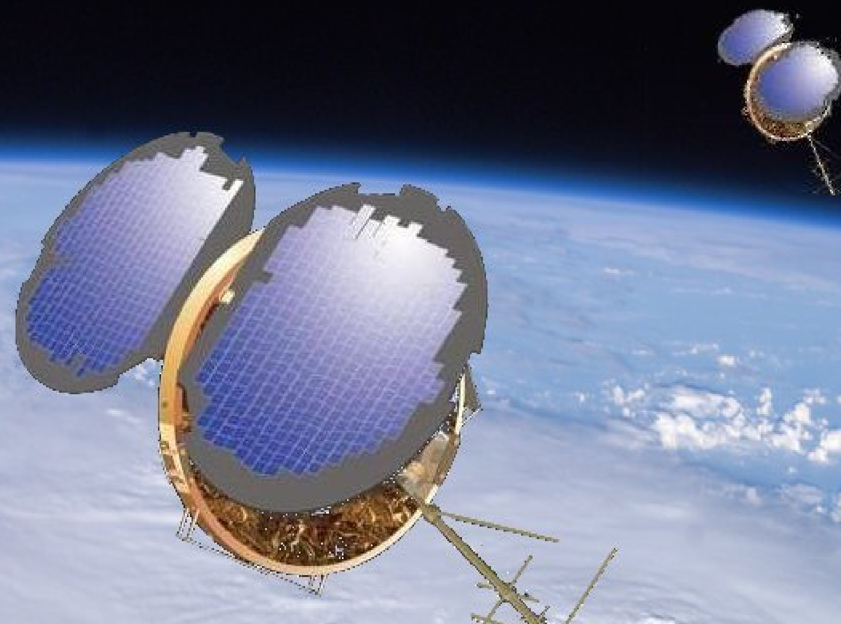


Recent Advances in Radio Occultation Science and Applications

Rick Anthes

UCAR COSMIC Program

Strategic Planning Meeting on COSMIC-1 and COSMIC-2

Washington DC

Jan 29, 2014

COSMIC Sponsors and Partners

US Government

- NSF
- NOAA
- NASA
- Air Force
- Navy (ONR, NRL)

International

- NSPO, Taiwan
- CWB, Taiwan
- TTFRI, Taiwan
- EUMETSAT, Europe
- KASI, Korea
- IEEC, Spain

Other

- Universities
- NCAR
- Private sector
- Broad Reach Engineering
- Orbital Sciences

Outline of Presentation

- Uses and characteristics of RO observations (a review)
- Impact of RO observations on research and operations
- Tropical cyclone observations, research, and predictions
- RO and the atmospheric boundary layer (ABL)
- RO and precipitable water
- RO as anchor (unbiased) observations in NWP
- RO as climate benchmark observations
- RO as cal/val for IR and microwave sounders (AIRS, ATMS, AMSU)
- RO and space weather
- References (many slides have references in “Notes” section)

Scientific Uses of Radio Occultation Data

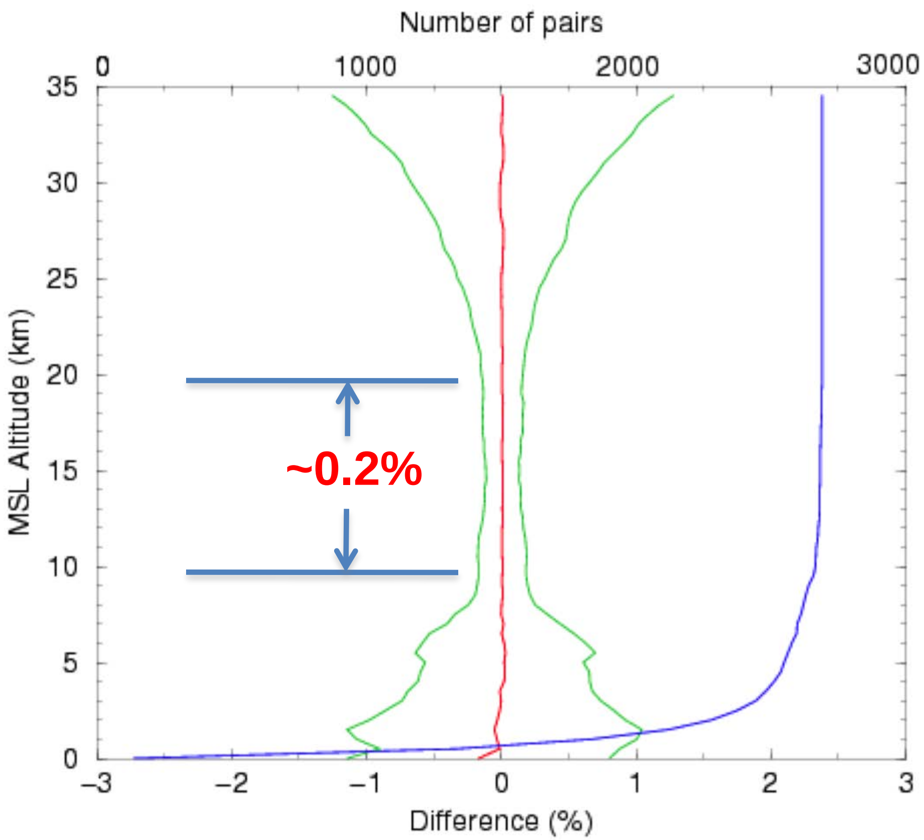
- **Weather**
  - Improve global weather analyses, particularly over data void regions such as the oceans, tropics, and polar regions
  - Improve skill of numerical weather prediction models
  - Improve understanding of tropical, mid-latitude and polar weather systems and their interactions
- **Ionosphere and Space Weather**
  - Observe global electronic density distribution
  - Improve the analysis and prediction of space weather
  - Improve monitoring/prediction of scintillation (e.g. equatorial plasma bubbles, sporadic E clouds)
- **Climate**
  - Monitor climate change and variability with unprecedented accuracy- **world's most accurate, precise, and stable thermometer from space!**
  - Evaluate global climate models and analyses
  - Calibrate infrared and microwave sensors and retrieval algorithms

Characteristics of RO Data

- **Limb sounding geometry complementary to ground and space nadir viewing instruments**
- **Global coverage**
- **Profiles ionosphere, stratosphere and troposphere**
- **High accuracy (equivalent to <0.5 K; average accuracy <0.1 K)**
- **High precision (0.02-0.05 K)**
- **High vertical resolution (0.1 km near surface – 1 km tropopause)**
- **Only system from space to profile atmospheric boundary layer (ABL)**
- **All weather-minimally affected by aerosols, clouds or precipitation**
- **Independent height and pressure**
- **Requires no first guess sounding**
- **No calibration required**
- **Climate benchmark quality-tied to SI standards**
- **Independent of processing center**
- **Independent of mission**
- **No instrument drift**
- **No satellite-to-satellite bias**
- **Compact sensor, low power, low cost**

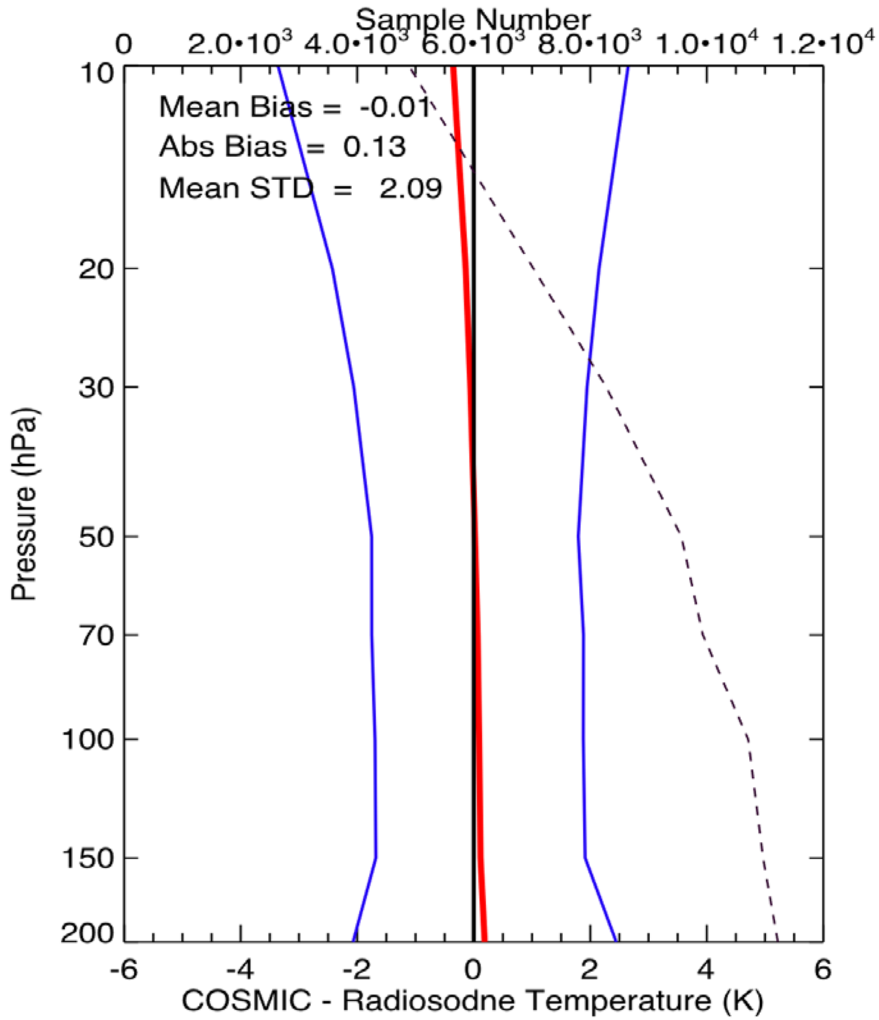
All of these characteristics have been demonstrated in peer-reviewed literature.

Precision of RO
From Collocated COSMIC Soundings



Refractivity (N) difference for pairs of COSMIC RO measurements (FM3-FM4) with tangent point separation less than 10 km. The blue line shows the number of pairs of nearby soundings with height. The red line shows the mean difference, and the green lines show the standard deviations of the differences plotted around the mean.

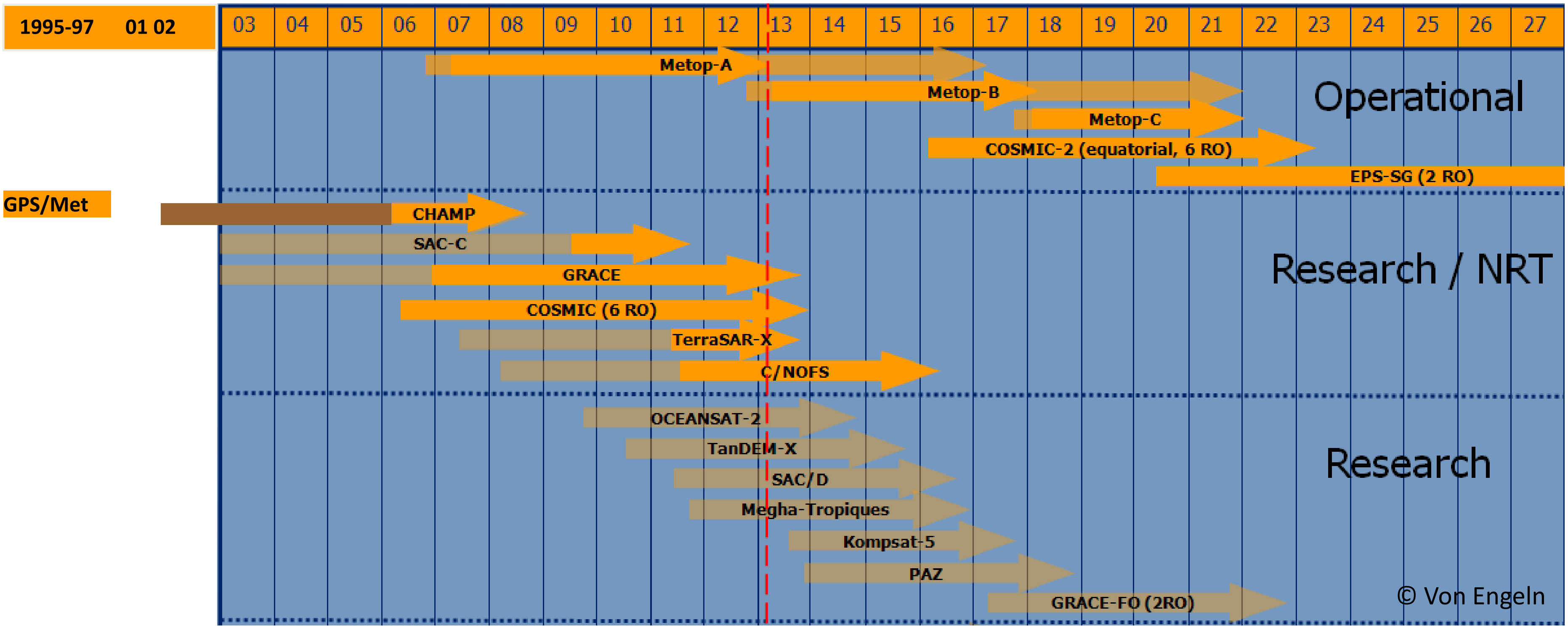
Accuracy of RO temperature compared to radiosondes



Accuracy of RO in the upper troposphere and lower stratosphere is better than 0.5 K

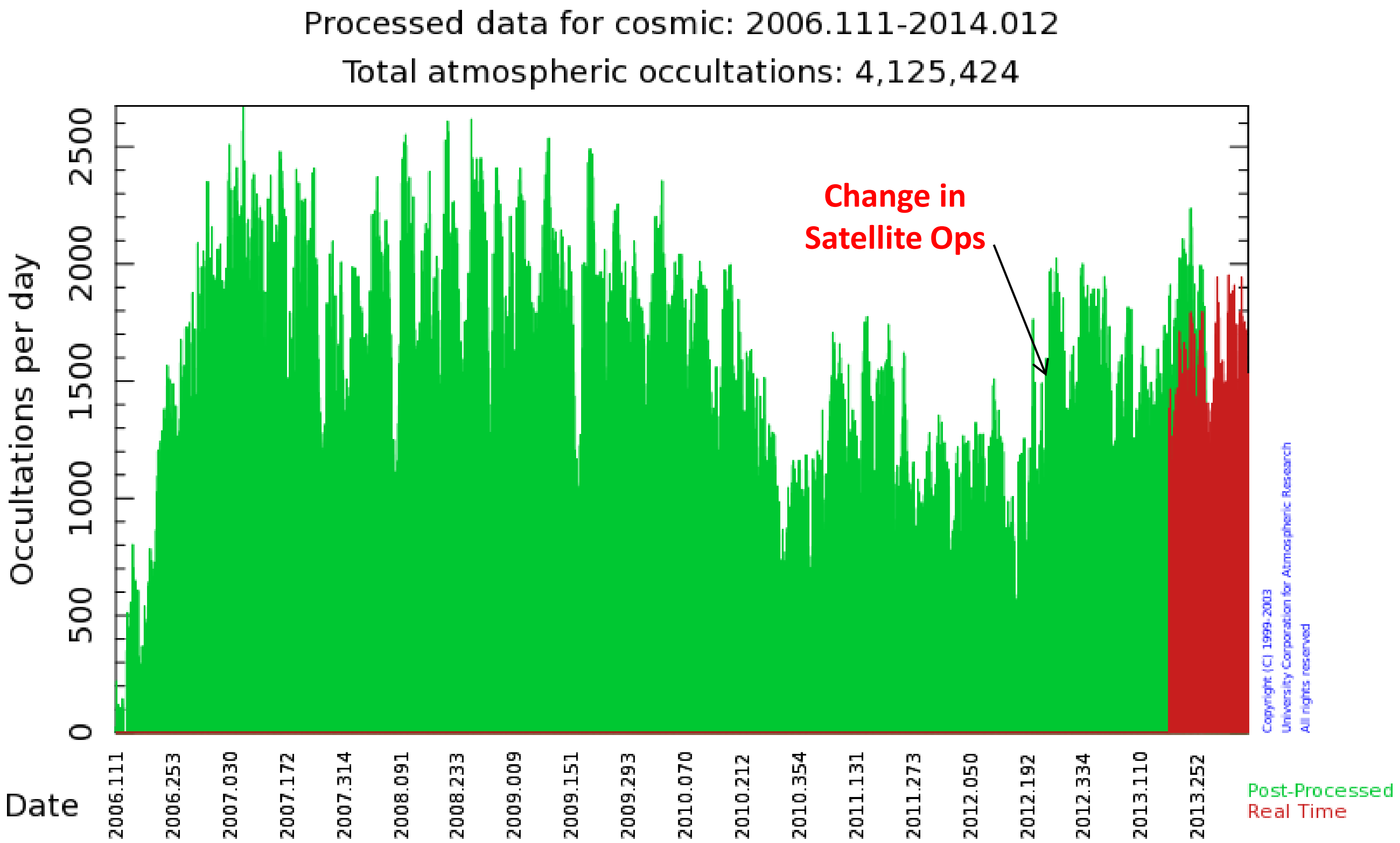
RO Mission Status

(as of May 2013)



With COSMIC-2 Polar Constellation we will have good global coverage. Without C-2 Polar there will be a serious gap in middle and polar latitudes.

~ 4.1 Million Profiles in Real Time 4/21/06 – 1/12/2014



COSMIC Data Products

- **LEO POD and excess phase (<15 cm, <0.15mm/s 3D rms)**
- **~4.1M neutral atmospheric profiles:**
  - Bending angle noise ~1.5 micro-rad
  - Refractivity precision 0.1-0.2 % between 8-30km
- **> 3.8M Absolute TEC data arcs:**
  - Absolute accuracy ~ 1-3 TECU, Relative accuracy 0.3 TECU
- **~3.8M Electron Density Profiles:**
  - NmF2 (F2 layer peak) Accuracy ~20% (compared to Ionosondes)
  - hmF2 (F2 layer height) Accuracy ~20 km (compared to Ionosondes)
- **Scintillation Indices (S4):**
  - ~4.1M available from occultation profile events (altitudes < 120 km)
  - 1 Hz data available from > 4M line of sight tracks to all GPS in view
- **TIP Night-side Radiances:**
  - TIP set new standard for sensitivity of UV instruments, ~500 counts/s/Rayleigh
  - > 17,800 hours of quality controlled data

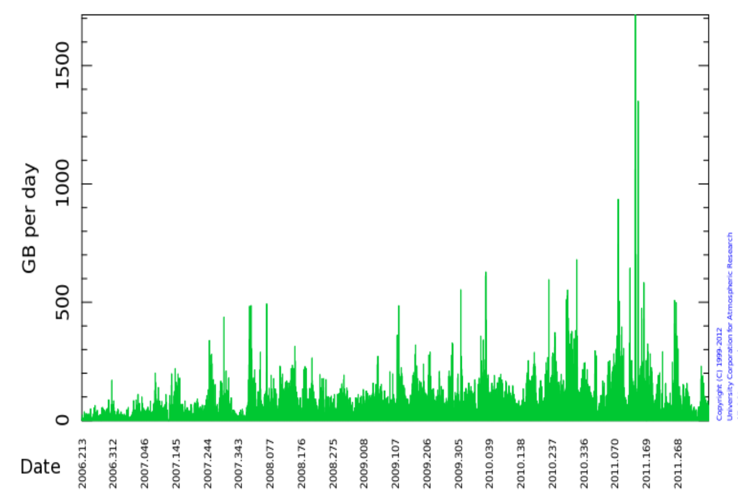
CDAAC Support to the Community

- Supporting 2,668 data users from 75 countries
- Providing NRT data to NWPs, AFWA
- Providing NRT, Post-Processed, and climate Re-analysis products from 9 RO missions
- Development of improved RO data processing algorithms
- Providing data, software and processing support to community

Last Updated: Wed Jan 15 23:25:01 MST 2014

MISSION	Total Atm Occs	Total Ion Occs
CHAMP	399968	303291
CNOFS	123984	0
COSMIC	4130252	3750909
GPSMET	5002	0
GPSMETAS	4666	0
GRACE	286272	138729
METOPA	993084	0
SACC	353808	0
TSX	276549	0
Total	**6573585**	**4192929**

Data Downloaded ~300TB (1/3 from university community)



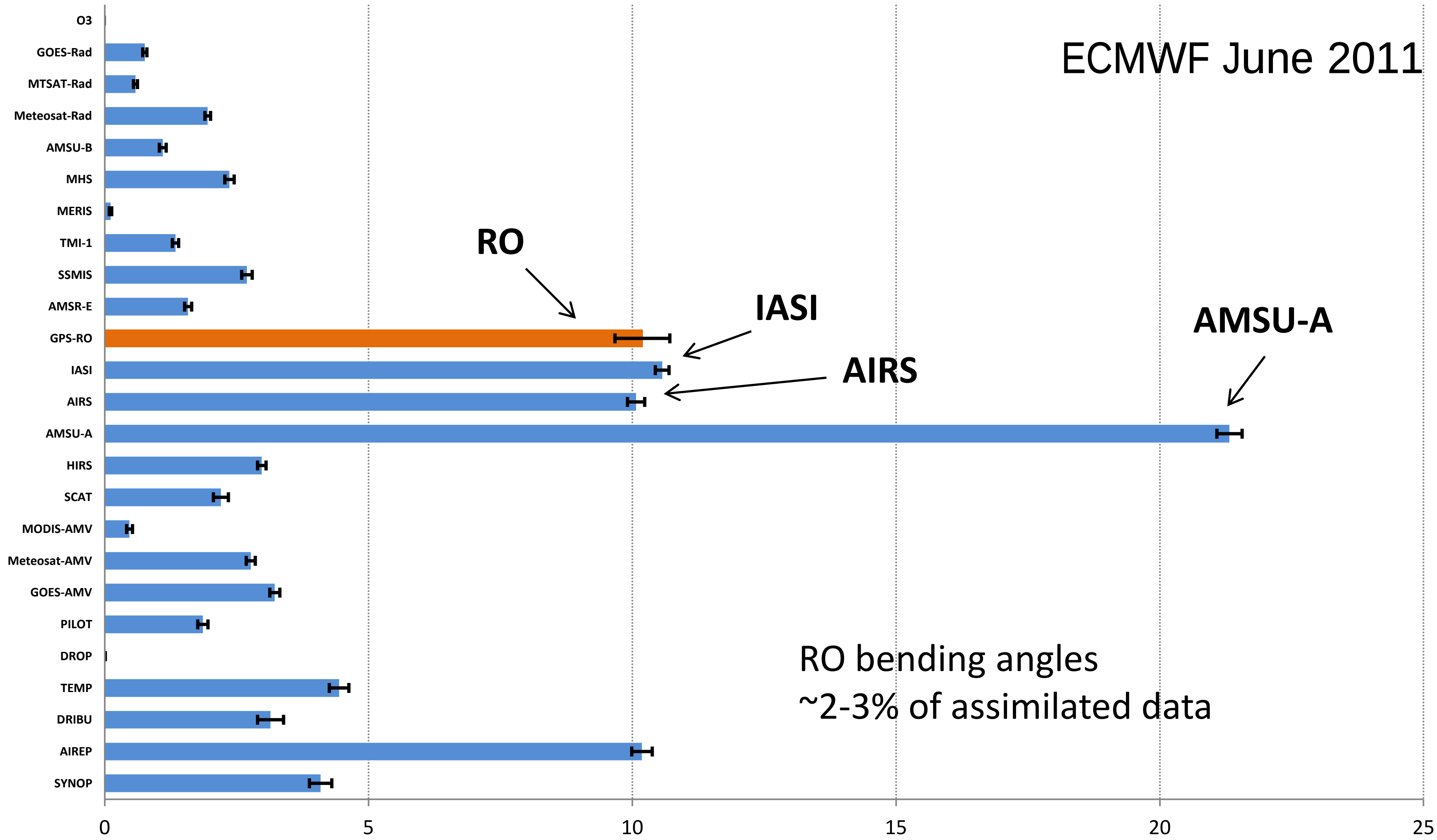
Reviewed Publications 1995-2013

• Radio Occultation	1154
• RO and COSMIC	267
• RO and Ionosphere or Space Wx	465
• RO and Weather or Forecasting	235
• RO and Climate	243

COSMIC has been referenced in 23% of all publications on RO since 1995.
RO is important in space weather, tropospheric weather and weather forecasting, and climate.

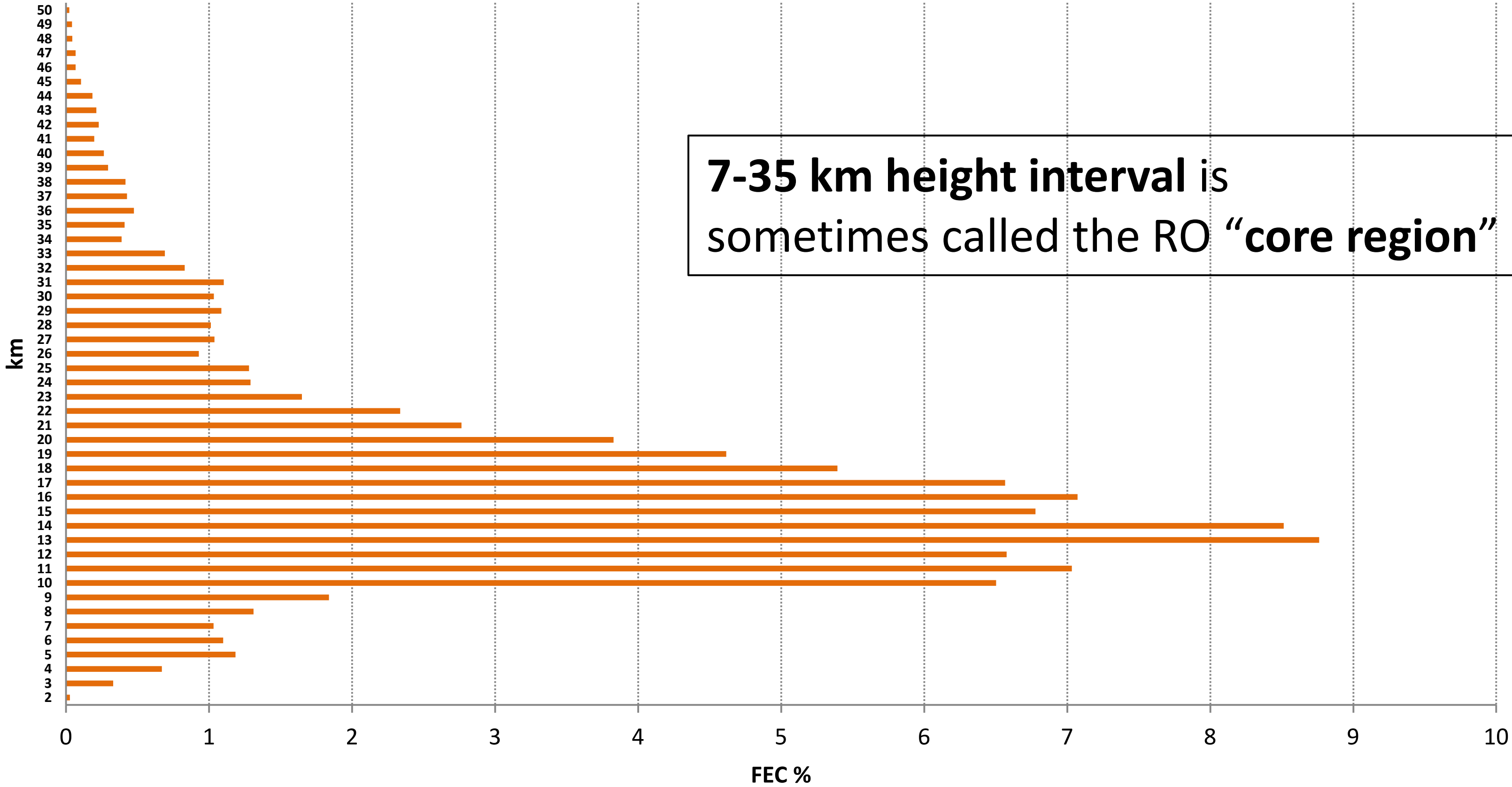
Source: Web of Science

Contributions to forecast accuracy by observing system



Four of the type five observational systems contributing the operational weather forecasting accuracy are sounding systems. RO is typically in the top five, even though the number of soundings is small compared to other sounding systems

Heights where RO contributes most to forecast accuracy in 2011



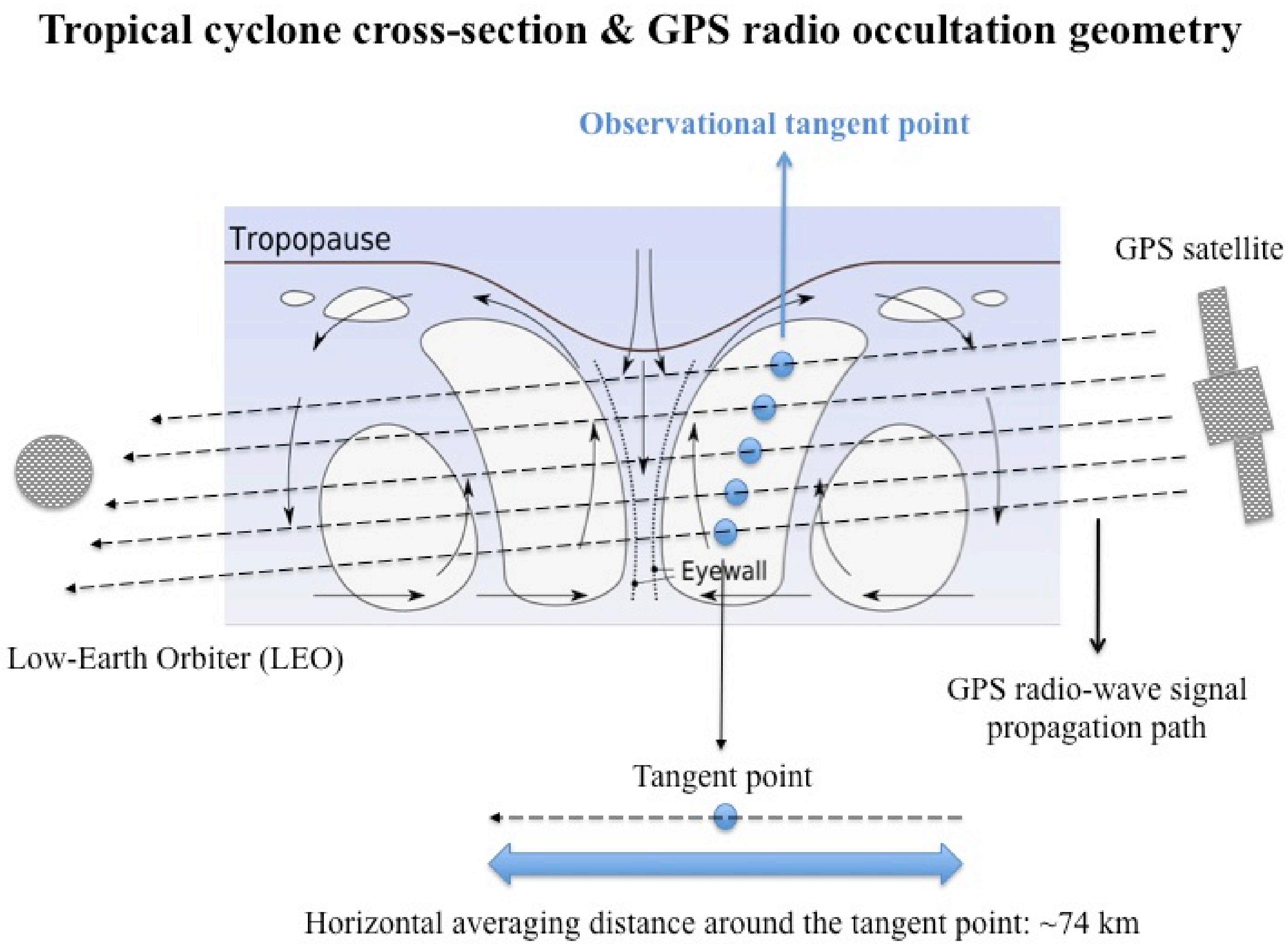
Remark: Agrees with early 1D-Var information content studies.

RO contributes most in the 7-35 km region. This is the region of the jet stream and tropopause, very important regions for weather forecasting and climate. With COSMIC-2 we expect the contribution to increase in the middle and lower troposphere.

RO and tropical cyclones

- Considerable uncertainties in analyses over the tropics
- RO observations are of high vertical resolution and high accuracy and minimally affected by clouds and precipitation
- Advantages for tropical cyclone observation and prediction:
  - Water vapor: Important for convective development, genesis, intensity, track and precipitation forecasts
  - Temperature: Important for large-scale circulations and track forecasts
  - Can estimate intensity of TC using RO
- COSMIC has demonstrated significant impact in TC forecasts; COSMIC-2 with 5X number of higher quality observations will be significantly better

Tropical cyclone structure from RO



Observational tests of hurricane intensity estimations using GPS radio occultations. Vergados, Luo, Emanuel, and Mannucci, 2014, *JGR* (accepted for publication)

Tropical cyclone cloud-top height and vertical temperature structure detection using RO

Typhoon Nakri 31 May 2008

White line Calipso track
Black line RO tangent points

We take CALIOP as "truth"
and compare with RO

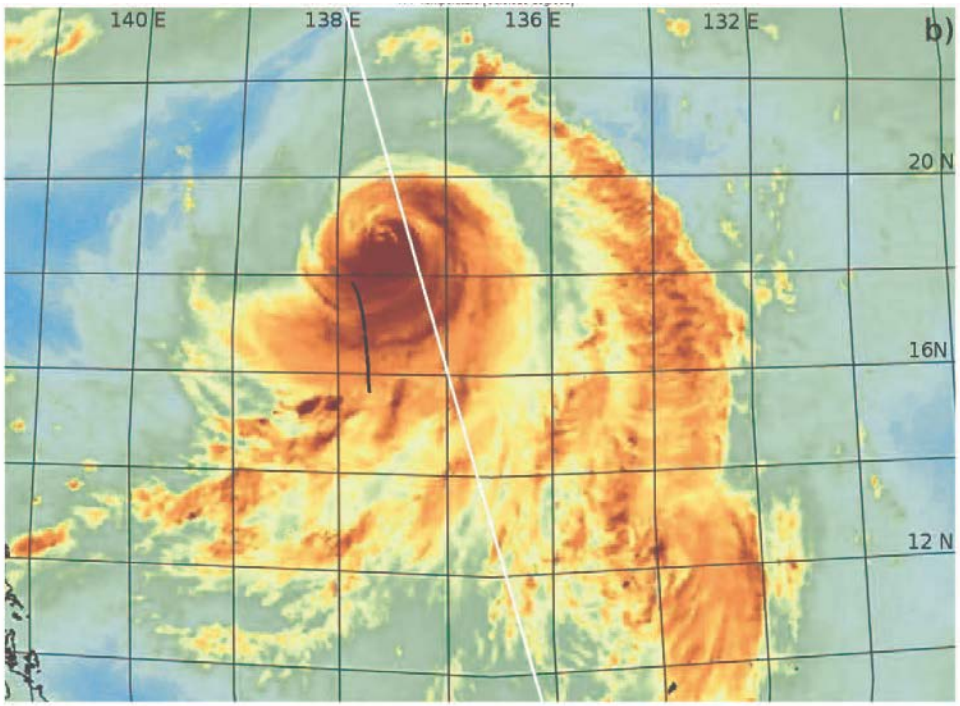
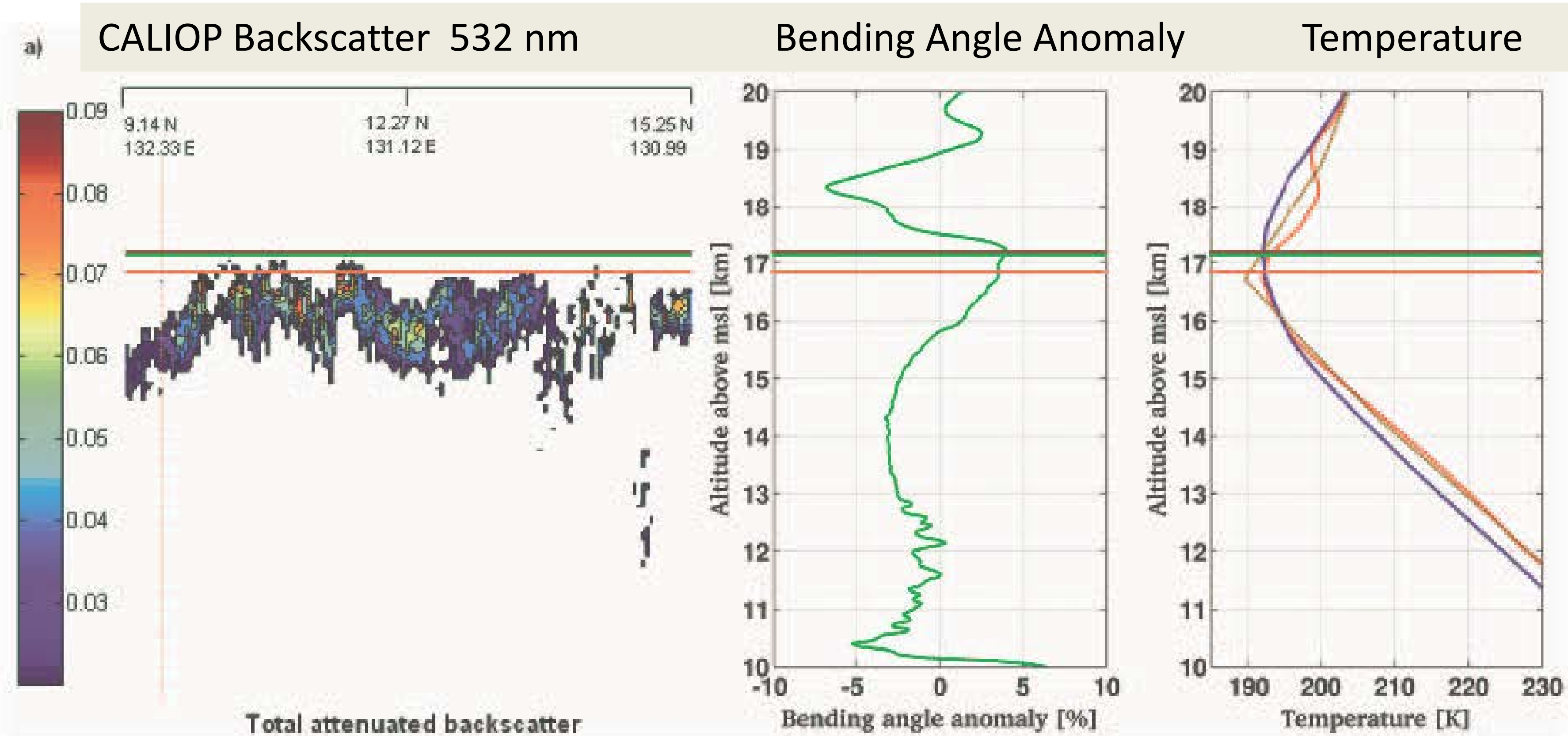


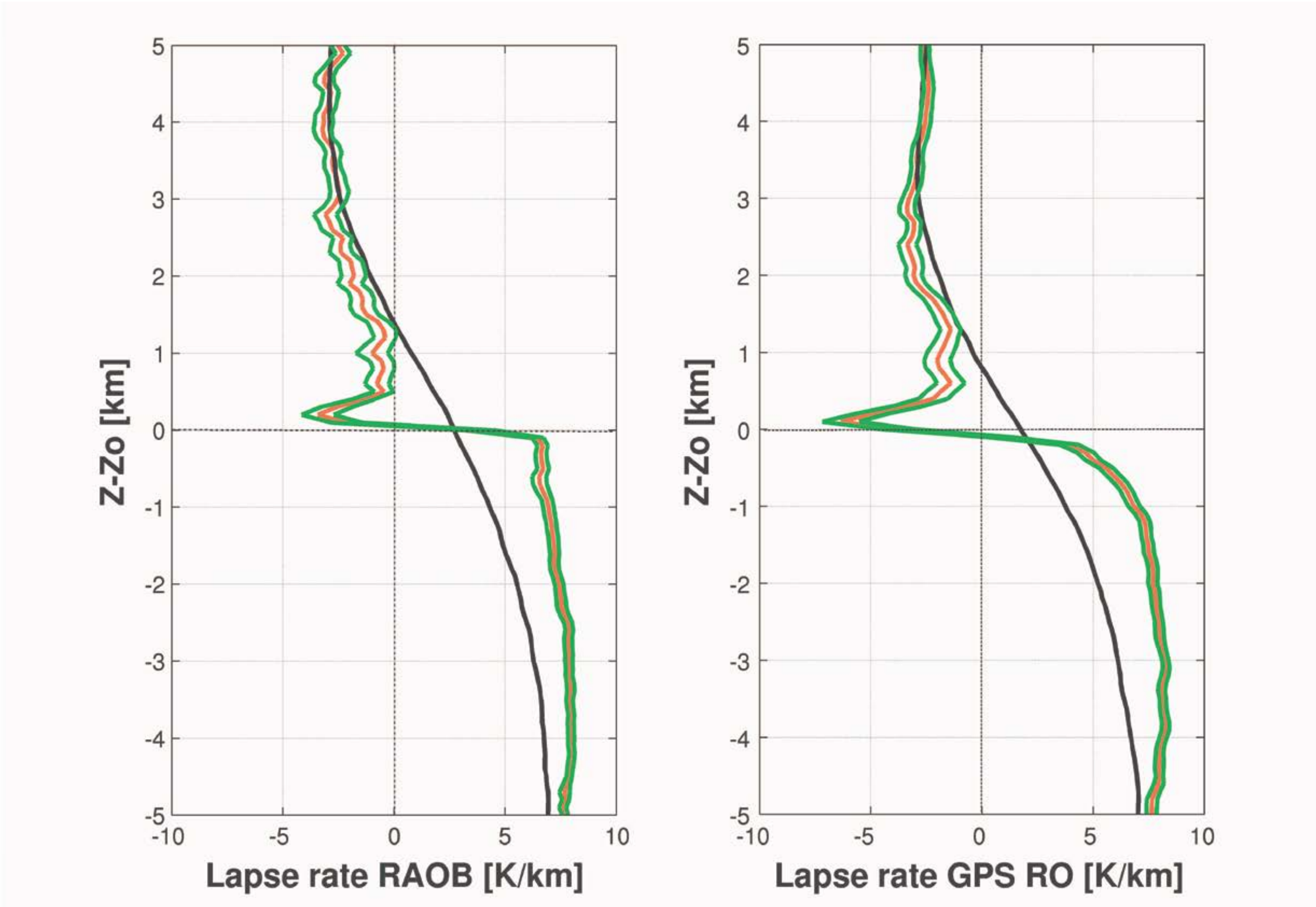
Figure 3. Structure of Krosa (top) on the 2nd of October 2007. Structure of Nakri (bottom) on the 31st of May 2008. Colors denote GMS brightness temperature (° Celsius) in the

Typhoon Krosa 2 October 2007

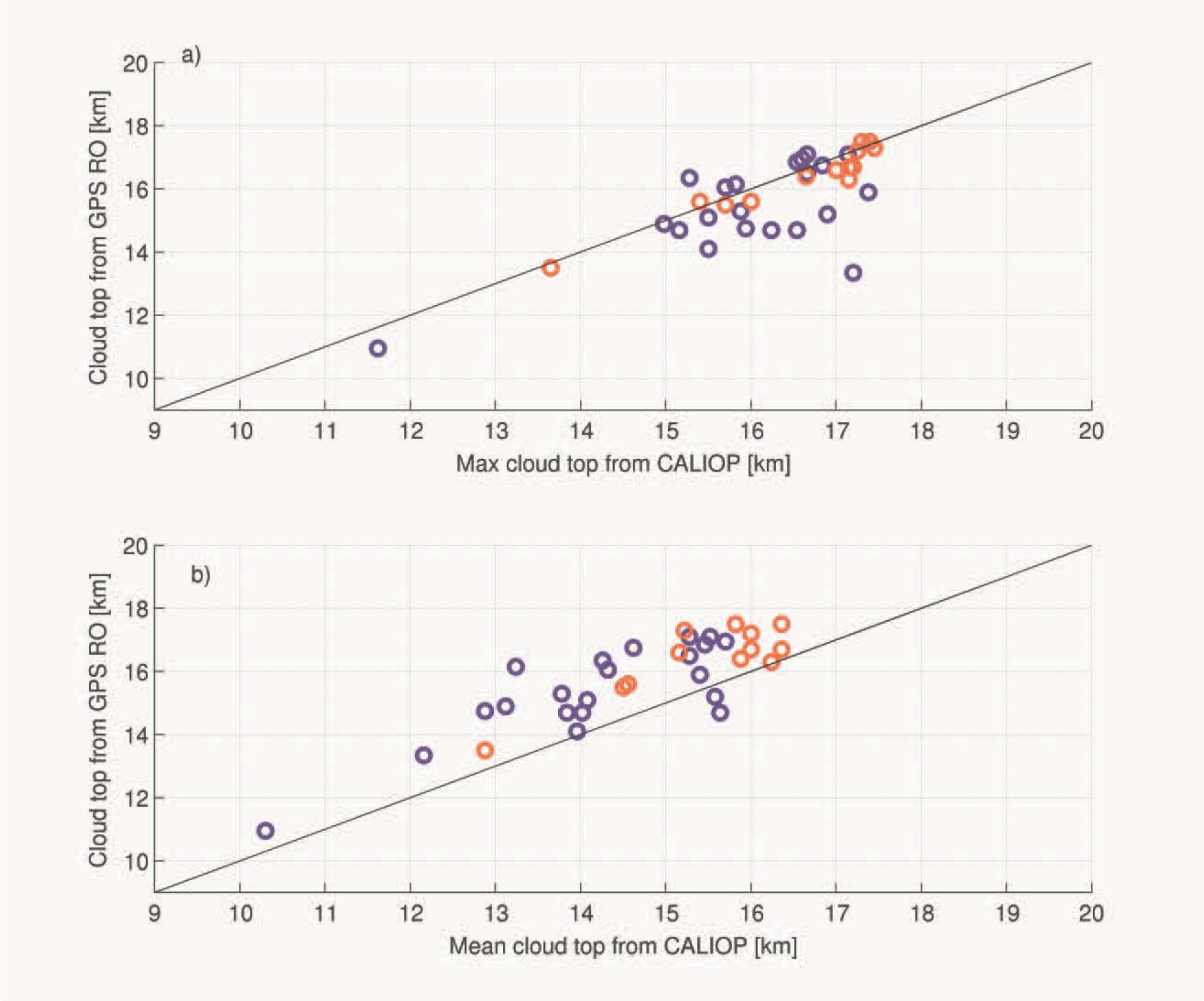


Temperature profiles: Red is RO, brown ECMWF, blue climatology. Horizontal red line is coldest point of RO profile. Green line is altitude of maximum bending angle anomaly.

Lapse rates with respect to cloud top from radiosonde and COSMIC RO in Typhoon Krosa (2007)



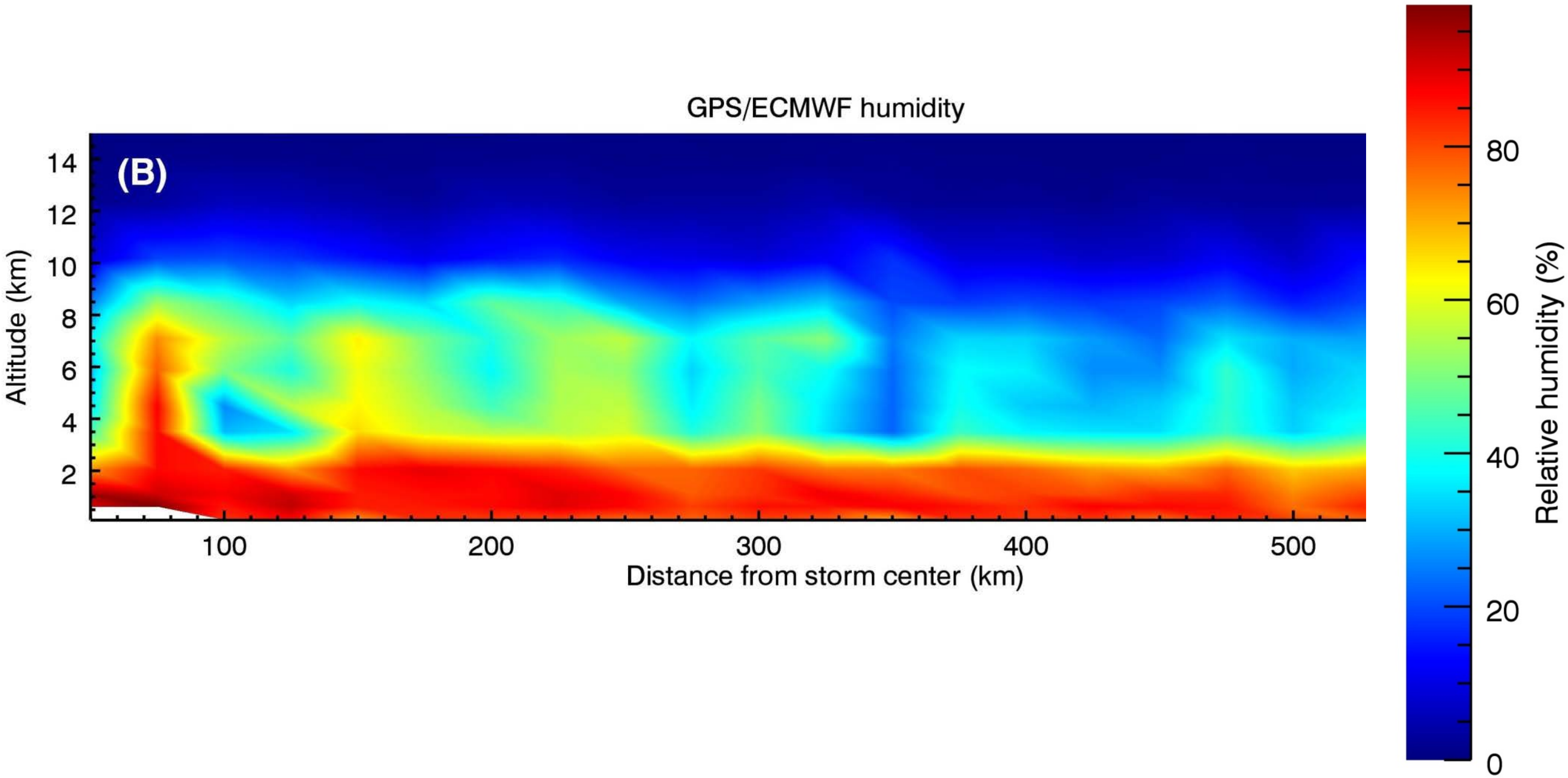
Cloud top from RO vs. CALIOP in Typhoon Krosa (2007)



RO can accurately determine cloud top height in Tropical Cyclones

Tropical cyclone humidity from RO

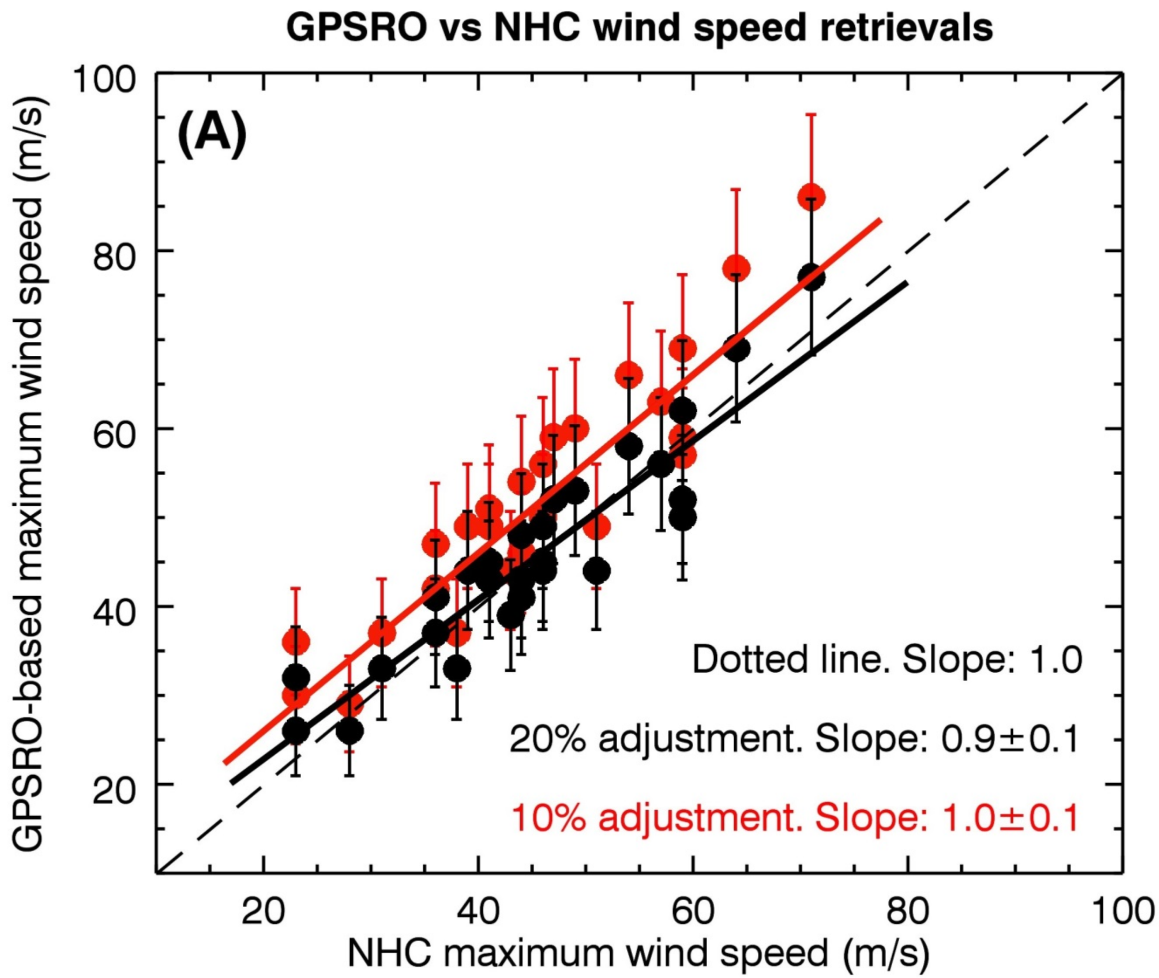
Vertical cross section of composite TC relative humidity from RO observations of refractivity using ECMWF temperature to derive RH.



"We conclude that GPSRO data can contribute significantly to the understanding and modeling of the vertical structures of TCs." (Vergados, Mannucci and Su, JGR 2013)

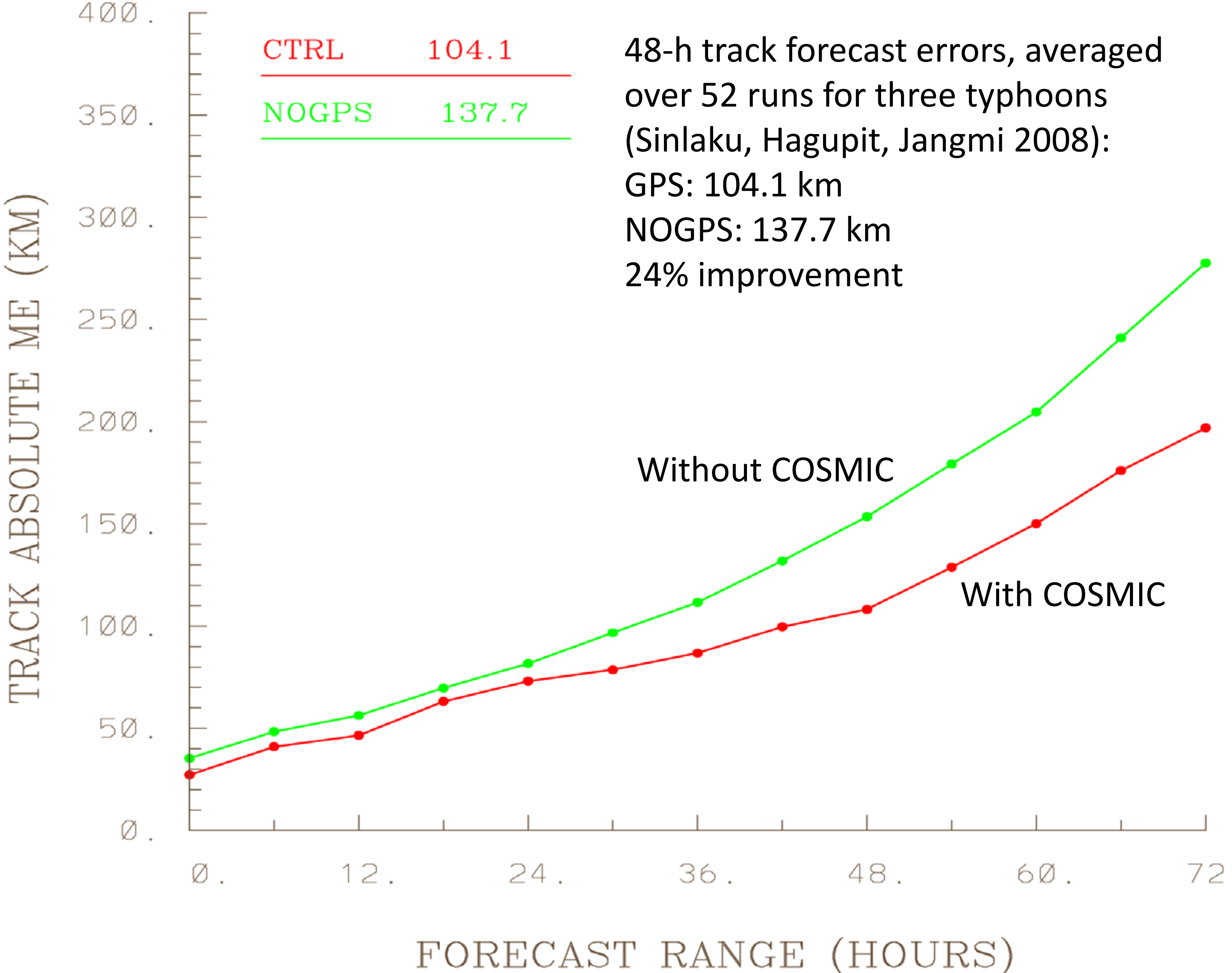
Tropical cyclone intensity from RO

Outflow temperatures in the eyewall region of 27 hurricanes in 2004–2011 were obtained from RO. With ocean surface temperatures from NASA Modern Era-Retrospective Analysis for Research and Applications (MERRA), it was possible to estimate hurricane intensities using a simplified hurricane model.



Observational tests of hurricane intensity estimations using GPS radio occultations. Vergados, Luo, Emanuel, and Mannucci, 2014, *JGR* (accepted for publication)

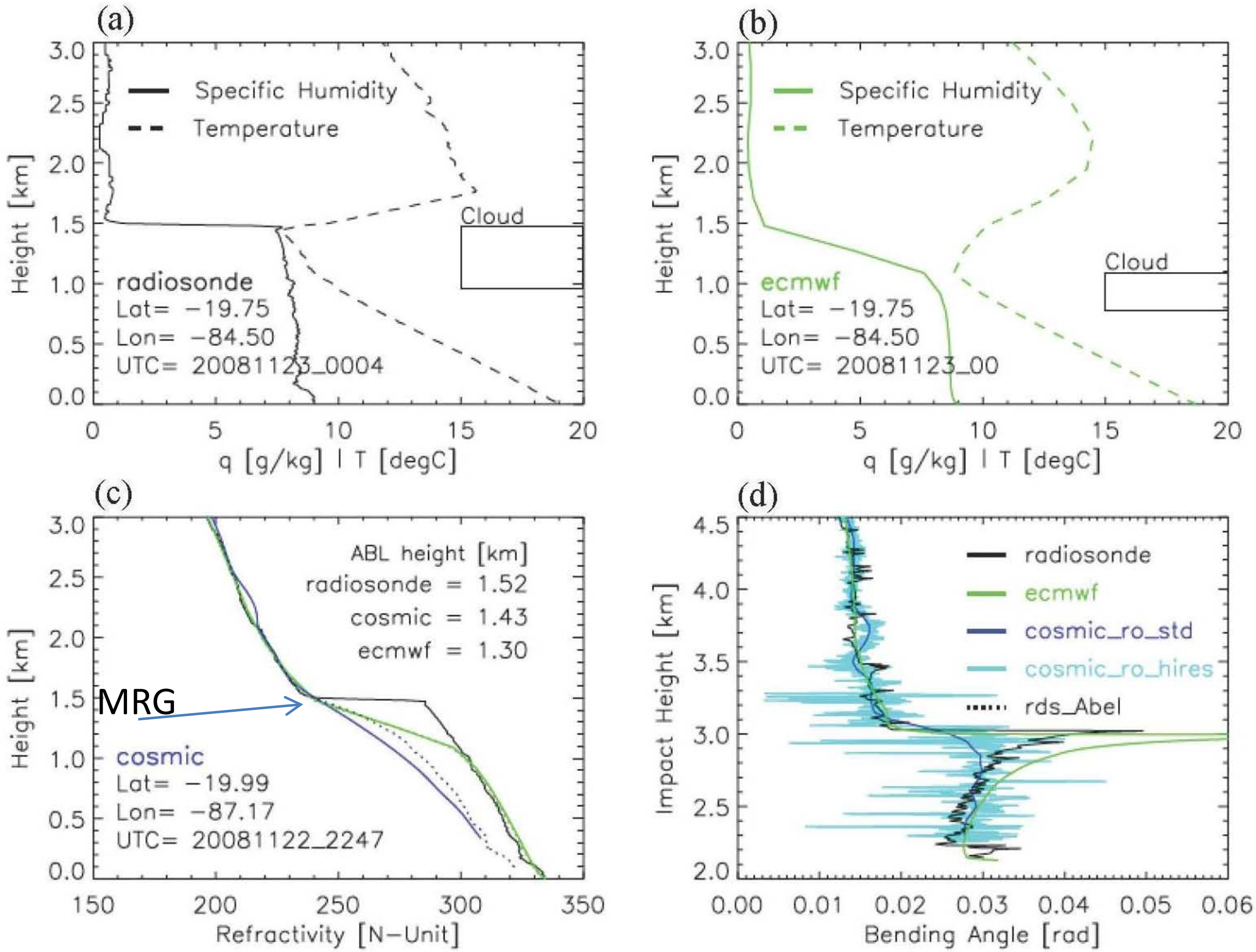
Forecast track errors for 52 TC forecasts in 2008



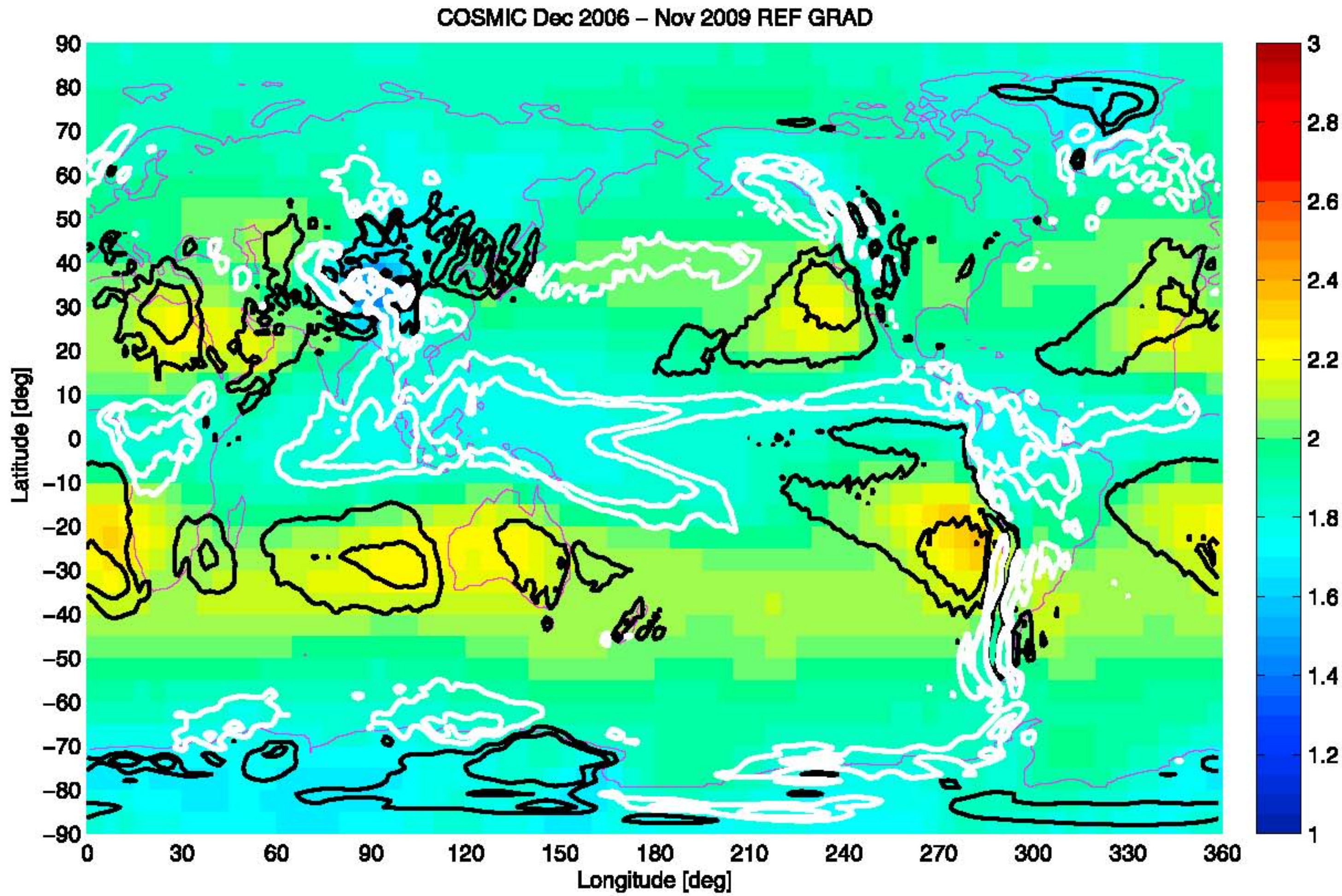
Planetary Boundary Layer Studies using RO

PBL profiles over VOCALS region off Coast of South America

PBL H defined in RO profile as height of minimum refractivity gradient (MRG)

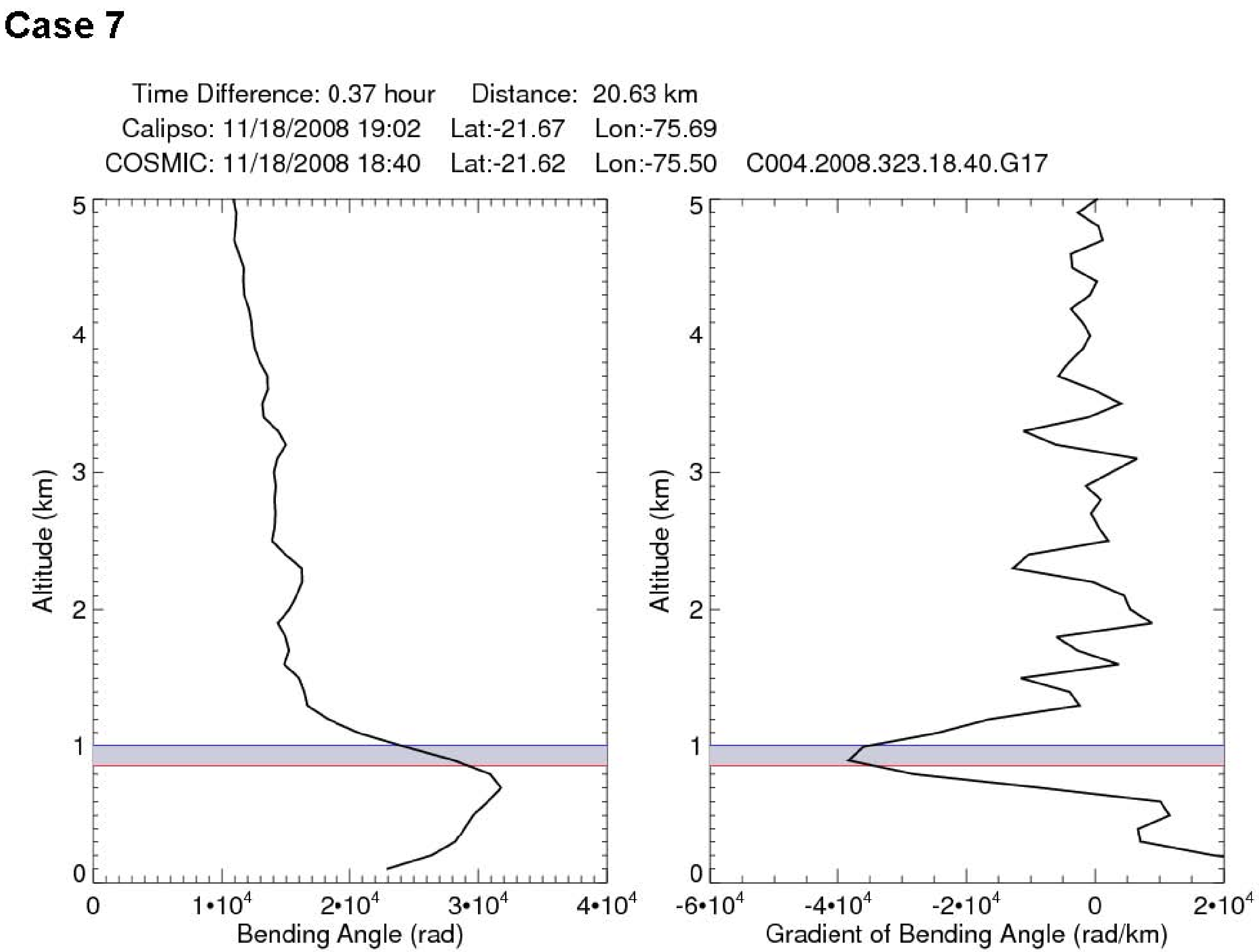


ABL climatology from COSMIC refractivity profiles



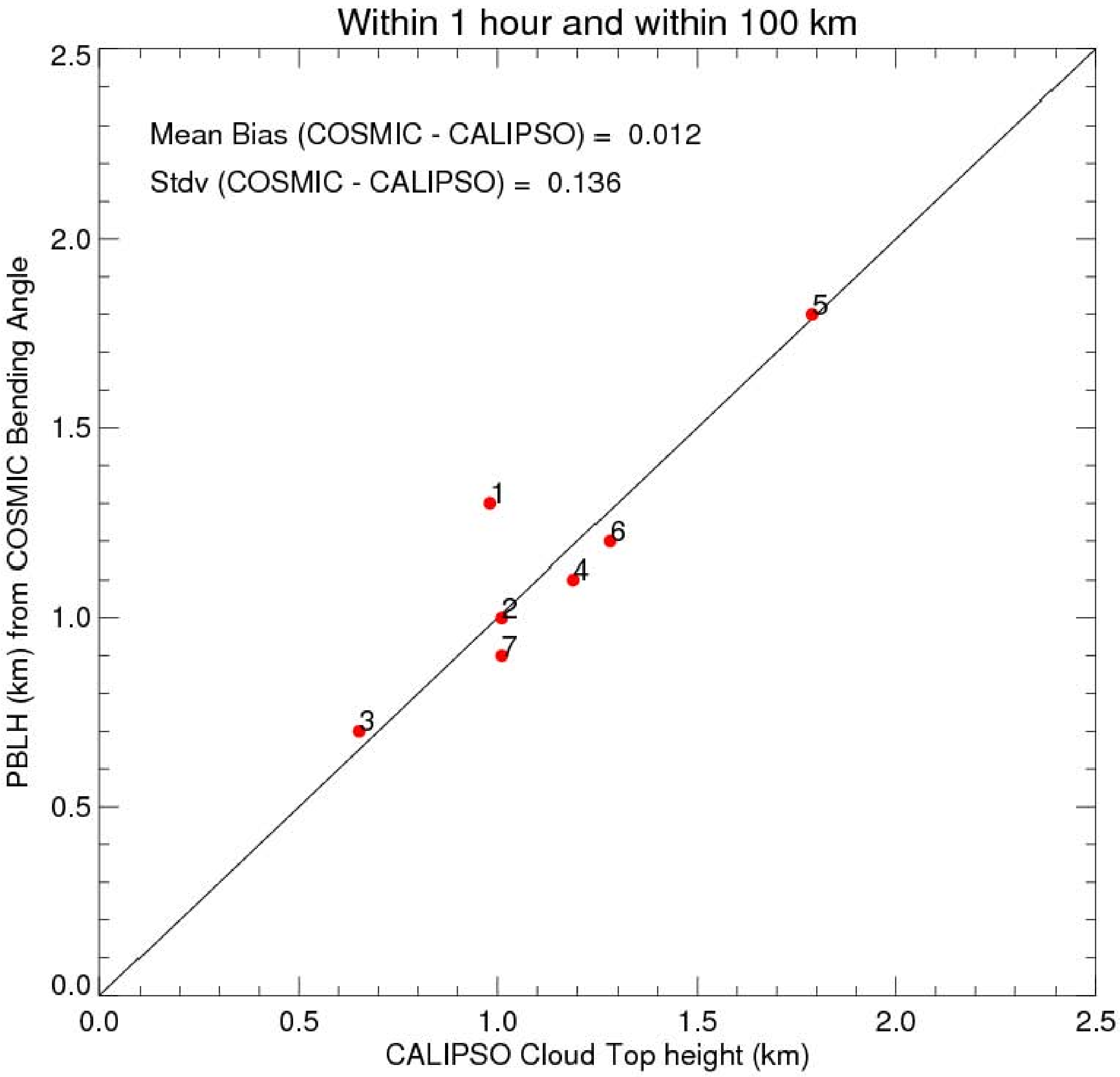
Perhaps surprisingly, RO is an effective way to observe the ABL globally. The ABL is an important aspect of the weather and climate system.

Comparison of CALIPSO-CALIOP Cloud Top Heights and COSMIC ABL Heights Over VOCALS region



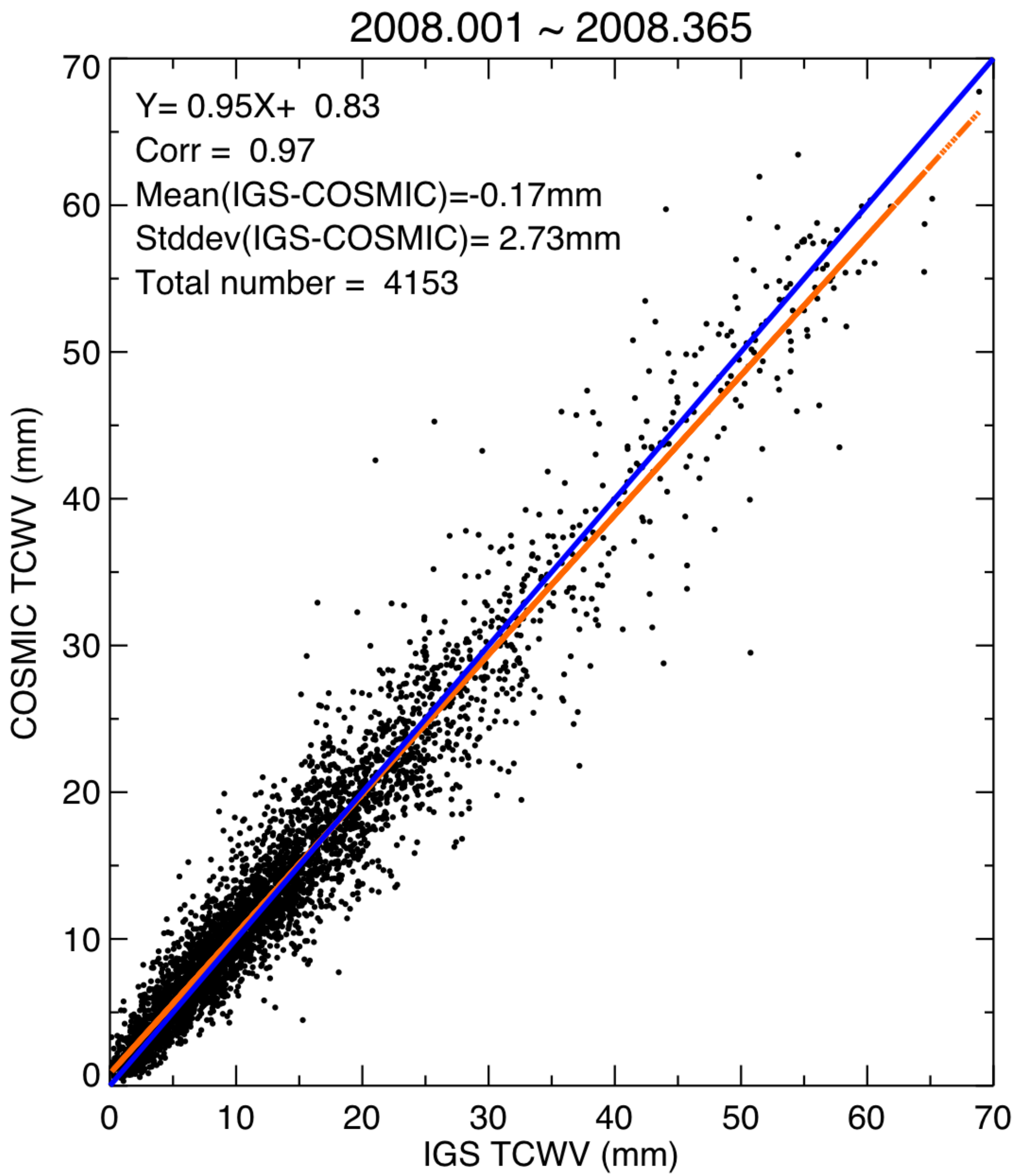
The gradient of the bending angle profile is a good indicator of ABL cloud height.

RO ABL Heights vs. CALIOP Cloud top height over VOCALS region



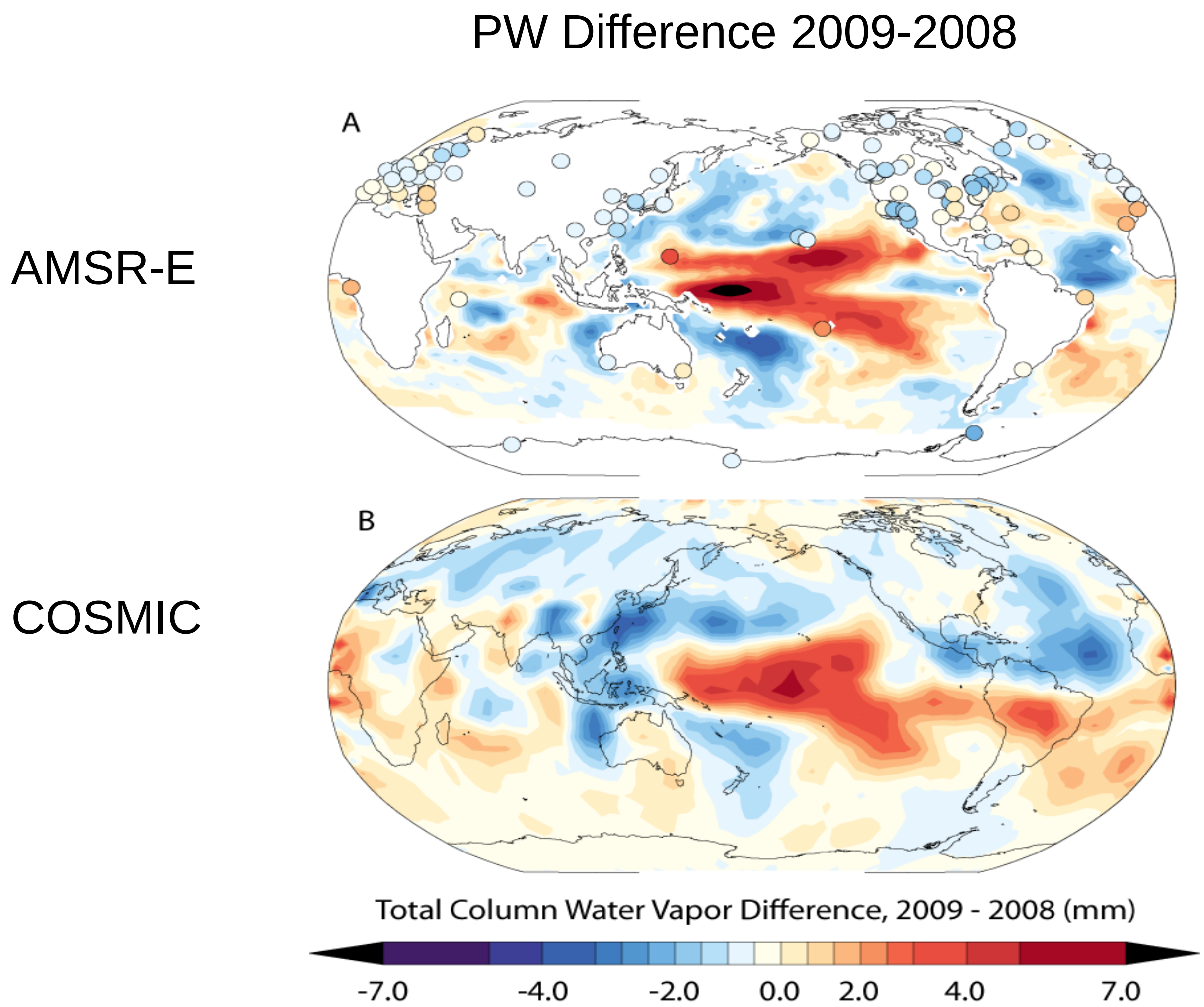
RO is an excellent global observing system for ABL heights.

COSMIC RO PW agrees very well with ground-based GPS PW

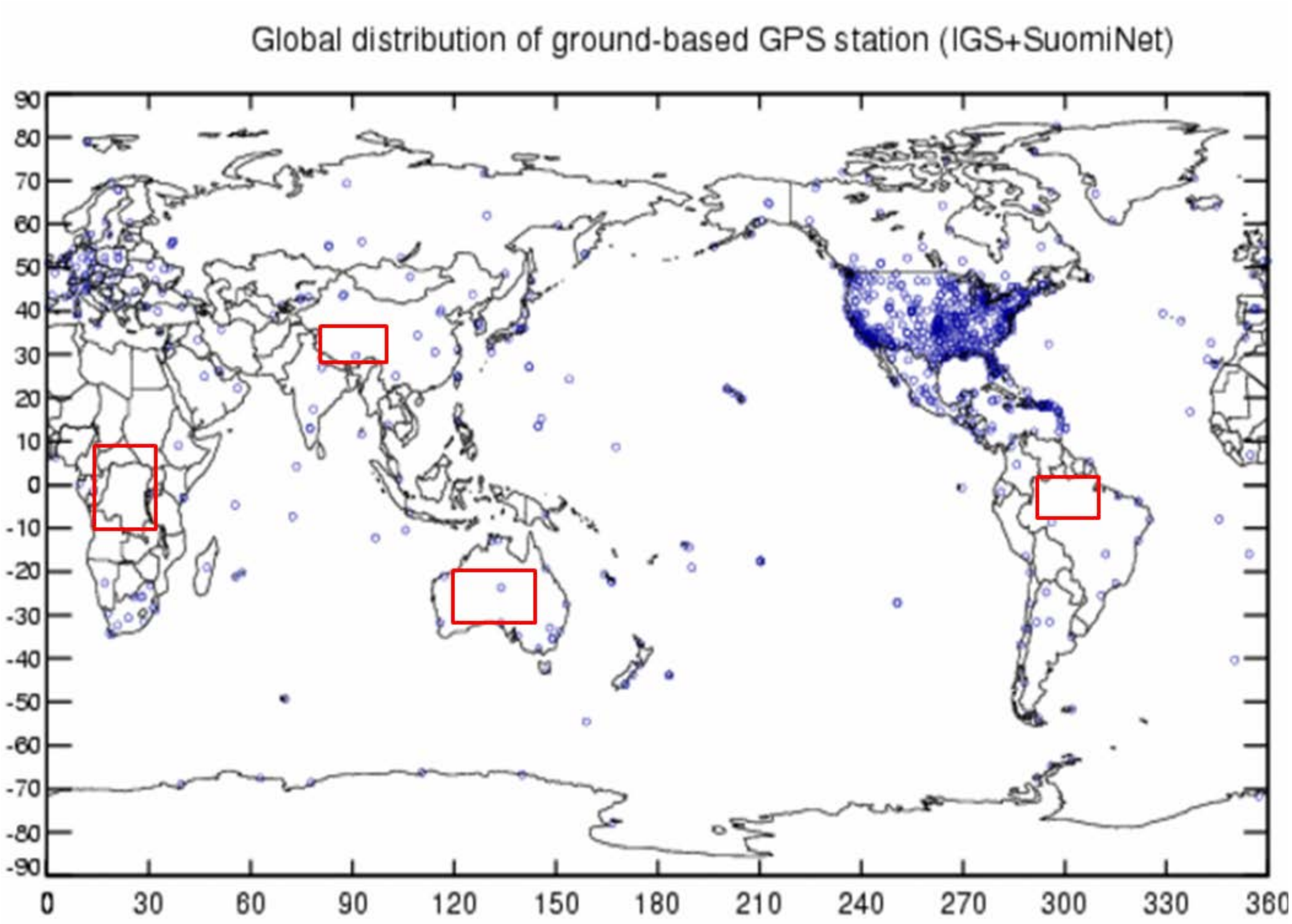


Precipitable Water (PW) from RO

Using Precipitable Water to detect ENSO signals

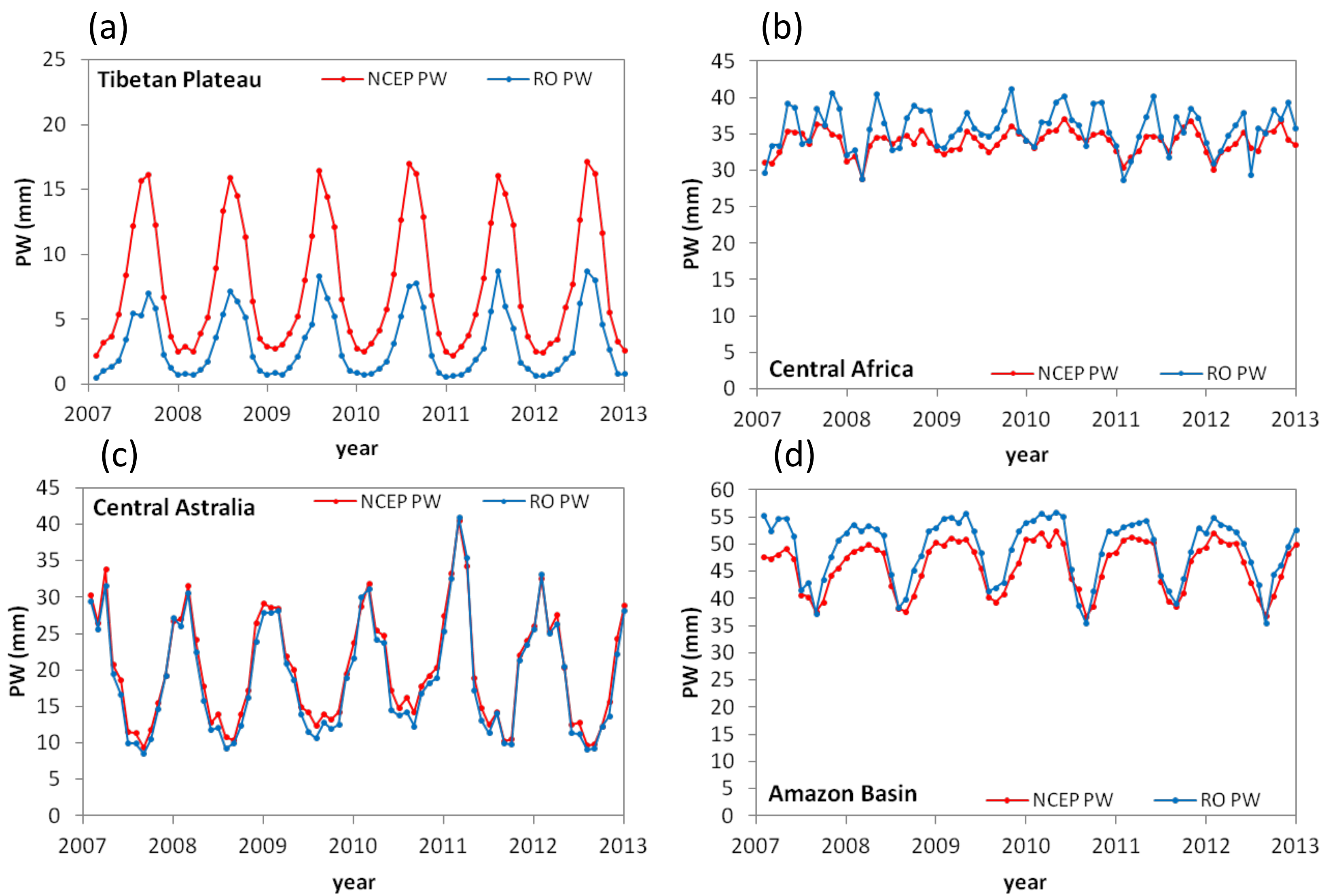


Global Comparisons of COSMIC and NCEP PW



Distribution of IGS stations (including Suominet in USA). The red boxes indicate the four local regions for PW analysis, Amazon basin, Africa, Tibetan plateau, and Australia.

NCEP and COSMIC PW in Specific Regions 2007-11



NCEP PW agrees well with COSMIC in Central Australia, but shows differences in other regions due to model terrain (Tibet) and other model issues.

RO, IR, and Microwave are complementary

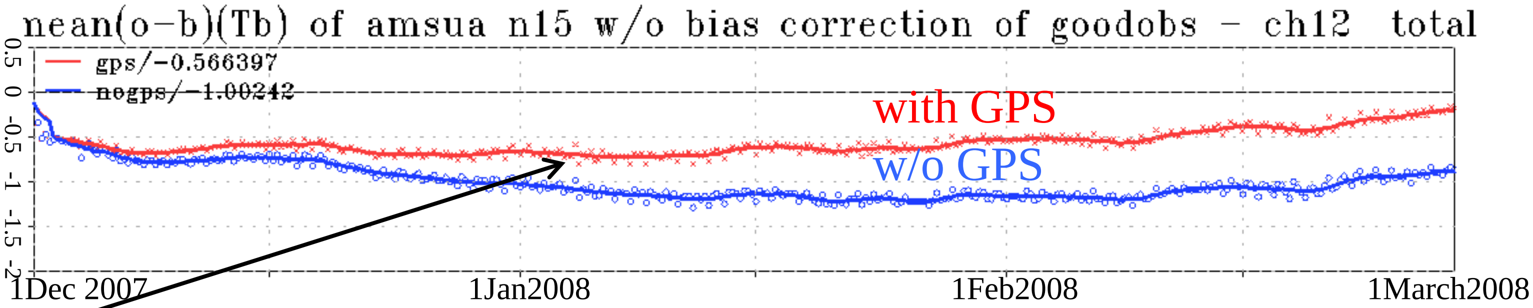
- Three systems provide independent information
- RO “anchors” NWP and reduces bias corrections needed for IR and microwave observations in NWP models
- RO can be used to calibrate and validate IR and microwave retrievals
- RO is a valuable complement to NPP and JPSS

Impact of RO on satellite radiance assimilation

- Satellite radiance observations contain systematic errors (biases), and so require the use of bias corrections
- These biases corrections do not account for model biases. Model analyses and forecasts thus require some data to be assimilated without bias corrections to ‘anchor’ the model, avoiding a drift of the bias corrections in the radiance observations
- RO is an <u>anchor measurement</u>: unbiased or bias is small enough so they do not need bias corrections
- Thus RO has both direct and indirect benefits-assimilation of useful information AND improving effect of bias corrections in other observations.

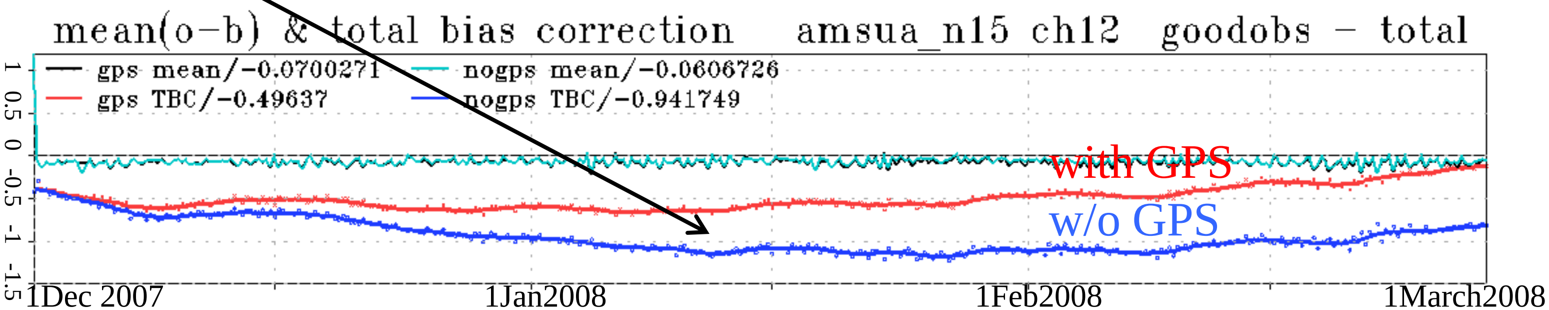
Bias Corrections in NCEP model AMSU-A NOAA-15, Channel 12 (~10 mb)

Temporal evolution of (o-b) without bias correction



Difference of ~ 0.5 K

Temporal evolution of the total bias correction



Assimilation of RO observations reduces the AMSU-A bias corrections

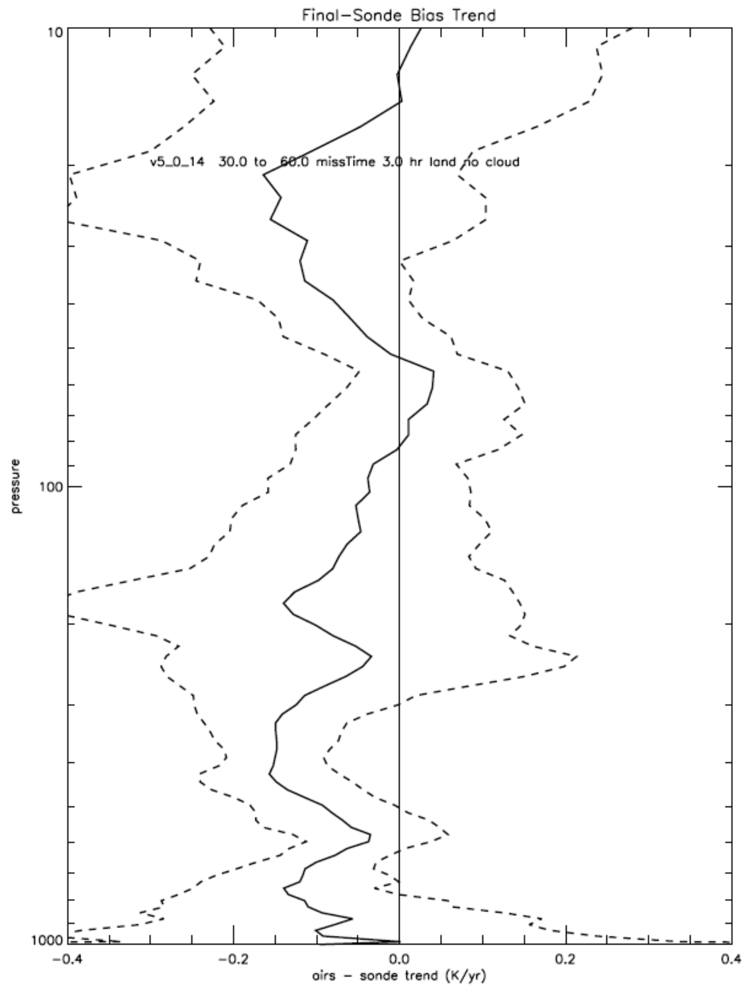
Calibration and reduction of biases in AIRS and AMSU

AIRS and AMSU exhibit biases in temperatures, limiting their value in observing long-term climate change. These biases have diverse and complex dependencies on the temperature being measured, the season and geographical location, surface conditions, and sensor temperature. RO can help by:

1. Monitoring the long term stability of retrievals/measurements

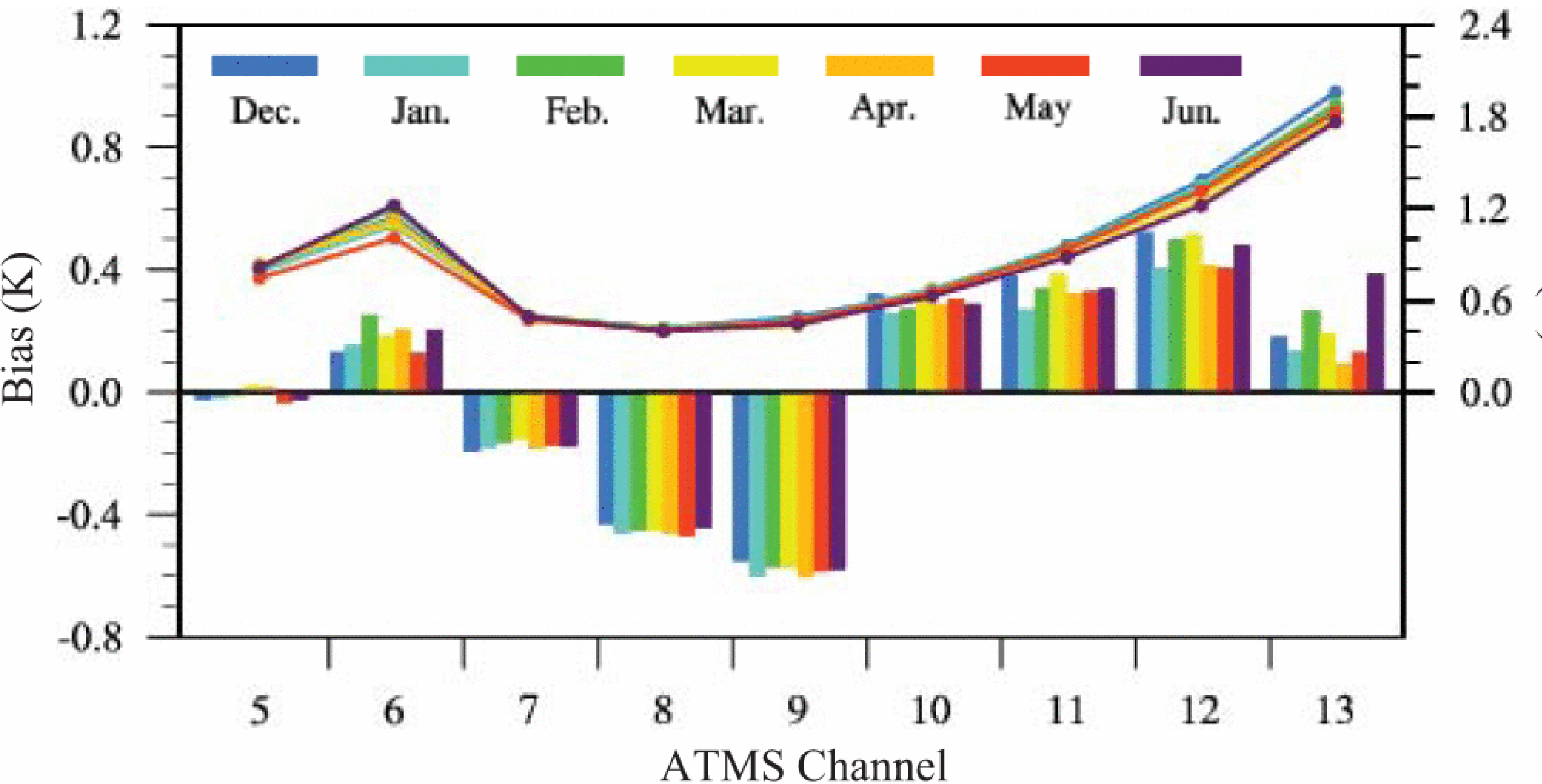
2. Improving Temperature and Moisture Retrievals in Troposphere and Lower Stratosphere.

AIRS-radiosonde trend 30-60 N over land no Cloud



Vertical average is -0.1 K/yr, Comparable to expected climate trend

Calibration of Advanced Technology Microwave Sounder (ATMS) on Suomi NPP using COSMIC RO Measurements

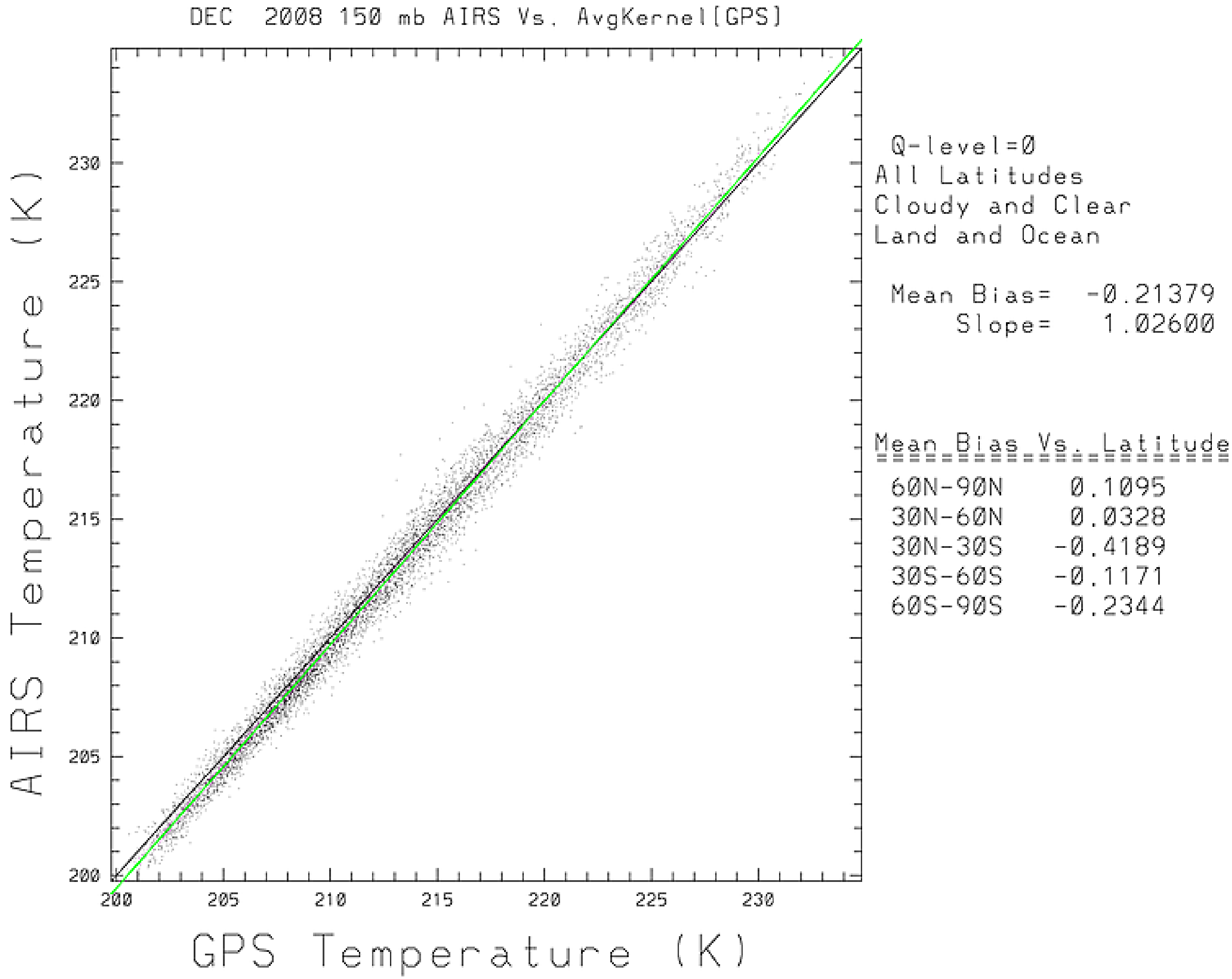


"With the high quality of GPS RO observations..., ATMS upper-level temperature sounding channels are calibrated with known absolute accuracy." Zou, Lin and Weng, 2014, IEEE.

AIRS vs. COSMIC Temperature (K)

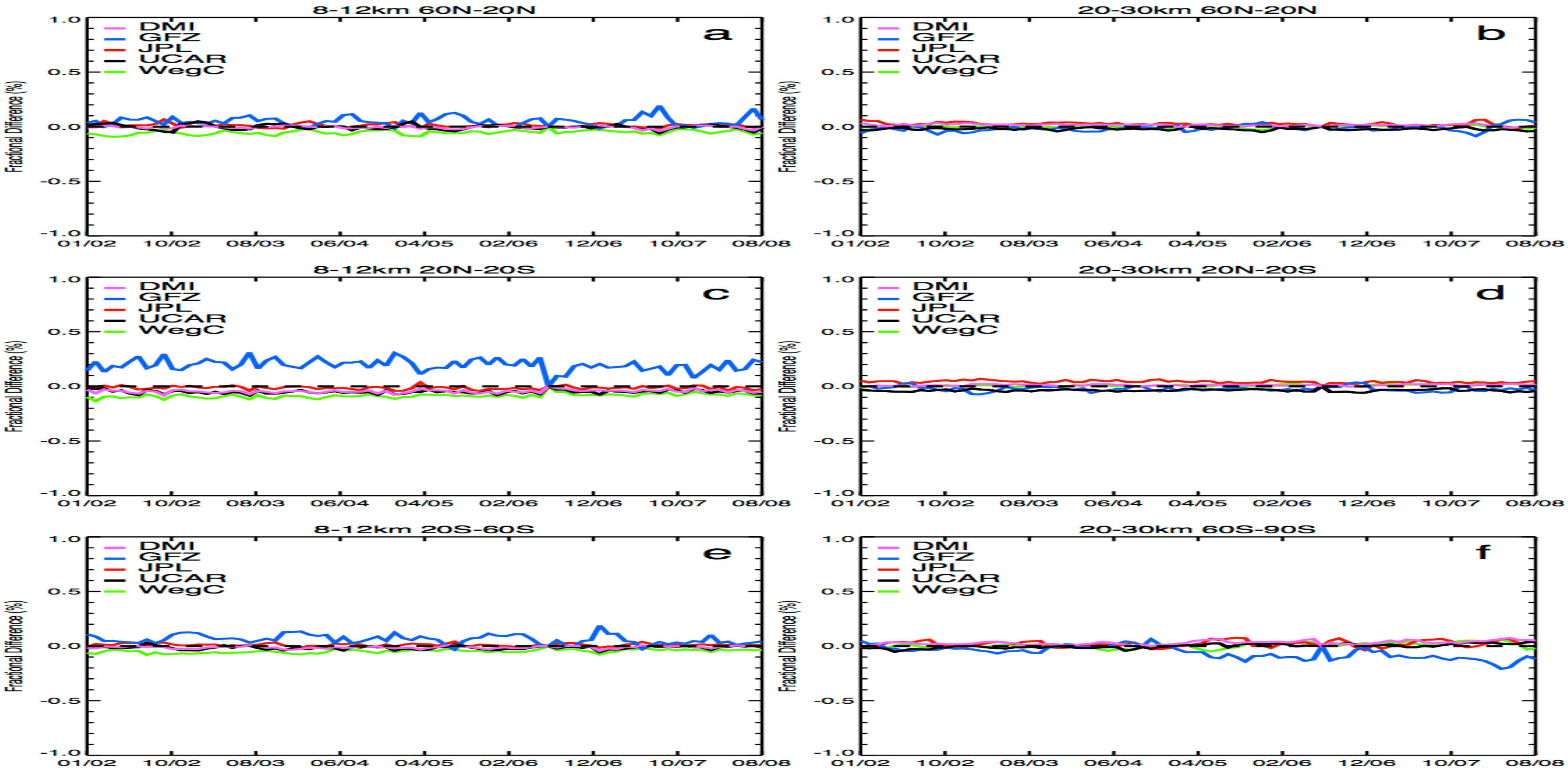
Corr ~ 1.0

We can use the defined slope and offset to calibrate AIRS temperatures



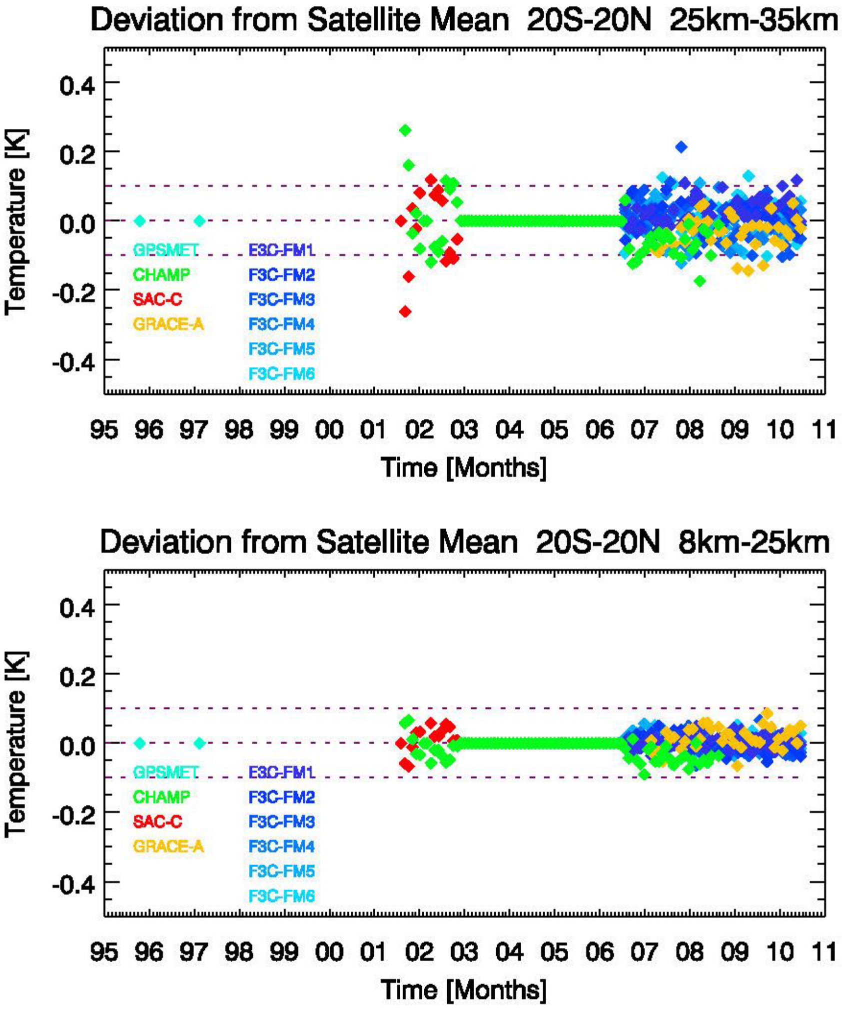
Agreement here is very good, validating AIRS retrieval algorithms and calibration

Agreement of RO retrievals data from different centers (DMI, GFZ, JPL, UCAR and WegC) supports RO as a benchmark climate observation



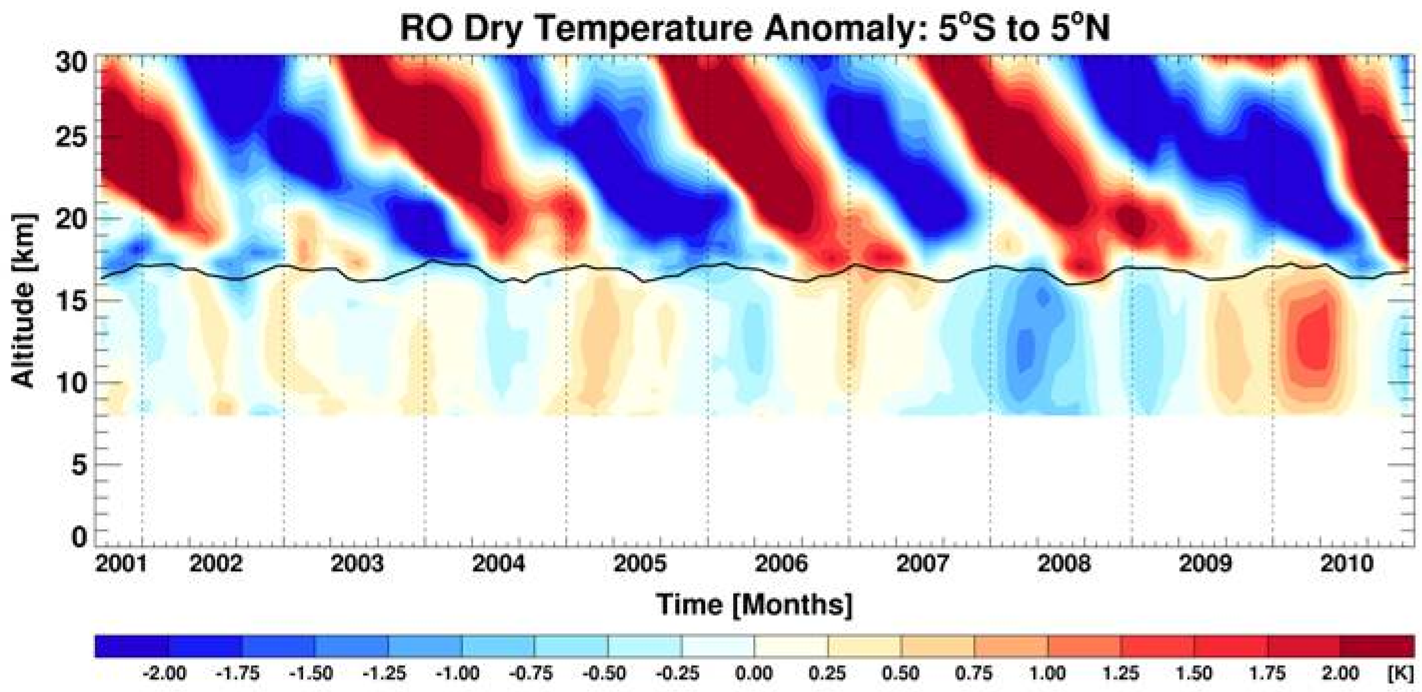
Time series of fractional refractivity anomalies among five centers for the 8-12 km layer for different latitude bands. Agreement generally within 0.1%.

Agreement within 0.1K between different instruments and satellites support RO as a climate benchmark observation (GPS/MET, CHAMP, SAC-C, GRACE-A and six COSMIC)



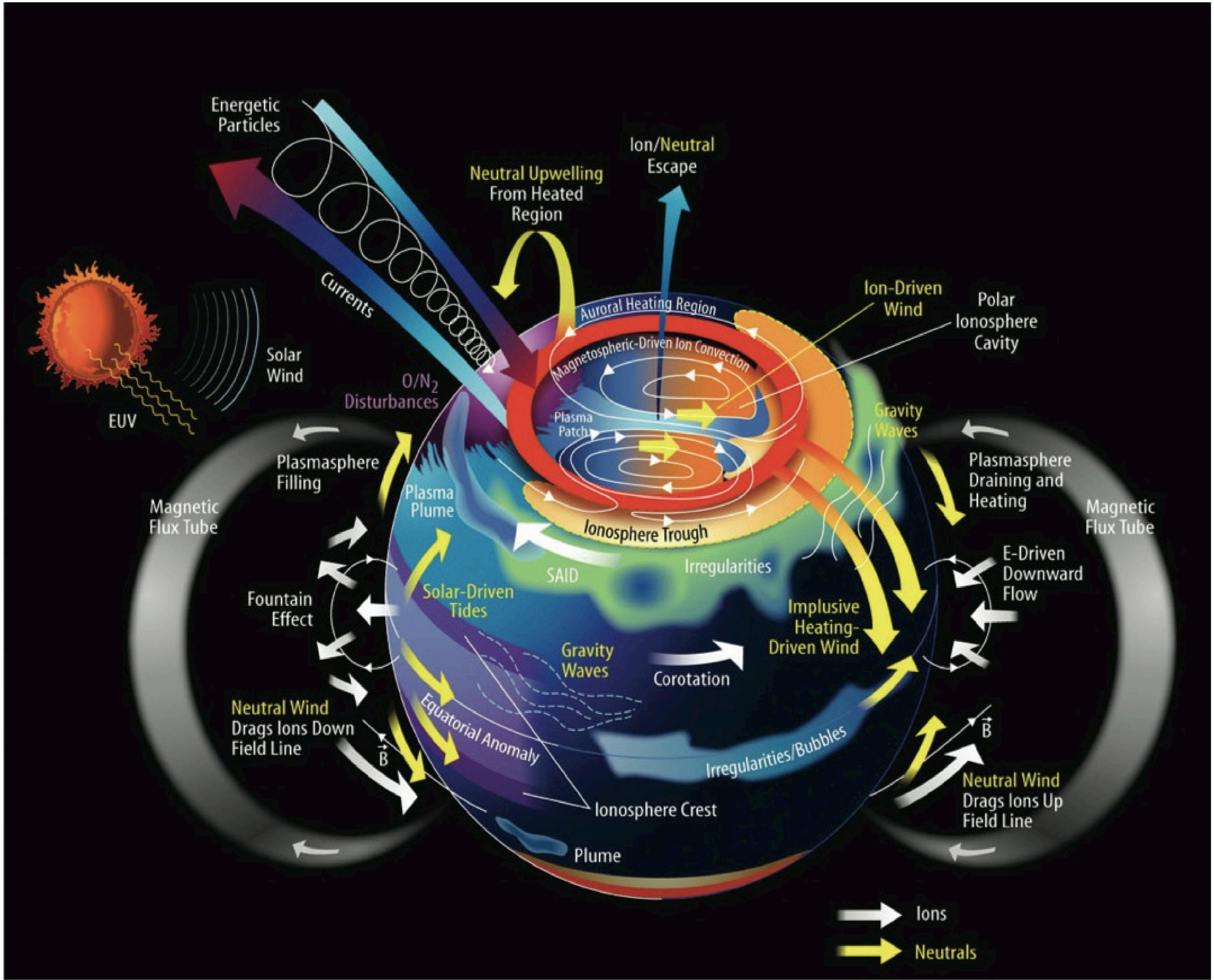
ENSO and QBO – Climate Variability in RO Data

- **El Niño Southern Oscillation (ENSO)**
- Phenomenon with quasi-periodicity of 3 to 7 years **in troposphere**
- changes in sea surface temperature of tropical Pacific
- ocean-atmosphere coupling
- **ENSO, QBO – natural variability modes in trend detection**



[Scherllin-Pirscher et al. 2012]

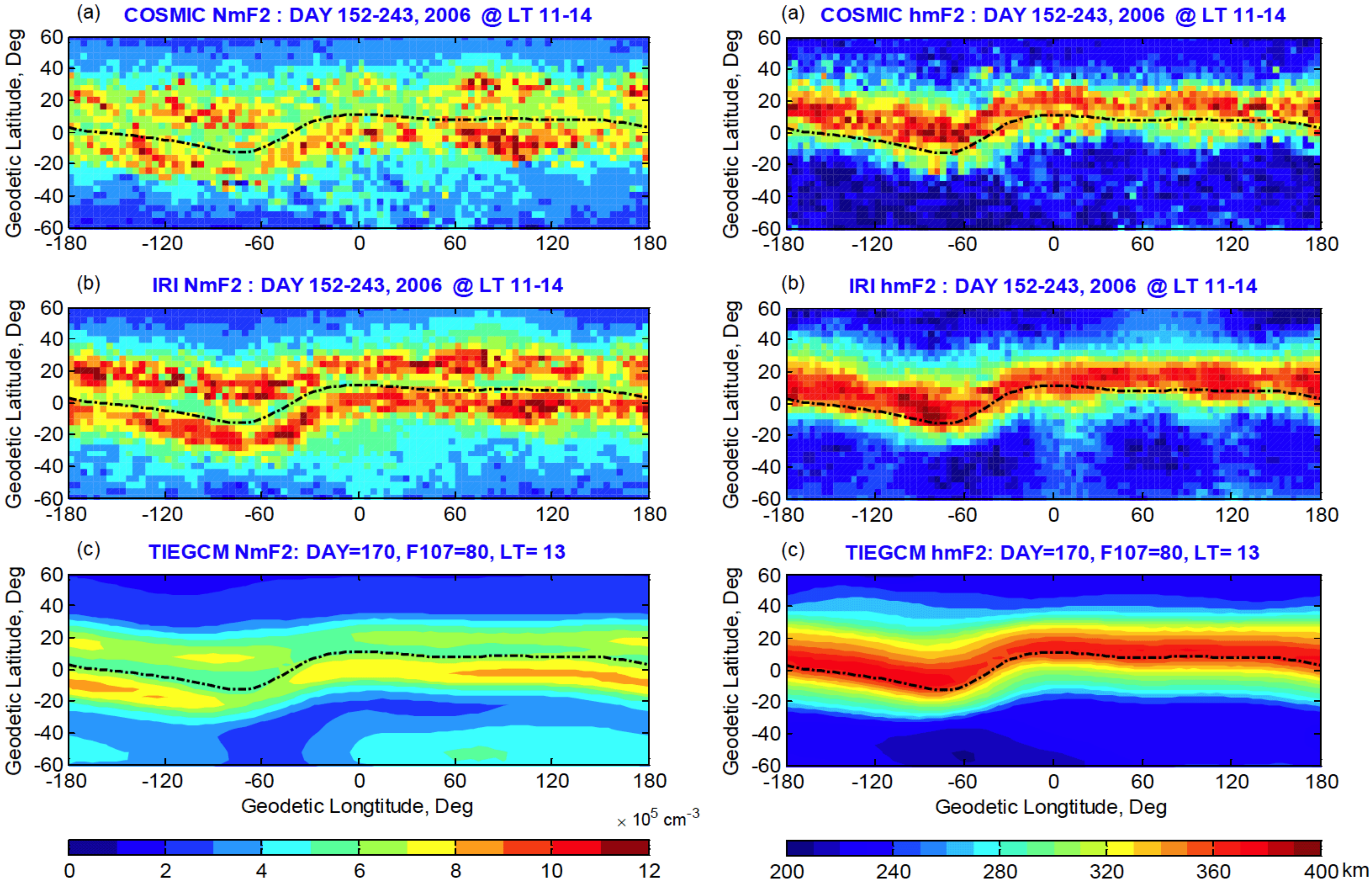
Ionospheric (Space) Weather



COSMIC Space Weather Data Products

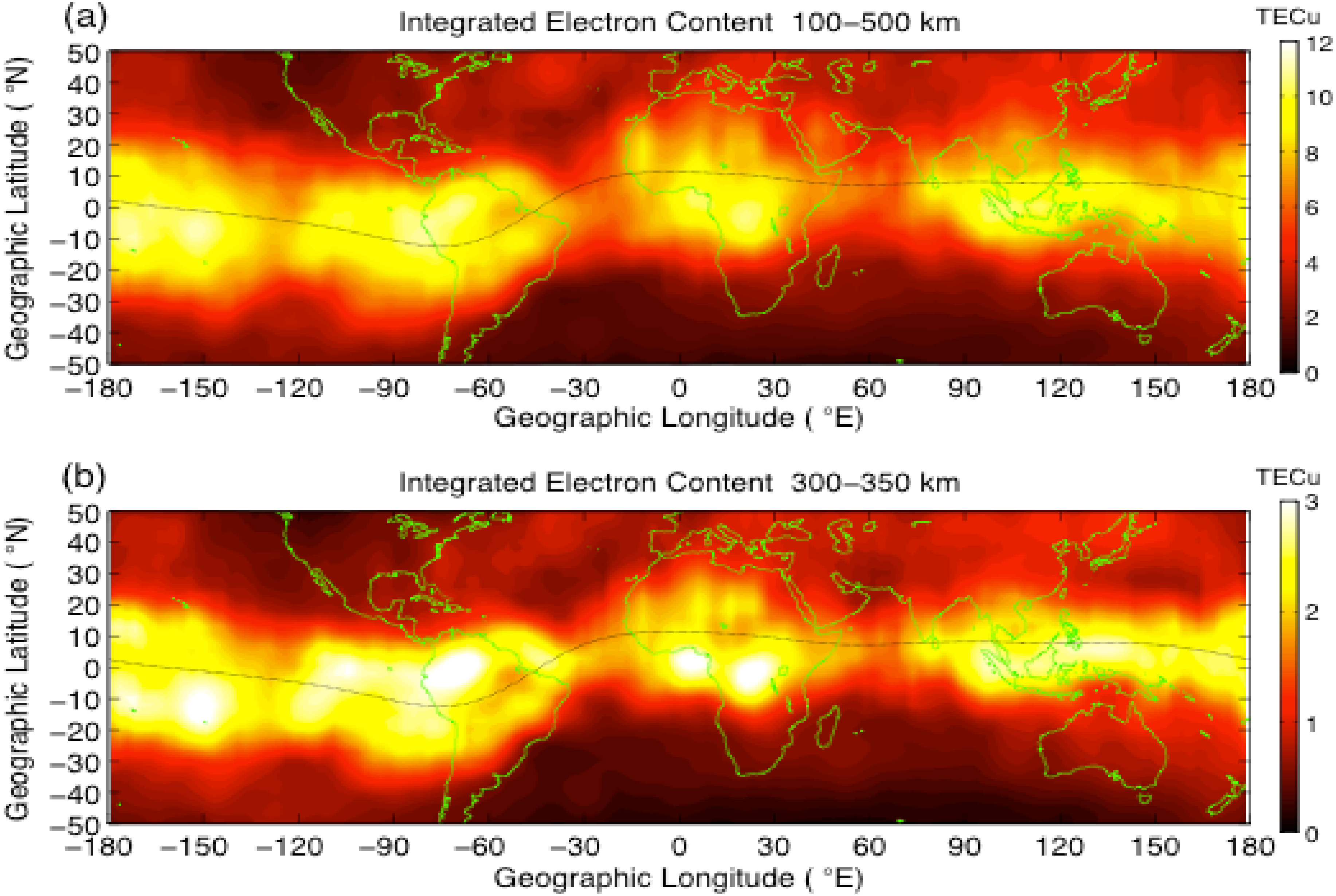
- ~3.8M Absolute TEC data arcs:
  - Absolute accuracy demonstrated at < 1-3 TECU
  - Relative accuracy < 0.3 TECU
- ~3.8M Electron Density Profiles:
  - NmF2 (F2 layer peak) Accuracy ~20% (compared to Ionosondes)
  - hmF2 (F2 layer height) Accuracy ~20 km
- Scintillation Indices (S4):
  - ~4M available from occultation profile events (altitudes < 120 km)
  - Available from ~4M lines of sight to all GPS in view
- ~80% available within 3 hrs, ~50% in 1 hr, and ~10% in ½ hr

Ionospheric Climatology from COSMIC, IRI empirical model, and TIEGCM model



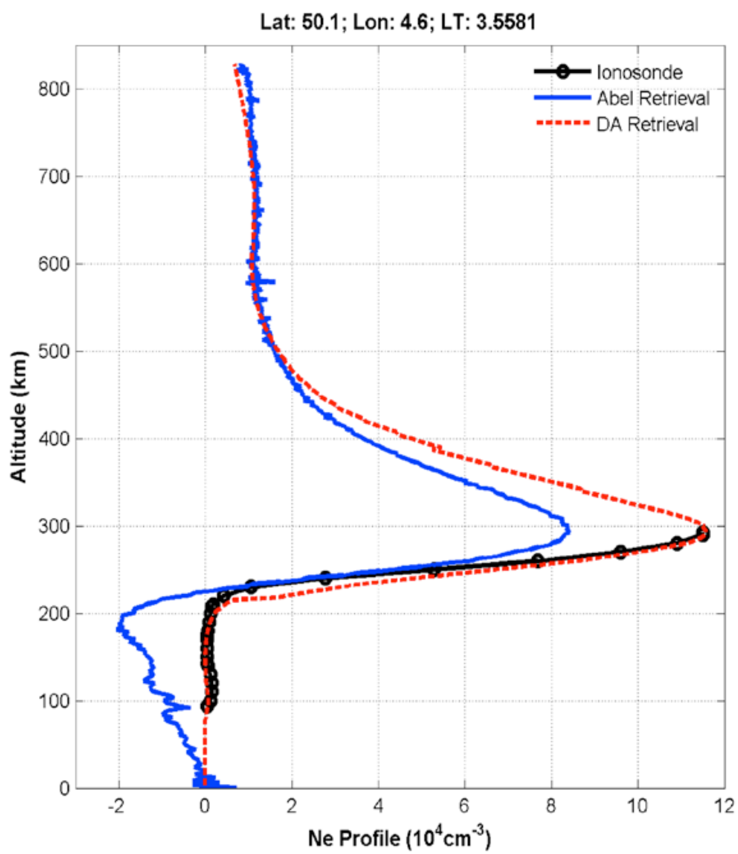
Wave-4 structure in Integrated Electron Content

FORMOSAT-3/COSMIC electron content observations: 2000~2200 LT



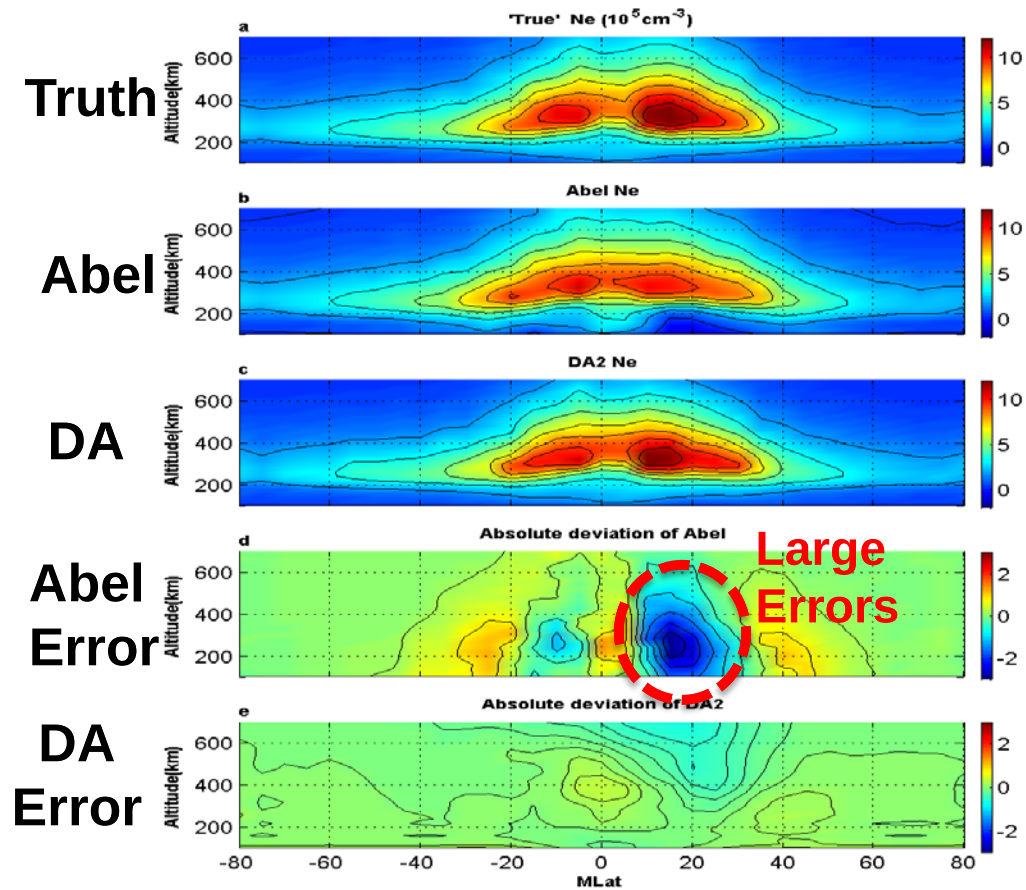
Data Assimilation Retrieval of Electron Density Profiles from Radio Occultation Measurements-an improvement over Abel Retrieval

Comparison of standard COSMIC Abel retrieval and data assimilation retrieval with Ionosonde data

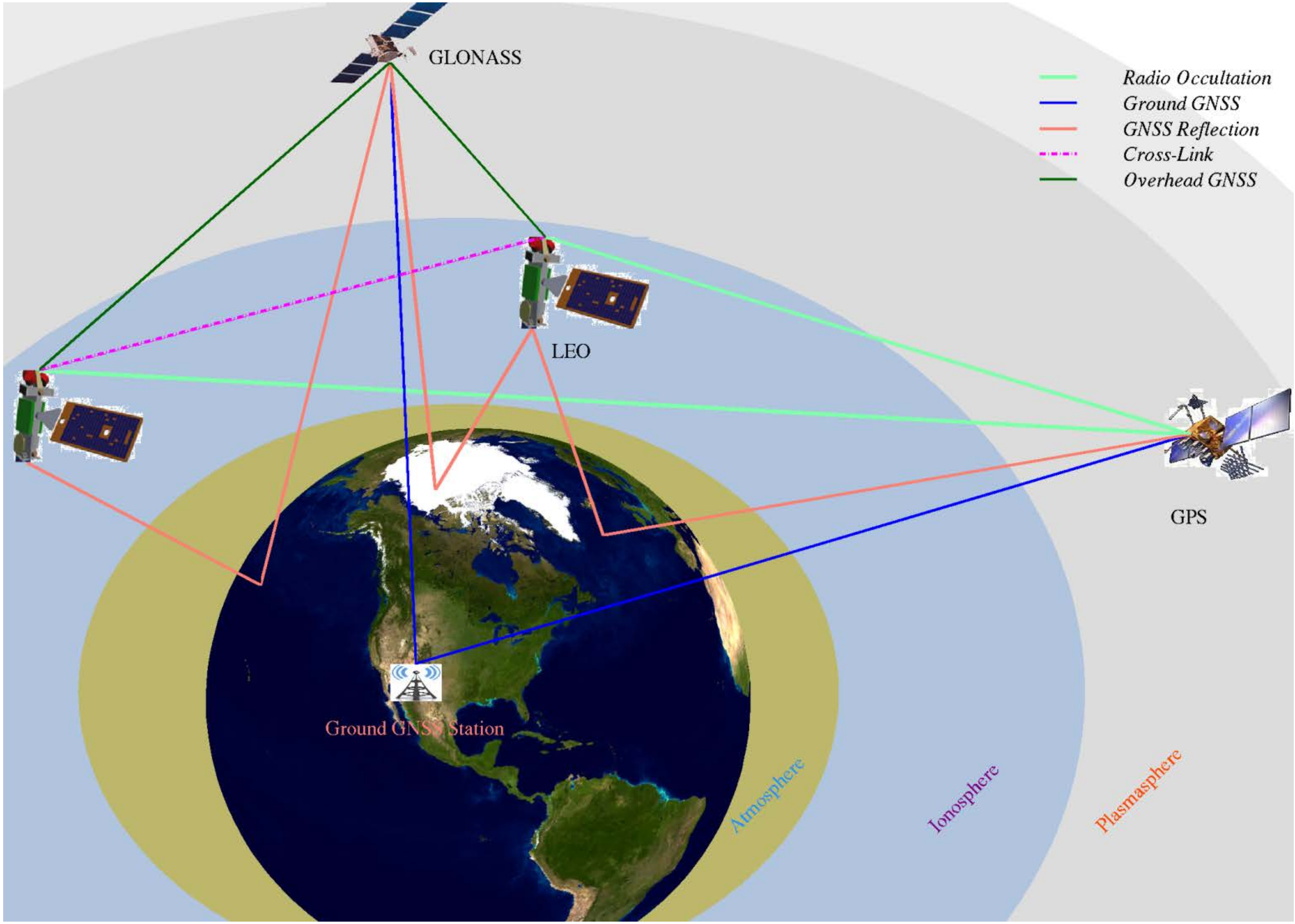


Yue, X., W. S. Schreiner, Y.-C. Lin, C. Rocken, Y.-H. Kuo, and B. Zhao, 2010: Data Assimilation Retrieval of Electron Density Profiles from Radio Occultation Measurements. *J. Geophys. Res., 116, A03317, doi:10.1029/2010JA015980*

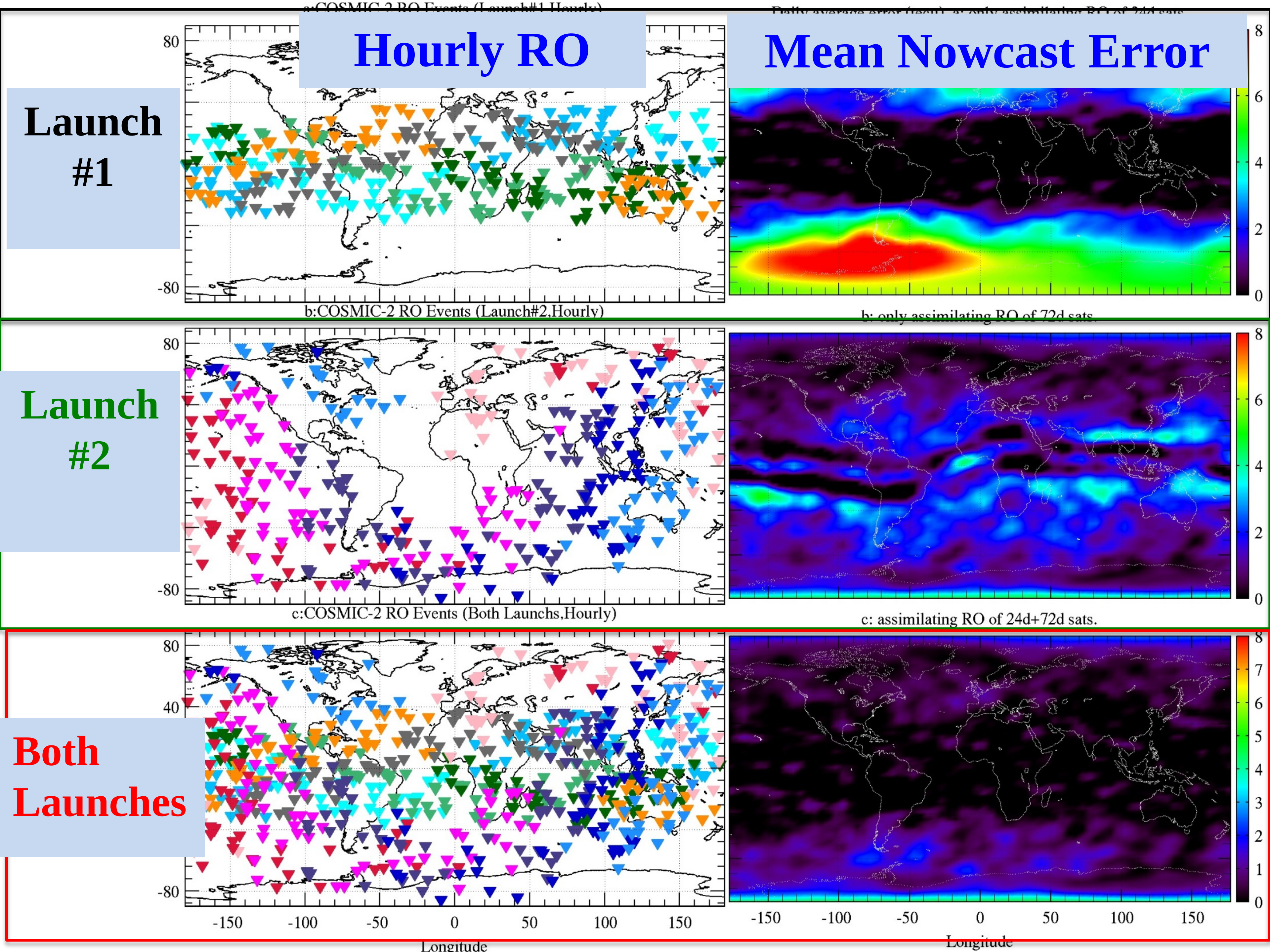
Simulation of retrieval errors for standard COSMIC Abel retrievals and data assimilation retrievals



Geomagnetic latitude and altitude variations of electron density during noon time (LT=13)



OSSE study on imaging the ionosphere by assimilating ground-based GNSS, LEO GNSS (RO, ocean reflection, overhead un-occultation), and LEO-LEO Cross link (Yue et al., 2013)



Hourly RO
Mean Nowcast Error
Launch #1
Launch #2
Both Launches
b:COSMIC-2 RO Events (Launch#2,Hourly)
b: only assimilating RO of 72d sats.
c:COSMIC-2 RO Events (Both Launchs,Hourly)
c: assimilating RO of 24d+72d sats.
Longitude
Longitude

Global mean error in TEC for Equatorial, polar and both obits of COSMIC-2