Planetary Boundary Layer Studies with GPS-RO

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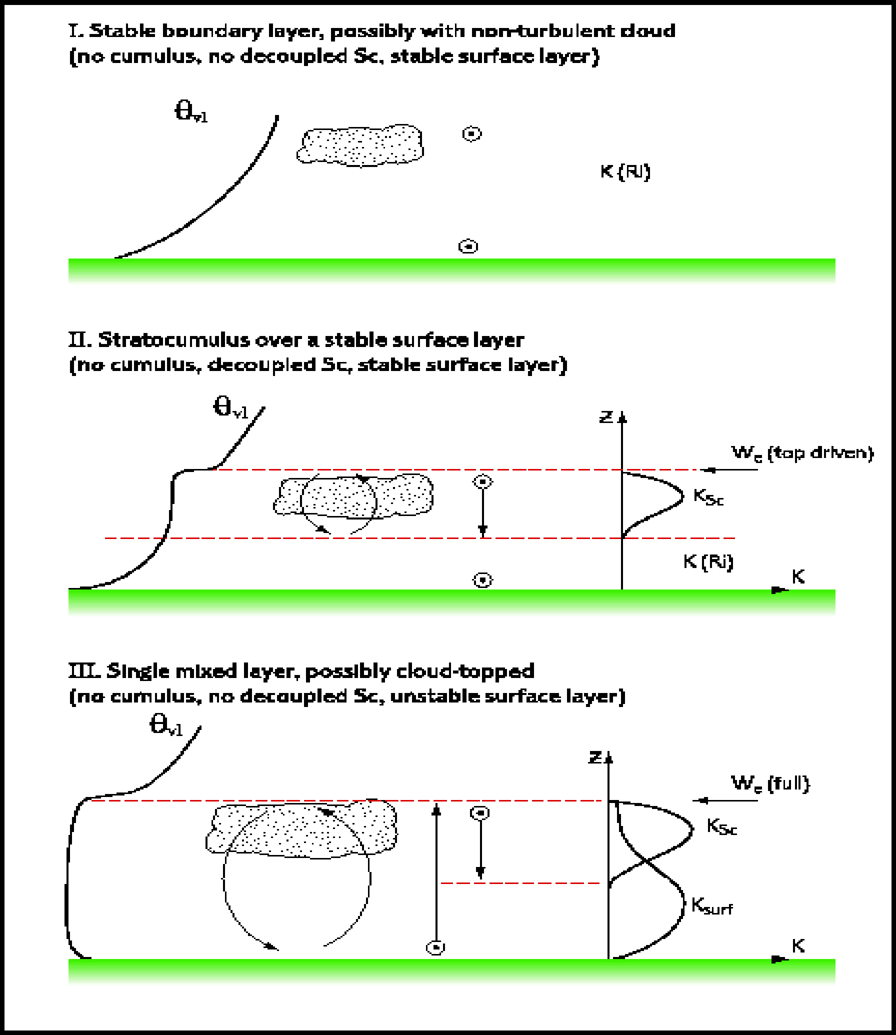
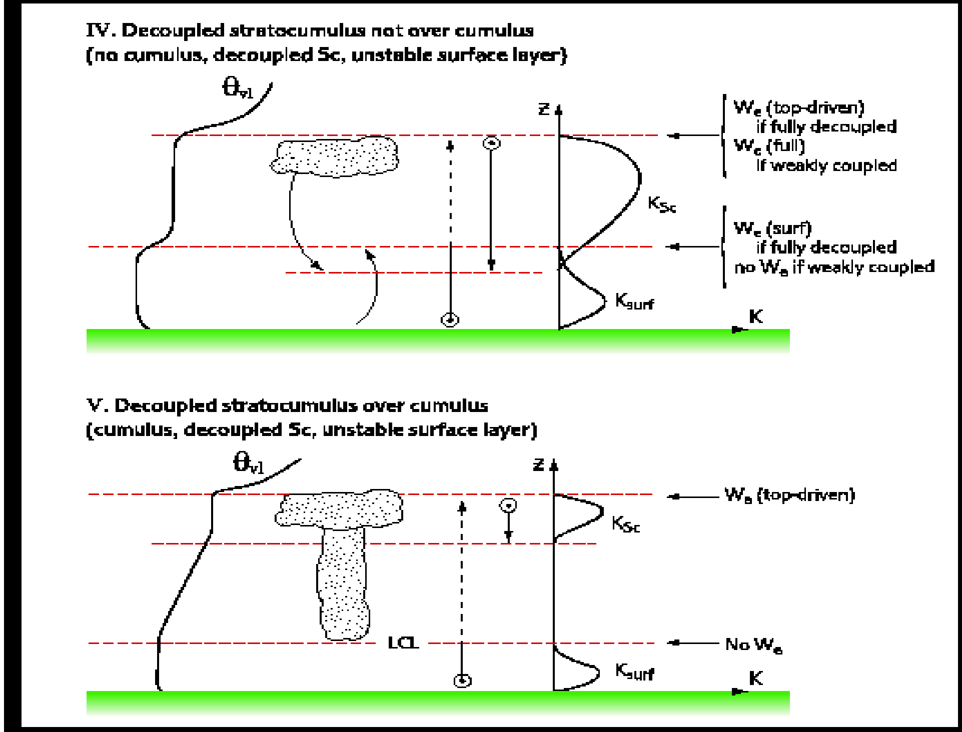
ECMWF, Reading, United Kingdom

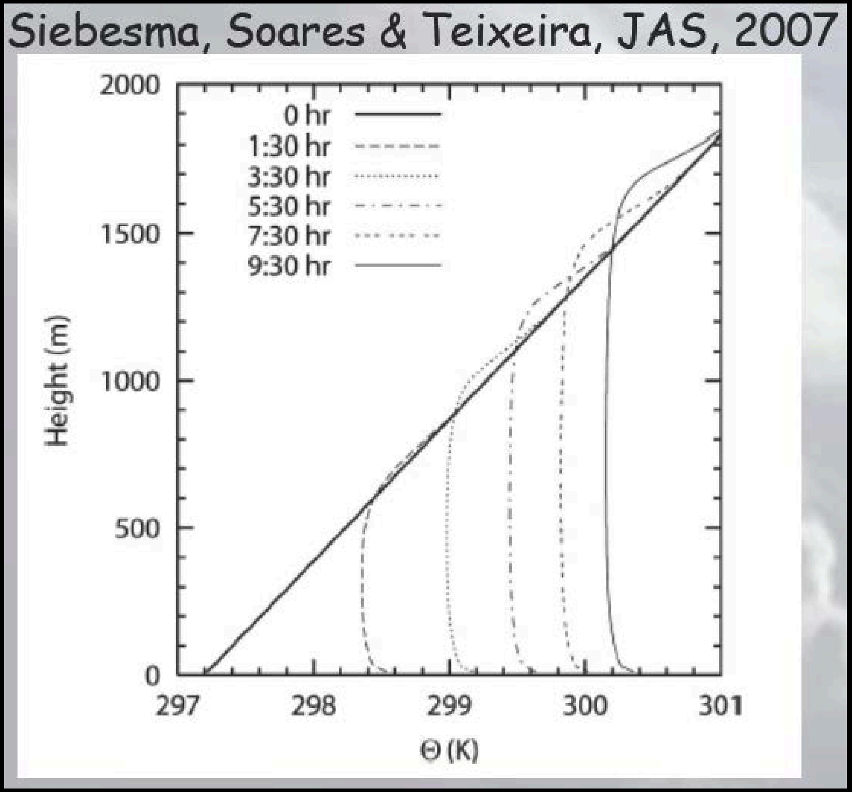
Different PBL Vertical Structure



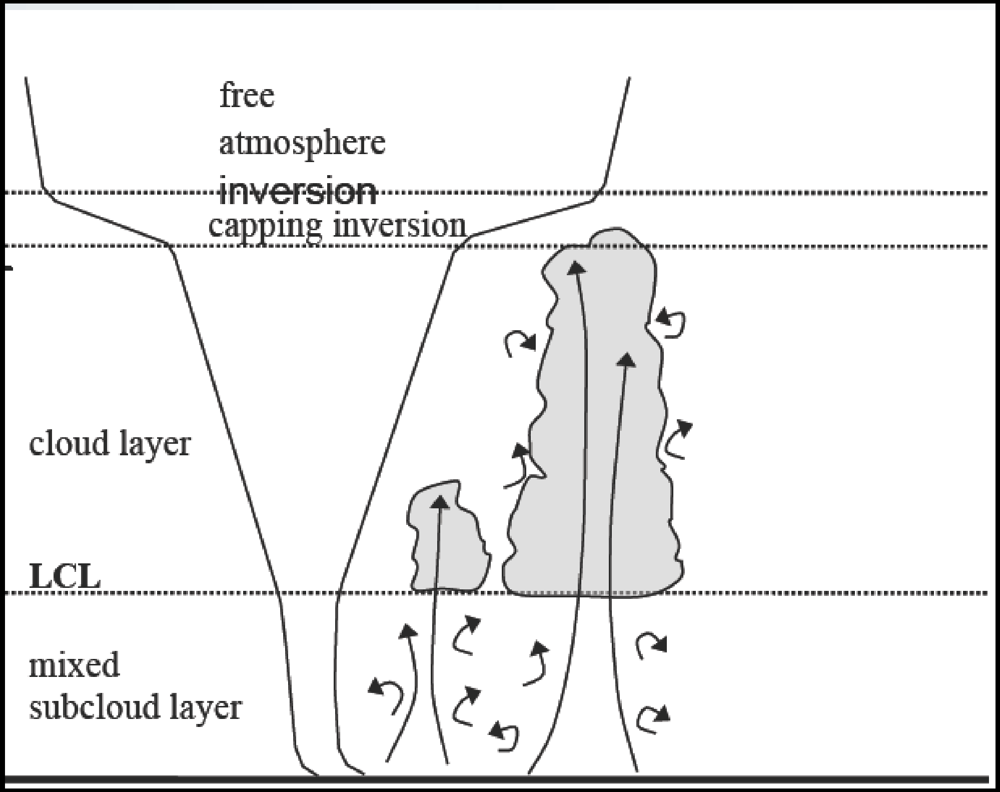


Lock et al., 2000, MWR

Dry & Wet PBL



Well-mixed dry PBL (LES)



Cloudy (wet) PBL

Courtesy of J. Teixeira

Planetary Boundary Layer

- Key component of the weather and climate system, Interface between earth's surface and the free troposphere (affect energy and mass flux), of prime importance to climate, weather, and air quality

- Governing the evolution of low clouds (large uncertainty in climate feedback according to IPCC-2007/2013 report)

- PBL height – or mixing height (MH): fundamental parameter characterize the vertical extent of mixing within the boundary layer and the level at which exchange with the free troposphere occurs

Challenges for PBL Simulations & Observations

- Model:
  - Lack of capability to simulate the low clouds
  - Lack of understanding of physical processes (turbulence, precipitation, radiation, aerosol-cloud interaction, ocean-atmosphere interaction)
- Observation:
  - Require high-resolution (~100m) to characterize the ABL (1-2 km) and the thin transition layer (~200m) at the PBL top (challenge with passive sounders)
  - Frequent cloud existence at the PBL top (challenge with infrared sounder)

PBL height definition

- Traditional definition based on profile data
  - Relative humidity (rh)
  - Specific humidity (sq)
  - Temperature (surface-based & elevated inversion) (temp)
  - Potential temperature
  - Virtual Potential temperature (Parcel method)
  - Richardson # (potential energy/kinetic energy) – used in model
- GPS RO (profile)
  - Refractivity: N=f(P, T, Pw) (refr)
  - Bending angle (bend)
  - Dry temperature (dryT)
- Other observations (with PBL top tracer)
  - Lidar (CALIPSO) – cloud-top height
  - MISR – Stereo height
  - Sodar

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  - Bending angle (bend)
  - Temperature/Specific humidity (model dependent)
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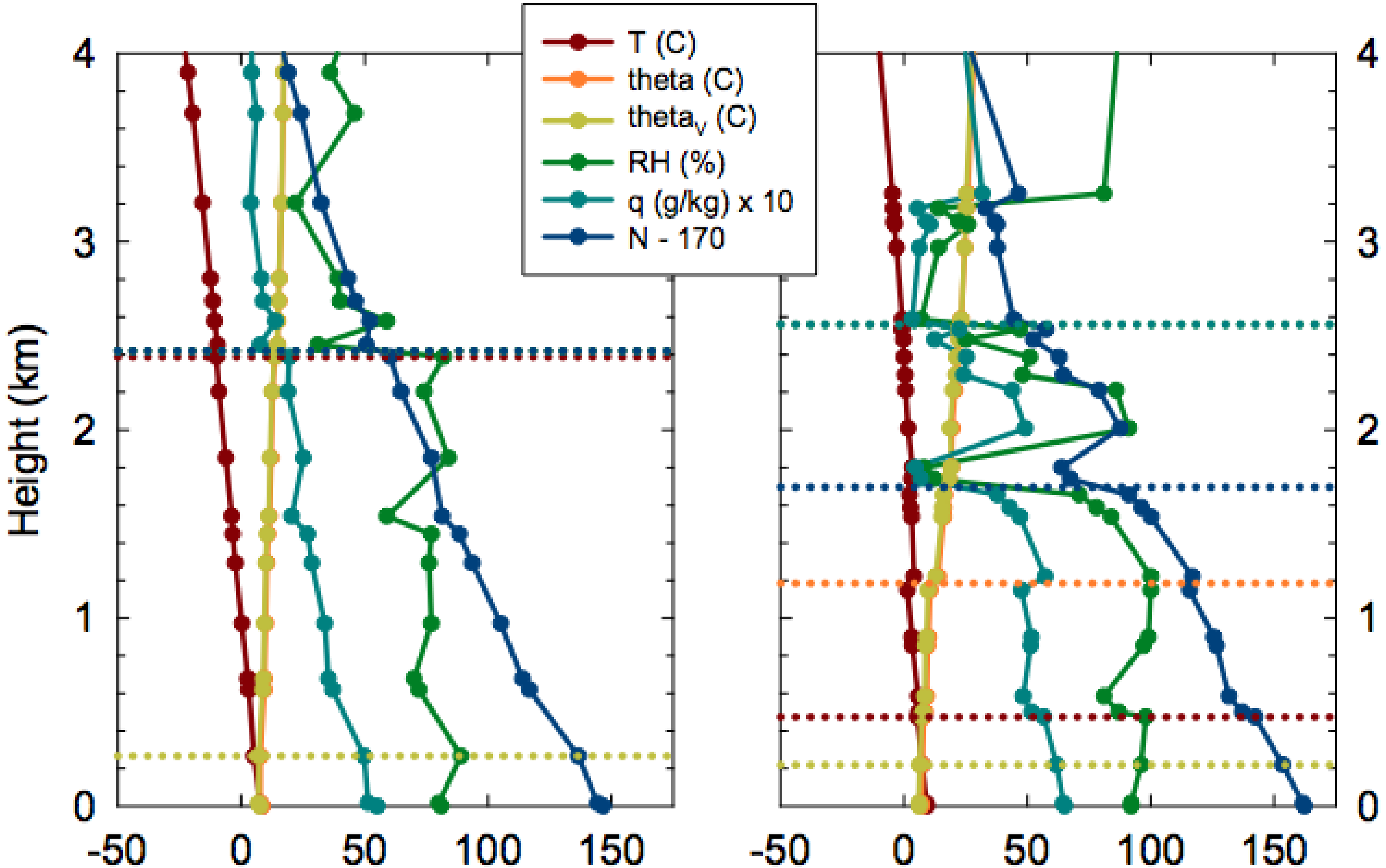
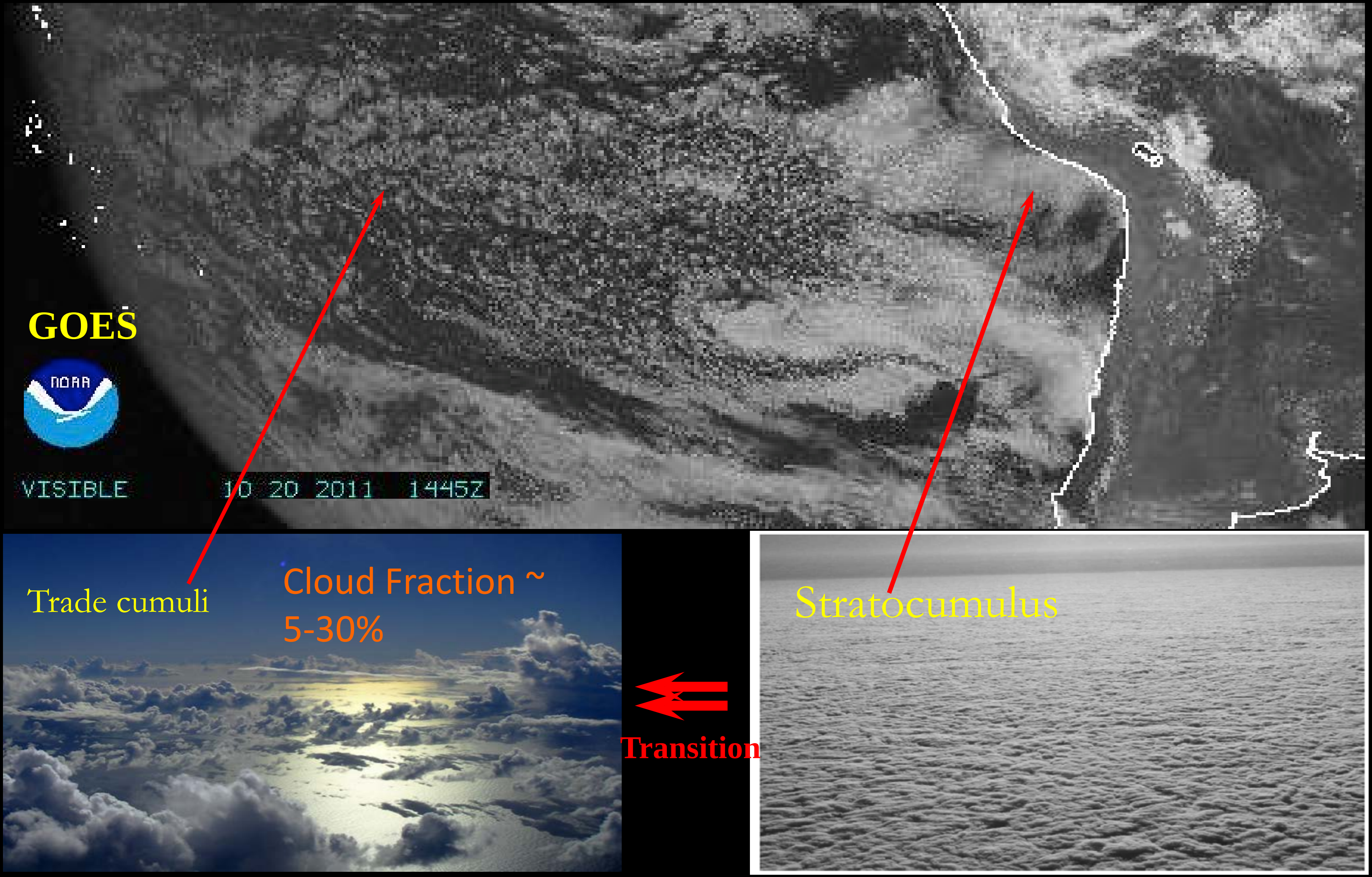


Seidel et al., JGR, 2010

Figure 3. Planetary boundary layer height estimates using six methods for Lerwick, United Kingdom, for (left) 1100 UTC 17 February 2007 and (right) 2300 UTC 23 December 2006. Profiles include temperature, potential temperature (Θ), virtual potential temperature (Θ_v), relative humidity, specific humidity, and refractivity (N). Estimated PBL heights are shown by dashed horizontal lines. These soundings do not indicate the presence of surface-based inversions.

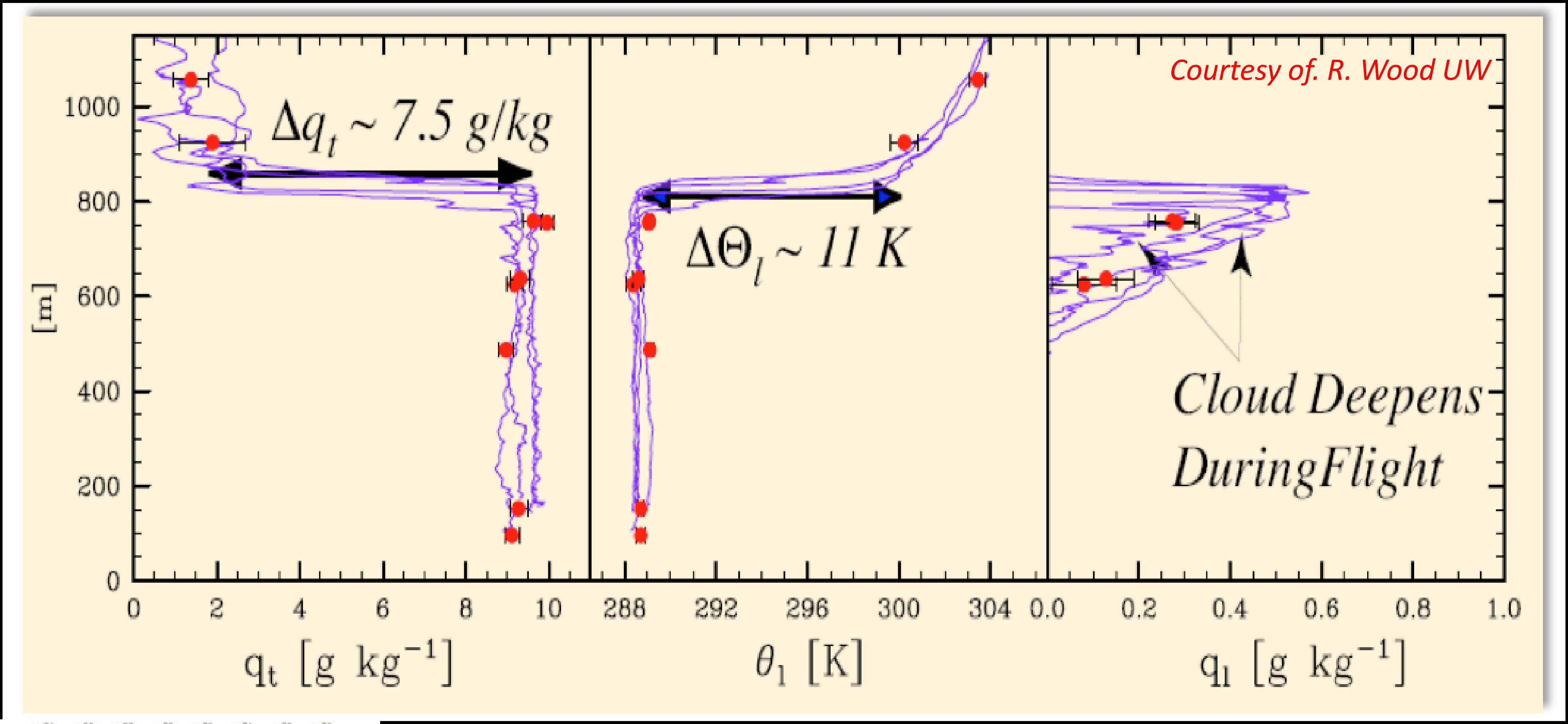
PBL Clouds

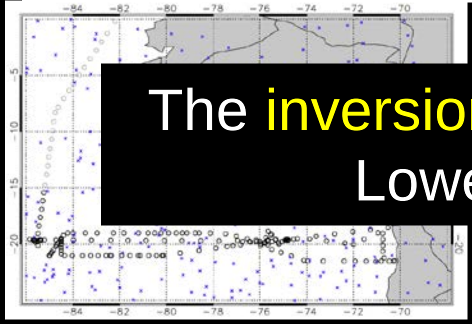


Bottom photographs courtesy of Dr. Bjorn Stevens

PBL Structure over Southeast Pacific

(VOCALS Radiosonde vs ECMWF)



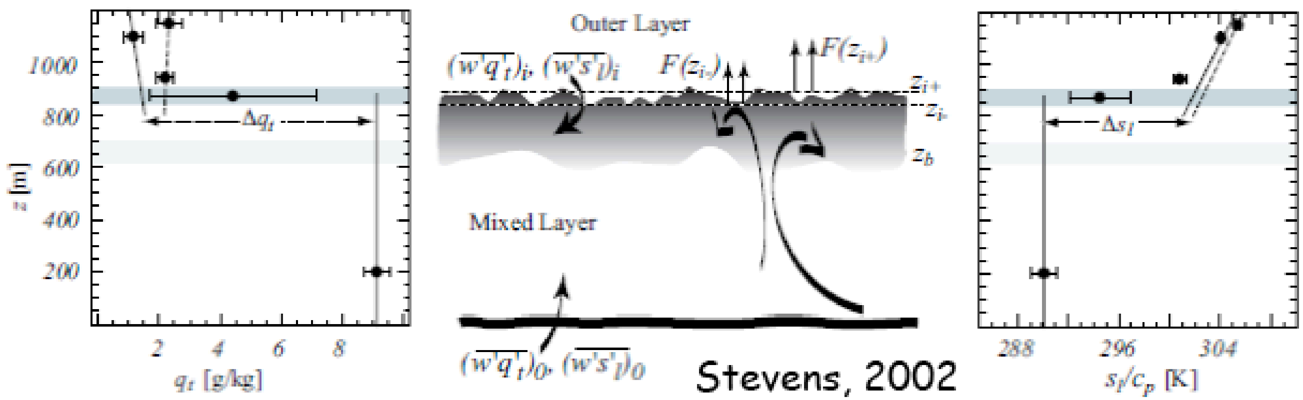


The inversion-base height is consistent with Cloud-top-height

Lower boundary layer height → lower clouds

Minimalist approach – based on simple theories/models

Courtesy of R. Wood from UW



Stevens, 2002

Model Equations – moist conserved variables are assumed well-mixed:

$$z_i \frac{D\theta_l}{Dt} = c_d U_{10}(\theta_{ls} - \theta_l) + w_e(\theta_l^+ - \theta_l) - \Delta F_R + P_0$$

$$z_i \frac{Dq}{Dt} = c_d U_{10}(q_s - q) + w_e(q^+ - q) - P_0$$

$$\frac{Dz_i}{Dt} = w_e - w_s$$

e.g. Lilly, QJRMS, 1968

Unsolved issues: *w_e closure; P_0* closure

➔ w_e on buoyancy/TKE

Simple example: $w_e = a\frac{R}{\Delta\theta_v}$

➔ P_0 based on LWP, N_d

Only 3 parameters need to be measured to fully constrain problem (as long as forcing is well defined): e.g. LWP, Cloud top temperature and height

Principles of Radio Occultation Technique

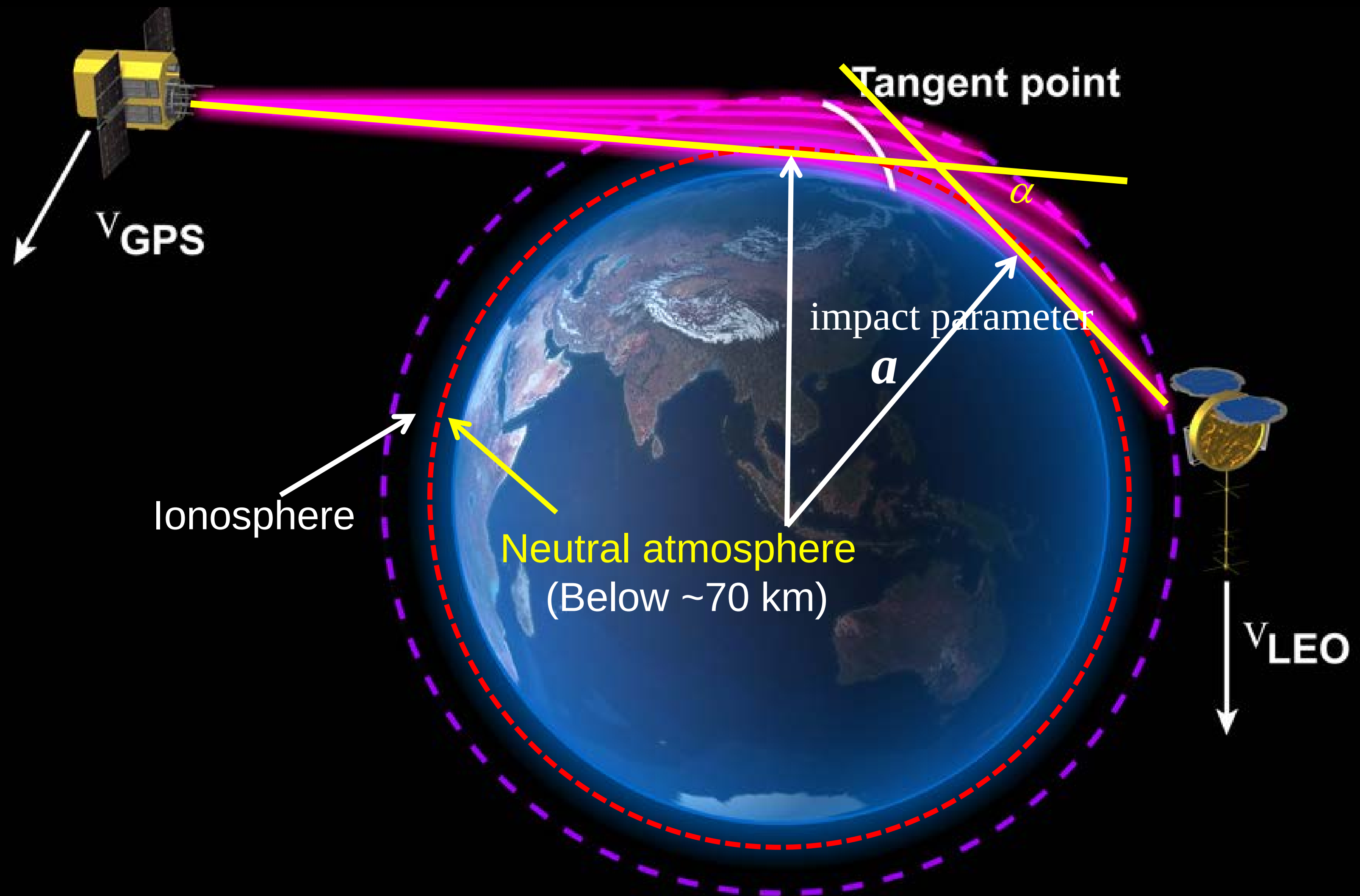


Figure Courtesy of UCAR COSMIC Group

Atmospheric Refractivity

Refractivity $N=10^6(n-1)$, and refractive index $n=c/v$, where c and v is the light velocity in a vacuum and in the atmosphere, respectively.

$$N = 77.6\frac{P}{T} + 3.73\times 10^{5}\frac{P_w}{T^2}$$

Hydrostatic Dry & **Wet terms** — Neutral atmosphere(<70 km)

Ionospheric term — Dominate above 70 km

- The **Wet term** becomes important in the troposphere and can constitute up to 30% of refractivity at the surface in the tropics
- In the presence of water vapor, external information information is needed to obtain temperature and water vapor
- Liquid water and aerosols are generally ignored
- *T_dry* = 77.6 *P*/*N*

PBL height from GPS RO

Unique capabilities

- Sensitivity to vertical structure of water vapor and temperature inversion with high vertical resolution (~100 m)
- All-weather (not degraded by clouds or precipitation)
- Diurnal cycle coverage (COSMIC)

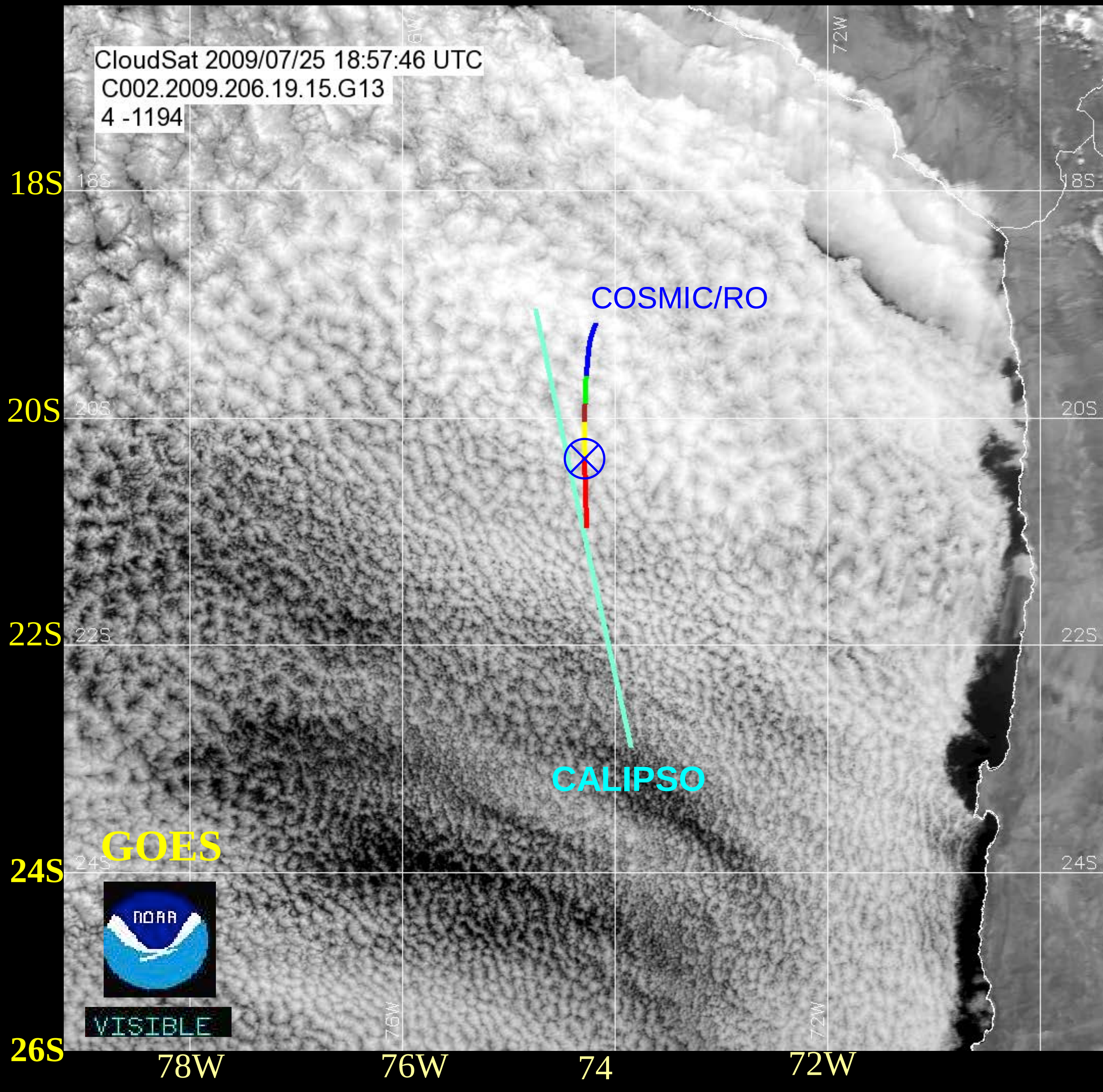
Limitations

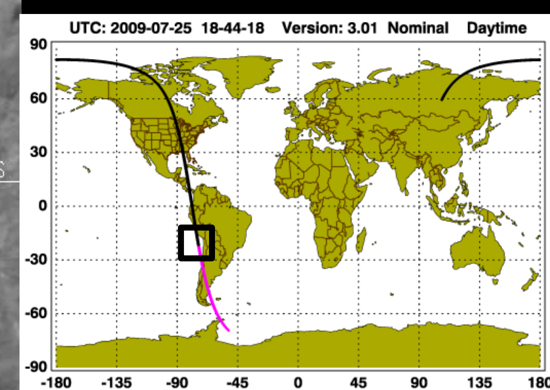
- Relative coarse horizontal resolution (~ 100 km)
- Profile depth penetration issues
- Negative refractivity bias (dry bias) under certain conditions

PBL Height
vs.
Low Cloud Top Height

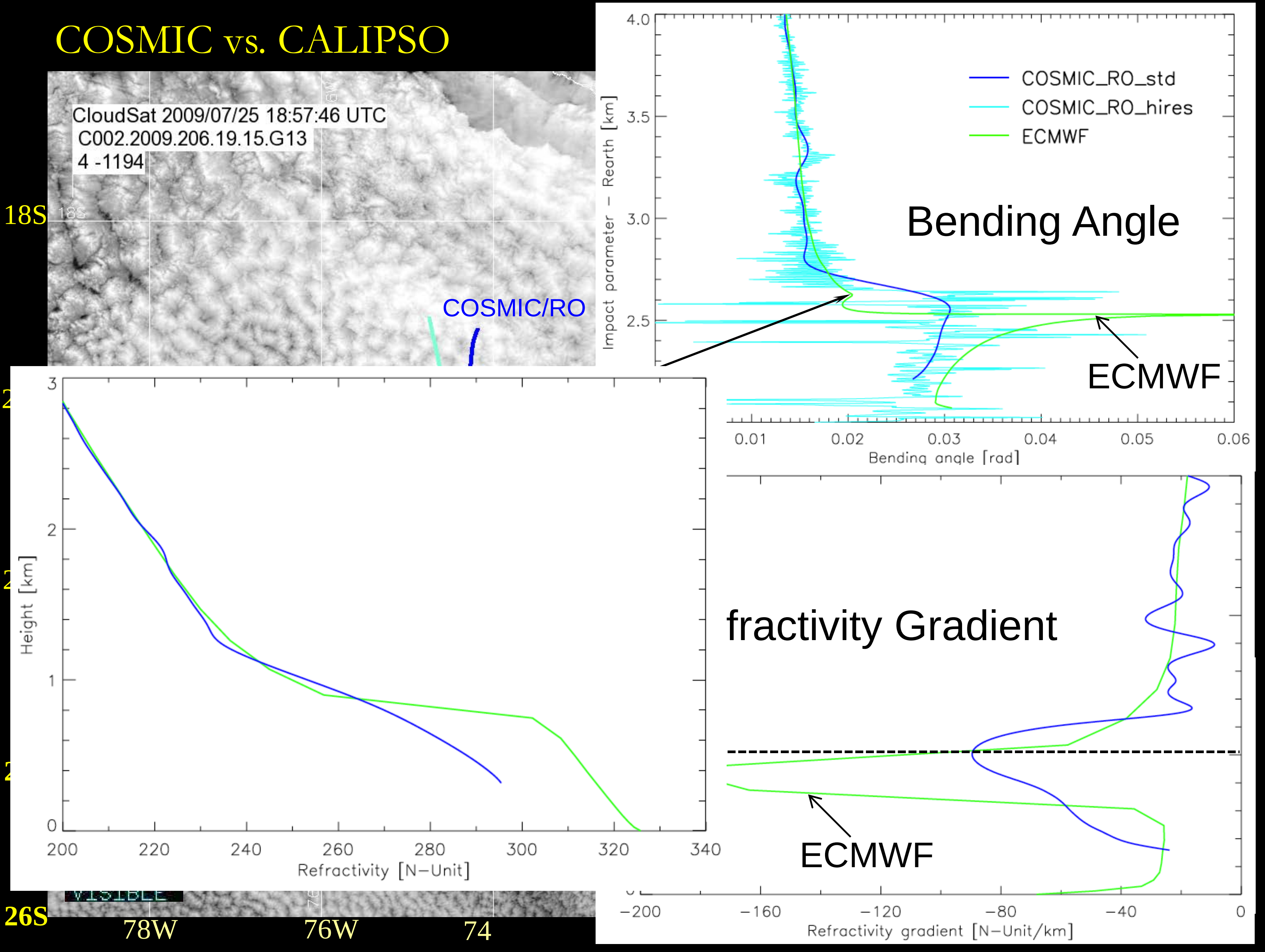
COSMIC vs. CALIPSO

Near-coincident COSMIC vs. CALIPSO (<18min apart)

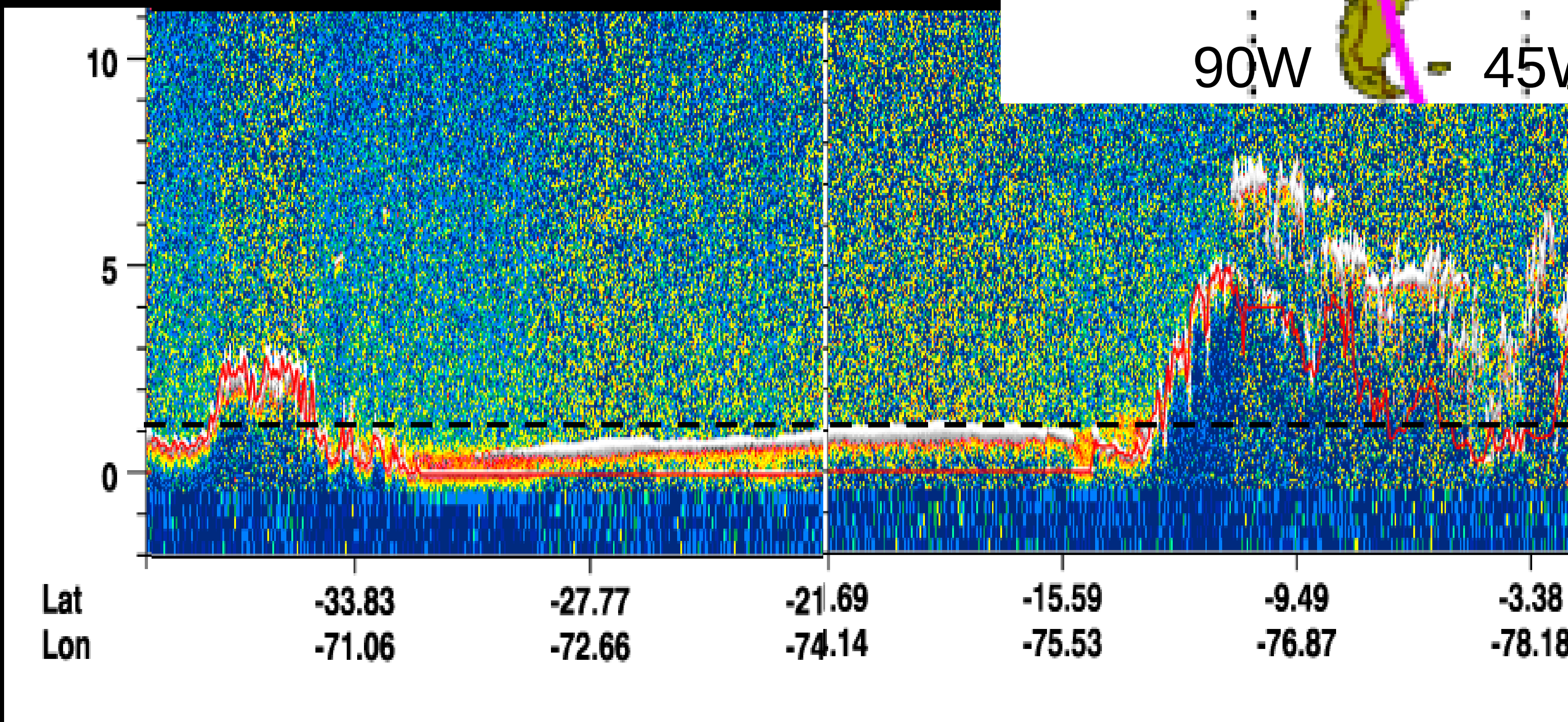


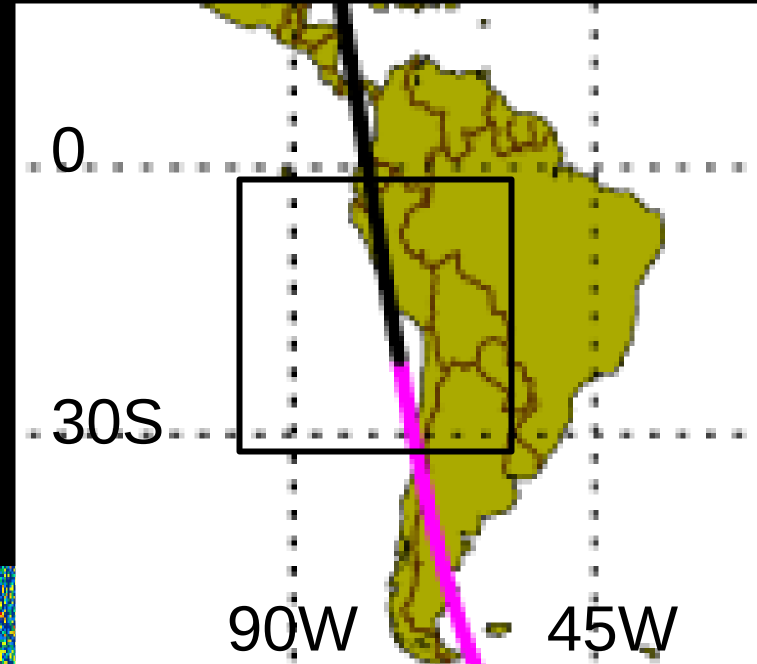


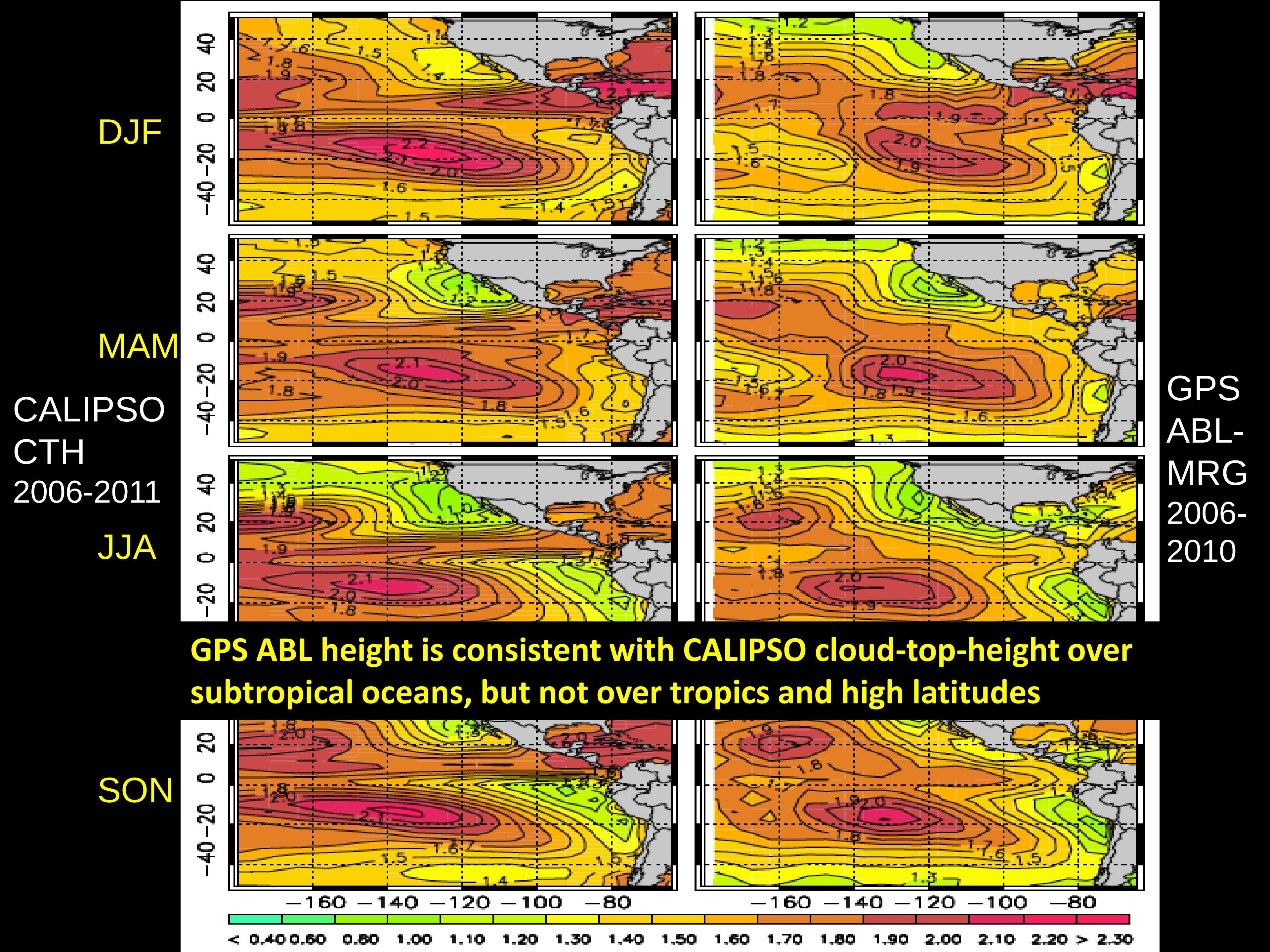
COSMIC vs. CALIPSO



Cloud-Top-Height
~1km (21.7S, 74.1W)
CALIPSO (lidar)







GPS ABL height is consistent with CALIPSO cloud-top-height over subtropical oceans, but not over tropics and high latitudes

PBL Height Definition

Simulation Study with ERA-interim

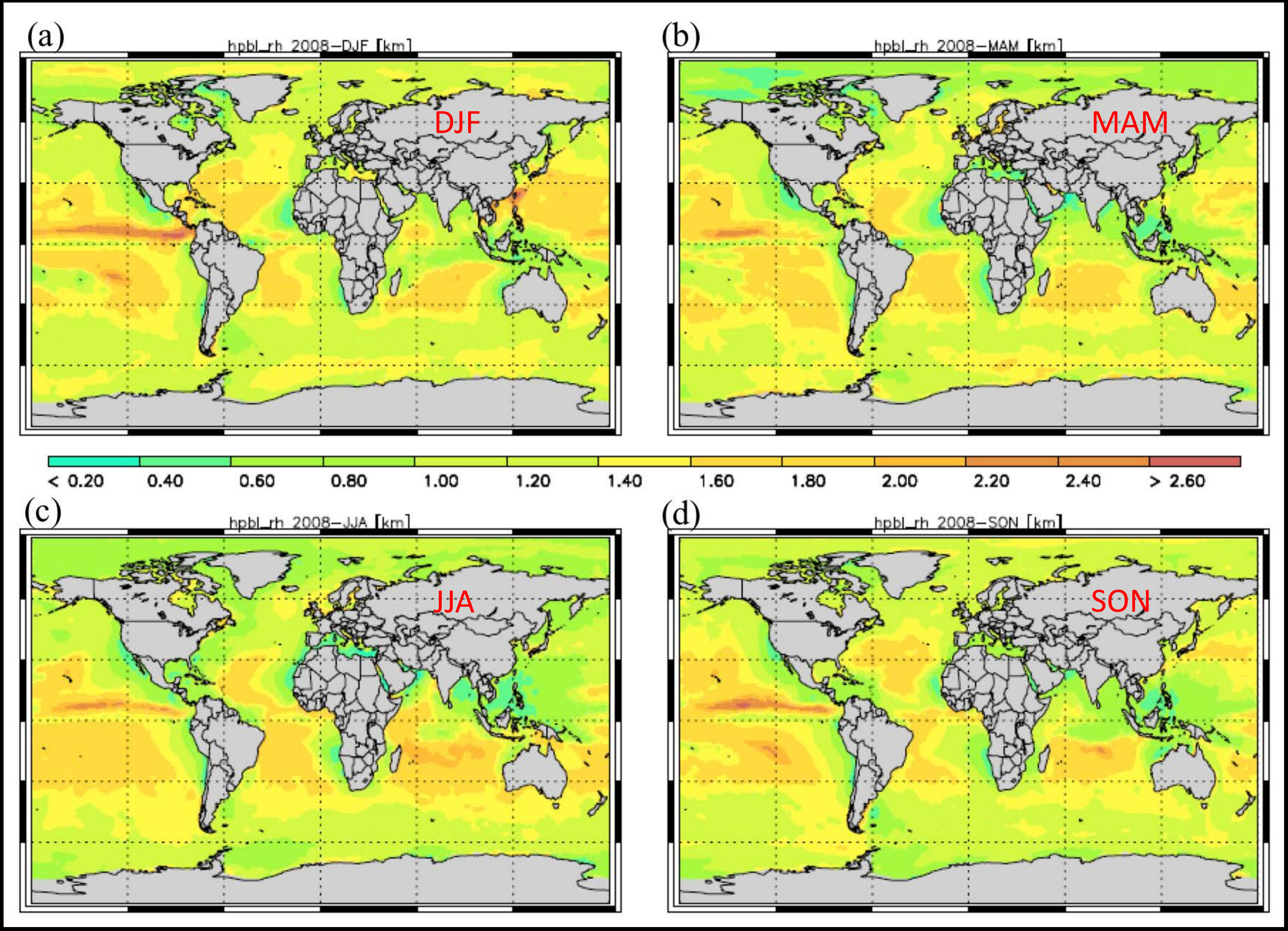
Collaborators:
Stig Syndergaard, Kent Lauritsen (DMI),
Axel Von Engeln (Eumetsat) and Ian Culverwell (UK Met Office)

Supported by EUMETSAT ROM-SAF

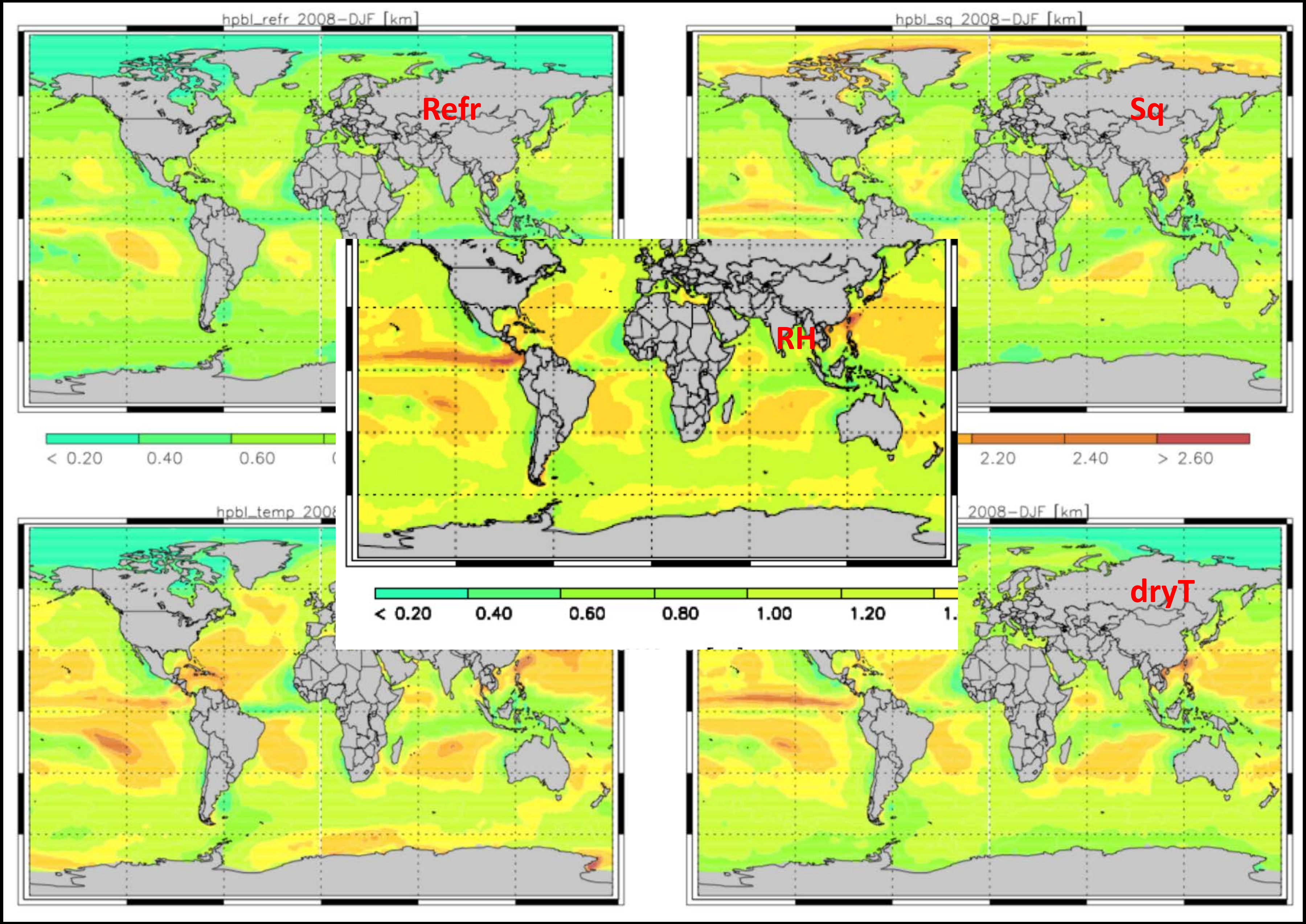
GPS RO PBL Simulation Study

- Data
  - ERA-interim (2008) – 1deg resolution (60 levels)
  - Advantage: uniform, relatively high resolution, global coverage
- Develop PBL height detection algorithm
  - Gradient method
  - Parameters: RH, SQ, Temp, Refr, dryT, Bend
- PBL height climatology (over ocean)
  - Monthly mean
  - Seasonal mean
- PBL height difference among definitions
  - Identify regions of significant difference
  - Correlation among PBL height definitions

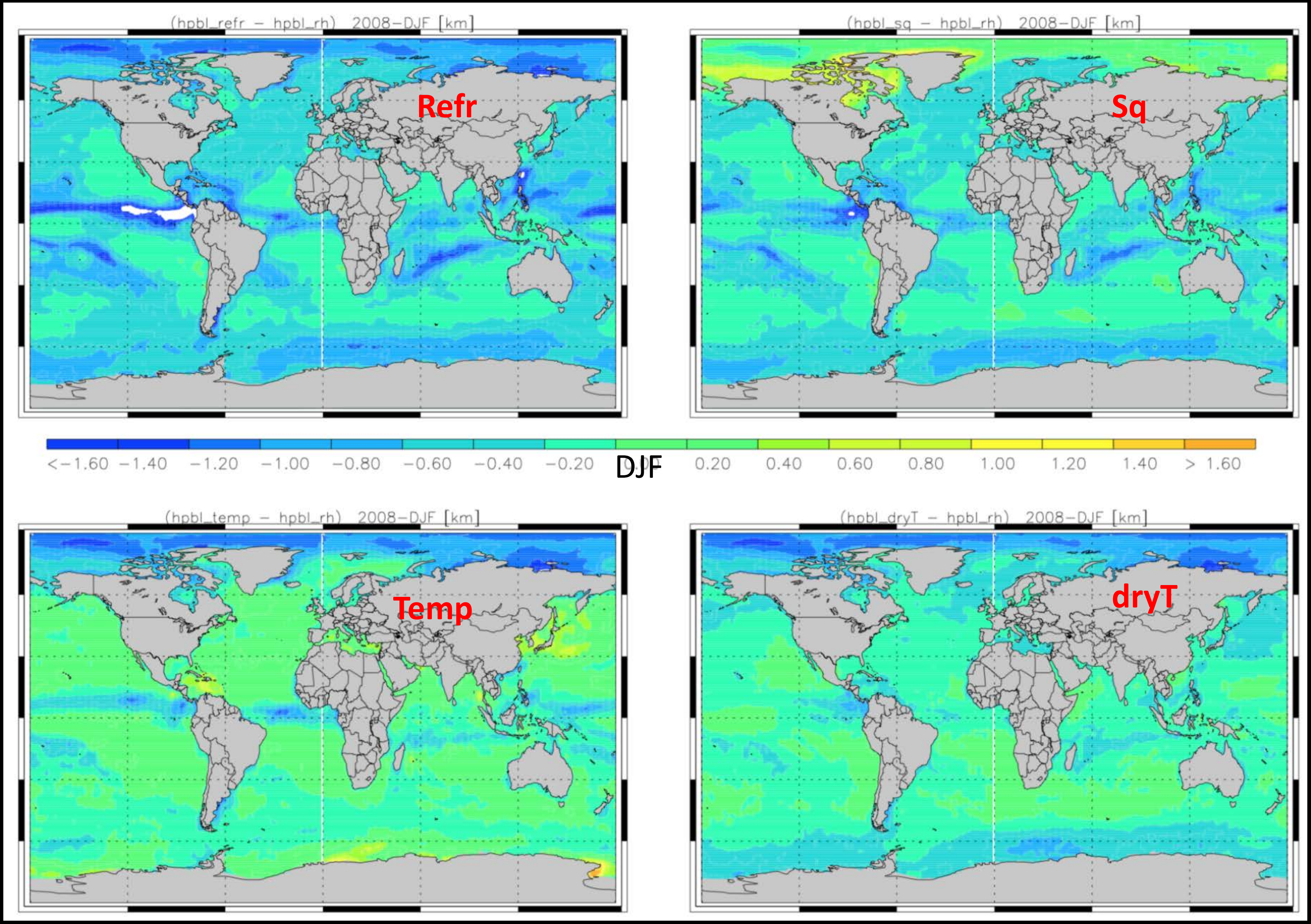
Hpbl_RH (Four- Season in 2008)



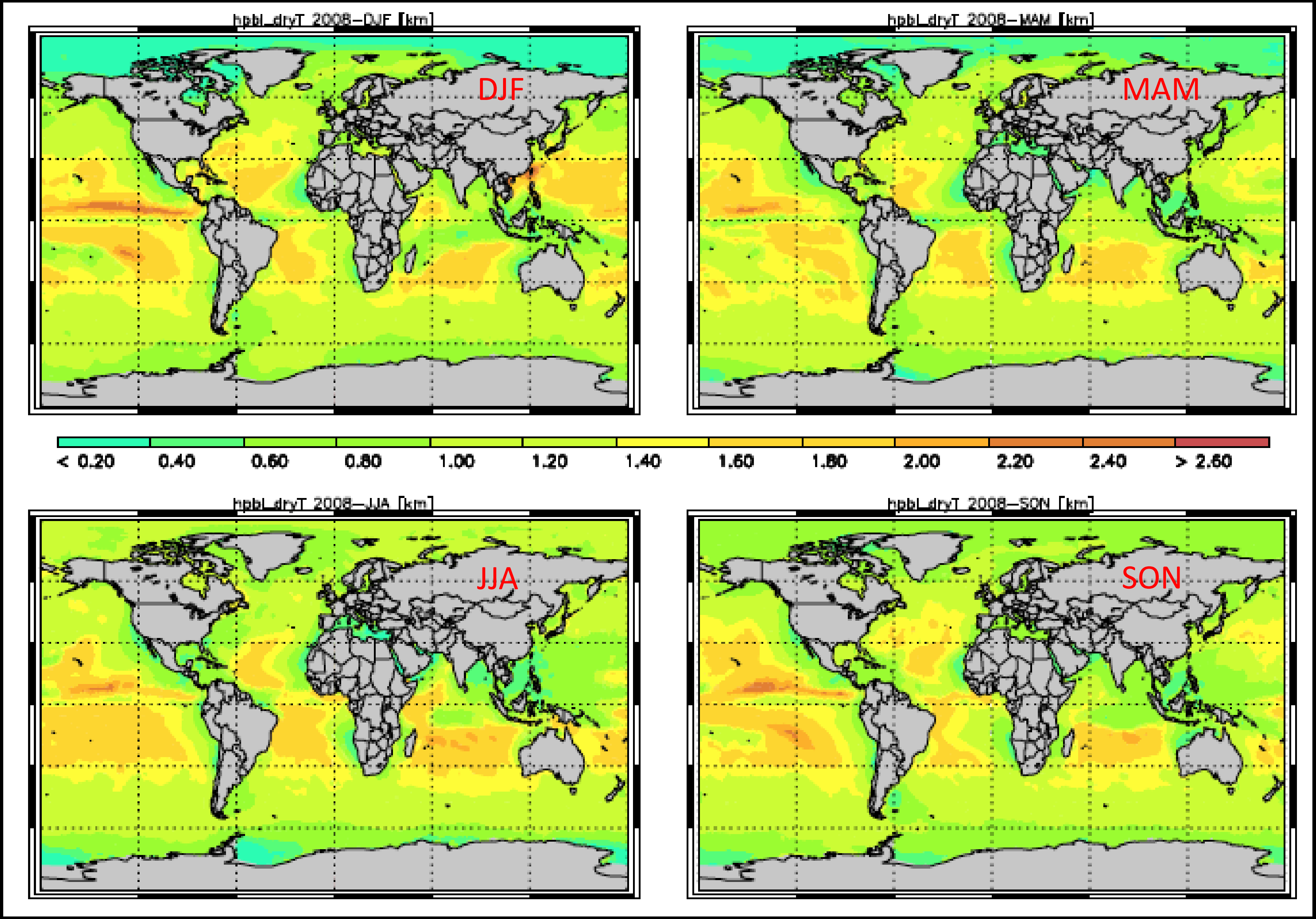
PBL Height from other definition (2008-DJF)



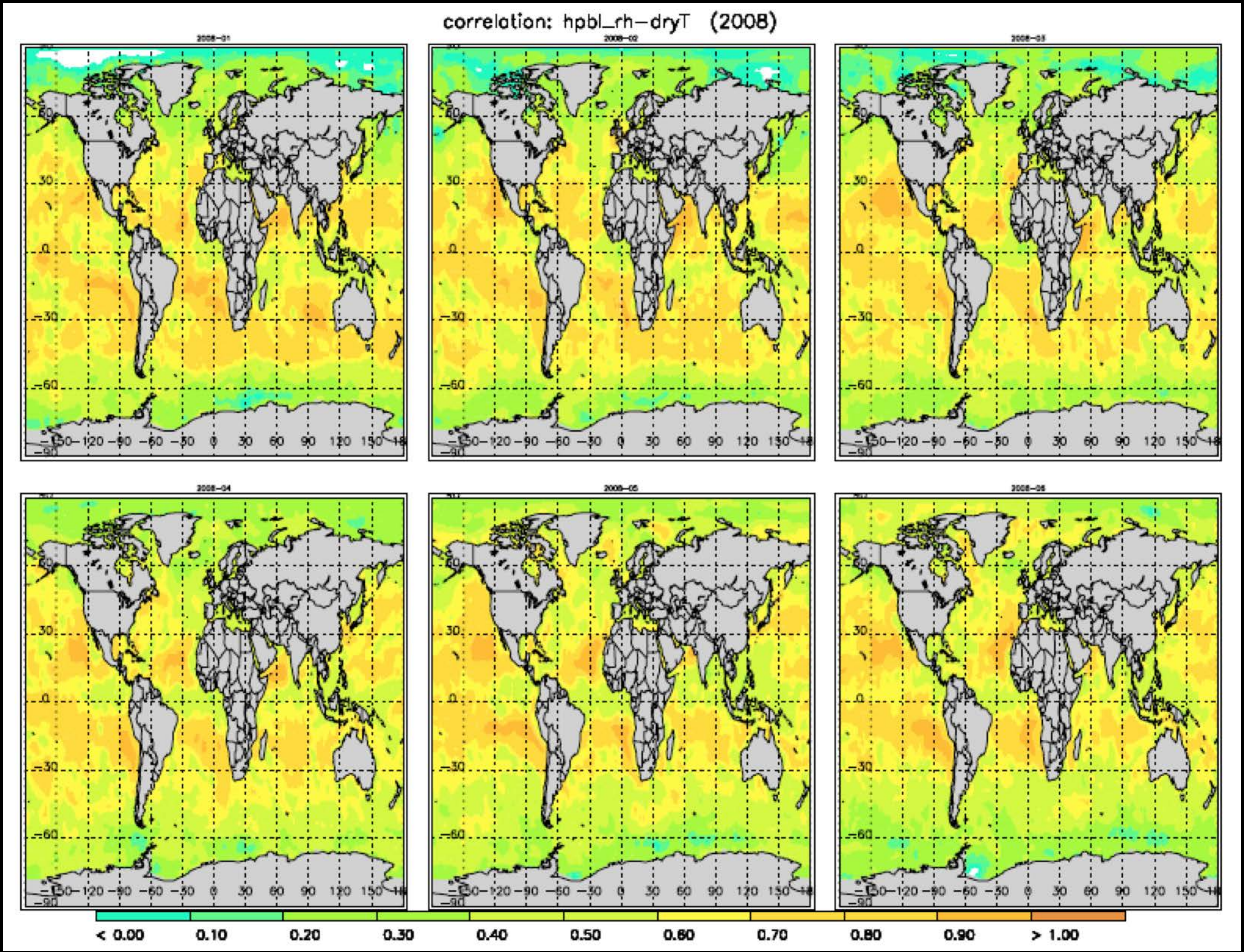
PBL Height Difference from hpbl_RH (2008-DJF)



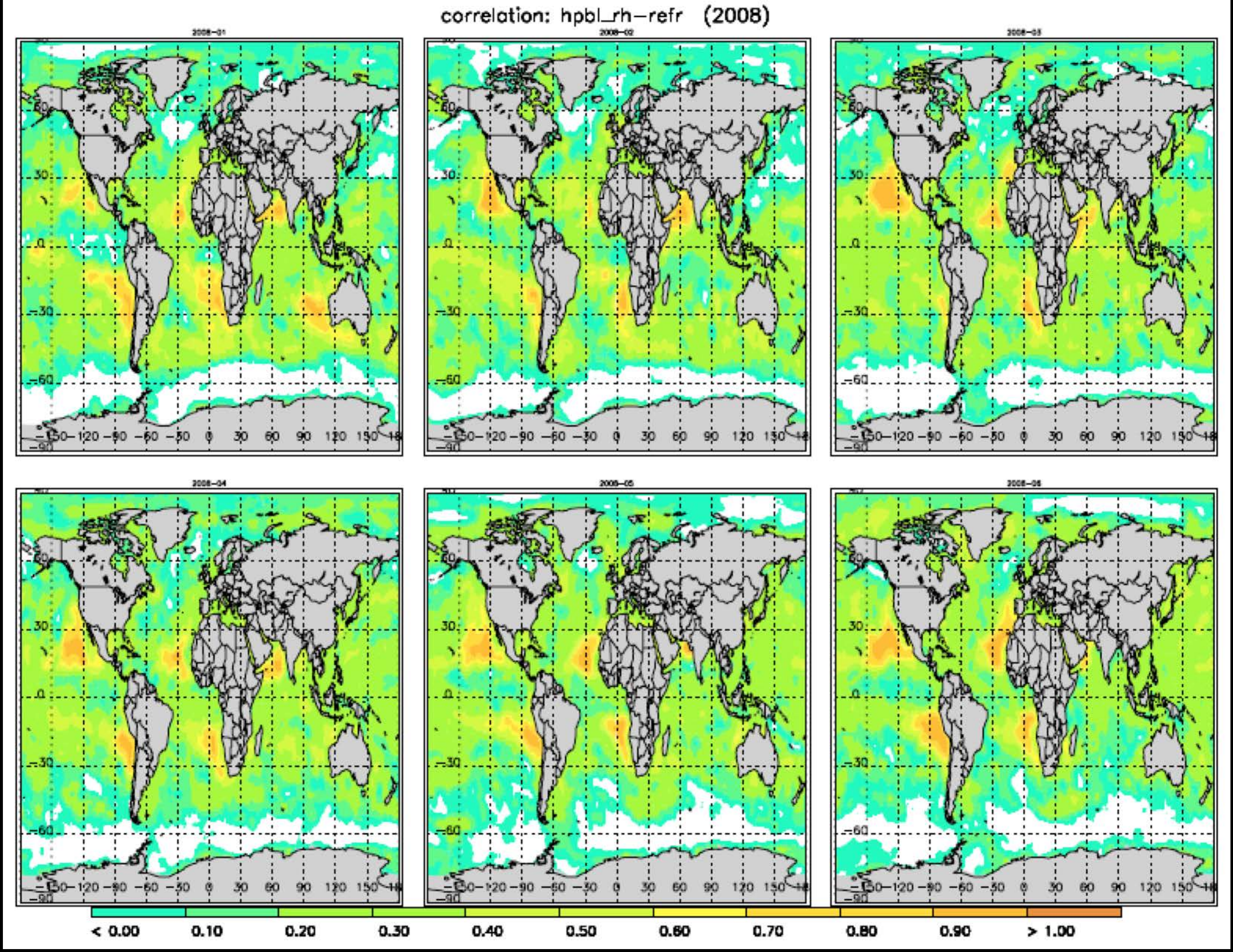
Hpbl_dryT (Four- Season - 2008)



Correlation between hpbl_RH & hpbl_dryT (Jan-June, 2008)



Correlation between hpbl_RH & hpbl_Refr (Jan-June, 2008)



Conclusions

- PBL height based on dry temperature (dryT) is most consistent and highly correlated with RH, except over polar regions
- Refractivity is mostly consistent with bending angle definition.
- Refractivity and specific humidity are more sensitive to the shallow mixing layer (below 800m) over equatorial and subtropical trade-wind regions as compared with RH/dryT
- Humidity definition (RH/q) should be avoid over polar region, especially in winter time.
- Dry temperature is highly consistent with temperature definition over Arctic, but slightly less near Antarctic.

Conclusions

- GPS RO signal is very sensitive to the sharp moisture gradient beneath the inversion (PBL top).
- COSMIC RO shows consistent PBL heights with radiosonde and CALIPSO over subtropical oceans.
- GPS observations can be used to diagnose the ABL representation in models and help reduce the uncertainty of low cloud feedback in climate model prediction.
- Systematic biases in the GPS RO refractivity are likely caused by super-refraction (or ducting) and can be reconstructed with external physical constraints.

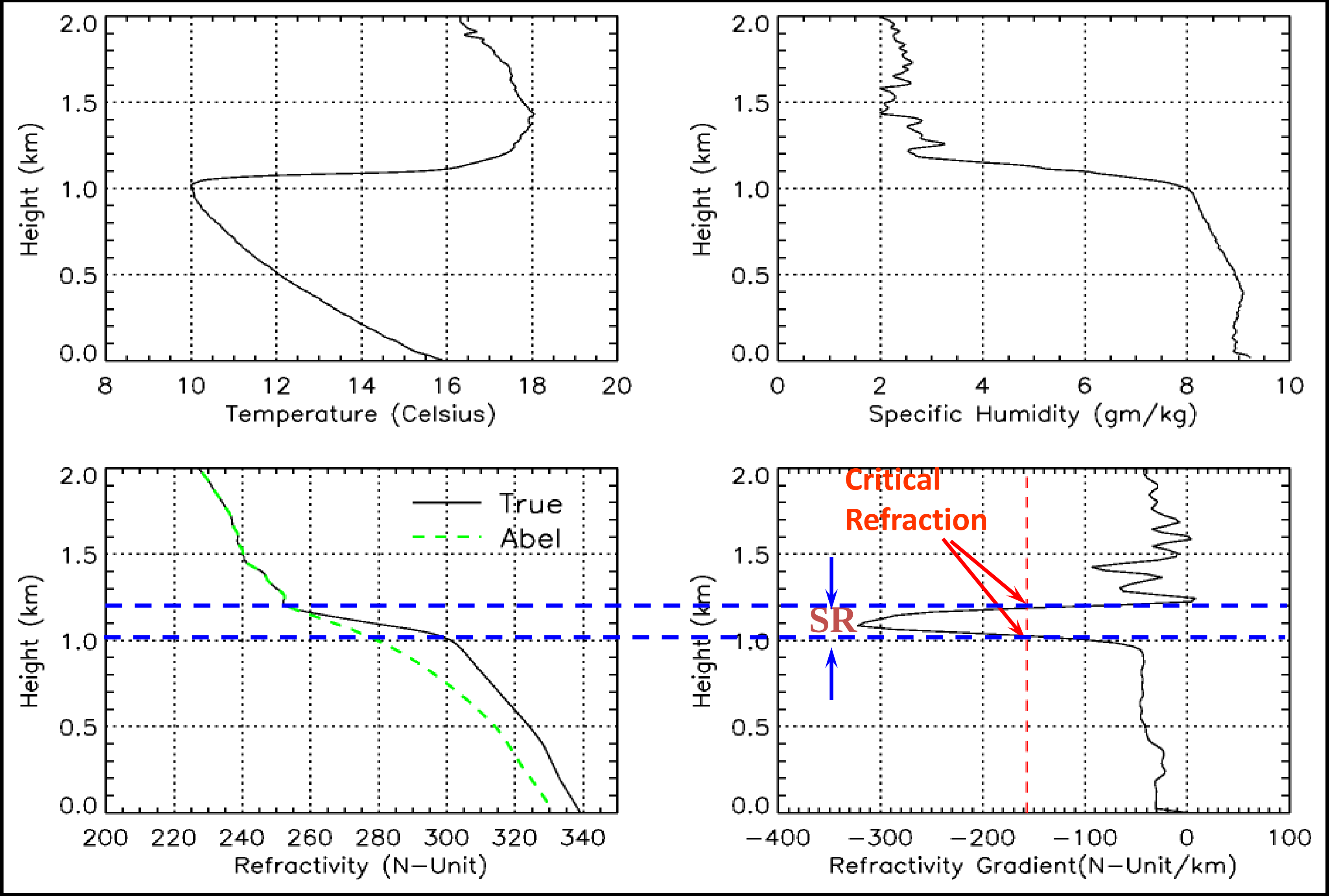
Limitation of GPS RO for ABL Sensing

Near-coincident Case over Southeast Pacific

Radiosonde/COSMIC/ECMWF

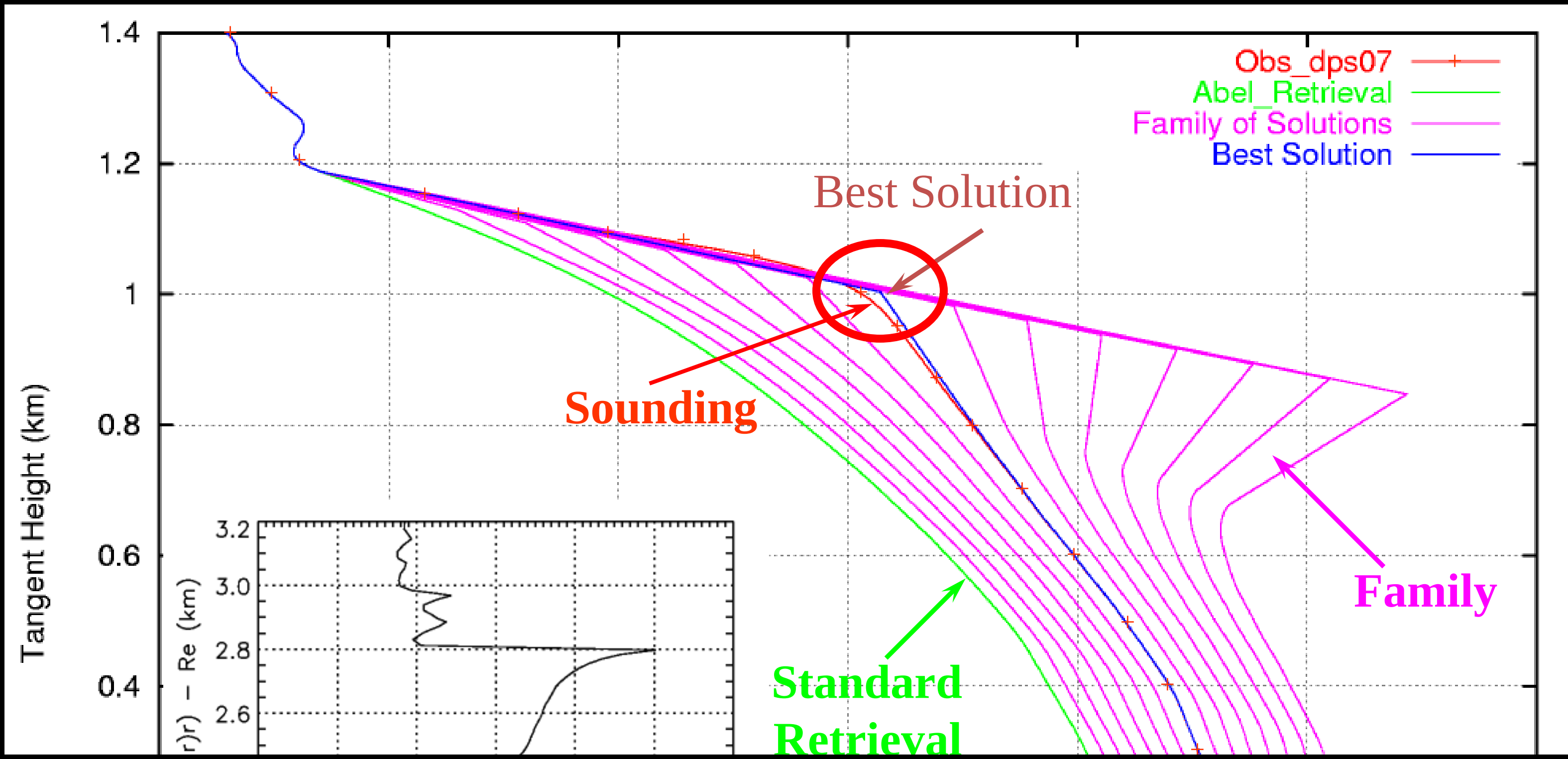
Systematic *N*-bias ???.

ABL Refractivity bias due to Super-refraction (ducting)



Dropsonde from DYCOMSII (Bjorn Stevens)

N-bias - *Non-unique* Abel-inversion problem

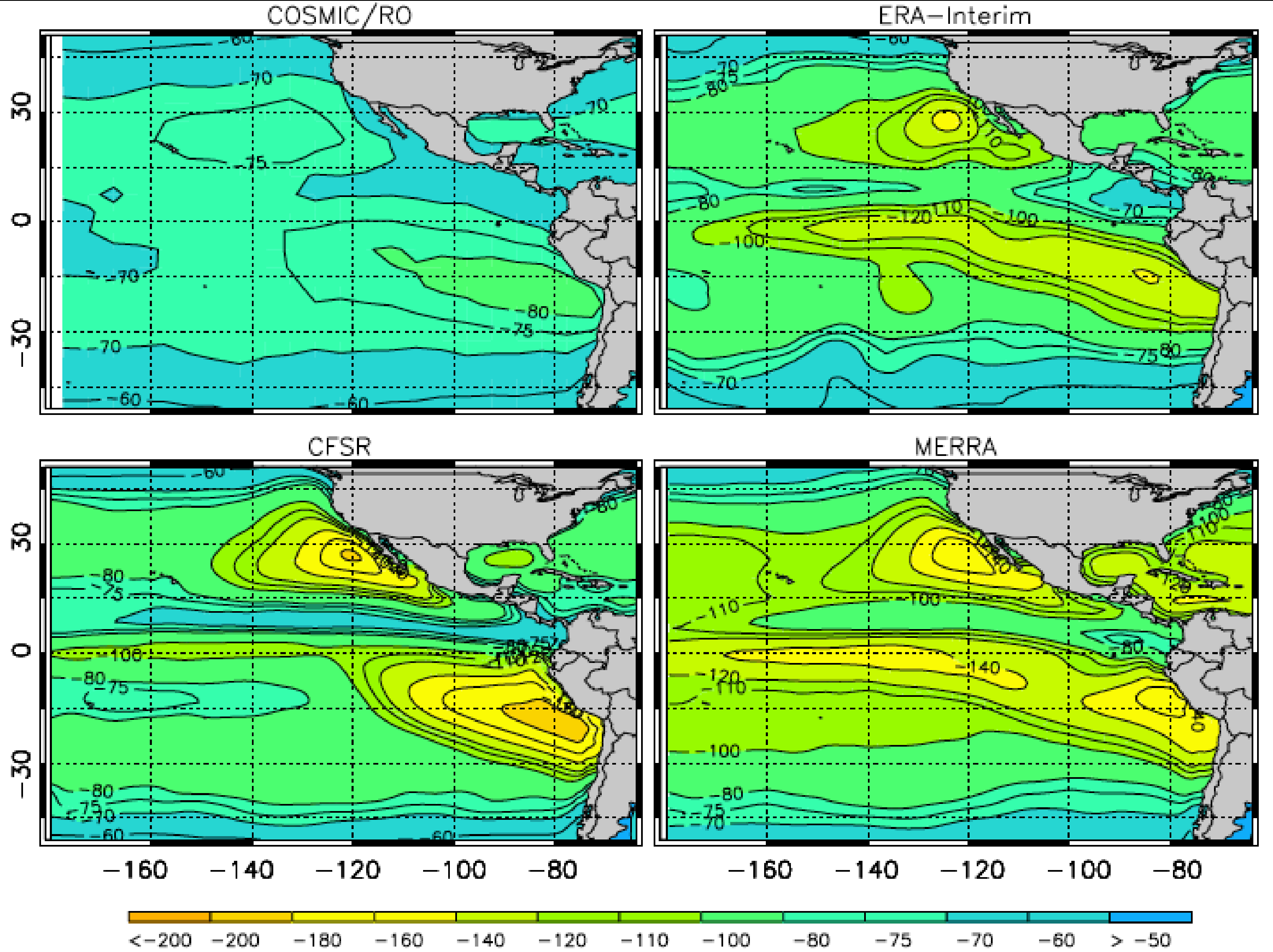


Assimilating bending angle does **NOT** solve *N*-bias problem

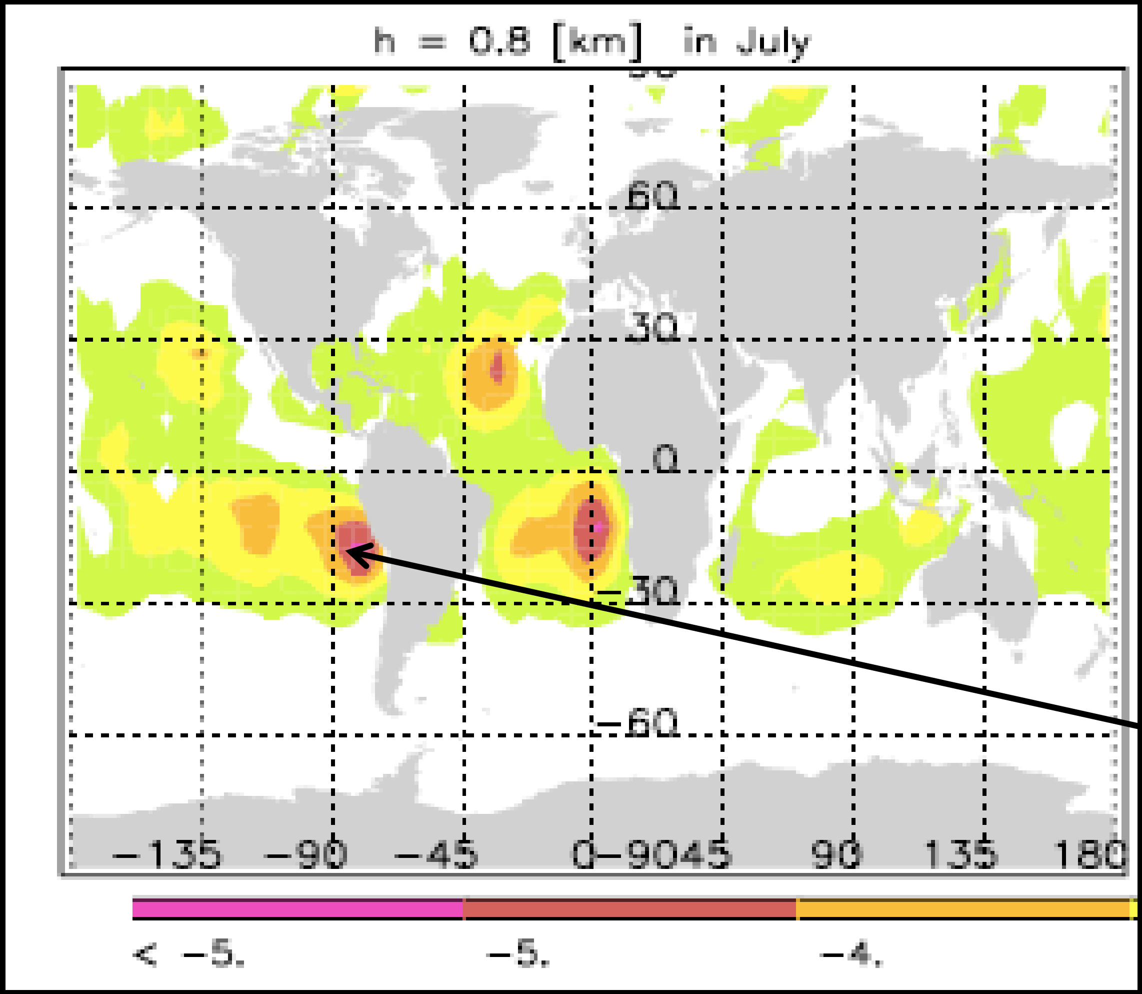
The the biased (+/-) model refractivity profiles (pink) CAN'T be distinguished from the forward simulated bending in the presence of duct.

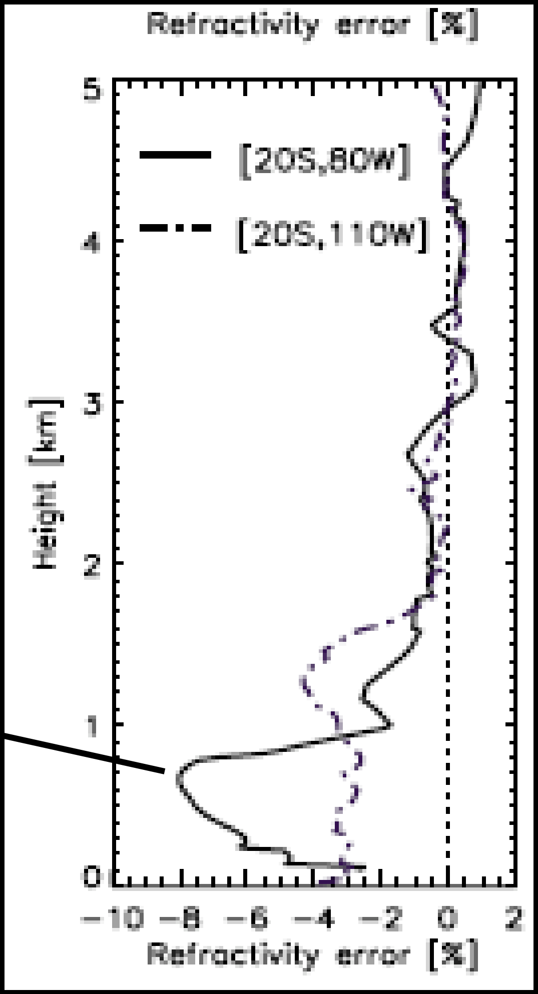
Xie et al., *JTECH*, 2006

Maximum refractivity-gradient below 5 km
(COSMIC vs. ERA-int/CFSR/MERRA) 2007-2009-SON



Systematic negative *N*-bias over subtropical eastern oceans inside ABL

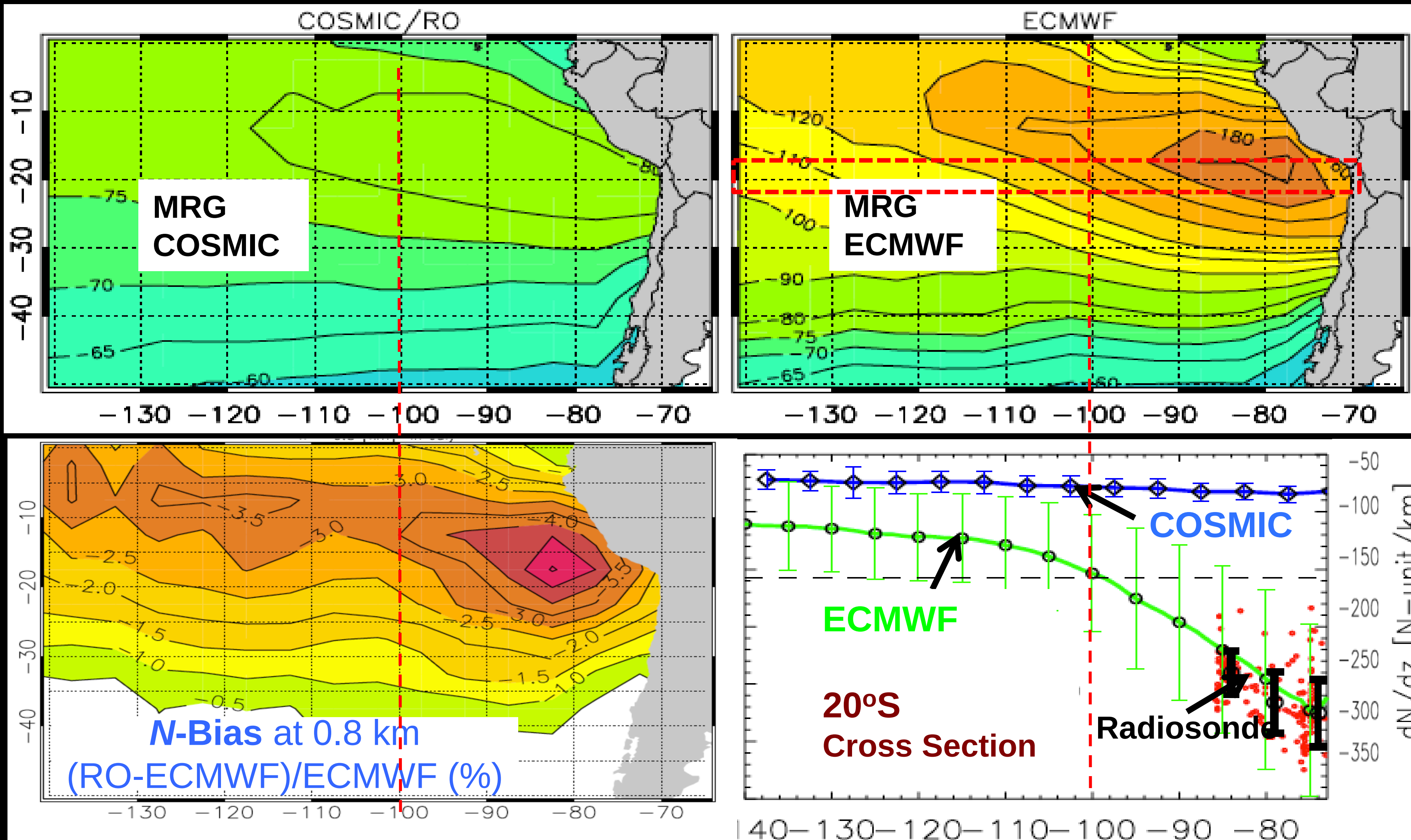




(Refr_GPSRO - Refr_ECMWF) / Refr_ECMWF * 100

Xie et al., *GRL* 2010

Maximum Refractivity Gradient (MRG) vs. *N*-Bias

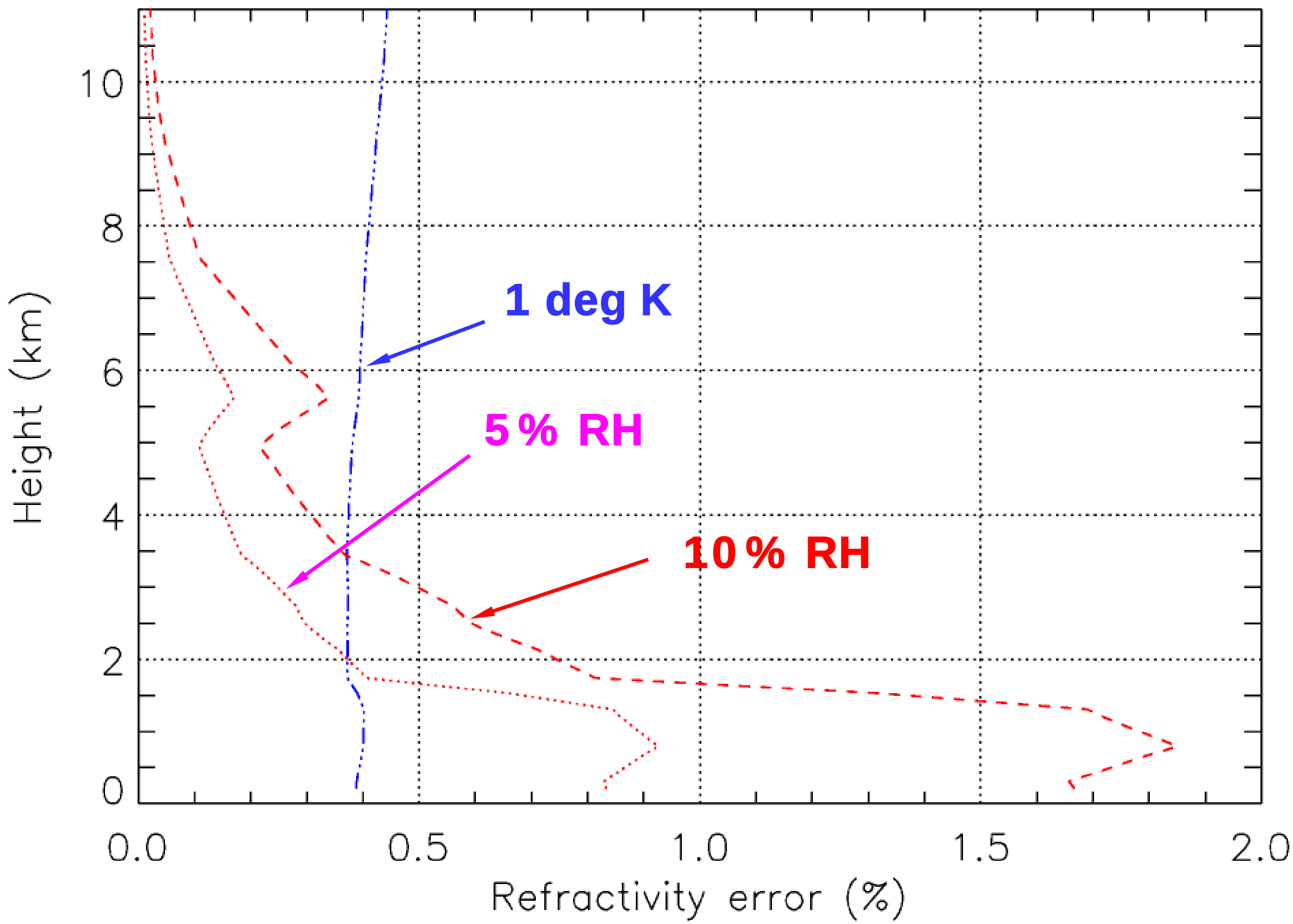


Xie et al., *ACP* (2012)

Future of GNSS RO

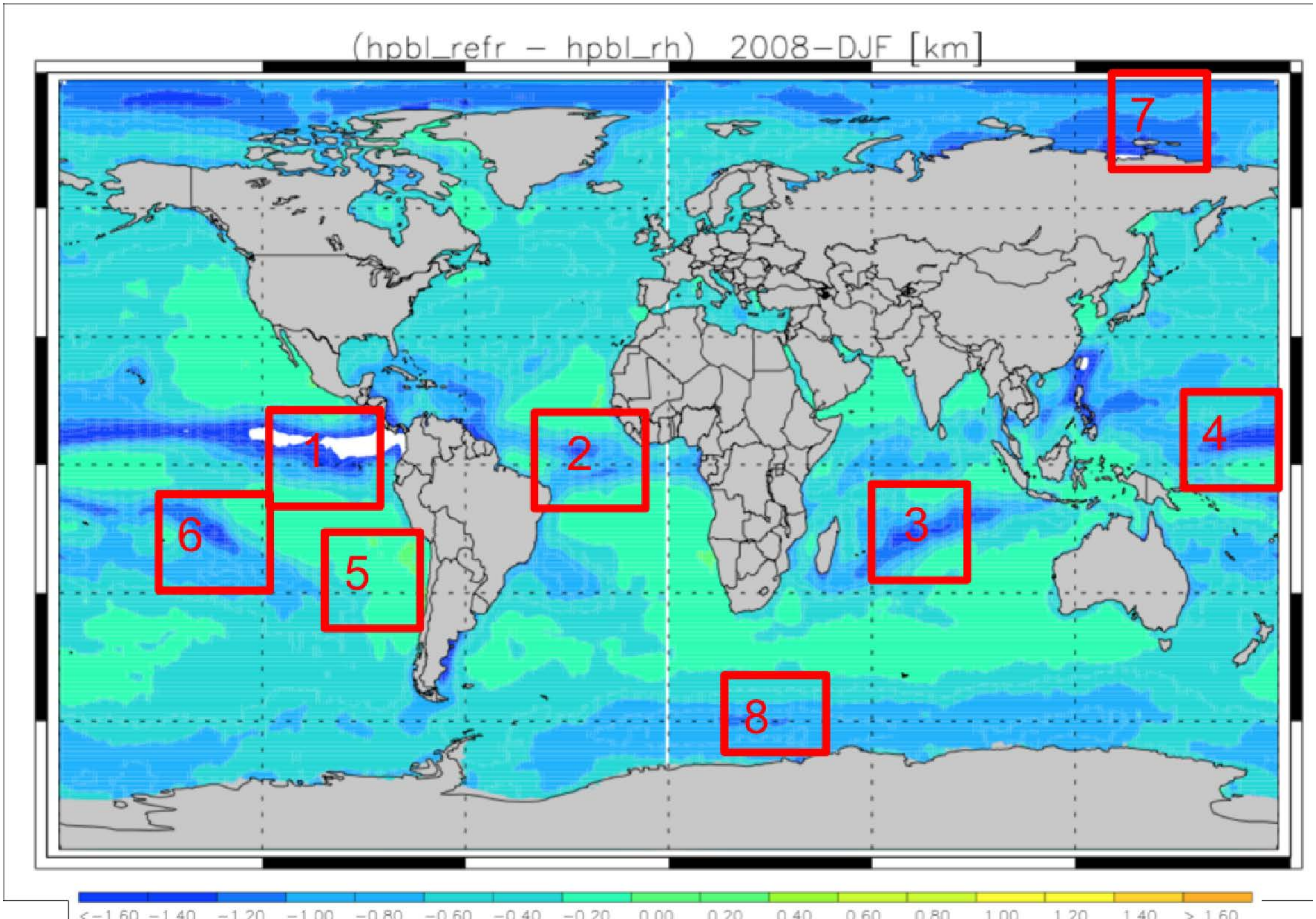
- COSMIC-II will provide much higher sampling and will greatly benefit the weather and climate research communities.
- Airborne radio occultation is a unique complement to space-borne GNSS satellite RO sounding and has the advantage of denser observations for regional studies.
- The future SABLE mission will provide much needed thermodynamic structure, clouds, winds information to attack the large uncertainties involved in low cloud and ABL physical processes.

$$N = 77.6\frac{P}{T} + 3.73\times 10^5\frac{P_w}{T^2} - 40.3\times 10^6\frac{n_e}{f^2}$$

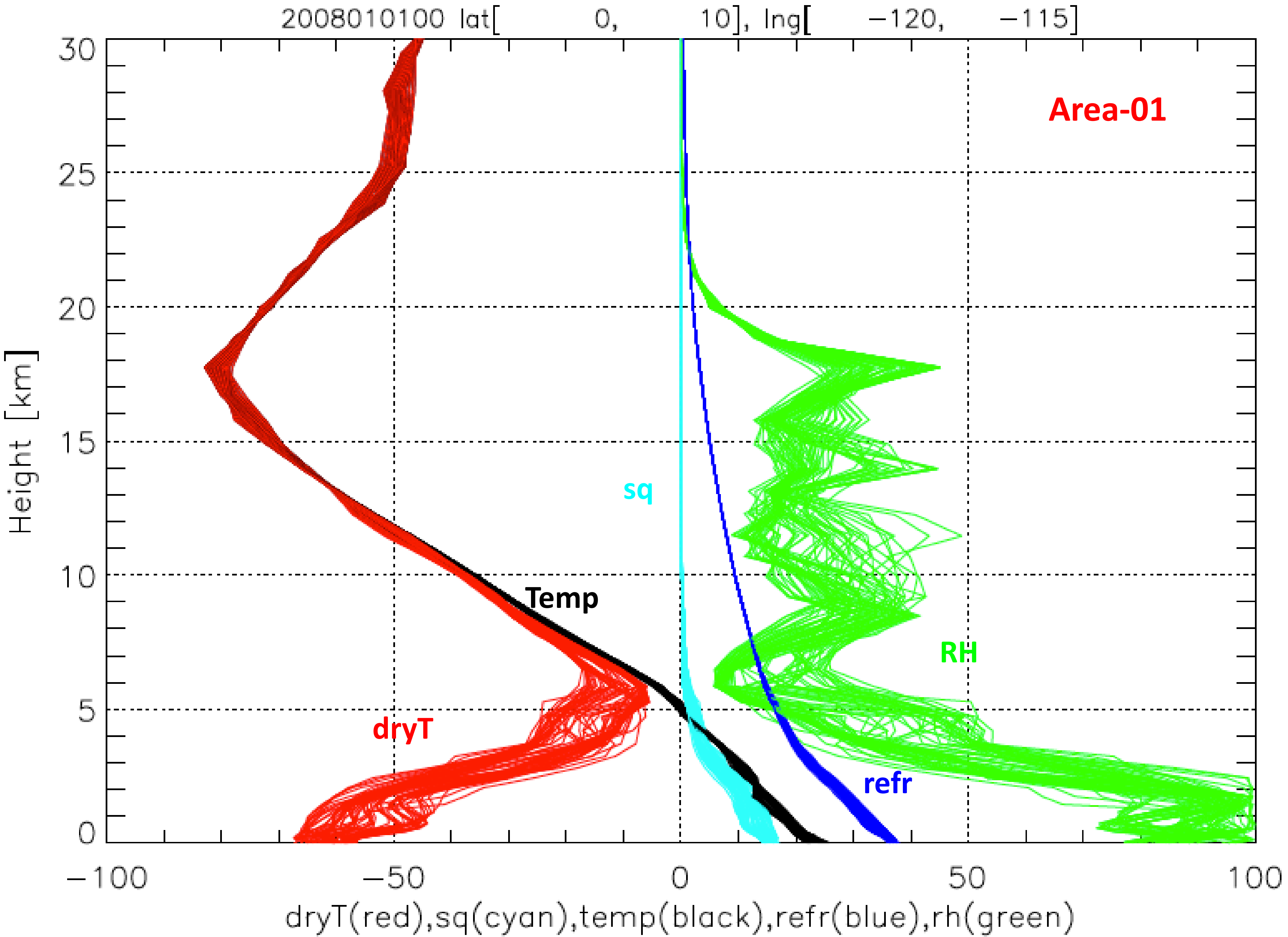


Xie et al., TGRS, 2008

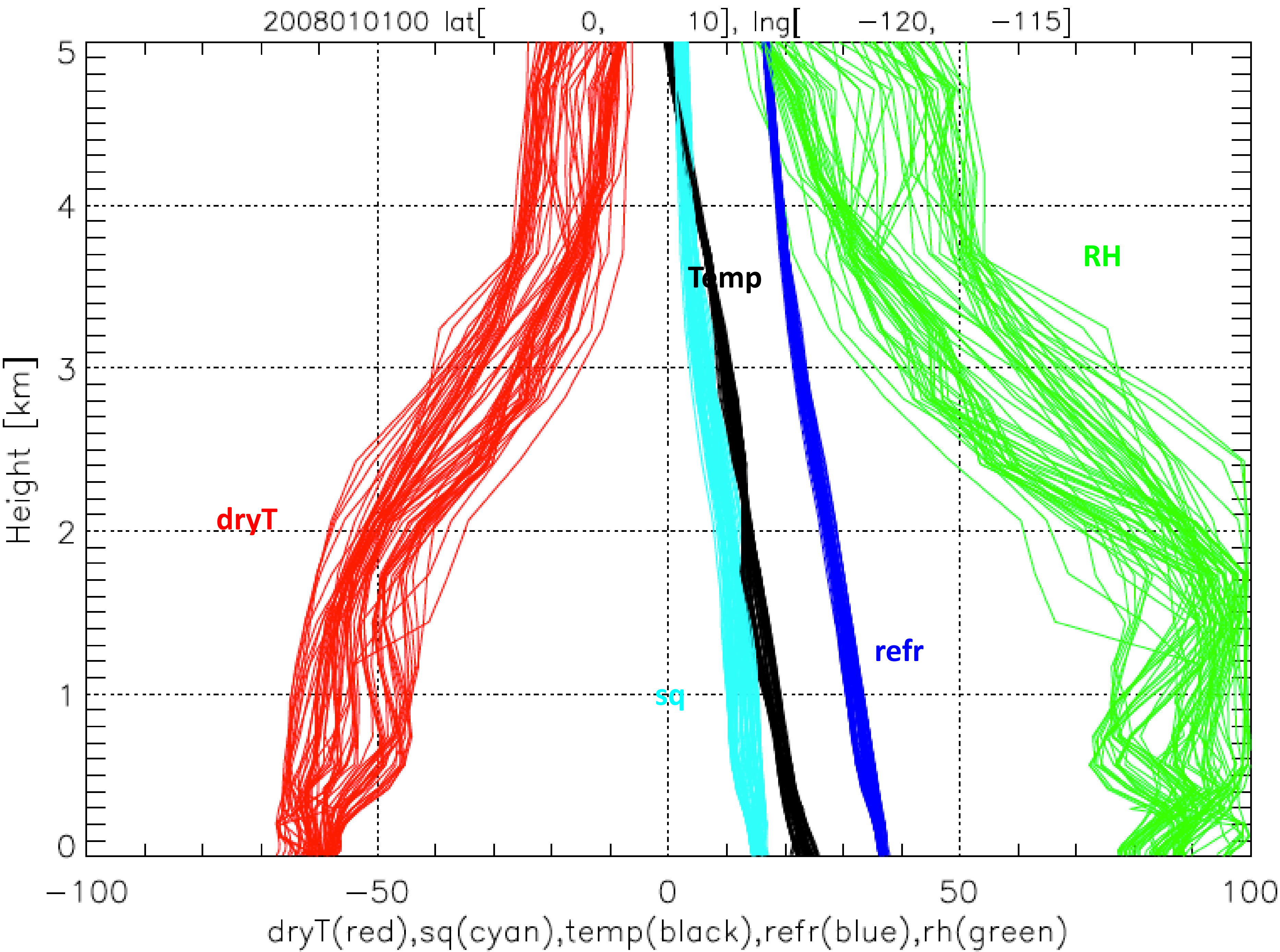
Selected Regions of Interests



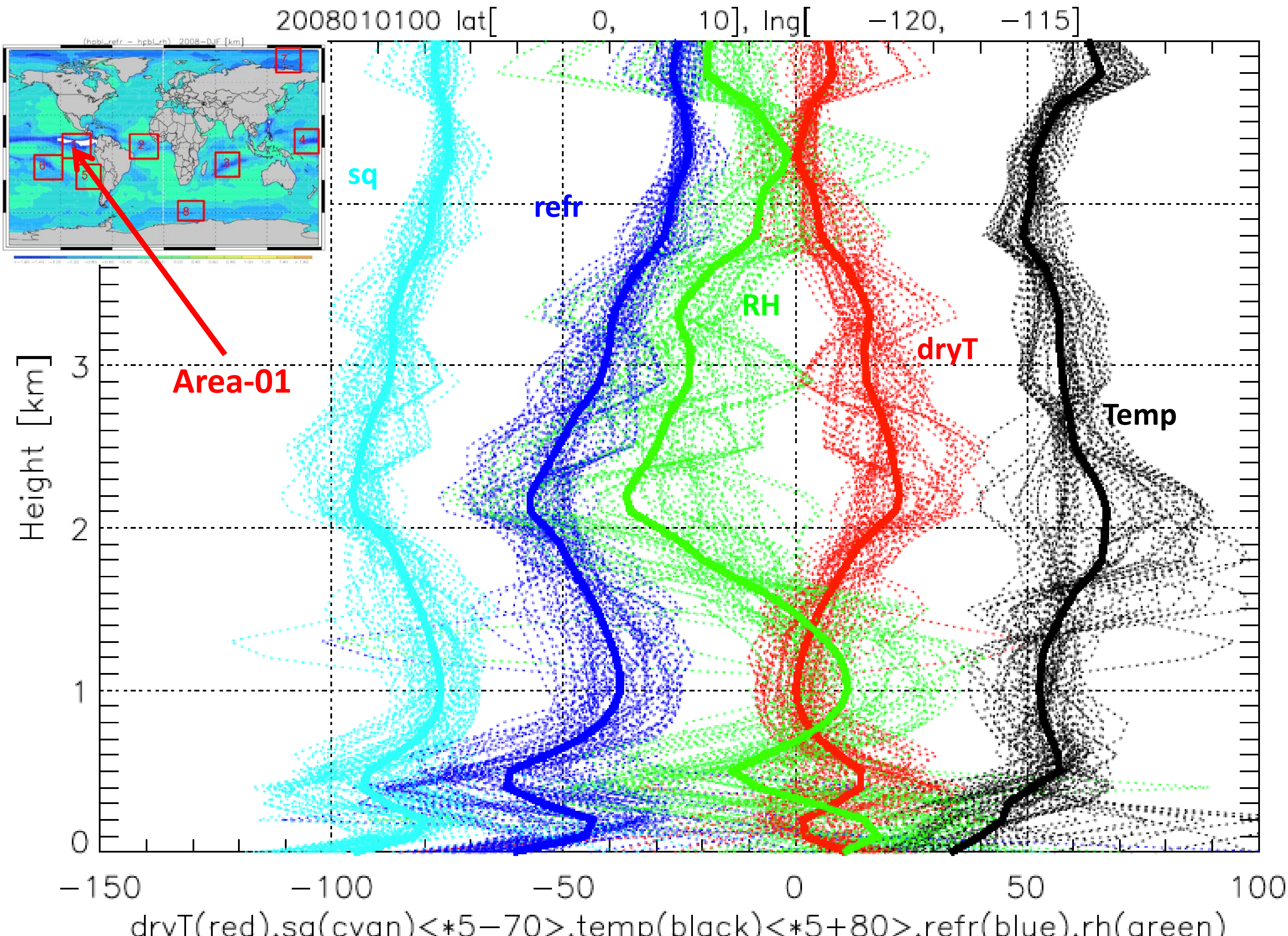
PBL Height Difference between hpbl_Refr-RH (2008-DJF)



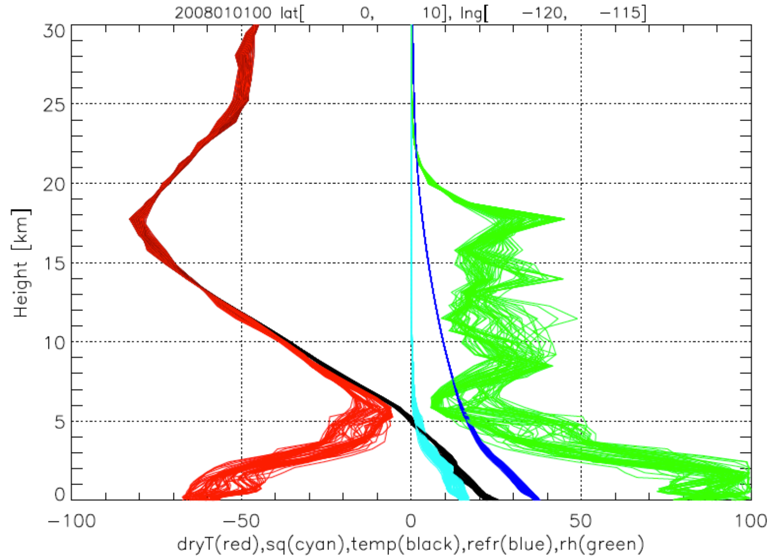
2008010100 lat[0, 10], lng[-120, -115]
Area-01
Height [km]
30
25
20
15
10
5
0
sq
Temp
RH
dryT
refr
-100
-50
0
50
100
dryT(red),sq(cyan),temp(black),refr(blue),rh(green)



2008010100 lat[0, 10], lng[-120, -115]
Height [km]
dryT(red),sq(cyan),temp(black),refr(blue),rh(green)
dryT
Temp
sq
refr
RH



2008010100 lat[0, 10], lng[-120, -115]
Height [km]
dryT(red),sq(cyan)<*5-70>,temp(black)<*5+80>,refr(blue),rh(green)
sq
refr
RH
dryT
Temp
Area-01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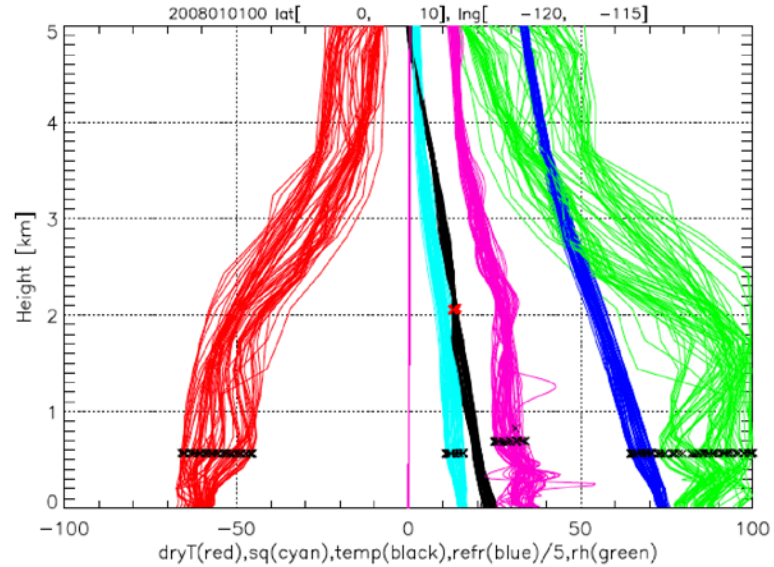
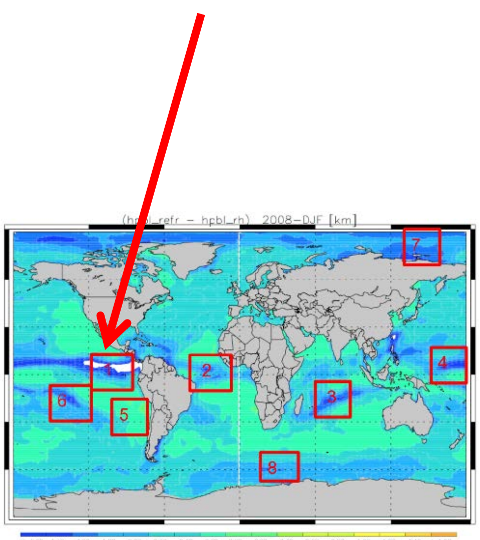
Height [km]
dryT(red),sq(cyan),temp(black),refr(blue),rh(green)


2008010100 lat[0, 10], lng[−120, −115]
Height [km]
dryT(red),sq(cyan),temp(black),refr(blue)/5,rh(green)

Area-01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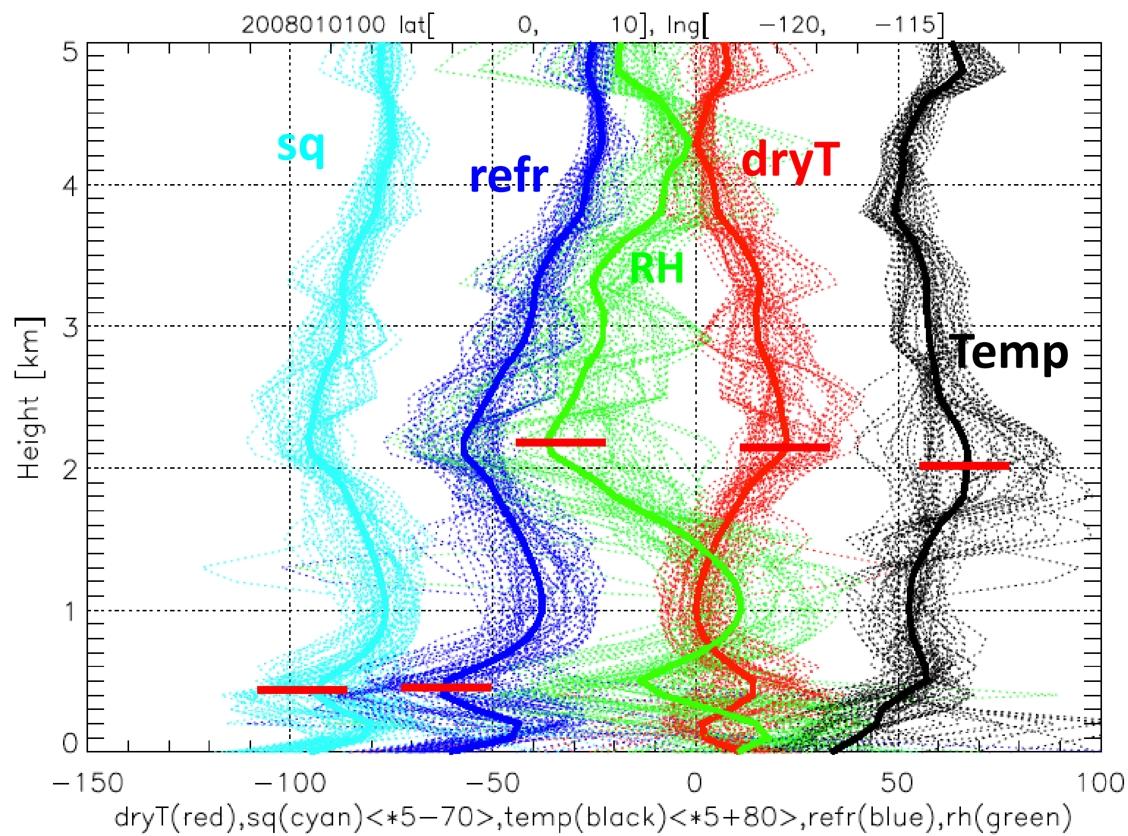
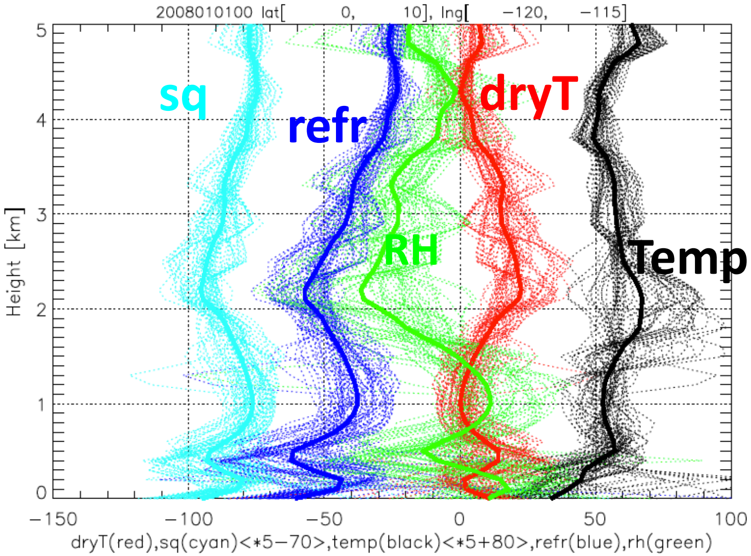
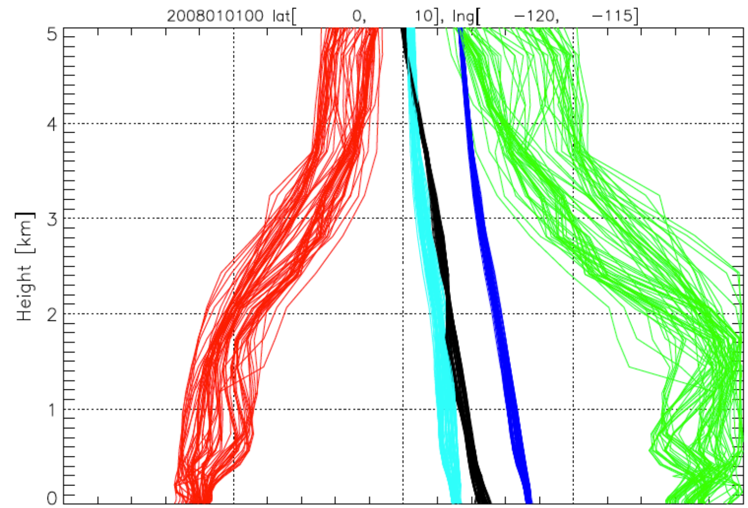
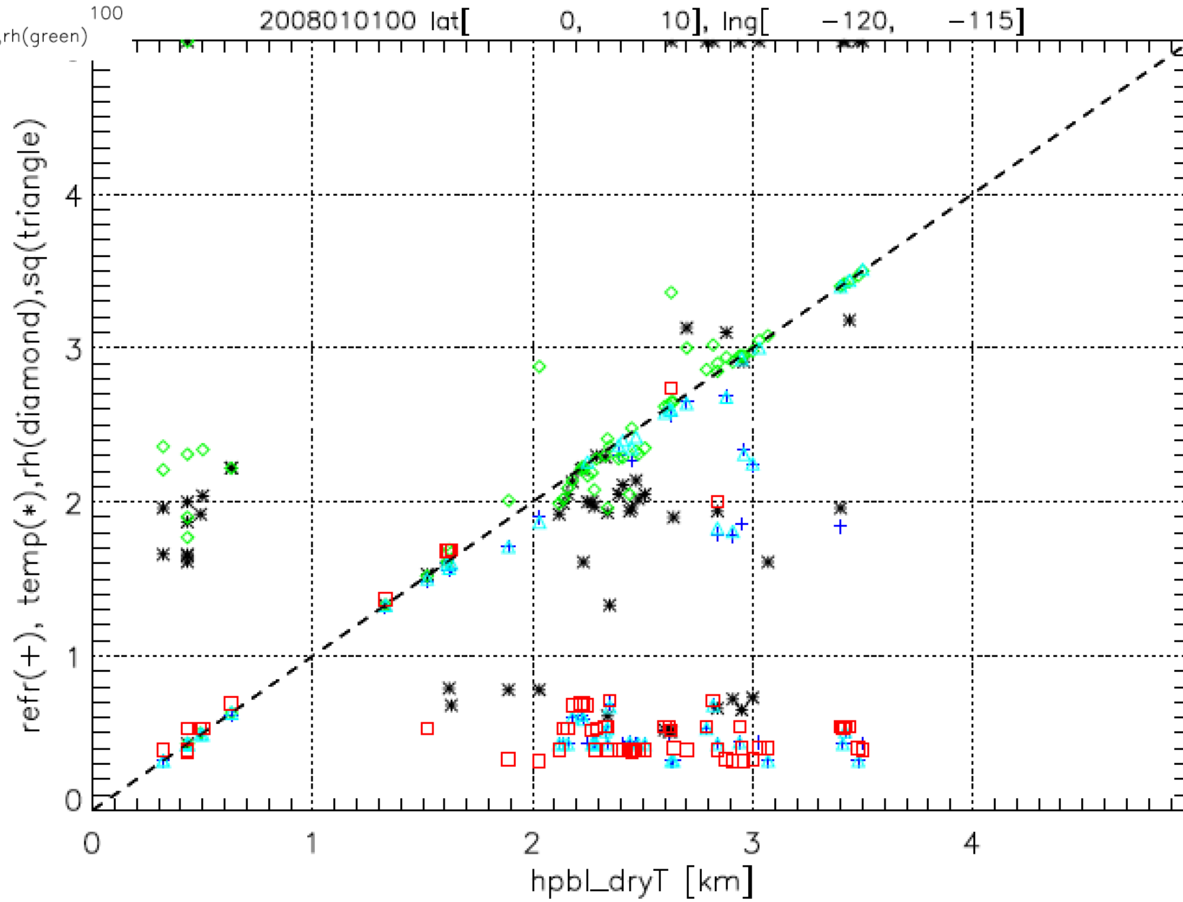
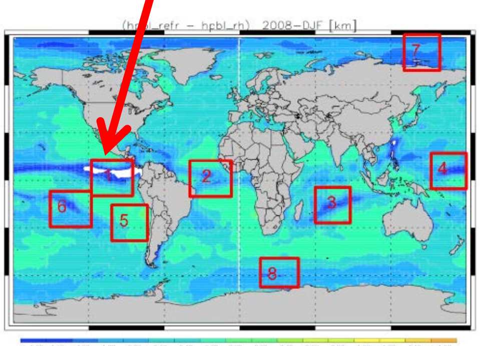

2008010100 lat[0, 10], lng[−120, −115]
sq
refr
dryT
RH
Temp
Height [km]
dryT(red),sq(cyan)<*5−70>,temp(black)<*5+80>,refr(blue),rh(green)

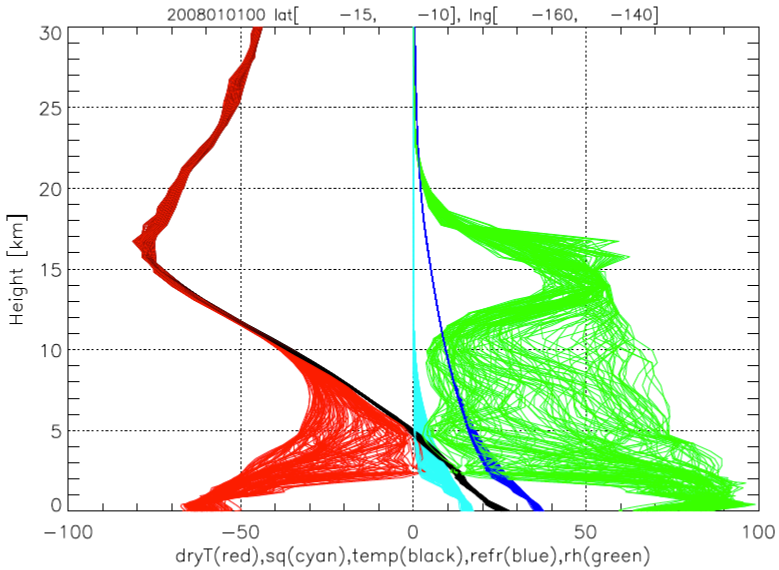

2008010100 lat[0, 10], lng[-120, -115]
sq
refr
dryT
RH
Temp
Height [km]
dryT(red),sq(cyan)<*5-70>,temp(black)<*5+80>,refr(blue),rh(green)

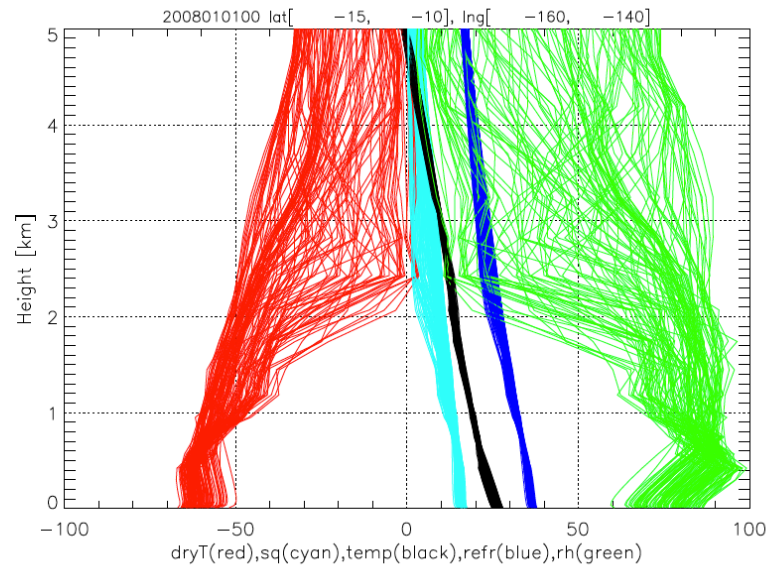

2008010100 lat[0, 10], lng[-120, -115]
Height [km]


2008010100 lat[0, 10], lng[-120, -115]
refr(+), temp(*),rh(diamond),sq(triangle)
hpbl_dryT [km]

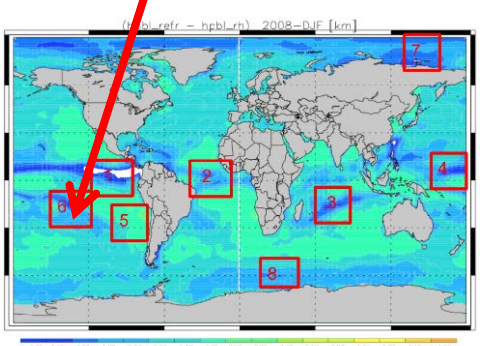
Area-01

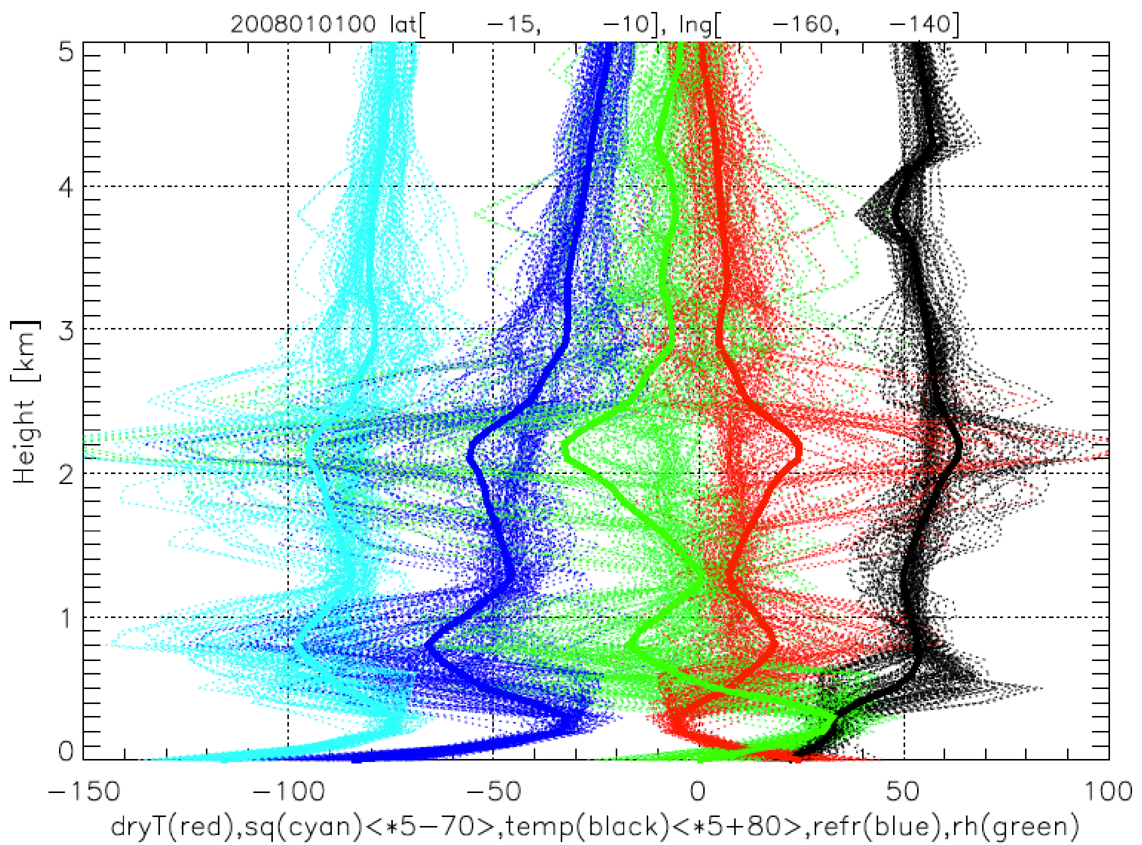


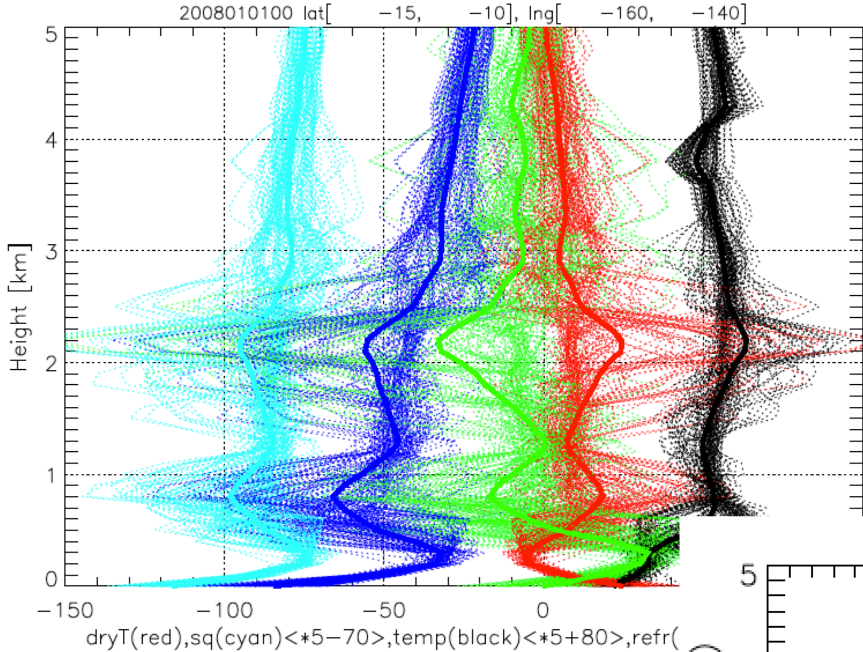

2008010100 lat[−15, −10], lng[−160, −140]
Height [km]
dryT(red),sq(cyan),temp(black),refr(blue),rh(green)

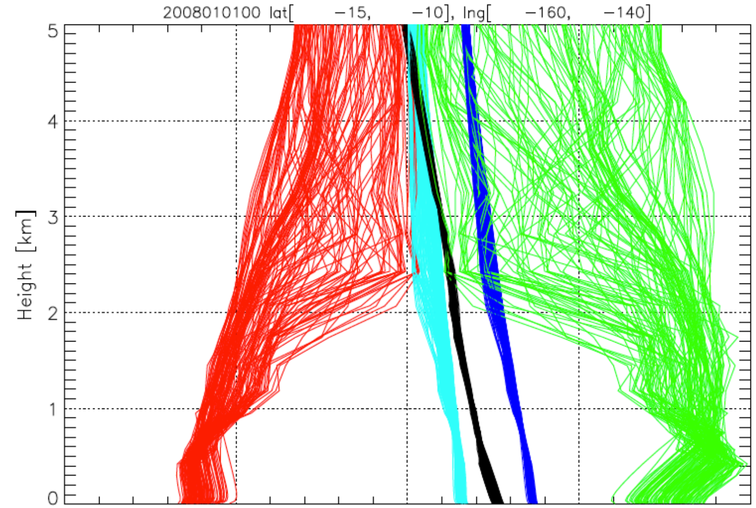

2008010100 lat[−15, −10], lng[−160, −140]
Height [km]
dryT(red),sq(cyan),temp(black),refr(blue),rh(green)

Area-06

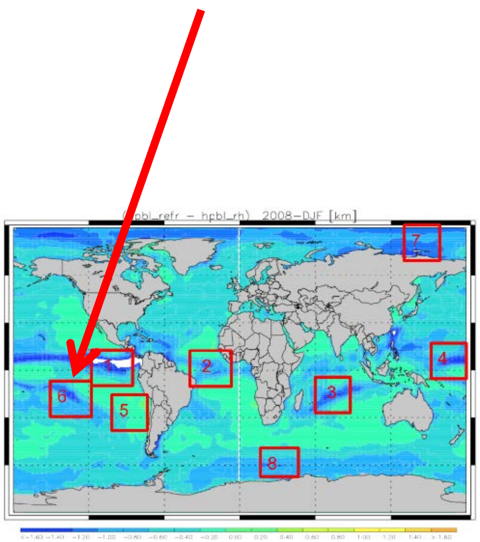

(hpbl_refr − hpbl_rh) 2008-DJF [km]
1
2
3
4
5
6
7
8

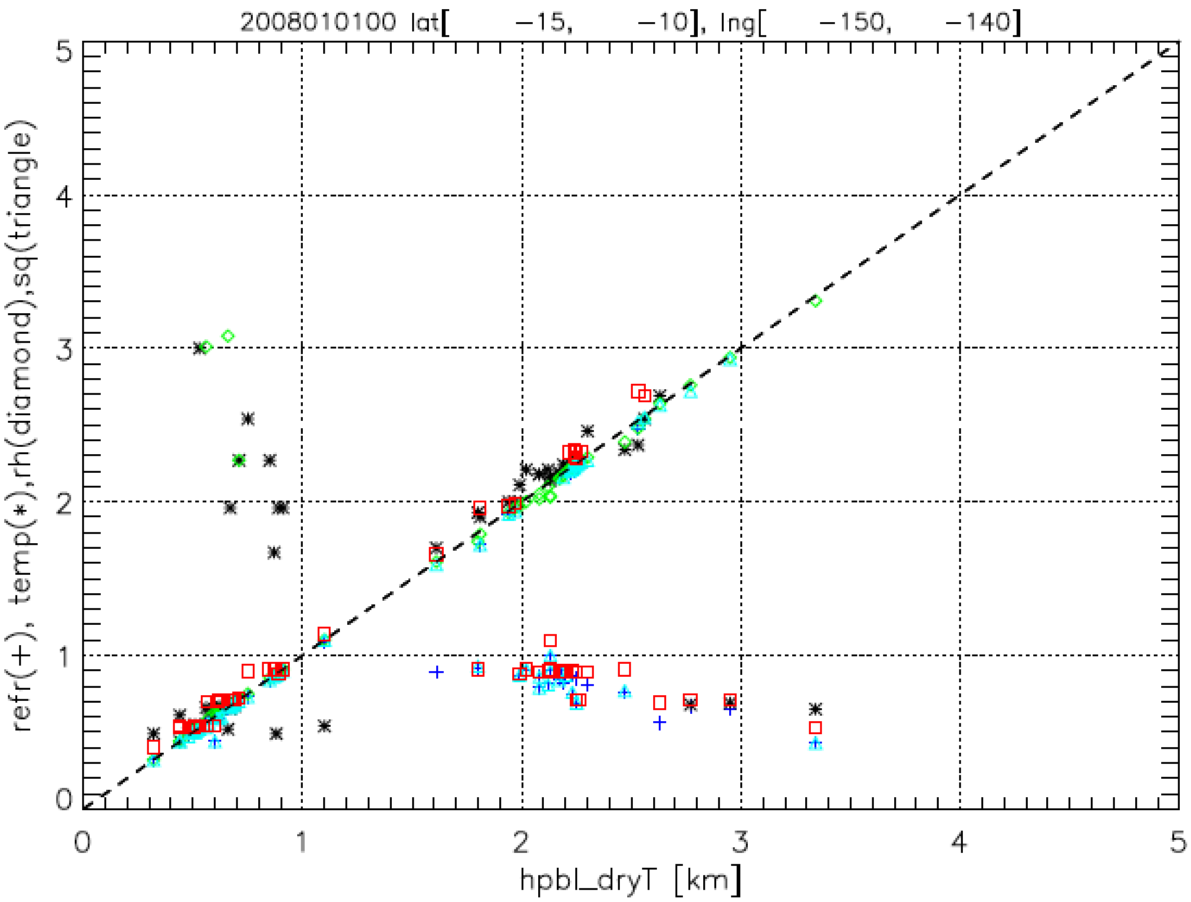

2008010100 lat[−15, −10], lng[−160, −140]
Height [km]
dryT(red),sq(cyan)<*5−70>,temp(black)<*5+80>,refr(blue),rh(green)

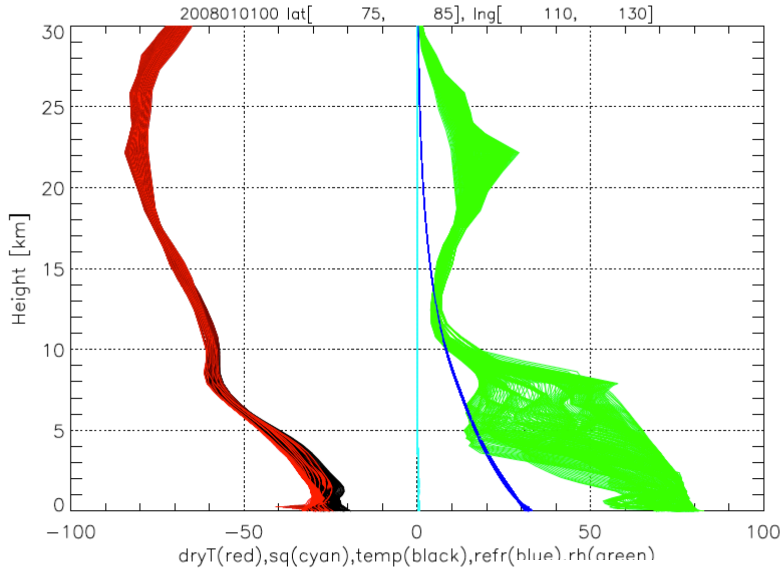

2008010100 lat[−15, −10], lng[−160, −140]
Height [km]
dryT(red),sq(cyan)<*5−70>,temp(black)<*5+80>,refr(

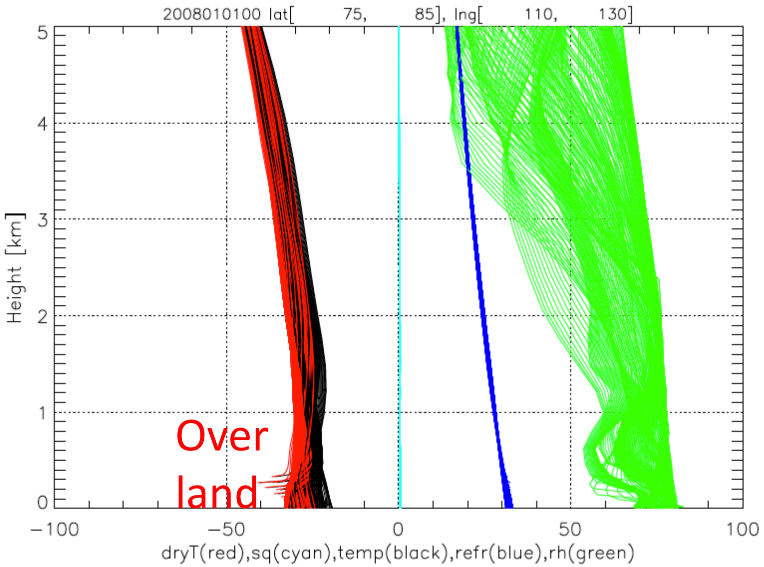

2008010100 lat[−15, −10], lng[−160, −140]
Height [km]

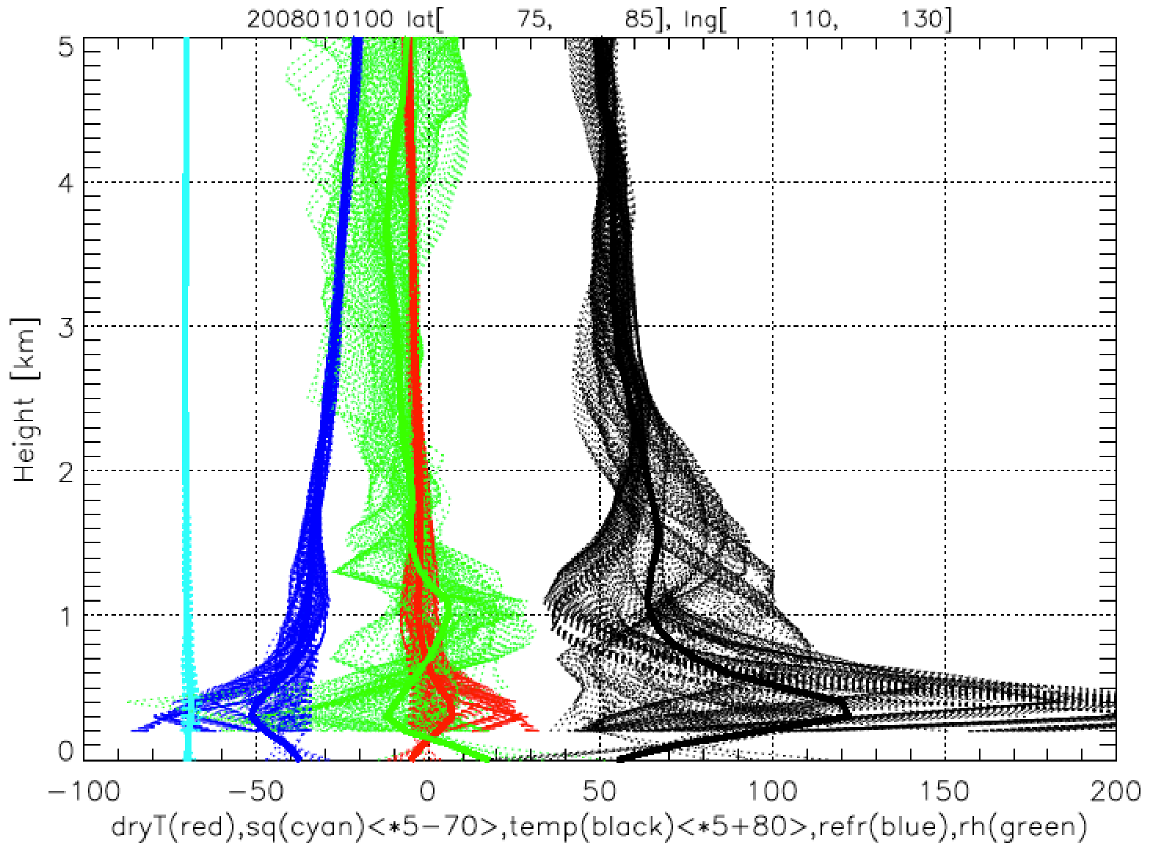
Area-06



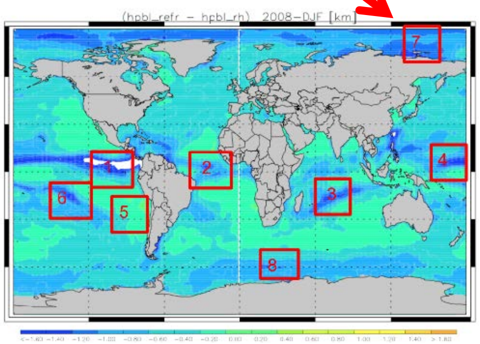

2008010100 lat[−15, −10], lng[−150, −140]
refr(+), temp(*),rh(diamond),sq(triangle)
hpbl_dryT [km]

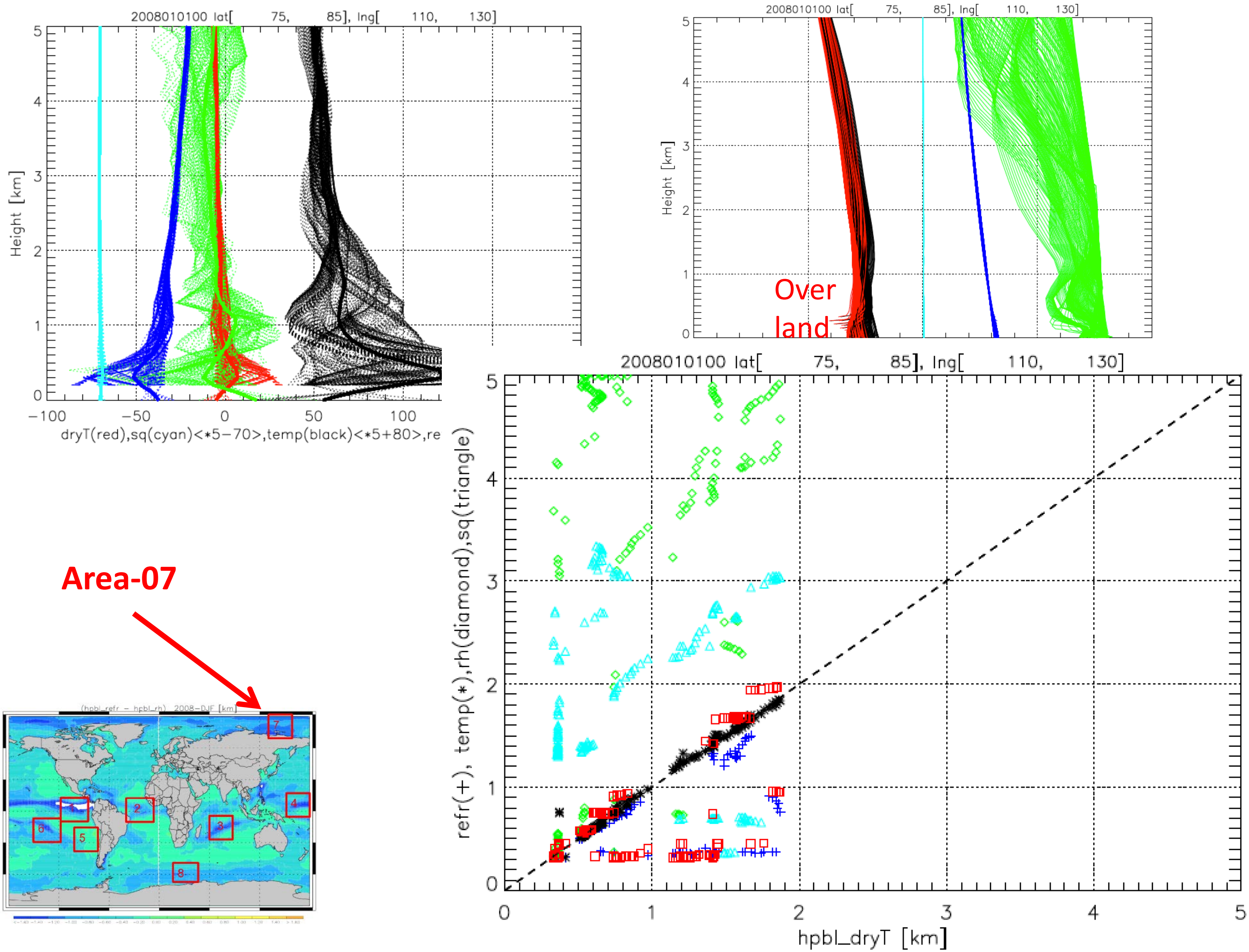

2008010100 lat[75, 85], lng[110, 130]
Height [km]
dryT(red),sq(cyan),temp(black),refr(blue),rh(green)


2008010100 lat[75, 85], lng[110, 130]
Height [km]
Over land
dryT(red),sq(cyan),temp(black),refr(blue),rh(green)

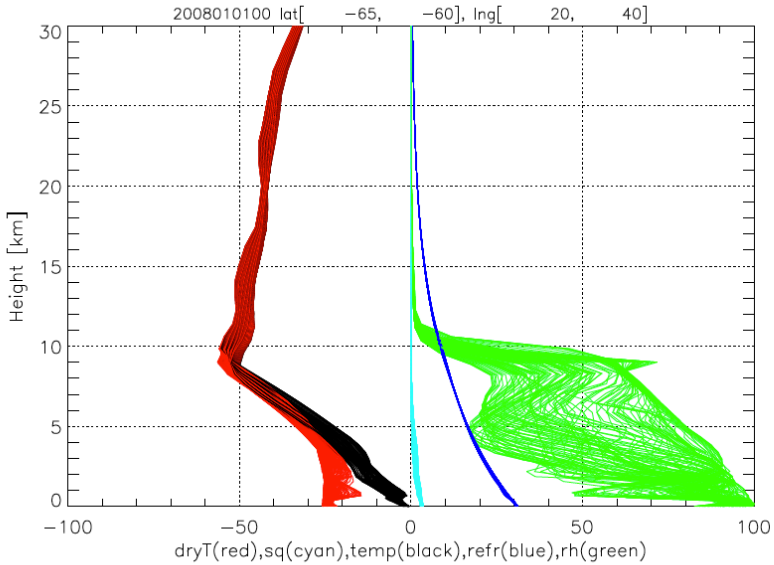

2008010100 lat[75, 85], lng[110, 130]
Height [km]
dryT(red),sq(cyan)<*5-70>,temp(black)<*5+80>,refr(blue),rh(green)

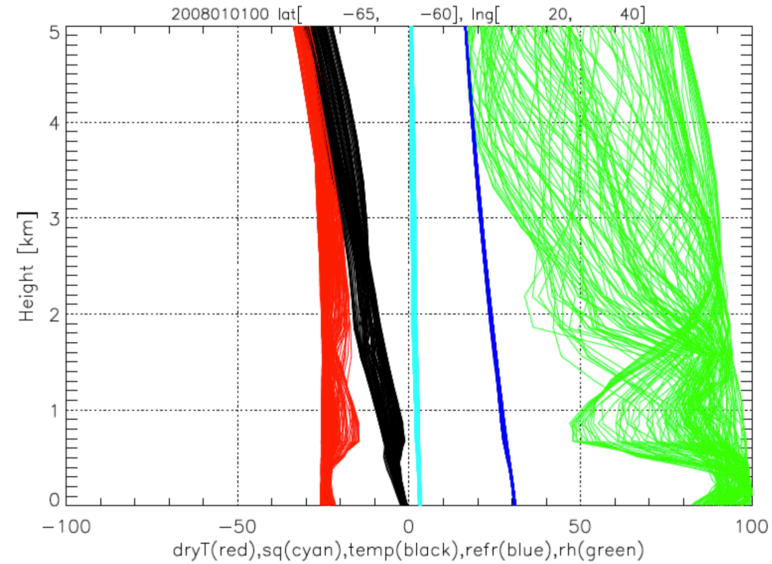
Area-07


(hpbl_refr – hpbl_rh) 2008–DJF [km]
7
4
1
2
3
6
5
8

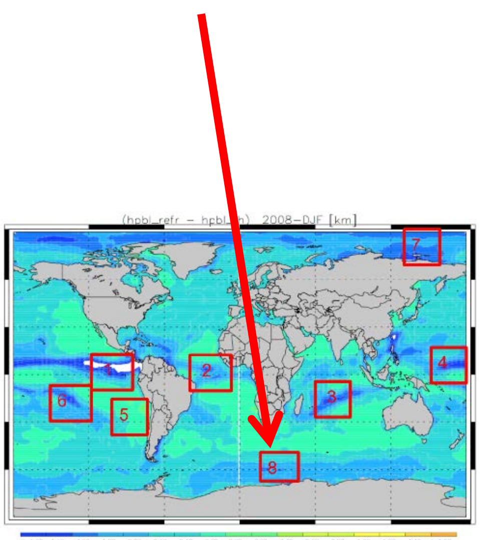


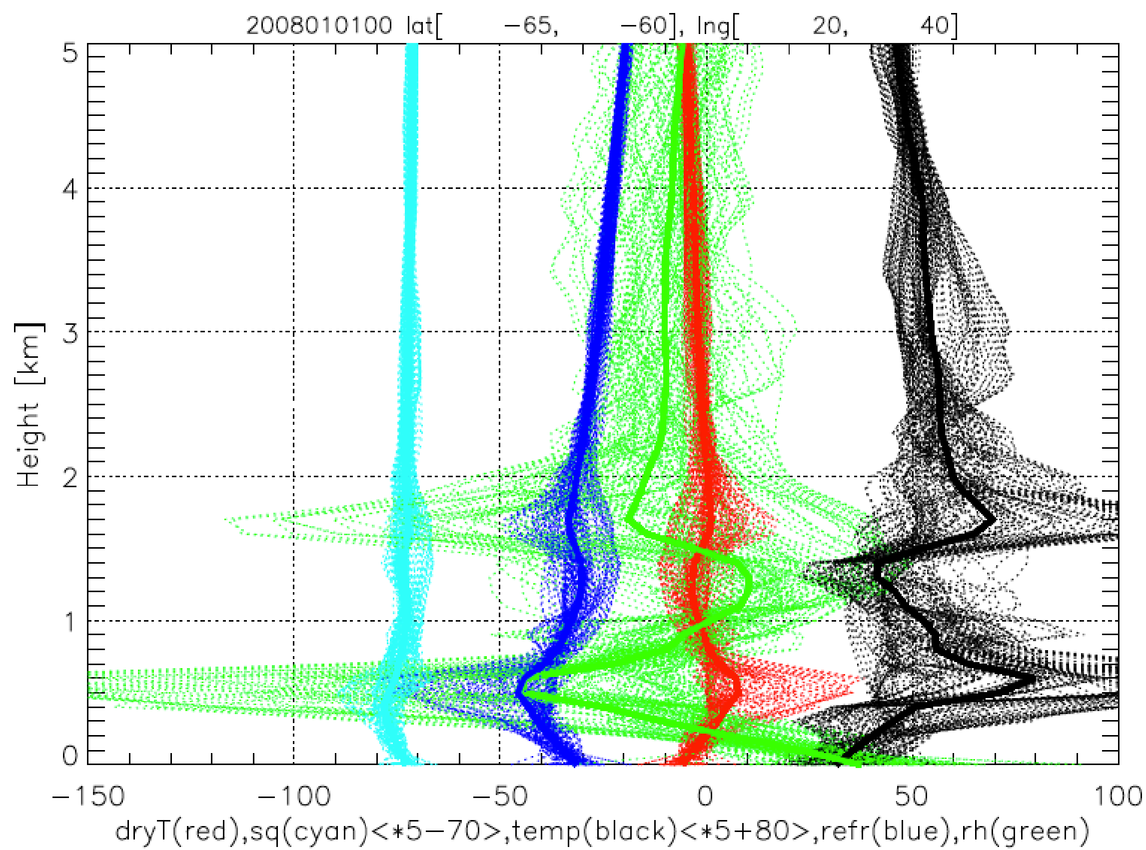
2008010100 lat[75, 85], lng[110, 130]
Height [km]
dryT(red),sq(cyan)<*5-70>,temp(black)<*5+80>,re
2008010100 lat[75, 85], lng[110, 130]
Height [km]
Over land
2008010100 lat[75, 85], lng[110, 130]
refr(+), temp(*),rh(diamond),sq(triangle)
hpbl_dryT [km]
Area-07
(hpbl_refr − hpbl_rh) 2008−DJF [km]

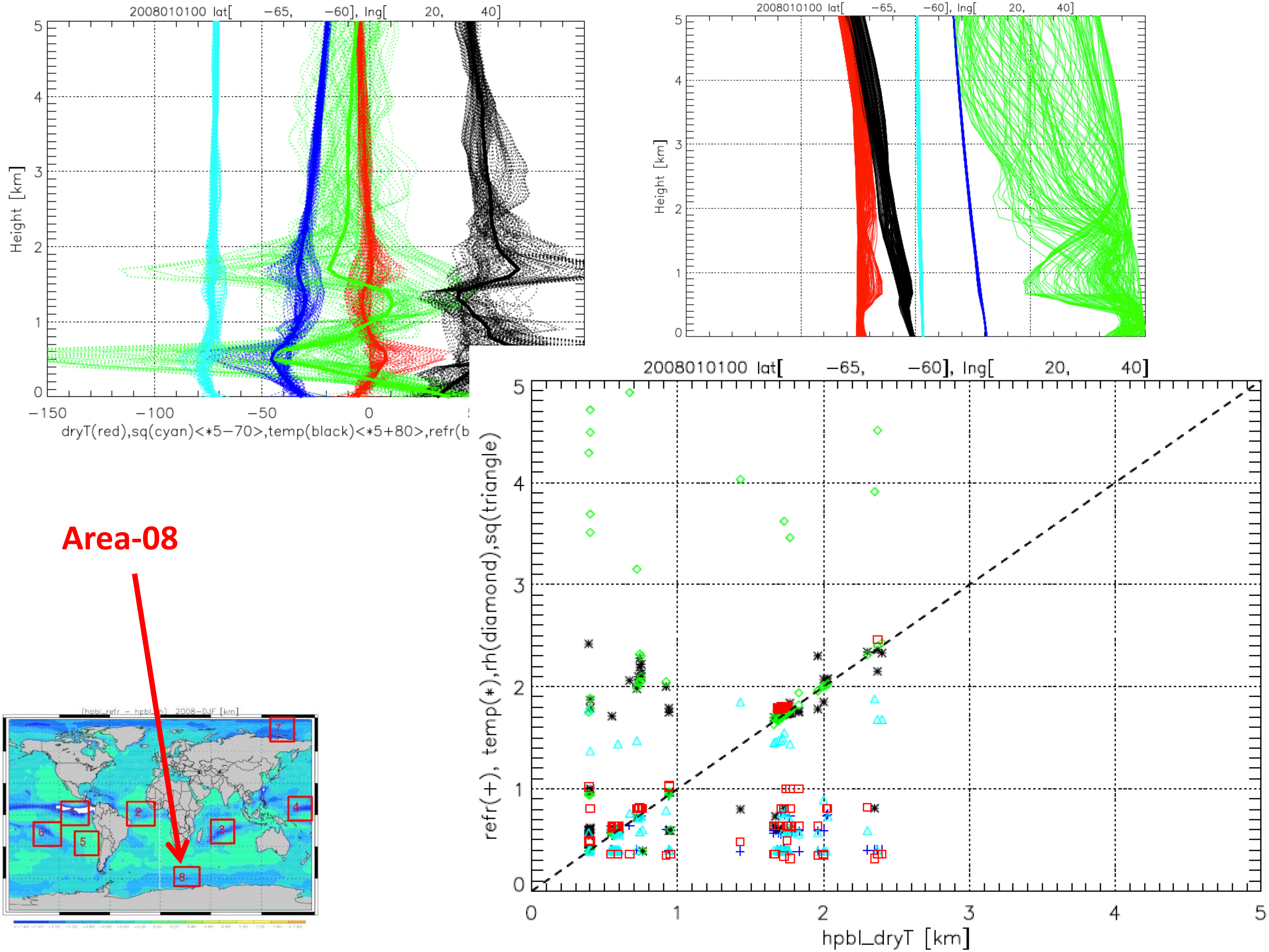

2008010100 lat[-65, -60], lng[20, 40]
Height [km]
dryT(red),sq(cyan),temp(black),refr(blue),rh(green)


2008010100 lat[-65, -60], lng[20, 40]
Height [km]
dryT(red),sq(cyan),temp(black),refr(blue),rh(green)

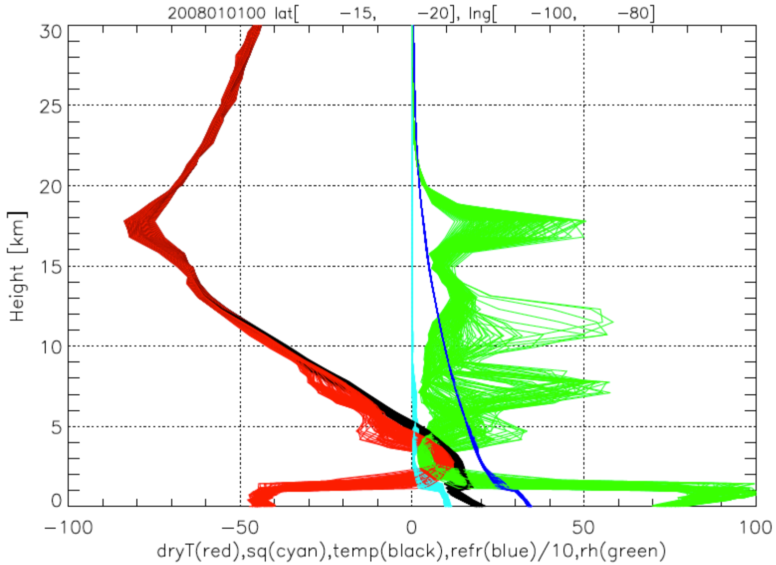
Area-08

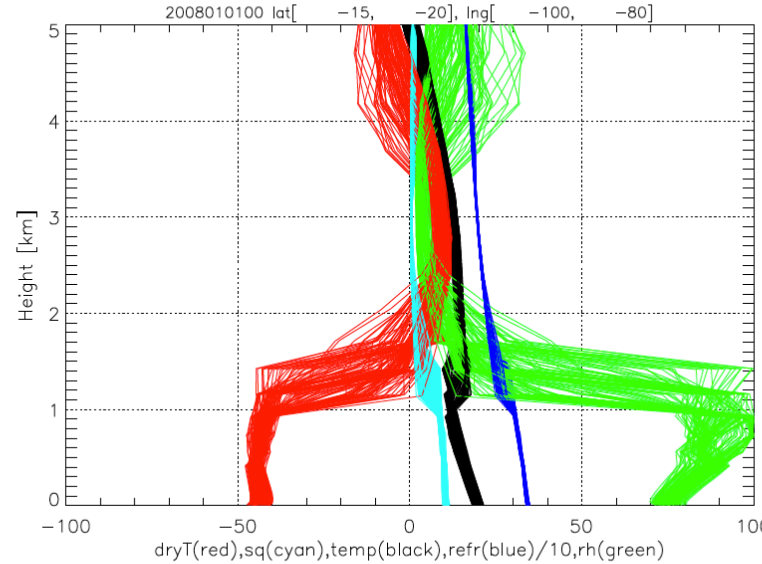



2008010100 lat[-65, -60], lng[20, 40]
Height [km]
dryT(red),sq(cyan)<*5-70>,temp(black)<*5+80>,refr(blue),rh(green)

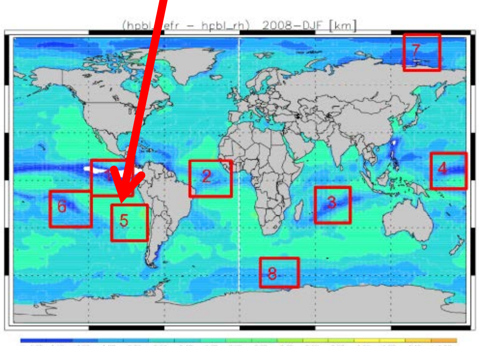


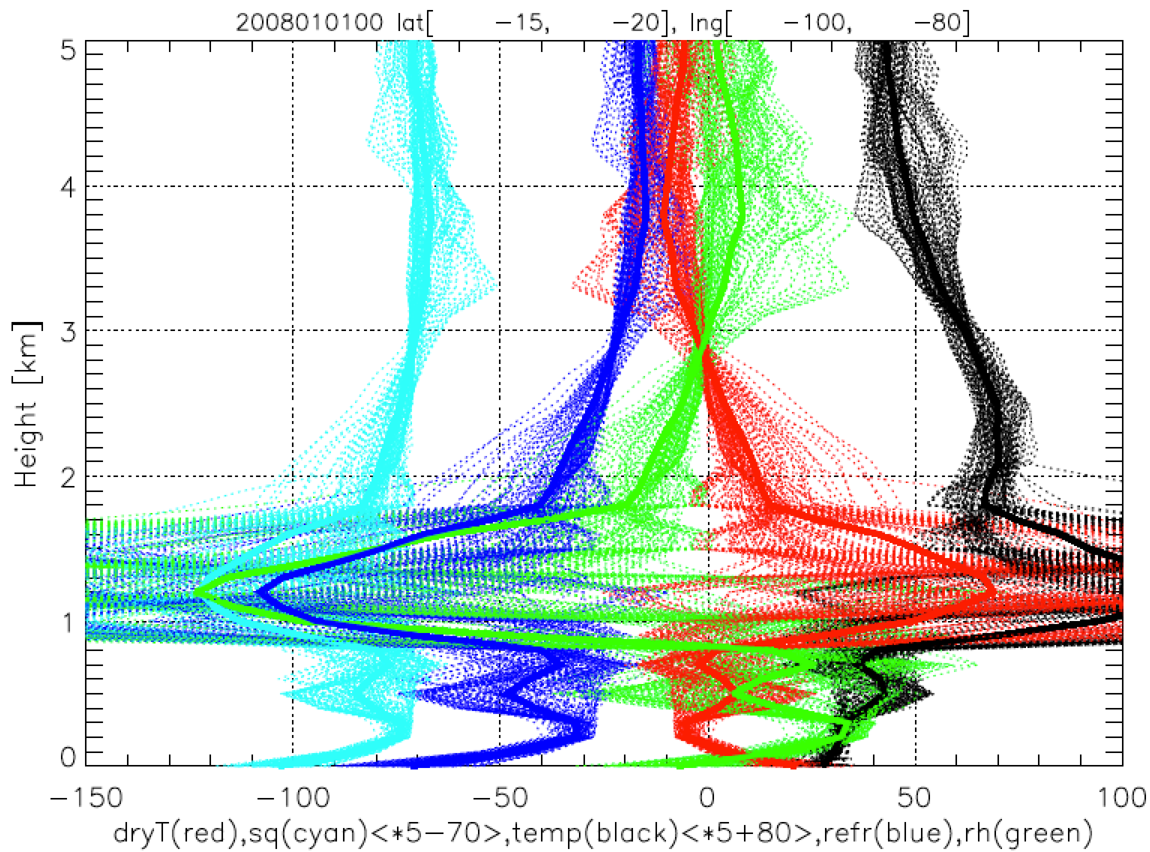
2008010100 lat[-65, -60], lng[20, 40]
Height [km]
dryT(red),sq(cyan)<*5-70>,temp(black)<*5+80>,refr(b
2008010100 lat[-65, -60], lng[20, 40]
Height [km]
2008010100 lat[-65, -60], lng[20, 40]
refr(+), temp(*),rh(diamond),sq(triangle)
hpbl_dryT [km]
Area-08
(hpbl_refr - hpbl_...) 2008-DJF [km]

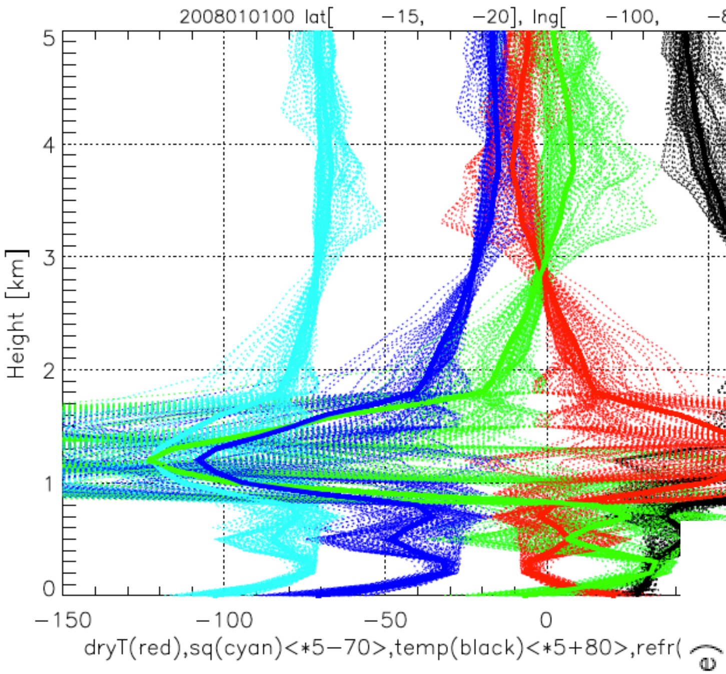

2008010100 lat[−15, −20], lng[−100, −80]
Height [km]
dryT(red),sq(cyan),temp(black),refr(blue)/10,rh(green)


2008010100 lat[−15, −20], lng[−100, −80]
Height [km]
dryT(red),sq(cyan),temp(black),refr(blue)/10,rh(green)

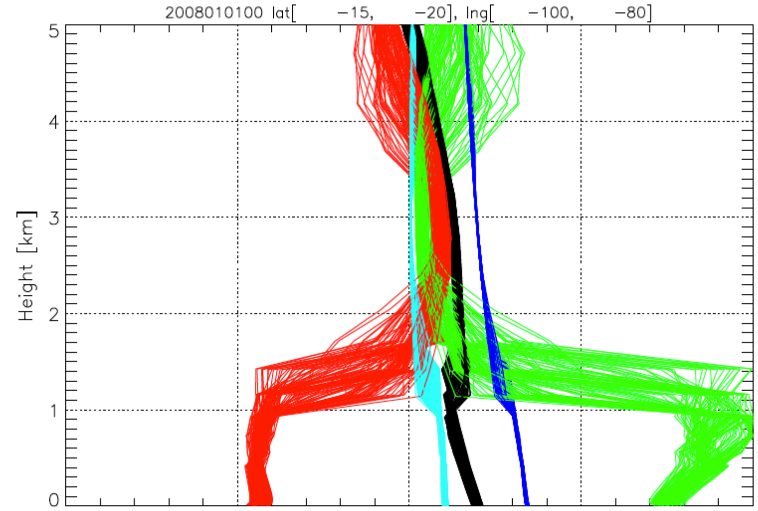
Area-05


2008−DJF [km]

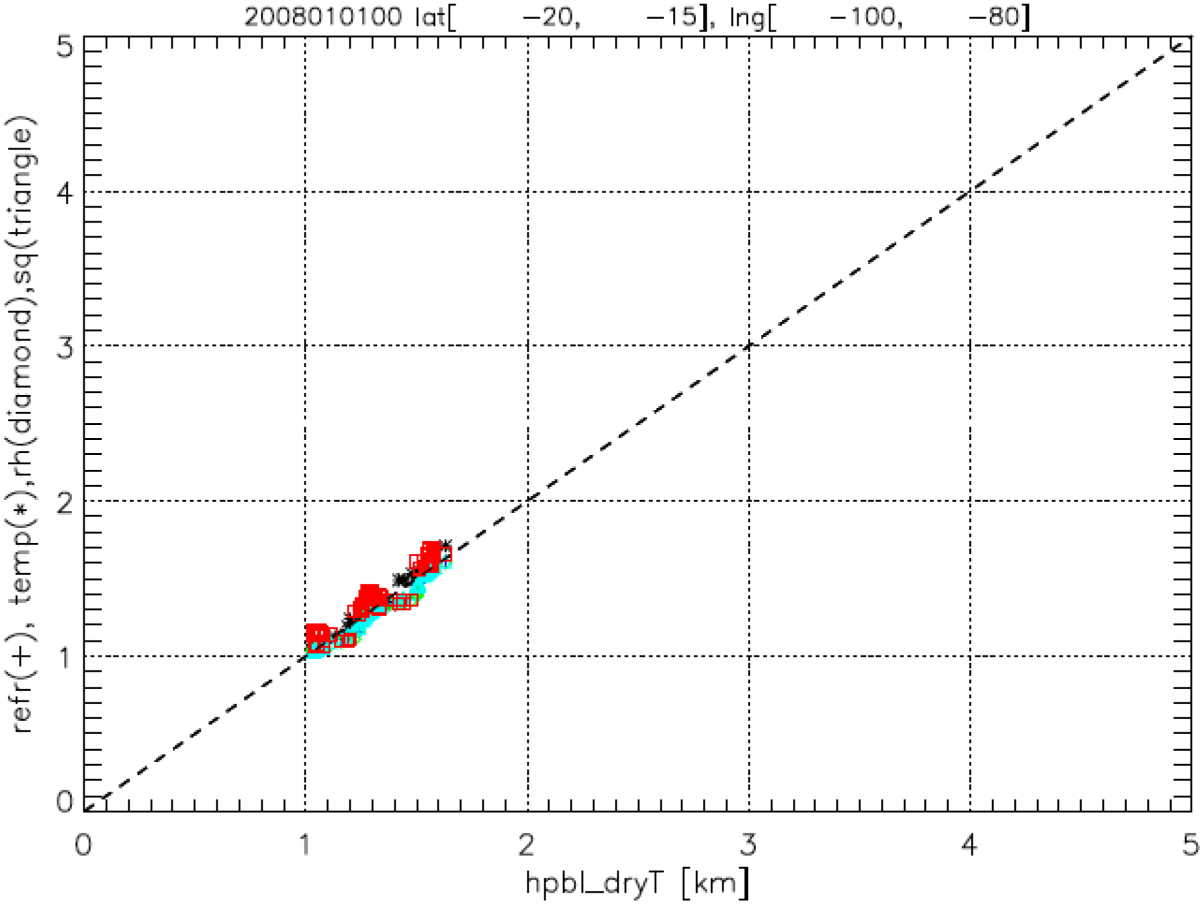

2008010100 lat[−15, −20], lng[−100, −80]
Height [km]
dryT(red),sq(cyan)<*5−70>,temp(black)<*5+80>,refr(blue),rh(green)



2008010100 lat[−15, −20], lng[−100, −80]
Height [km]
dryT(red),sq(cyan)<*5−70>,temp(black)<*5+80>,refr(

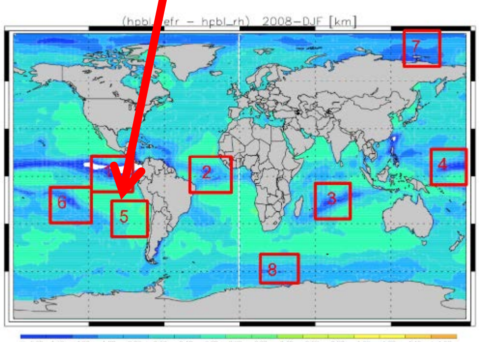


2008010100 lat[−15, −20], lng[−100, −80]
Height [km]



2008010100 lat[−20, −15], lng[−100, −80]
refr(+), temp(*),rh(diamond),sq(triangle)
hpbl_dryT [km]

Area-05



(hpbl_refr − hpbl_rh) 2008−DJF [km]
1
2
3
4
5
6
7
8