Boundary Layer Verification

ECMWF training course

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Aim of this lecture

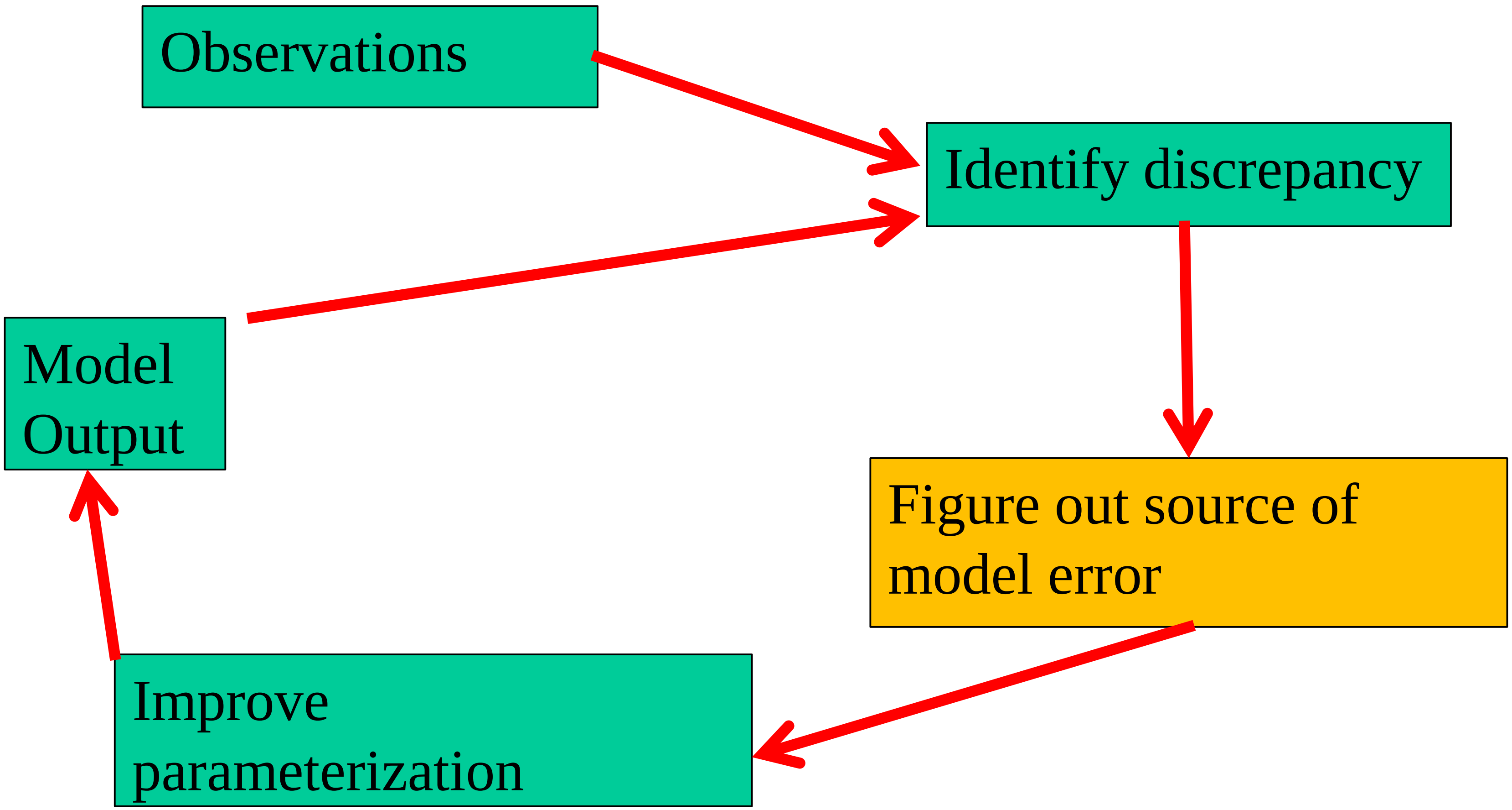
- To give an overview over strategies for boundary layer evaluation
- By the end of this session you should be able to:
  - Identify data sources and products suitable for BL verification
  - Recognize the strengths and limitations of the verification strategies discussed
  - Choose a suitable verification method to investigate model errors in boundary layer height, transport and cloudiness.

smog over NYC

Overview

- General strategy for process-oriented model evaluation
- What does the BL parameterization do?
- Broad categories of BL parameterizations
- Which aspects of the BL can we evaluate?
  – What does each aspect tell us about the BL?
- What observations are available
  – What are the observations' advantages and limitations?
- Examples
  – Clear convective BL
  – Cloud topped convective BL
  – Stable BL

Basic strategy for model evaluation and improvement:

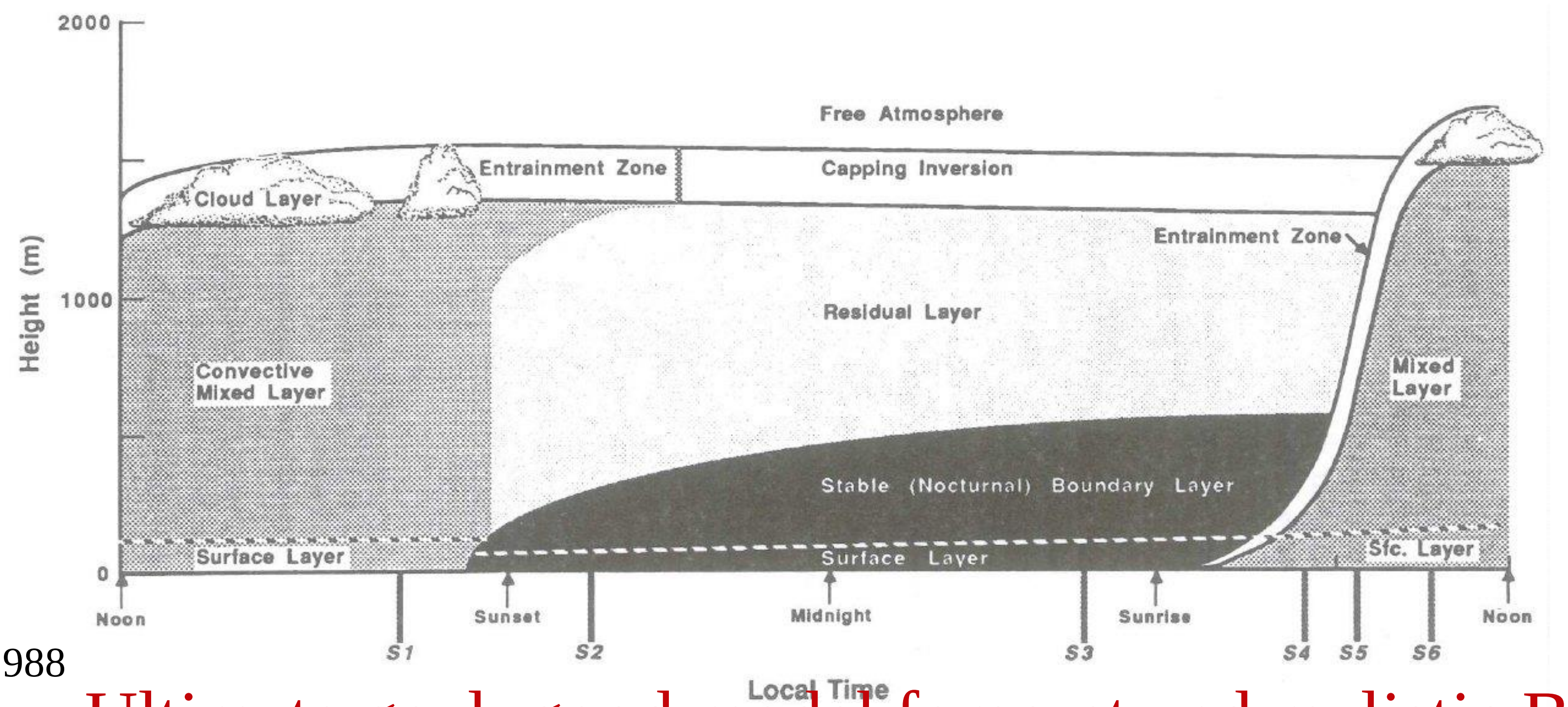


When and where does error occur?
Which parameterization(s) is/are involved?

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

Broad categories of BL parameterizations

Unified BL schemes

•Attempt to integrate BL (and shallow cloud) effects in one scheme to allow seamless transition

•Often statistical schemes (i.e. making explicit assumptions about PDFs of modelled variables) using moist-conserved variables

•Limitation: May not work well for mixed-phase or ice

•Examples: DualM (Neggers et al. 2009), CLUBB (Larson et al. 2012)

Specialized BL scheme

•One parameterization for each discrete BL type

•Simplifies parameterization for each type, parameterization for each type ideally suited

•Limitation: must identify BL type reliably, is noisy (lots of if statements)

•Example: Met-Office (Lock et al. 2000)

Most models use a mixture of these, with some switching involved

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

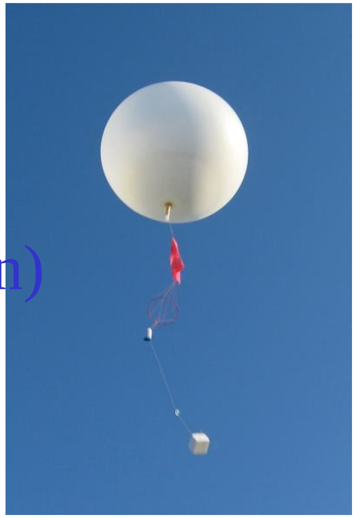
depth of BL
good bulk measure of transport

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

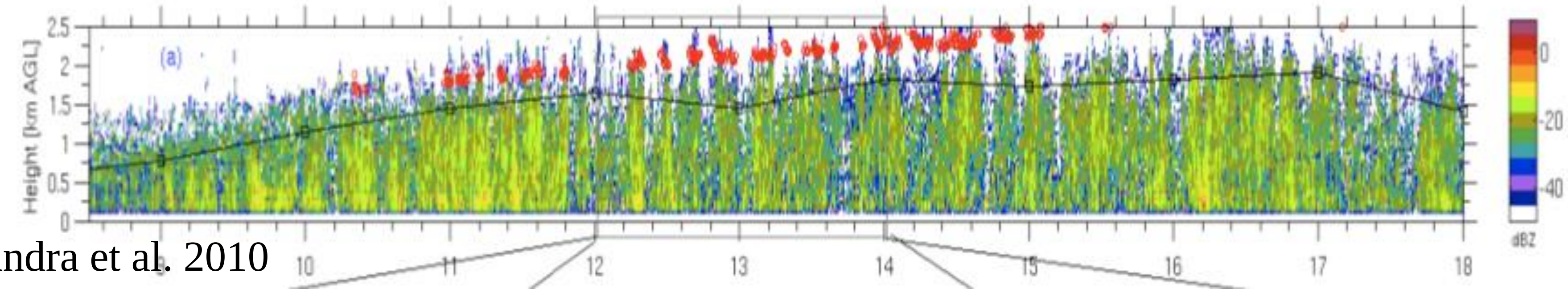
turbulent transport within BL (statistics/PDFs of air motion, moisture, temperature)
details of parameterized processes

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

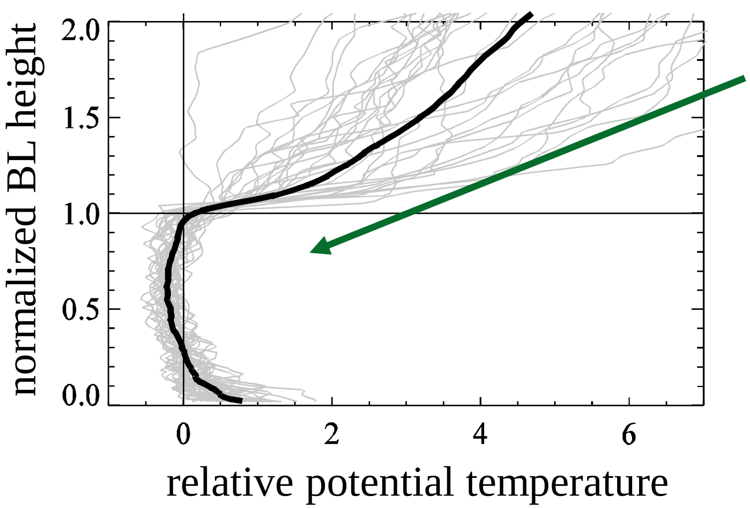


Figure: Martin Köhler

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:

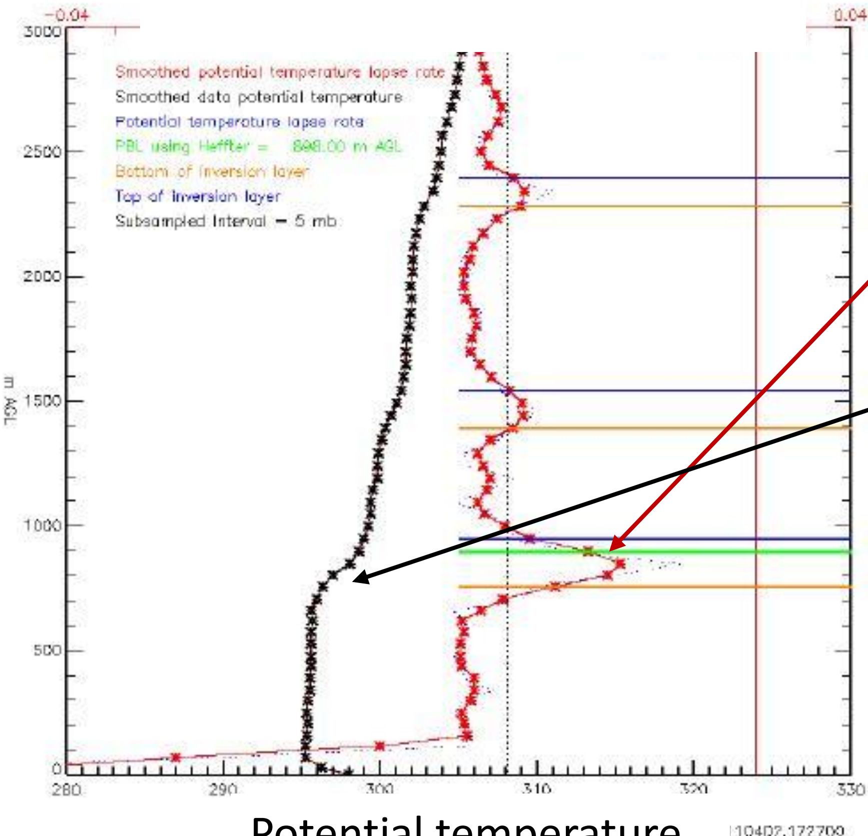
- Heffter (1980) (1) – check profile for **gradient** (conv. only)
- Liu and Liang Method (2010) (1+) – combination theta **gradient** and **wind** profile (all BL types)
- Richardson number method (2) – turbulent/laminar transition of **flow** (all BL types)

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

Liu and Liang method

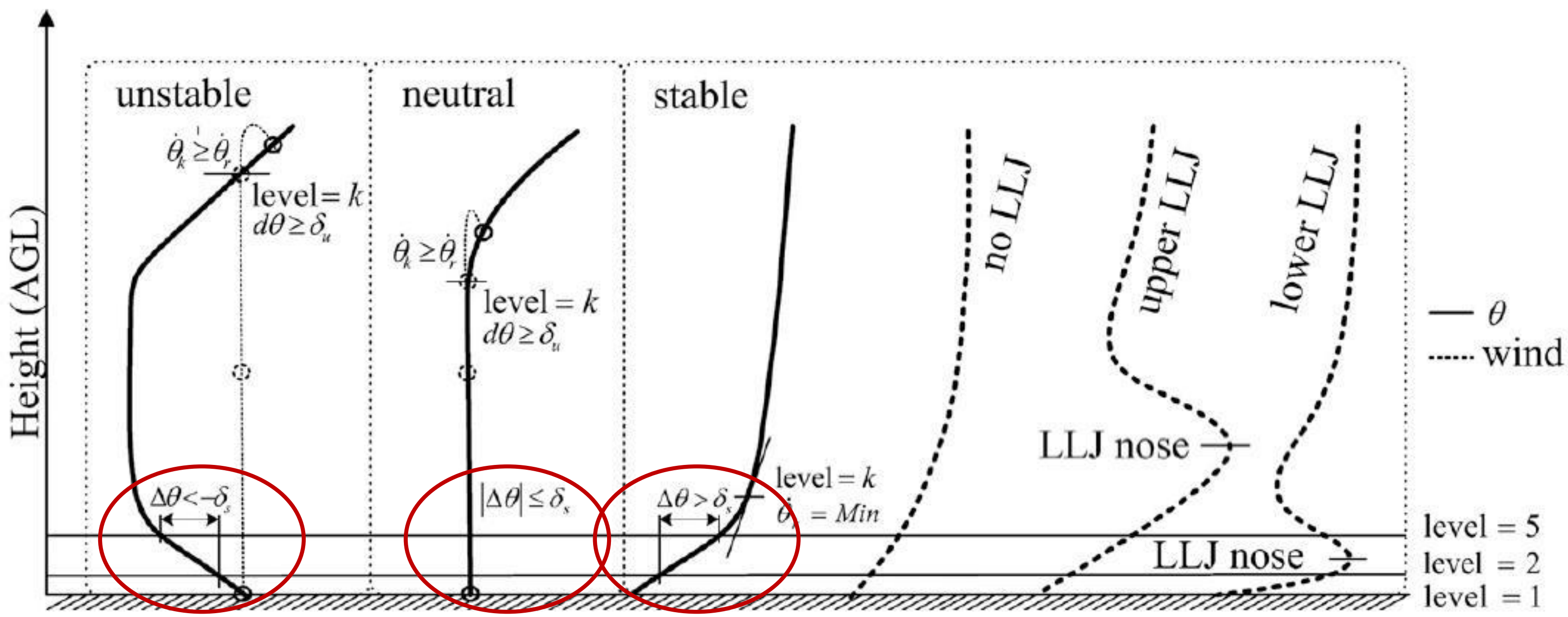


FIG. 3. Illustration of idealized PBL regimes (CBL, NRL, SBL) and PBLH determination procedure ($\Delta_\theta = \theta_5 - \theta_2$; $d\theta = \theta_k - \theta_1$).

First, determine which type of BL is present, based on Θ difference between two near-surface levels

$$\theta_5 - \theta_2 \begin{cases} < -\delta_s & \text{for} \quad \text{CBL} \rightarrow \text{an unstable regime} \\ > +\delta_s & \text{for} \quad \text{SBL} \rightarrow \text{a stable regime} \\ \text{else} & \text{for} \quad \text{NRL} \rightarrow \text{a neutral regime} \end{cases}$$

Liu and Liang, 2010

Liu and Liang method: convective BL

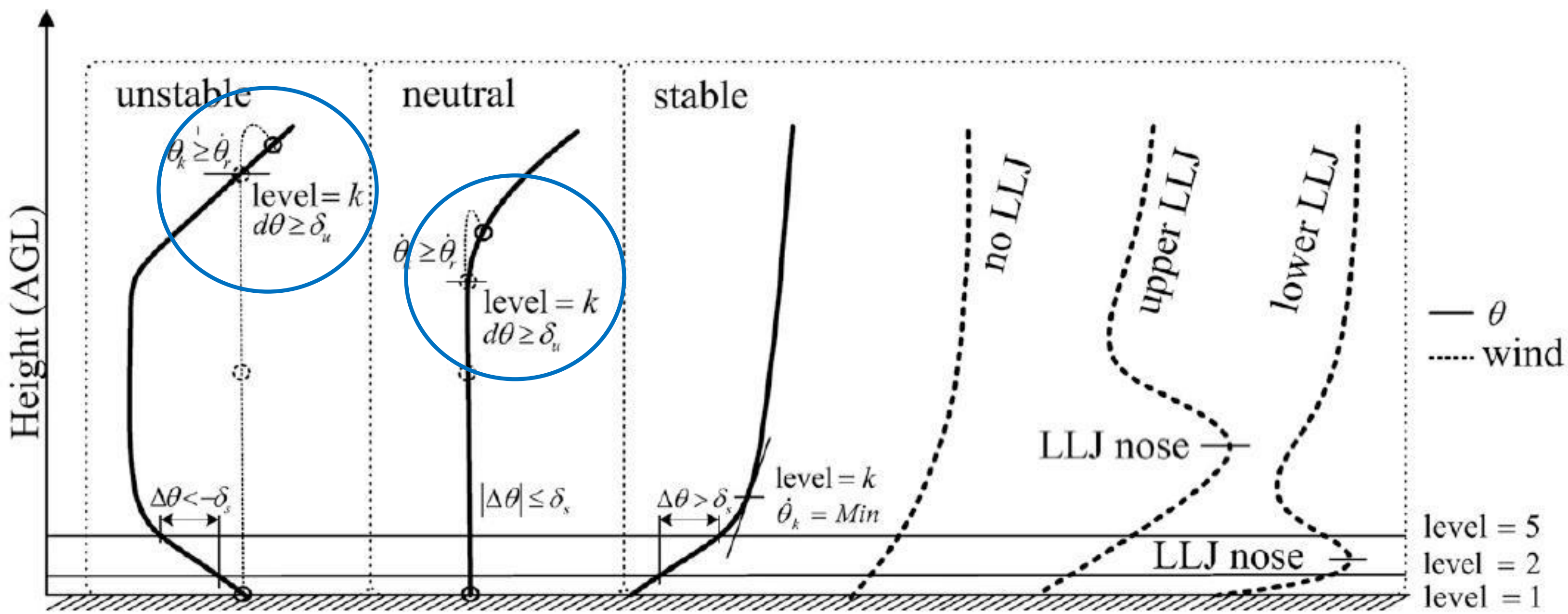


FIG. 3. Illustration of idealized PBL regimes (CBL, NRL, SBL) and PBLH determination procedure ($\Delta_\theta = \theta_5 - \theta_2$; $d\theta = \theta_k - \theta_1$).

For convective and neutral cases: Lift parcel adiabatically from surface to neutral buoyancy (i.e. same environmental Θ as parcel), and Θ gradient exceeds minimum value (similar in concept to Heffter).

Parameters $\delta_{s,}$ δ_u and critical Θ gradient are empirical numbers, differing for ocean and land.

Liu and Liang, 2010

Liu and Liang method: stable BL

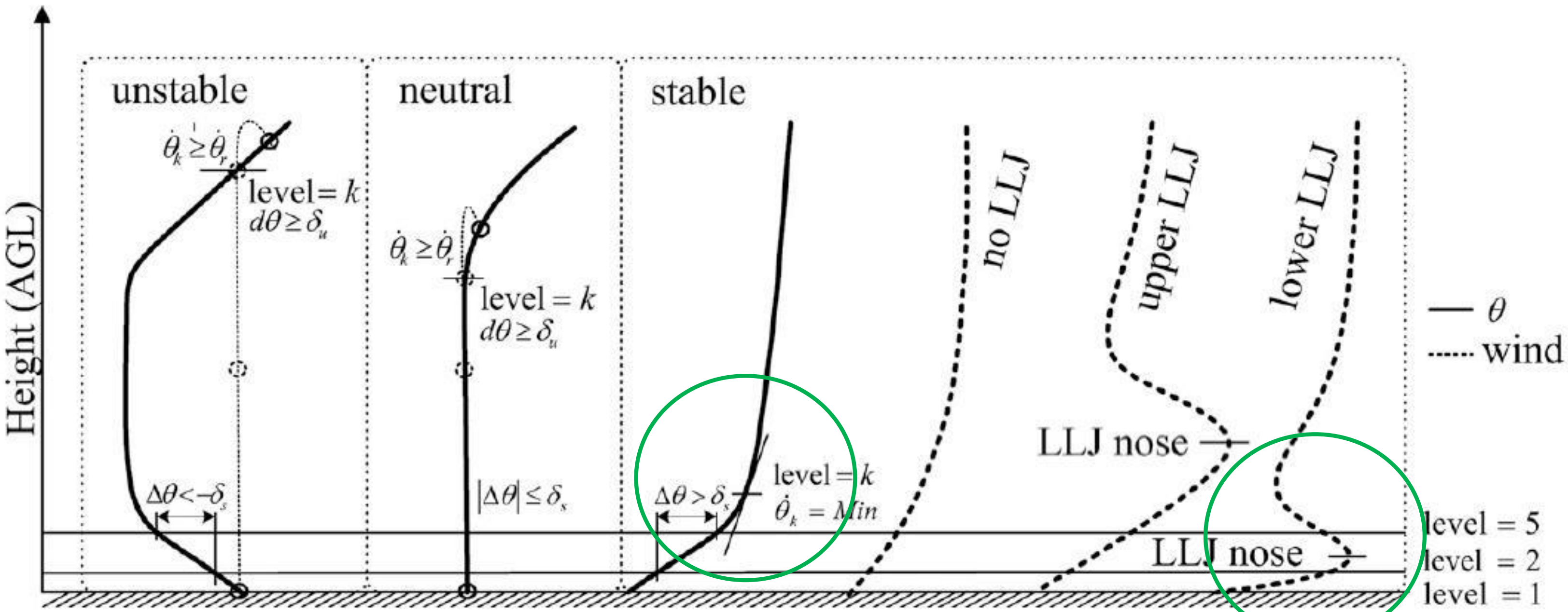


FIG. 3. Illustration of idealized PBL regimes (CBL, NRL, SBL) and PBLH determination procedure ($\Delta_\theta = \theta_5 - \theta_2$; $d\theta = \theta_k - \theta_1$).

Stable case: Search for a minimum in θ gradient (top of bulk stable layer). If wind profile indicates presence of a low-level jet, assign level of jet nose as PBL height if it is below the bulk layer top.

Advantage: Method can be applied to all profiles, not just convective cases.

Liu and Liang, 2010

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:

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

- 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)

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

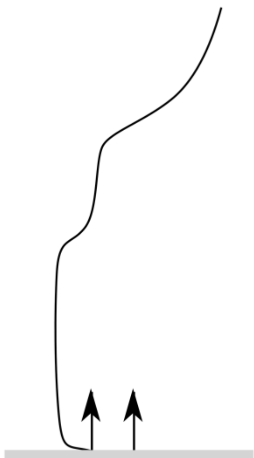
flux Richardson number

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

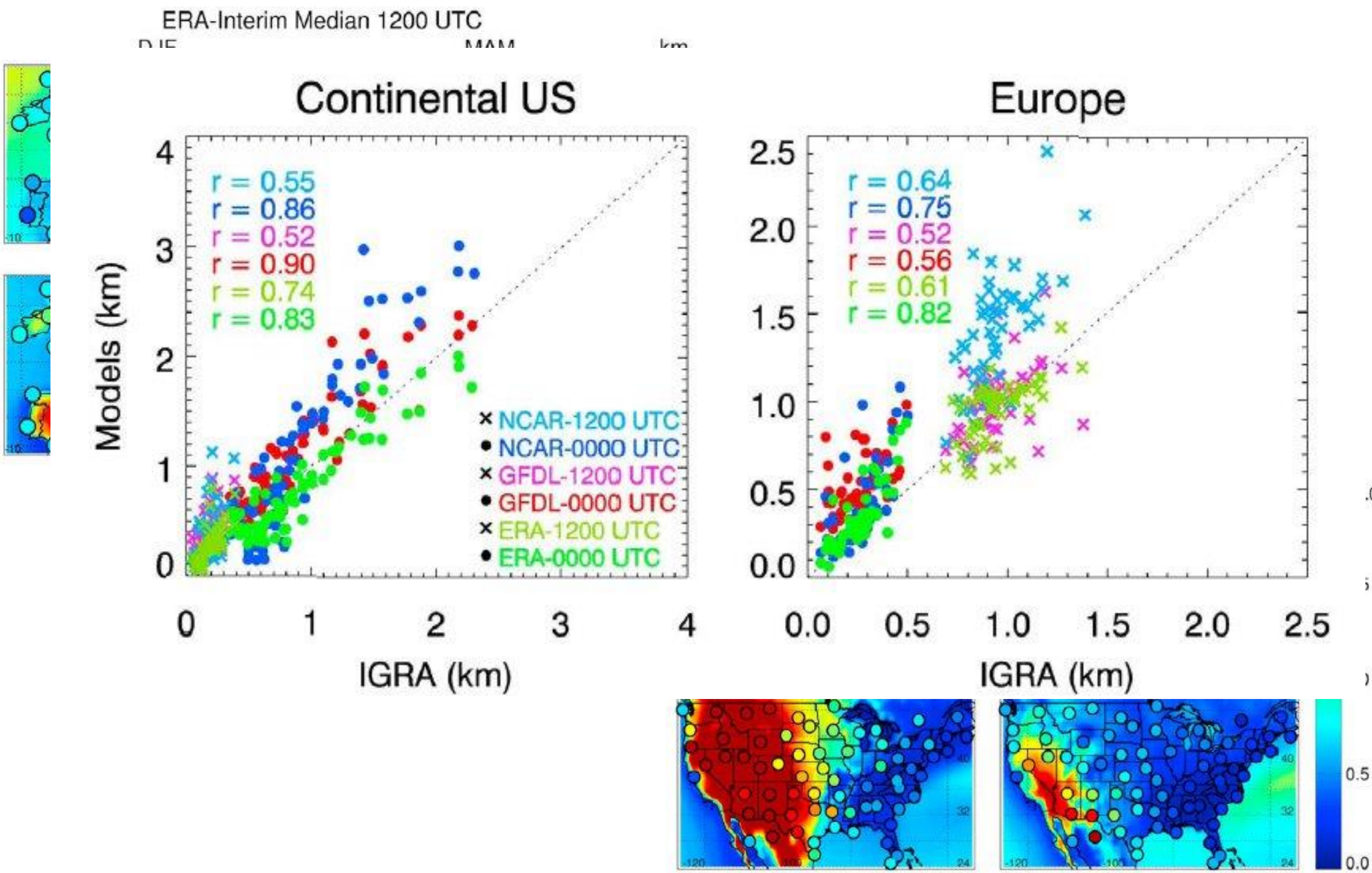
Ignore surface friction effects, much smaller than shear

Limitations:

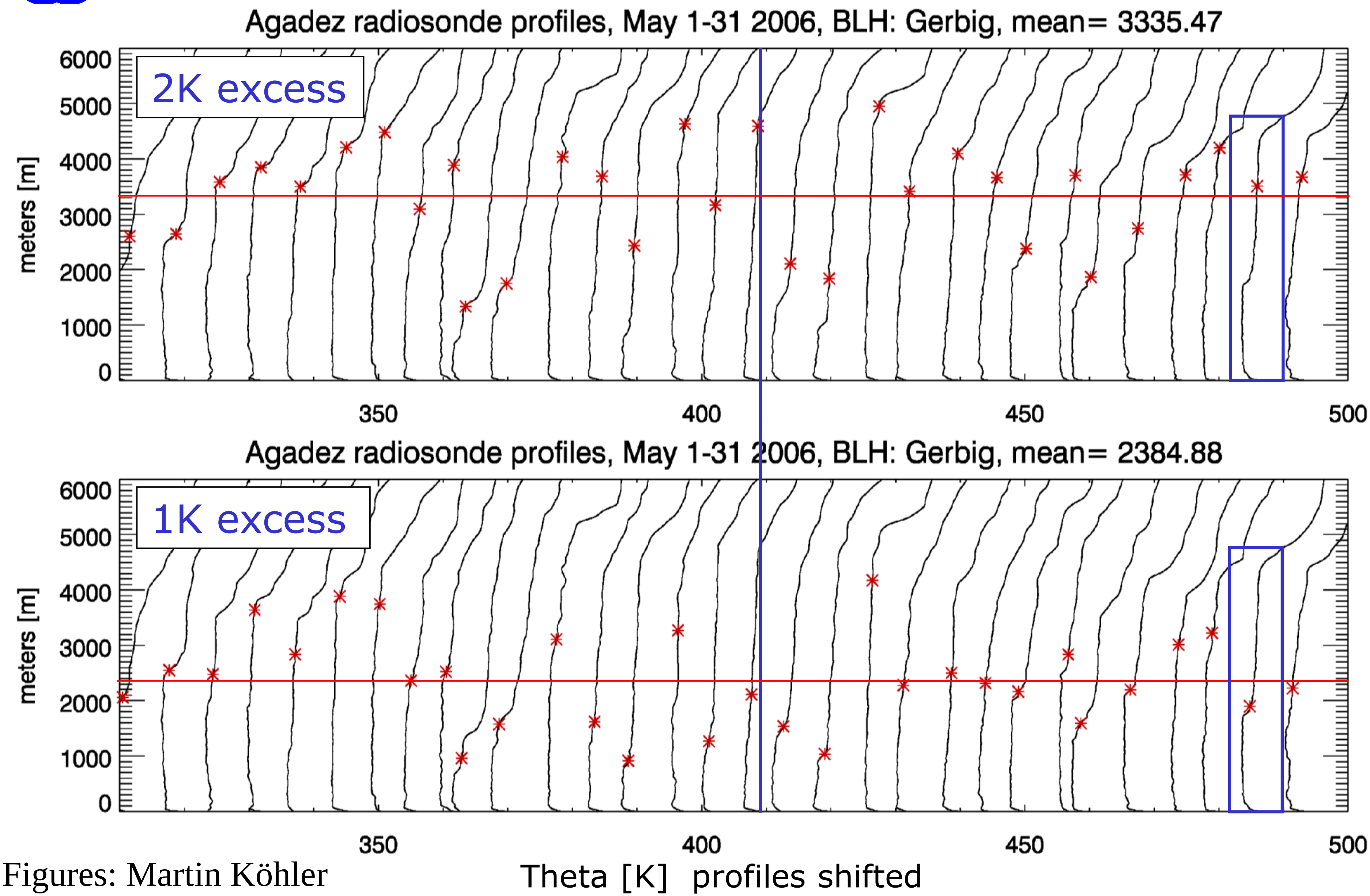
- Values for critical Ri based on lab experiment, but we're using bulk approximation (smoothing gradients), so critical Ri will be different from lab
- Subject to smoothing/resolution of profile
- Some versions give excess energy to buoyant parcel based on sensible heat flux – not reliable field, and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



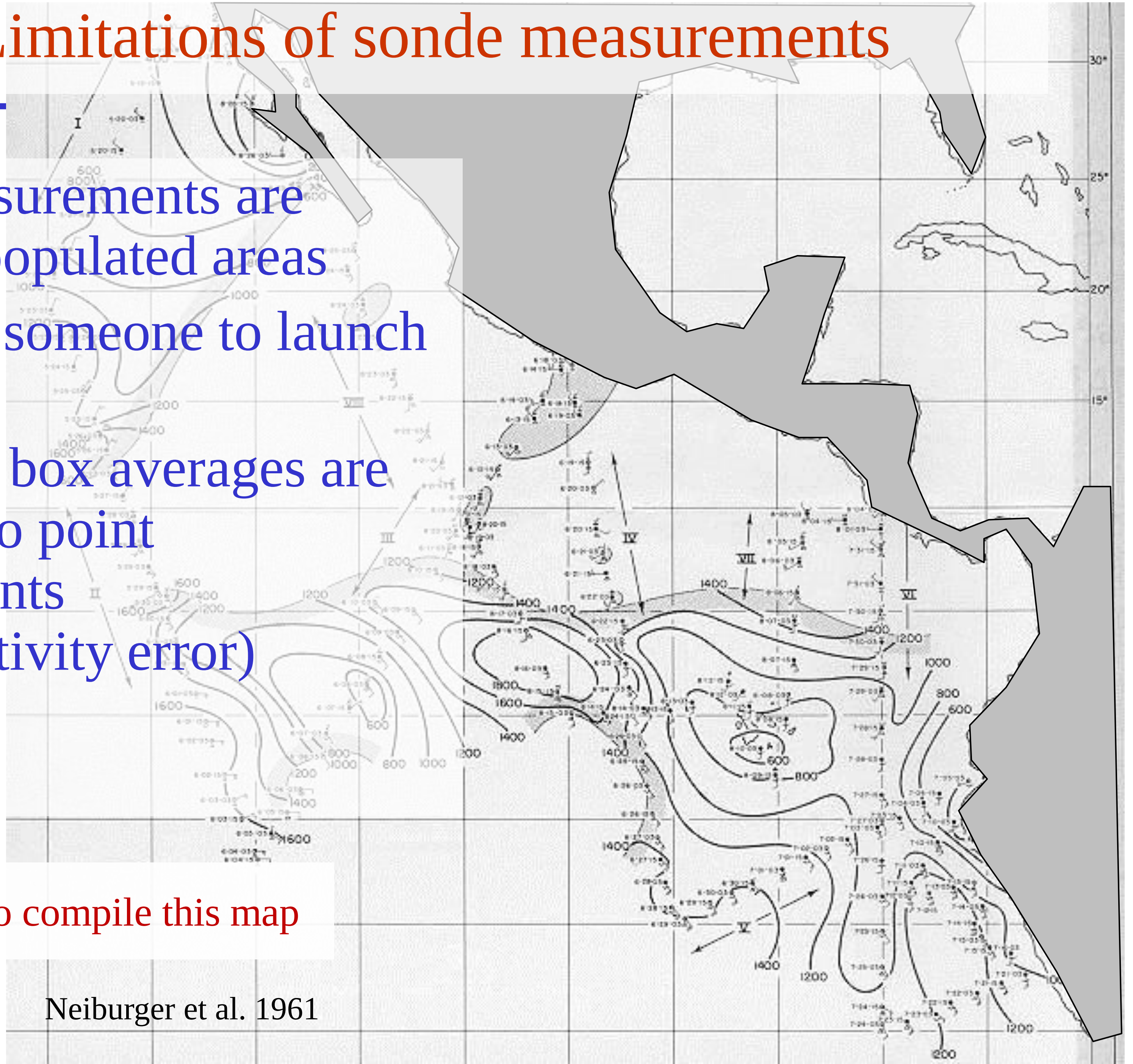
Example: dry convective boundary layer NW Africa



Figures: Martin Köhler

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)



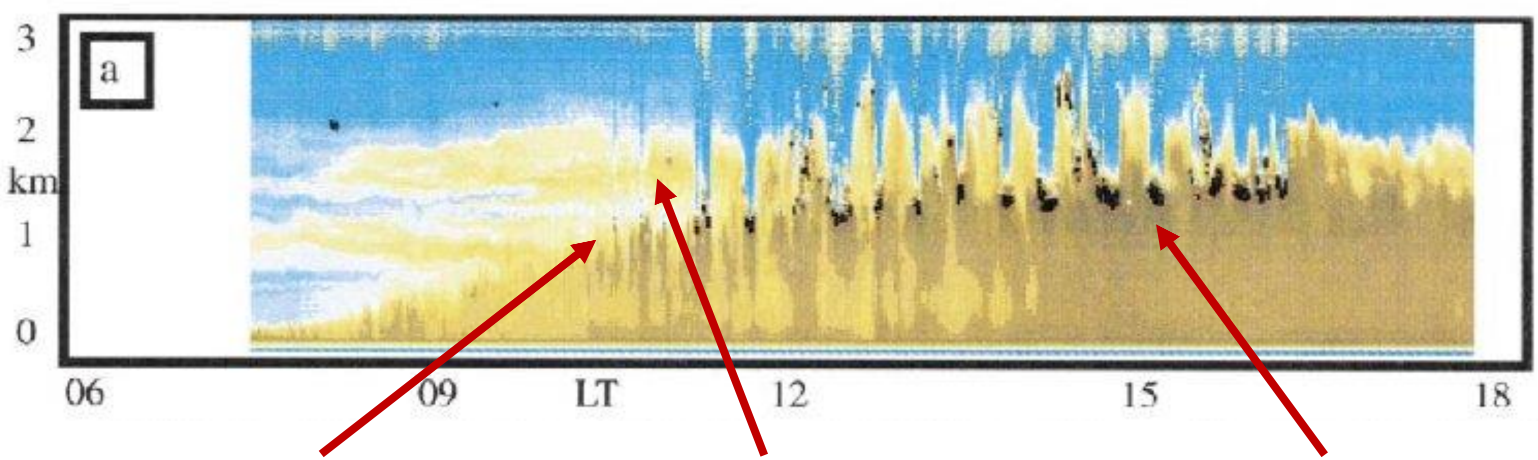
Took many years to compile this map

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

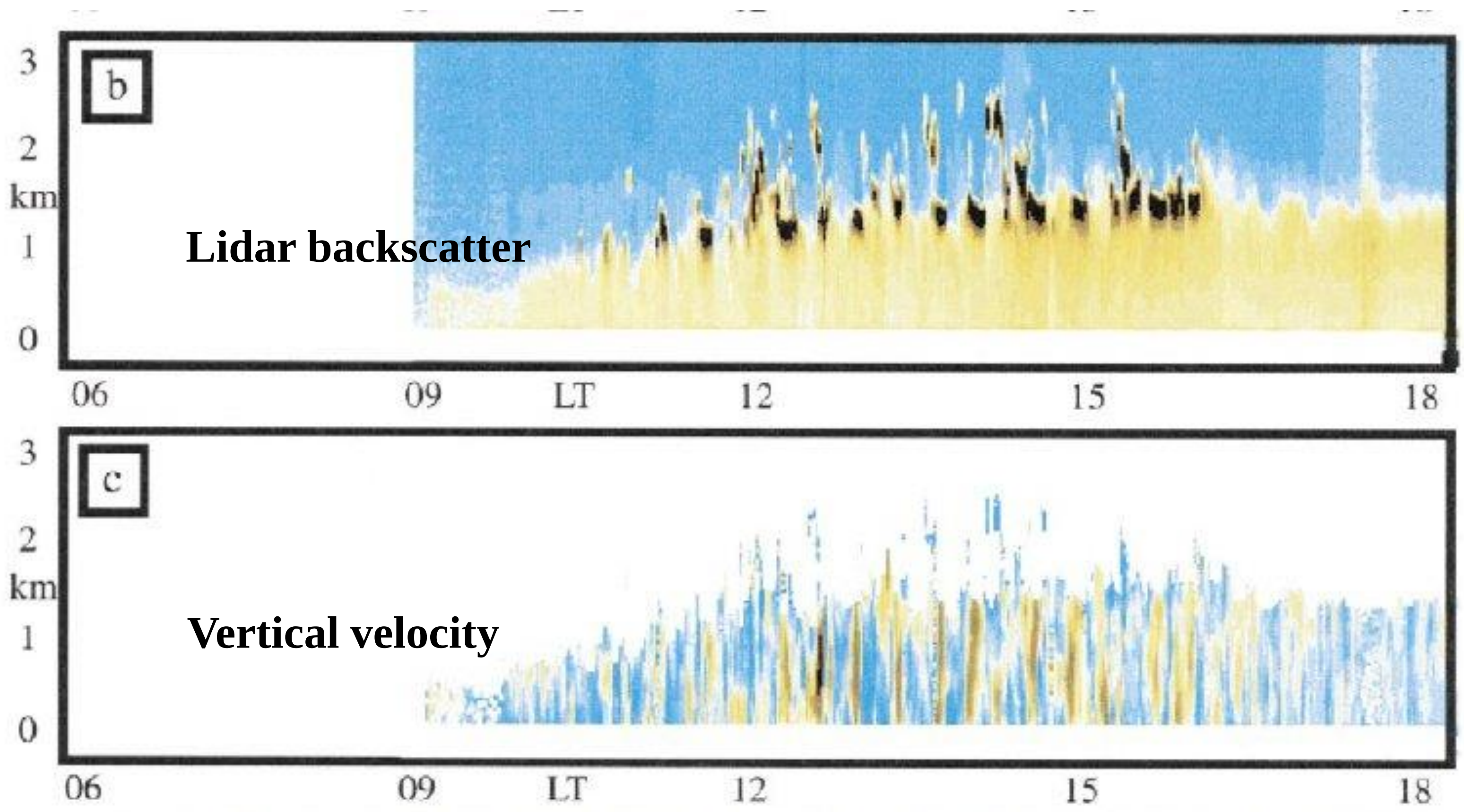
elevated aerosol layer

attenuated signal due to clouds

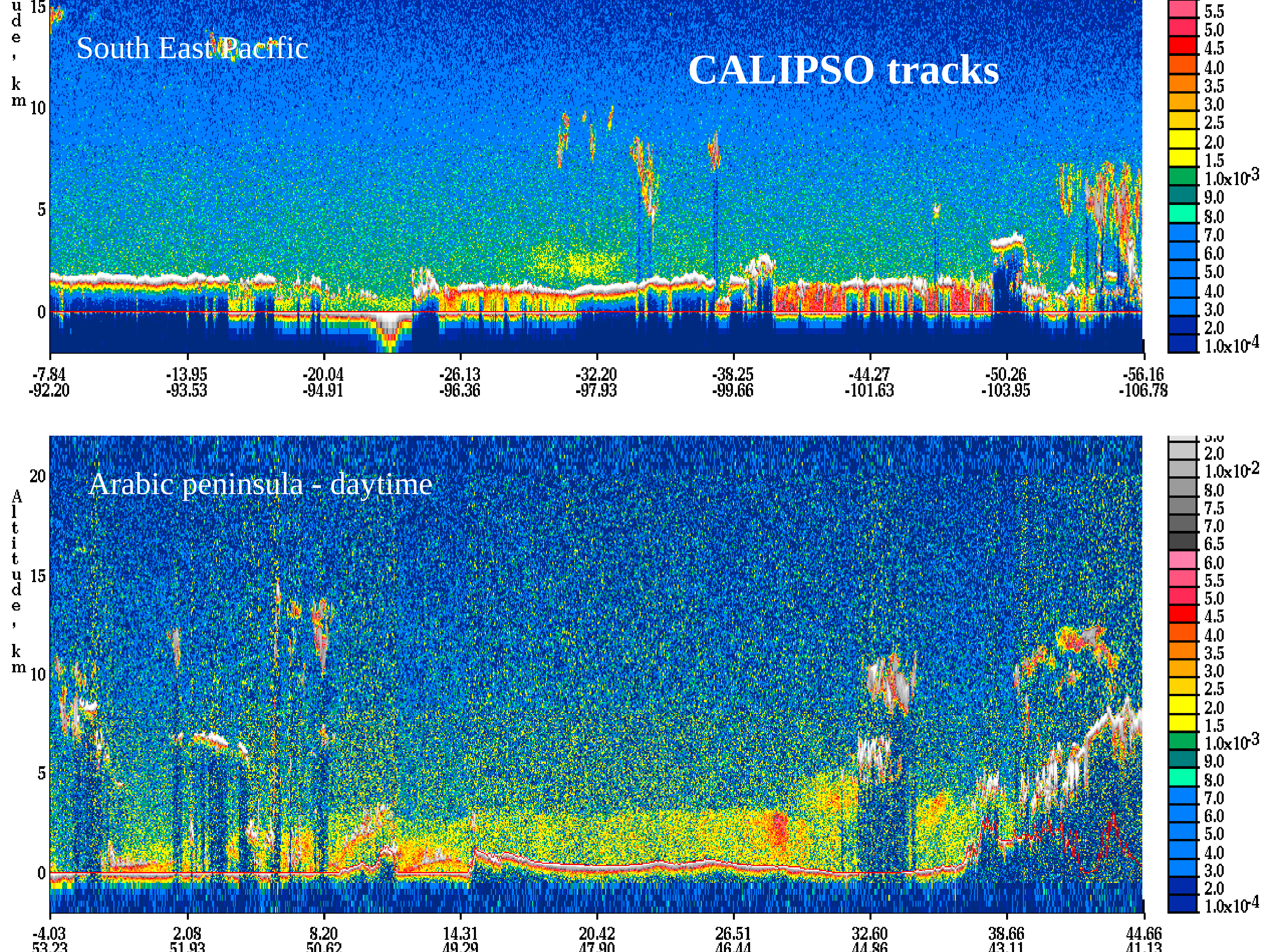
Cohn and Angevine, 2000

Additional information from lidar

Doppler Lidar



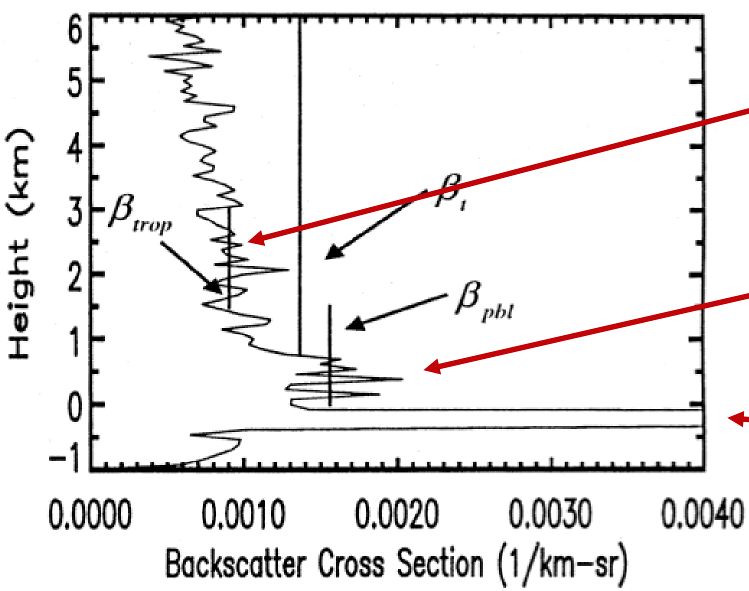
In addition to backscatter, get vertical velocity from doppler lidar. Helps define BLH, but also provides information on **turbulent motion**



South East Pacific
CALIPSO tracks
Arabic peninsula - daytime
Altitude, km
-7.84 -92.20
-13.95 -93.53
-20.04 -94.91
-26.13 -96.36
-32.20 -97.93
-38.25 -99.66
-44.27 -101.63
-50.26 -103.95
-56.16 -106.78
-4.03 53.23
2.08 51.93
8.20 50.62
14.31 49.29
20.42 47.90
26.51 46.44
32.60 44.86
38.66 43.11
44.66 41.13

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

Lidar-derived BLH from GLAS

Only 50 days of data yield a much more comprehensive picture than Neiburger's map.

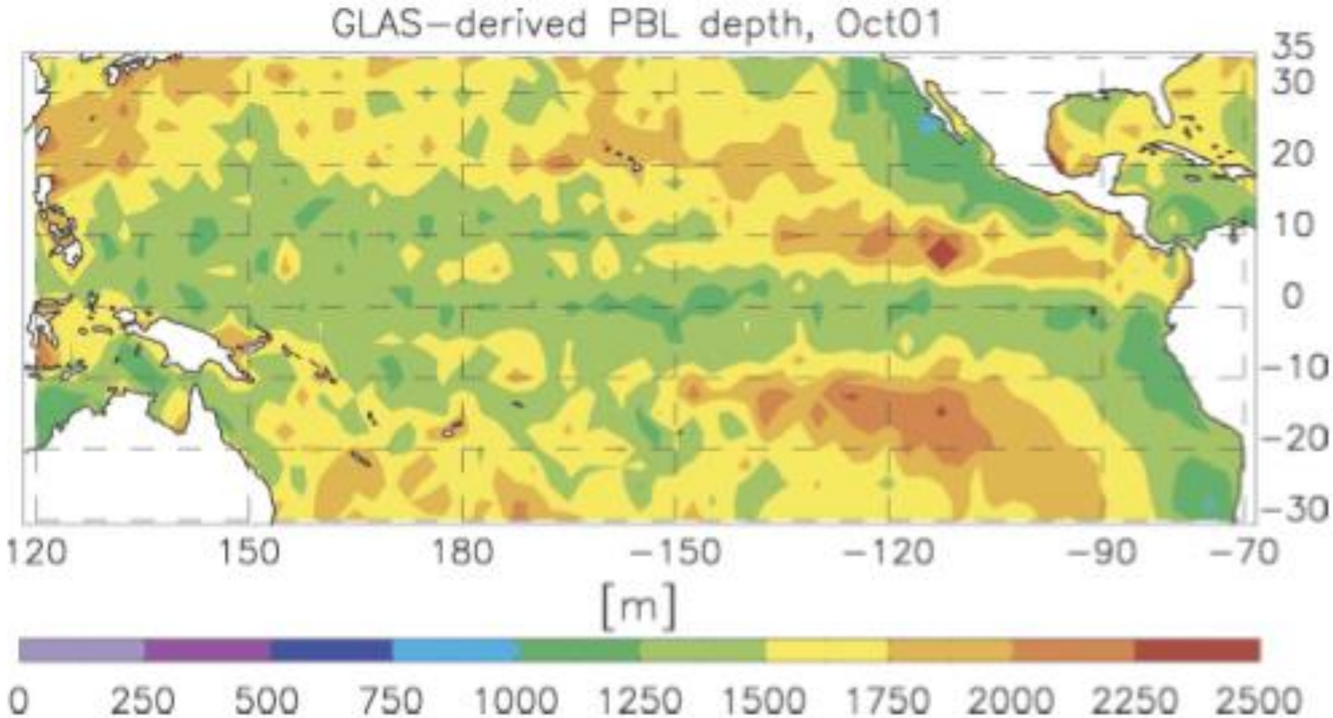
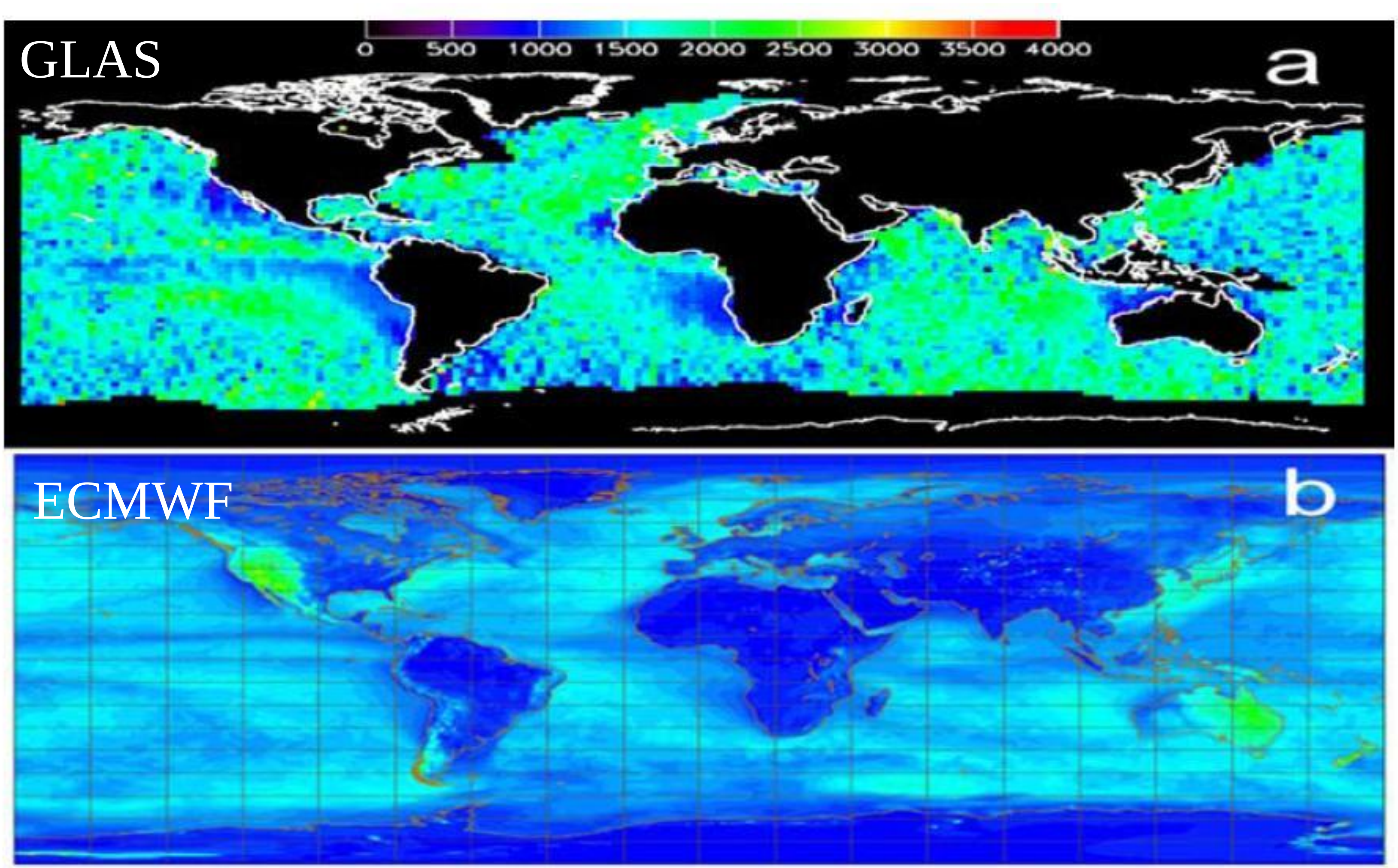


FIG. 1. GLAS-derived boundary layer depth, averaged from 26 Sep to 18 Nov 2003. Retrievals with PBL depths exceeding 3500 m have been excluded.

Ahlgrimm & Randall, 2006

GLAS - ECMWF BLH comparison

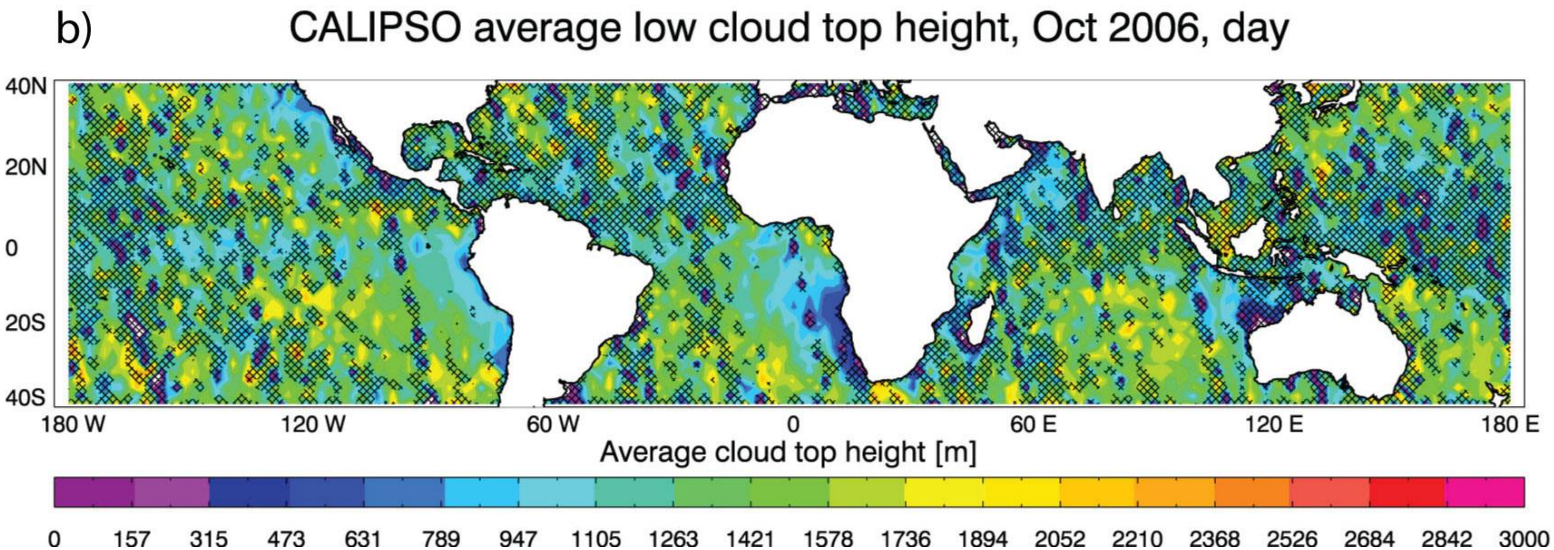


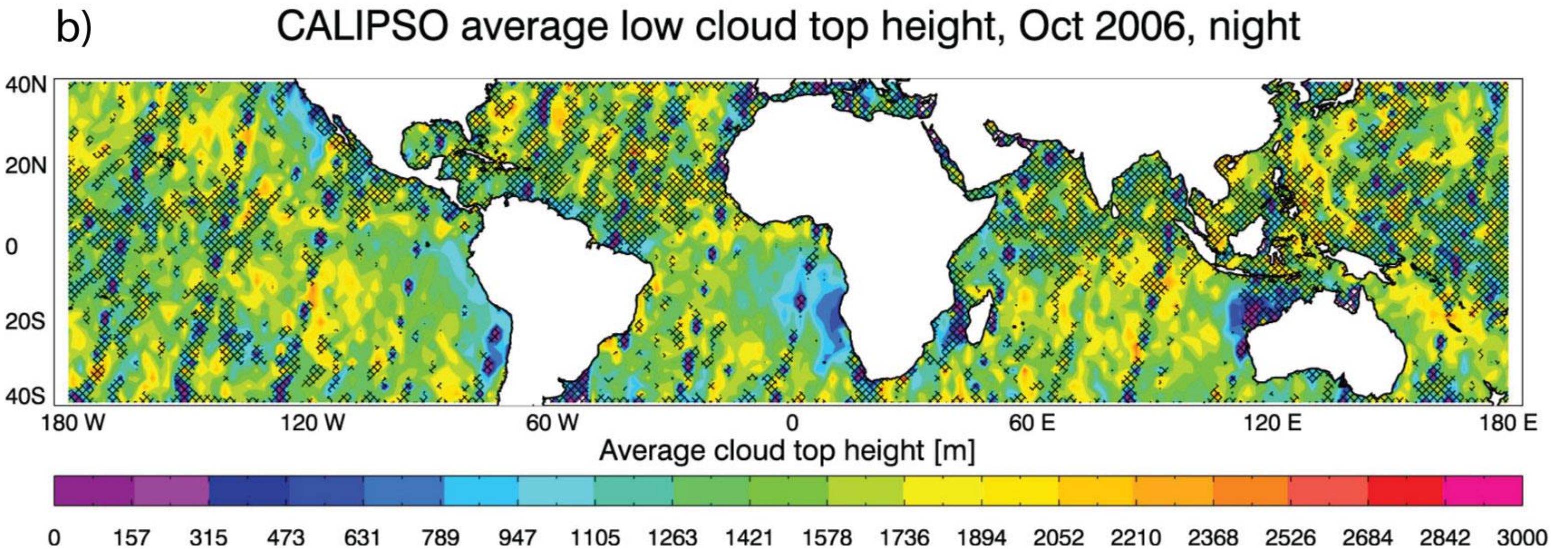
200-500m shallow in model, patterns good

Figure 4. (a) The GLAS-derived boundary layer height for October 2003 and (b) the ECMWF model 6-hour PBL height forecast (valid 00 UTC) averaged over the month of October 2003. The height scale in meters, valid for both Figures 4a and 4b, is given at the top of Figure 4a.

Palm et al. 2005

Diurnal cycle from CALIPSO





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)

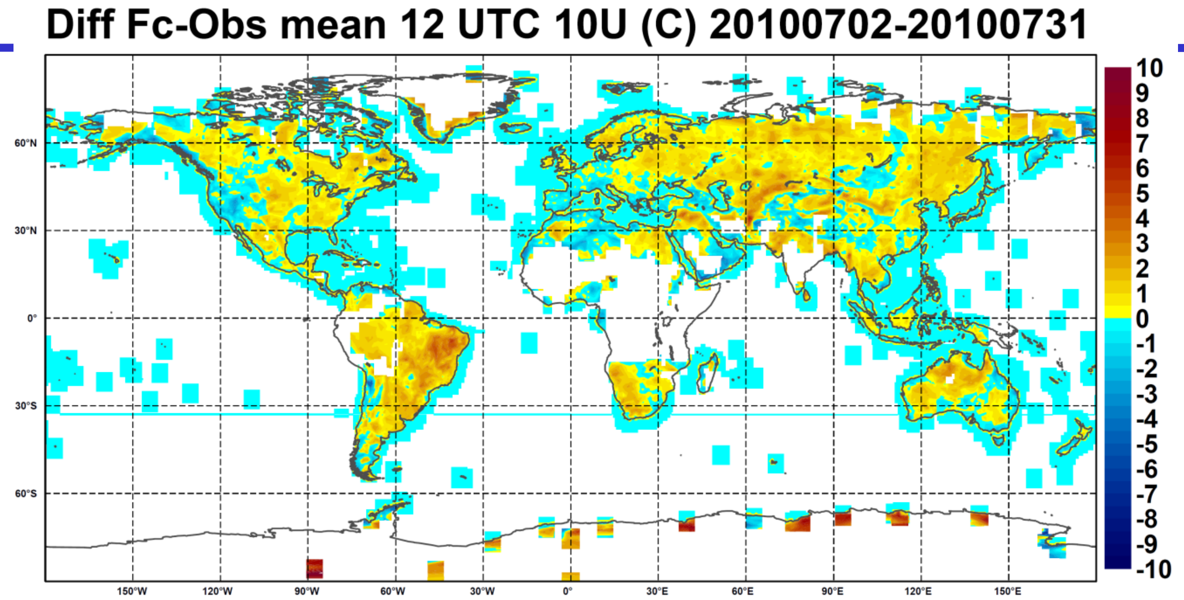
2m temperature and humidity, 10m winds

- 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

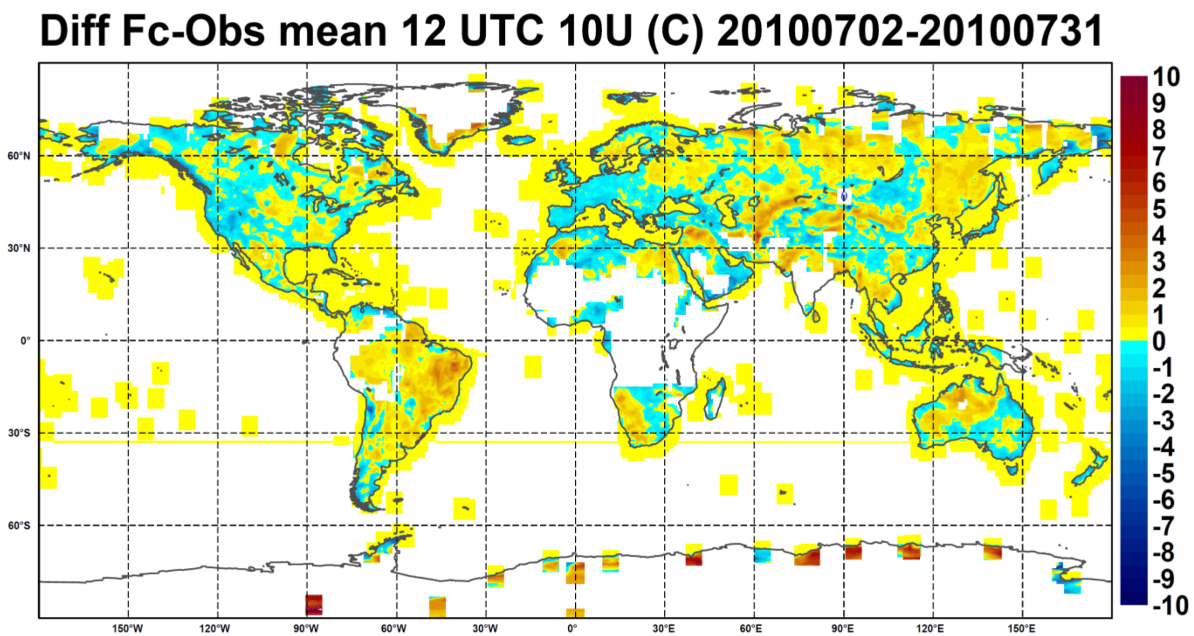
http://s0.geograph.org.uk/photos/16/66/166689_99dc7723.jpg

10m wind biases compared to synop observations

OLD

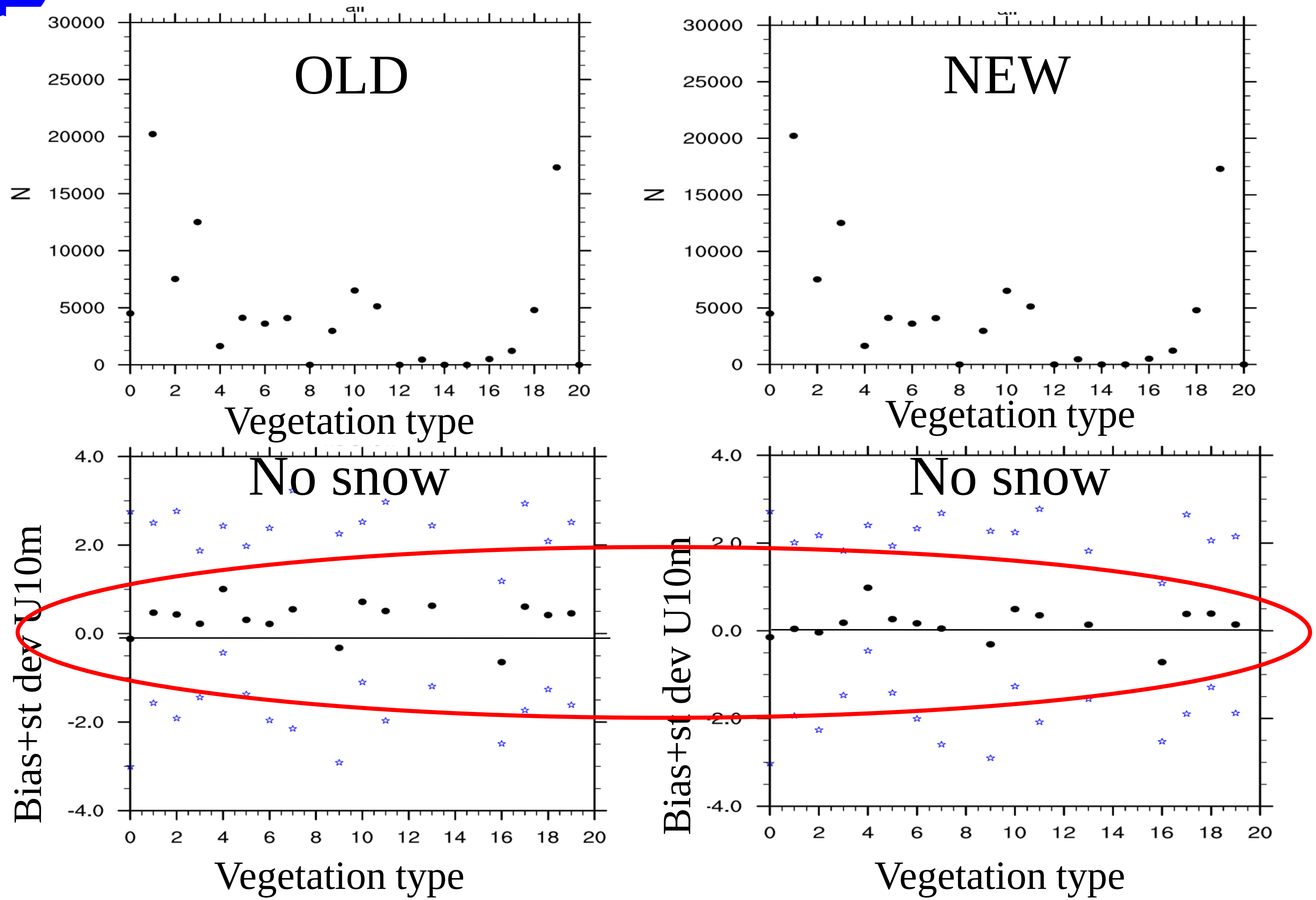


NEW



Irina Sandu

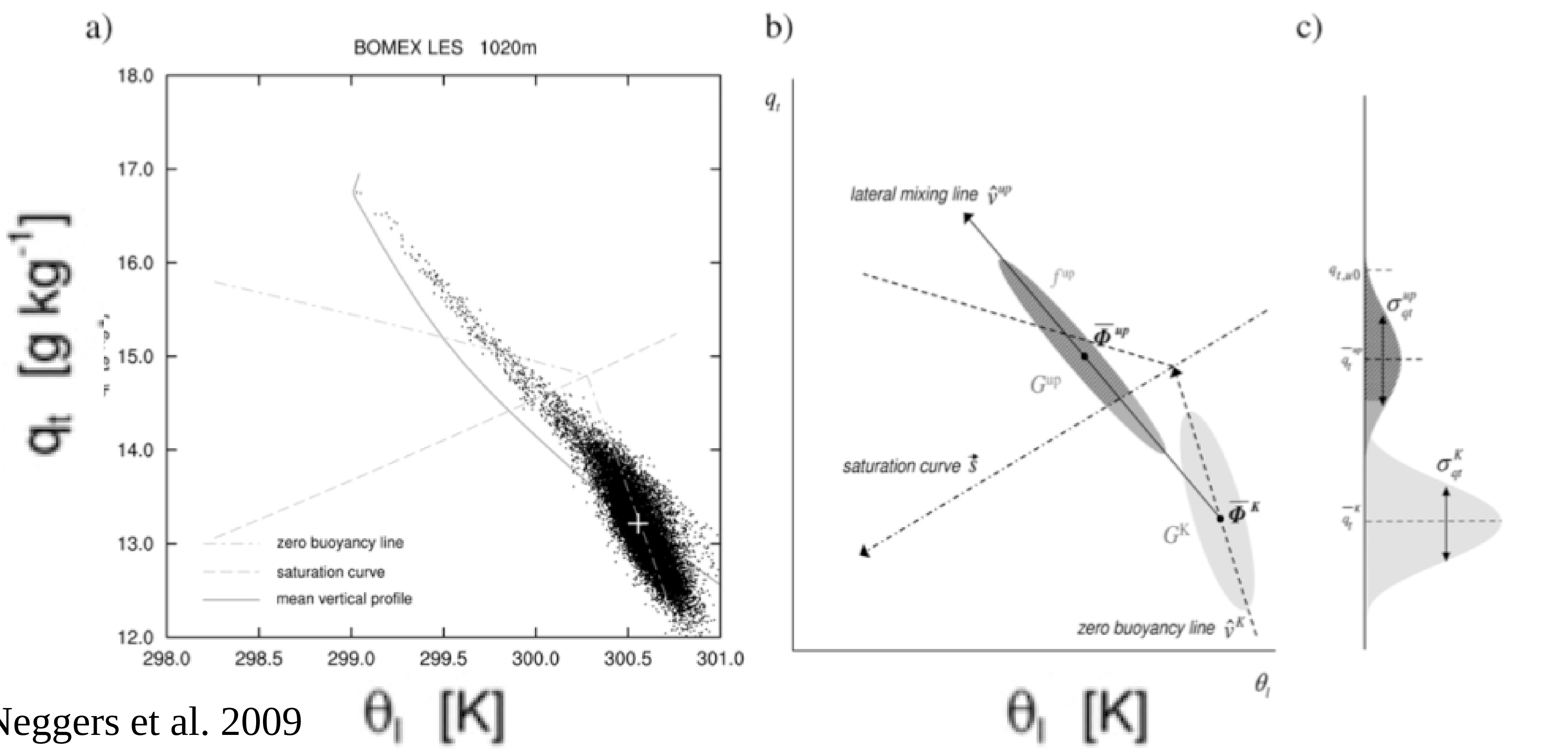
Example: 10m winds



Irina Sandu

Example: Evaluating turbulent transport (DualM)

- Dual Mass Flux parameterization - example of statistical scheme mixing K-diffusion and mass flux approach
- Updraft and environmental properties are described by PDFs, based on LES
- Need to evaluate PDFs!



Neggers et al. 2009

Bomex: trade cumulus regime

Stevens et al. 2001

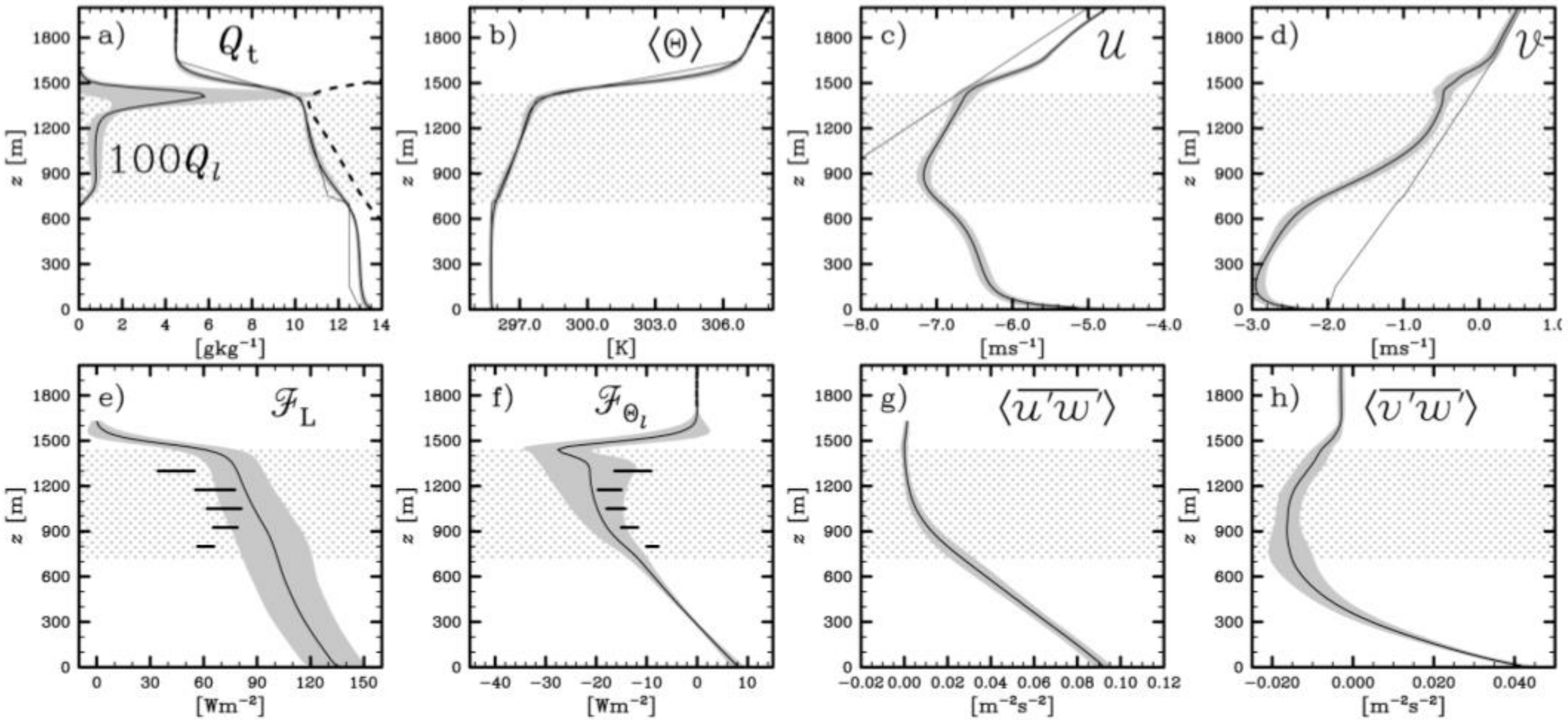
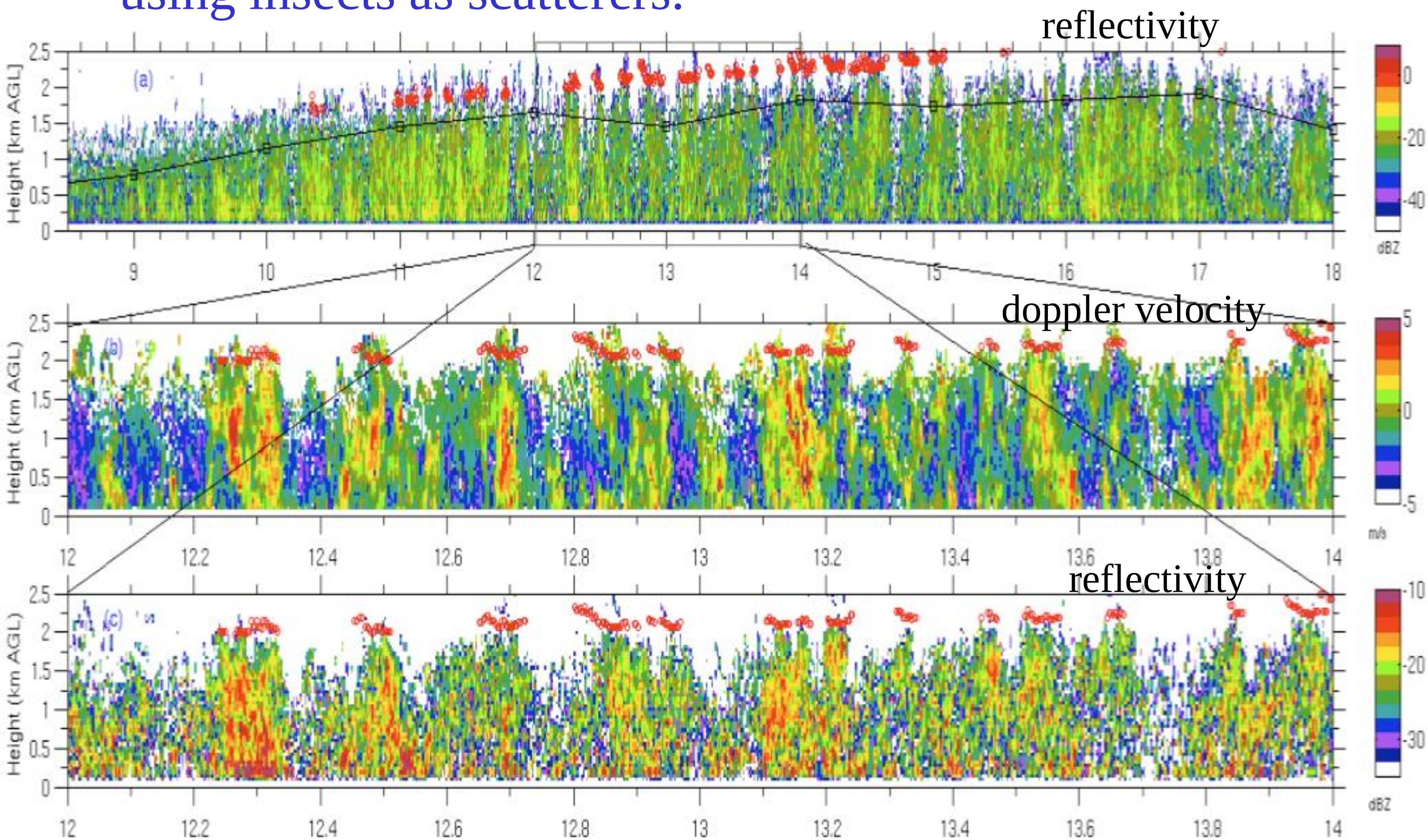


FIG. 3. Mean profiles averaged over analysis period and displayed following format of previous figure. Thin solid lines delineate initial state. Plotted, clockwise from top left are (a) total-water Q_t and liquid water Q_l mixing ratios, (b) potential temperature Θ, (c) zonal wind $\mathcal{U}$, (d) meridional wind $\mathcal{V}$, (e) total-water mixing ratio flux $\mathcal{F}_L$, (f) liquid water potential temperature flux $\mathcal{F}_{\theta_l}$, (g) zonal momentum flux, and (h) meridional momentum flux. All the fluxes are the sum of the resolved and SGS fluxes. (e) and (f) The mass-flux estimate of the flux is also shown by the short horizontal lines at five heights [see section 4b(1) for details]. (a) The thin dashed line denotes Q_s in the cloud layer.

Model fluxes via LES, constrain LES results with observations

Example: vertical motion from radar

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



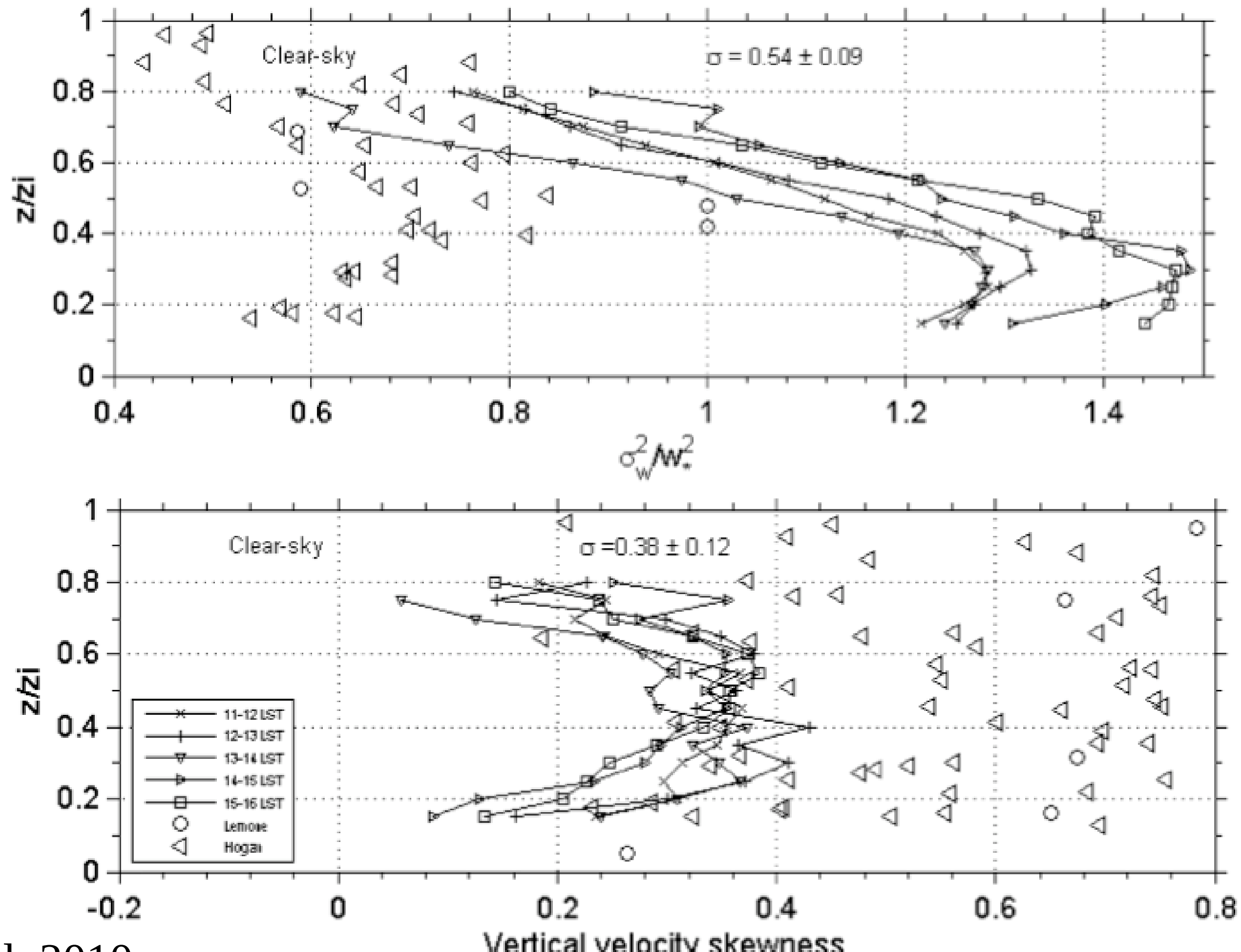
Chandra et al. 2010

local time

red dots: ceilometer cloud base

Turbulent characteristics: vertical motion

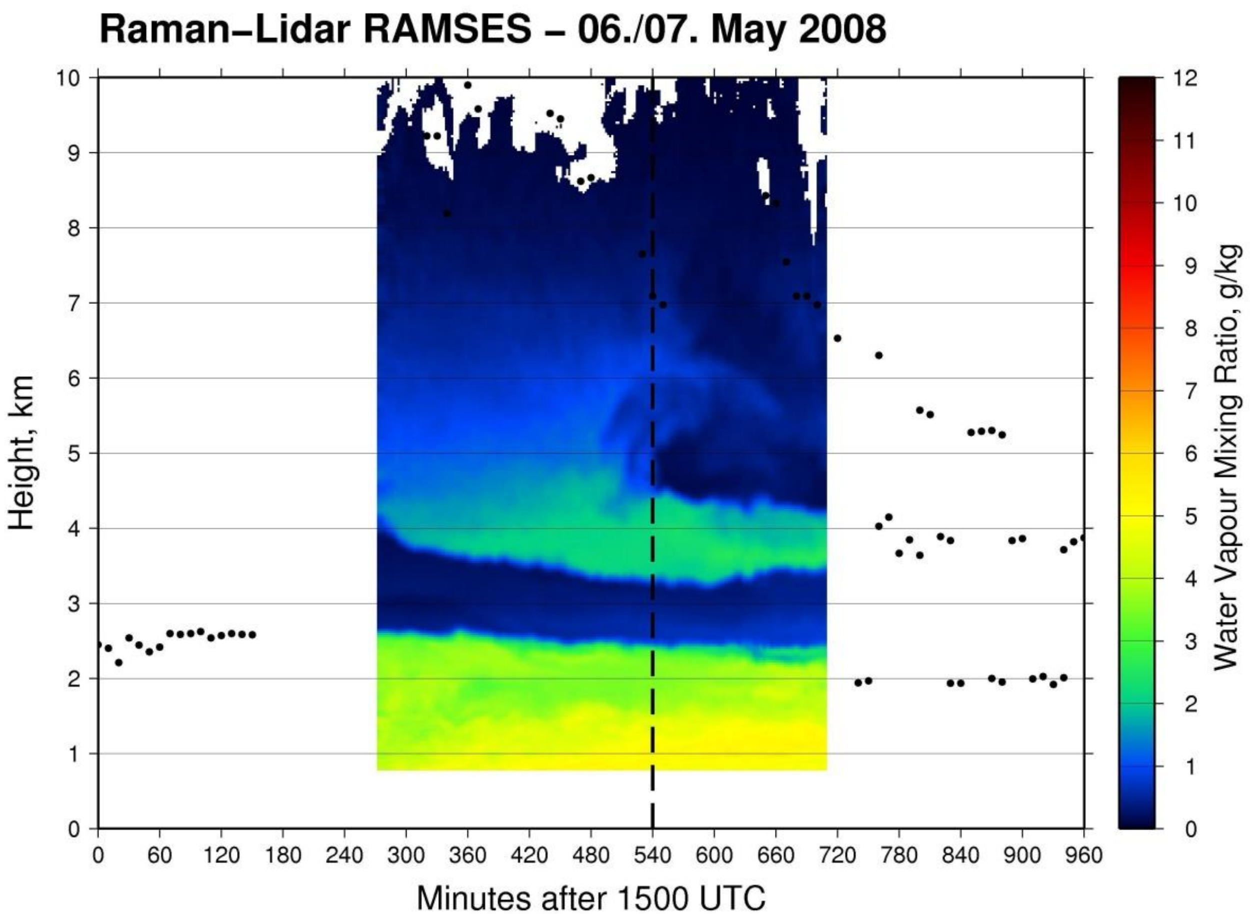
Variance and skewness statistics in the convective BL (cloud free) from four summer seasons at ARM SGP



Chandra et al. 2010

Turbulent characteristics: humidity

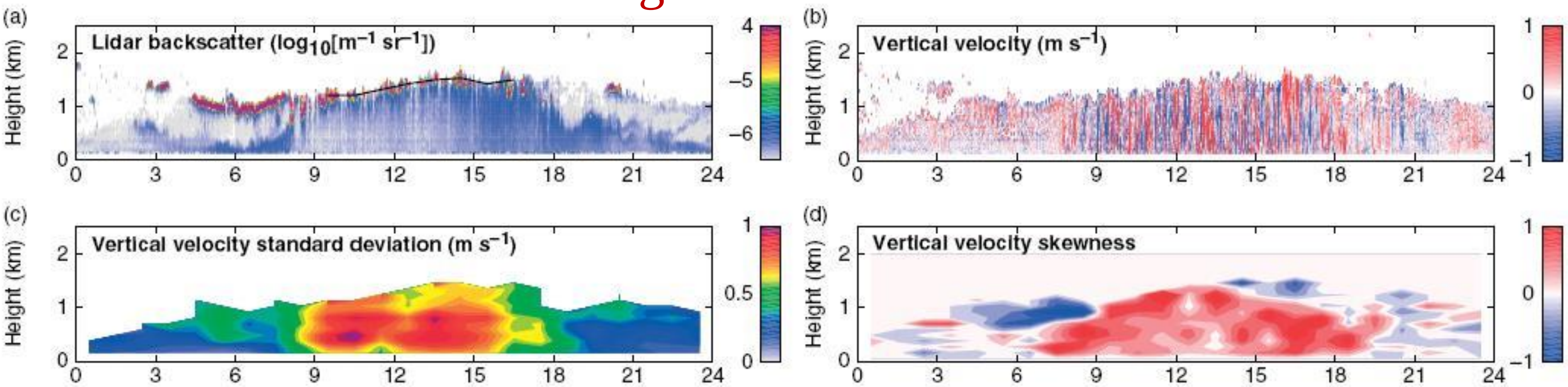
Raman lidar provides high resolution (in time and space) water vapor observations



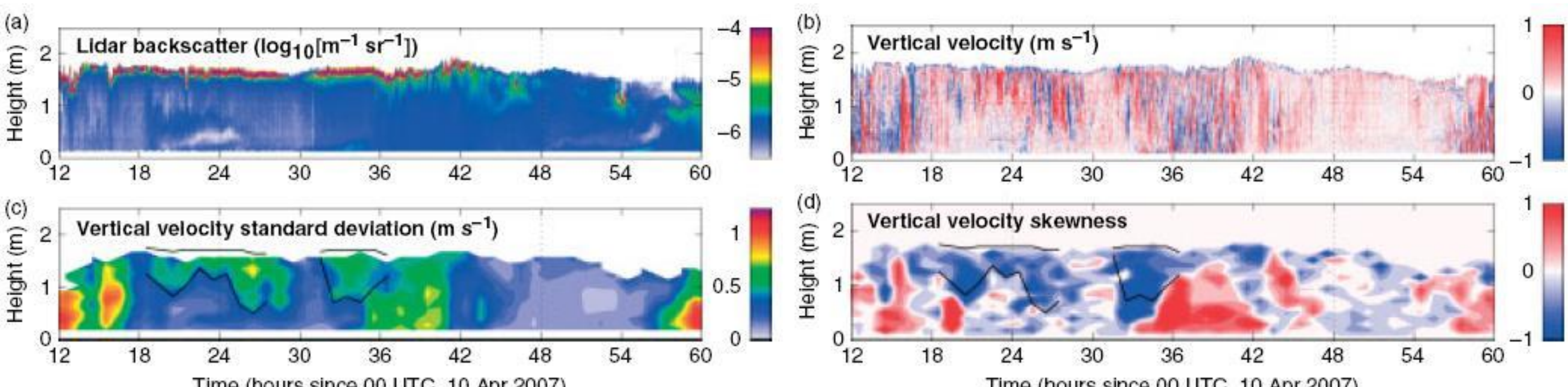
Plot: Franz Berger (DWD)

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

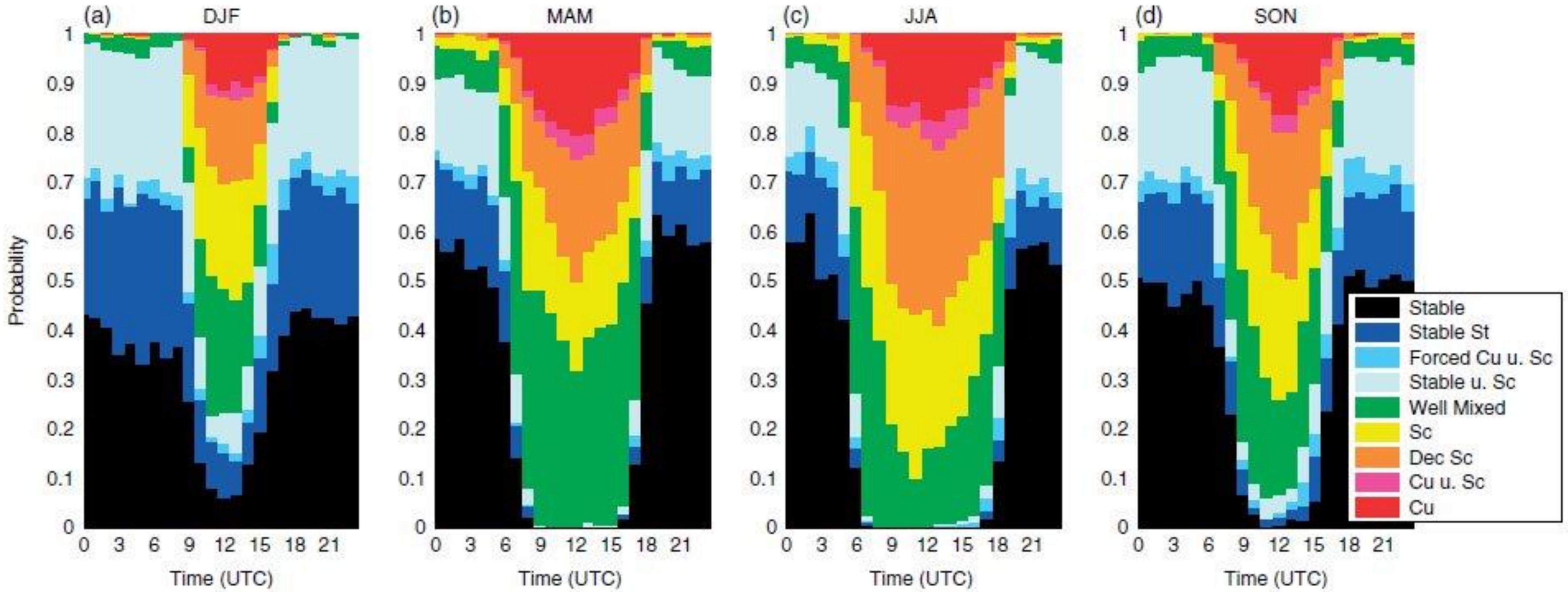


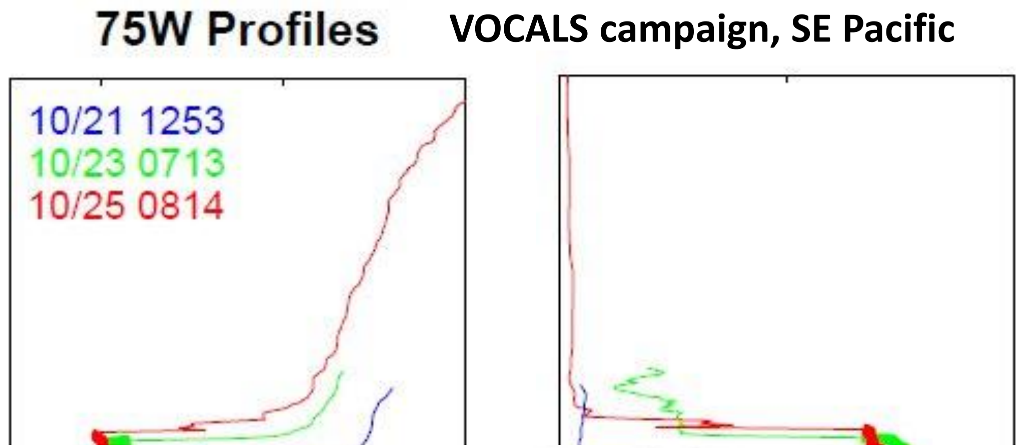
Figure 9. The diurnal distribution of boundary-layer types as a function of season: (a) winter, (b) spring, (c) summer, and (d) autumn.

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

Harvey et al. 2013

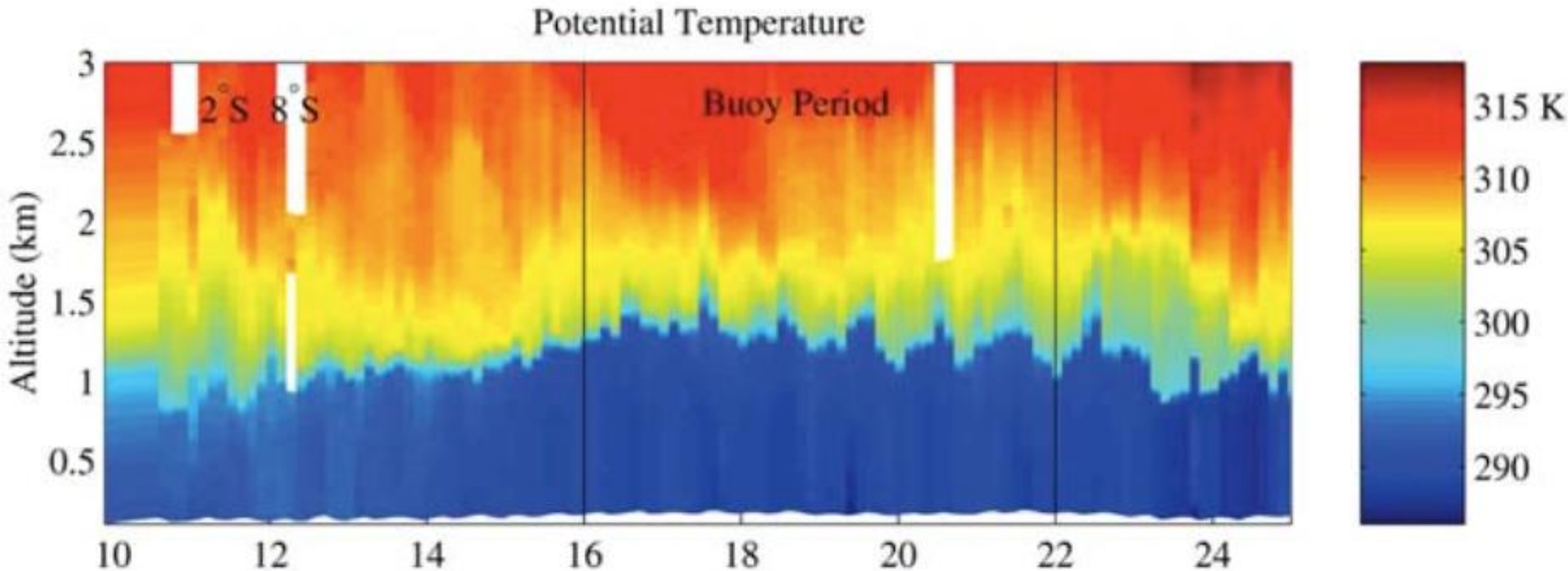
Example: cloud topped BL

VOCALS campaign, SE Pacific



Bretherton et al. 2010

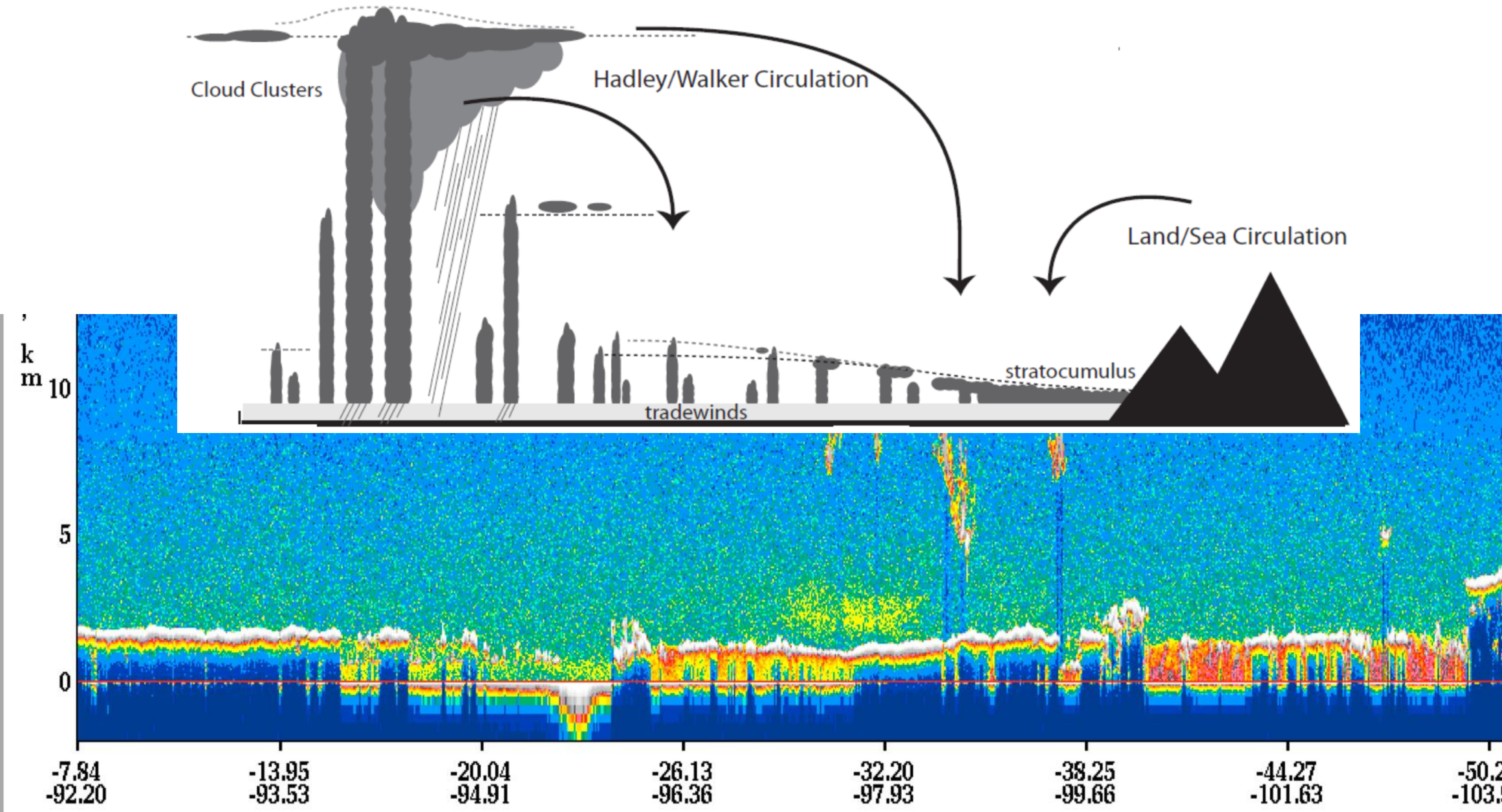
- Very strong inversion signal,
- Easy to pick out from profile
- Very strong backscatter signal from lidar
- Easy to detect cloud top/base



Bretherton et al. 2004, BAMS

Example: cloud topped BL

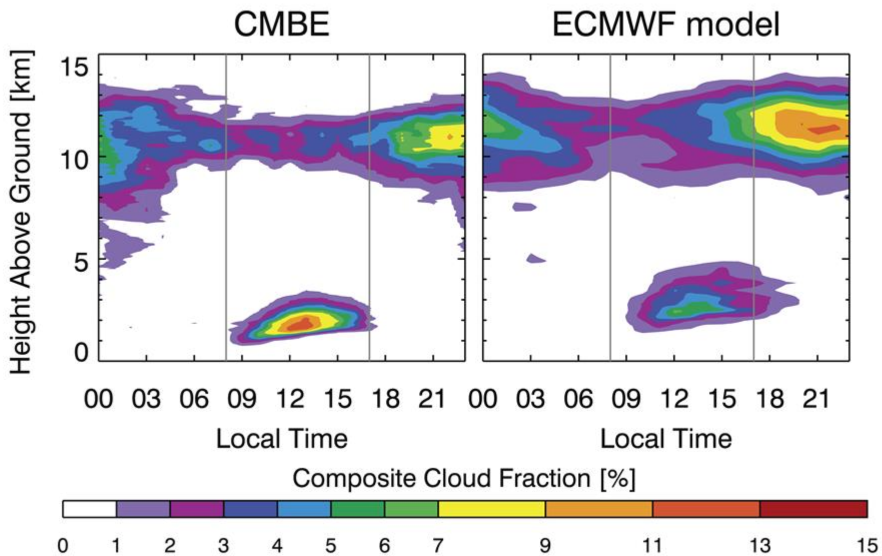
Difficulty: how to define BL top?



Observations relating to BL forcing

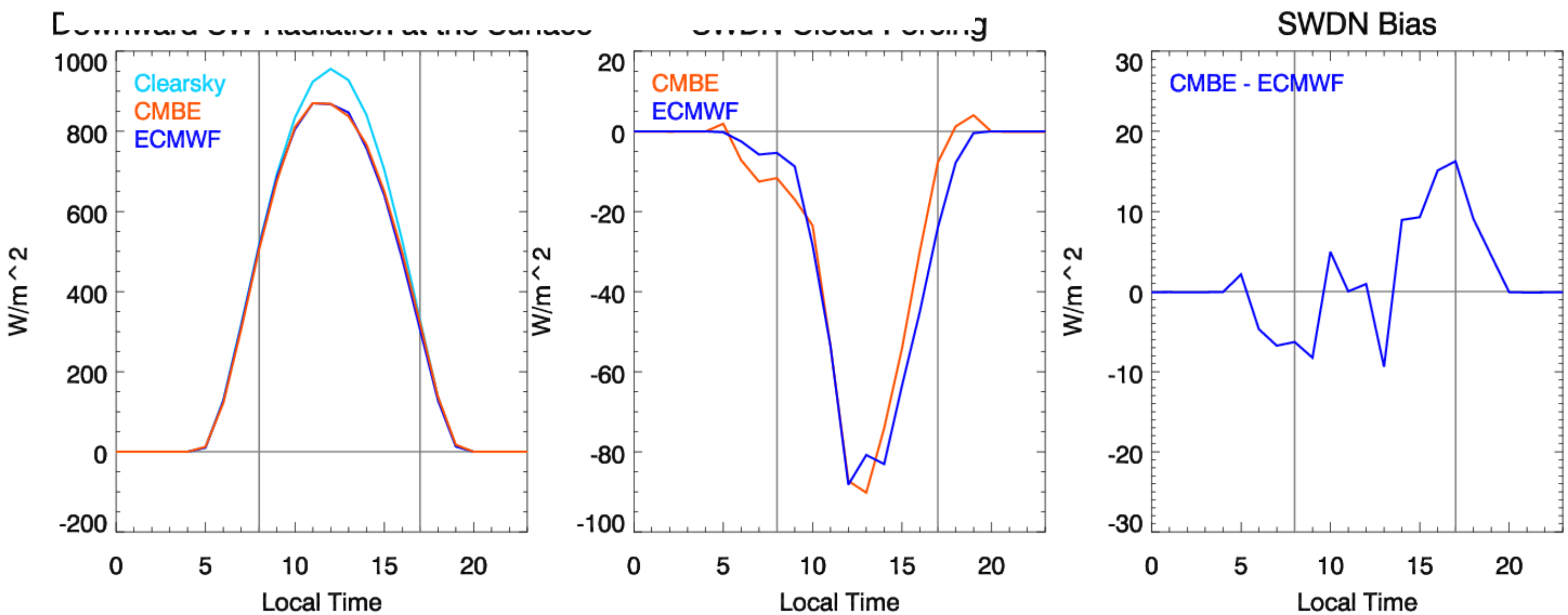
- Surface radiation (optical properties of cloud, top-driven strength of turbulence)
- Cloud liquid and drizzle retrievals from radar (cloud properties, autoconversion/accretion and evaporation processes)
- Cloud mask from radar/lidar (cloud occurrence, triggering of BL types)
- Surface fluxes (BL types)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

Examples from the IFS: Fair weather cumulus



Compensating errors in this regime:

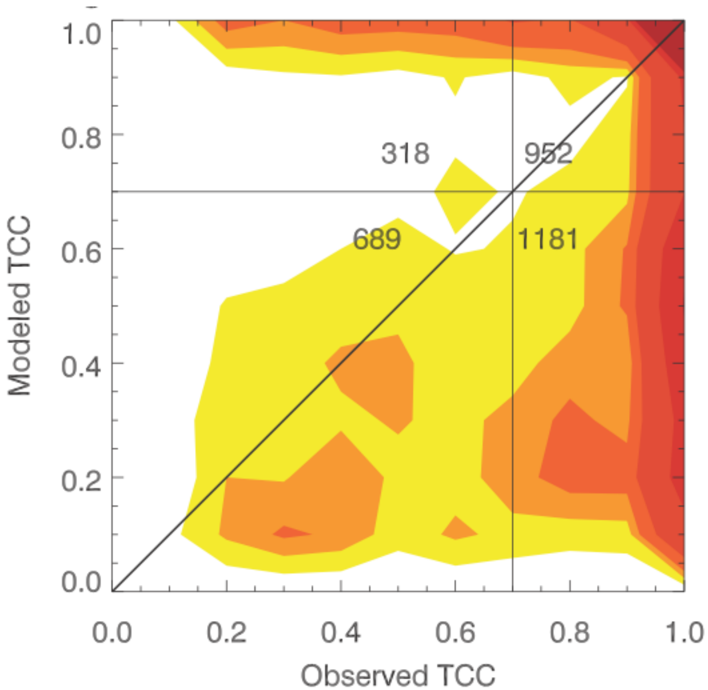
- BL scheme not triggering cloud often enough
- Cloud amount when present ok
- Cloud liquid overestimated



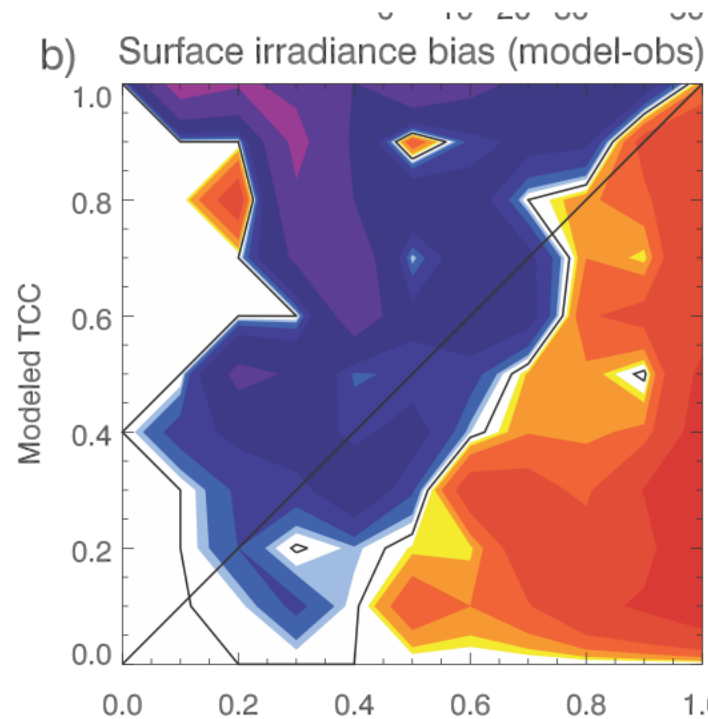
Ahlgrimm and Forbes, 2012

Examples from the IFS: Marine BL cloud

Joint PDF of cloud fraction



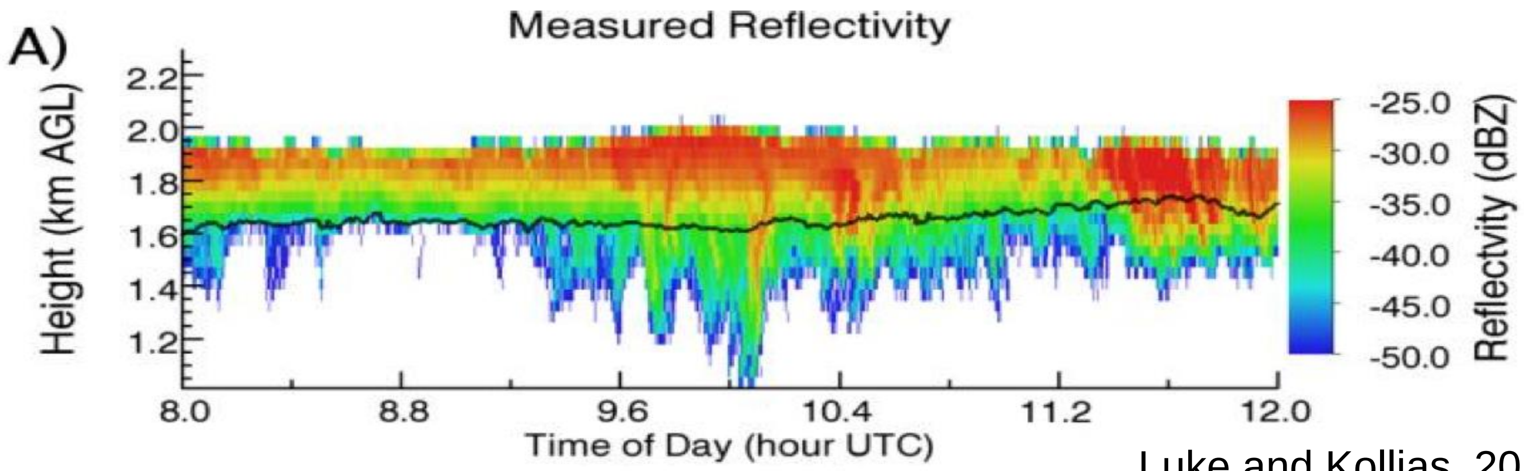
Model has few cloud fractions between 60-90%:
BL type "stratocumulus" vs. cloud generated by shallow convection scheme - triggering



"Broken" BL clouds have opposite SW bias from "overcast" BL clouds:
Cloud properties incorrect (in this case, main cause: LWP)

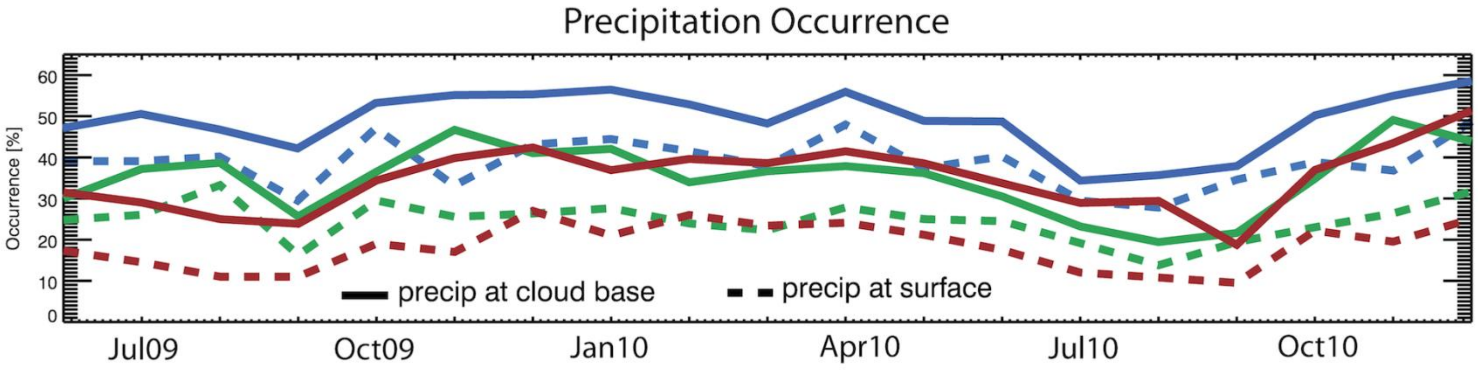
Ahlgrimm and Forbes, 2014

Examples from the IFS: Marine BL cloud



Luke and Kollias, 2013

Precipitation occurrence overestimated at cloud base and the surface:
Alterations to autoconversion/accretion and evaporation parameterizations



Summary & Considerations

- What parameter do you want to verify?
- What observations are most suitable?
- Define parameter in model and observations in as equitable and objective a manner as possible.
- Compare!
- Are your results representative?
- How do model errors relate to parameterization?

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