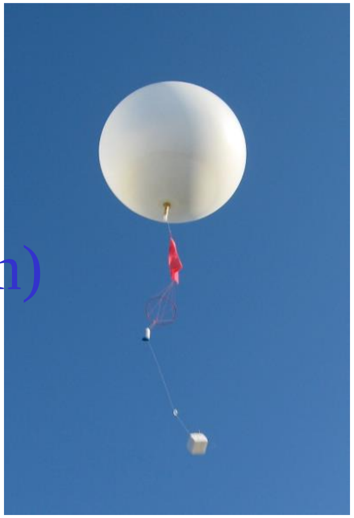
turbulent transport within BL (statistics/PDFs of air motion, moisture, temperature)

details of parameterized processes

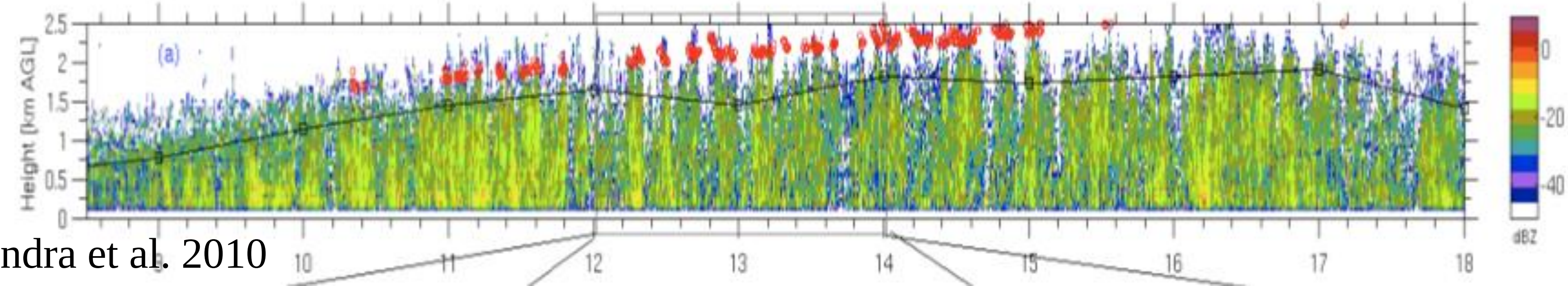
boundaries (entrainment, surface fluxes, clouds etc.)

forcing

Available observations



- SYNOP (2m temp/humidity, 10m winds)
- Radiosondes (profiles of temp/humidity)
- Lidar observations from ground (e.g. ceilometer, Raman) or space (CALIPSO) – BLH, vertical motion in BL, hi-res humidity
- Radar observations from ground (e.g. wind profiler, cloud radar) and space (CloudSat) – BLH, vertical motion in subcloud and cloud layer
- Other satellite products: BLH from GPS, BLH from MODIS



Chandra et al. 2010

Example: Boundary Layer Height

Definitions of BL:

- affected by surface, responds to surface forcing on timescales of ~1 hour (Stull)
- layer where flow is turbulent
- layer where temperature and moisture are well-mixed (convective BL)

Composite of typical **potential temperature profile** of inversion-topped convective boundary layer

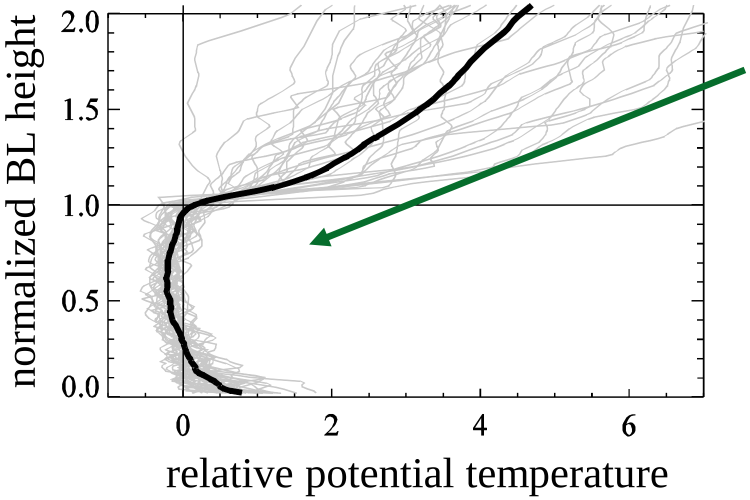


Figure: Martin Köhler

Motivation: depth and **mixed-layer mean T/q** describe BL state pretty well

Many **sources of observations**: radiosonde, lidar, radar

Boundary Layer Height from Radiosondes

Three methods:

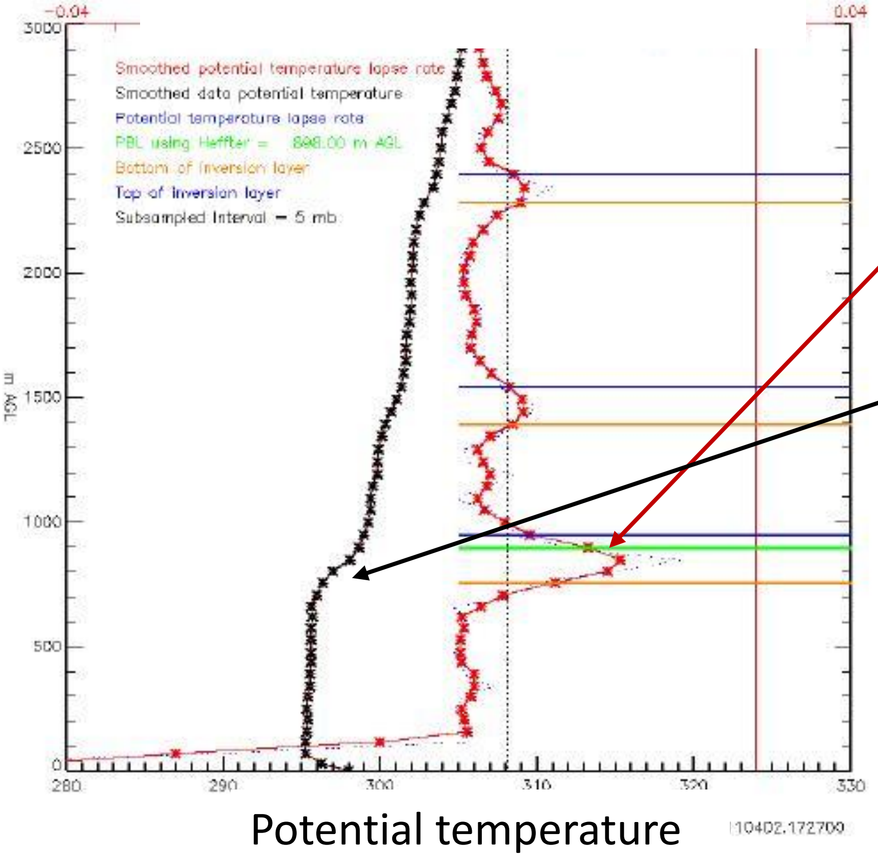
- Heffter (1980) (1) – check profile for **gradient** (conv. only)
- Liu and Liang Method (2010) (1+) – combination theta **gradient** and **wind** profile (all BL types)
- Richardson number method (2) – turbulent/laminar transition of **flow** (all BL types)

Must apply same method to observations and model data for equitable comparison!

For a good overview, see Seidel et al. 2010

Heffter method to determine PBL height

Potential temperature gradient



Potential temperature

Figure 1: PBL determination using Heffter method when the profile was subsampled and smoothed at 5 mb and 15 mb respectively at SGP on April 02, 2011.

Potential temperature gradient exceeds 0.005 K/m

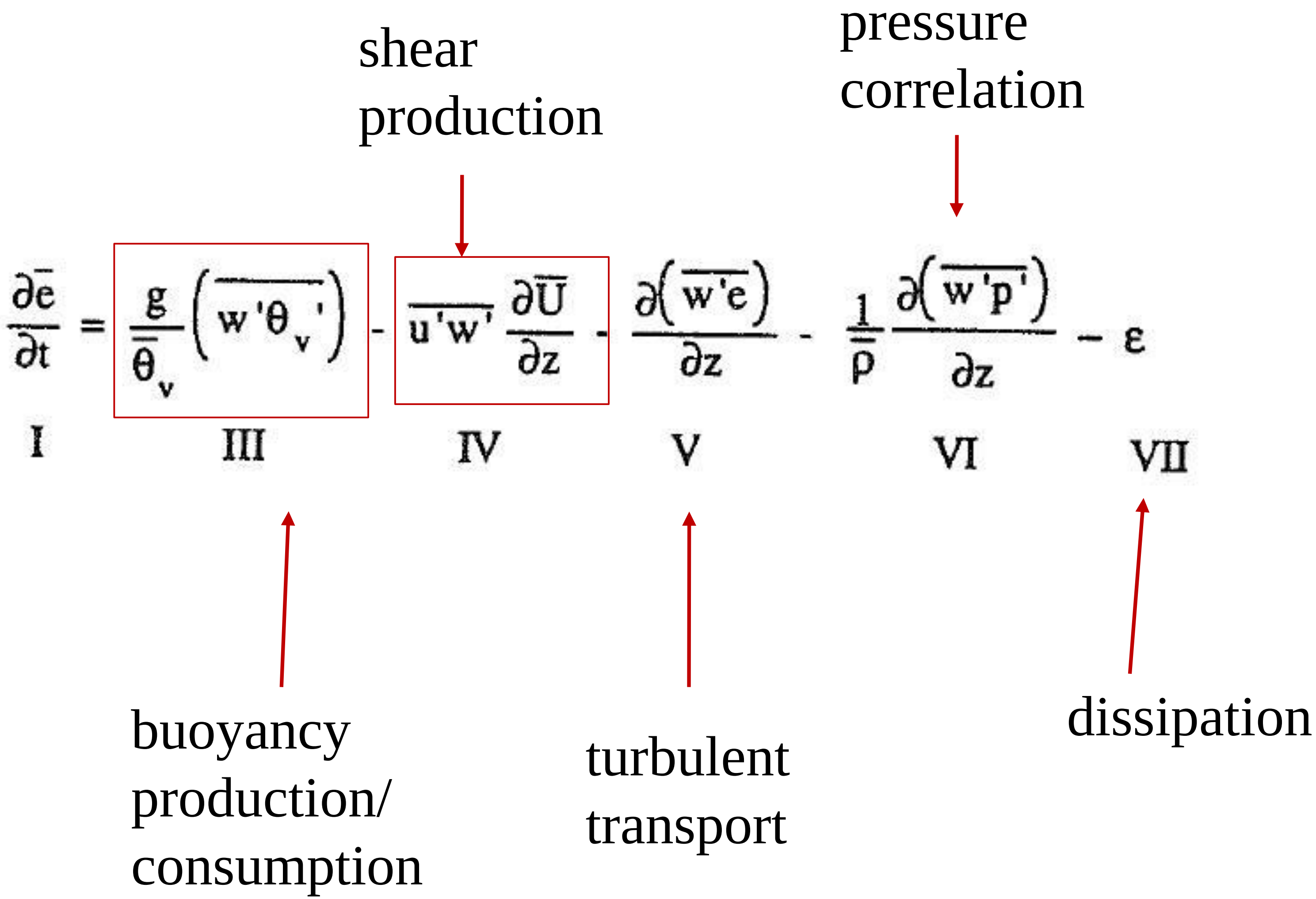
Pot. temperature change across inversion layer exceeds 2K

Note:

- Works on **convective BL only**
- May detect more than one layer
- Detection is subject to smoothing applied to data

Sivaraman et al., 2012, ASR STM poster presentation

BLH definition based on turbulent vs. laminar flow



shear production

pressure correlation

$$\frac{\partial \bar{e}}{\partial t} = \boxed{\frac{g}{\bar{\theta}_v}\left(\overline{w'\theta_v'}\right)} - \boxed{\overline{u'w'}\frac{\partial \bar{U}}{\partial z}} - \frac{\partial\left(\overline{w'e}\right)}{\partial z} - \frac{1}{\bar{\rho}}\frac{\partial\left(\overline{w'p'}\right)}{\partial z} - \varepsilon$$

I III IV V VI VII

buoyancy production/ consumption

turbulent transport

dissipation

Richardson number-based approach

- Richardson number defined as:

$$Ri = \frac{\text{buoyancy production/consumption}}{\text{shear production (usually negative)}}$$

- flow is turbulent if Ri is negative
- flow is laminar if Ri above critical value
- calculate Ri for model/radiosonde profile and define BL height as level where Ri exceeds critical number

Problem: defined only in turbulent air!
“Flux Richardson number”

$$R_f = \frac{\left(\frac{g}{\overline{\theta_v}}\right)\left(\overline{w'\theta_v'}\right)}{\left(\overline{u'w'}\right)\frac{\partial \overline{U}}{\partial z} + \left(\overline{v'w'}\right)\frac{\partial \overline{V}}{\partial z}}$$

Gradient Richardson number

- Alternative: relate turbulent fluxes to vertical gradients (K-theory)

$$R_f = \frac{\left(\frac{g}{\overline{\theta}_v}\right)\overline{(w'\theta_v')}}{\overline{(u'w')}\frac{\partial \overline{U}}{\partial z} + \overline{(v'w')}\frac{\partial \overline{V}}{\partial z}} \qquad \longleftrightarrow \qquad Ri = \frac{\frac{g}{\overline{\theta}_v}\frac{\partial \overline{\theta}_v}{\partial z}}{\left[\left(\frac{\partial \overline{U}}{\partial z}\right)^2 + \left(\frac{\partial \overline{V}}{\partial z}\right)^2\right]}$$

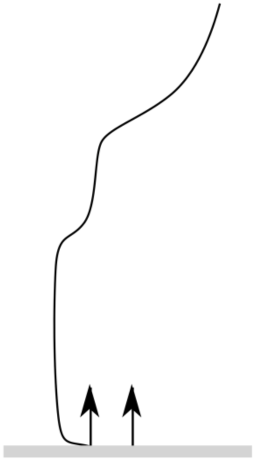
flux Richardson number

gradient Richardson number

Remaining problem: We don’t have local vertical gradients in model

Bulk Richardson number (Vogelezang and Holtslag 1996)

Solution: use discrete (bulk) gradients:



$$\mathrm{Ri}(z) = \frac{(g/\theta_{vs})(\theta_{vz} - \theta_{vs})(z - z_s)}{(u_z - \cancel{u_s})^2 + (v_z - \cancel{v_s})^2 + \left(\cancel{b} u_*^2\right)}$$

Surface winds assumed to be zero

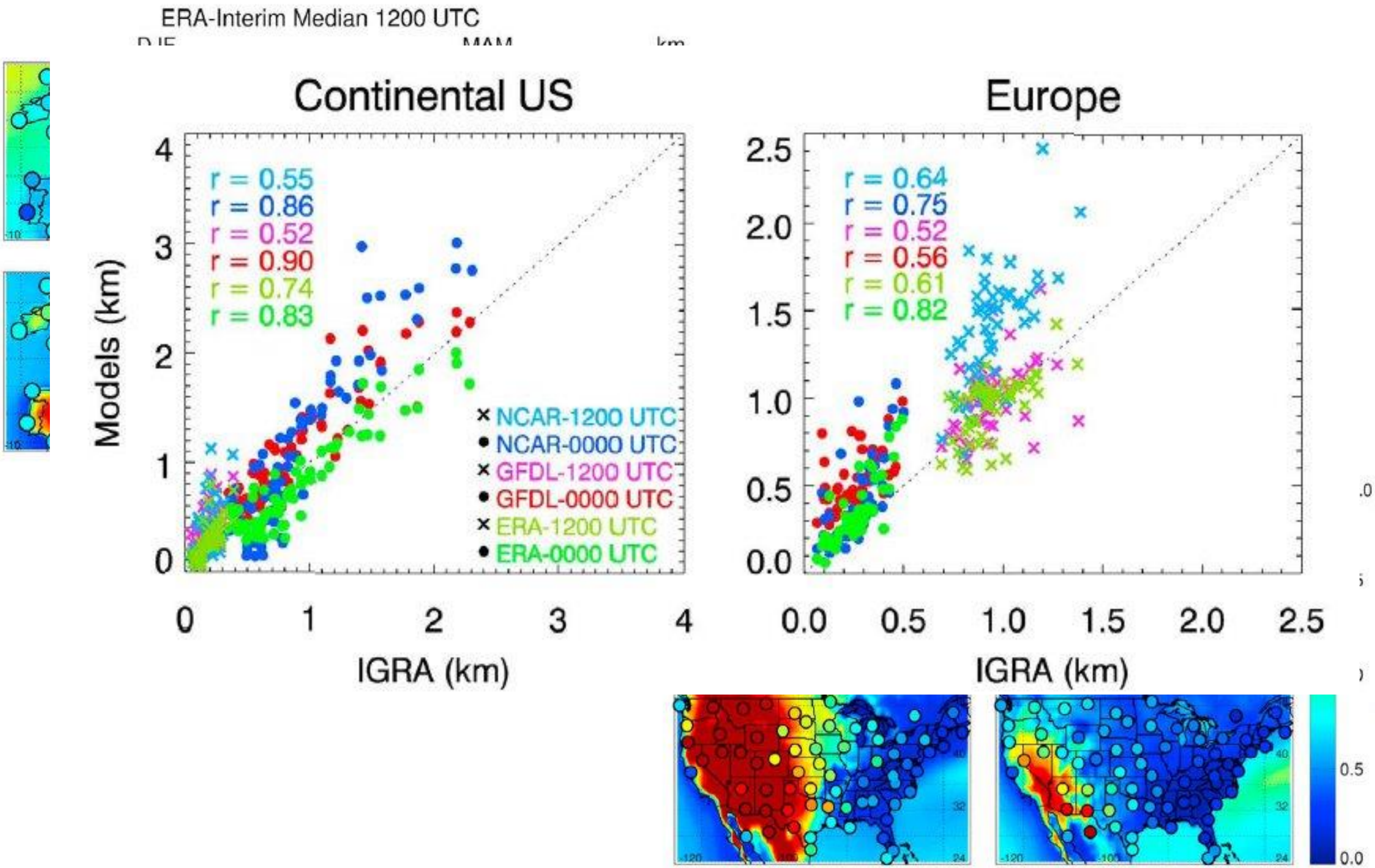
Ignore surface friction effects, much smaller than shear

Limitations:

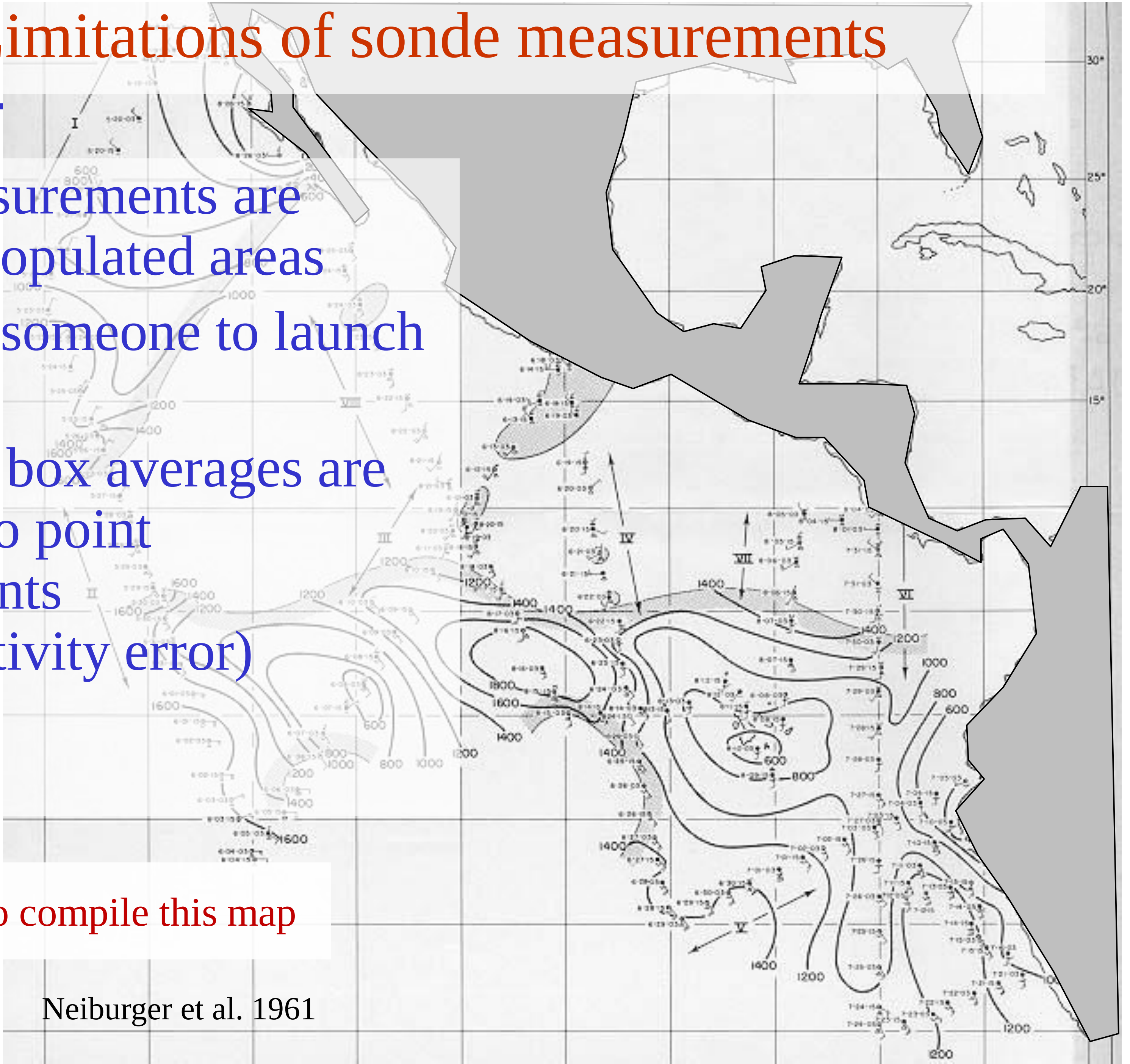
- Values for critical Ri based on lab experiment, but we’re using bulk approximation (smoothing gradients), so critical Ri will be different from lab
- Subject to smoothing/resolution of profile
- Some versions give excess energy to buoyant parcel based on sensible heat flux – not reliable field, and often not available from observations

This approach is used in the IFS for the diagnostic BLH in IFS.

ERA-I vs. Radiosonde (Seidel et al. 2012)



Limitations of sonde measurements



- Sonde measurements are limited to populated areas
- Depend on someone to launch them (cost)
- Model grid box averages are compared to point measurements (representativity error)

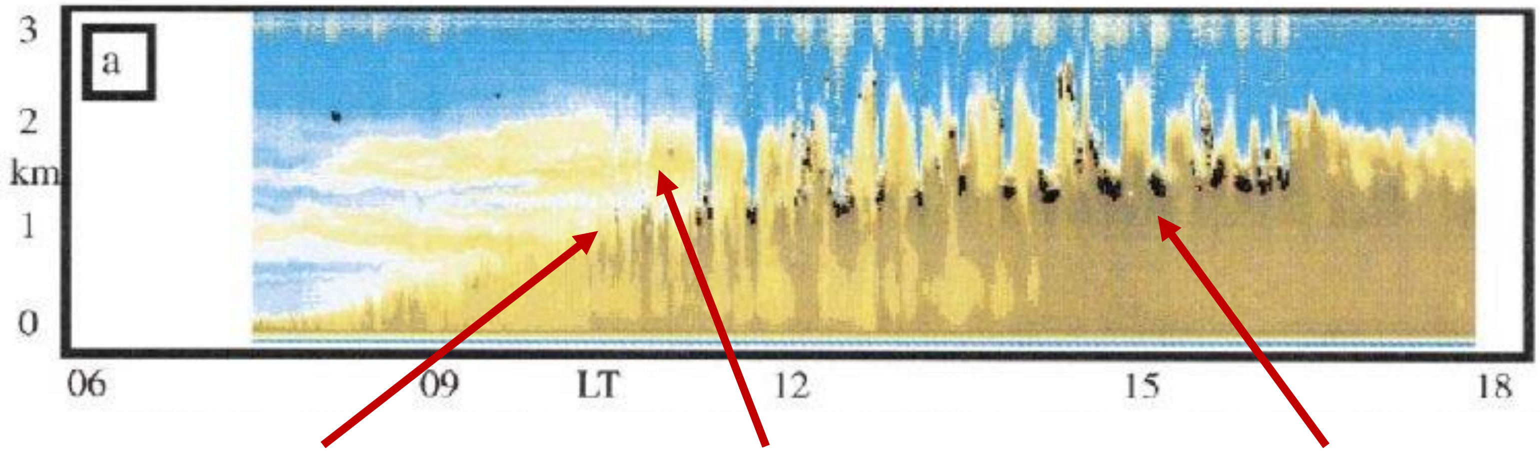
Took many years to compile this map

Neiburger et al. 1961

Boundary layer height from lidar

- Aerosols originating at surface are mixed throughout BL
- Lidar can identify gradient in aerosol concentration at the top of the BL – but may pick up residual layer (ground/satellite)
- For cloudy boundary layer, lidar will pick out top of cloud layer (satellite) or cloud base (ground)

Lidar backscatter (ground based)



top of the convective BL

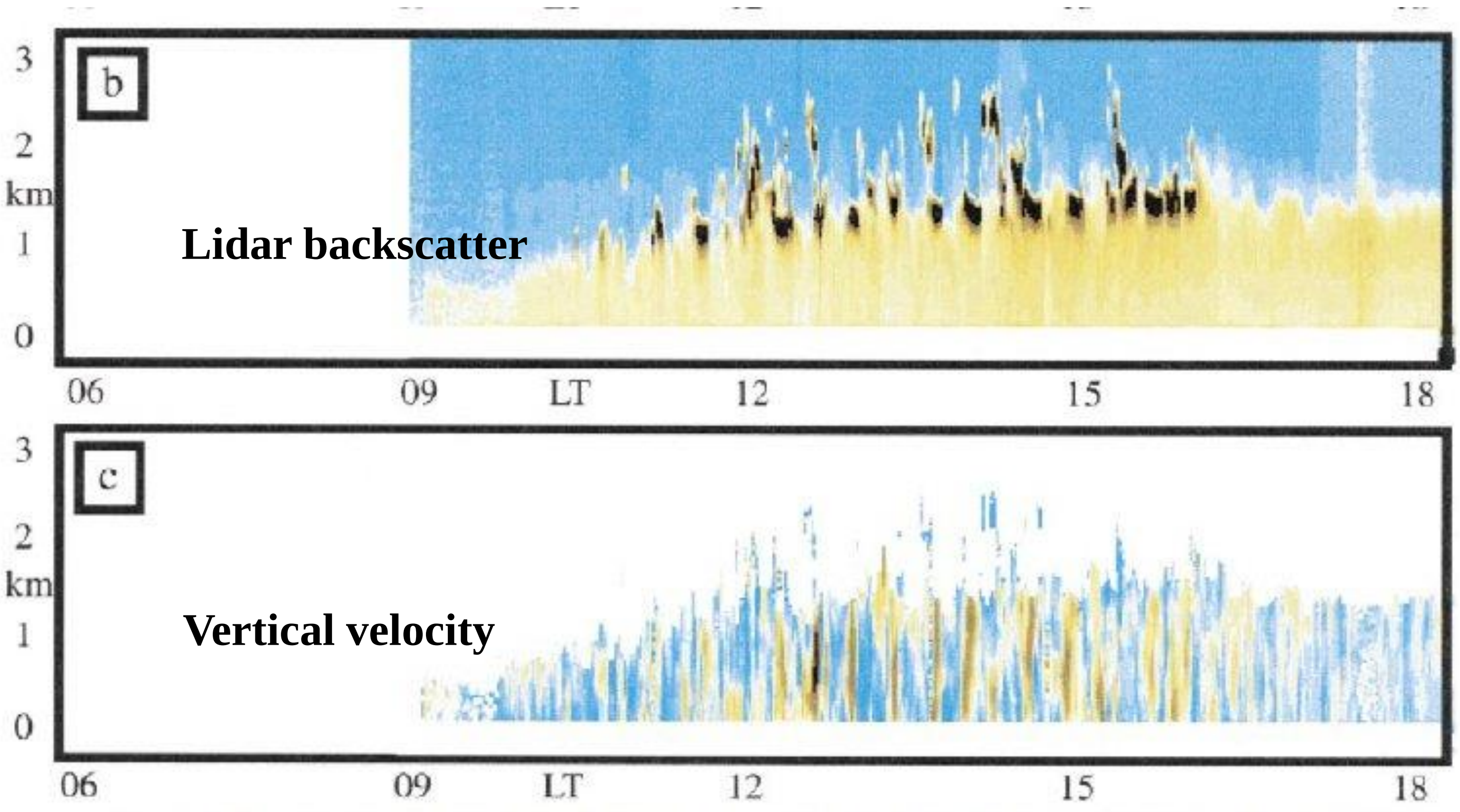
elevated aerosol layer

attenuated signal due to cloud

Cohn and Angevine, 2000

Additional information from lidar

Doppler Lidar

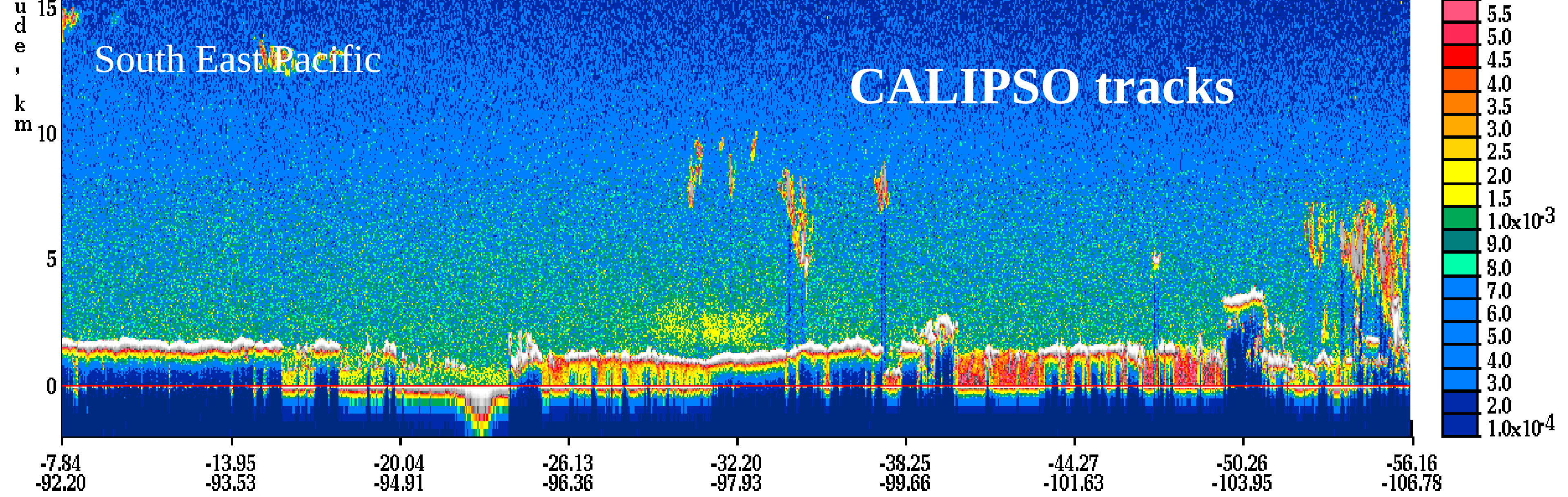


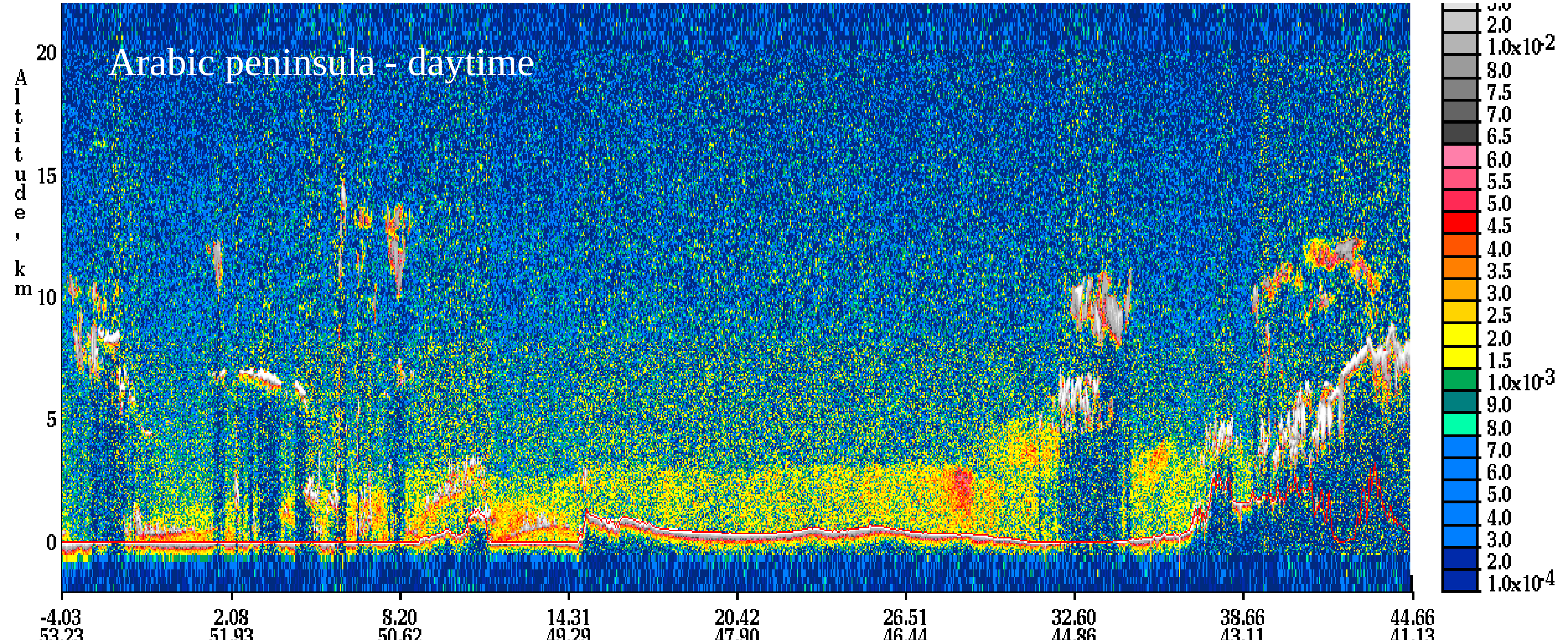
Lidar backscatter

Vertical velocity

In addition to backscatter, get vertical velocity from doppler lidar. Helps define BLH, but also provides information on **turbulent motion**

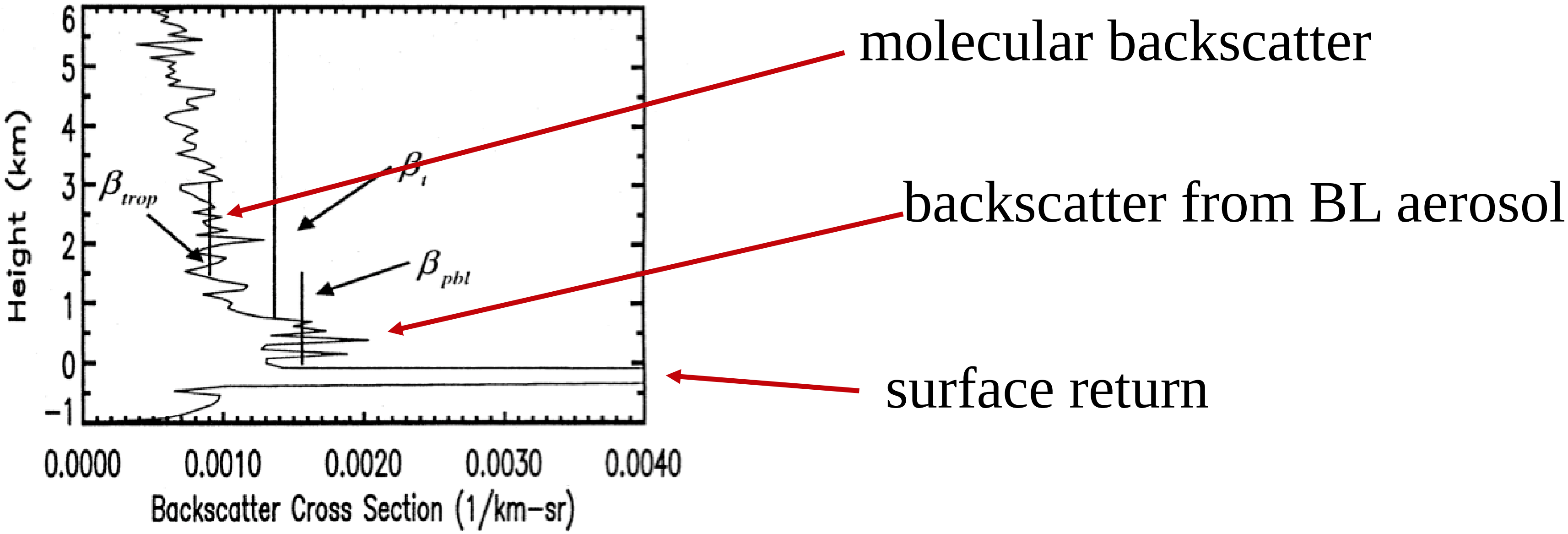
CALIPSO tracks





BLH from lidar how-to

- Easiest: use level 2 product (GLAS/CALIPSO)
- Algorithm searches from the ground up for significant drop in backscatter signal
- Align model observations in time and space with satellite track and compare directly, or compare statistics



molecular backscatter

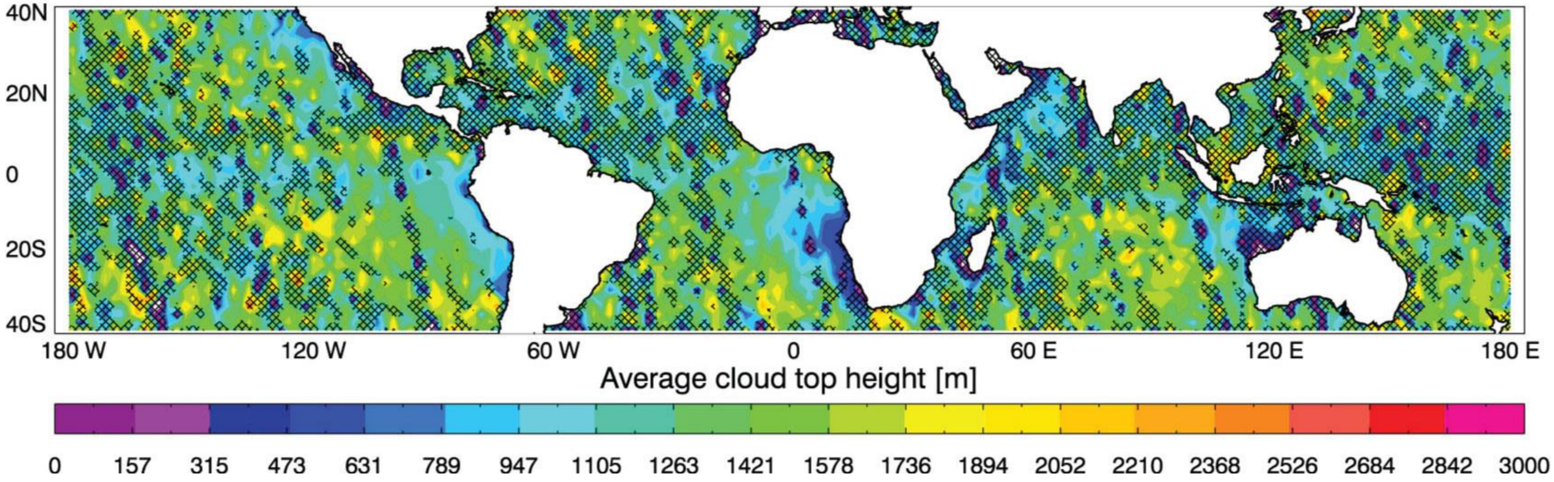
backscatter from BL aerosol

surface return

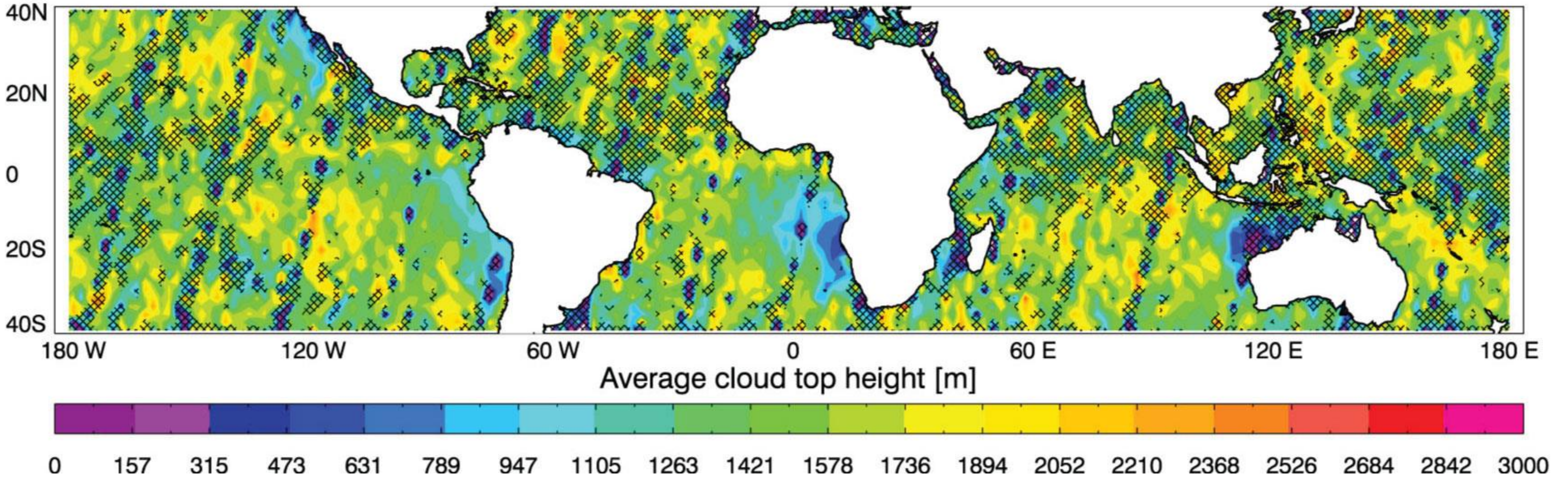
Figure: GLAS ATBD

Diurnal cycle from CALIPSO

b) CALIPSO average low cloud top height, Oct 2006, day



b) CALIPSO average low cloud top height, Oct 2006, night



BLH from lidar - Limitations

- Definition of BL top is tied to aerosol concentration - will pick residual layer
- Does not work well for cloudy conditions (excluding BL clouds), or when elevated aerosol layers are present
- Overpasses only twice daily, same local time (satellite)
- Difficult to monitor given location (satellite)
- Coverage (ground-based)

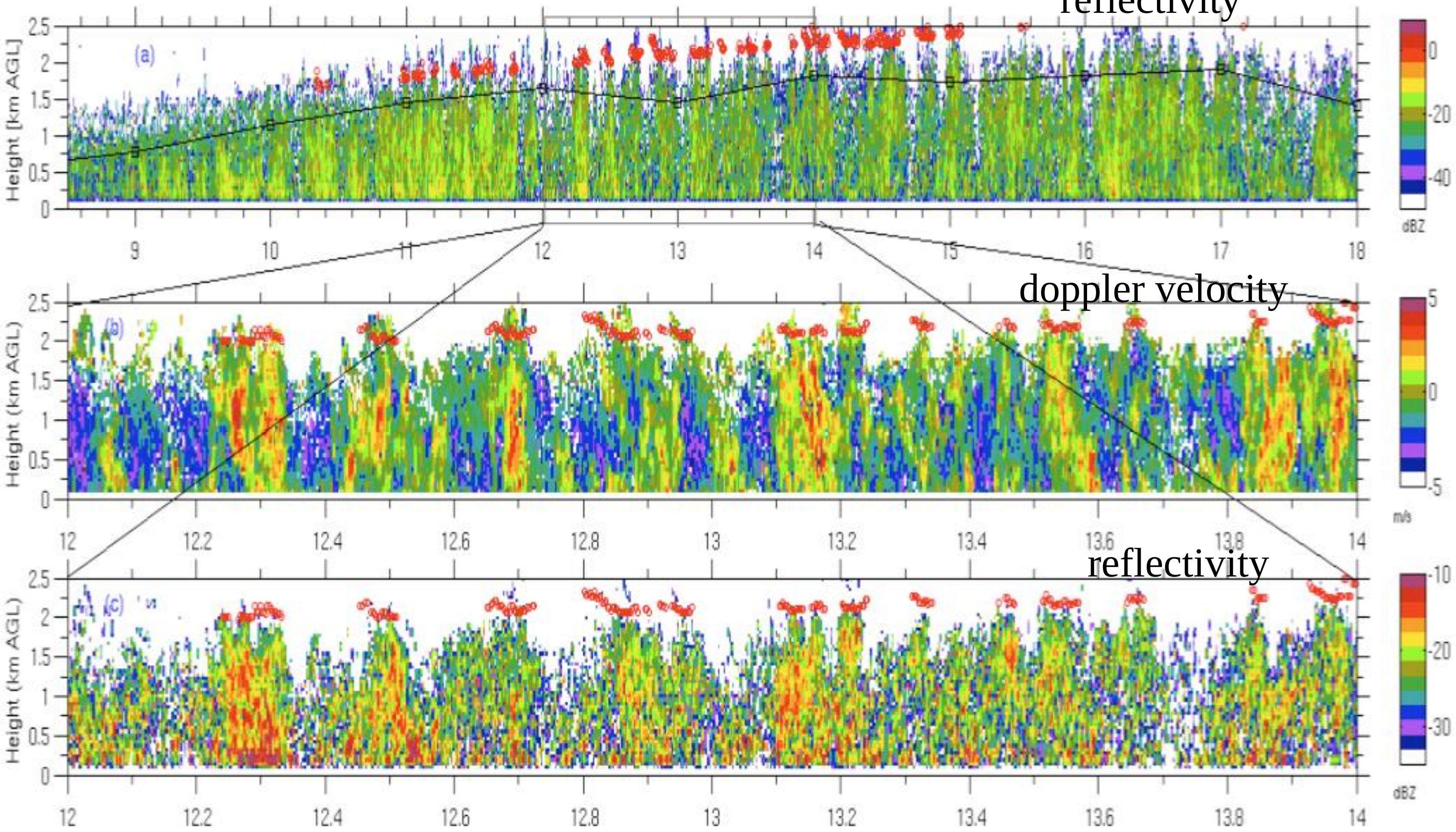
2m temperature and humidity, 10m winds

- This is where we live!
- We are BL creatures, and live (mostly) on land
- Plenty of SYNOP
- Point measurements
- Availability limited to populated areas
- An error in 2m temp/humidity or 10m winds can have many reasons – difficult to determine which one is at the root of the problem

http://s0.geograph.org.uk/photos/16/66/166689_99dc7723.jpg

Example: vertical motion from radar

Observations from mm-wavelength cloud radar at ARM SGP, using insects as scatterers.



reflectivity

doppler velocity

reflectivity

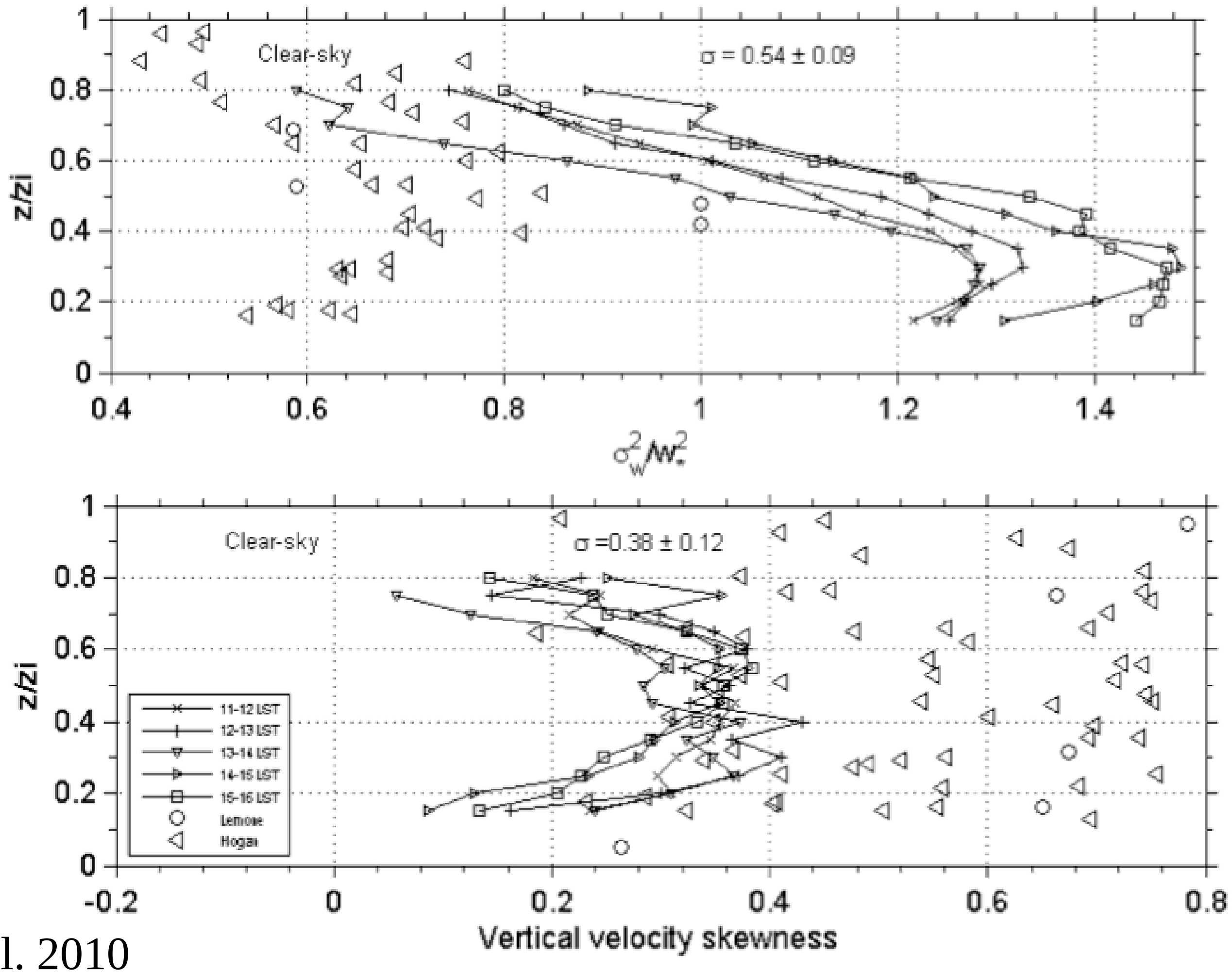
Chandra et al. 2010

local time

red dots: ceilometer cloud base

Turbulent characteristics: vertical motion

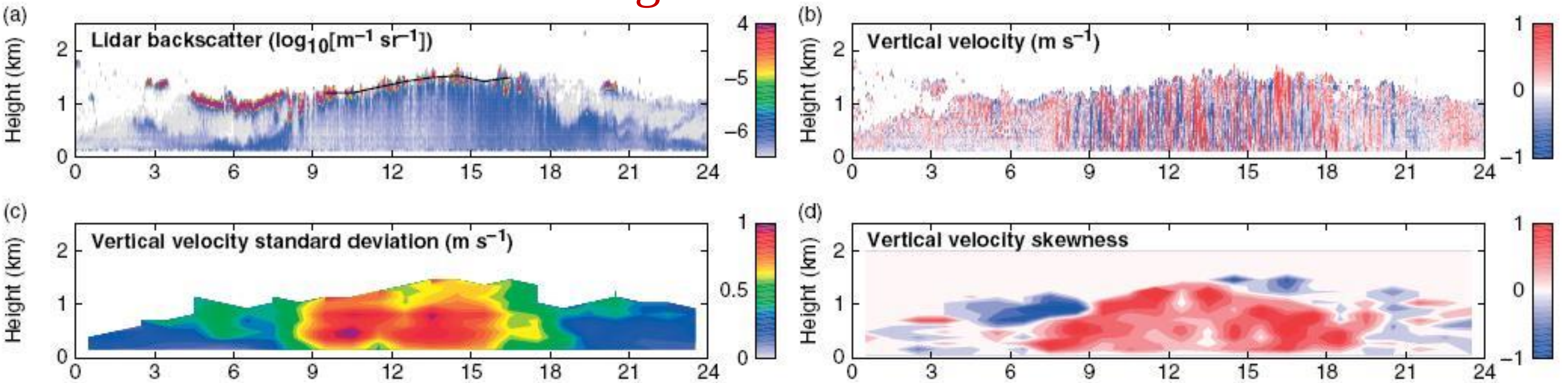
Variance and skewness statistics in the convective BL (cloud free) from four summer seasons at ARM SGP



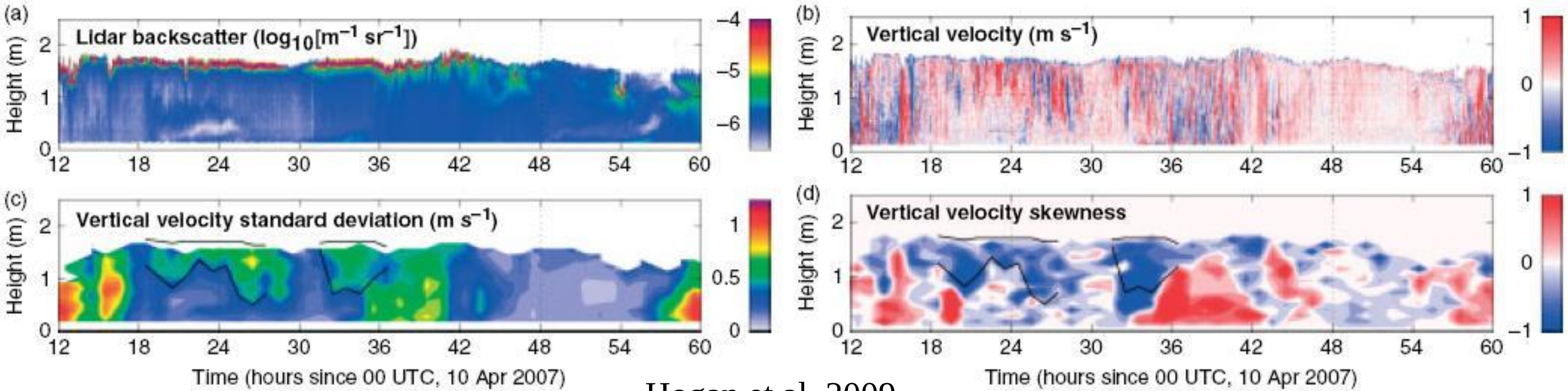
Chandra et al. 2010

Example: lidar and discrete BL types

Use higher order moments!



Skewness of vertical velocity distribution from doppler lidar distinguishes surface-driven vs. cloud-top driven turbulence



Hogan et al. 2009

Doppler lidar: BL types

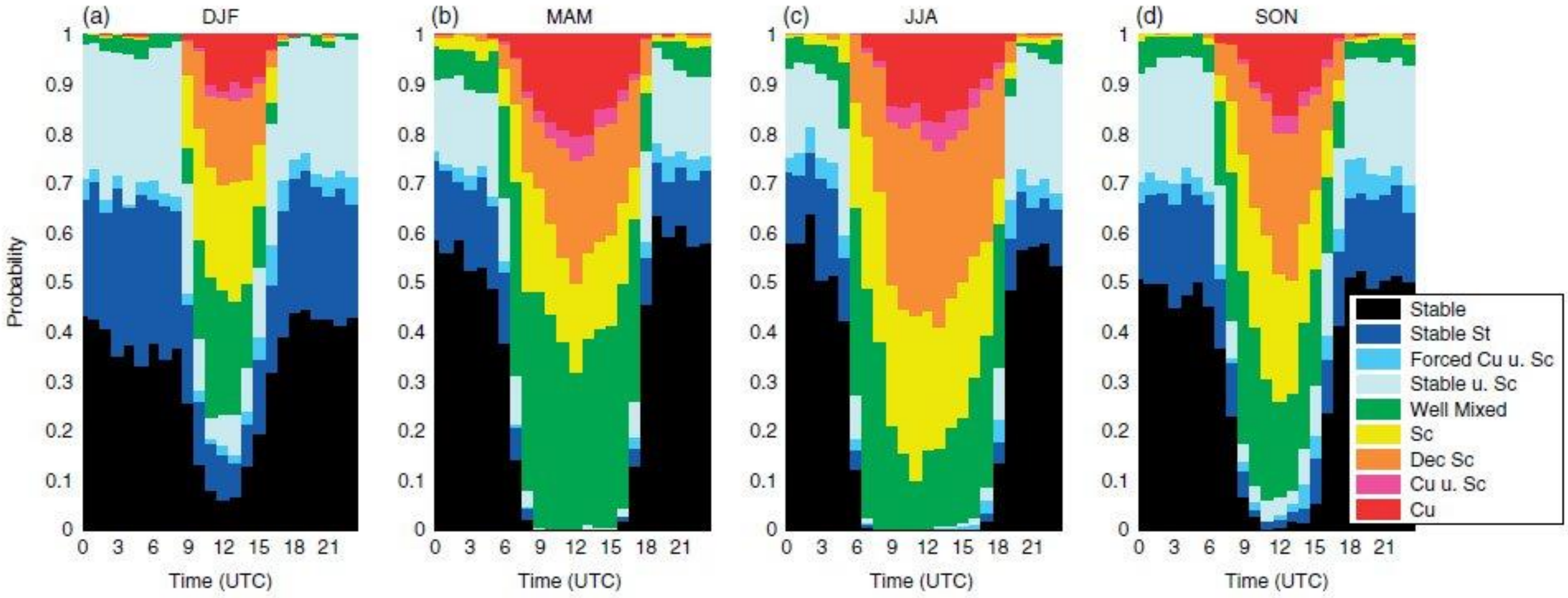


Figure 9. The diurnal distribution of boundary-layer types as a function of season: (a) winter, (b) spring, (c) summer, and (d) autumn.

BL type occurrence at Chilbolton, based on Met Office BL types

Harvey et al. 2013

Observations relating to BL forcing

- Surface radiation (optical properties of cloud, top-driven strength of turbulence)
- Cloud liquid and drizzle retrievals from radar (cloud properties, autoconversion/accretion and evaporation processes)
- Cloud mask from radar/lidar (cloud occurrence, triggering of BL types)
- Surface fluxes (BL types)
- Entrainment

Summary & Considerations

Different approaches to verification (climate statistics, case studies, composites), different techniques (model-to-obs, obs-to-model) and a **range of observations** are required to validate and improve cloud parametrizations.

Need to **understand the limitations** of observational data. Ensure we are **comparing like with like**. Use complementary observations - **synergy.**

The model developer **needs to understand physical processes** to improve the model. Requires theory and modelling, and novel techniques for extracting information from observations.