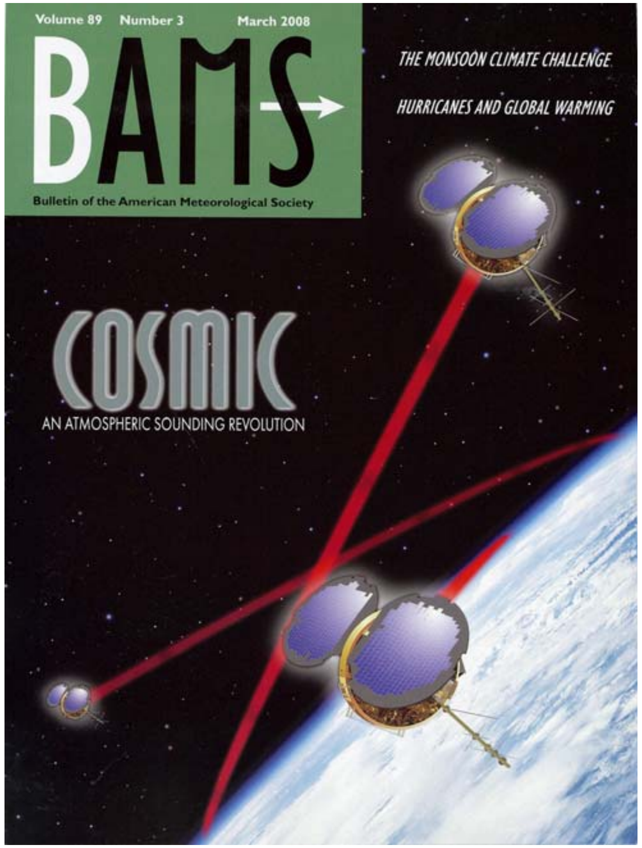
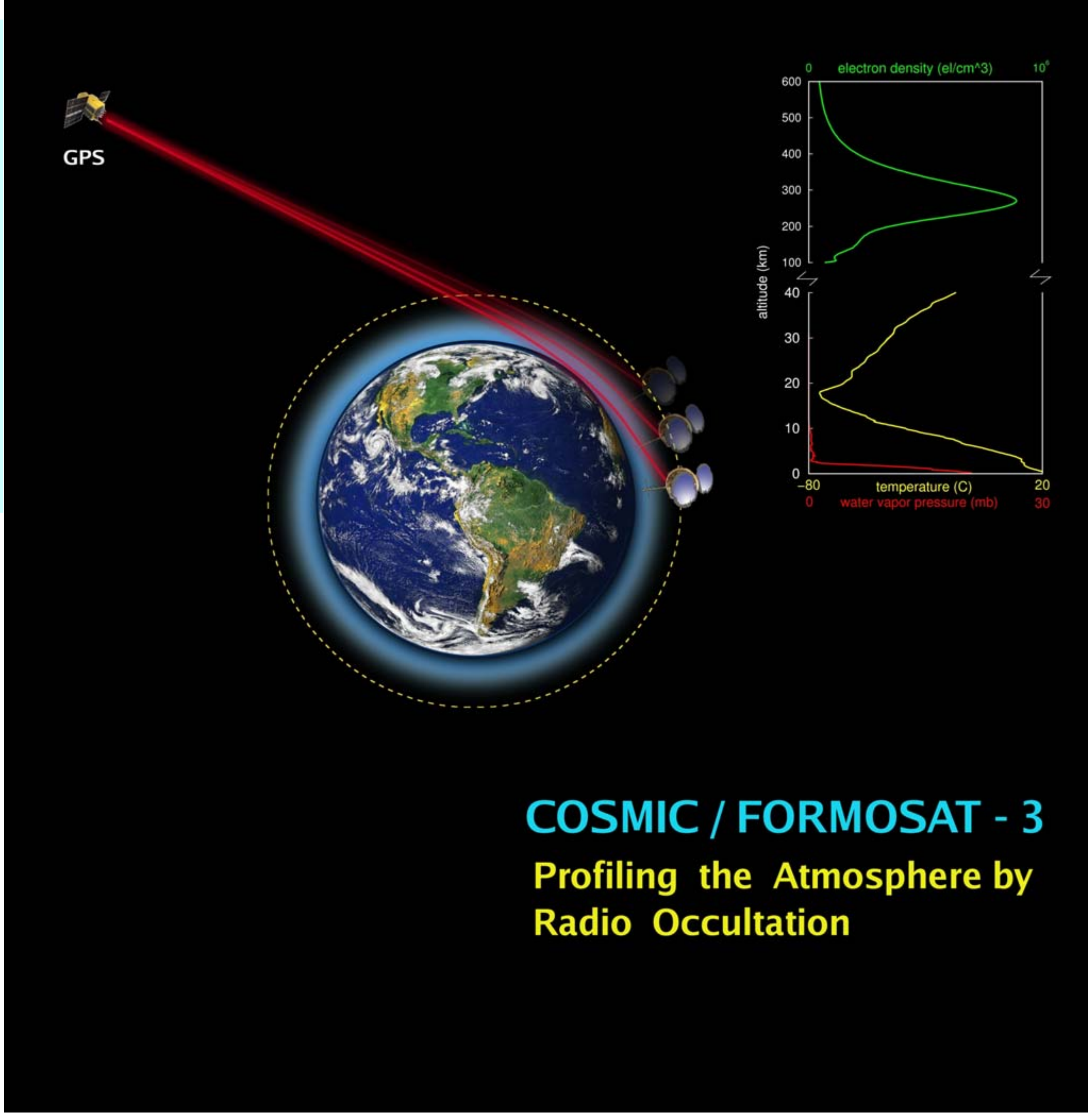
Exploring the Atmosphere With Radio Occultation- contributions to weather, climate and space weather

OPAC 2010
Rick Anthes
6 September 2010





Outline of talk

From GPS/MET to COSMIC-15 years of progress!

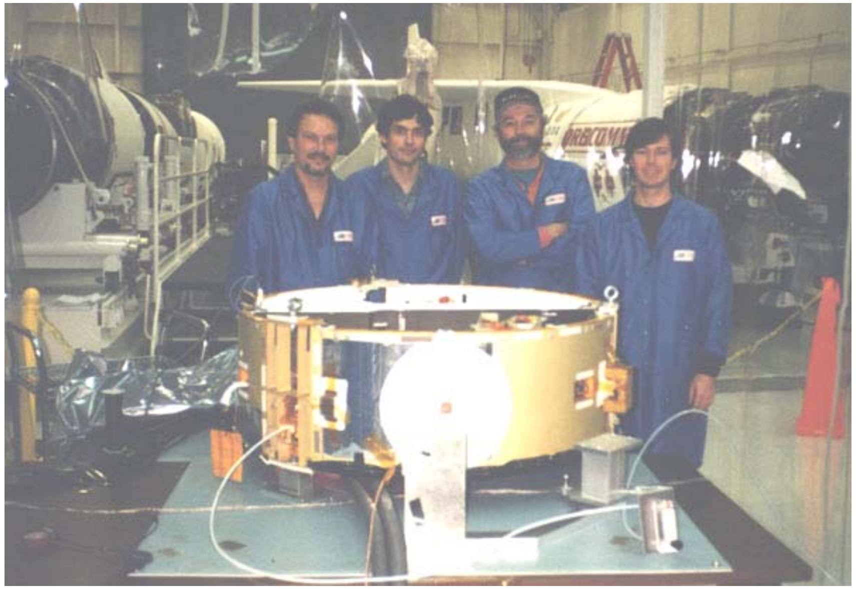
- A few results from GPS/MET
- Progress since GPS/MET
  - Improvements in RO retrievals since GPS/MET
  - Characteristics of RO observations (accuracy and precision)
  - Weather phenomena highlights
  - Numerical weather prediction highlights
  - Climate highlights
  - Space weather highlights
- Some remaining challenges

Acknowledgment and Thanks…

to the many people around the world who have made RO successful!

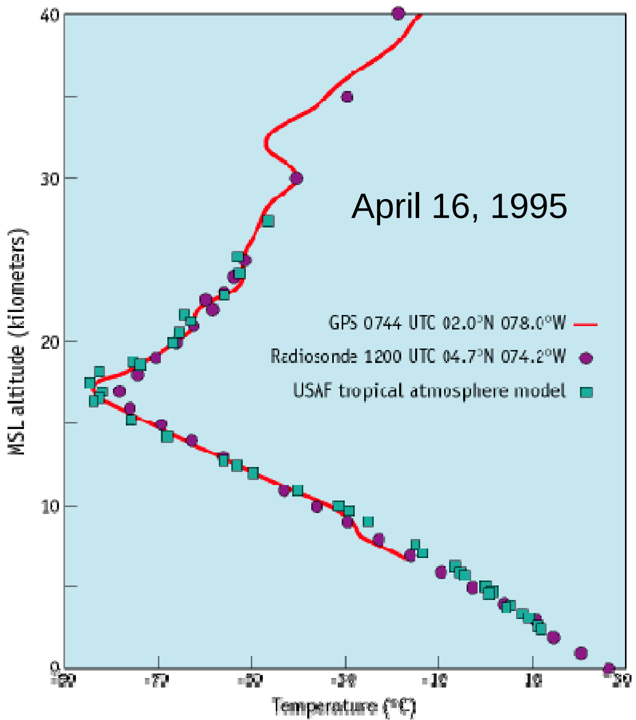
COSMIC Users Workshop Oct. 2009

GPS/MET Proof of Concept Mission



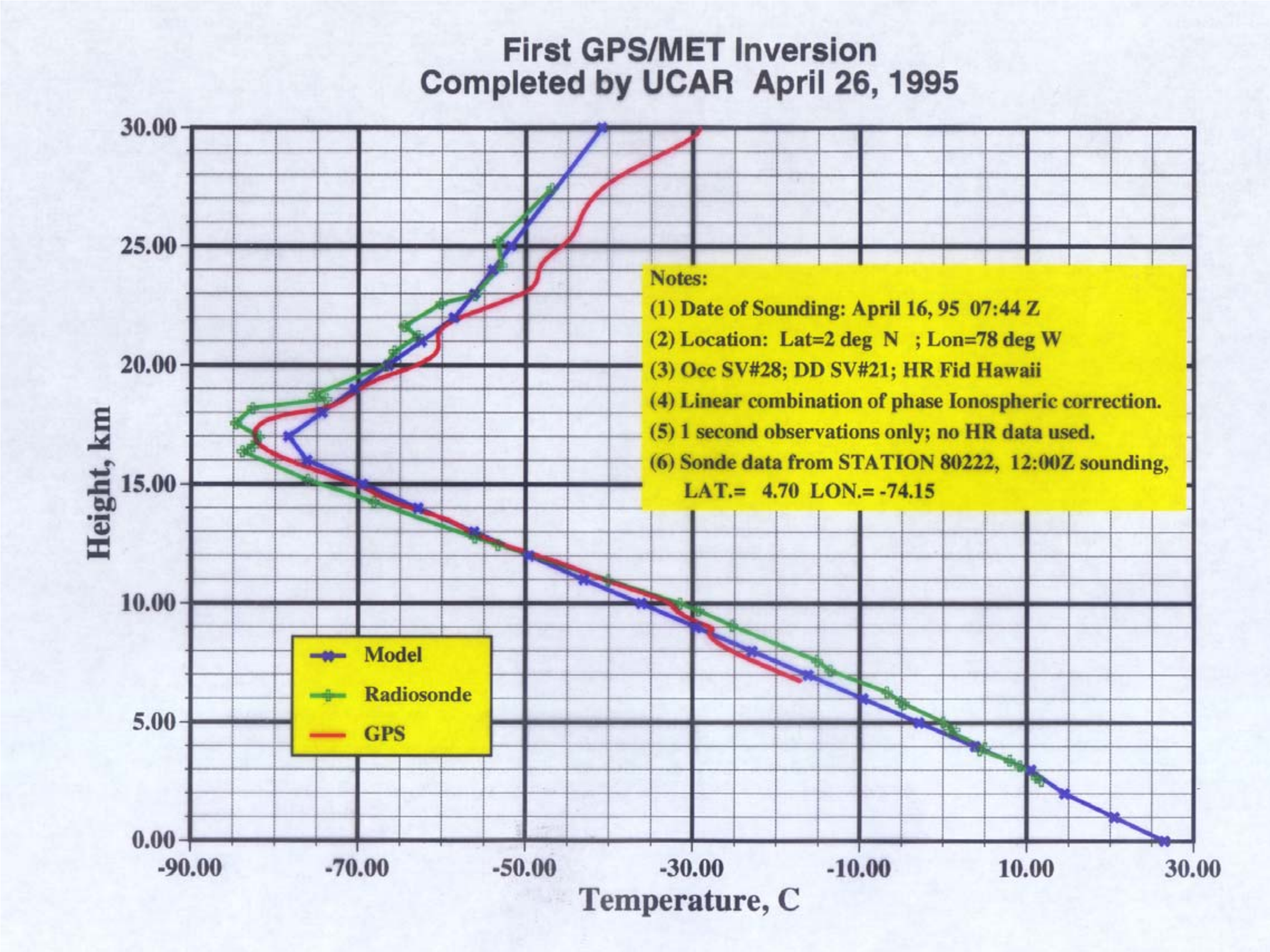
Mike Exner (UCAR), Charley Dunn (JPL), Tom Meehan (JPL), ????

Micro-Lab-1



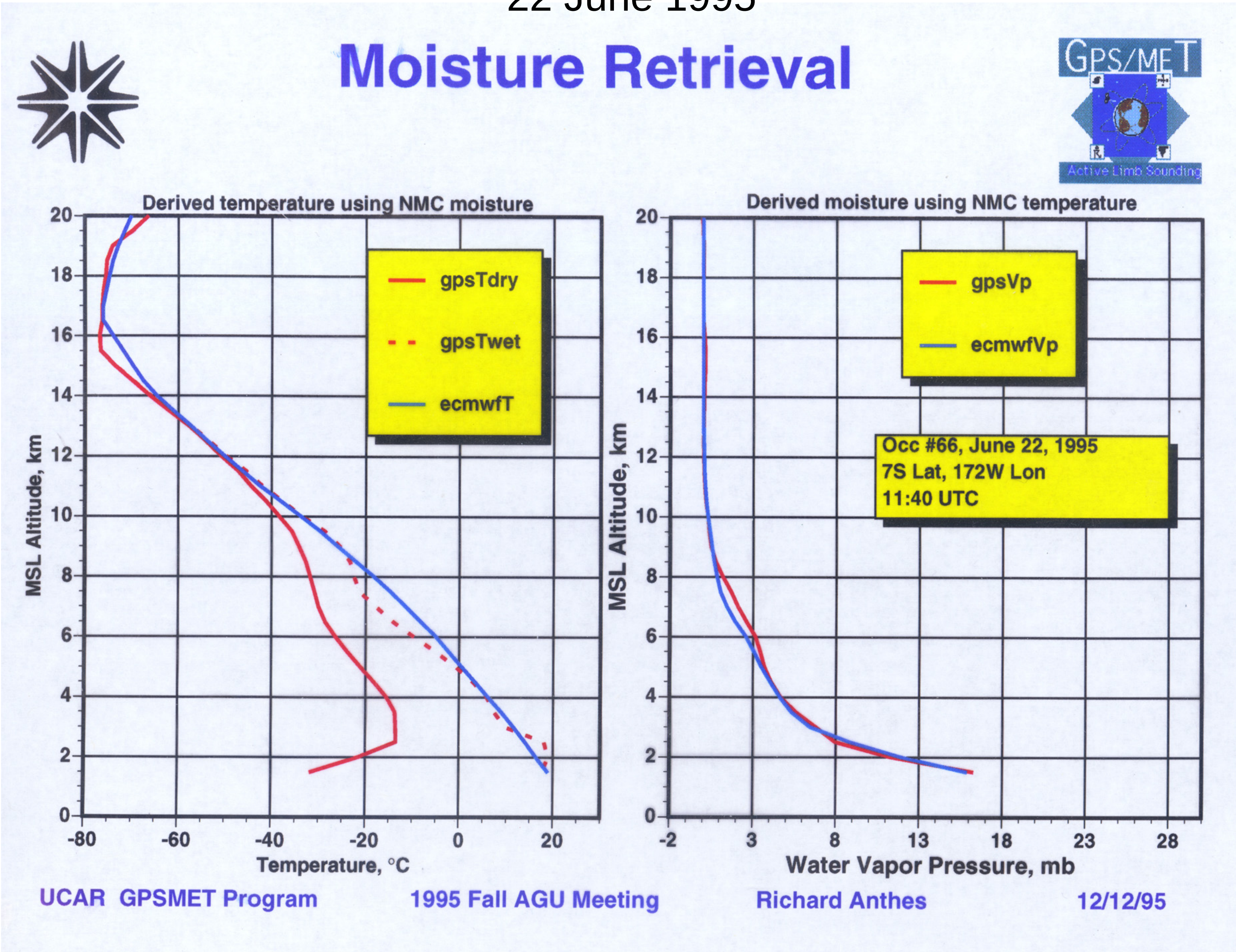
The first RO profile from Earth

First GPS/MET retrieval (University of Arizona)



Ben Herman and Da Sheng Feng, U. Arizona

An early water vapor and "wet" temperature retrieval.
22 June 1995



ca 1995
Not much has changed-but all claims verified-and more!

Key GPS/MET Advantages

GPS/MET
Active Limb Sounding

Feature	Weather Prediction	Climate & Global Change	Space Weather
• Limb Sounding Geometry Complementary to Ground and Space Nadir Viewing Instruments	X	X	X
• High Accuracy	X	X	X
• High Vertical Resolution	X	X	X
• Full Global Coverage	X	X	X
• All Weather - Not affected by Clouds, Rain, Aerosols	X	X	X
• Independent Height & Pressure	X	X	
• Requires no "First Guess" (except for upper boundary)	X	X	
• Independent of "radiosonde calibration"	X	X	
• No Long Term Drift		X	
• No Satellite-to-Satellite Bias		X	

UCAR GPS/MET Program Office

Characteristics of GPS RO Data

- **Limb sounding geometry complementary to ground and space nadir viewing instruments**
- **Global coverage**
- **Profiles ionosphere, stratosphere and troposphere**
- **Only observing system from space that can profile the ABL**
- **High accuracy (equivalent to <1 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 observe atmospheric boundary layer**
- **All weather-minimally affected by aerosols, clouds or precipitation**
- **Independent height and pressure**
- **Requires no first guess sounding**
- **No calibration required**
- **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. 9/3/10

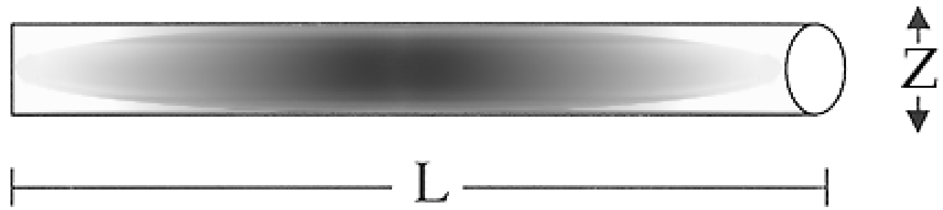
Early (ca 1995) Issues with RO and GPS/MET

- **Representativeness: Horizontal “average” ~300 km (Claim: no good for weather analyses and predictions)**

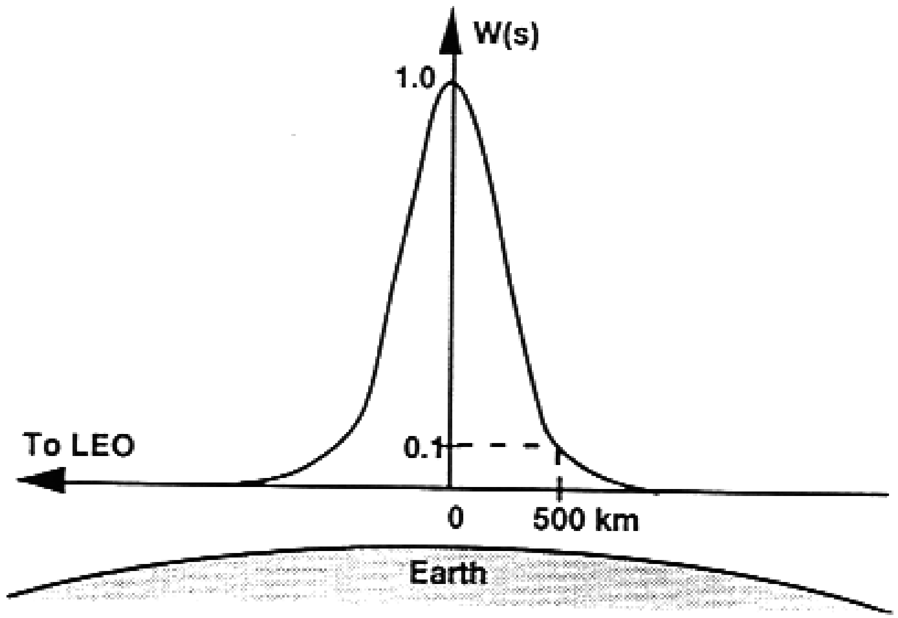
- **Penetration to lower troposphere (Claim: no good below about 5-8 km)**

- **Negative N bias in lower troposphere, tropical regions (Claim: no good for climate)**

Observed Atmospheric Volume



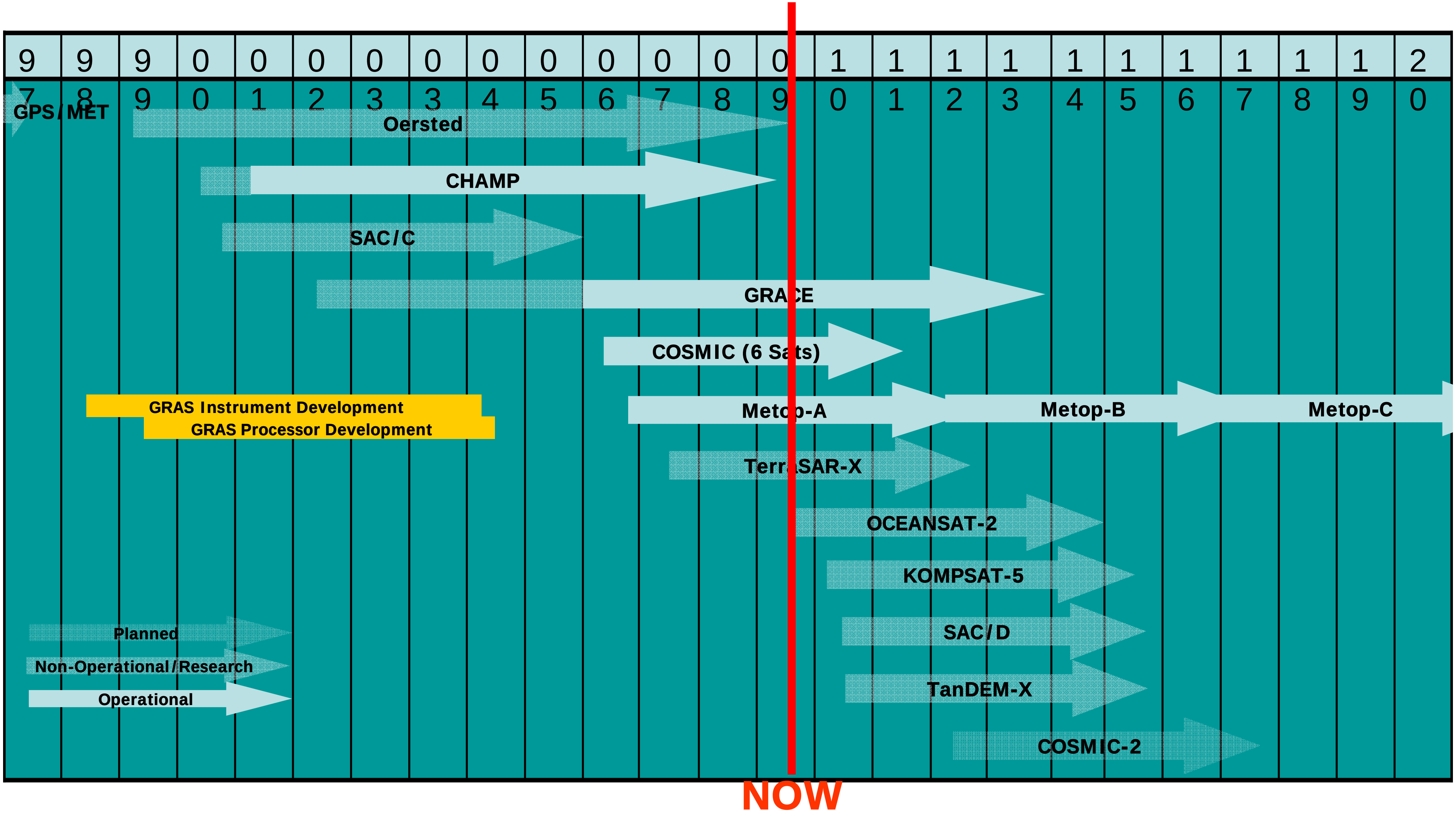
L~300 km
Z~1 km



Progress since GPS/MET

- Additional RO missions
- Improved receiver, tracking and retrieval algorithms
- Meteorological case studies
- Numerical Weather Prediction
- Climate
- Space Weather
- Hundreds of peer-reviewed papers on RO
- Most of early criticisms addressed

Radio Occultation Instruments



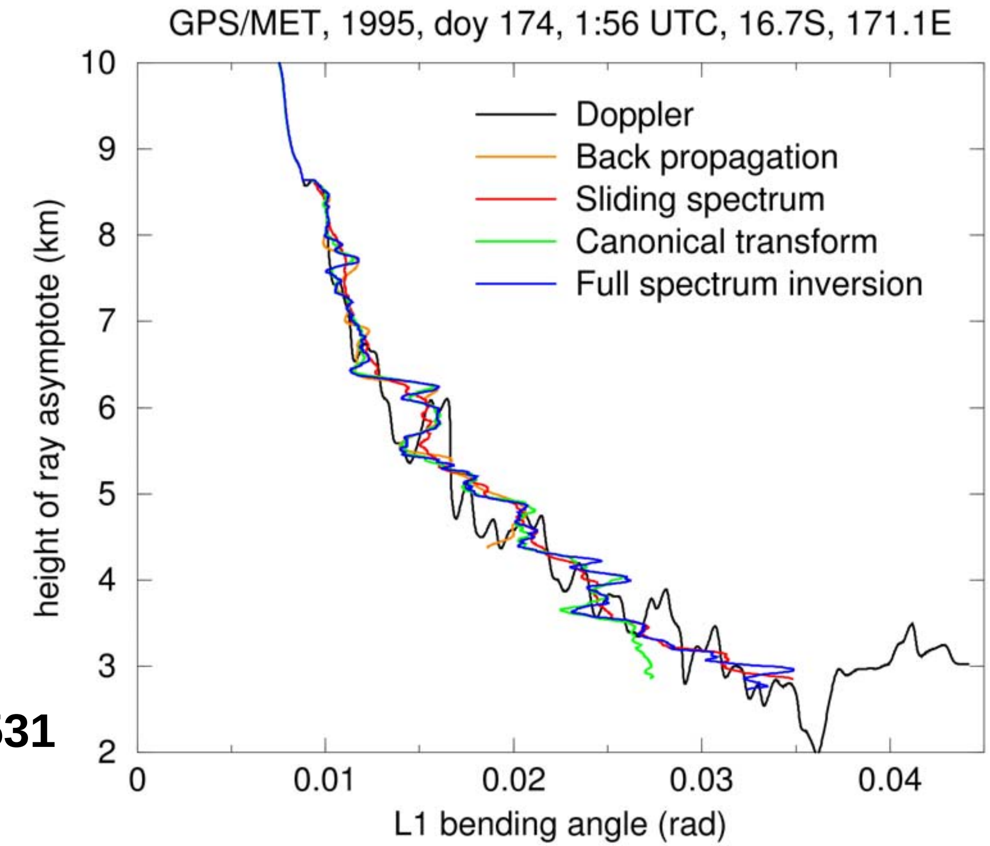
Progress in inversion methods (1)

All RO inversion methods use the assumption of local spherical symmetry.

Geometric optics (GO-uses phase data only); needs single path propagation; provides accurate solutions in the UT and above; does not work in the LT.

Radio-holographic (wave optics-WO) methods (use phase & amplitude); solve for the multipath propagation in LT:

- back propagation
- sliding spectral methods
- canonical transform (CT)
- full spectrum inversion (FSI)
- phase matching (PM)
- CT2 (canonical transform 2, (equivalent to FSI)



Kuo et al., 2004, JMSJ, 82(B1), 507-531

Progress in inversion methods (2)

back propagation (BP) - propagates complex wave field measured on the observation trajectory back to limb (in the single-path region), then calculates bending from phase.

sliding spectral (SS) methods - perform spectral analysis of the measured wave field in a sliding aperture to identify multiple rays and estimate their bending angles.

Most advanced WO methods are based on integral transform of the whole measured RO signal from coordinate to impact parameter representation: <u>canonical transform</u> (CT); <u>full spectrum inversion</u> (FSI); <u>phase matching</u> (PM); <u>canonical transform 2</u> (CT2)

CT - uses BP to straight line;
FSI, CT2 - use representations of approximate impact parameter;
CT, FSI, CT2 - are computationally efficient (reduce to FTT, do not use BP);
PM - can be used for verification of other methods

The difference between inversion results obtained with CT, FSI, PM, CT2 is much smaller than other errors of RO in LT

RO Results with Open Loop (OL) Tracking

OL tracking uses frequency model without feedback (allows tracking of rising occultations).

Better penetration of OL (50% below ~1 km) compared to Phase Lock Loop (PLL) tracking (50% below ~4 km - global, below ~6 km - tropics).

Smaller N-bias in tropics of OL compared to PLL. The residual OL N-bias may be caused by lower-tropospheric propagation effects (e.g., super-refraction).

Larger standard deviation of retrieved N and ECMWF N of the OL than PL in lower troposphere---may be related to both RO (1) and analysis (2) errors.

(1) OL, generally, results in lower SNR (larger errors) than correctly operating PLL.

(2) It can be that PLL is not penetrating in those cases when analysis has larger errors.

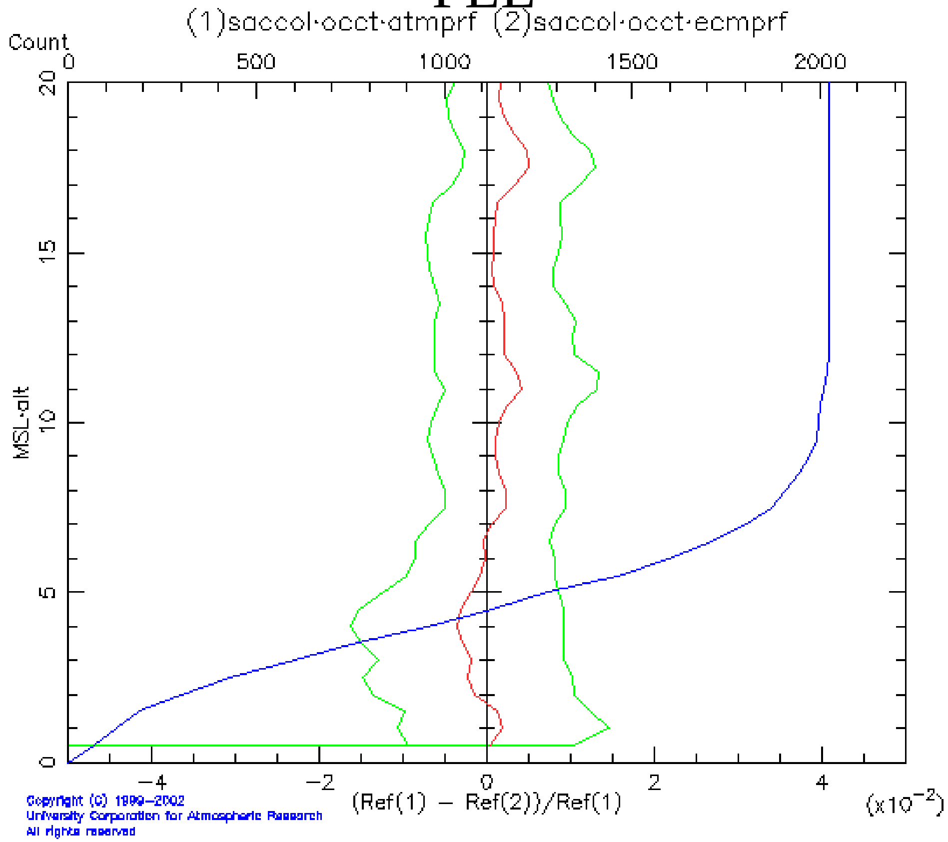
S. Sokolovskiy, UCAR, Aug. 2005

Improvement of Open Loop (OL) over Phase-Lock-Loop (PLL)

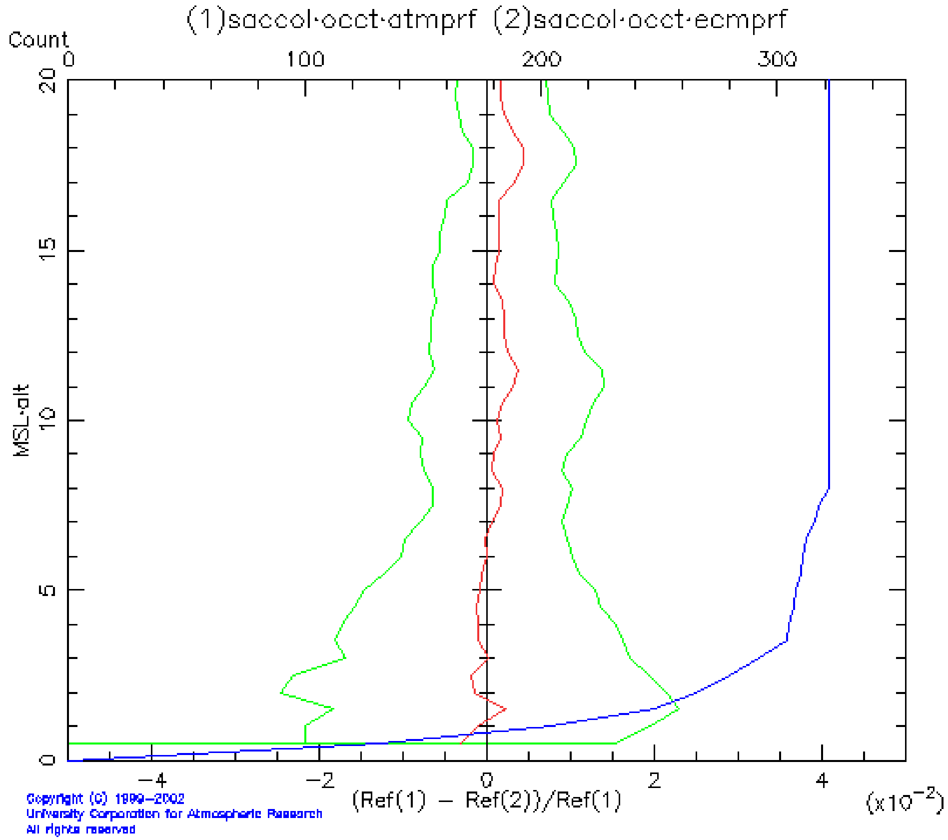
Comparison of the SAC-C N to ECMWF analysis

global

PLL



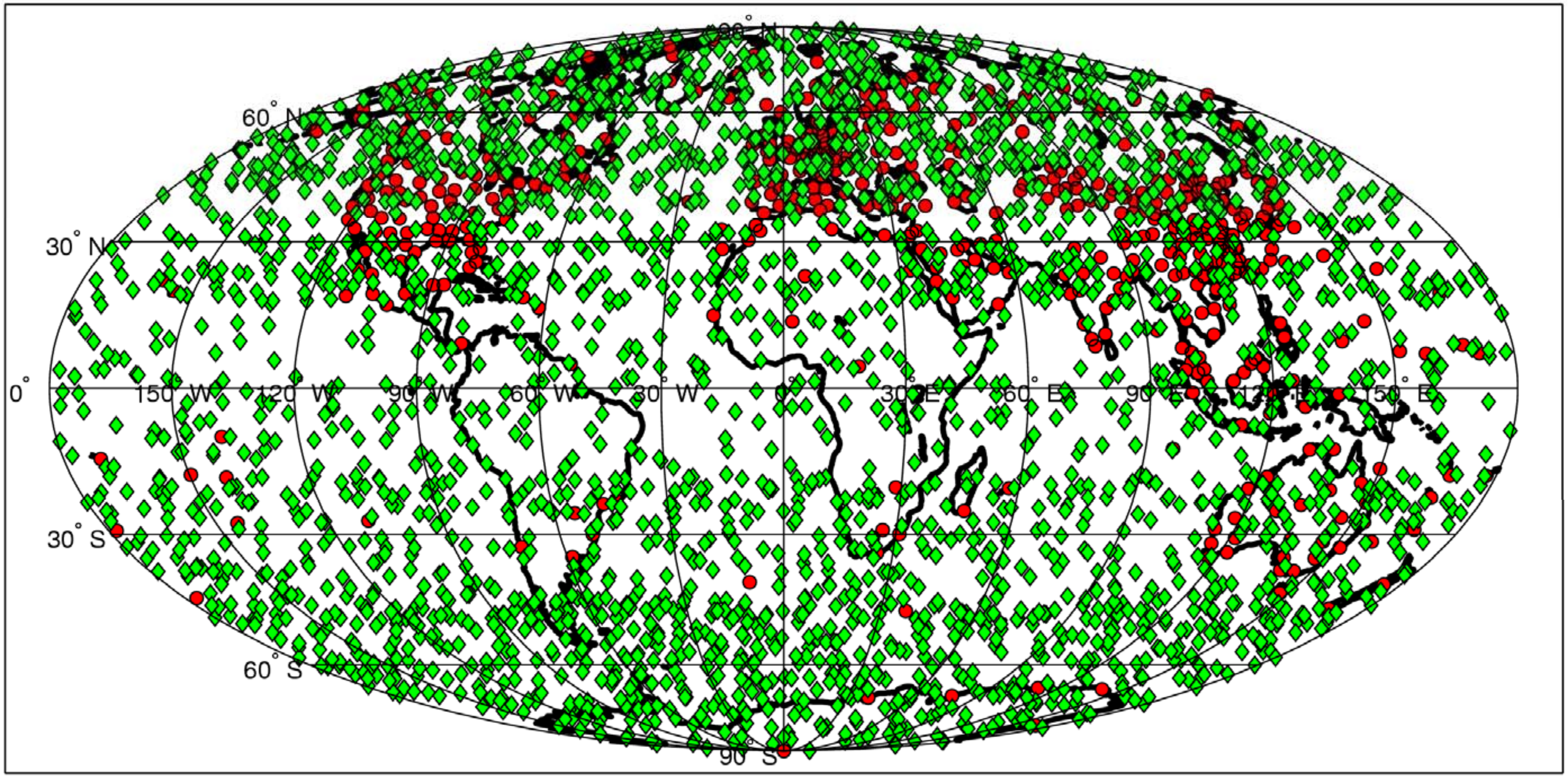
OL



- better penetration;
- larger standard deviation

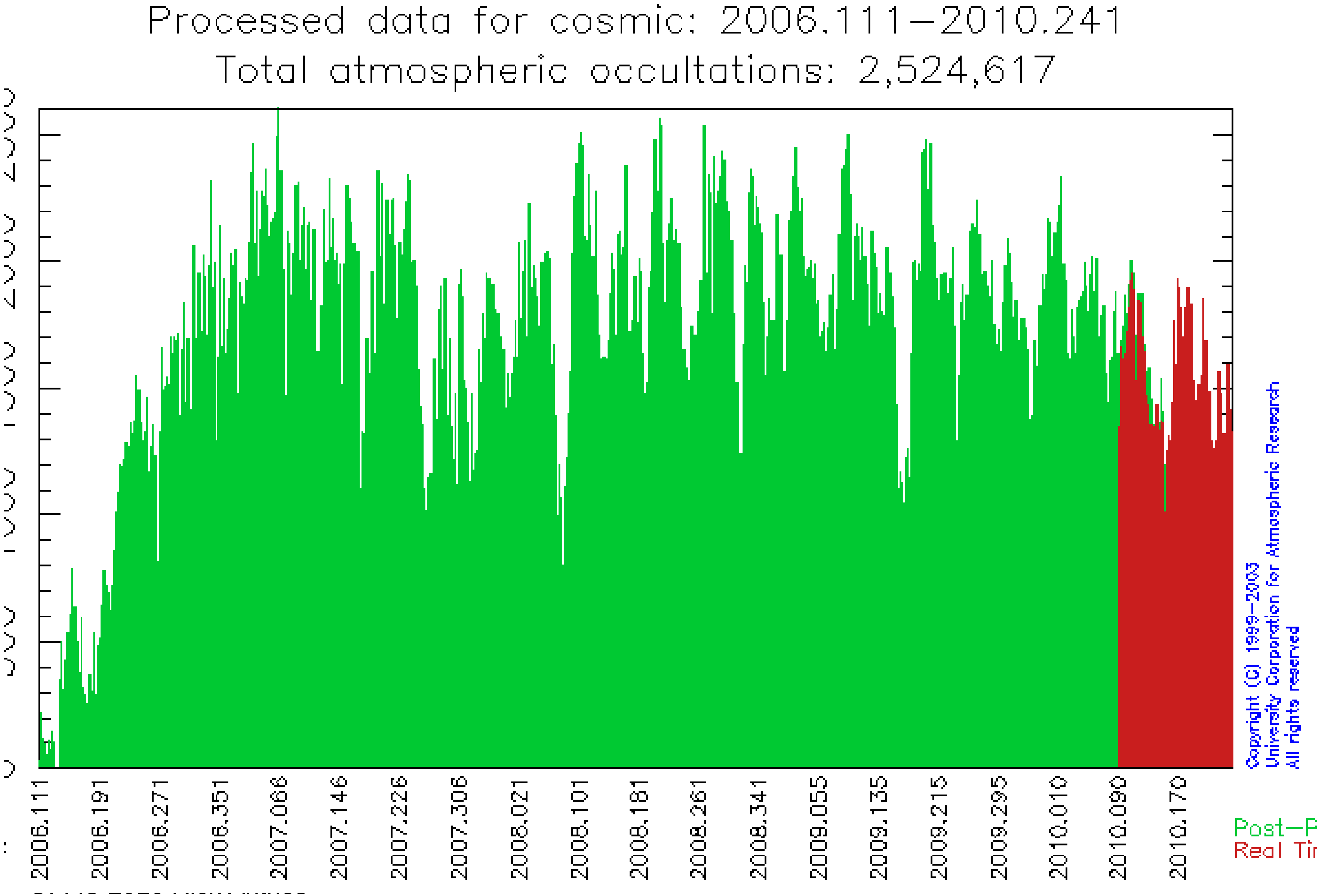
Other improvements (COSMIC vs. GPS/MET)

Occultation Locations for COSMIC, 6 S/C, 6 Planes, 24 Hrs

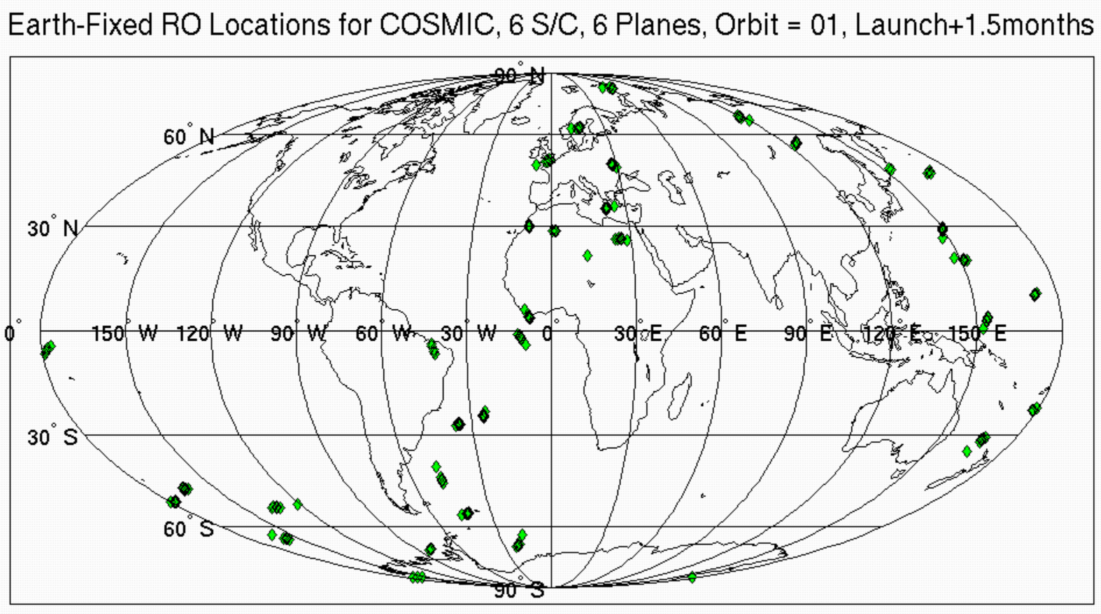


This may well be the most viewed slide from COSMIC. It was first shown in the late 1990s to Bob Corell (NSF-GEO AD) and others.

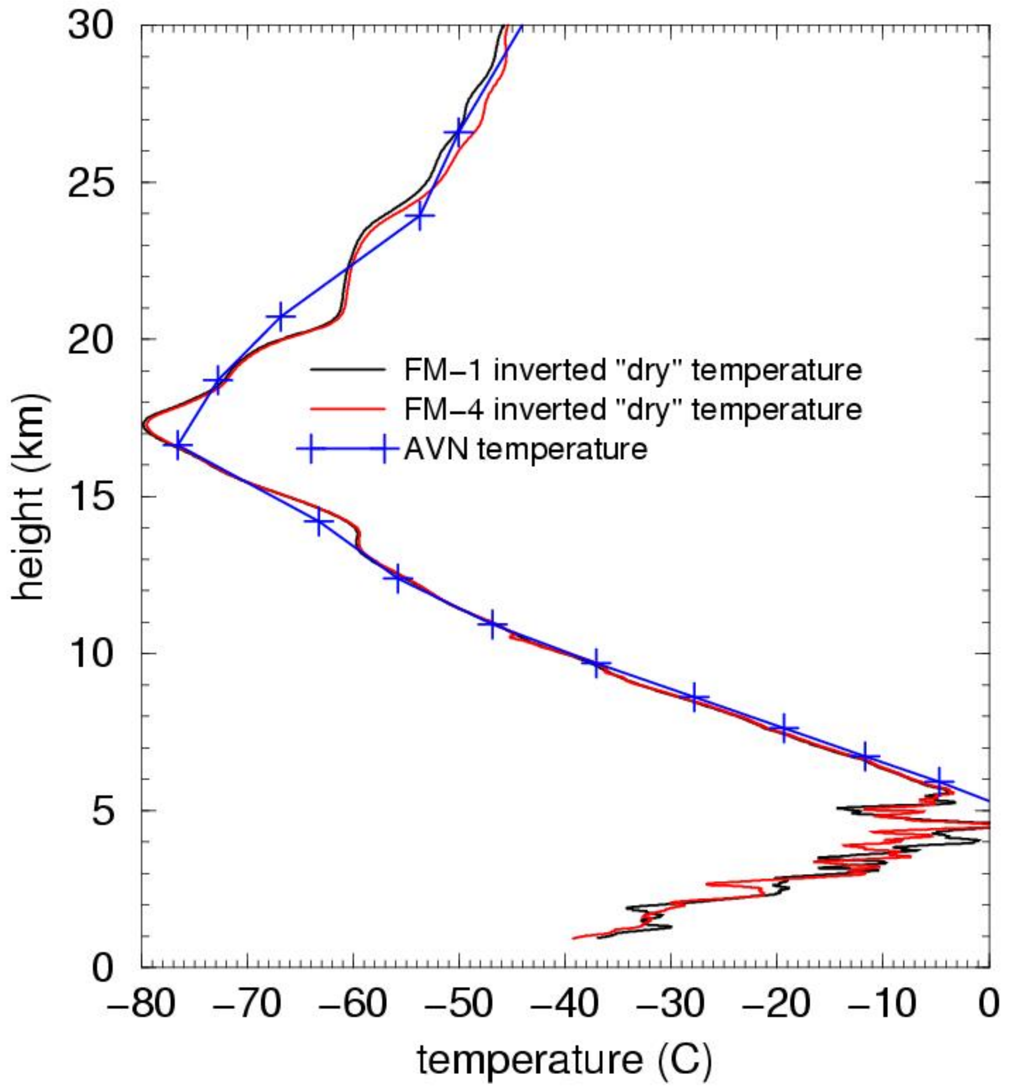
Number of good occultations per day through August 29, 2010



RO Precision
In weeks after launch, COSMIC satellites were very close together

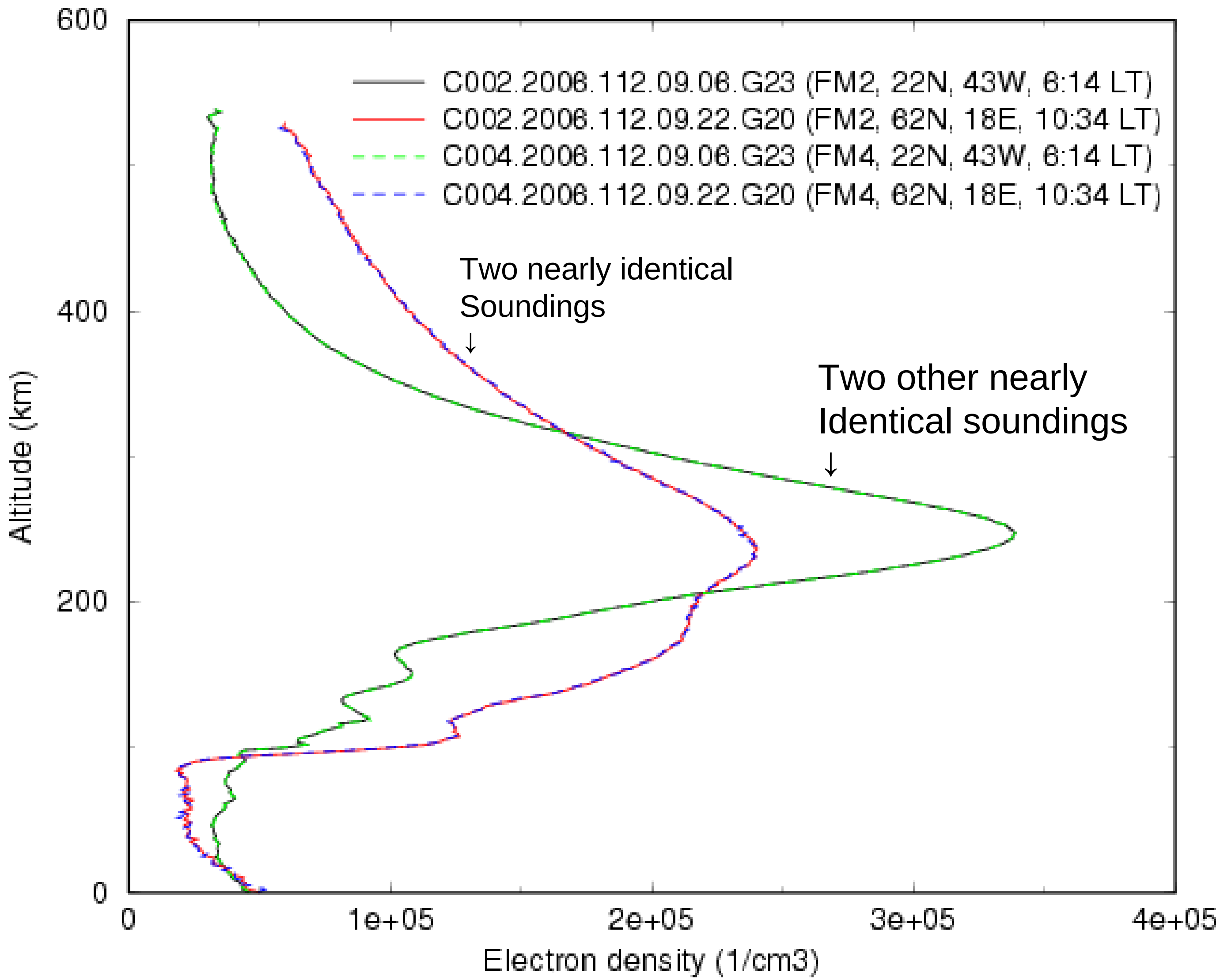


Early atmospheric profile results - coincident profiles from separate but very close in space/time satellites and instruments.



Some Amazing First Ionosphere Profile Comparisons…

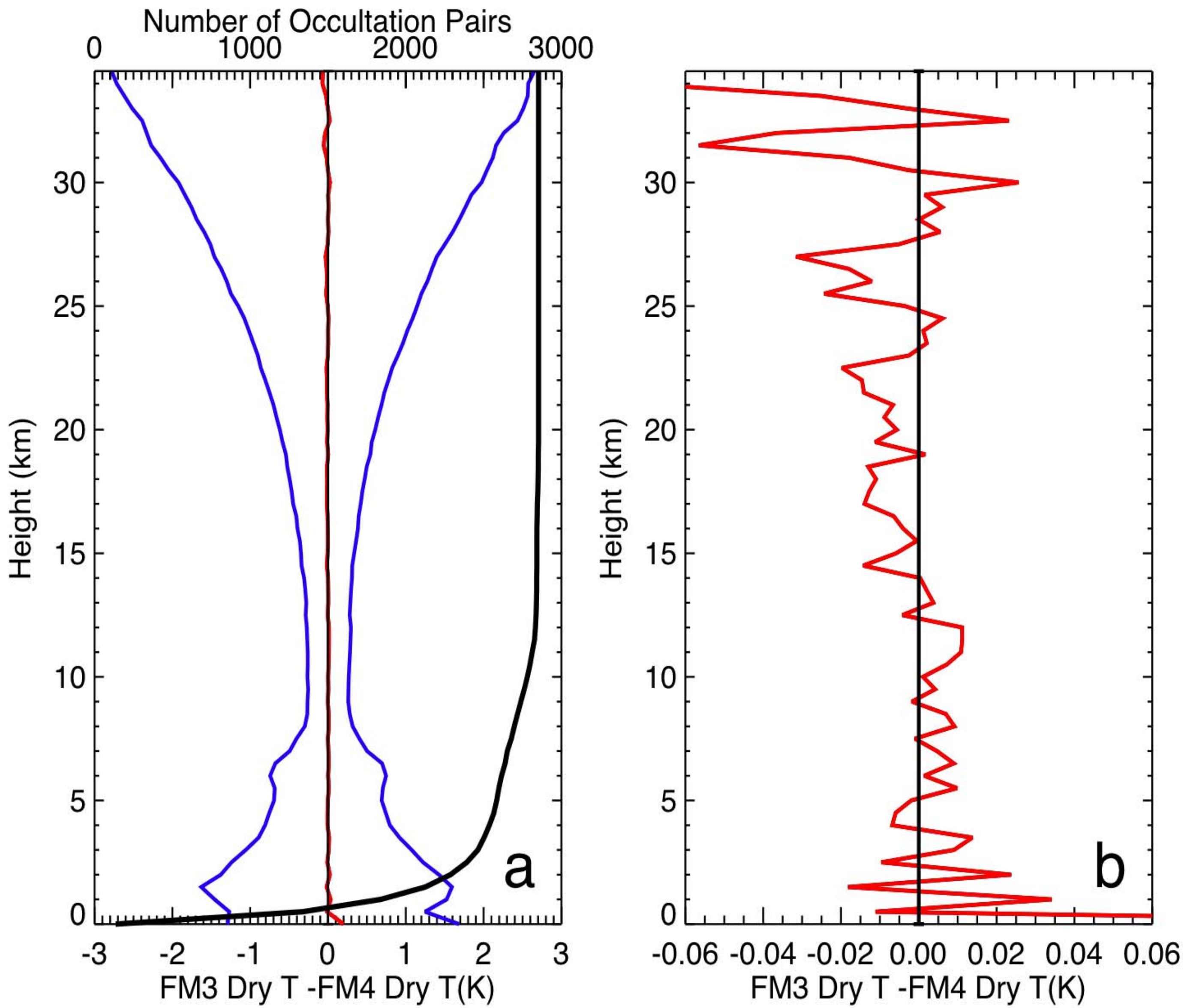
Coincident occultations from two different COSMIC satellites



- FM2 and FM4 within 30 km of each other
- FM2 about 4 seconds behind FM4
- At any given time FM2 is within 1 km of where FM4 was 4 seconds earlier
- FM2 and FM4 orbit altitudes differ by a few hundred meters

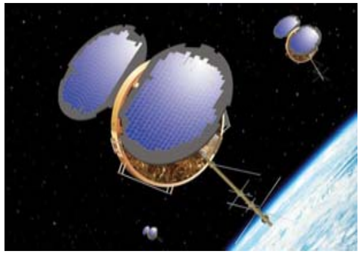
Note: There are four soundings plotted here, two pairs of nearly identical Soundings!

Precision of RO Data

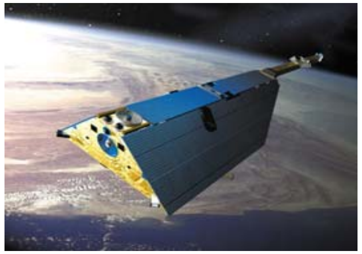


With 0.02-0.05 K precision at all vertical levels, COSMIC data are useful to inter-calibrate measurements from other satellites

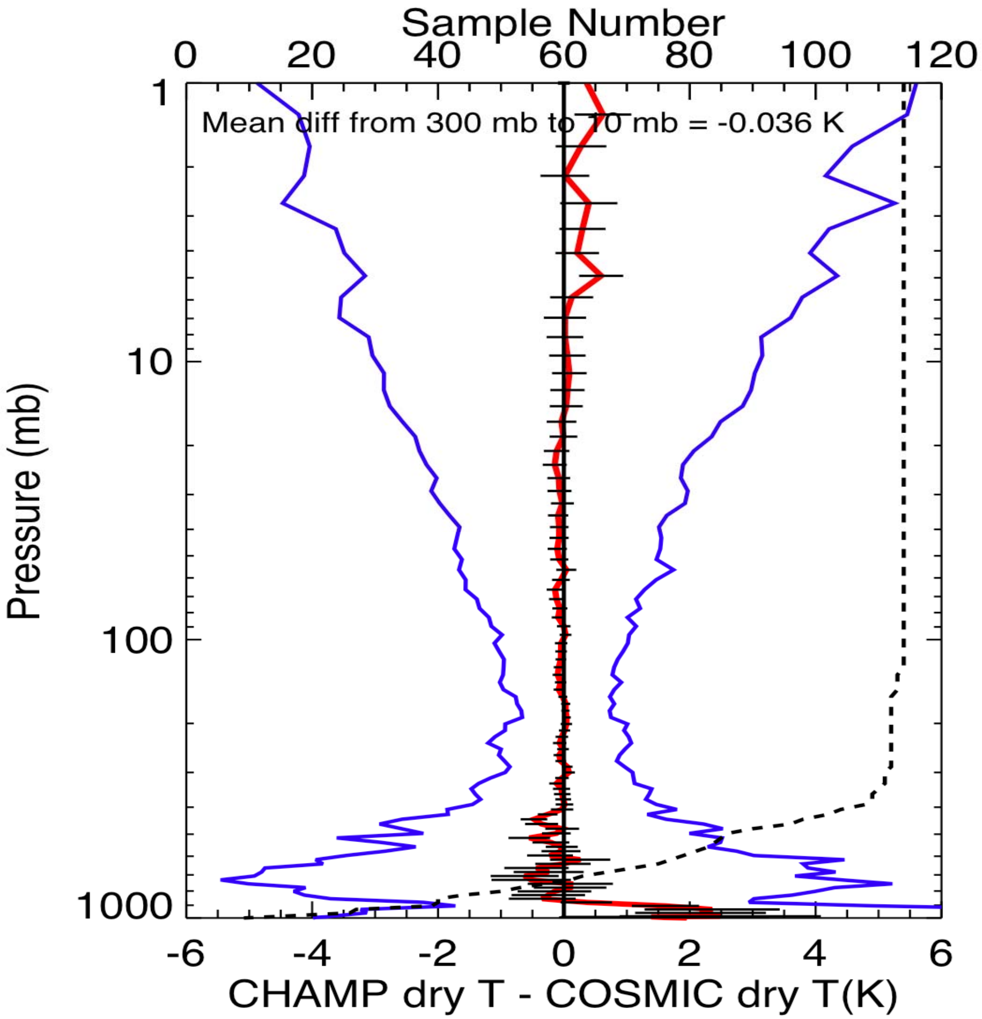
Dry temperature difference between 2 nearby COSMIC Satellites (FM3, FM4) within 10 km of each other. No significant bias.



Long-term stability



Global COSMIC-CHAMP Comparison from 200607-200707



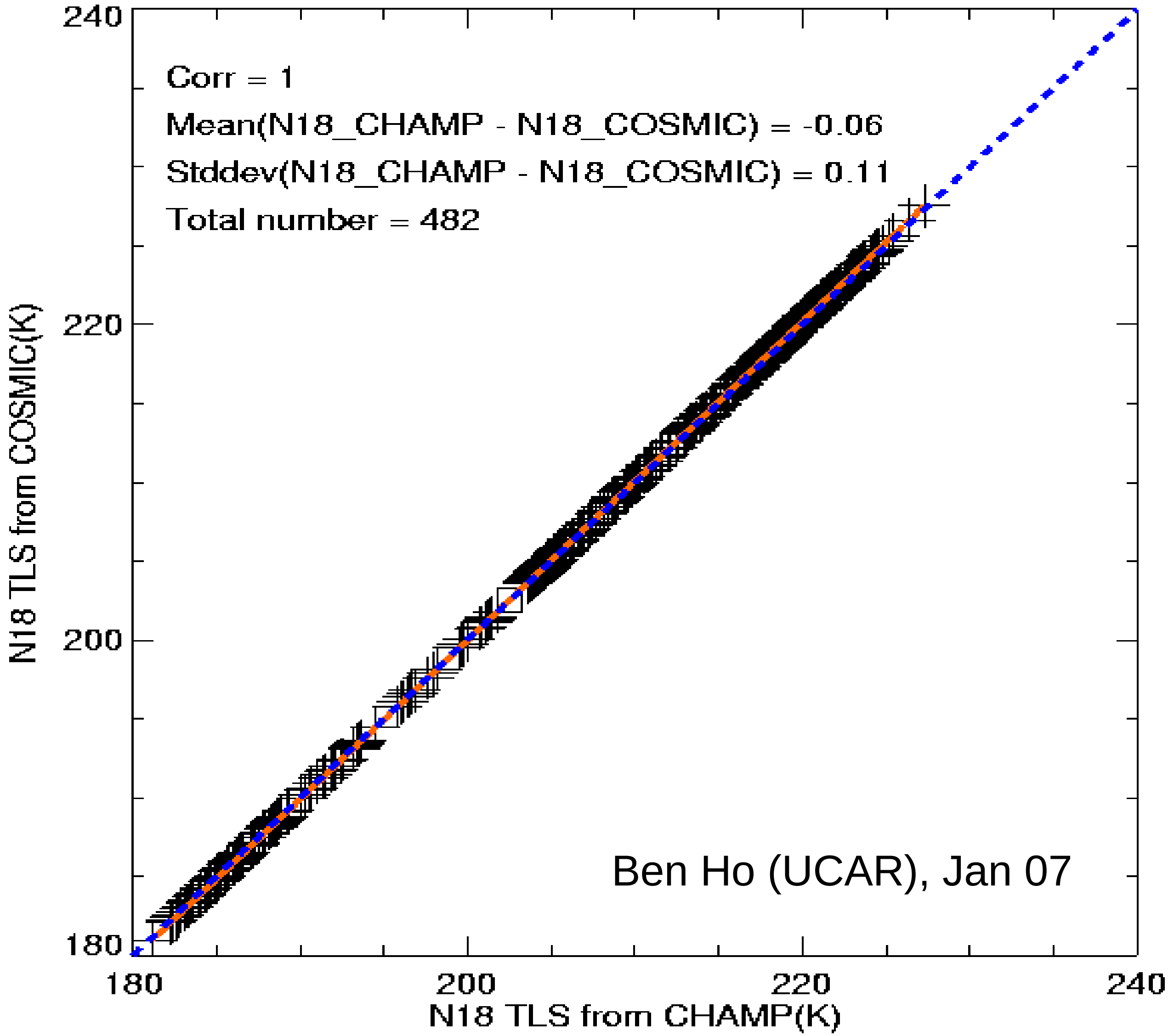
Within 60 Mins
and 50 Km

- Comparison of measurements between old and new instrument
- CHAMP launched in 2001
- COSMIC launched 2006

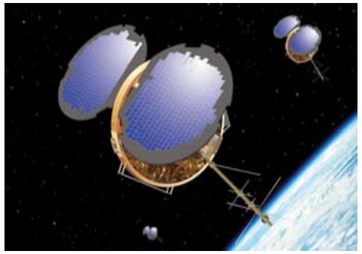
Don’t need to have stable calibration reference

Mean bias < 0.05 K

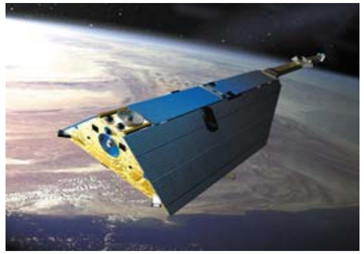
Temperature Lower Stratosphere (TLS) Comparison with GPS Sensors Launched 6 yrs Apart



N18 TLS est. from COSMIC v. N18 AMSU TLS est. from CHAMP

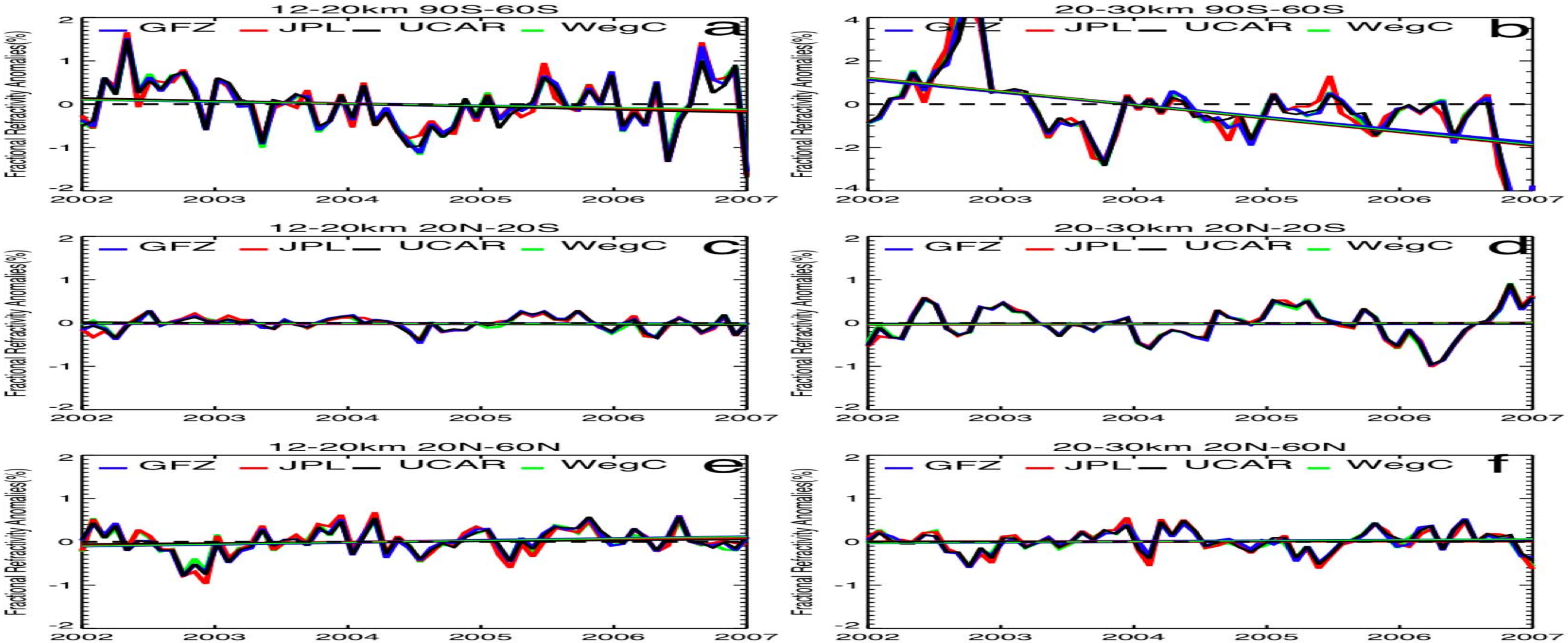


Reproducibility of RO data by different centers



Comparison of RO data processed by GFZ, JPL, UCAR, and WegC

Fractional Refractivity Anomalies



(Ho et al. JGR, 2009)

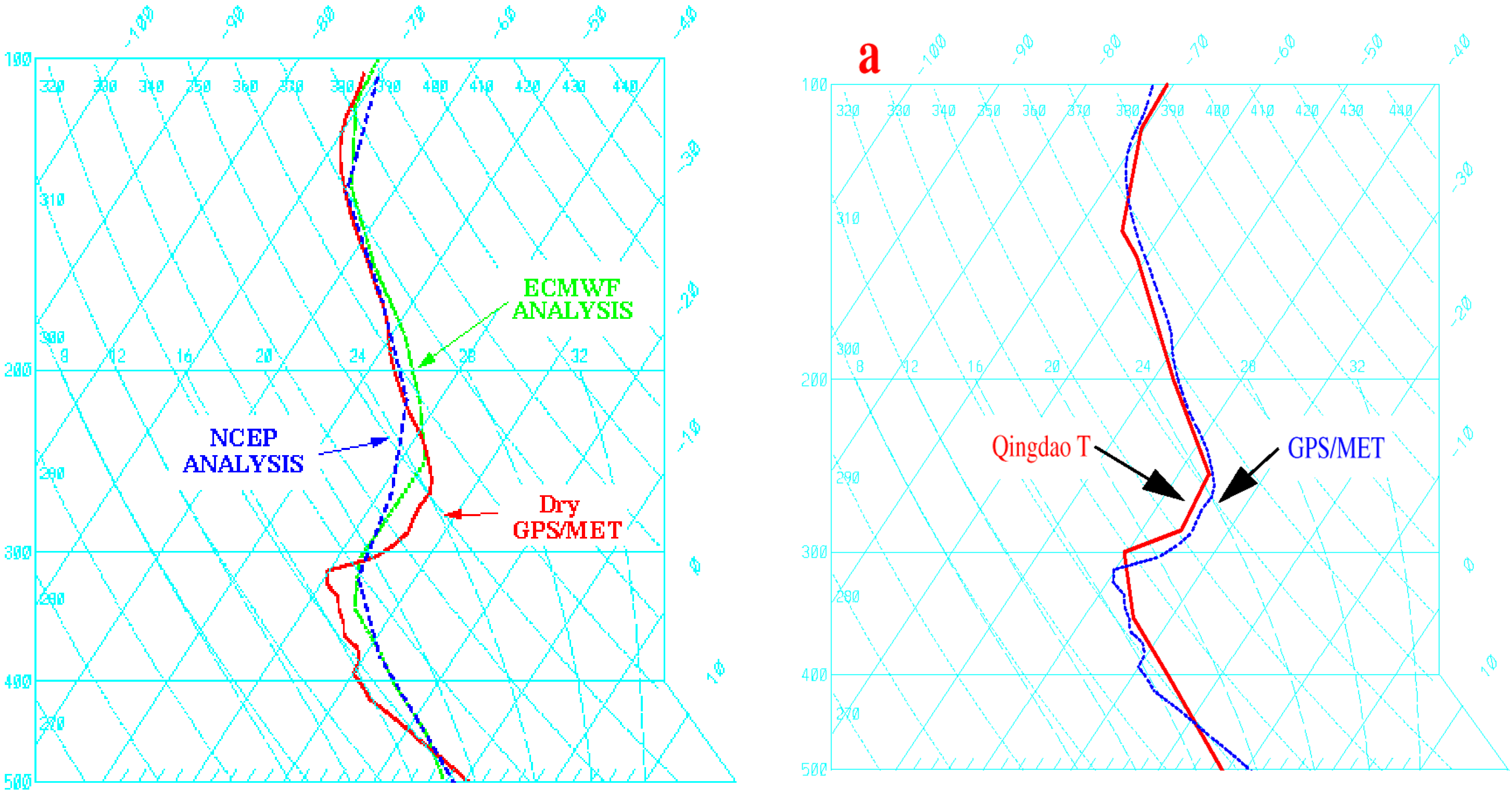
Independent of processing procedures : the trend from GPS RO data processed by different centers < 0.03%/5yrs

Use of Radio Occultation Data

- **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
- **Weather**
  - Improve global weather analyses, particularly over data void regions such as the oceans and polar regions
  - Improve skill of global and regional 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
  - Monitor ionospheric scintillation
  - Improve the analysis and prediction of space weather.

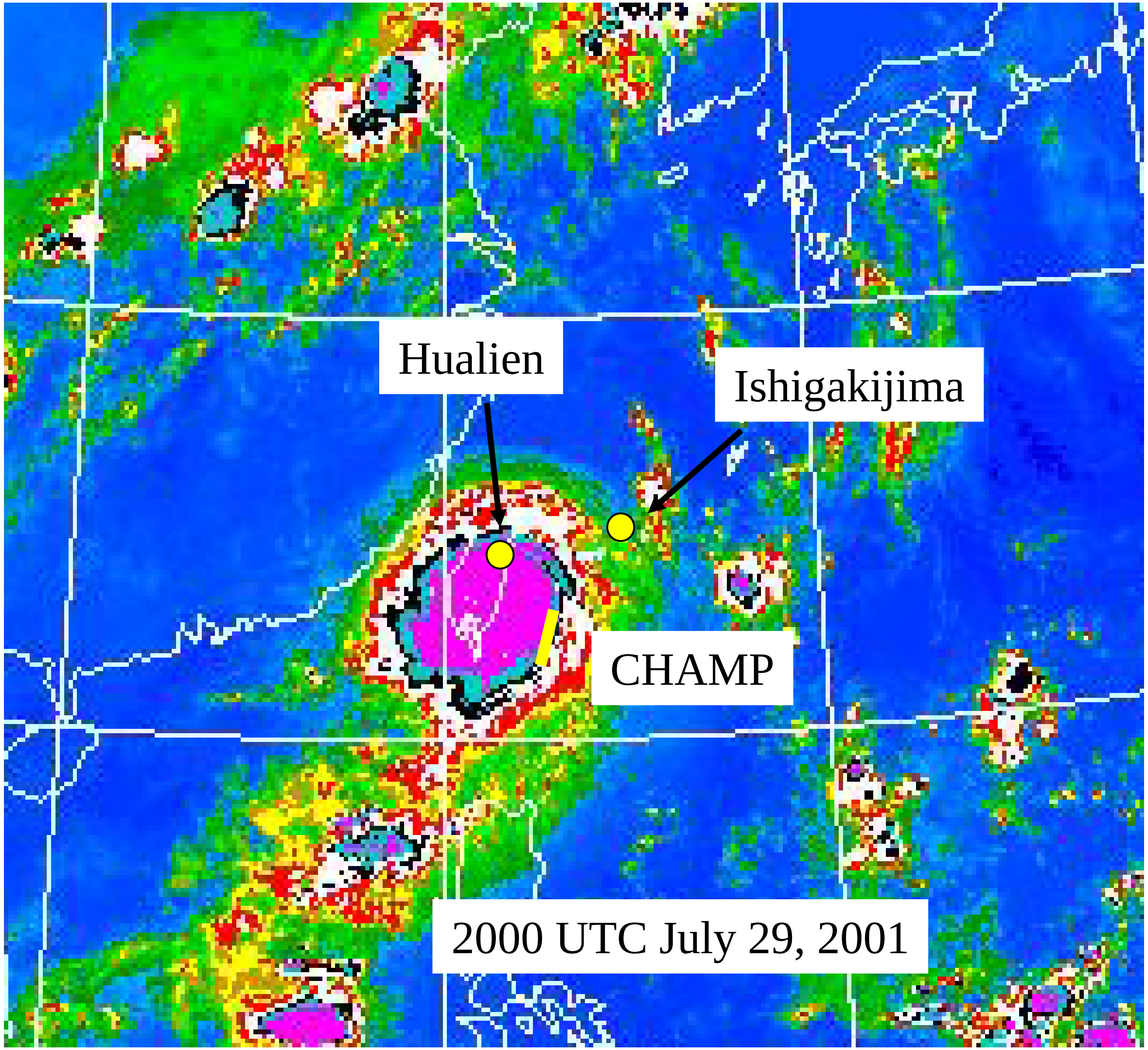
Weather Phenomena

A GPS/MET sounding through an intense upper-level front



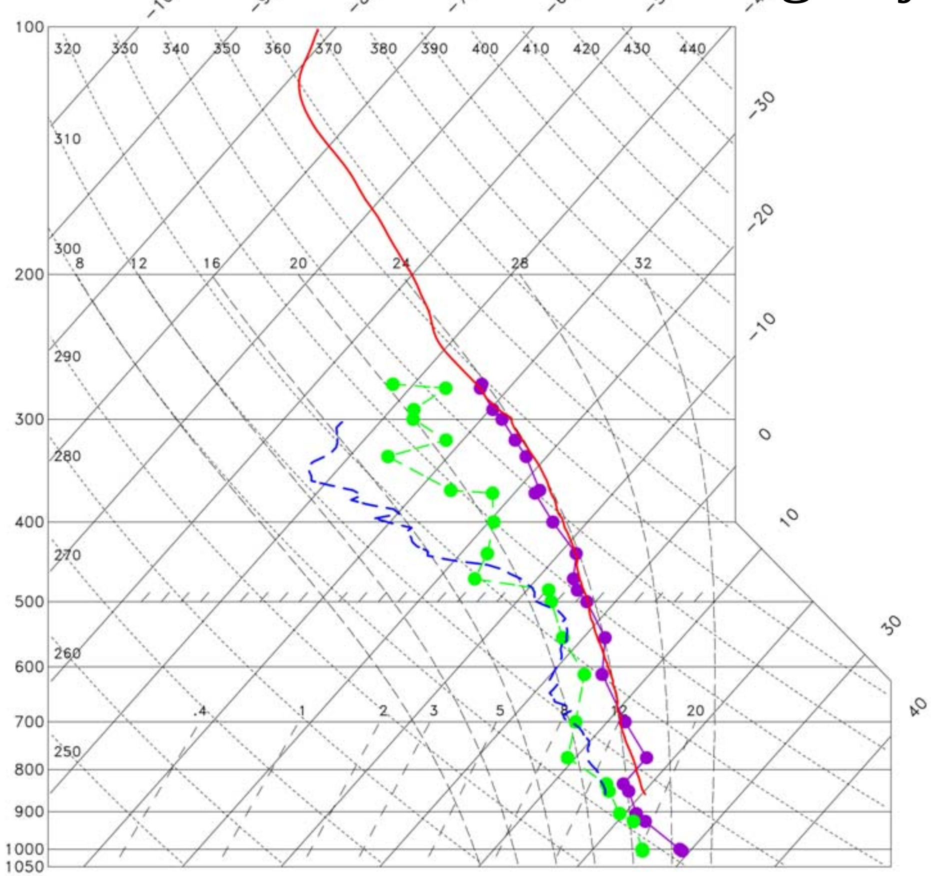
0055 UTC October 22, 1995 over China

CHAMP sounding in Typhoon

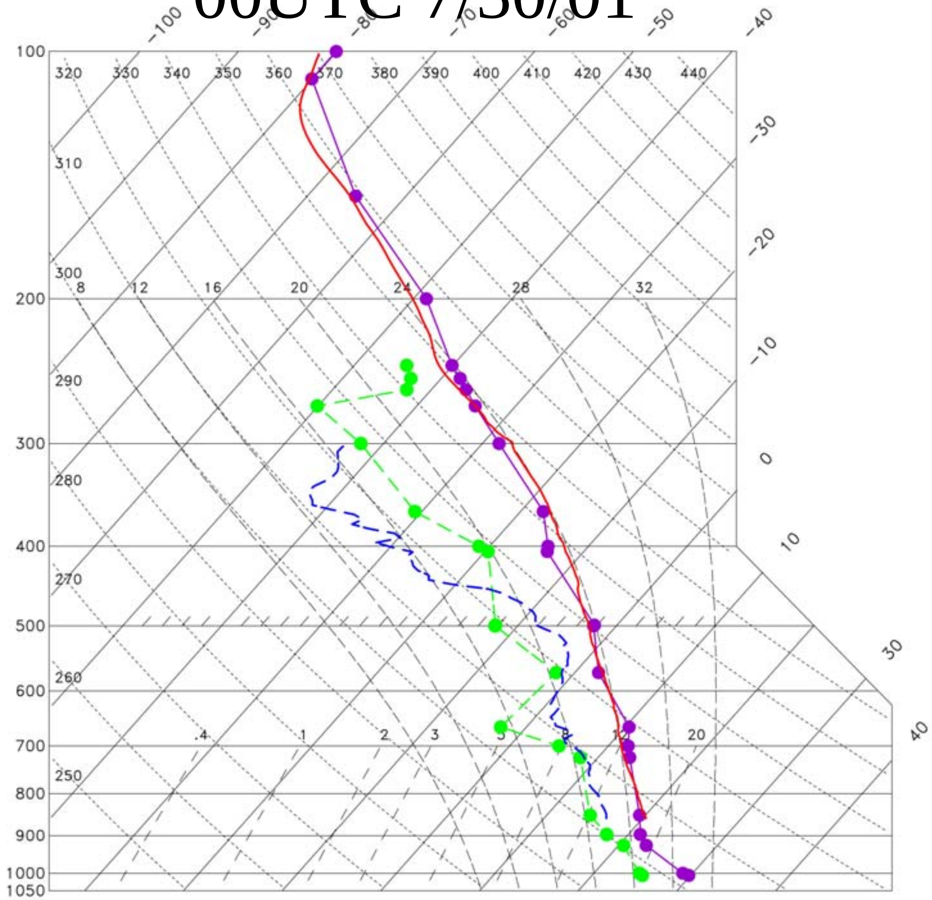


CHAMP compared to two radiosondes in Typhoon

18UTC 7/29/01 Ishigakijima 00UTC 7/30/01



ISHIGAKIJIMA (47918) RAOBS (DOTS) 1800 UTC, July 29, 2001 (24.33N, 124.17E)
CHAMP (LINES) 2008 UTC, July 29, 2001 (21.74N, 122.90E)
Distance 317.39 km

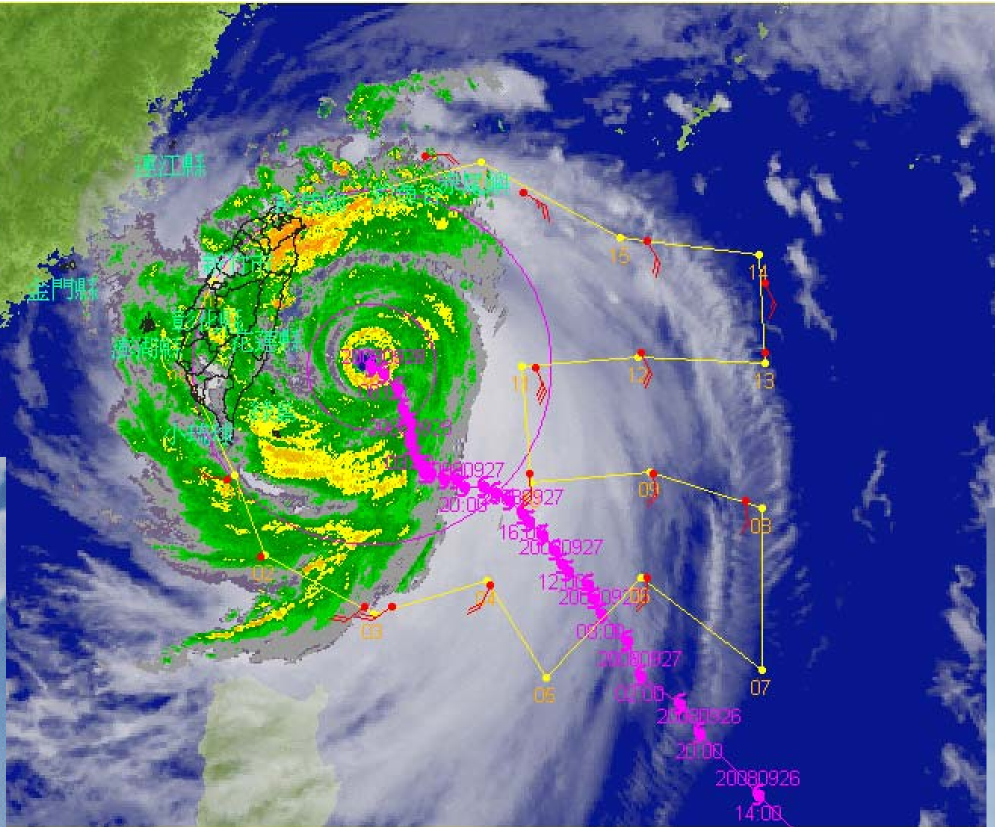


ISHIGAKIJIMA (47918) RAOBS (DOTS) 0000 UTC, July 30, 2001 (24.33N, 124.17E)
CHAMP (LINES) 2008 UTC, July 29, 2001 (21.74N, 122.90E)
Distance 317.39 km

CHAMP (red/blue lines): 2008 UTC 29 July 2001

Comparison COSMIC and in-situ sounding data in Typhoon Jangmi

Dropsonde: DOTSTAR 2007-2008 (May-Oct., typhoon season)

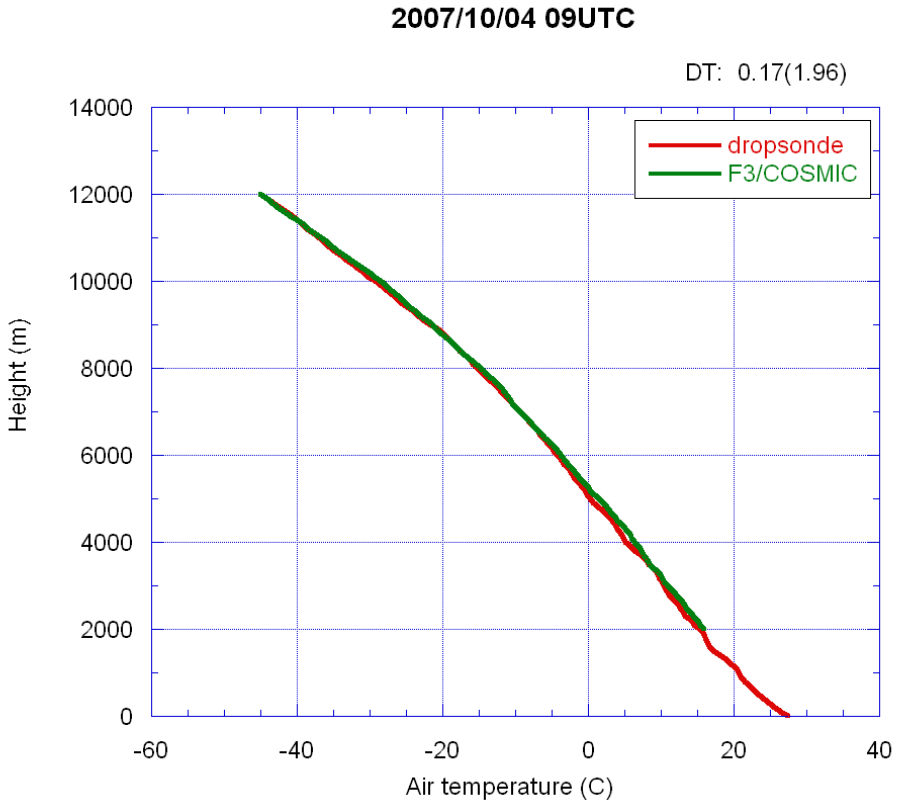


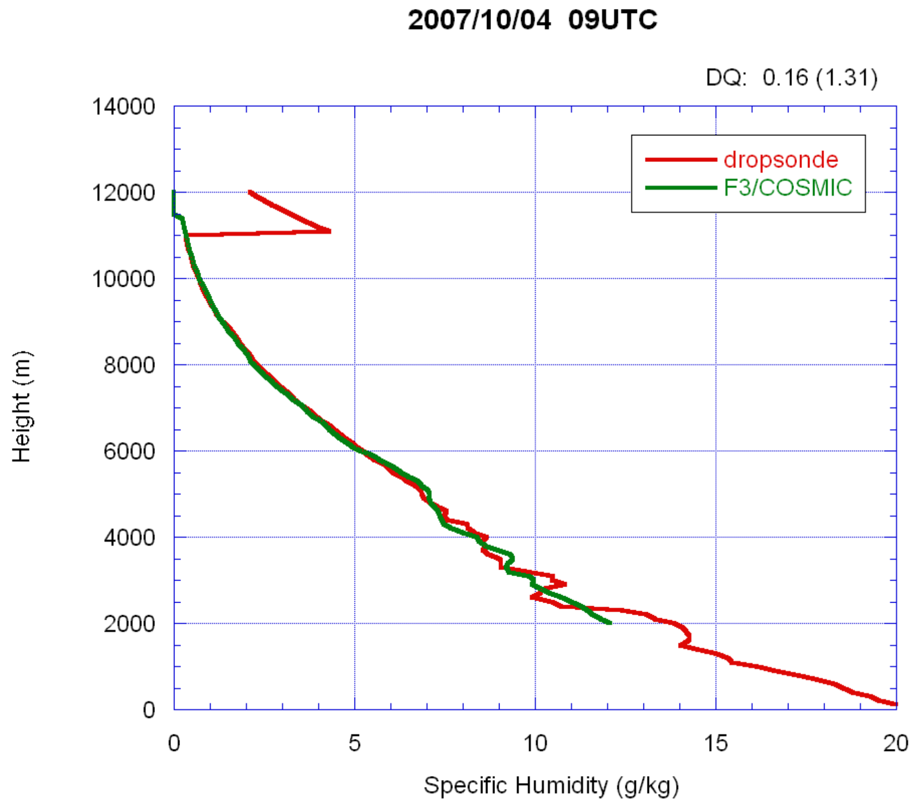
09/28,2008 Typhoon Jangmi

Po-Hsiung Lin
National Taiwan University

ck Anthes

Dropsonde minus F3/COSMIC





DT: 0.17 ± 1.96 (℃)

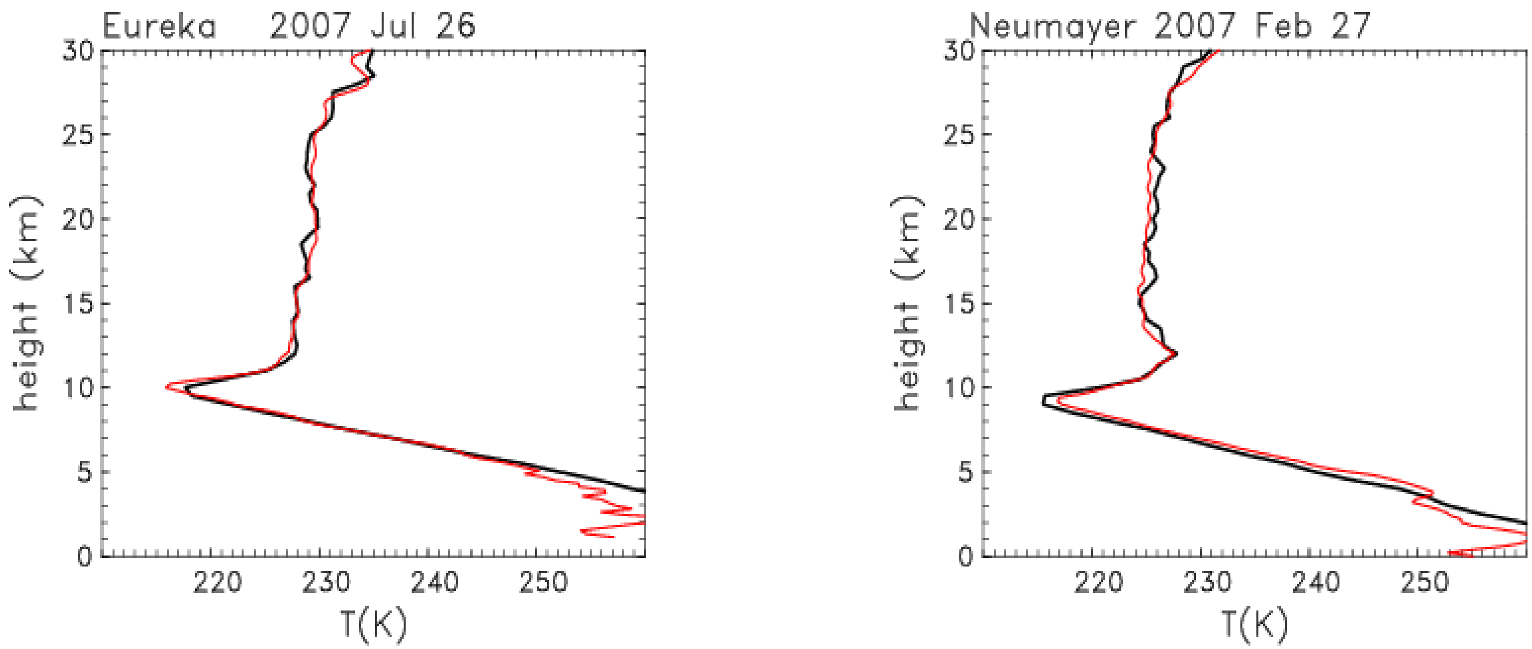
DQ: 0.16 ± 1.31 (g/kg)

The polar summer Tropopause Inversion Layer

Bill Randel
Atmospheric Chemistry Division, NCAR

The polar summer tropopause inversion layer

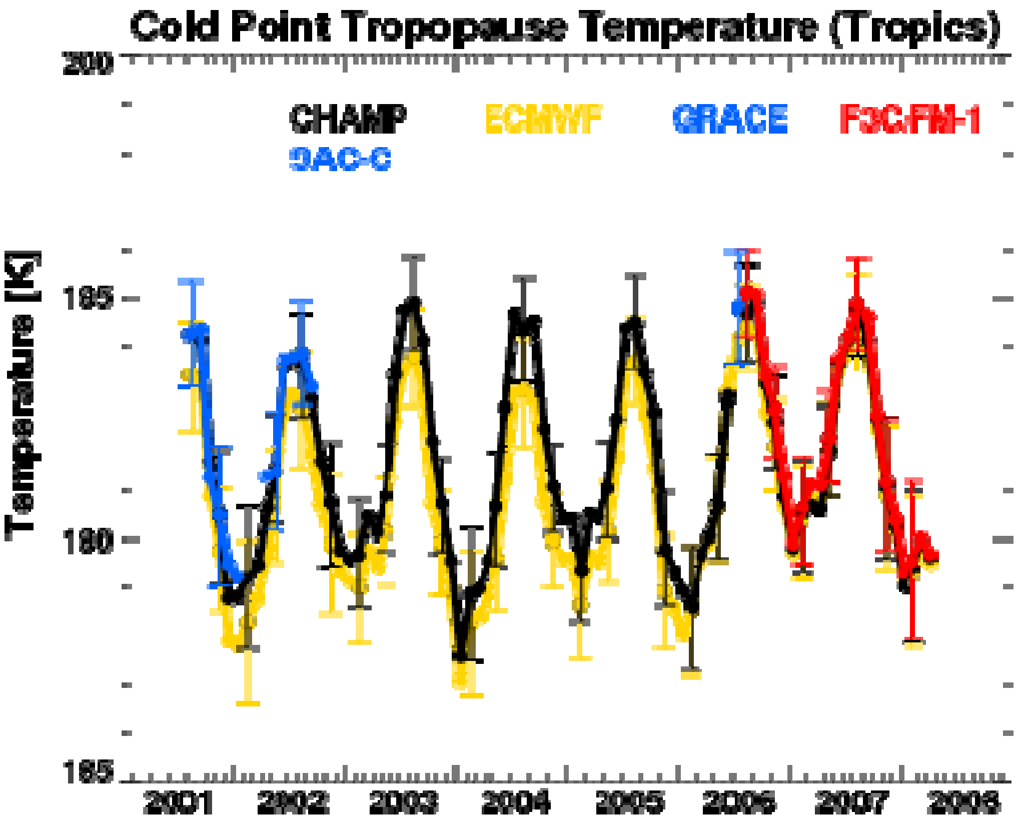
Radiosonde at Eureka (80° N)

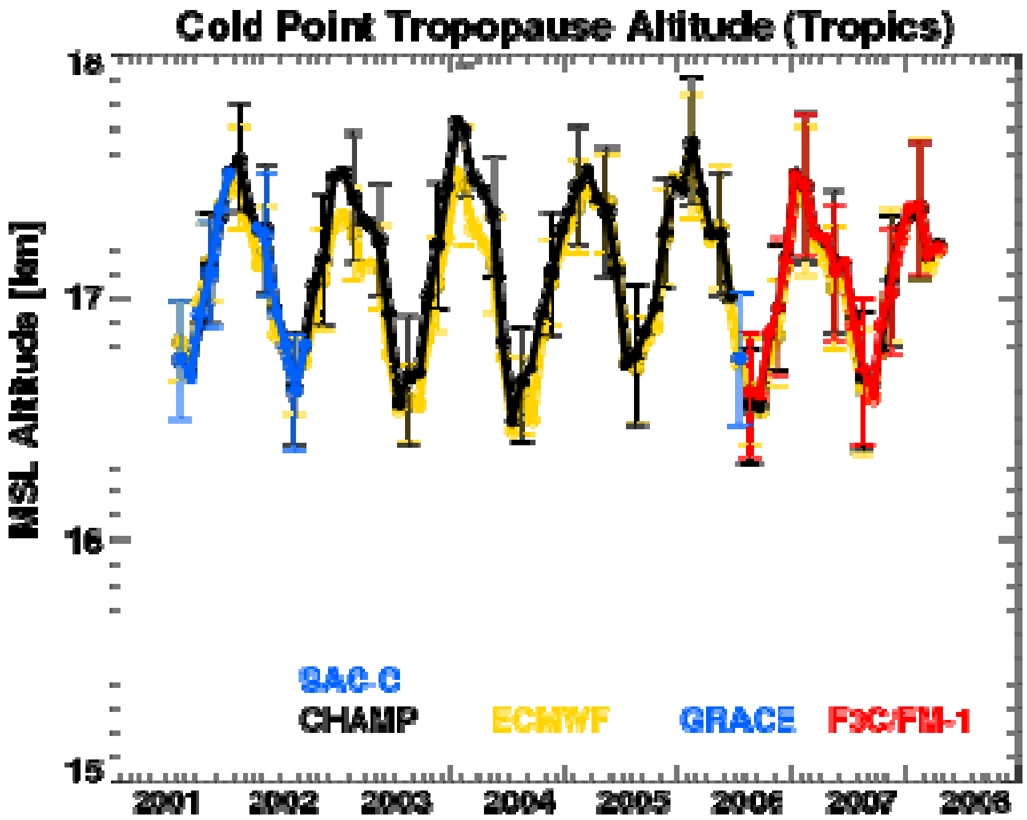


•Important for understanding dynamical (and chemical) coupling between troposphere and stratosphere

• COSMIC allows ~100 times more observations than radiosondes, to study space-time variability of inversion layer

Temporal Evolution: CPTP

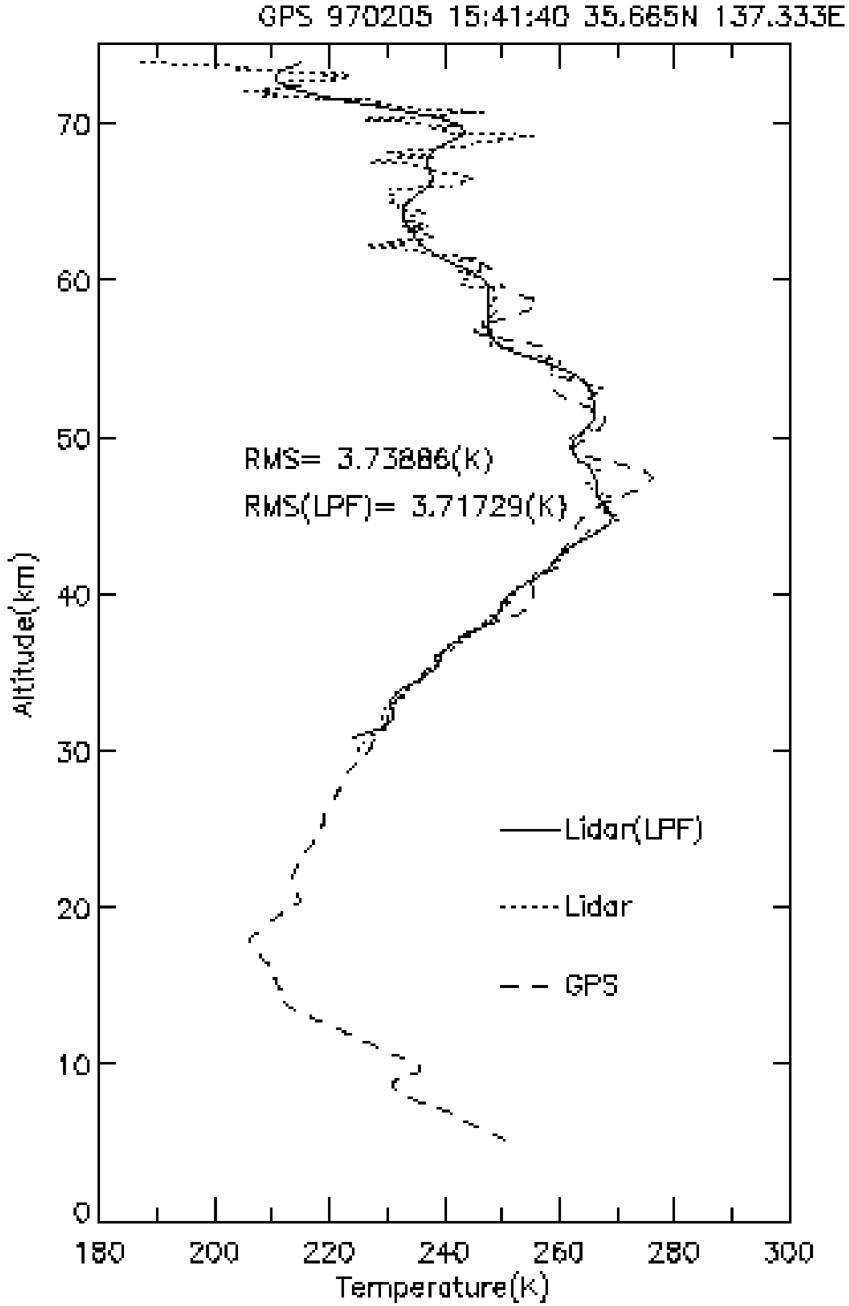




Borsche, Foelsche, Pircher and Kirchengrast, 4th Asian Space Conf Taipei 2008

Gravity Wave Studies

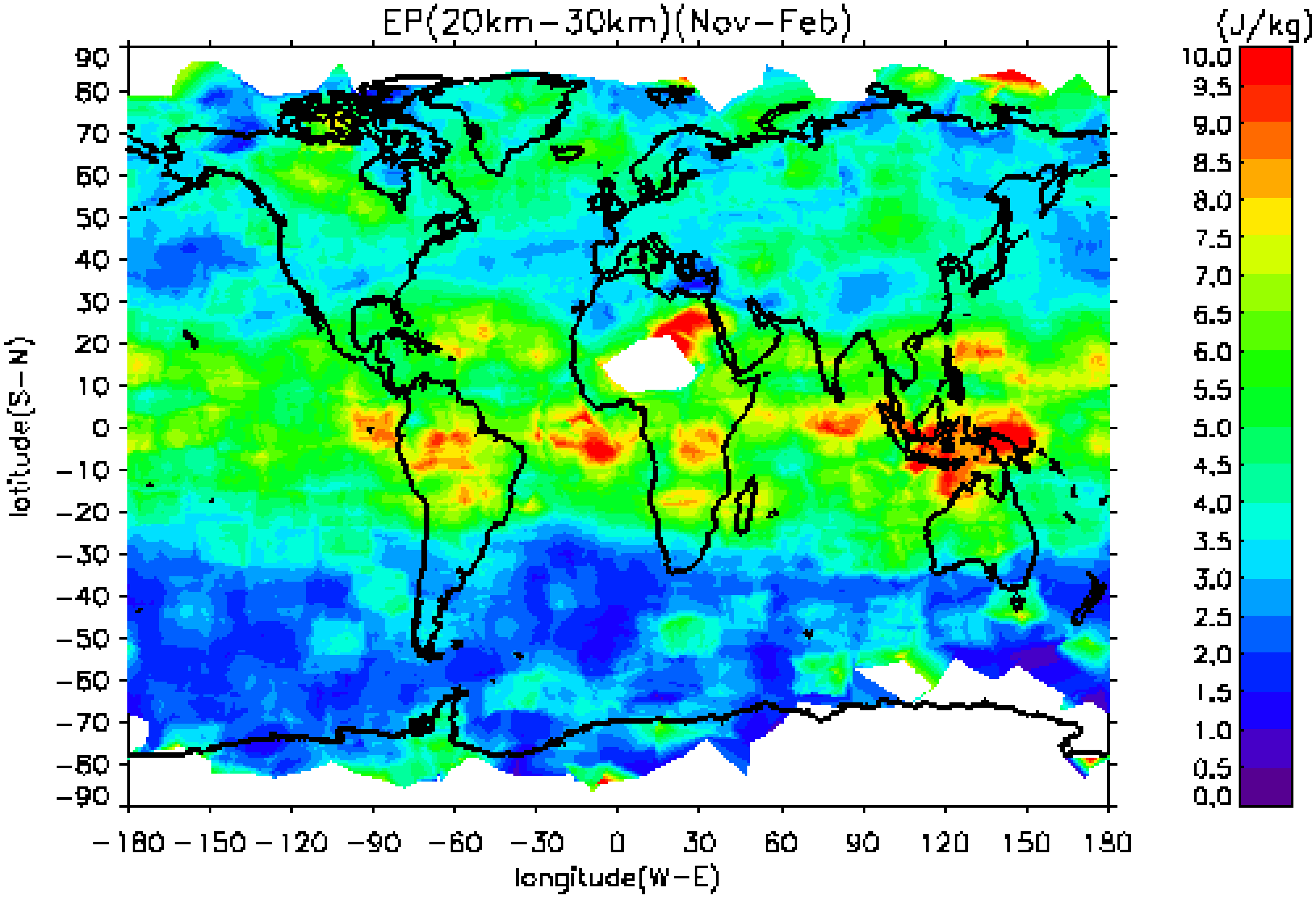
Gravity waves and stratospheric dynamics



Tsuda et al., personal communication, 1999. TAO (2000) p. 132

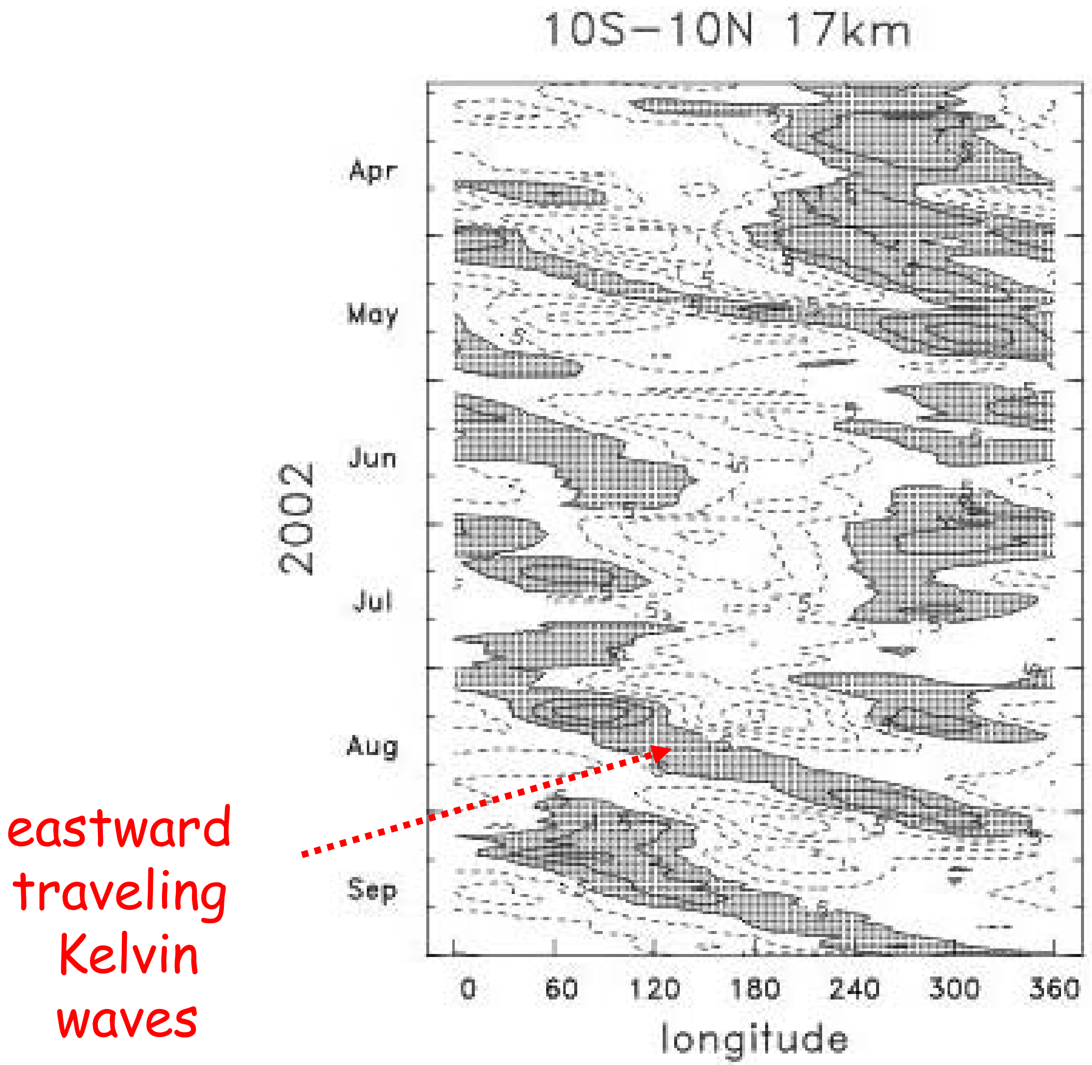
Gravity wave climatology

Potential energy due to gravity waves computed from 1996/97 GPS/MET T data



Tsuda *et al.*, 2000

Kelvin waves near the tropopause

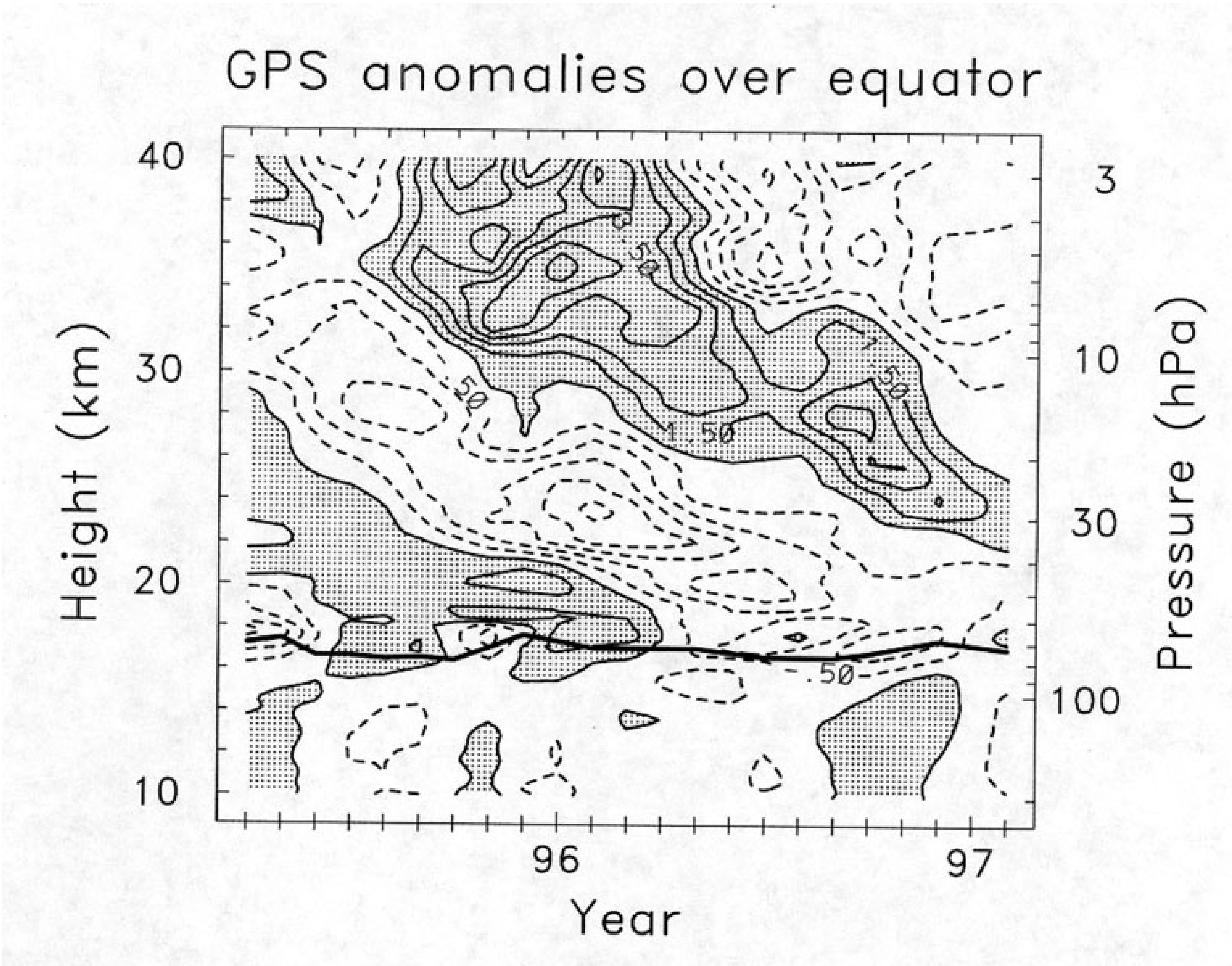


Randel and Wu, 2004

QBO over Equator

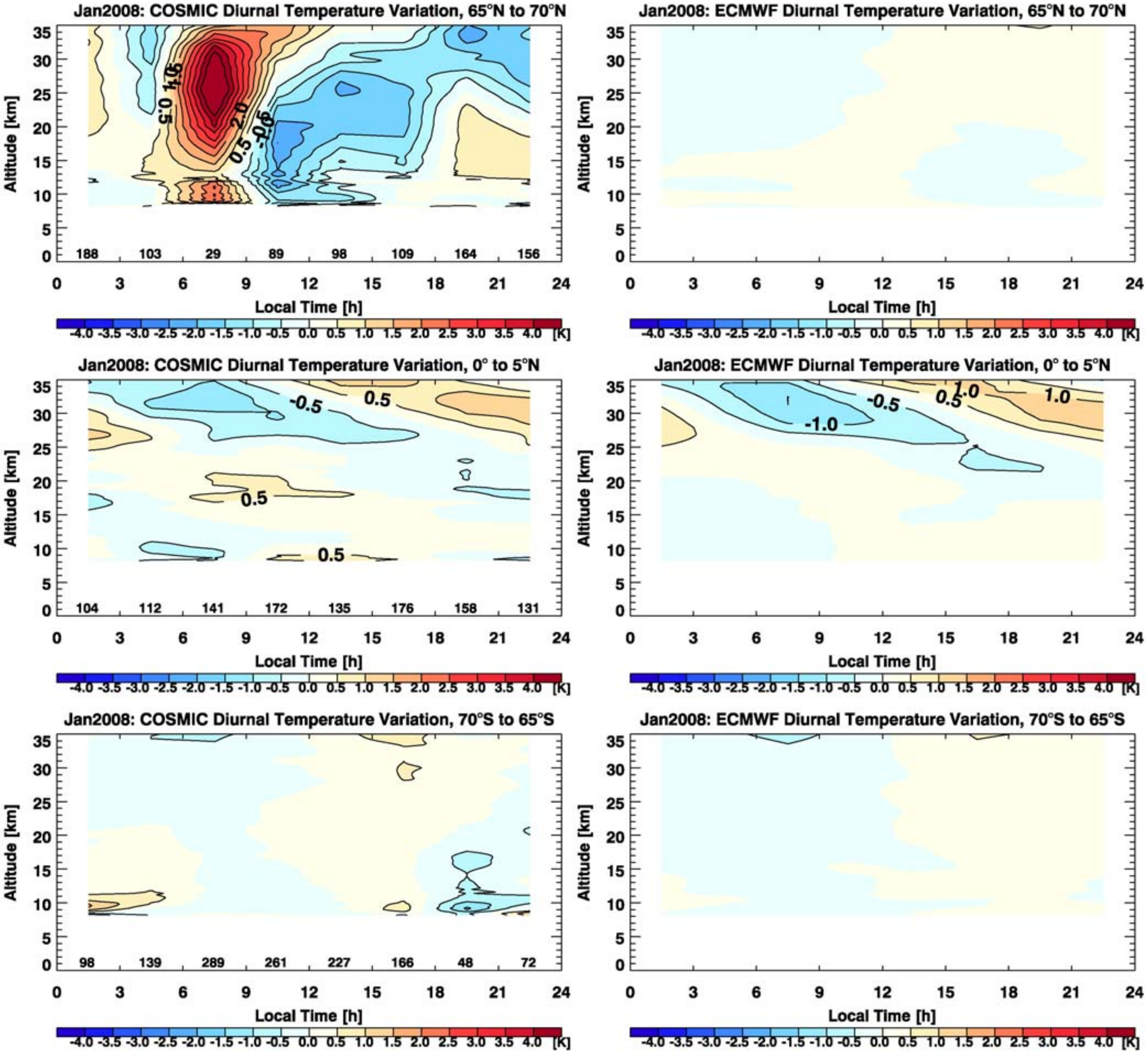
Deseasonalized
T anomalies.
4S-4N.
Downward prop
patterns assoc
with QBO.

Contours 0.5 K



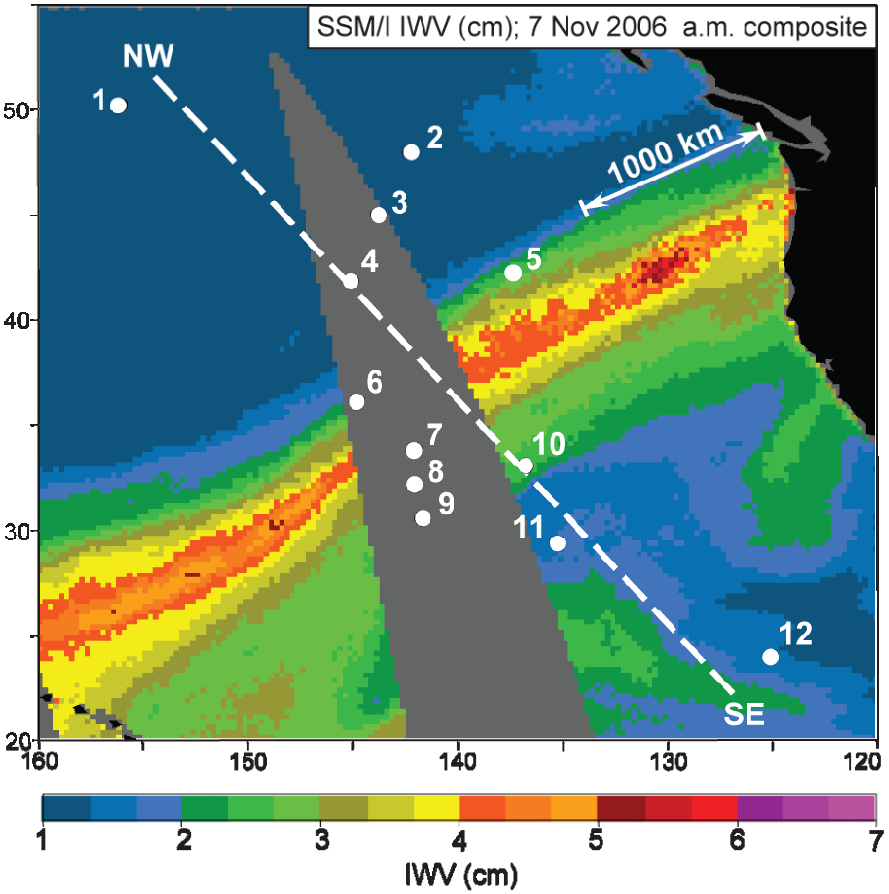
Randel *et al.*, 2003

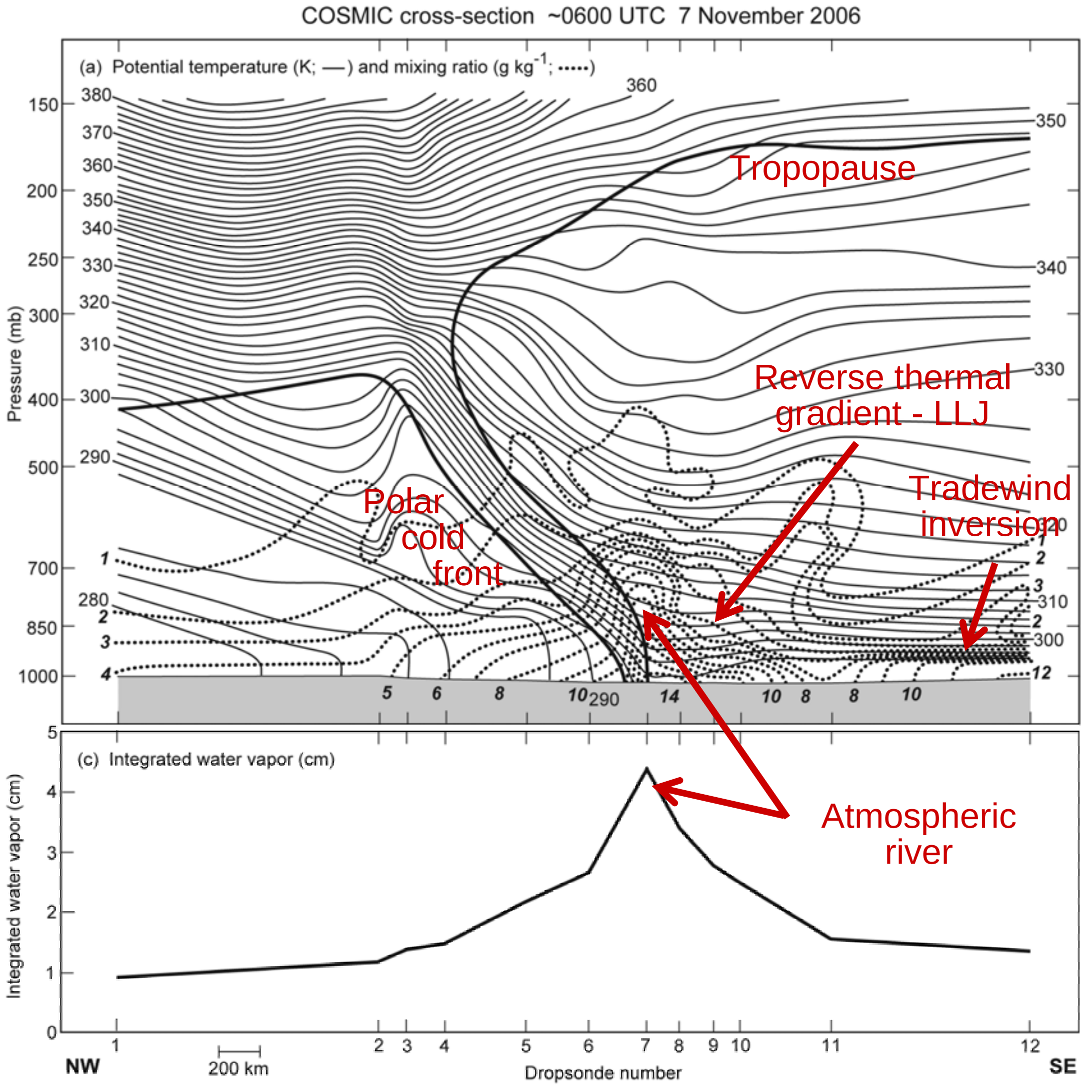
Diurnal tides from COSMIC



Pirscher, Foelsche, Borsche, Kirchengast and Kuo, JGR 2010

COSMIC-Derived Cross Section of an Atmospheric River



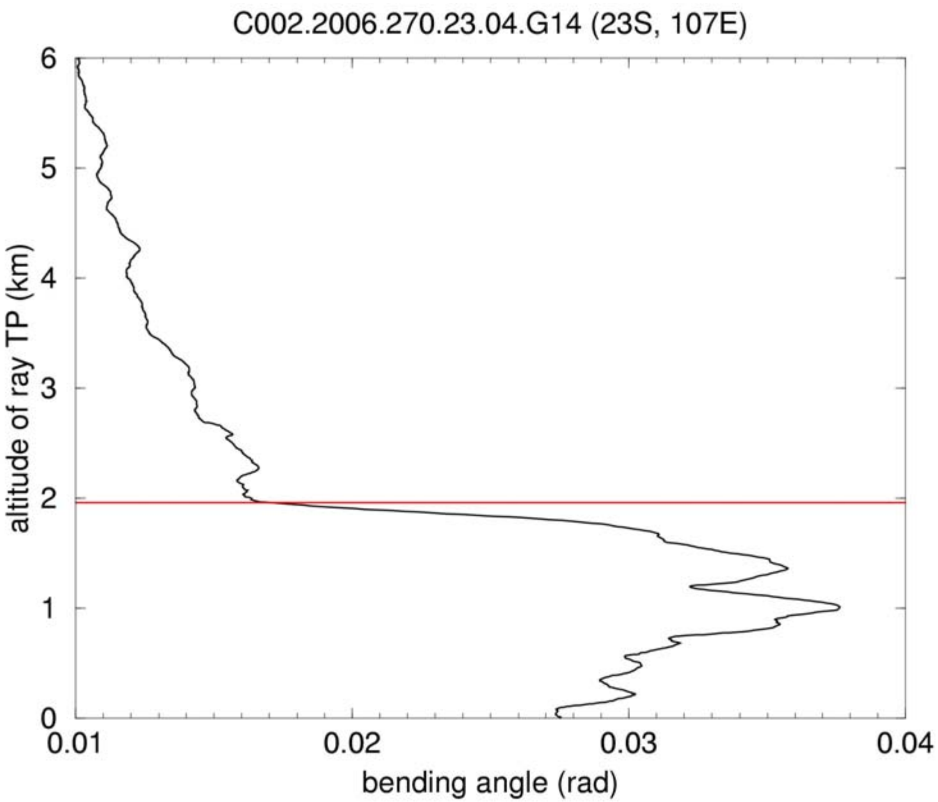


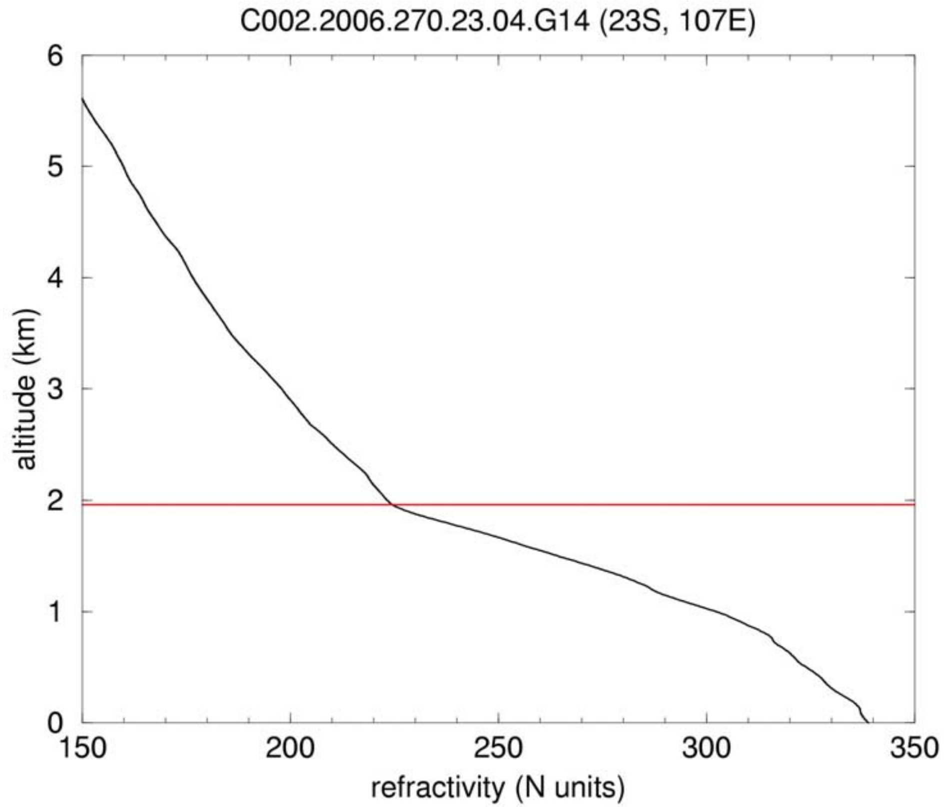
- 12 COSMIC soundings used to construct X-section along NW-SE axis through the AR
- The COSMIC soundings yield cross-sectional thermodynamic structures comparable in character and detail to previous aircraft-based dropsonde surveys.

ABL Studies

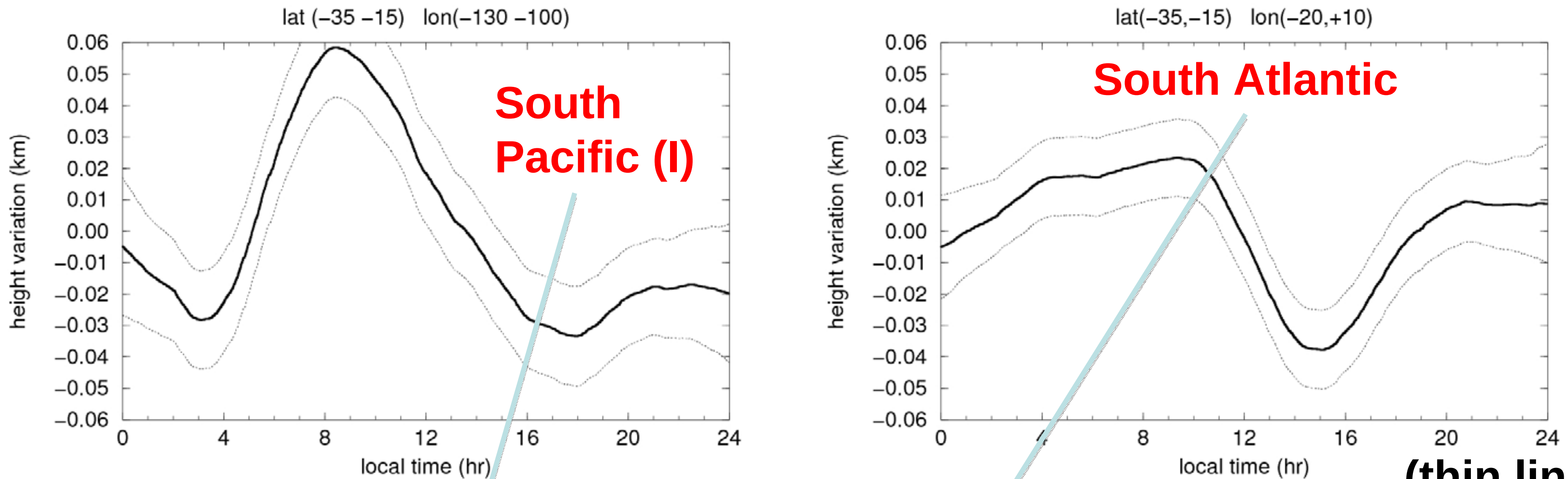
- RO only technology for profiling atmospheric boundary layer from space

First atmospheric boundary layer measurements from space.
Sharp boundary (ABL top) at ~ 2 km altitude

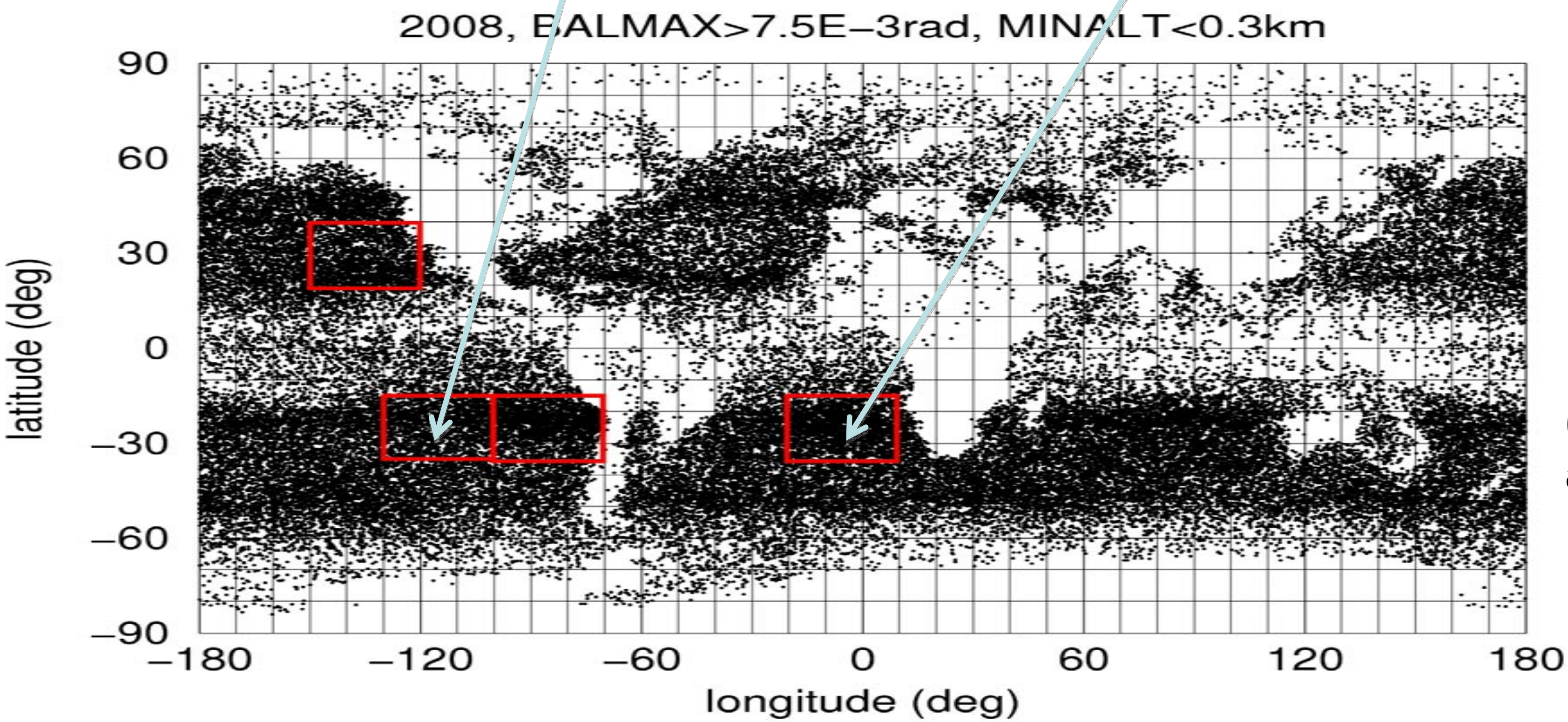




Diurnal variations of the ABL depth over the Ocean



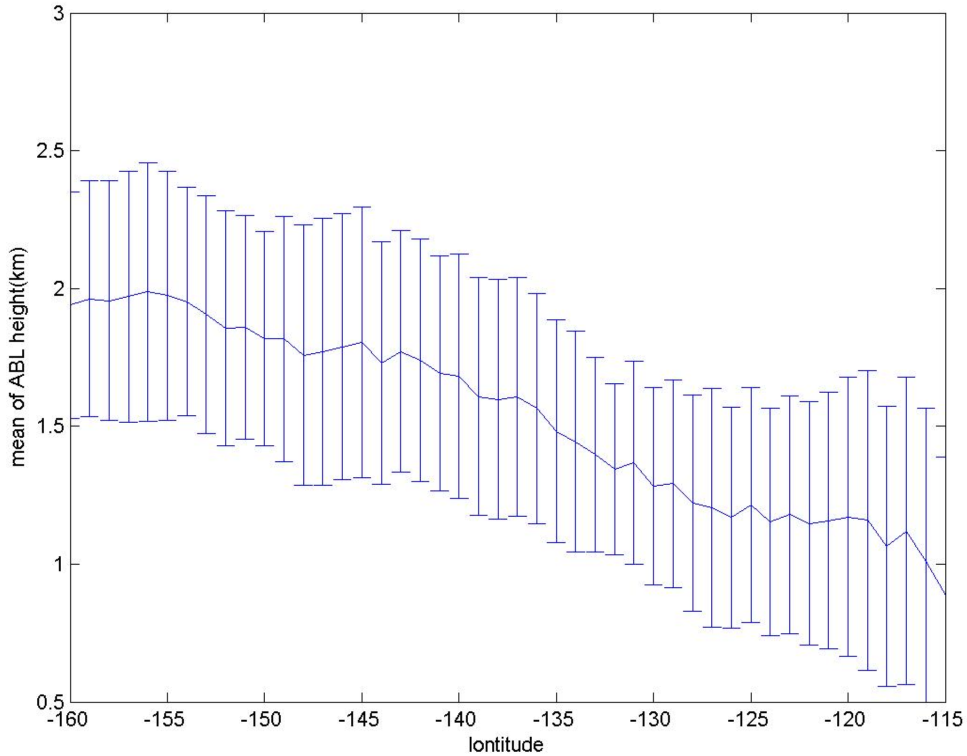
(thin lines – standard deviations of the mean)



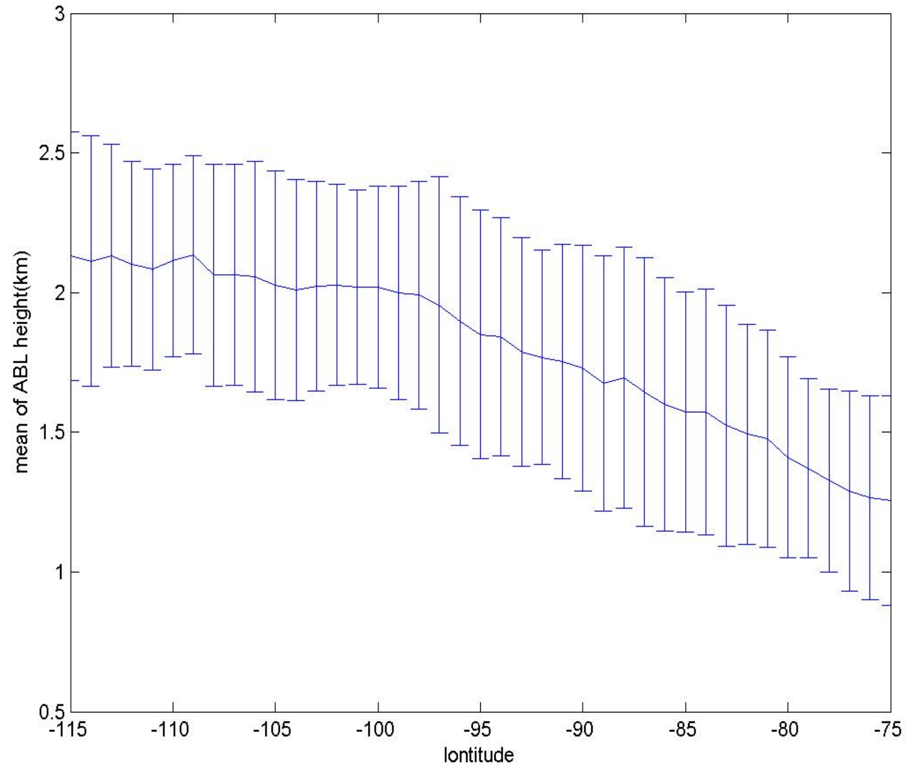
(Sokolovskiy et al., 2009, AMS)

ABL height estimated by COSMIC

California coast to Hawaii



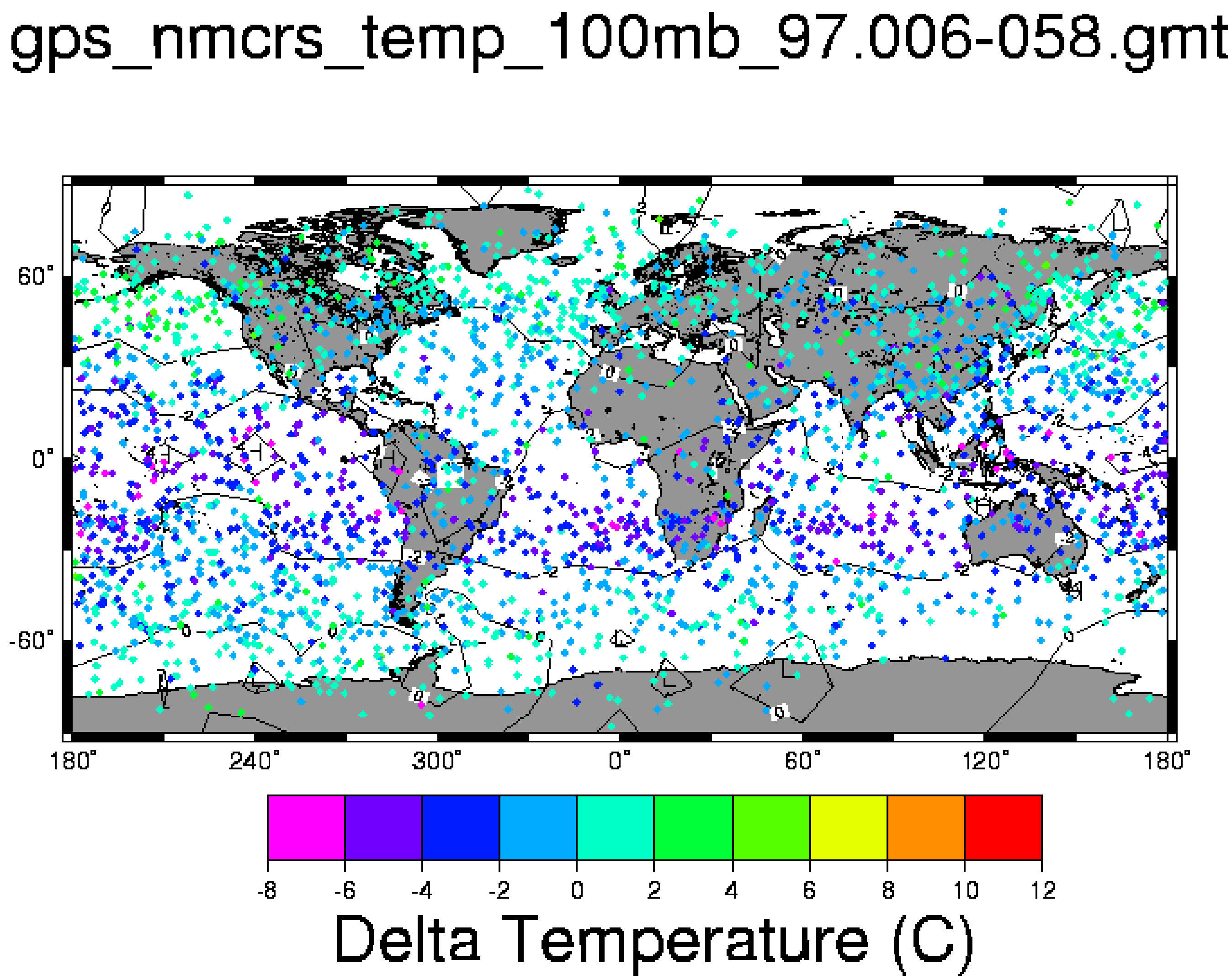
S. America - VOCALS region



Mean ABL height cross-section along the line AB (left) and DC (right). Vertical lines indicate the error bars

Numerical Weather Analyses and Predictions

GPS – NCEP/NCAR Reanalysis

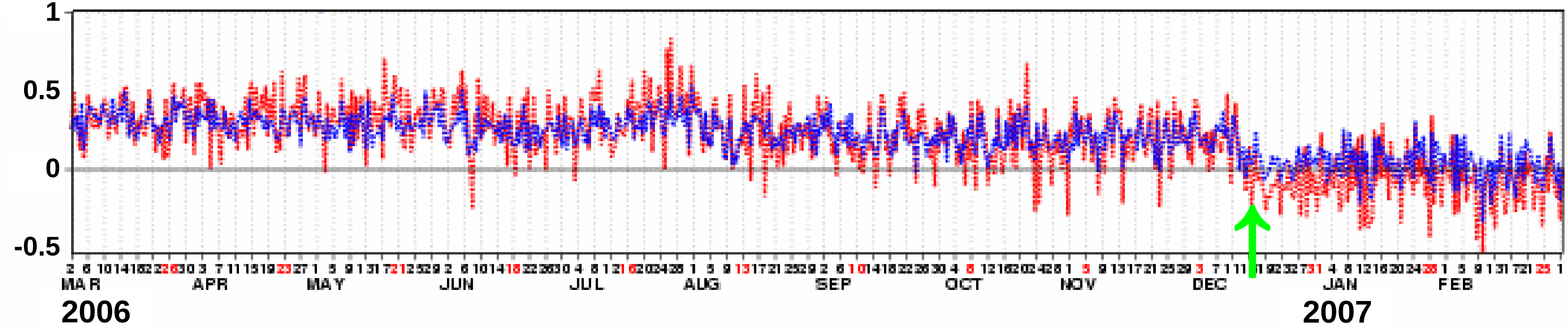


100 mb Temperature

Note large errors in reanalysis near Equator

ECMWF Operational implementation of GPSRO on Dec 12, 2006

Mean departures of analysis (blue) and background (red) from southern hemisphere radiosonde temperatures (K) at 100hPa

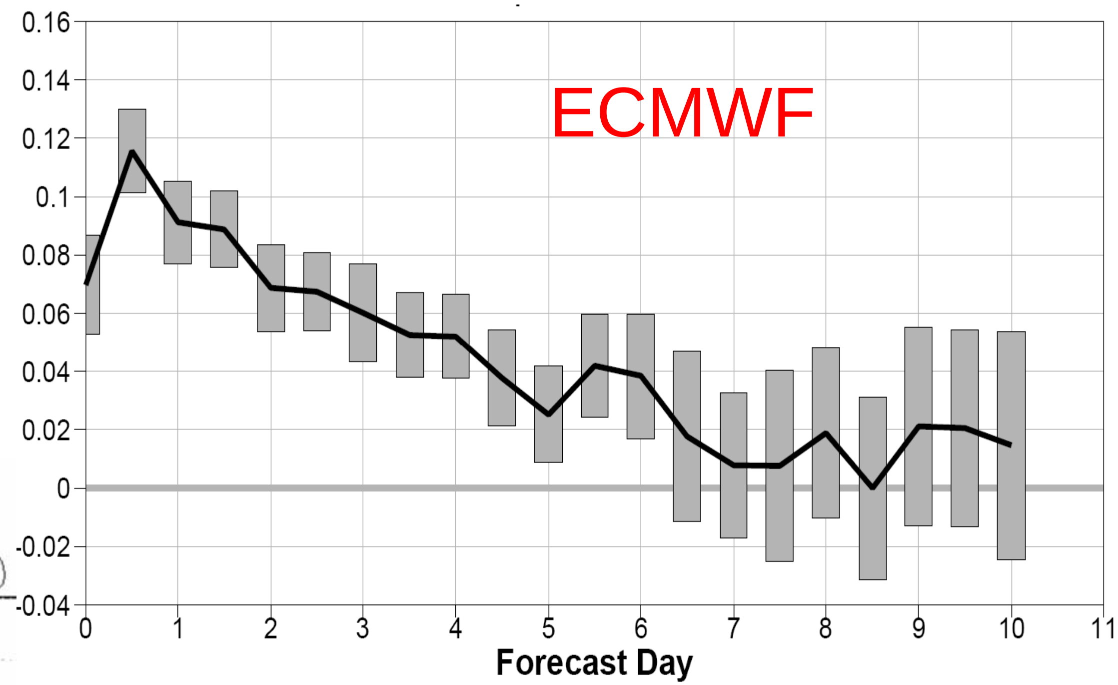


Obvious improvement in time series for operational ECMWF model.

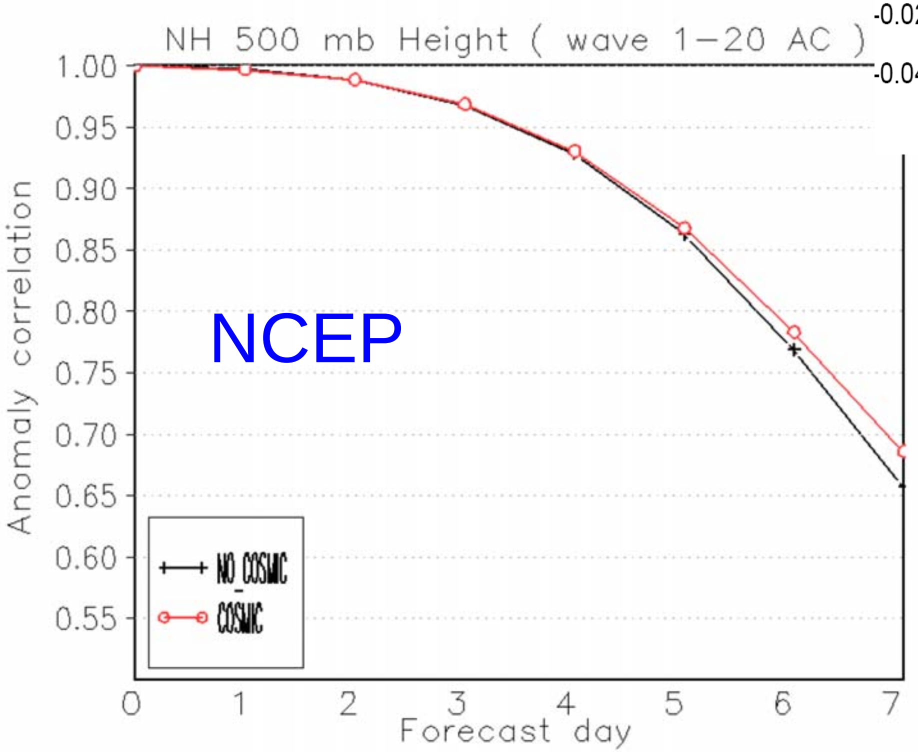
Dec 12, 2006 Operational implementation represented a quite conservative use of data. No measurements assimilated below 4 km, no rising occultations.

Nov 6, 2007 Operational assimilation of rising and setting occultations down to surface

Positive impact at ECMWF and NCEP when COSMIC data assimilated



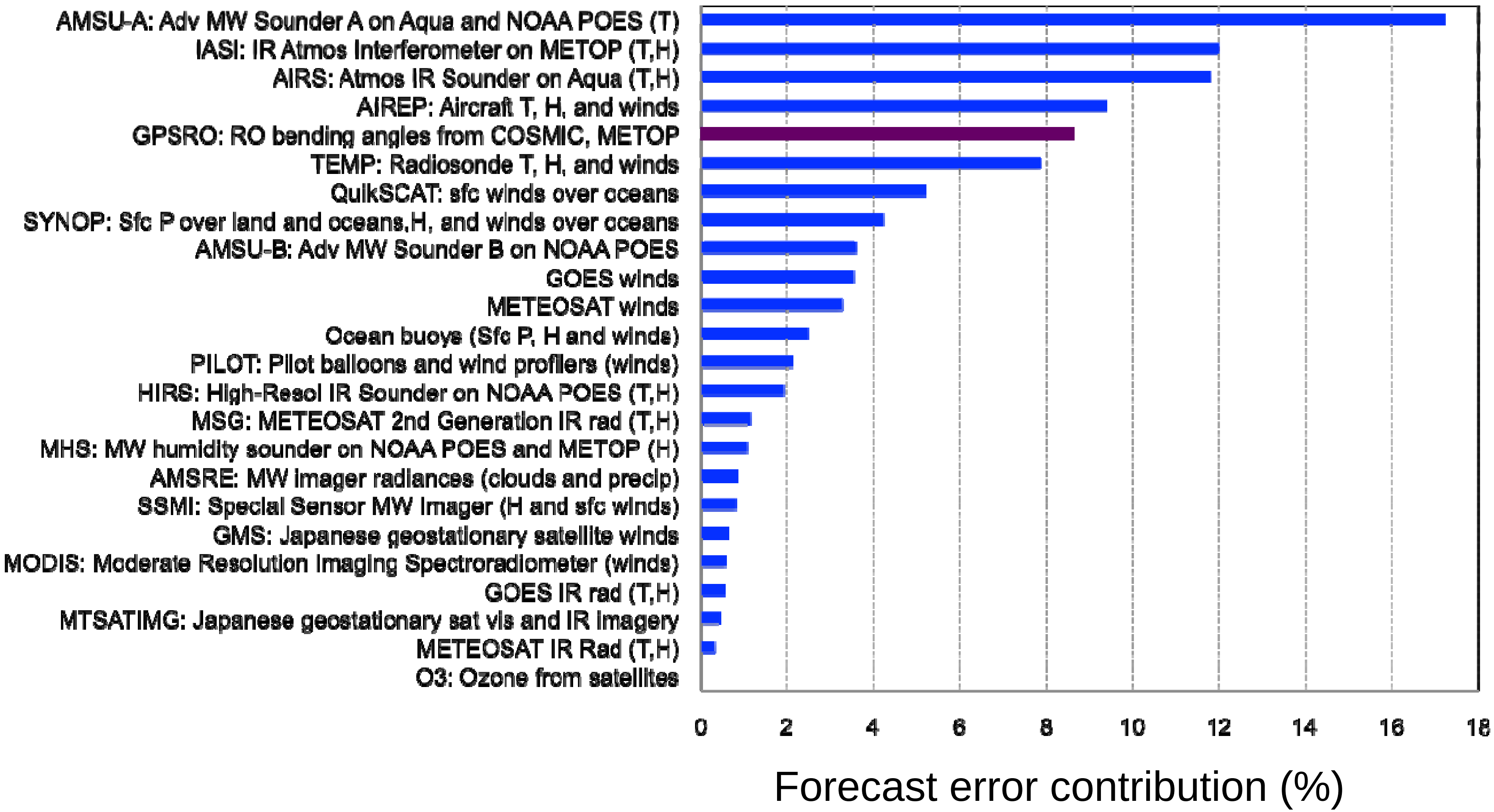
Anomaly correlation for 500 mb Height



Impact of COSMIC on the reduction of forecast errors for the 100 mb temperature over Southern Hemisphere.

0.12 means 12% improvement.

Operational ECMWF system September to December 2008. Averaged over all model layers and entire global atmosphere. % contribution of different observations to reduction in forecast error.

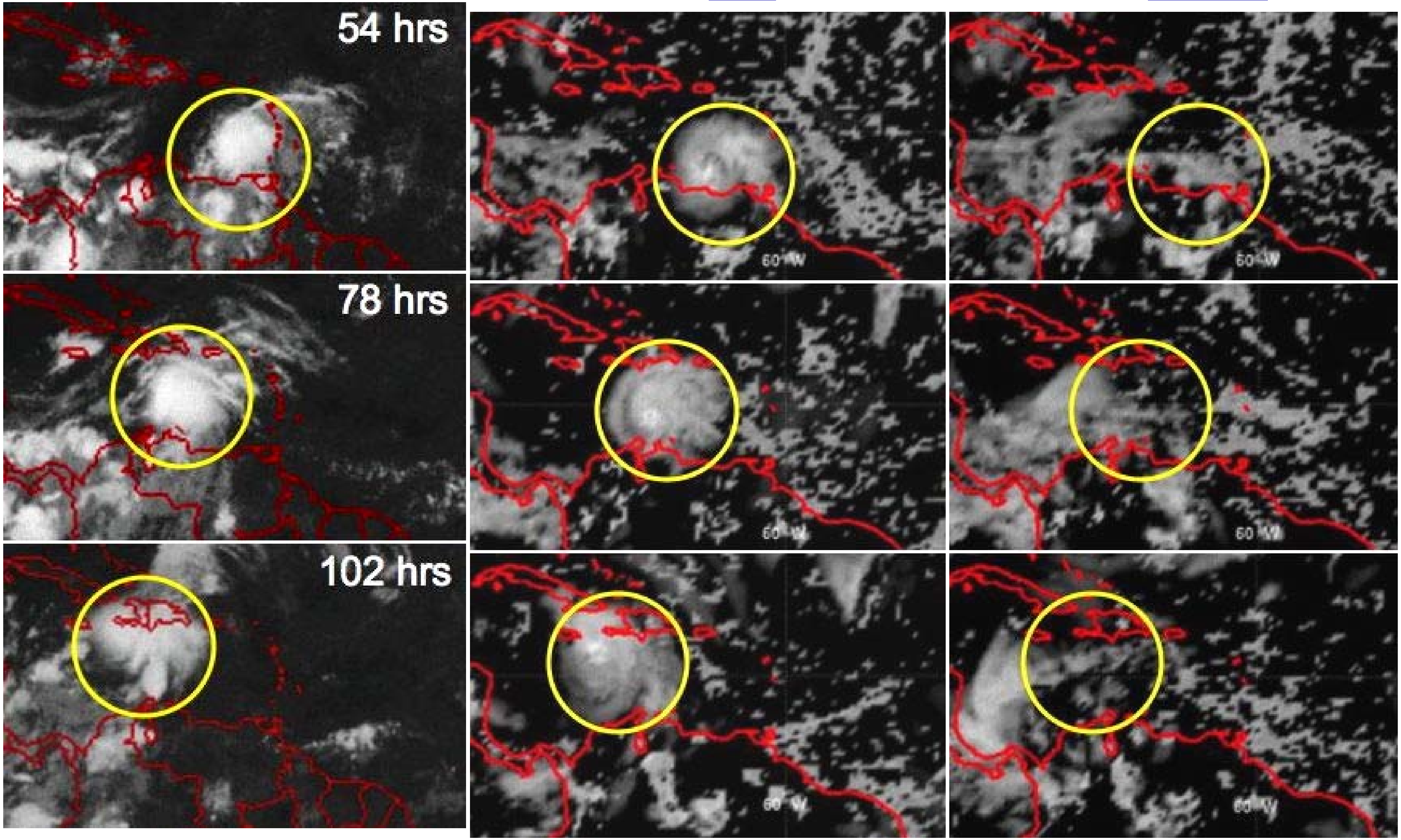


GPS RO has significant impact (ranked #5 among all observing systems) in reducing forecast errors, despite the small number of soundings.

Courtesy: Carla Cardinali and Sean Healy, ECMWF 22 Oct. 2009

NCAR 4-Day Ernesto (2006) Forecasts

The Actual Storm | Forecast with GPS | Forecast without GPS

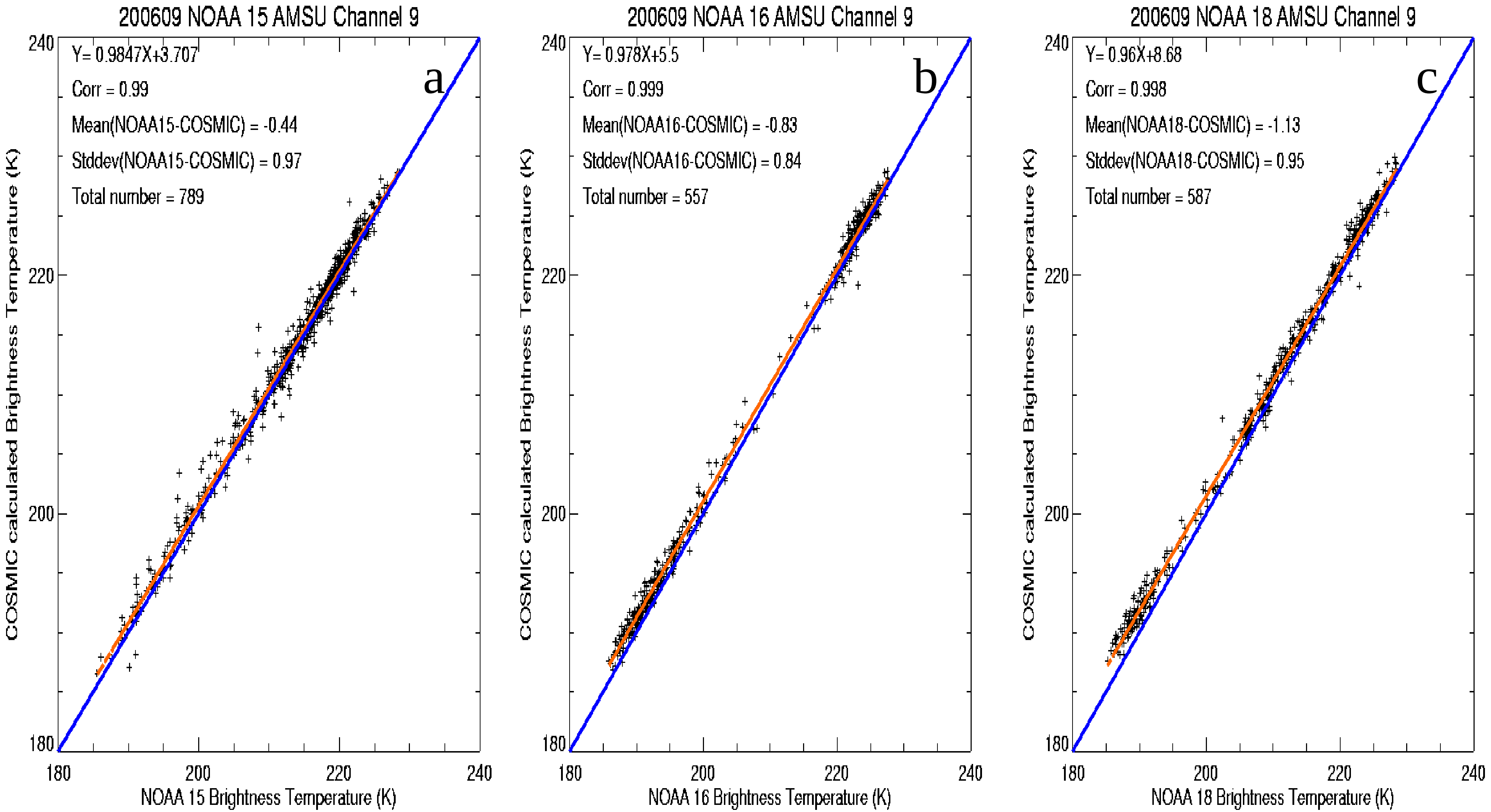


Y.-H. Kuo (NCAR), 2007

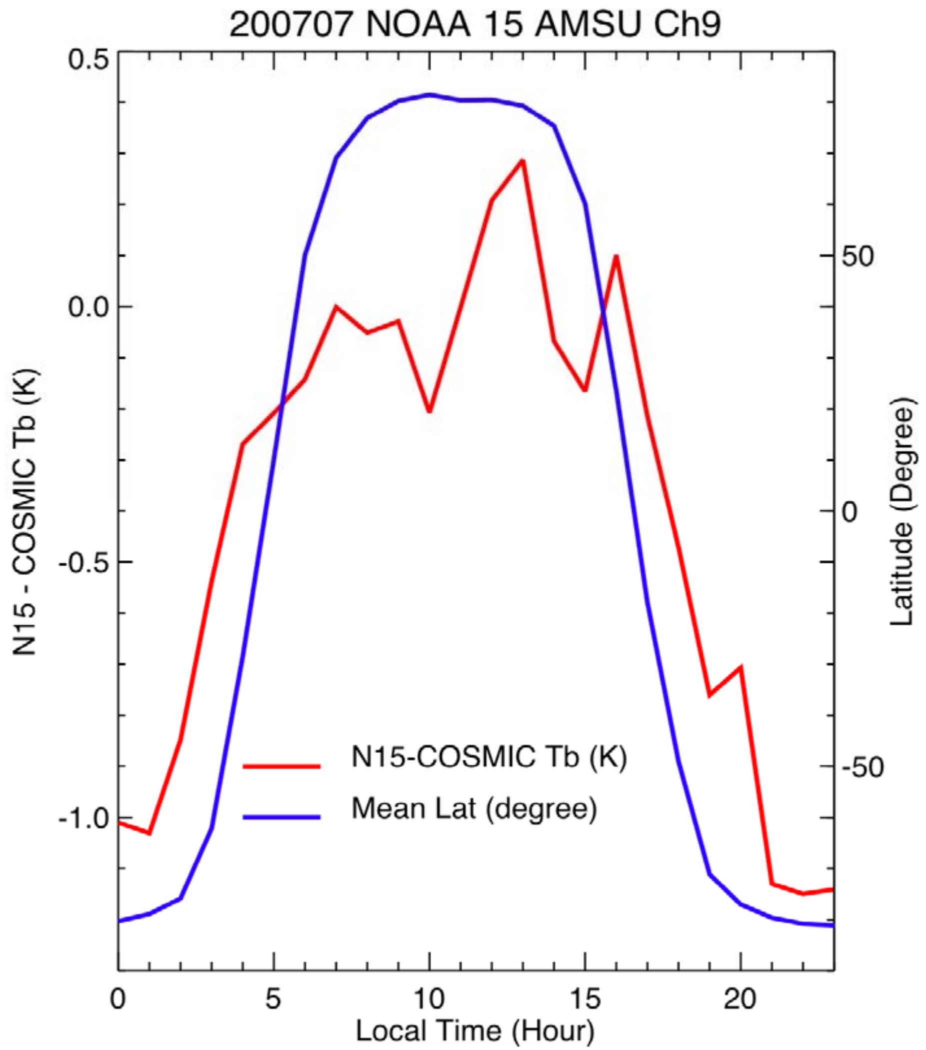
Climate Highlights

- Thanks to Ben Ho for many of these slides
- Ben’s talk will be on Wednesday, 8 September-don’t miss it!

COSMIC data to calibrate AMSU on NOAA satellites



Use of RO Data to Identify the Location/local-time Dependent Brightness Temperature Biases for Climate Studies

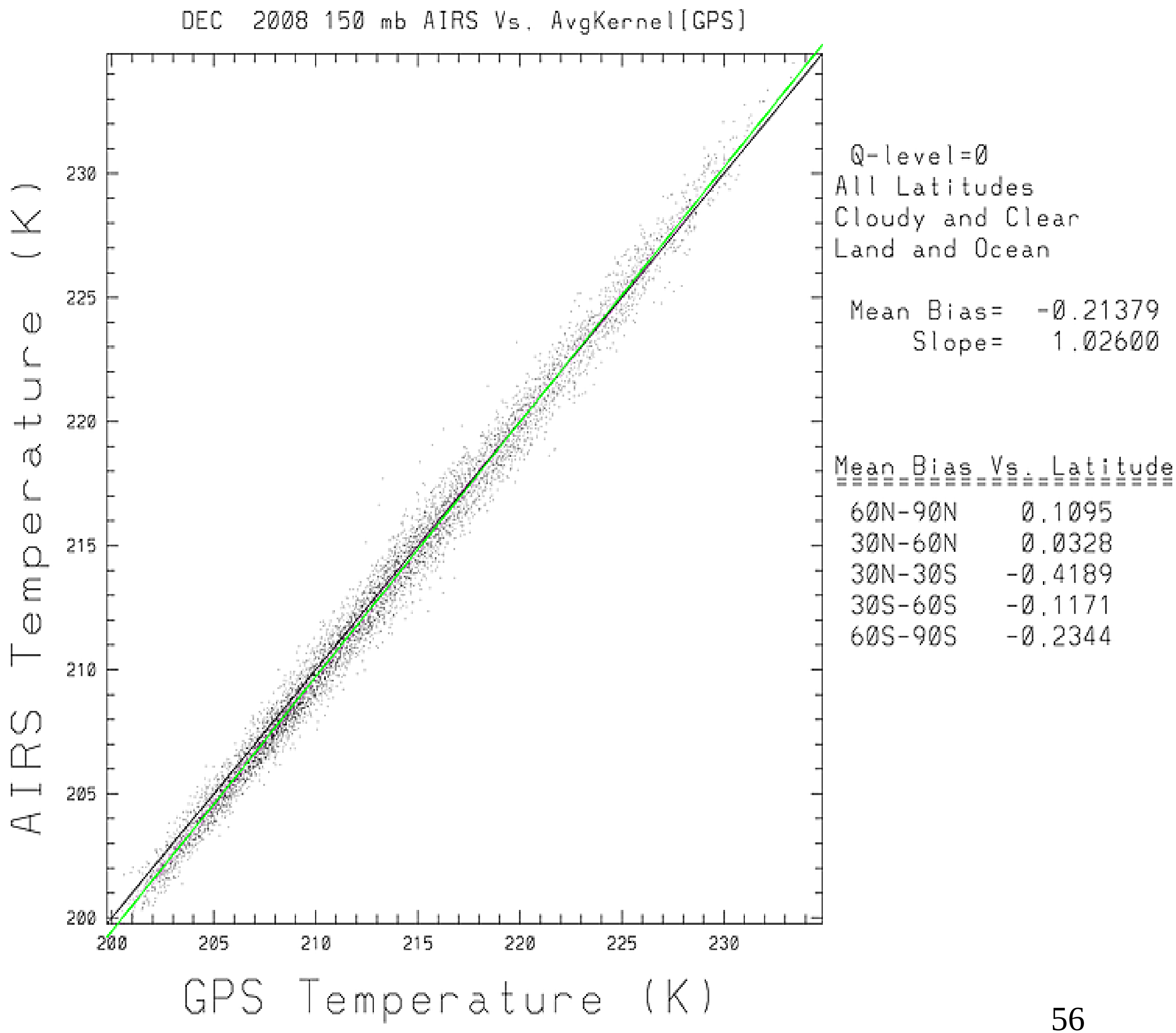


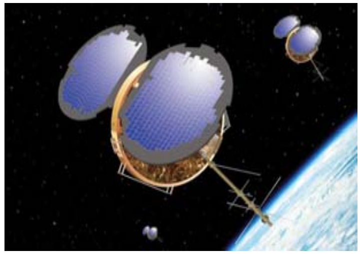
Because RO data are not affected by temperature variations of the satellite, they are very useful to identify the microwave brightness temperature anomalies due to the heating or cooling of the satellite

150 mb AIRS vs. smoothed COSMIC Temperature (K)

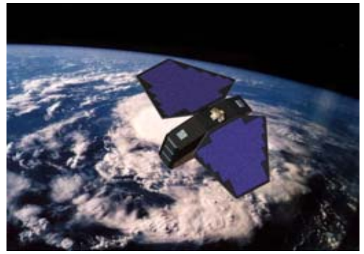
Corr ~ 1.0

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

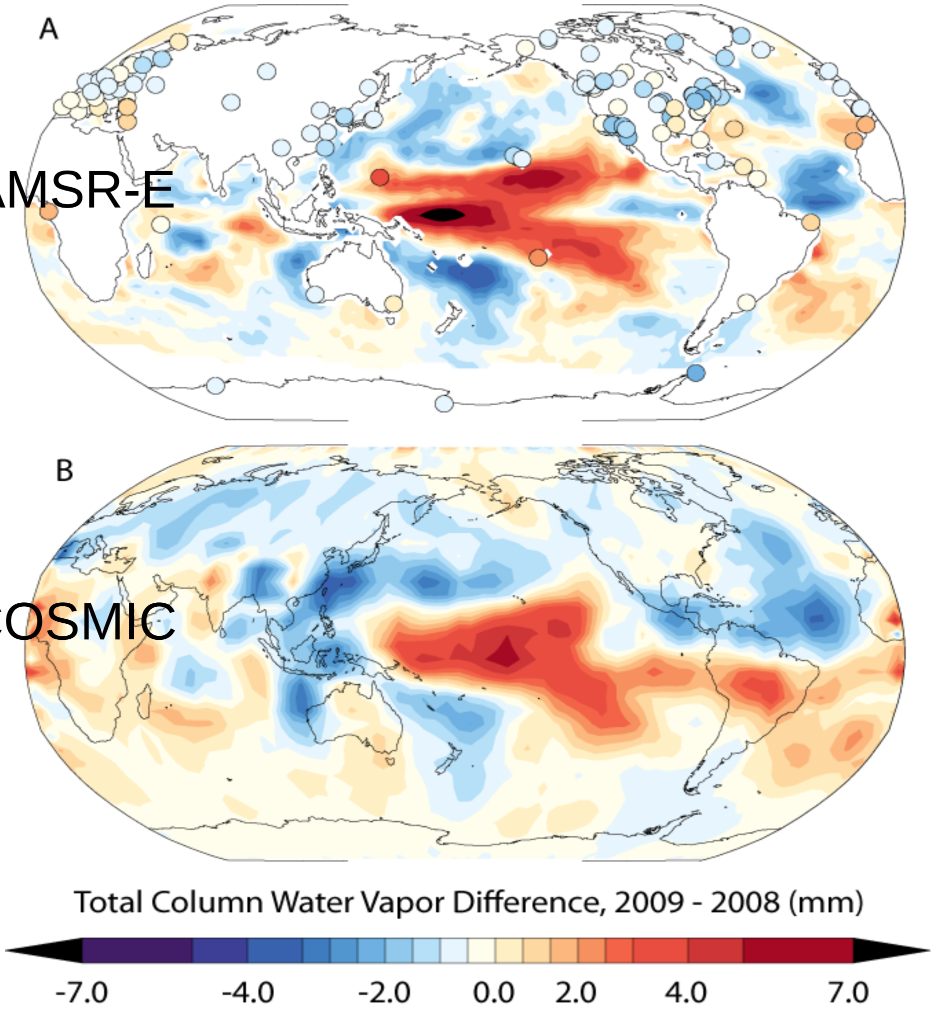




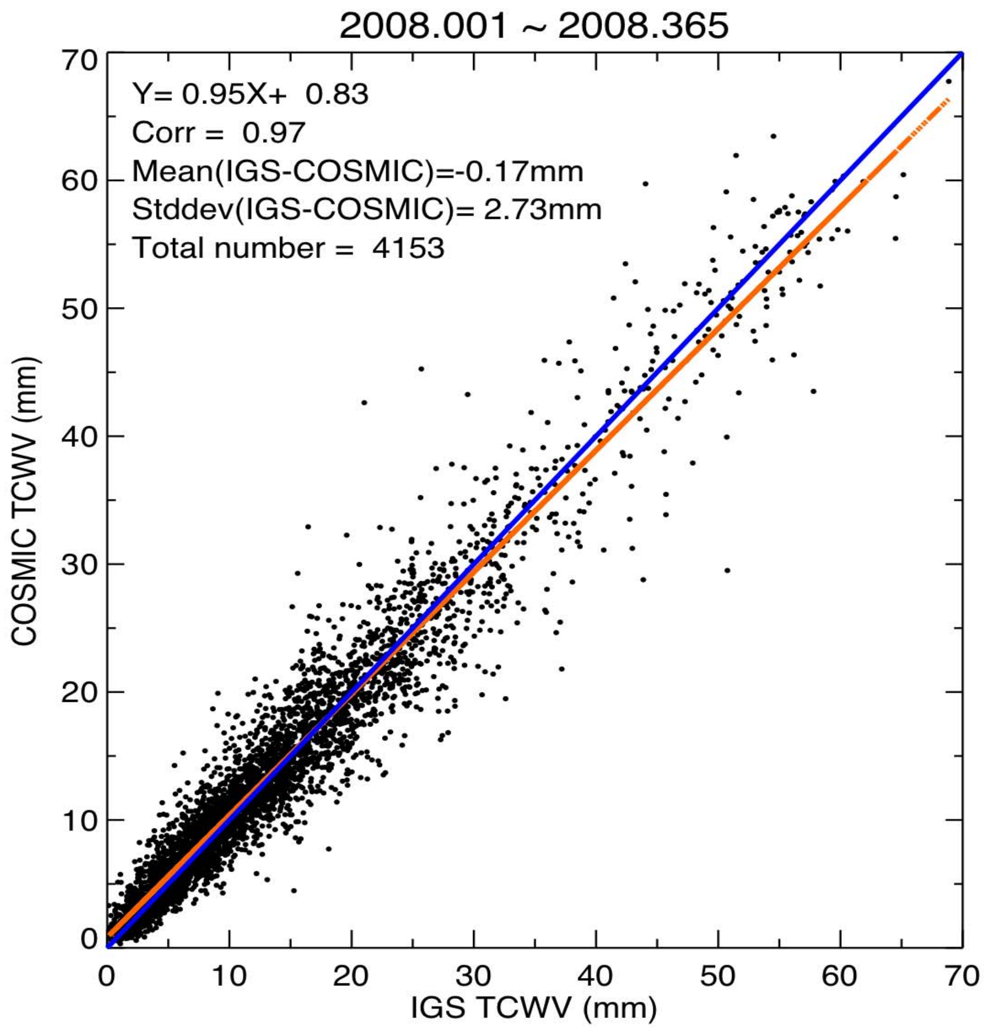
COSMIC vs. AMSR-E and GB-GPS total column water vapor



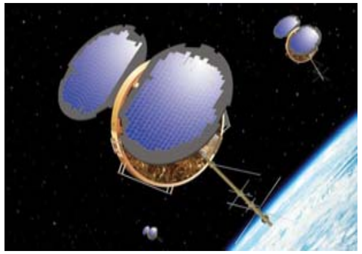
TWP 2009-2008



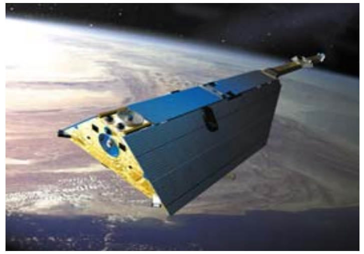
(Mears et al., 2010 BAMS)

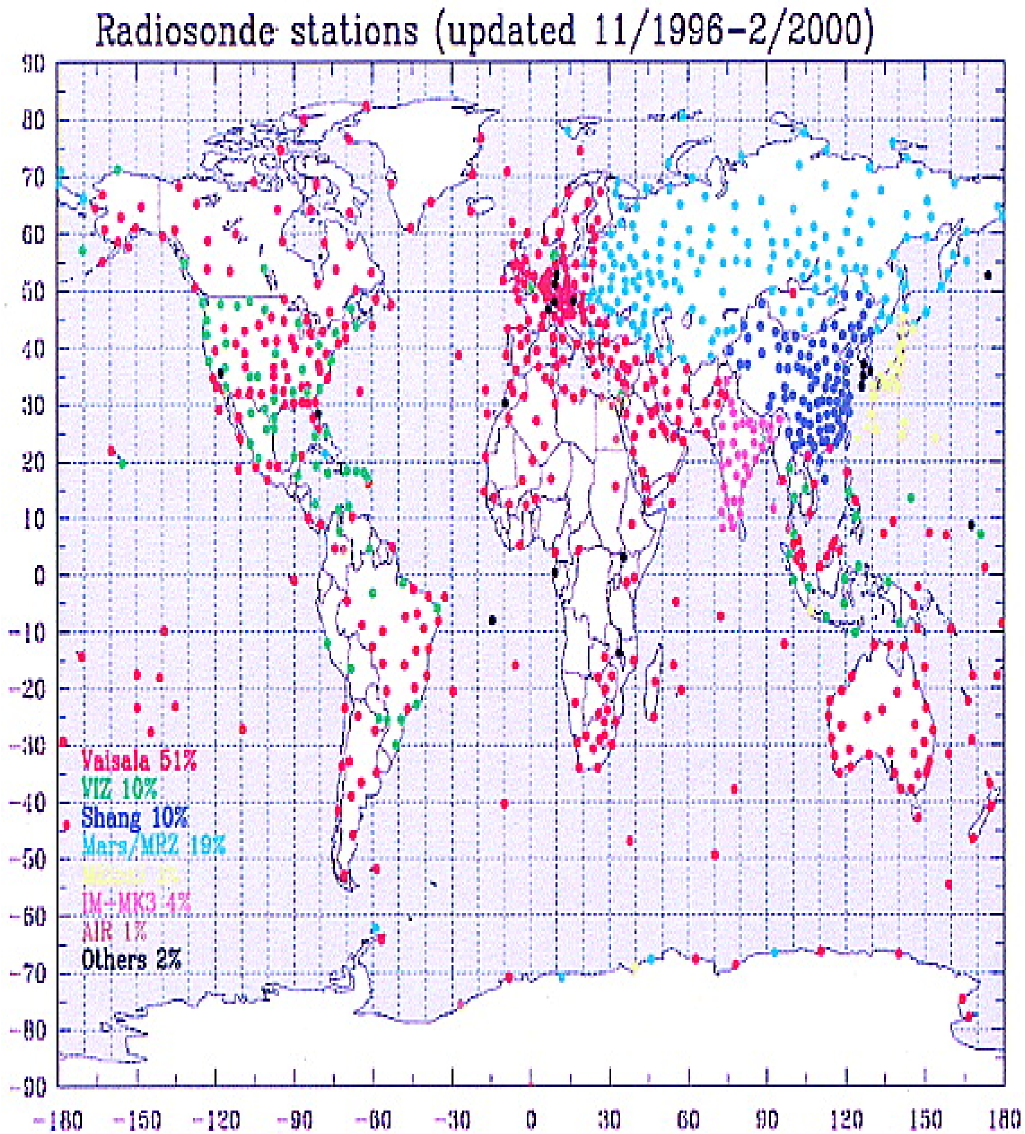


(Ho et al., 2010 BAMS)



Using RO data to assess the quality of radiosonde temperature measurements

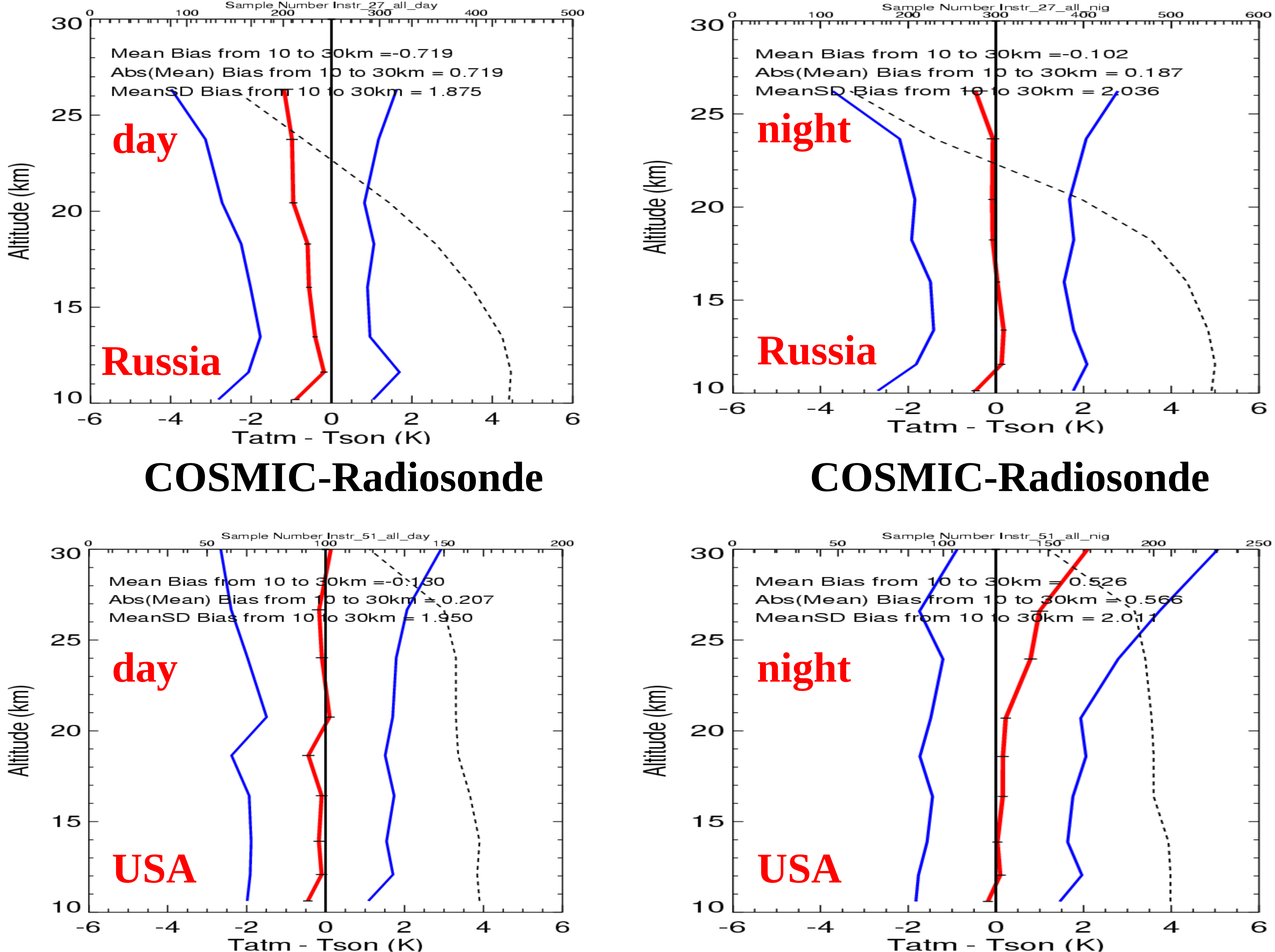




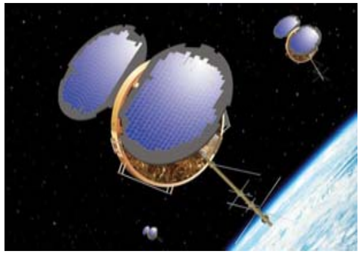
Radiosonde data from NCAR
- originally acquired from NCEP.
- contains the original data values transmitted by stations
- no radiative or other corrections from NCEP are included in this dataset

Region	Sonde Type	Matched Sample
Russia	AVK-MRZ	2000 (20%)
China	Shang	650 (6.1%)
USA	VIZ-B2	600 (5.9%)
Others	Vaisala	3140 (30%)

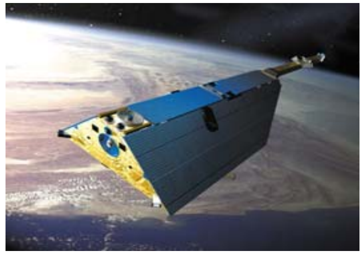
Collocate COSMIC/CHAMP and radiosonde profiles
< 200 km
< 3 hrs



Sample Number Instr_27_all_day
Mean Bias from 10 to 30km =-0.719
Abs(Mean) Bias from 10 to 30km = 0.719
MeanSD Bias from 10 to 30km = 1.875
day
Russia
Altitude (km)
Tatm - Tson (K)
Sample Number Instr_27_all_nig
Mean Bias from 10 to 30km =-0.102
Abs(Mean) Bias from 10 to 30km = 0.187
MeanSD Bias from 10 to 30km = 2.036
night
Russia
Altitude (km)
Tatm - Tson (K)
COSMIC-Radiosonde
COSMIC-Radiosonde
Sample Number Instr_51_all_day
Mean Bias from 10 to 30km =-0.130
Abs(Mean) Bias from 10 to 30km = 0.207
MeanSD Bias from 10 to 30km = 1.950
day
USA
Altitude (km)
Tatm - Tson (K)
Sample Number Instr_51_all_nig
Mean Bias from 10 to 30km = 0.526
Abs(Mean) Bias from 10 to 30km = 0.566
MeanSD Bias from 10 to 30km = 2.011
night
USA
Altitude (km)
Tatm - Tson (K)



Climate Conclusions



- **RO data can be used as a climate benchmark dataset**

-RO provides relatively uniform spatial/temporal coverage
-RO precision < 0.05K
- Satellite-to-satellite bias < 0.05K
-Independent of processing procedures : the trend from GPS RO data processed by different centers < 0.02%/5yrs

- **RO data can be used as benchmark measurements to inter-calibrate other instruments**

-COSMIC data are useful to distinguish the differences among N15, 16 and 18 AMSU data, and are useful to calibrate NOAA AMSU data.
-COSMIC data are useful to indentify AMSU location dependent bias
-RO data are useful to assess the quality of radiosonde data (diurnal bias due to radiative effect)

- **Above results show the potential for using RO data to fill the gap of climate data for lacking of NPOESS data and other data types.**

http://www.cosmic.ucar.edu/~spho/

Shu-peng Ben Ho, UCAR/COSMIC

Space Weather Highlights

COSMIC Space Weather Data Products

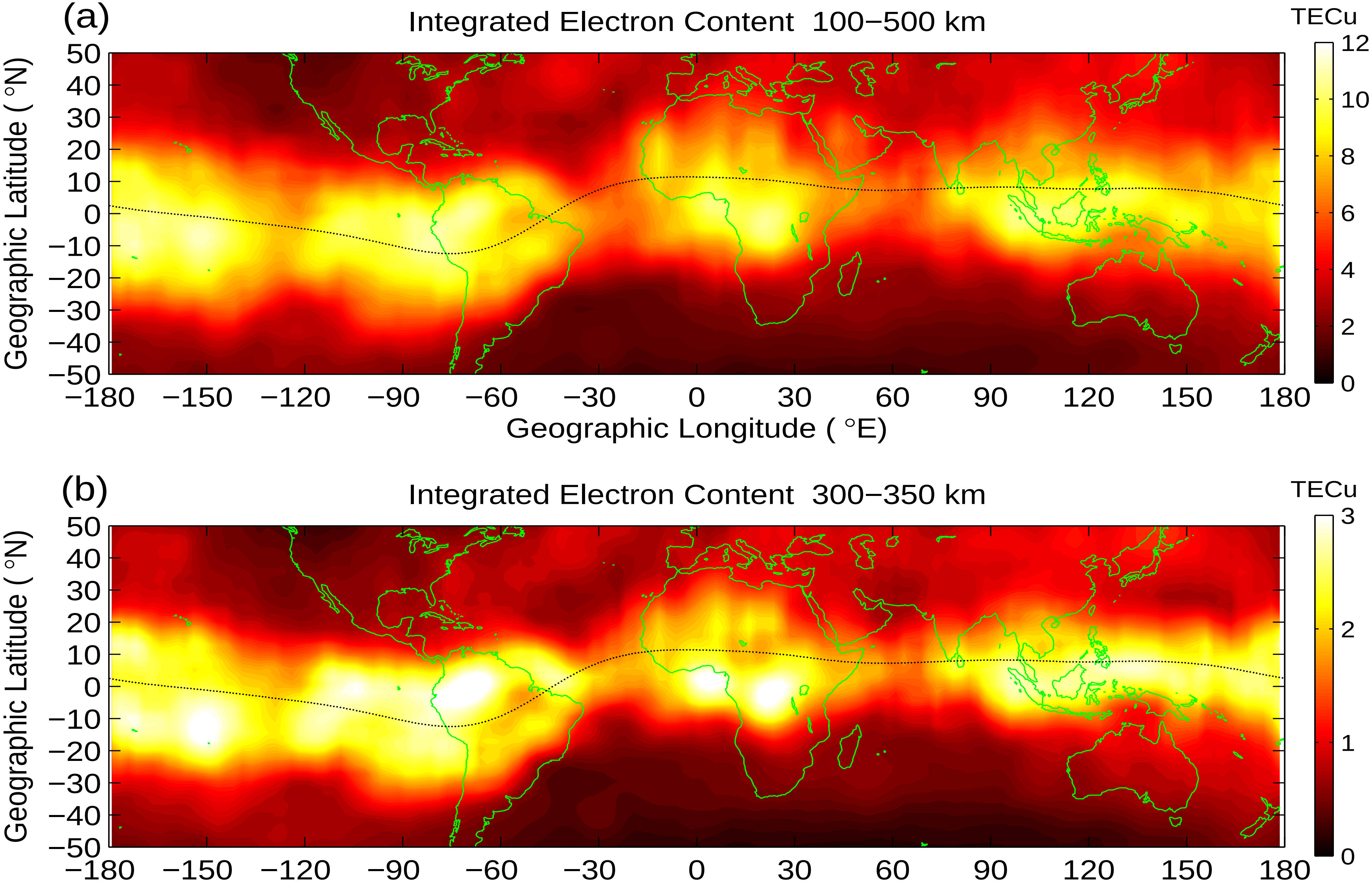
- ~3M Absolute TEC data arcs:
  - Absolute accuracy ~ 2-3 TECU
  - Relative accuracy ~ 0.0024 TECU at 1-Hz
- ~2.3M Electron Density Profiles:
  - NmF2 (F2 layer peak) Accuracy ~20% (compared to Ionosondes)
  - hmF2 (F2 layer height) Accuracy ~20 km
- Scintillation Indices (S4):
  - ~3M available from occultation profile events (altitudes < 120 km)
  - Available from ~3M lines of sight to all GPS in view
- ~90% available within 3 hrs, ~50% in 1 hr, and ~10% in ½ hr

Recent Ionosphere and Space Weather Studies With COSMIC

- **COSMIC EDPs used for verification of IRI and TIEGCM models (Lei et al., 2007)**
- **COSMIC EDPs used to estimate ionosphere High Transition Heights (HTH) and agree well with C/NOFS data (Yue et al., AGU, 2009)**
- **Mid-latitude summer nighttime anomaly (MSNA) of the ionosphere observed by COSMIC EDPs (Lin et al., 2009)**
- **Sporadic E layer climatology produced with COSMIC data (Wang, 2009)**
- **COSMIC EDPs and TIP data used to study the ionosphere disturbance during 15 Dec 2006 geomagnetic storm and found a long lasting positive storm effect in ionosphere (Pedatella et al., 2009)**
- **Strong relationship between behavior of ionosphere and Sudden Stratospheric Warming (Yue et al, 2010)**
- **JPL did many observation system simulation experiments (OSSE) and found that COSMIC-2 can advance the assimilation performance because of many more GPS TEC observations than current COSMIC (Pi et al., 2009)**

wave-4 longitudinal structure

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

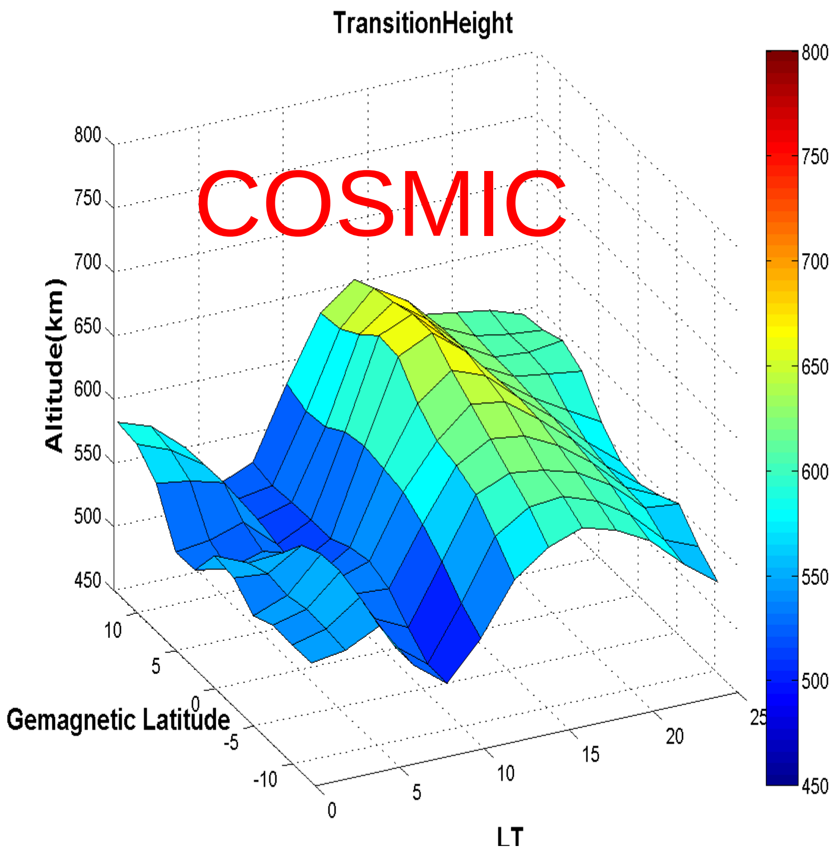


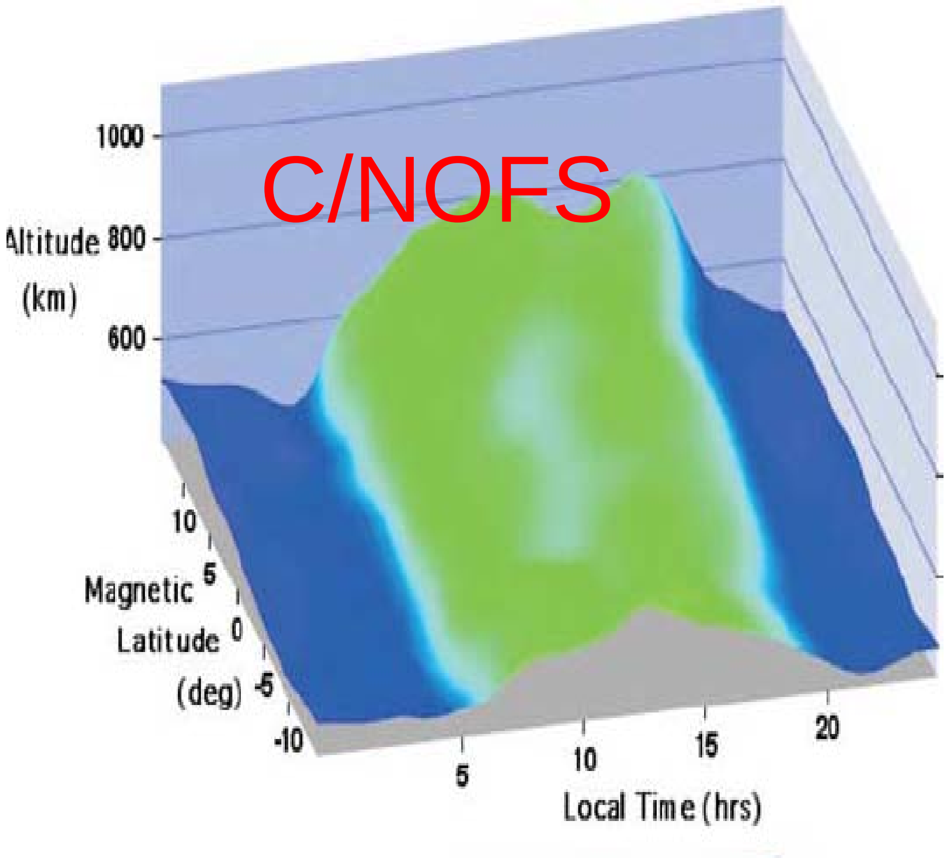
Lin and Liu et al. [GRL, 2007]

Ionospheric High Transition Height (HTH)

Comparison between COSMIC and C/NOFS observations of HTH
|lat| < 13, June-August, 2008

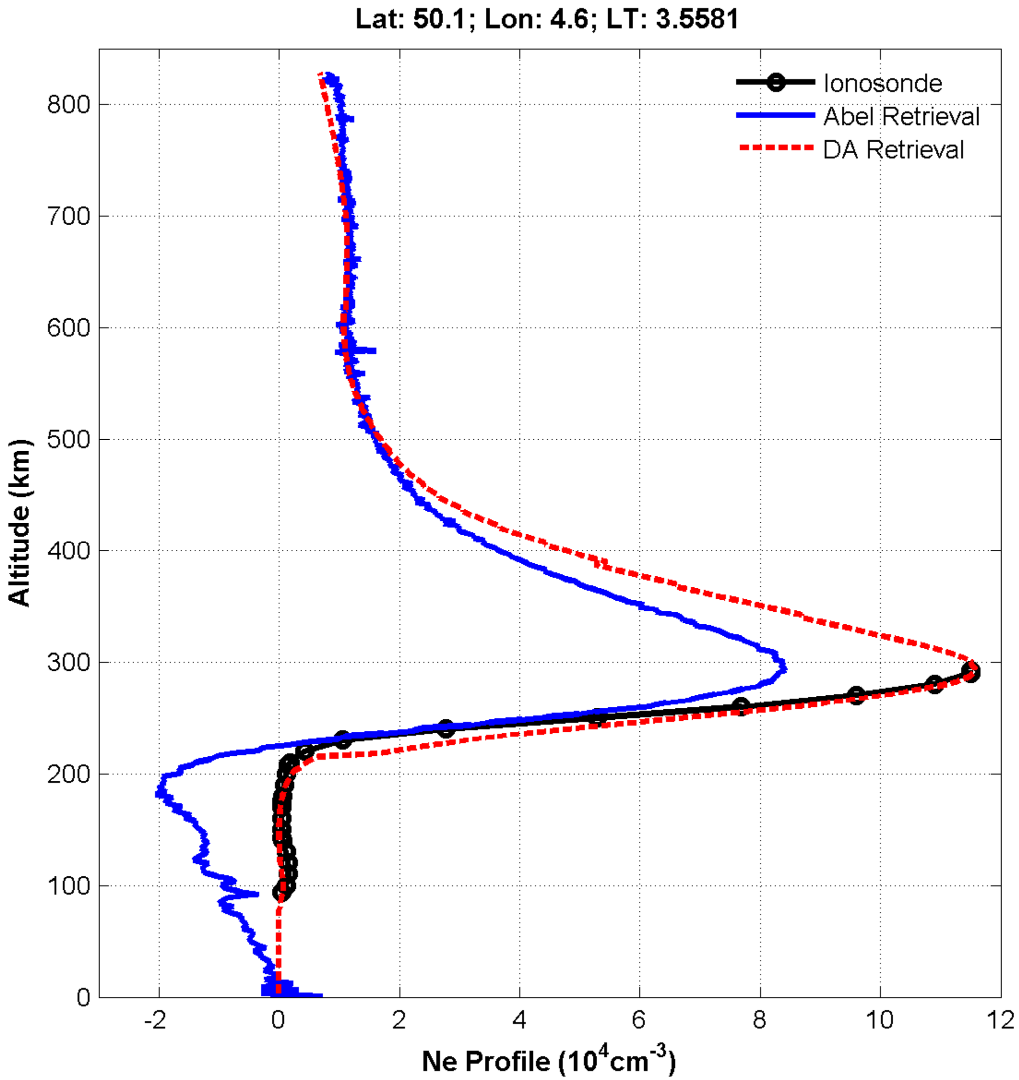
Heelis et al. 2009GL038652





Yue et al. 2009
Presented at AGU

New retrieval electron density profile



Data Assimilation Retrieval of Electron Density Profiles from Radio Occultation Measurements
Xinan Yue, William S. Schreiner, Jason Lin, Christian Rocken, Ying-Hwa Kuo. 2010 draft paper

k Anthes

New retrieval electron density profile

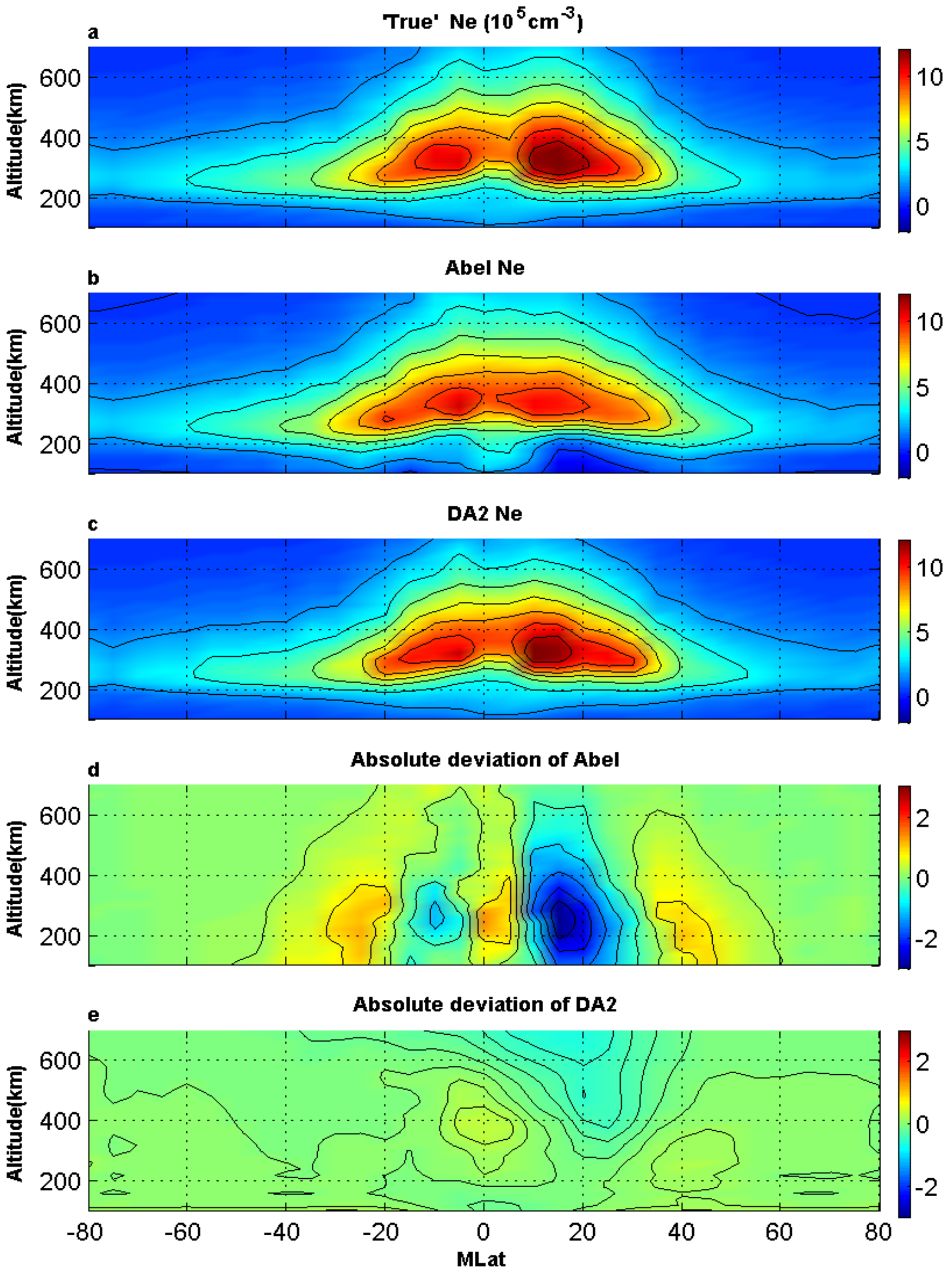


Figure 8a. Geomagnetic latitude and altitude variations of electron density during noon time (LT=13).
From a to e are ‘true’, Abel retrieval, Data assimilation retrieval, absolute error of Abel retrieval, and absolute error of data assimilation retrieval electron density, respectively.
(Yue et al., 2010)

Data Assimilation Retrieval of Electron Density Profiles from Radio Occultation Measurements
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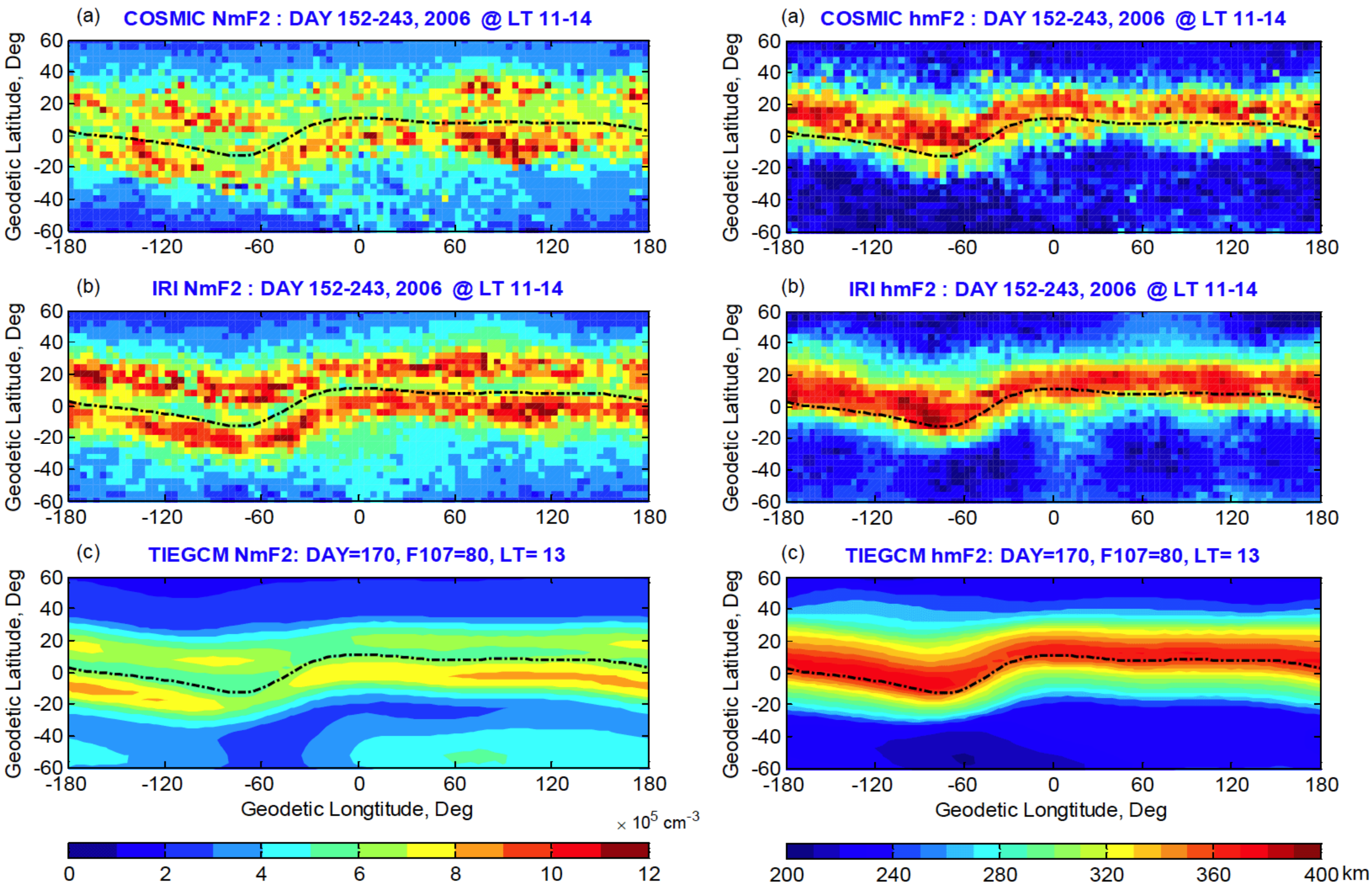
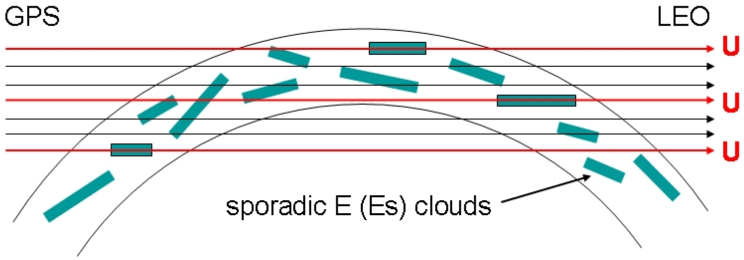
Ionospheric Climatology from COSMIC Data



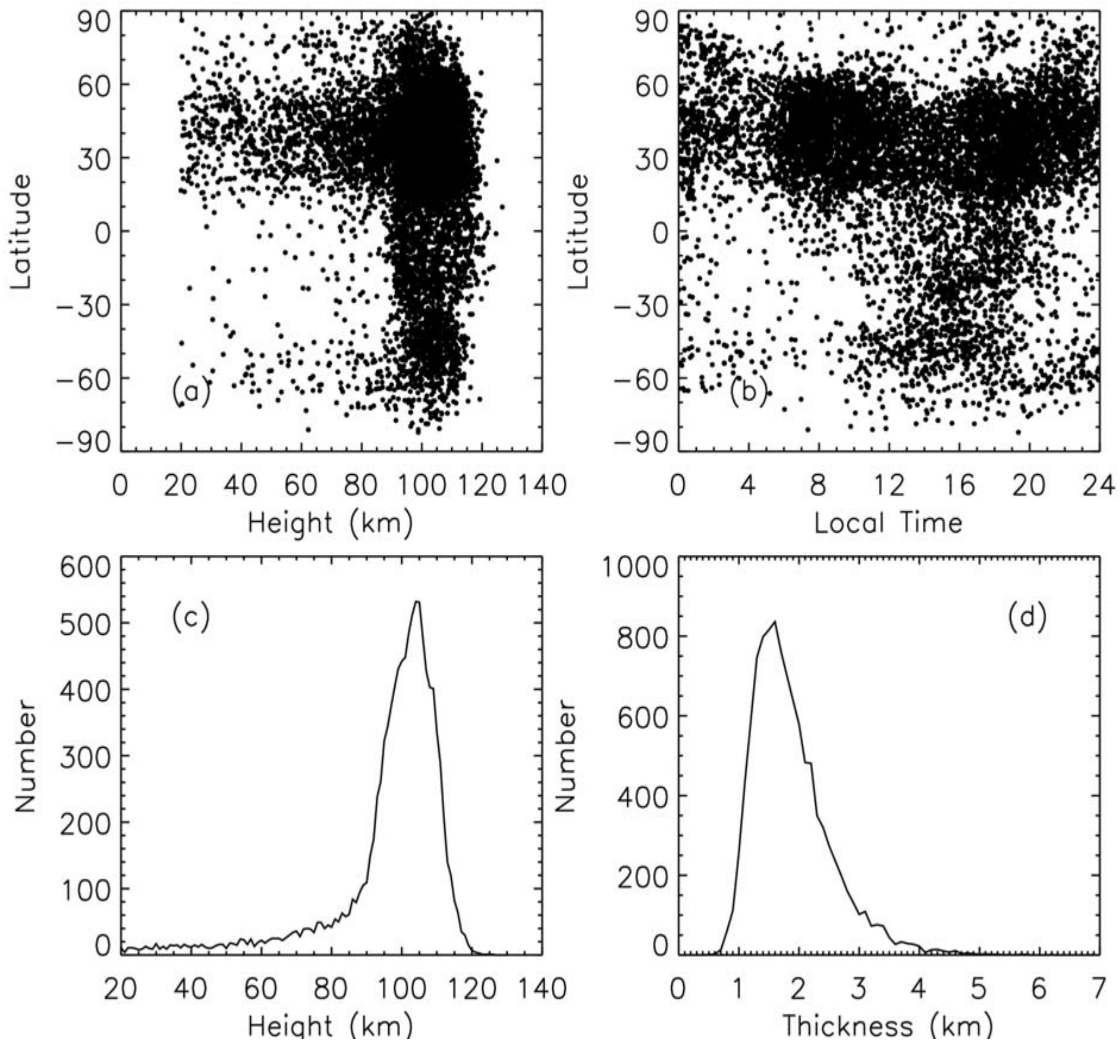
k Anthes

Study of the sporadic E (Es) clouds by RO

Previously, Es layer was studied by GPS RO based on scintillation. When Es clouds are aligned with the propagation direction they result in specific **U-shaped** structures (due to defocusing) observed in the amplitude of GPS RO signals. This allows to study morphology of the Es clouds.



July 2009



Z.Zeng and S.Sokolovskiy, GRL, 2010 (in press)

Remaining Challenges

- Lower tropospheric (0-5 km) retrievals—a very important part of the atmosphere!
  - How good are they?
  - How can they be improved?
  - How can they be better used for climate and NWP?
- Need more soundings per day, especially in tropics (for tropical cyclone prediction)
- Need lower latency (for space weather)

Summary and Conclusions

- Over the past two decades, we have seen tremendous progress in the development and application of GPS radio occultation technique: GPS/MET → SAC-C/CHAMP → COSMIC/FORMOSAT-3
- GPS RO has established itself as a high-accuracy, high vertical resolution, and low-cost global observing system.
- WMO, EUMETSAT, ECMWF, and the NRC Decadal Survey have recommended continuing RO observations operationally.
- With the planning and launch of COSMIC-2, an even greater impact can be expected.

We will hear much more about all of this later this week from the experts!

Acknowledgments

- NSF
- Taiwan’s NSPO and NSC
- NASA/JPL, NOAA, USAF, ONR, NRL

UCAR NSF NASA USAF NOAA NSPO ONR

Special thanks to Taiwan’s leaders, scientists and engineers.
Without Taiwan’s support none of this would have been possible!

And thanks to the Wegener Centre and University of Graz for hosting this workshop!