Applications of Radio Occultation Observations to Climate Studies

Formosat-3/COSMIC Science Summer Camp in Taiwan

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1 June 2005

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http://www.cosmic.ucar.edu

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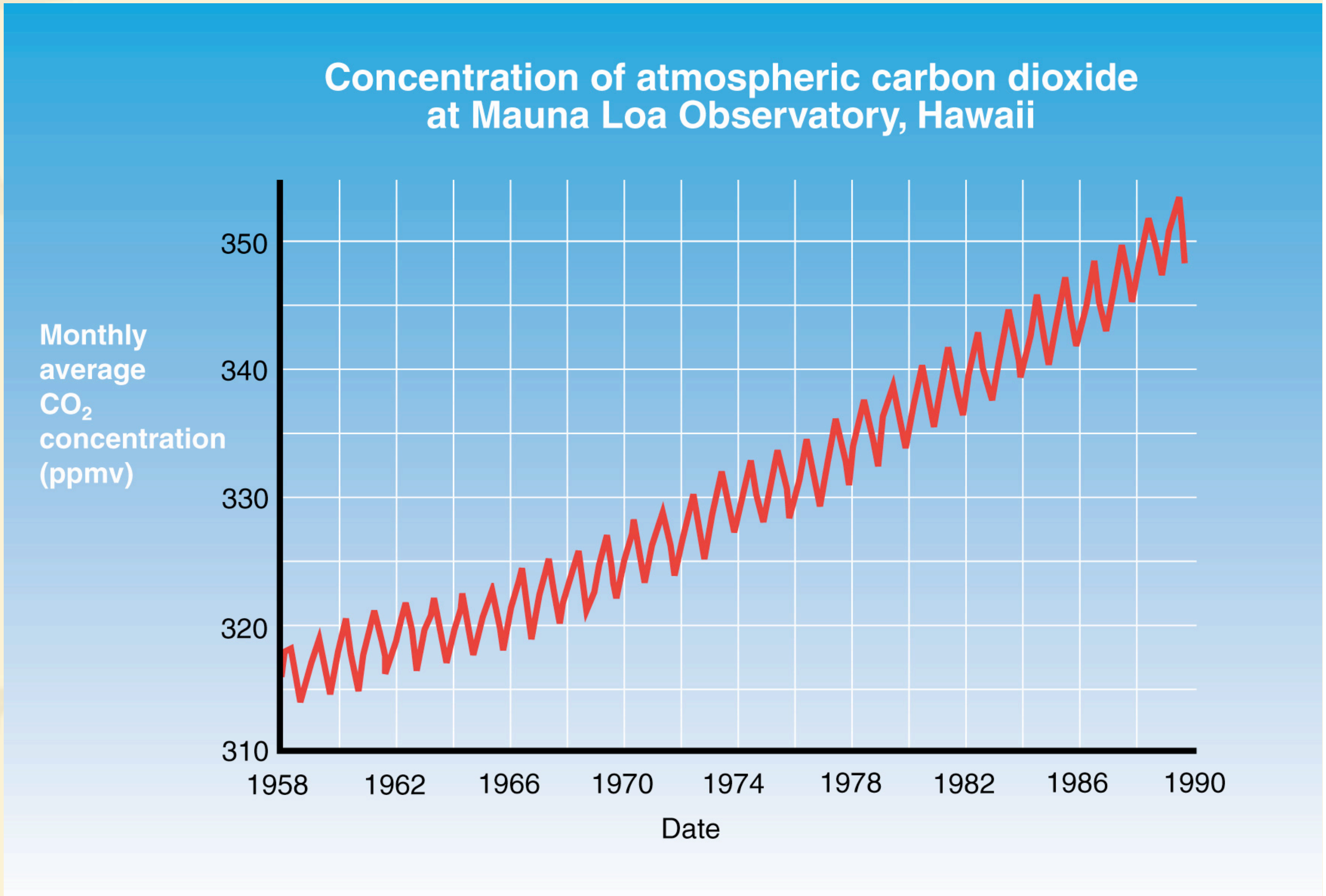
Ten Principles for Climate Monitoring (NRC, 1999)

1. **Management of Network Change**: Assess how and the extent to which a proposed change could influence the existing and future climatology.
2. **Parallel Testing**: Operate the old system simultaneously with the replacement system.
3. **Metadata**: Fully document each observing system and its operating procedures
4. **Data Quality and Continuity**: Assess data quality and homogeneity as a part of routine operation procedures.
5. **Integrated Environmental Assessment**: Anticipate the use of data in the development of environmental assessments.
6. **Historical Significance**: Maintain operation of observing systems that have provided homogeneous datasets over a period of many decades.
7. **Complementary Data**: Give the highest priority in the design and implementation of new sites or instrumentation within an observing system to data-poor regions, poorly observed variables, regions sensitive to change, and key measurements with inadequate temporal resolution.
8. **Climate Requirements**: Give network designers, operators, and instrument engineer's climate monitoring requirements at the outset of network design.
9. **Continuity of Purpose**: Maintain a stable, long-term commitment to these observations, and develop a clear transition plan from serving research needs to serving operational purposes.
10. **Data and Metadata Access**: Develop data management systems that facilitate access, use, and interpretation of data and products by users.

Benchmark Measurements

Benchmark measurements are independent of the local environment and comparable regardless of when or by whom the measurement is made



J. Anderson, Harvard

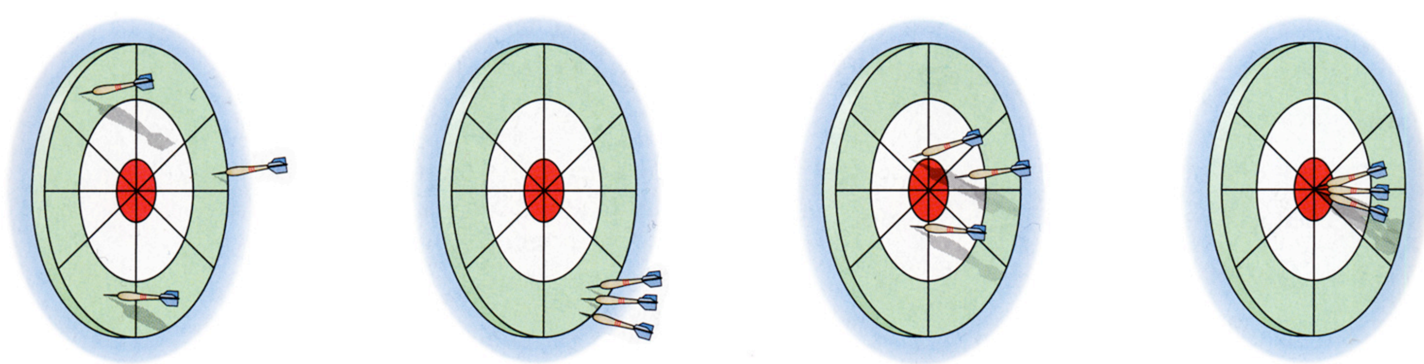
Climate Benchmark Obs

WHY ARE THEY NEEDED?

- Provide record of absolute values of key observables valid for all time

DEFINITION:

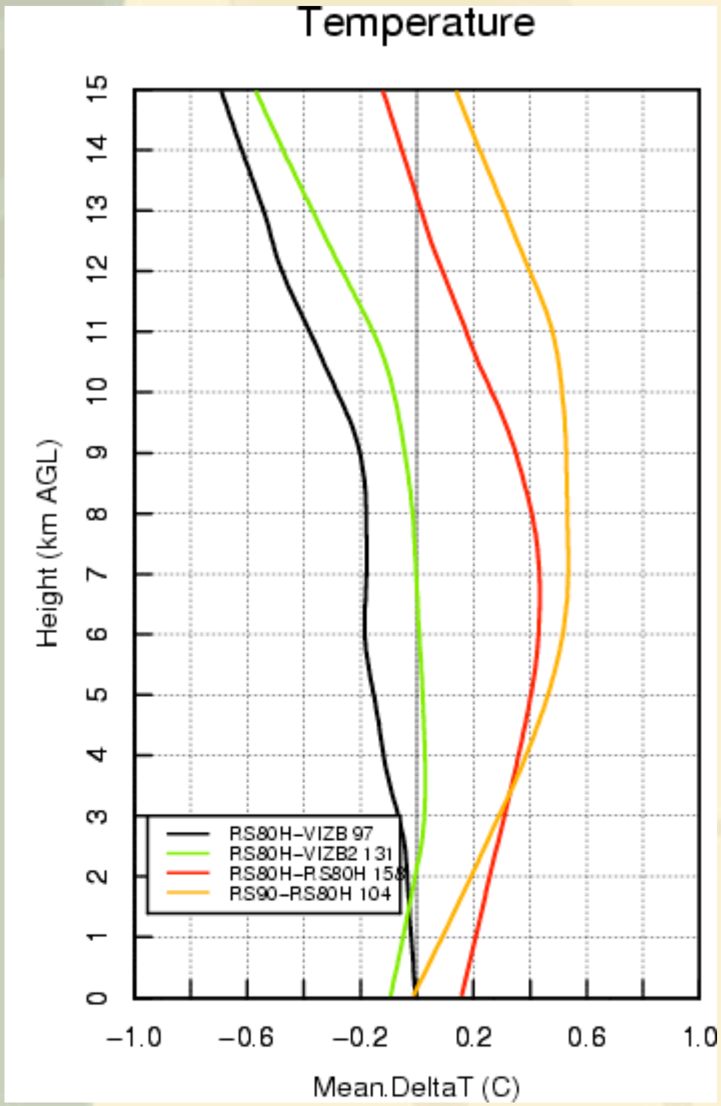
- Focus on accuracy that provides absolute reference in perpetuity
  - Accuracy: The measure of how close the result of the experiment comes to the “true” values
  - Precision: The measure of how exactly the result is determined without reference to any “true” value
- Measurement tied to irrefutable standards, with broad laboratory base
- Experimental strategy designed to reveal systematic errors through independent cross checks, open inspection, and continuous interrogation



(a) Low accuracy Low precision
(b) Low accuracy High precision
(c) High accuracy Low precision
(d) High accuracy High precision

J. Anderson, Harvard

Inadequacies of radiosondes for climate Applications.



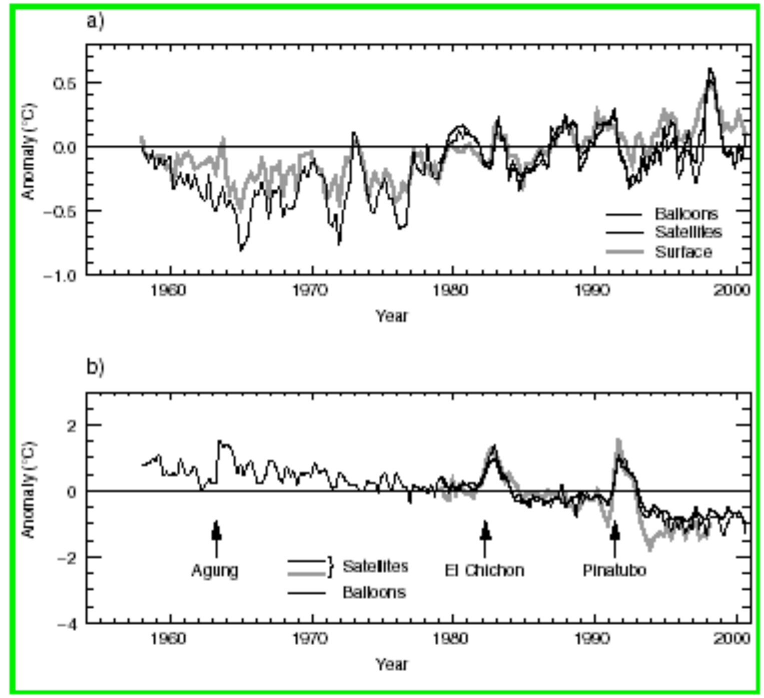


Figure 4: (a) Time-series of seasonal temperature anomalies of the troposphere based on balloons and satellites in addition to the surface. (b) Time-series of seasonal temperature anomalies of the lower stratosphere from balloons and satellites. [Based on Figure 2.12]

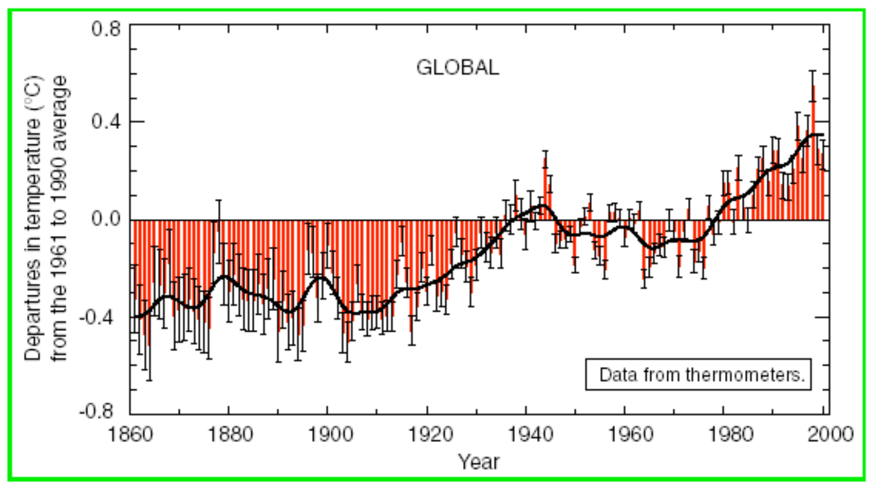
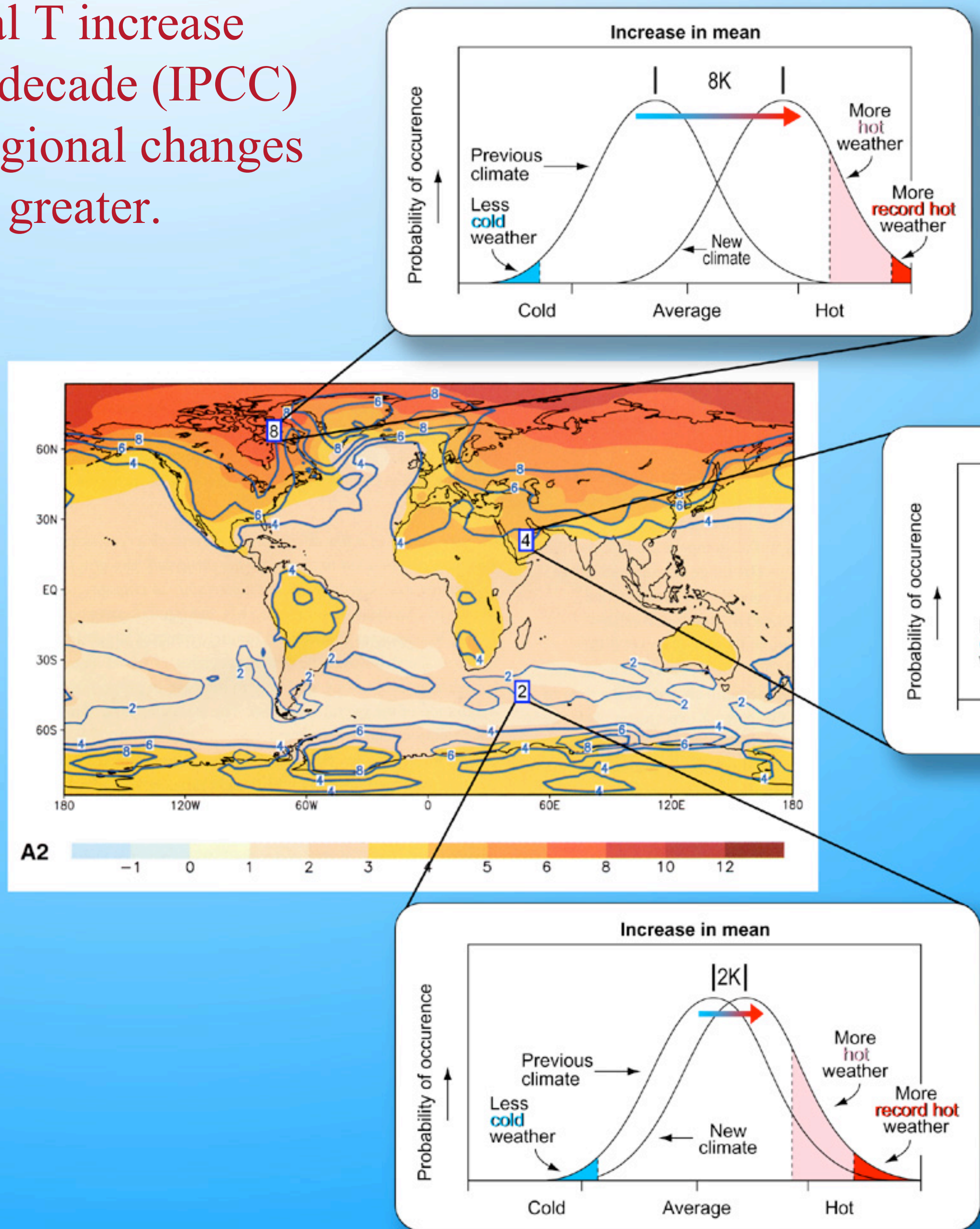


Figure 2: Combined annual land-surface air and sea surface temperature anomalies (°C) 1861 to 2000, relative to 1961 to 1990. Two standard error uncertainties are shown as bars on the annual number. [Based on Figure 2.7c]

June Wang, NCAR

Global T increase 0.2K/decade (IPCC) but regional changes much greater.

Accuracy of average RO T profiles <0.1K



J. Anderson, Harvard

Group on Earth Observations

Earth Observation Summit I
Washington, DC, July 31, 2003

Summit represented a high level governmental/political commitment to move toward a comprehensive, coordinated, global network:

- **Issued declaration to support this concept**
- **Launched development of 10-year implementation plan**
- **Established the Group on Earth Observations with US Co-Chair**

34 Nations

20 International Organizations

GCOS Implementation Plan for the Global Observing System for Climate October 2004

Action A20 (AF13): GPS RO measurements should be made available in real time, incorporated into operational data streams, and sustained over the long-term.

GCOS-92, WMO/TD No. 1219, October 2004

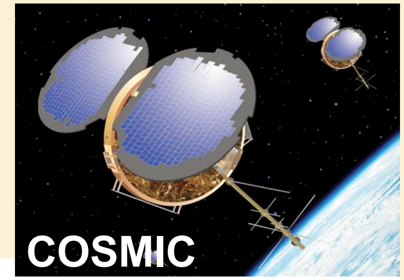
Radio Occultation (RO) Data

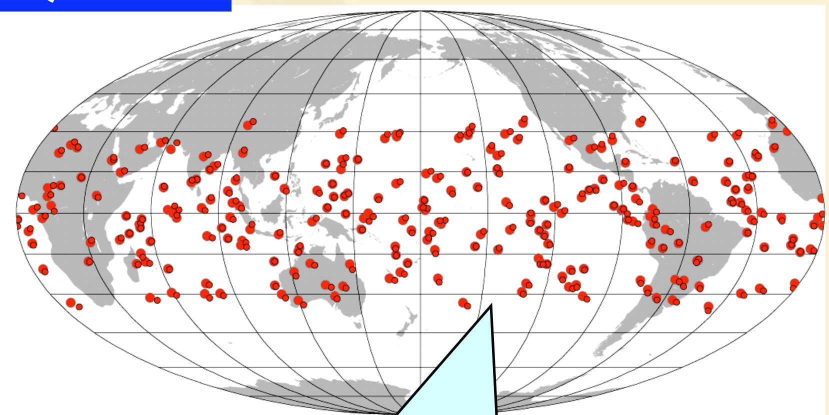
- **Climate:**
  - Characterize climate, its variability and change
  - Evaluate global climate models and analyses
  - Monitor climate change and variability with unprecedented accuracy- **world's most accurate thermometer!**
- **Meteorology:**
  - Improve global weather analyses, particularly over data void regions such as the oceans and polar regions
  - Improve skill of global and regional weather prediction models
  - Improve understanding of tropical, midlatitude and polar weather systems and their interactions
- **Ionosphere:**
  - Characterize global electronic density distribution
  - Observe the interactions among the upper stratosphere, mesosphere and ionosphere
  - Improve the analysis and prediction of space weather.

GPS radio occultation missions

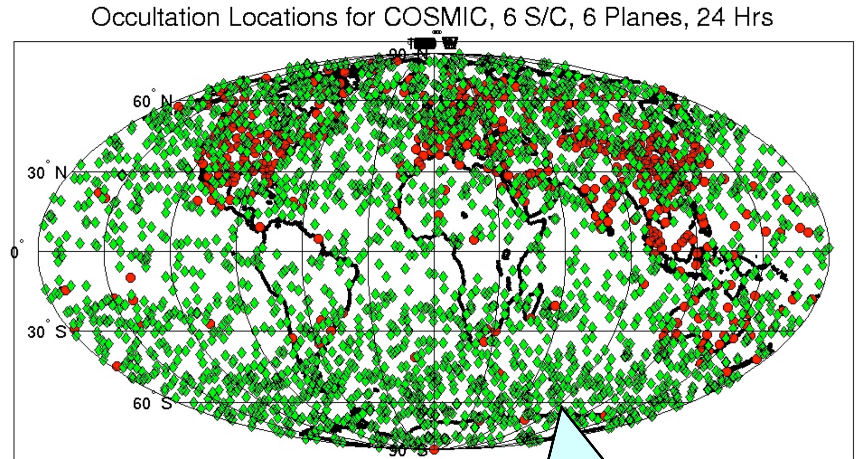
Mission	Launch-Duration	# Soundings/day	Remarks
GPS-MET	4/1995 2+	~125	Proof of Concept
CHAMP	11/2000 ~5	~250	Improved receiver, tracking
SAC-C	11/2000 ~3	~300	Improved receiver, open loop tracking test
GRACE	5/2002 ~5	~500	RO data not yet available
COSMIC	12/2005 ~5	~2500	Real time-ops
TerraSAR-X	7/2005 ~5	~400	COSMIC RX & Antennas
EQUARS	7/2006 ~3	~400	COSMIC RX & CHAMP antennas
METOP	4/2006 ~5	~500	Real time - ops
COSMIC II ?	3/2009 ~5	~5000	Real time-ops

Distribution of GPS Occultation events in 24 hrs with EQUARS (2006, inclination angle<20º) and COSMIC (2005, 6 LEO satellites at 72º)



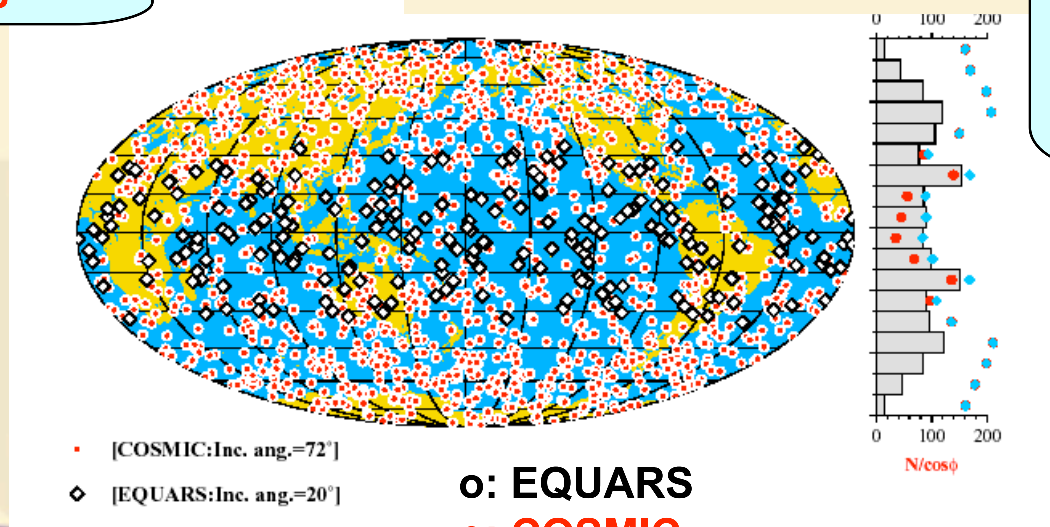


+



Dense data rate in equatorial region

Global coverage, but less data at low latitudes



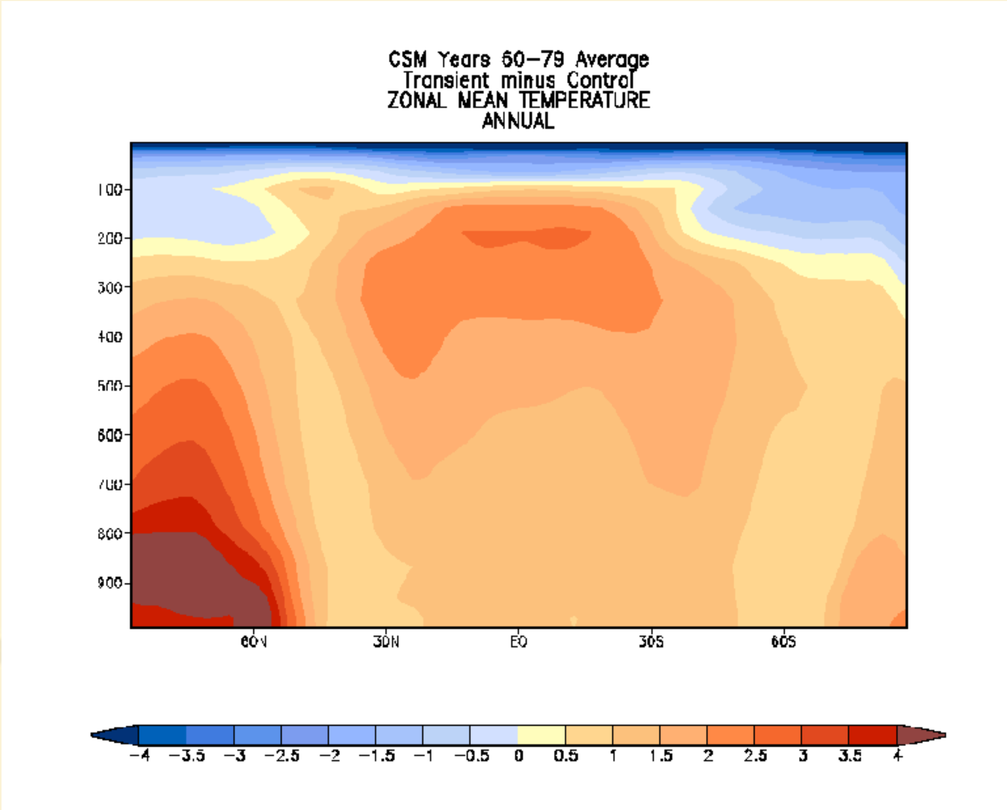
o: EQUARS
o: COSMIC

RO observations and Climate

- Benchmark observations
- Use with other sounding systems to improve global analyses of temperature and water vapor
- Process studies (e.g. tropospheric and stratospheric waves, tropopause structure)
- Validation of other observing systems
  - Reanalyses
  - Other satellite sounders (e.g. MSU, Schrøder et al., 2003)
  - Radiosondes
- Variables for climate trend and variability studies
  - Bending angle
  - Refractivity
  - Temperature
  - Water vapor
  - Geopotential heights as function of pressure

Climate

- **Perhaps the most accurate and stable global thermometer for estimating climate change**
- **Most accurate where model-predicted temperature changes are large in upper troposphere and lower stratosphere**



Meehl *et al*. 2000, J. Climate.

Atmospheric Refractivity N

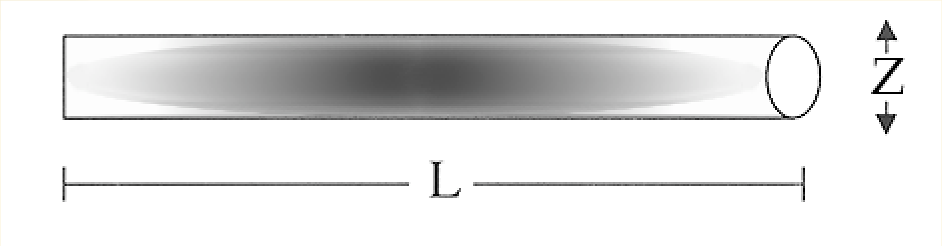
N: pressure (P)
temperature (T)
water vapor pressure (P_W)
electron density (n_e)
GPS frequency (f)

$$N = 77.6\frac{P}{T} + 3.73\times10^{-5}\frac{P_w}{T^2} - 4.03\times10^{7}\frac{n_e}{f^2}$$

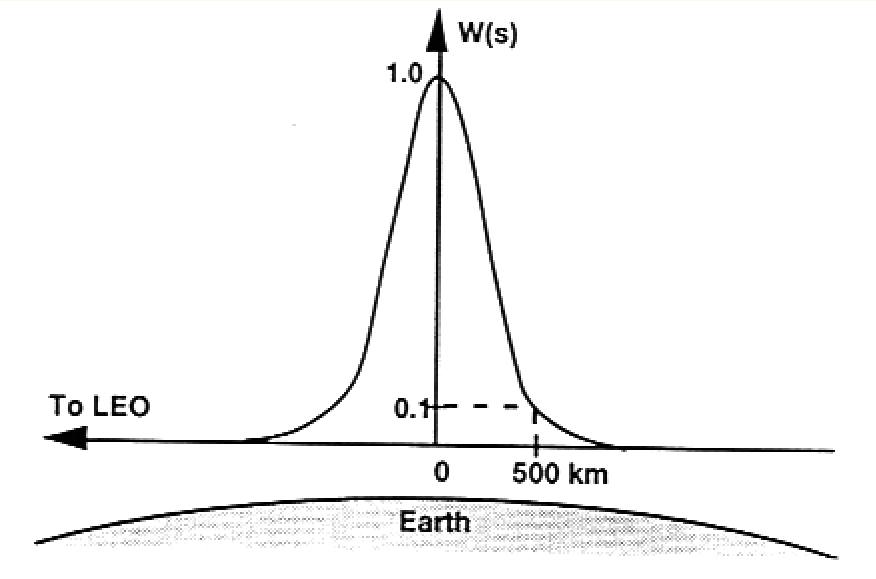
Characteristics of RO Data

- **Limb sounding geometry complementary to ground and space nadir viewing instruments**
- **Profiles ionosphere, stratosphere and troposphere**
- **High accuracy and precision (equivalent to < 1 deg K from 5-25 km)**
- **High vertical resolution (0.1 km surface - 1km tropopause)**
- **All weather-minimally affected by aerosols, clouds or precipitation**
- **Independent height and pressure**
- **Requires no first guess sounding or calibration**
- **No instrument drift**
- **No satellite-to-satellite bias**
- **Inexpensive**

Observed Atmospheric Volume



L~300 km
Z~1 km



Issues with RO

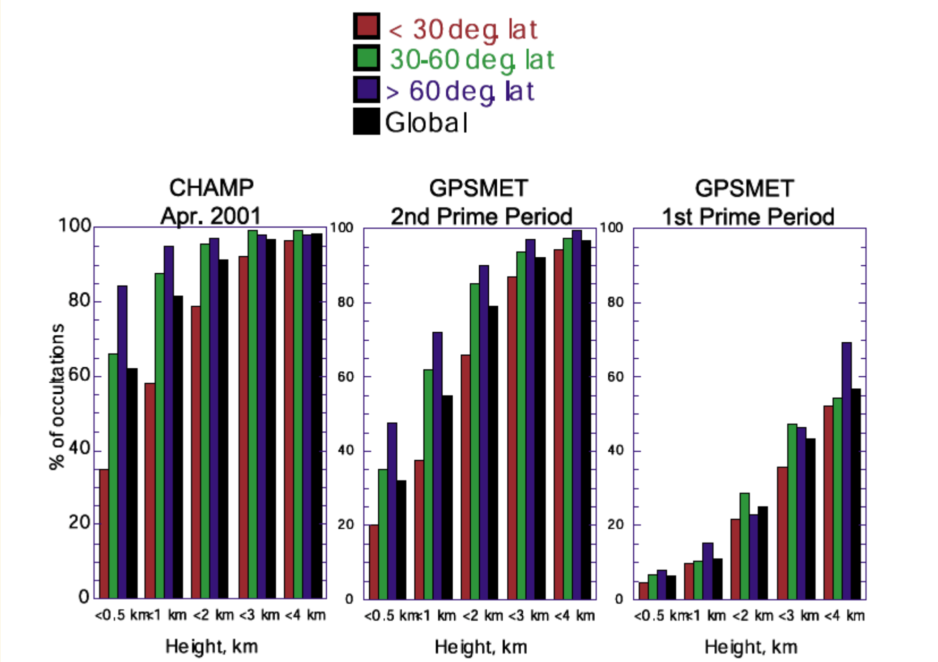
- Representativeness: Horizontal "average" ~300 km
- Penetration to lower troposphere
- Negative N bias in lower troposphere, tropical regions

Issues with GPS RO

- Representativeness: Horizontal “average” ~300 km
  - Fundamental to measurement
  - An advantage for climate studies

Issues with GPS RO

- Penetration to lower troposphere
  - GPS/MET median penetration ~500mb
  - CHAMP and SAC-C soundings penetration improved (Hajj *et al*., 2004)
    - % of sounding reaching 0.5 km or lower
      - 60% globally
      - 35% tropics
      - 85% latitudes higher than 60º



Final resolution of issue requires improved GPS receiver

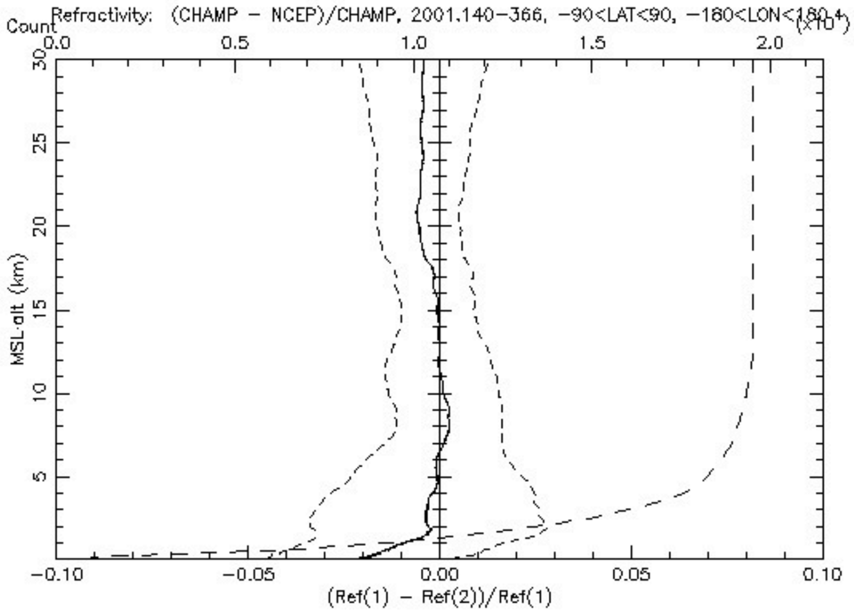
Issues with GPS RO

- **Negative N bias in lower troposphere, tropical regions**
  - A major problem for climate studies
  - Causes understood, partially resolved
    - Signal tracking algorithms
    - Super-refraction
  - Final resolution requires open-loop tracking and improved GPS receiver

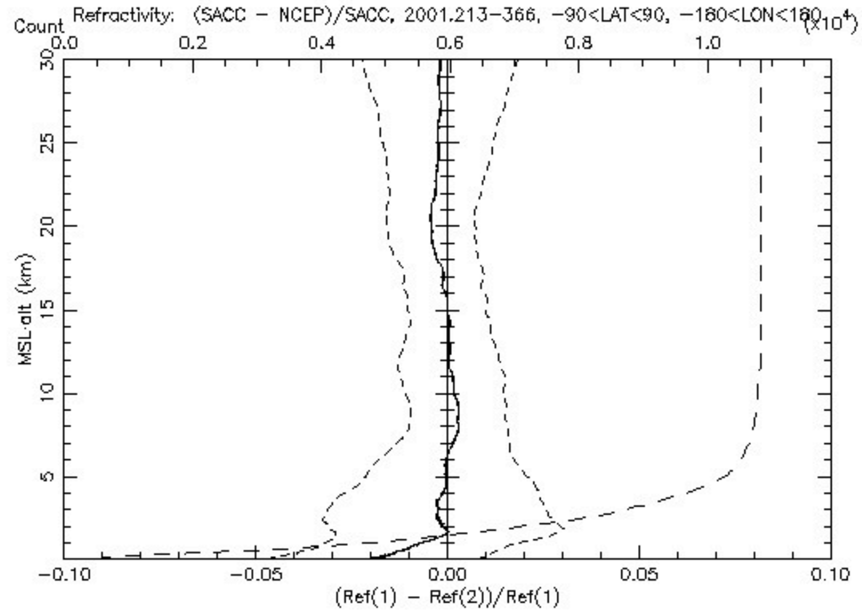
Validation Statistics with NCEP

Global

CHAMP



SAC-C

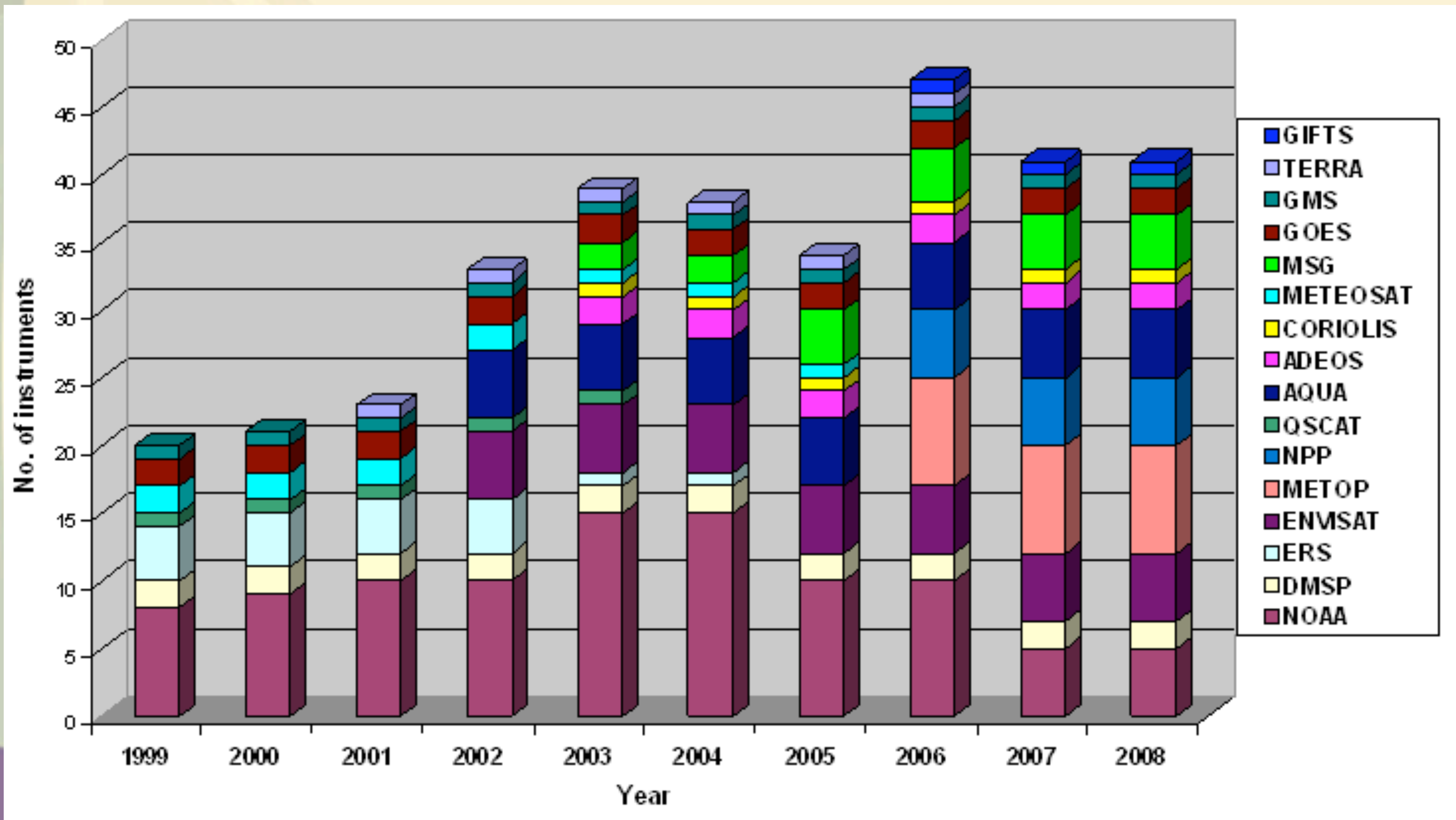


- Mean percent difference < 1% from 1 to 30 km
- Equivalent T error ~0.5 K
- Equivalent q error ~0.5 g/kg

Observations should cooperate not compete!

Sounding systems can work together to produce more accurate and higher resolution sounding than any one system by itself……..

Satellite sensors available for NWP
(from R.Saunders, Met Office)



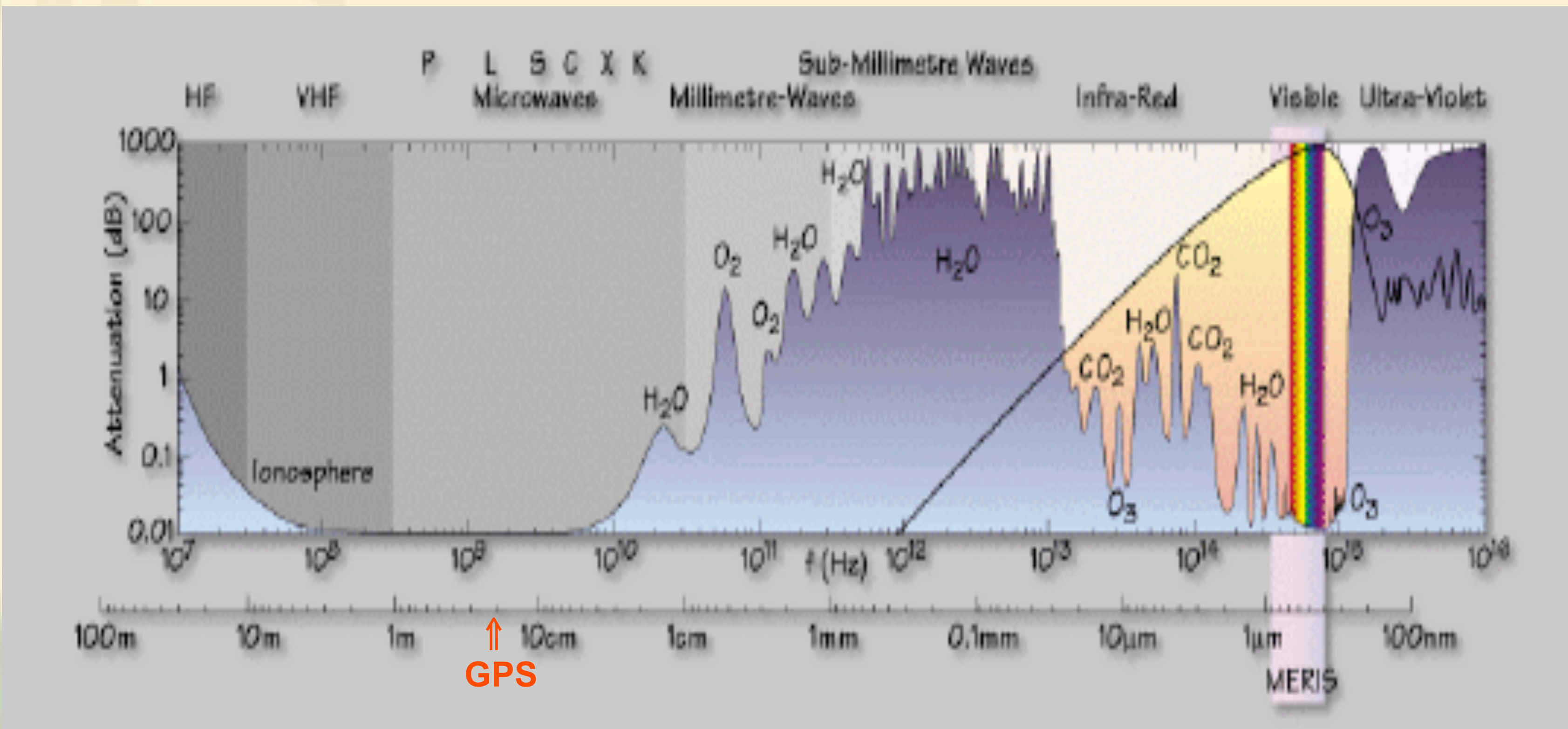
Depending on the wavelength, the radiation at the top of the atmosphere is sensitive to different atmospheric constituents

Scat, Altimeter

AMSU, Radio Occultation, SSM/I

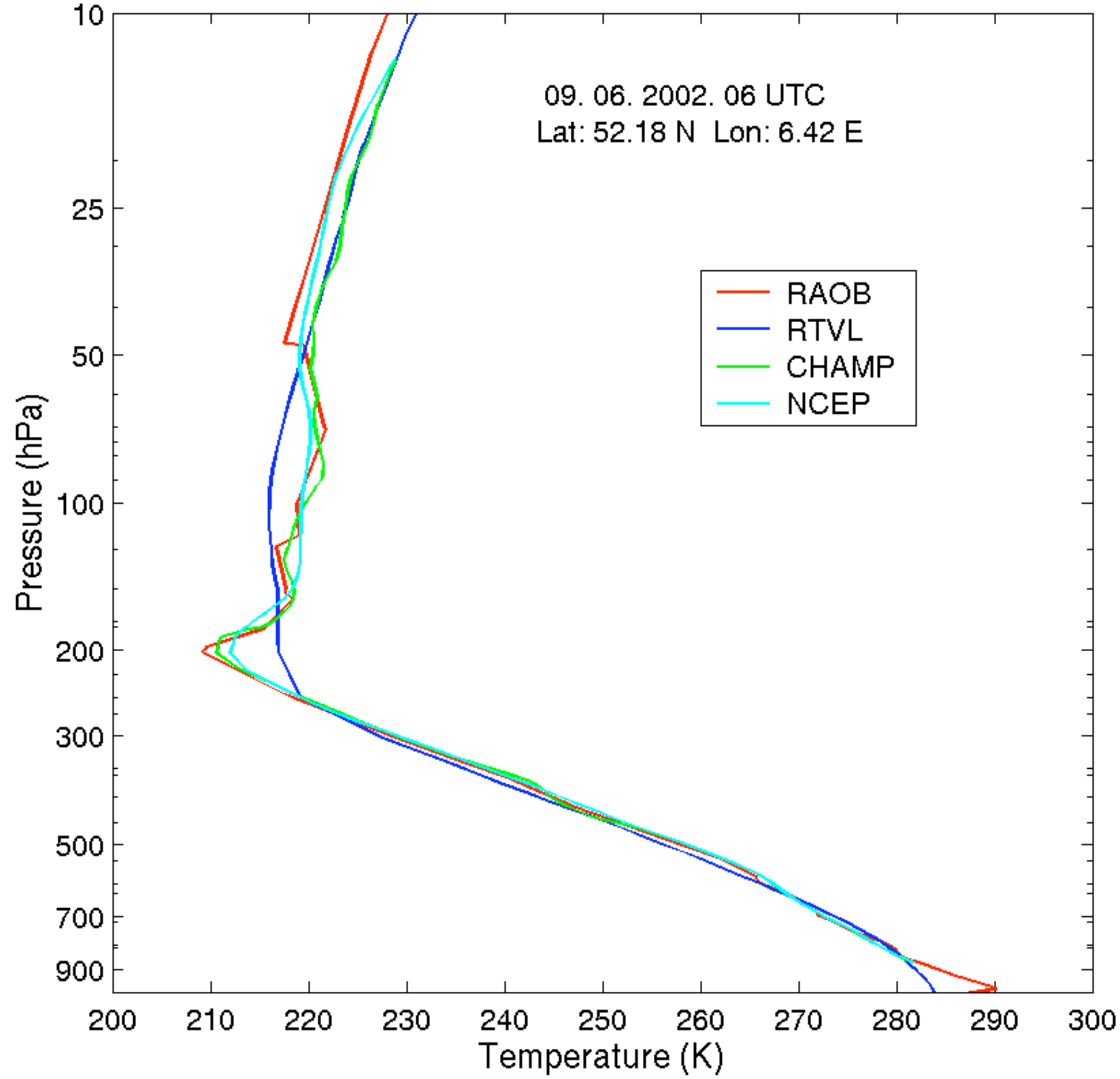
HIRS GOES METEOSAT AIRS

SBUV



Comparison of temperature profiles from the AIRS retrieval (blue), nearest RAOB observation (red), GPS CHAMP measurements (green), and collocated NCEP reanalysis (cyan) for 06 UTC on 6 September 2002 under clear sky conditions.

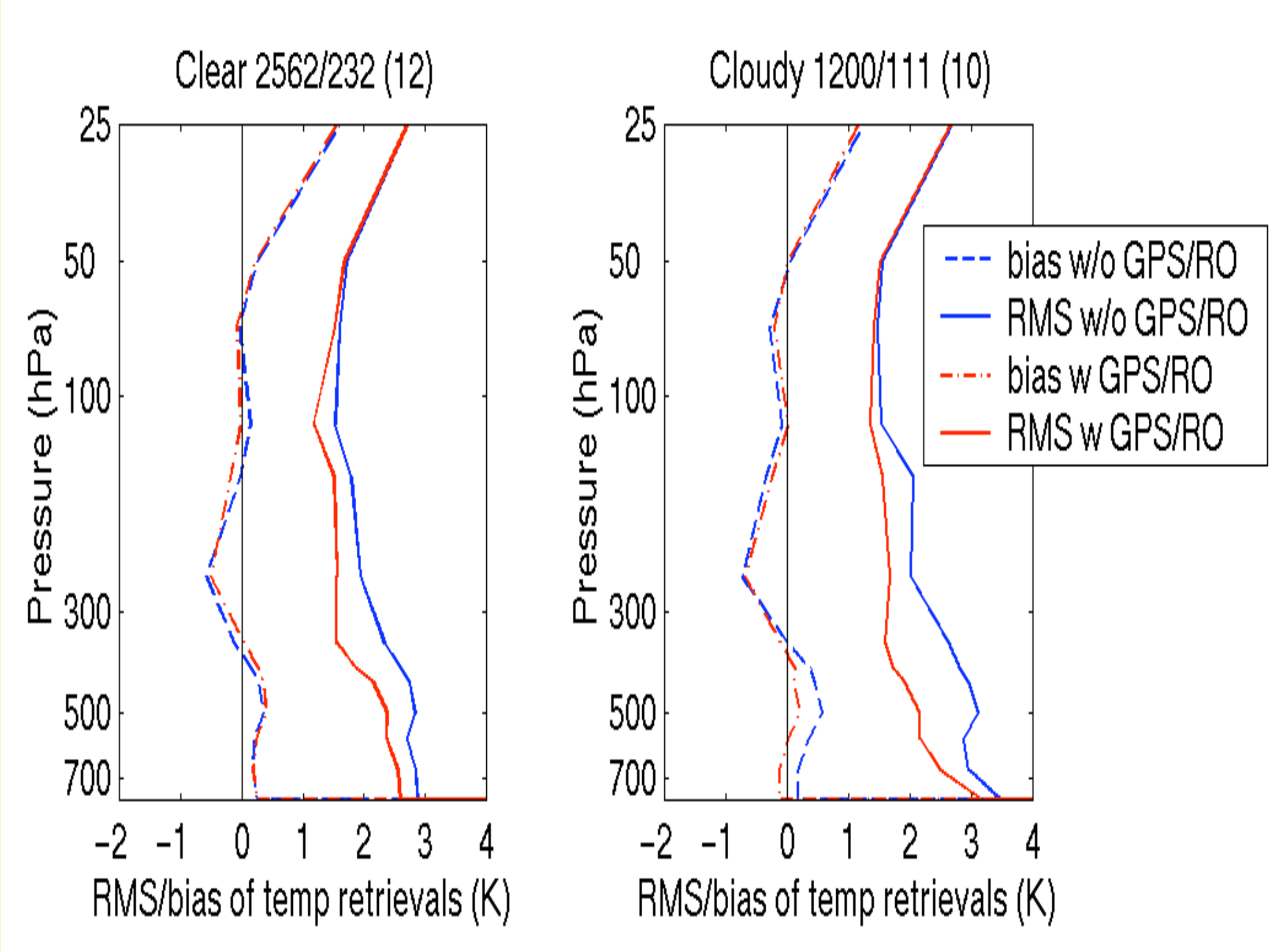
BORBAS et al - CIMSS



Combined Soundings at CIMSS

- RMS and bias of temperature profile retrievals from ATOVS alone (blue) and ATOVS plus CHAMP (red) with respect to radiosonde measurements in clear and cloudy conditions for the months of October 2001, January 2002, April 2002, and July 2002.

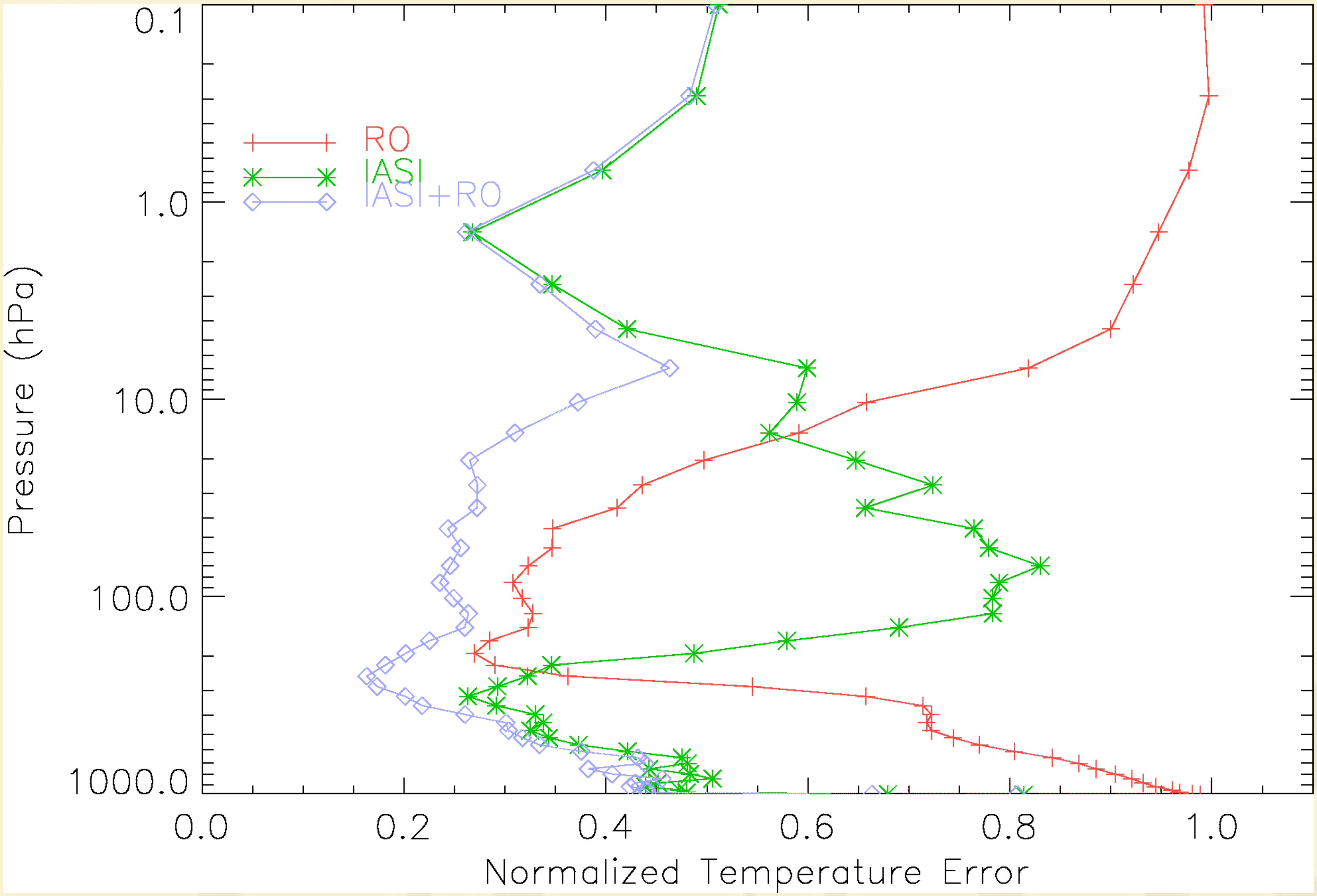
(Borbas et al, CIMSS)



Information content from1D-Var studies

IASI (Infrared Atmospheric Sounding Interferometer)

RO (Radio Occultation)

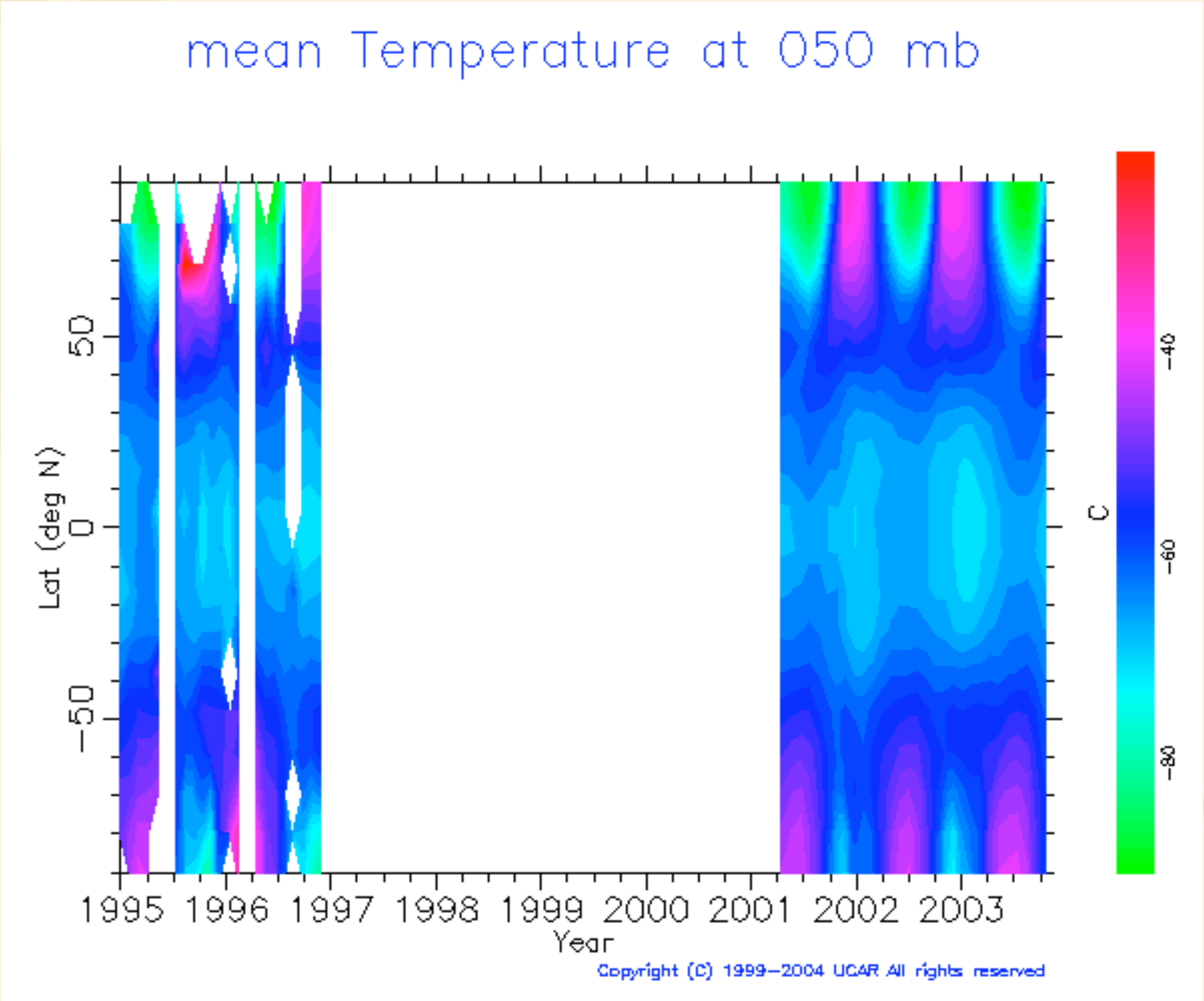


(Collard+Healy, QJRMS,2003)

Climate Monitoring and Process Studies

- Annual and interannual variability
- Gravity waves
- QBO
- Kelvin waves

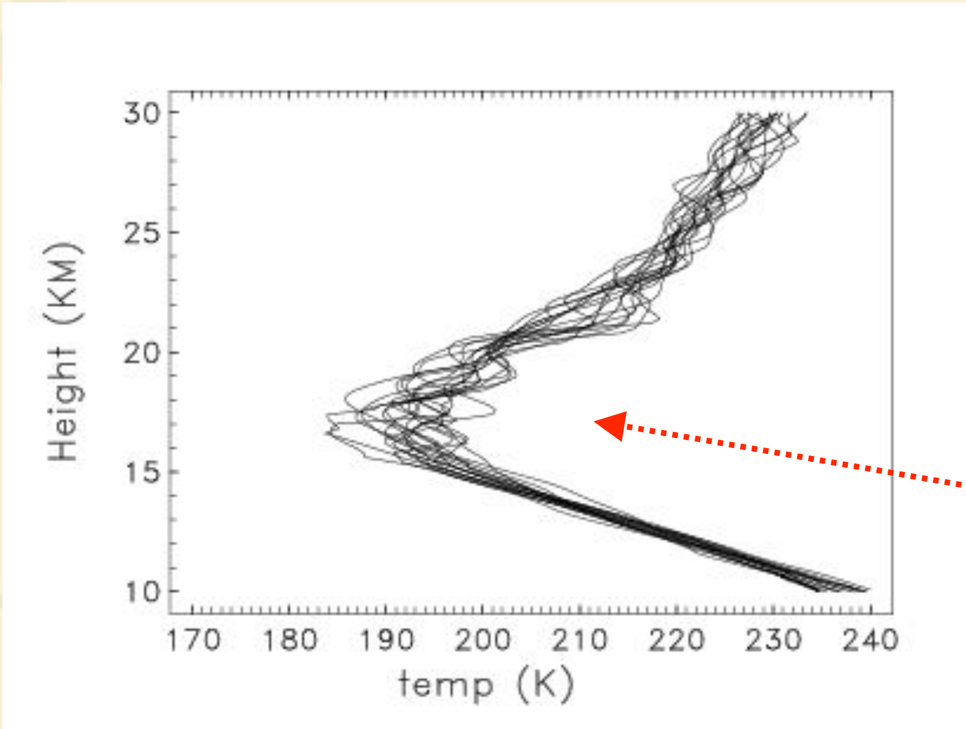
Annual and interannual variability



1995 - 2003 global mean temperatures at 50 mb

C. Rocken, UCAR

Gravity waves in GPS tropical temperature profiles

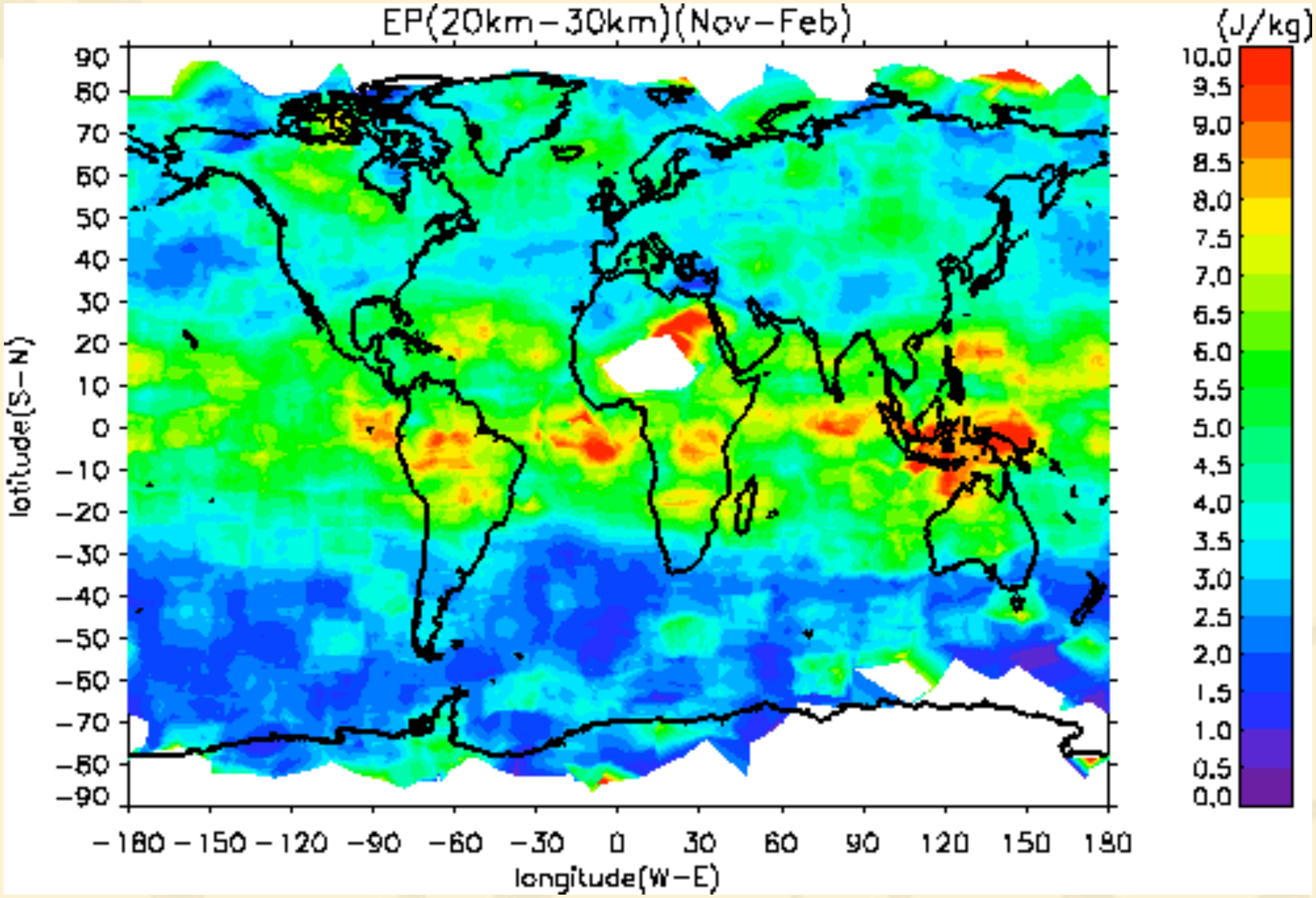


note enhanced variability above ~15 km

W. Randel, NCAR, COSMIC Retreat, Oct. 28, 2004

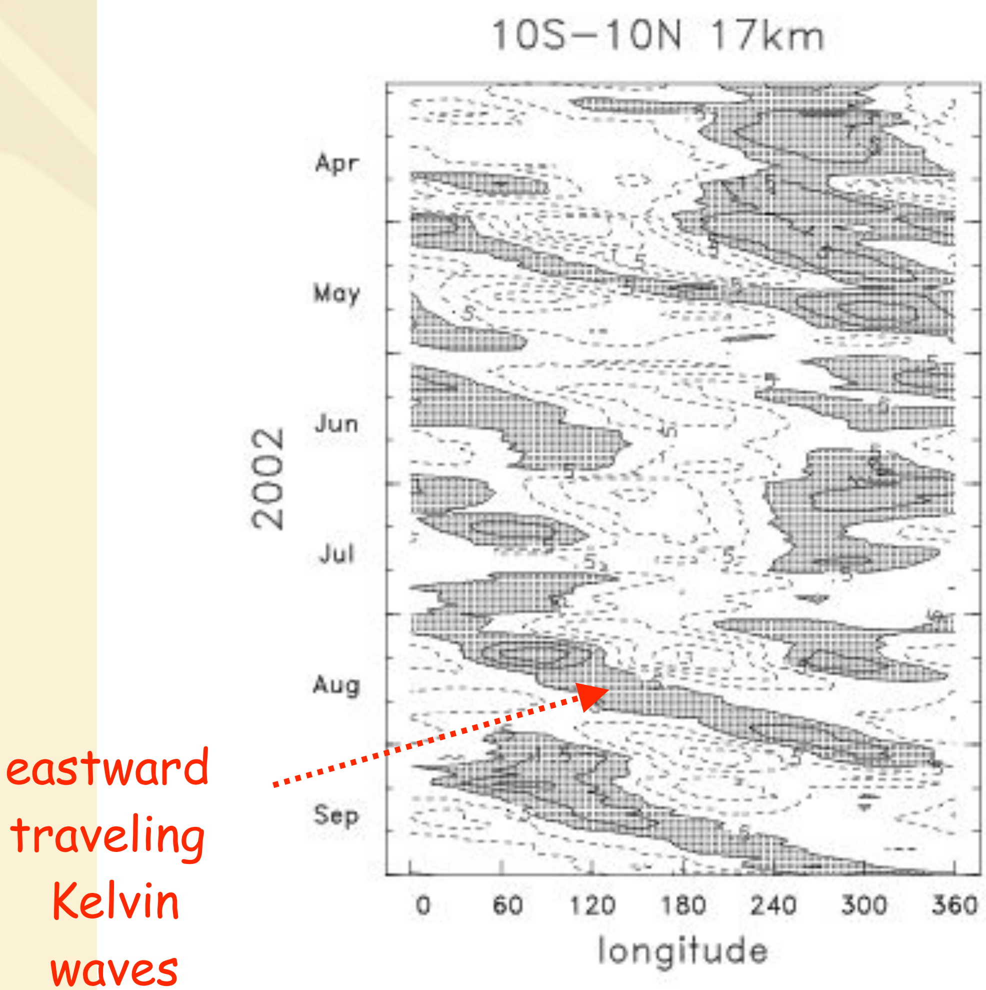
Gravity wave climatology

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



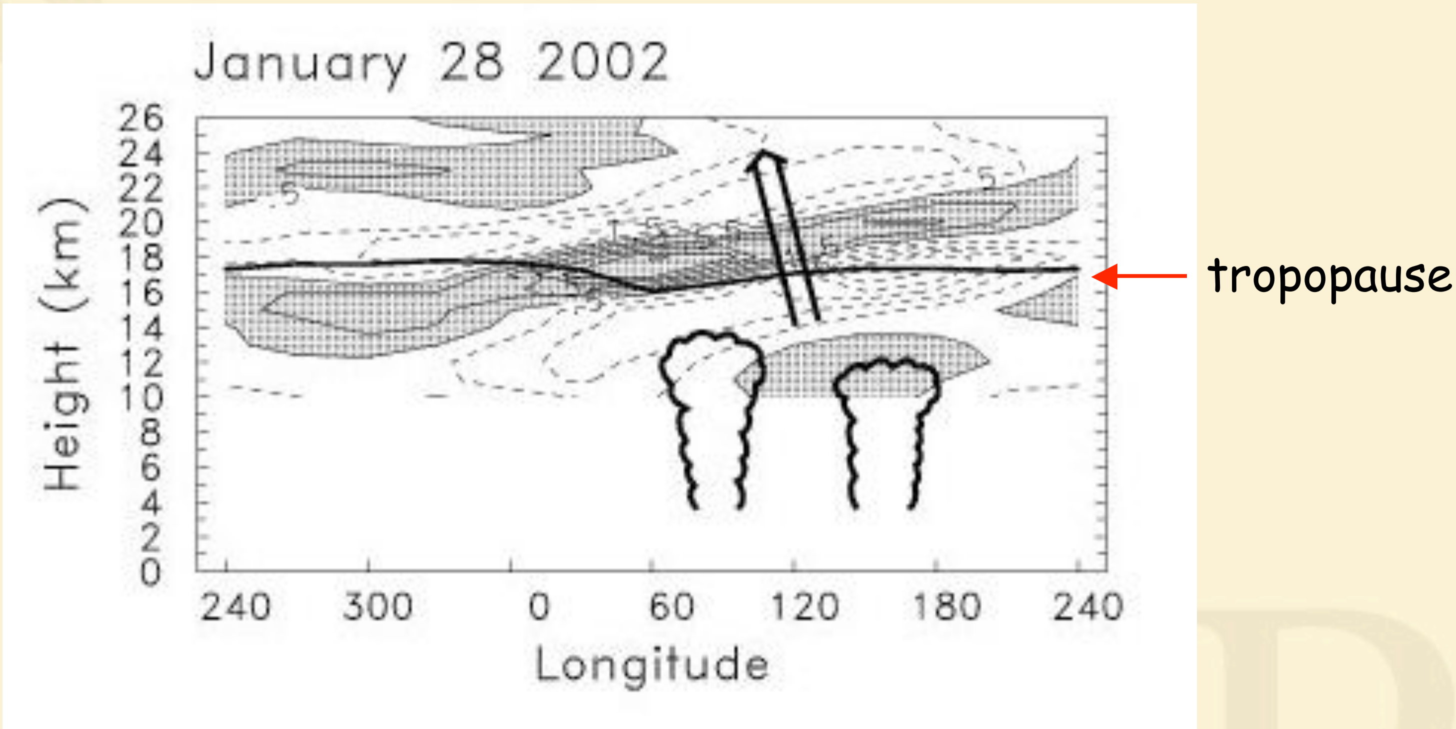
Tsuda *et al.*, 2000

Kelvin waves near the tropopause



Randel and Wu, 2004

Kelvin wave vertical structure

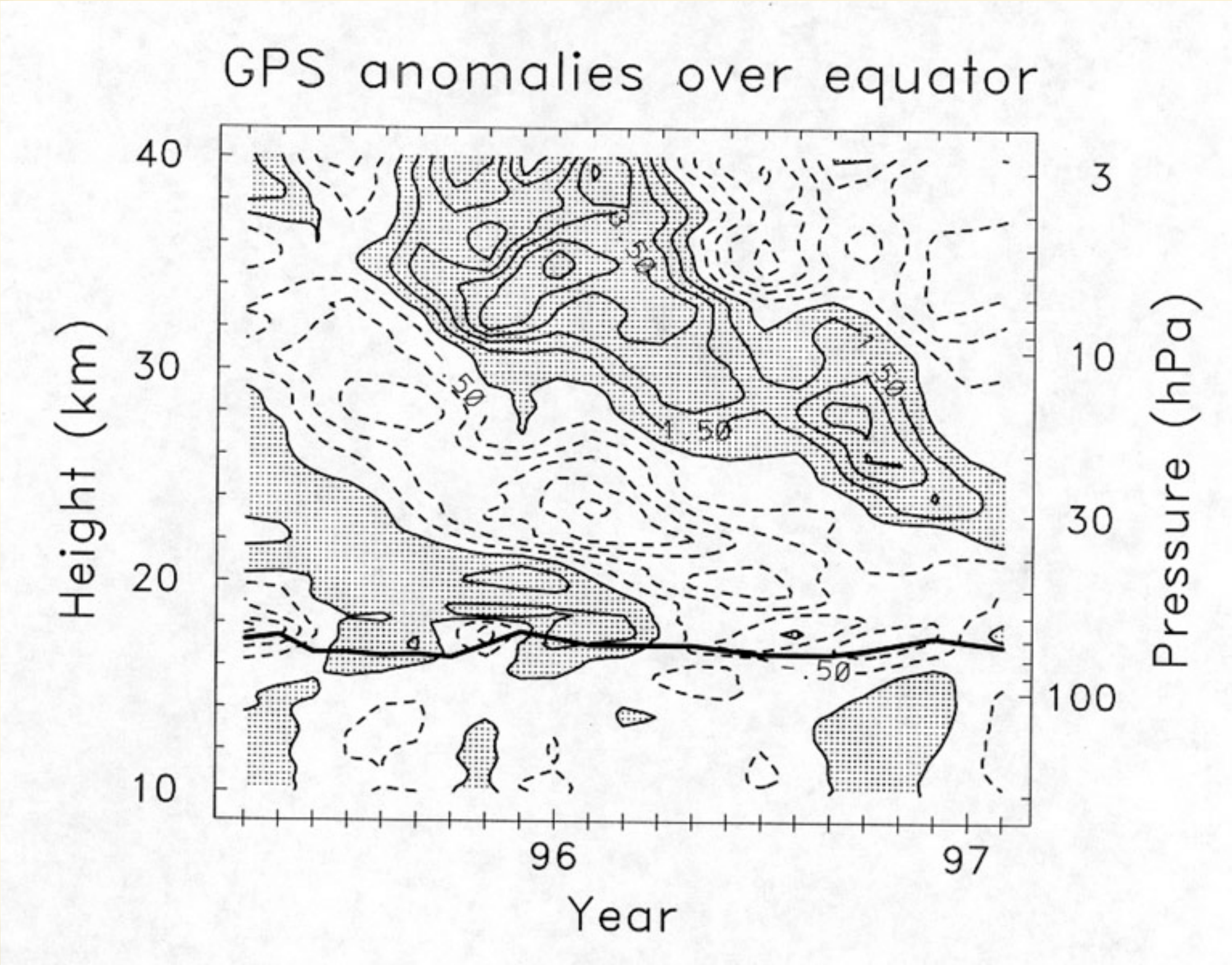


W. Randel, NCAR

QBO over Equator

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

Contours 0.5 K



Randel *et al*., 2003

Two-week average soundings near Equator

Note sharper tropopause in GPS/MET and warm bulge between 23 and 30 km (caused by QBO) which is underestimated in operational analyses.

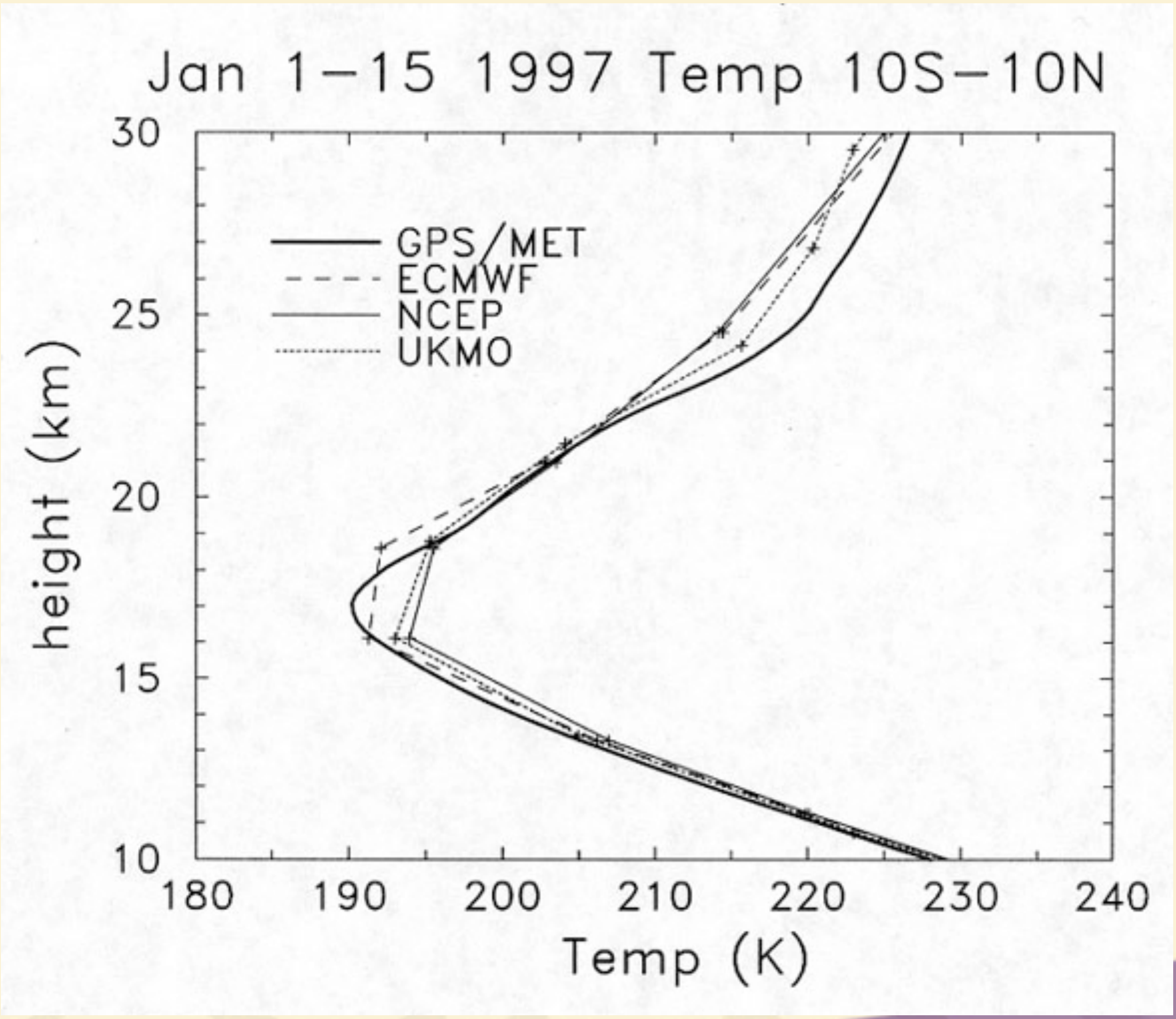
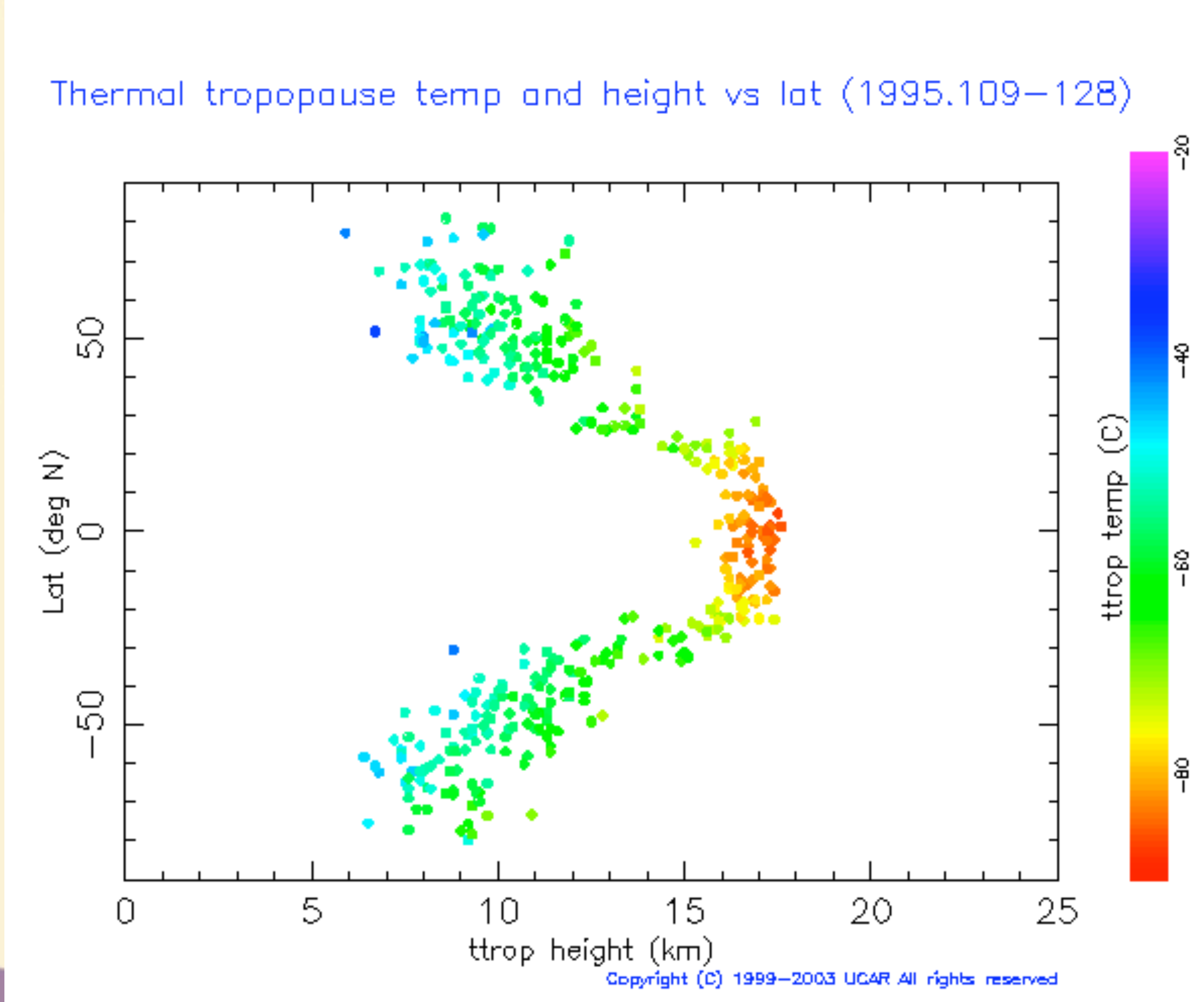
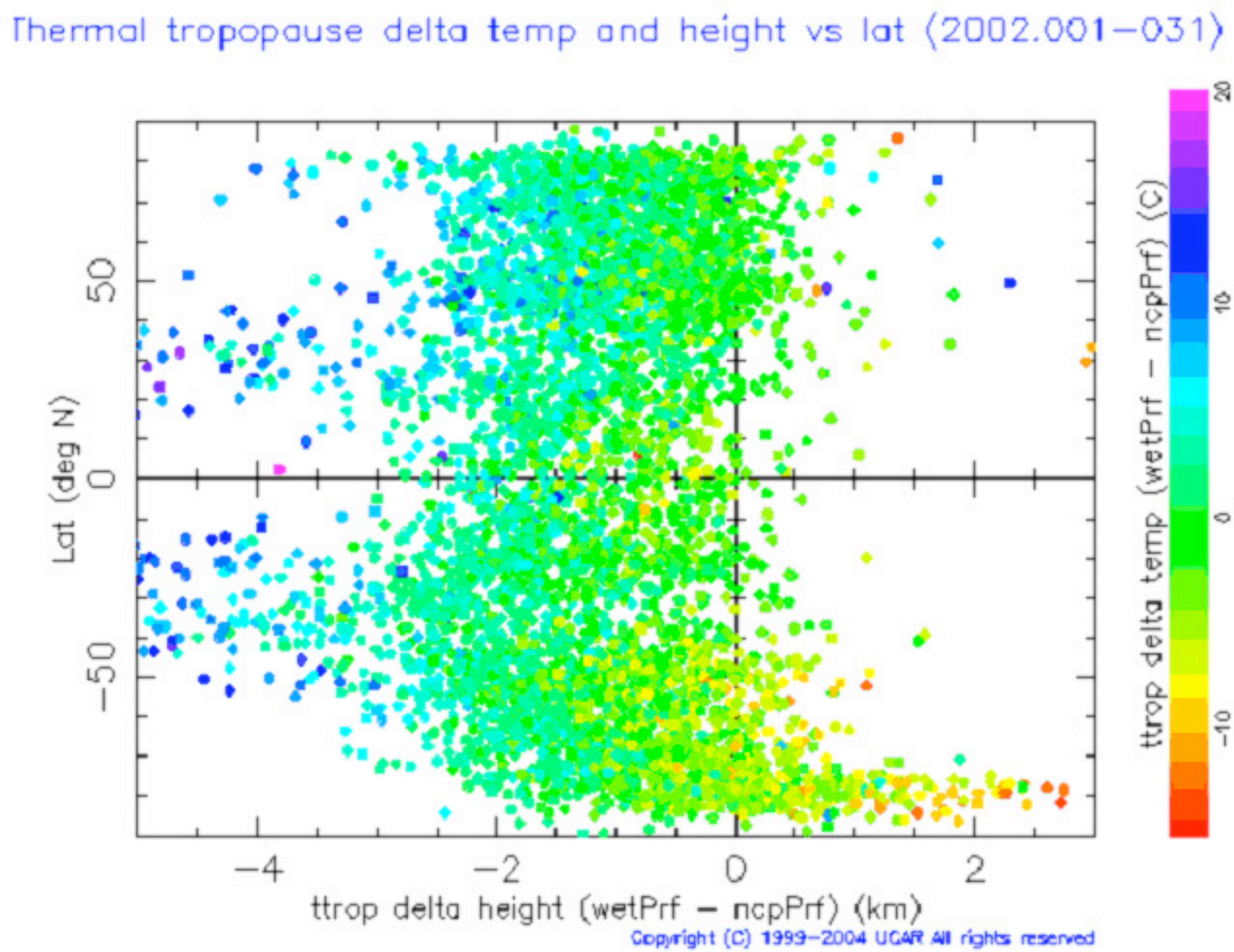


Fig. 3, Randel *et al*.,2003

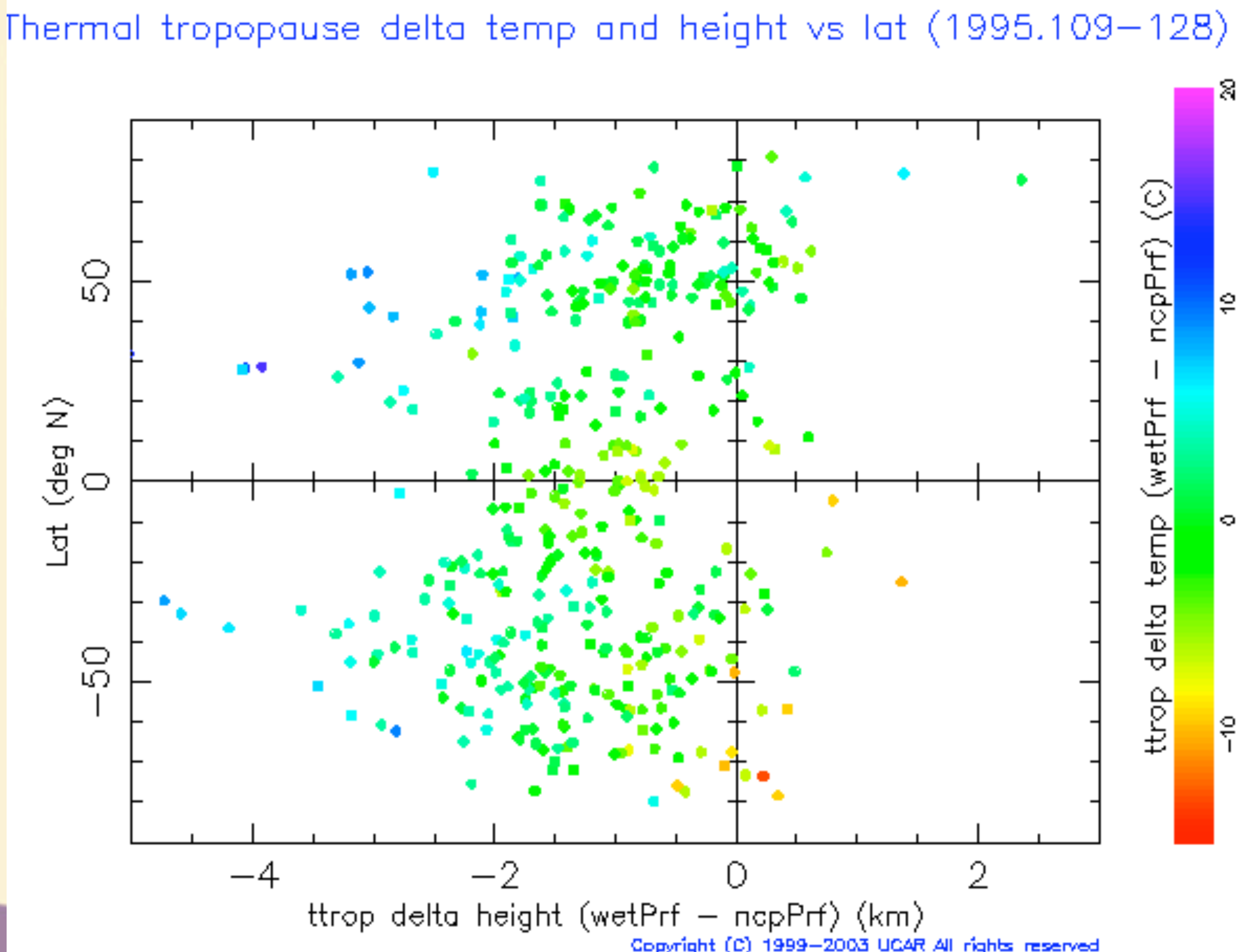
Thermal troposphere temperature and height vs. latitude 2001-2003



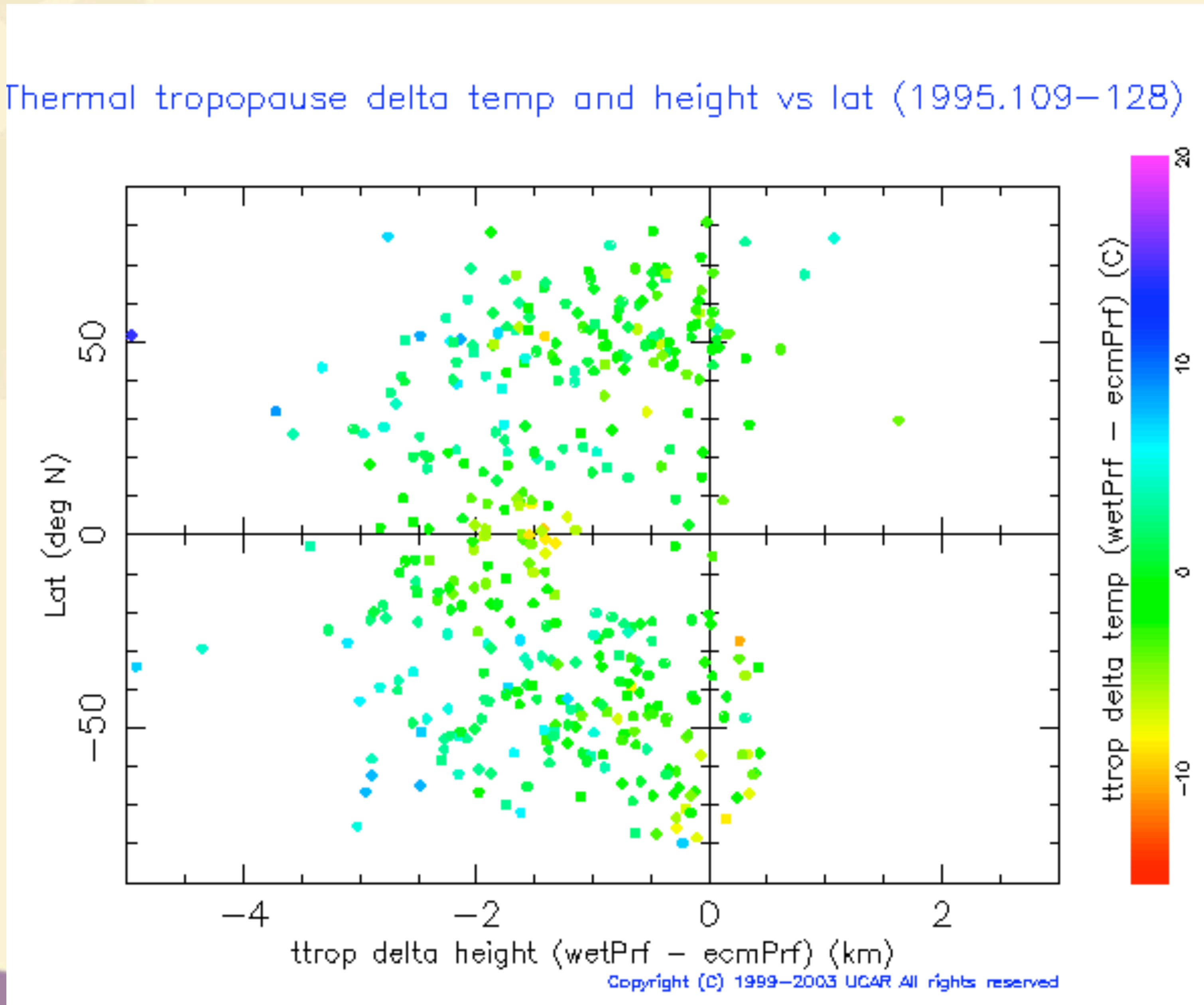
Difference in tropopause temperature and height: GPS-NCEP January 2002



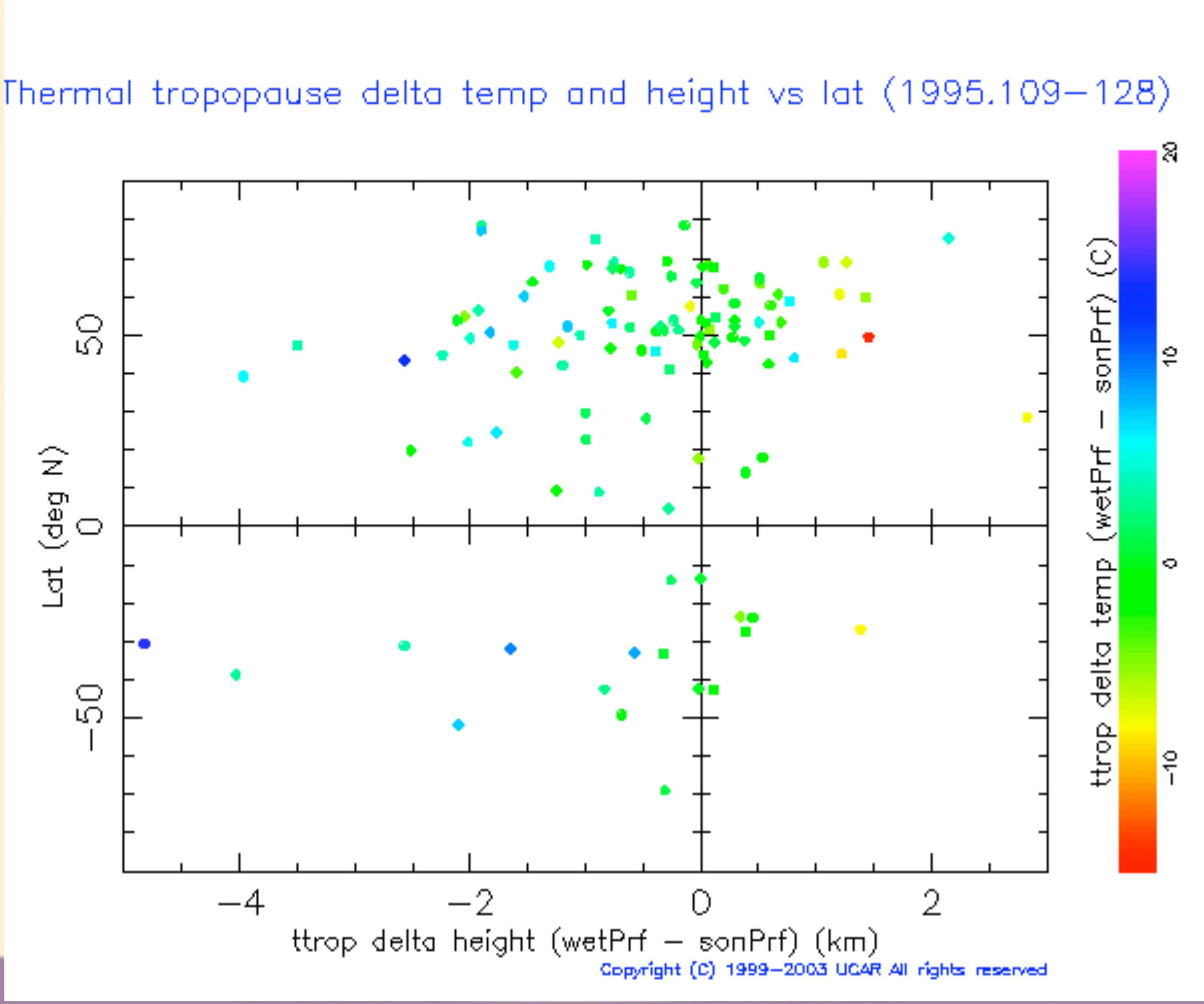
Difference in tropopause temperature and height: GPS-NCEP
Each image monthly data.



Difference in tropopause temperature and height: GPS-ECMWF

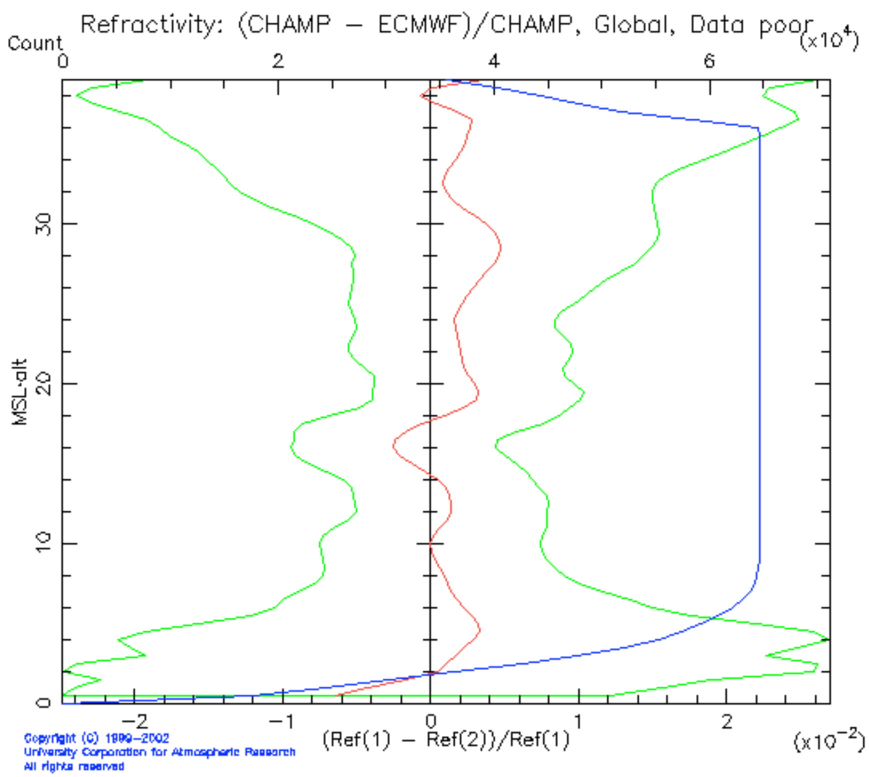


Difference in tropopause temperature and height: GPS-Radiosondes

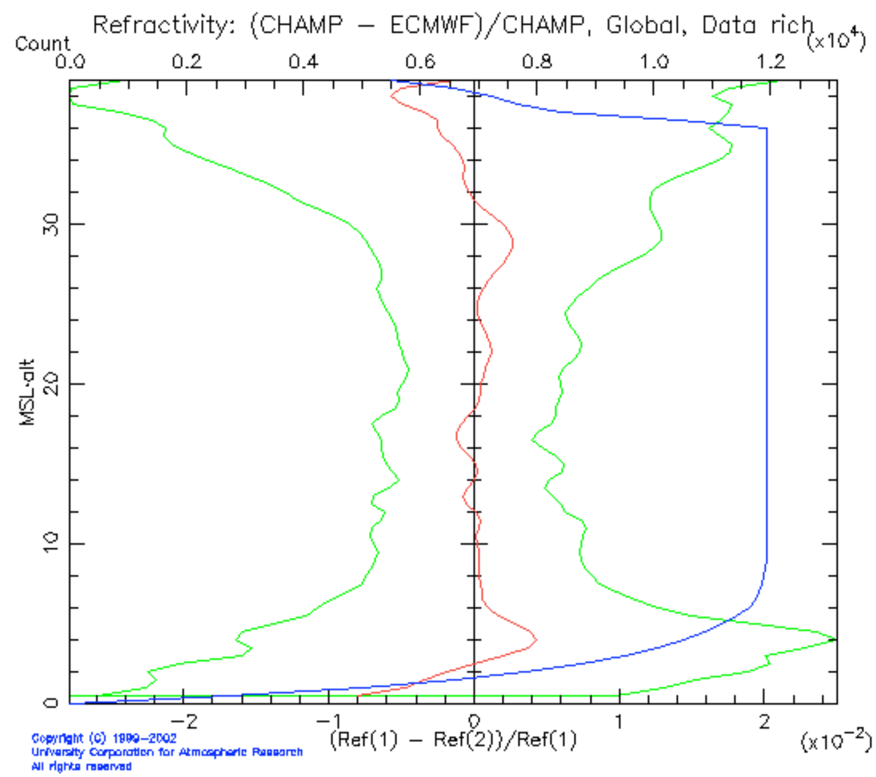


Using GPS soundings to evaluate global analyses

CHAMP - ECMWF



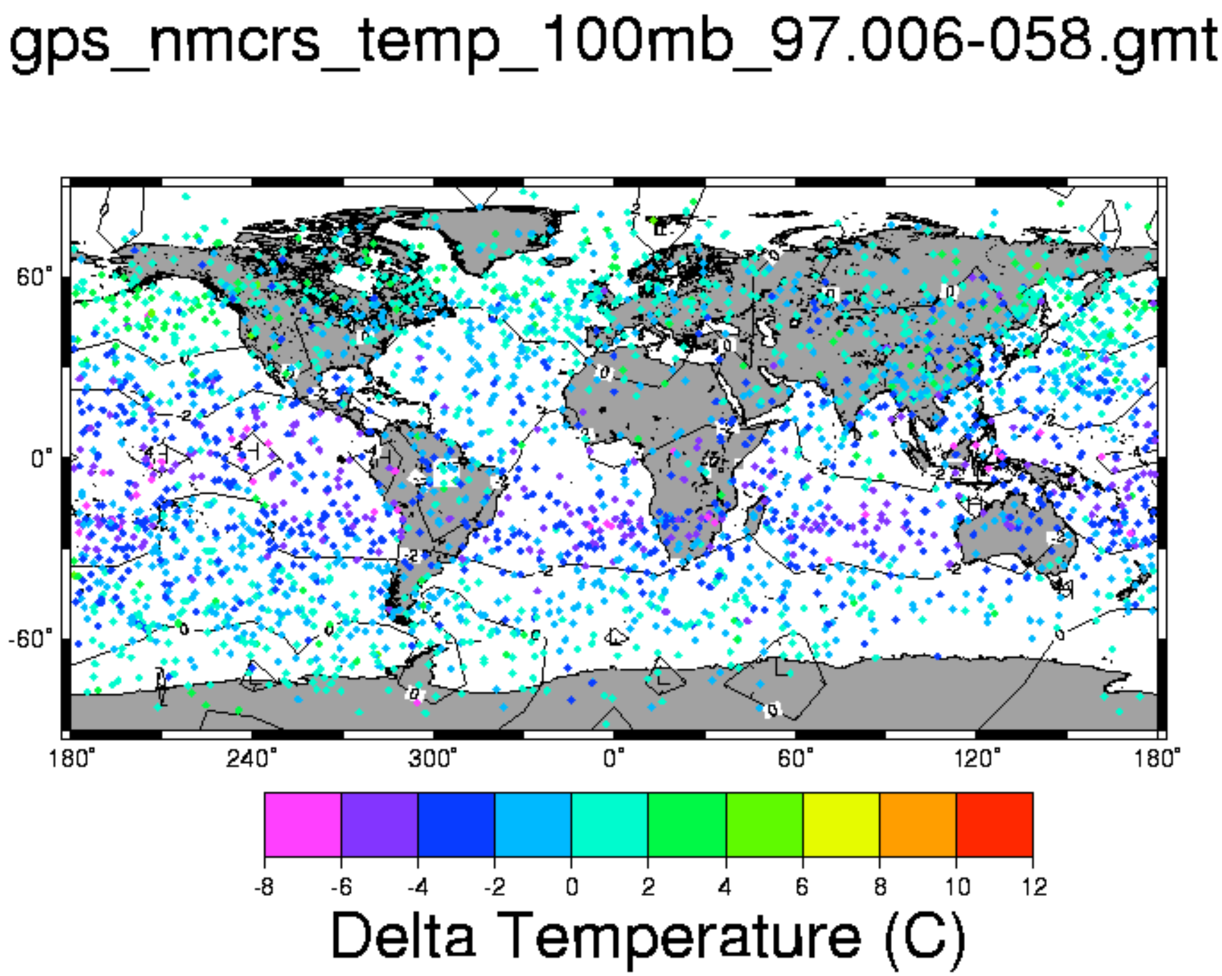
Data Poor regions



Data Rich regions

Comparison of RO profiles with ECMWF profiles in data rich (mostly land masses) and data poor regions (mostly oceanic regions). The better agreement from 5-30 km indicates superior ECMWF performance in data-rich regions

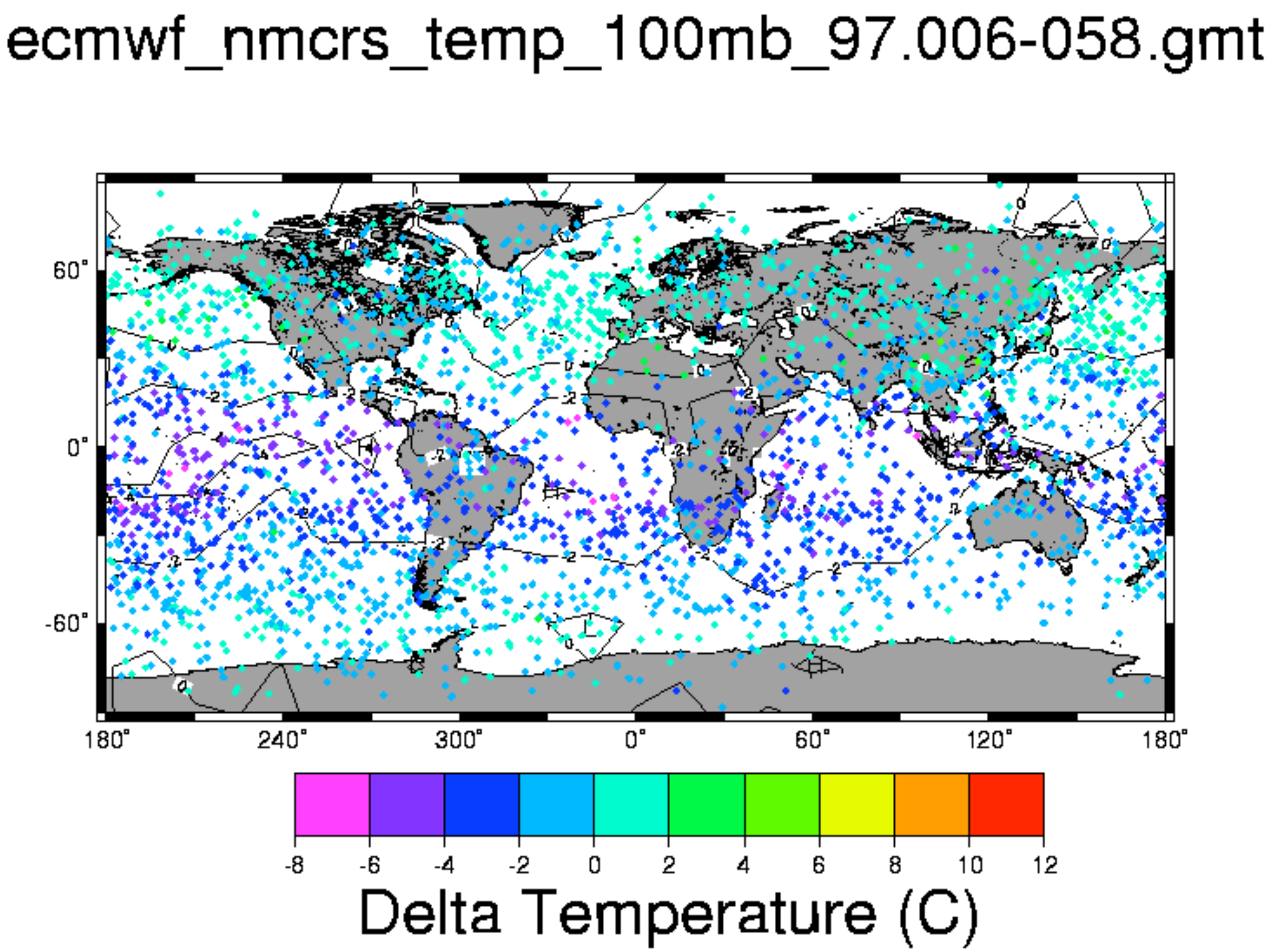
GPS – NCEP/NCAR Reanalysis



100 mb
Temperature

Note large errors in reanalysis near Equator

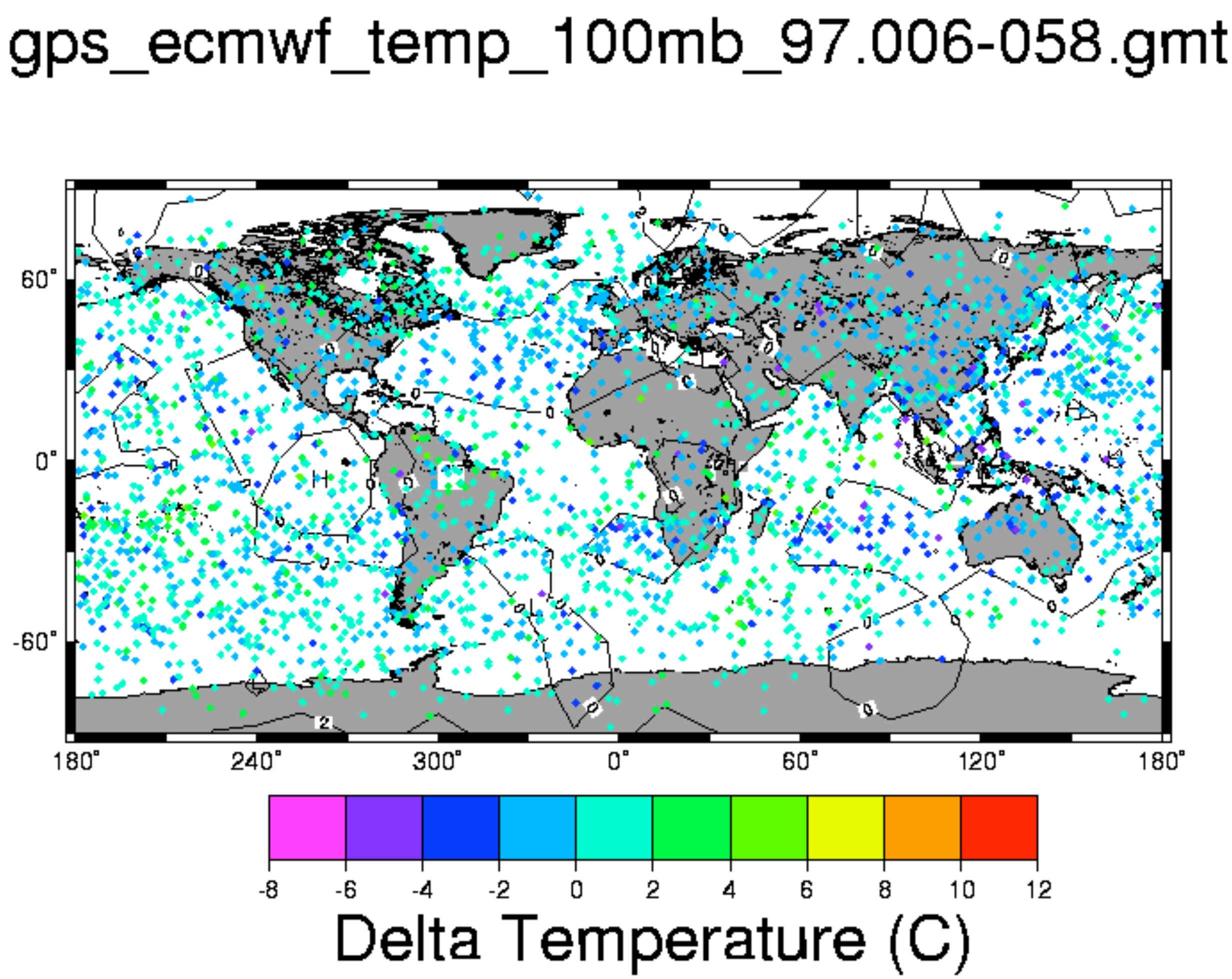
ECMWF – NCEP/NCAR reanalysis



100 mb
Temperature

Note same errors
When NCEP/NCAR
is compared with
ECMWF

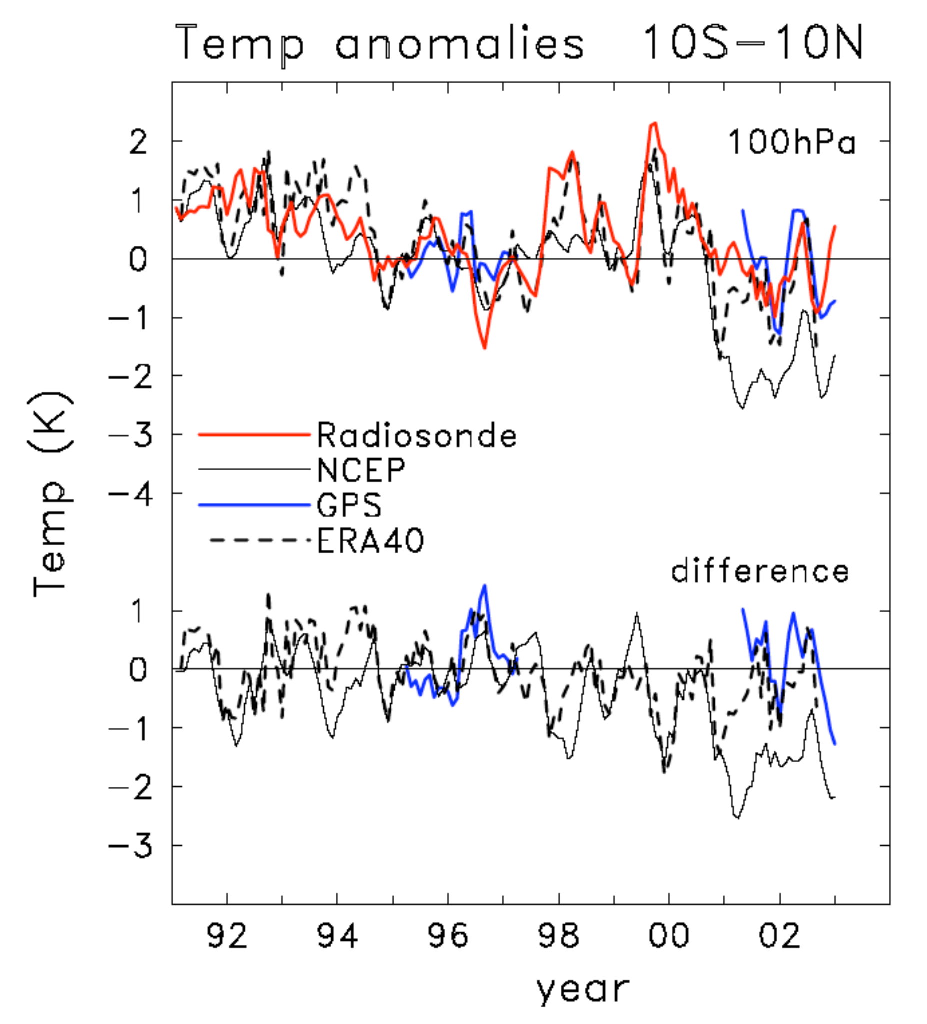
GPS – ECMWF analysis



100 mb
Temperature

ECMWF does not show nearly as large errors as NCEP/ NCAR

Evaluation of global reanalysis



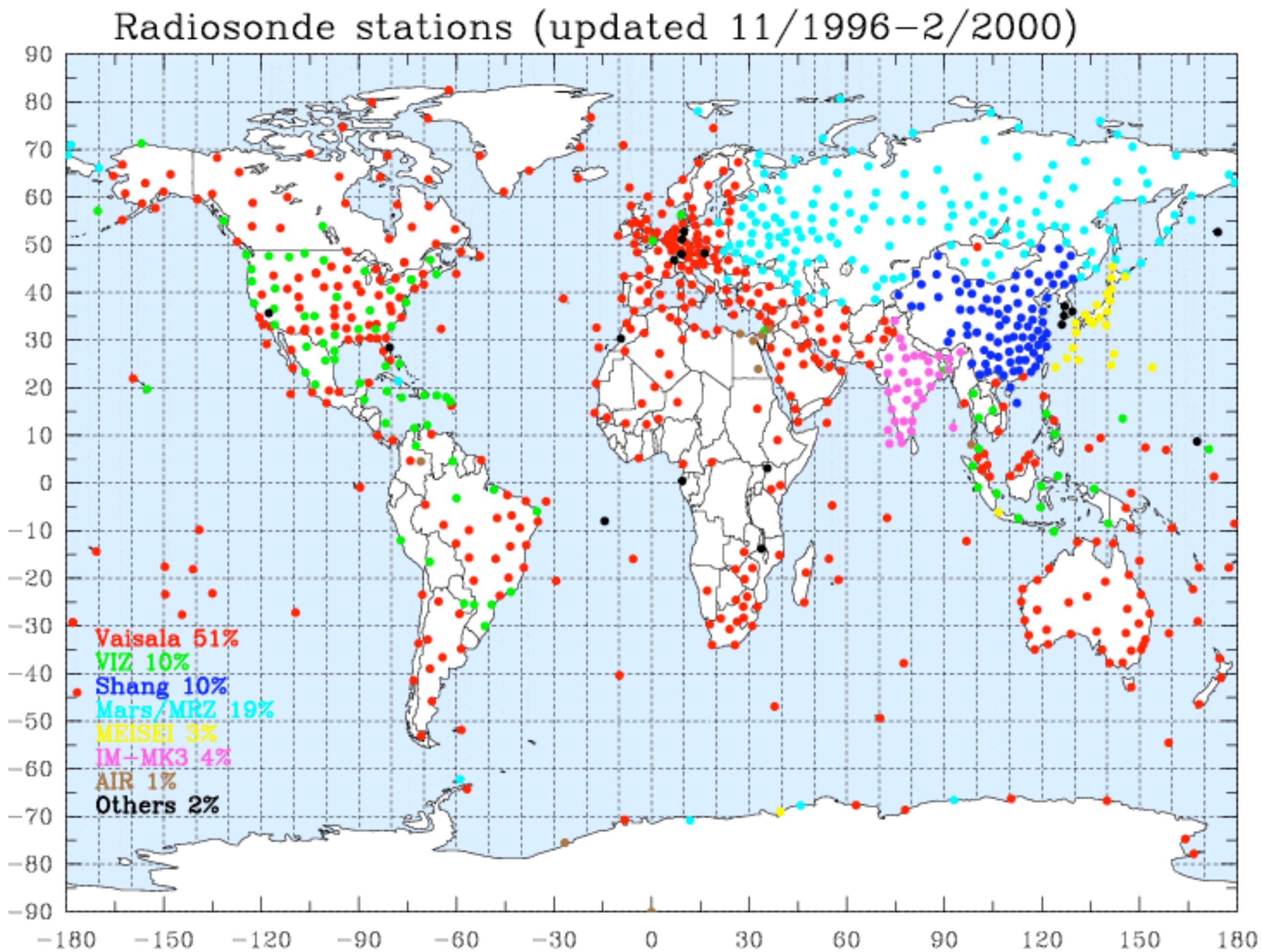
Top: time series of deseasonalized 100 mb temperature anomalies over 10° N-S, showing results from four different data sets. Each time series is normalized to be zero for April 1995 – February 1997.

Bottom: Difference of the respective time series with averaged radiosonde data. (Randel *et al.,* 2005)

"These interannual temperature changes near the tropical tropopause are really a hard thing to get a handle on, especially for historical changes. There are few radiosonde stations in the tropics and the longer records (~20+ years) almost all show biases due to instrumentation changes. Nadir sounding satellites aren't much help. And reanalyses have their own sets of problems. So GPS will make an especially key contribution in this region." Bill Randel, personal communication, May 23, 2005.

RO comparison with radiosondes

The role of radiosondes observations in the climatic record is limited, in part, by sensor characteristics that vary substantially in time and space.



Junhong Wang, NCAR

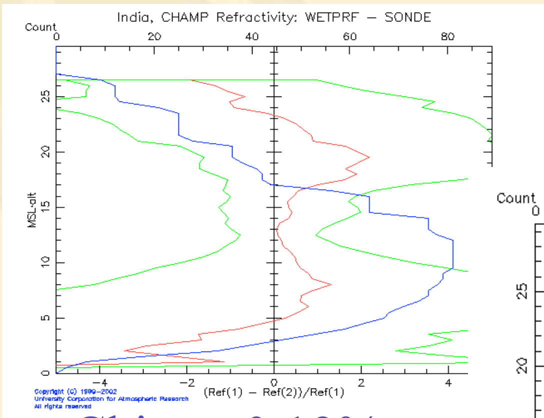
Quantifying Regional Differences

- Calculate the mean absolute difference in refractivity between CHAMP and Radiosondes (N_{CR}) between 5 ~ 25 km.
- Calculate the corresponding mean of the absolute value of the difference in refractivity between CHAMP and the ECMWF (N_{CE})
- Compute the ratio ($D = N_{CR} / N_{CE}$)
- Perform calculation using radiosonde data from different regions of the world from June 2001 to August 2003.

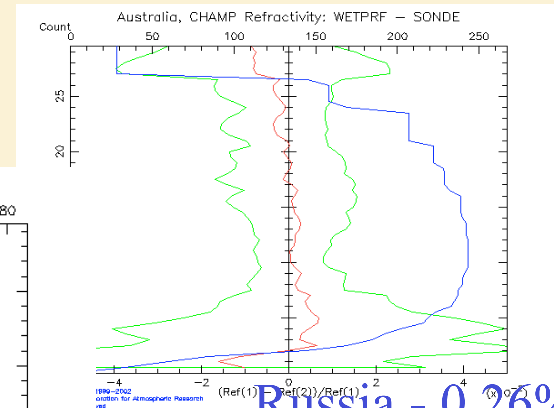
D.Rossiter and W. Kuo, NCAR

Comparison between CHAMP and Radiosonde

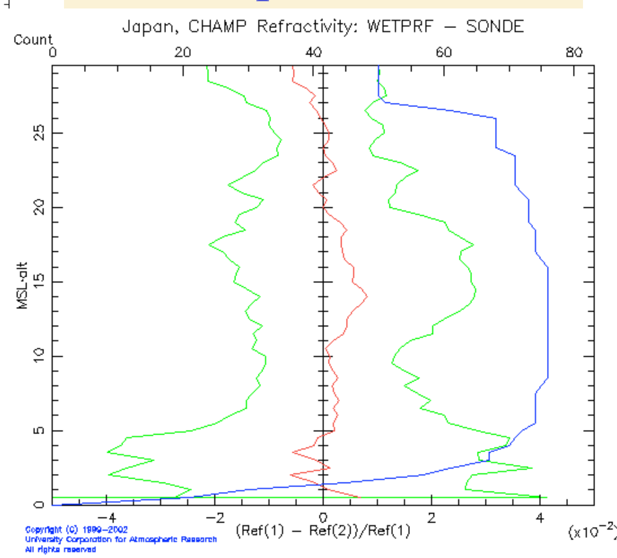
India - 0.77%



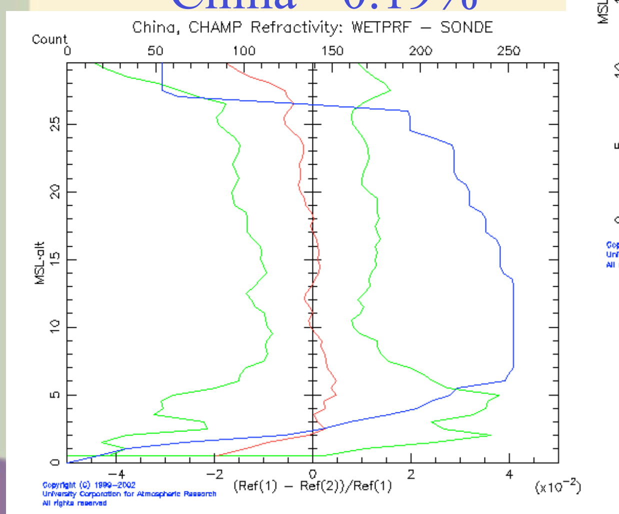
Australia - 0.19%



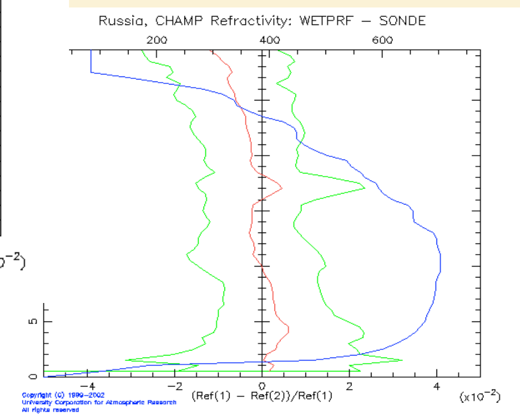
Japan - 0.28%



China - 0.19%

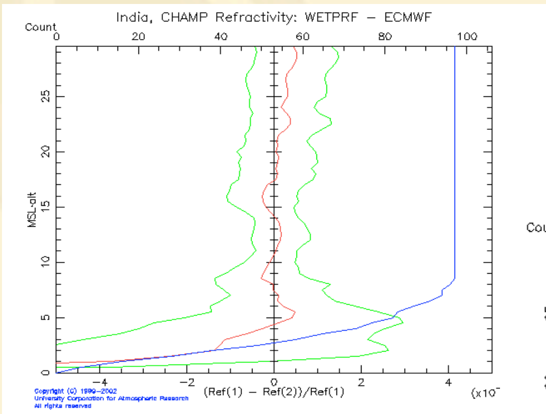


Russia - 0.26%

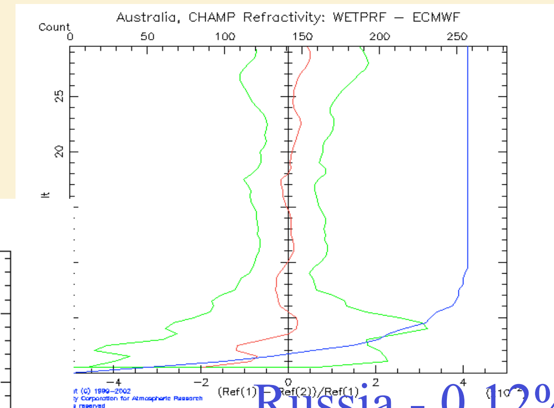


Comparison between CHAMP and ECMWF

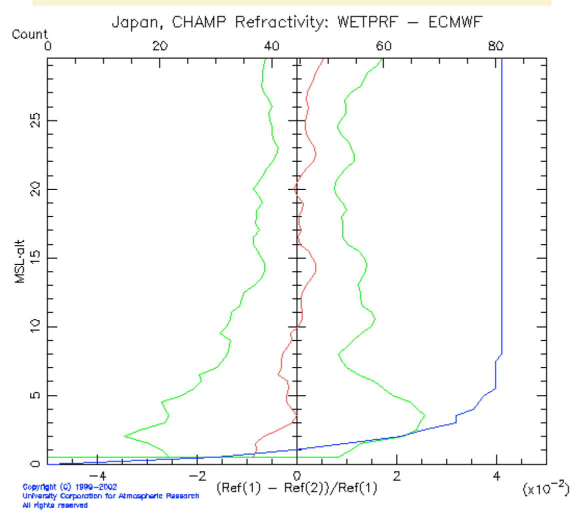
India - 0.17%



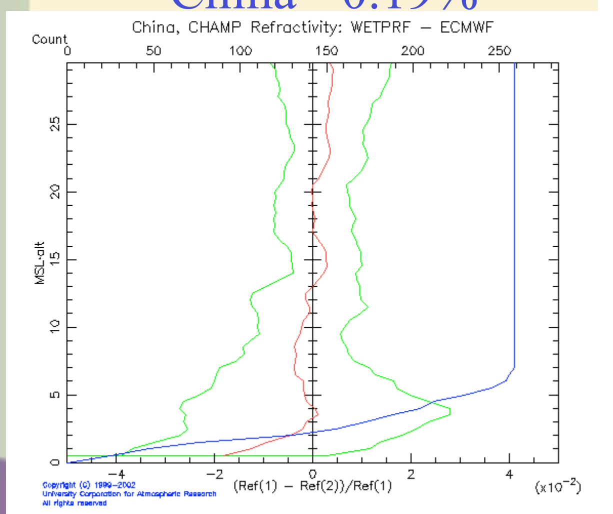
Australia - 0.14%



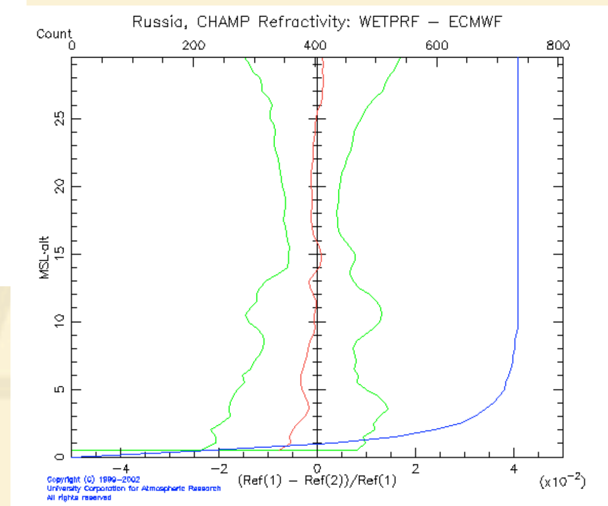
Japan - 0.18%



China - 0.19%



Russia - 0.12%

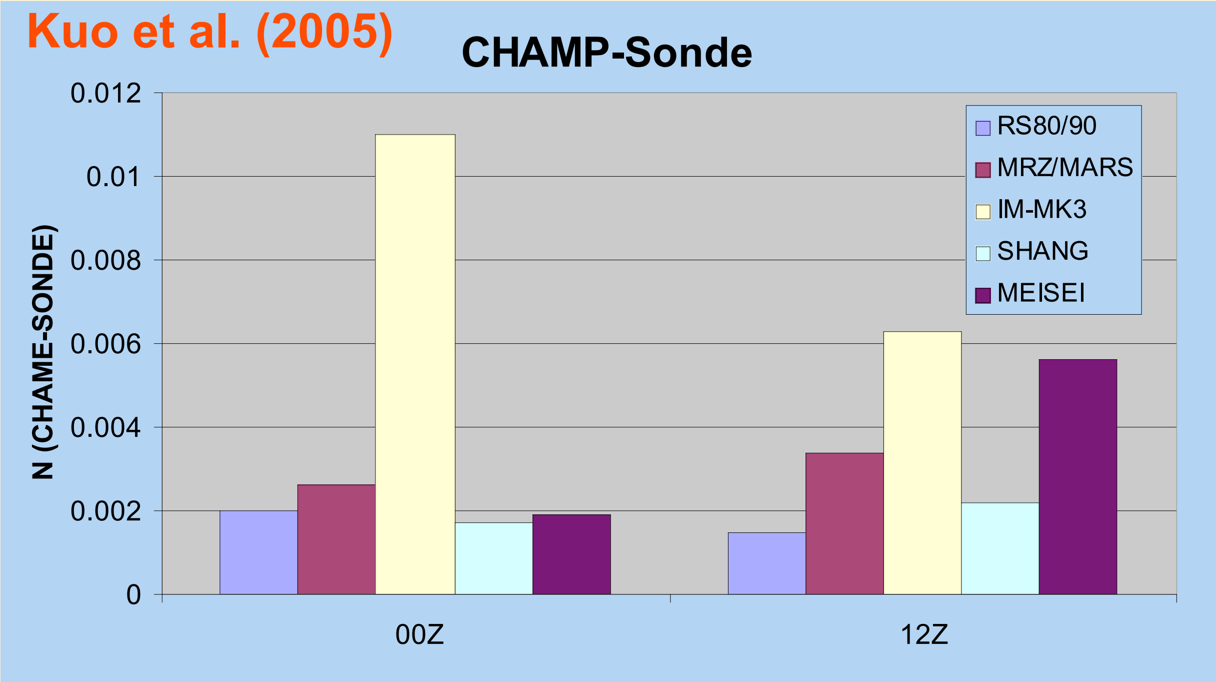


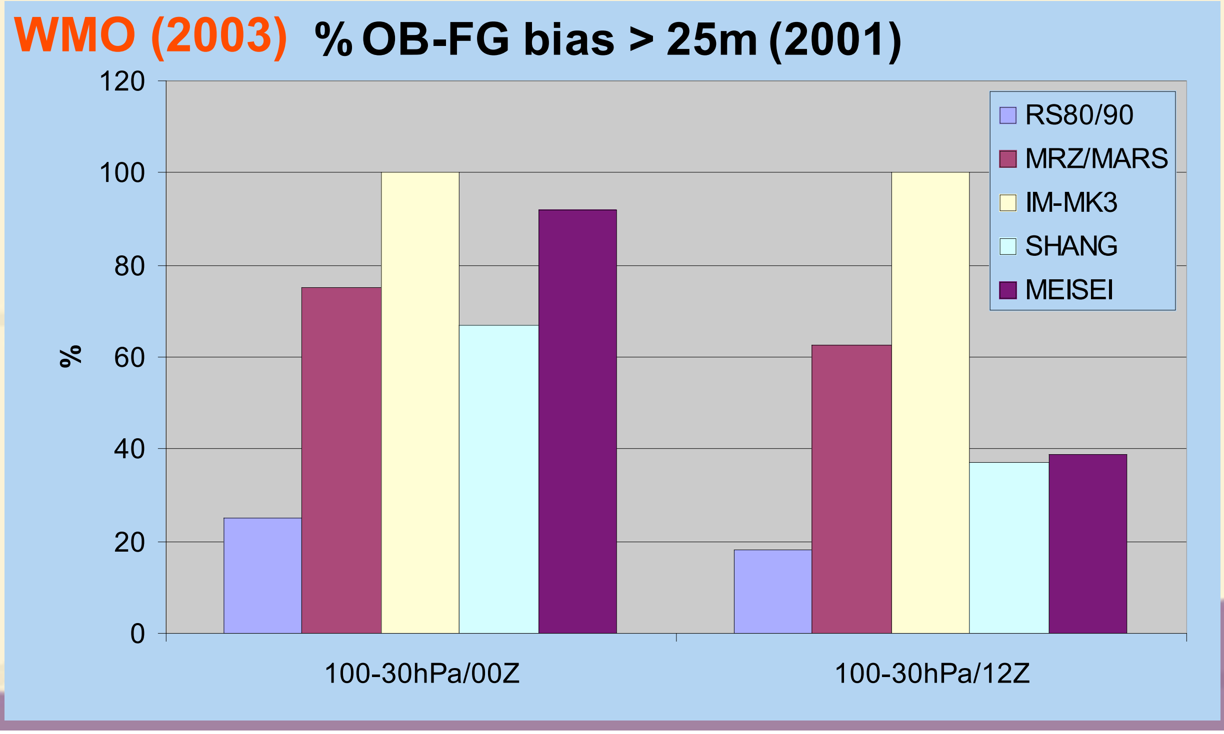
Statistics of CHAMP - Radiosonde Comparison

Region	Sonde Type	# of matches	[illegible]	[illegible]	N_{CR}/N_{CE}
India	IM-MK3	87	0.82/3.2	0.15/1.0	5.5
Russia	Mars	1003	0.30/1.3	0.09/0.9	3.3
Japan	MEISEI	107	0.26/1.7	0.14/1.1	1.9
China	Shanghai	402	0.19/1.4	0.15/1.0	1.3
Australia	Vaisala	366	0.18/1.3	0.13/0.9	1.4

Monitoring health of global radiosonde network.

J. Wang, NCAR

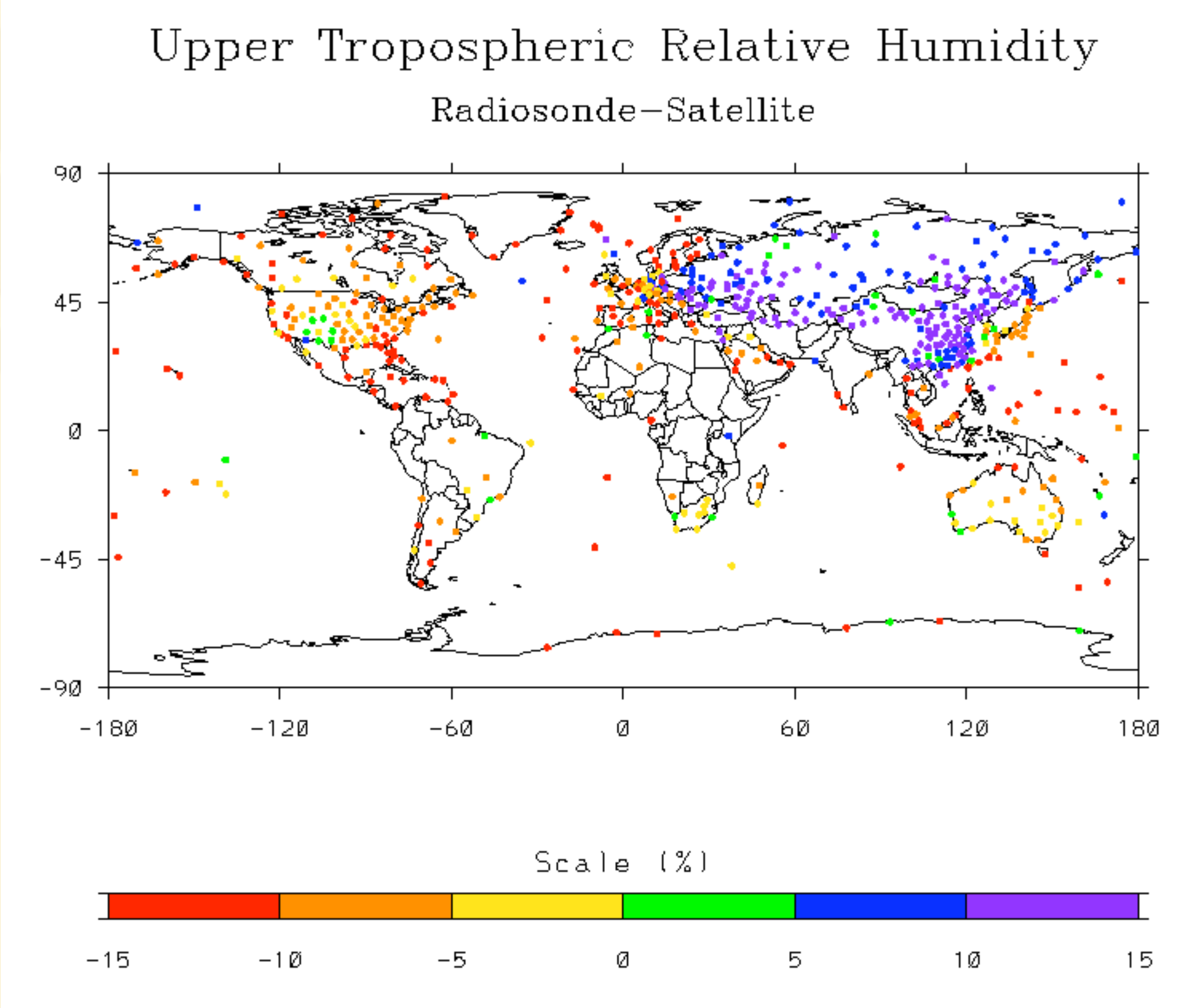




Future:

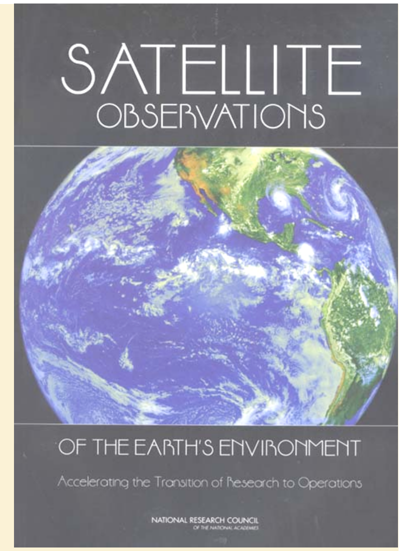
UTRH
GPS-RO

Please make the world moister!!!
(J. Wang)



Soden and Lanzante (1996)

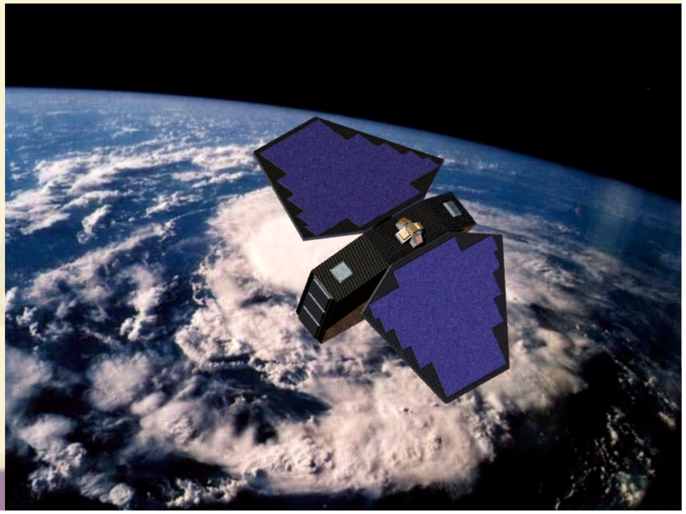
GPS RO-Research to Ops



- GPS radio occultation is a promising atmospheric observing system for both weather and climate:
  - Temperature, water vapor, electron density information
  - High vertical resolution
  - High accuracy (<1K)
  - Unaffected by clouds
  - Self calibrating, no instrument drift or satellite-to-satellite bias (important for climate detection)
- GPS RO data will be valuable to:
  - Weather prediction
  - Climate monitoring and analysis
    - World's most accurate atmospheric thermometer!
  - ionospheric research and space weather forecasting
  - Calibrate/complement/enhance other satellite observing systems
- Need plan for transition from research into operations

COSMIC II

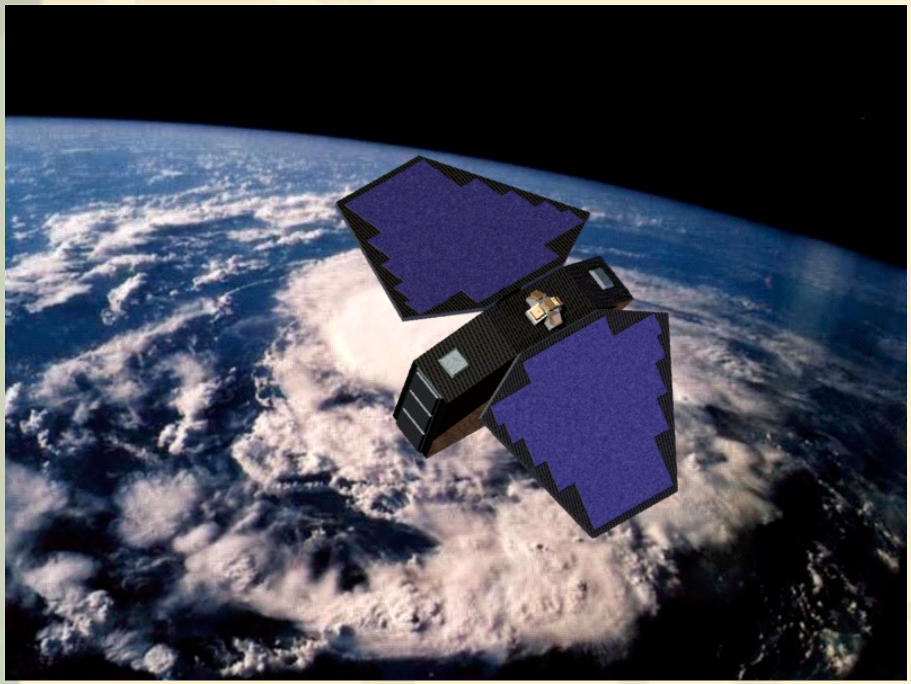
- Transition research into operations- maintain a constellation of small satellites in low Earth orbit producing RO observations to help meet the weather, climate and space weather operational requirements as part of the GEOSS.



COSMIC-II (C2)

- ~2500 (5000) high-quality, independent soundings to complement and improve infrared and microwave soundings
- Risk reduction
- Affordable (<$15M/year ongoing costs-total)
- Launch in 2009 would overlap COSMIC by one year, allowing tests of value of 5000 (7500) vs. 2500 soundings
- Major <u>new</u> contribution to GEOSS

[Higher number of soundings in ( ) if Galileo included]



C2 baseline concept spacecraft in flight

Total Mass Estimate: 24 Kg.
Total Orbit Average Power: 29 watts
Stowed Size: 50 cm x 40 cm x 10 cm

Improved occultation receiver
Reduced latency (<25 min)
GPS and Galileo tracking


Thank you from the COSMIC Team!