# Climate Applications of High Resolution Infrared Sounders

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NOAA/NESDIS/STAR

ECMWF/EUMETSAT NWP-SAF Workshop on the assimilation of IASI in NWP

# Climate Applications

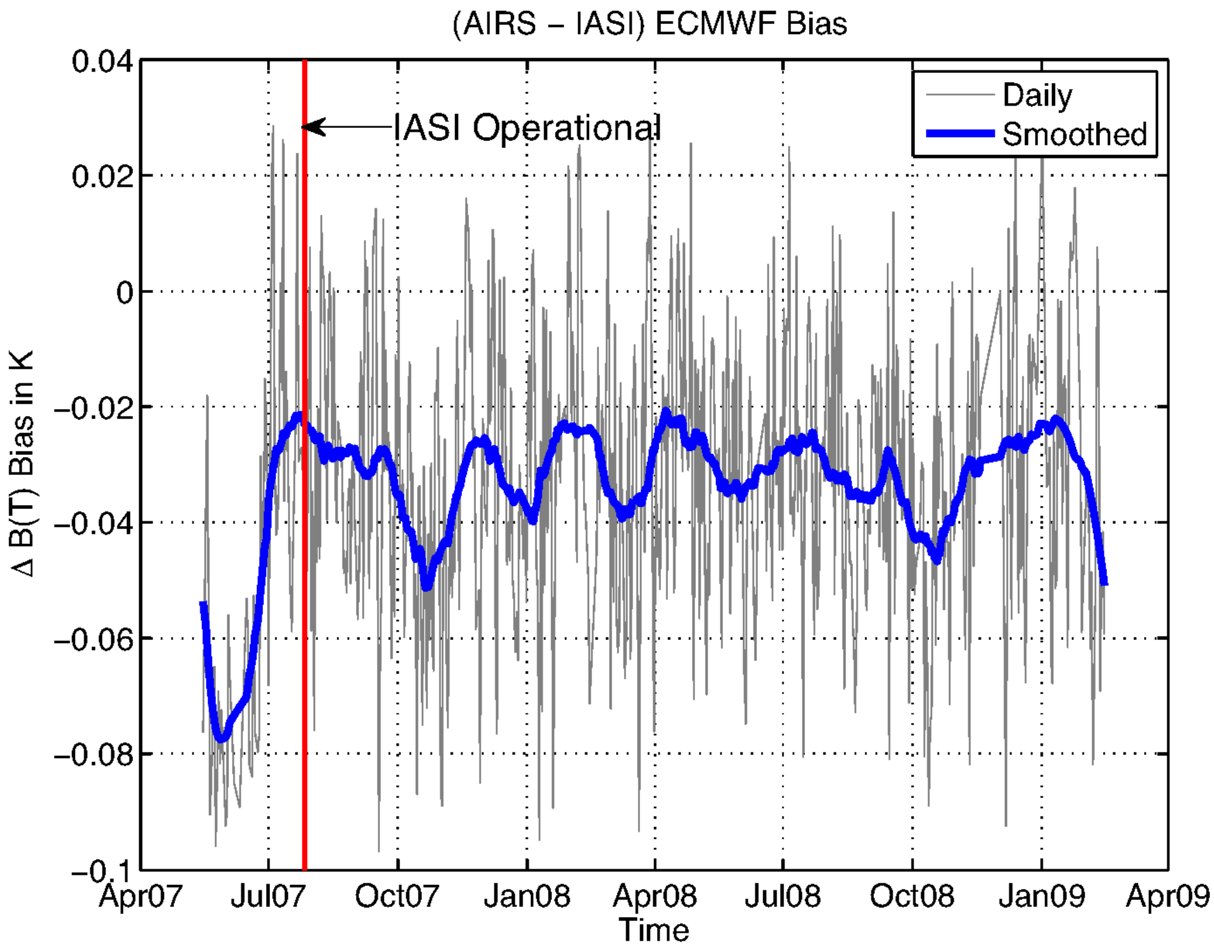
- Climate applications = information with high confidence
- Challenge - long term stability, accuracy, precision of observations.
- AIRS and IASI have exceptional long term stability and remarkable accuracy

# AIRS versus IASI Stability

-0.0019K/year ± 0.008K/year (corrected for lag-1 correlation of 0.45)



L. Strow
UMBC



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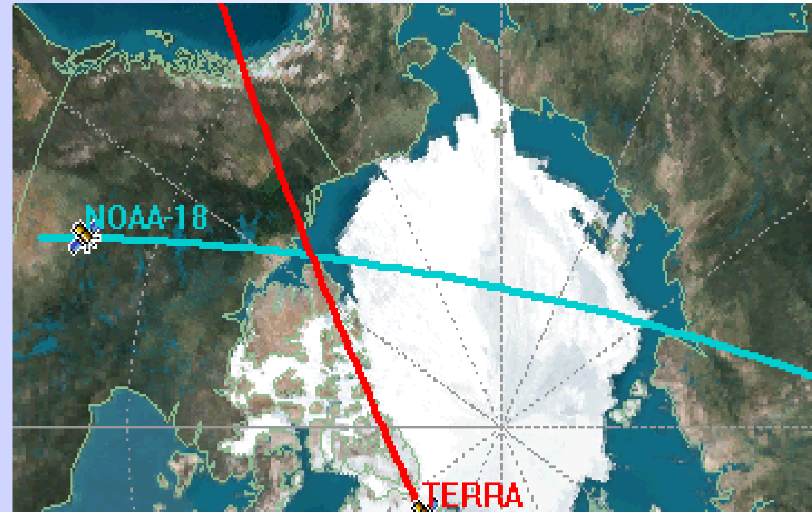
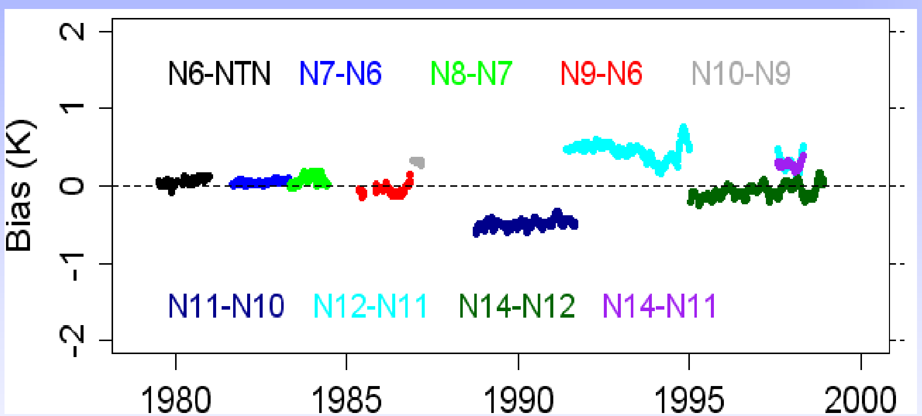
# Satellite Intercalibration

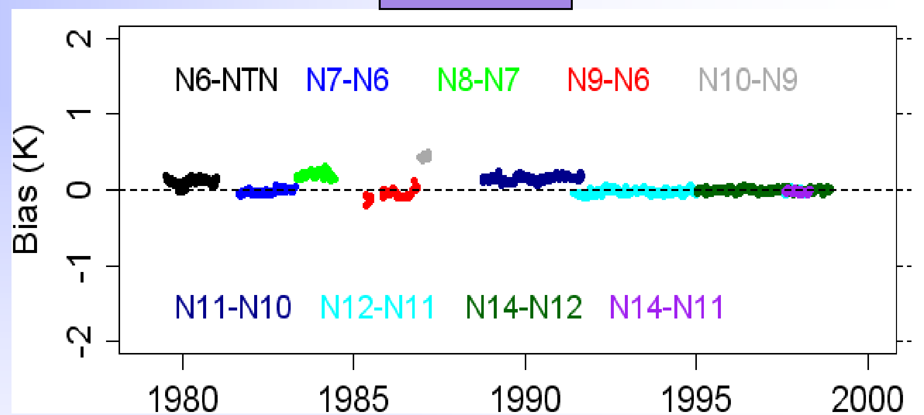
## MSU Channel 2 Observations: Before and After Intercalibration




Before




After




GLOBAL BIAS

NESDIS recalibrated MSU record is being used in climate reanalysis projects at NCEP and NASA and to derive reliable atmospheric temperature trends

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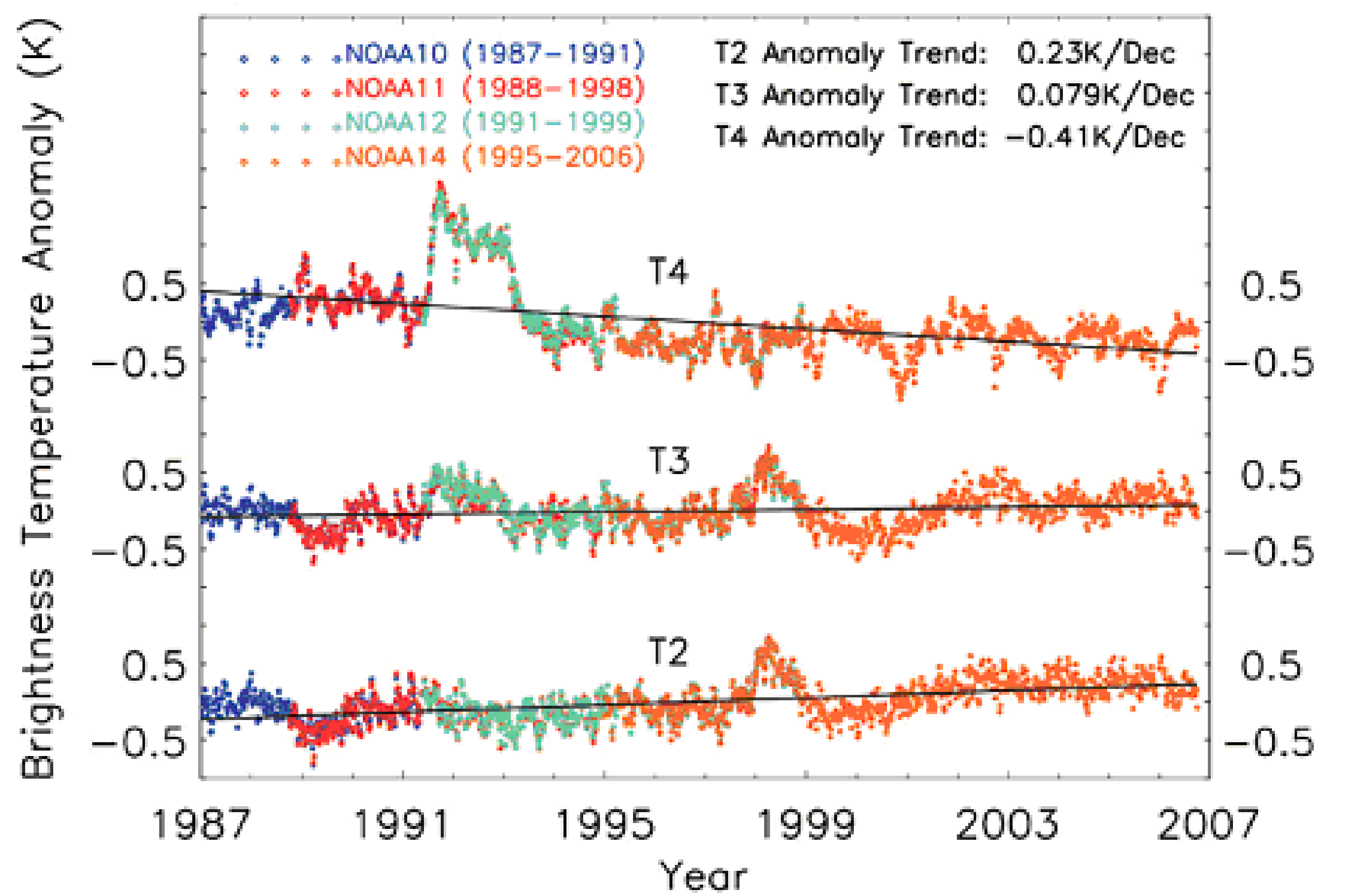


**Temperature trends over oceans in the mid-troposphere (T2), tropopause region (T3), and lower stratosphere (T4) from MSU channel 2, 3, and 4 observations (Zhu, Gao, and Goldberg, *J. Clim.*, In Press)**

After careful intercalibration there is still disagreement in with Christy and Mears. The data is not irrefutable

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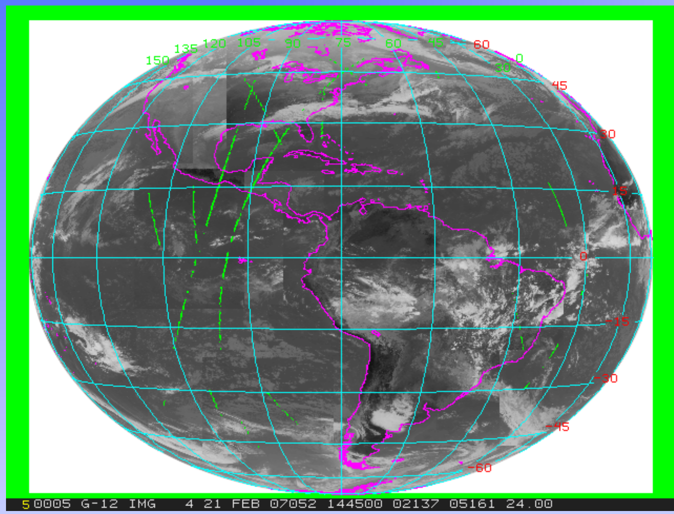
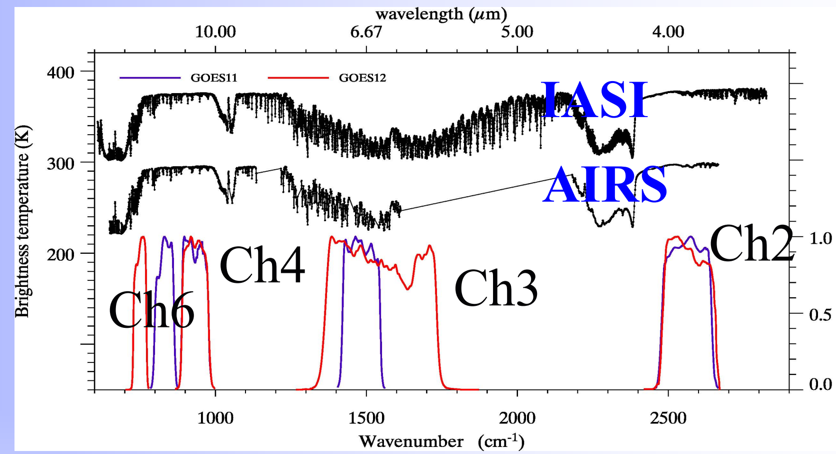
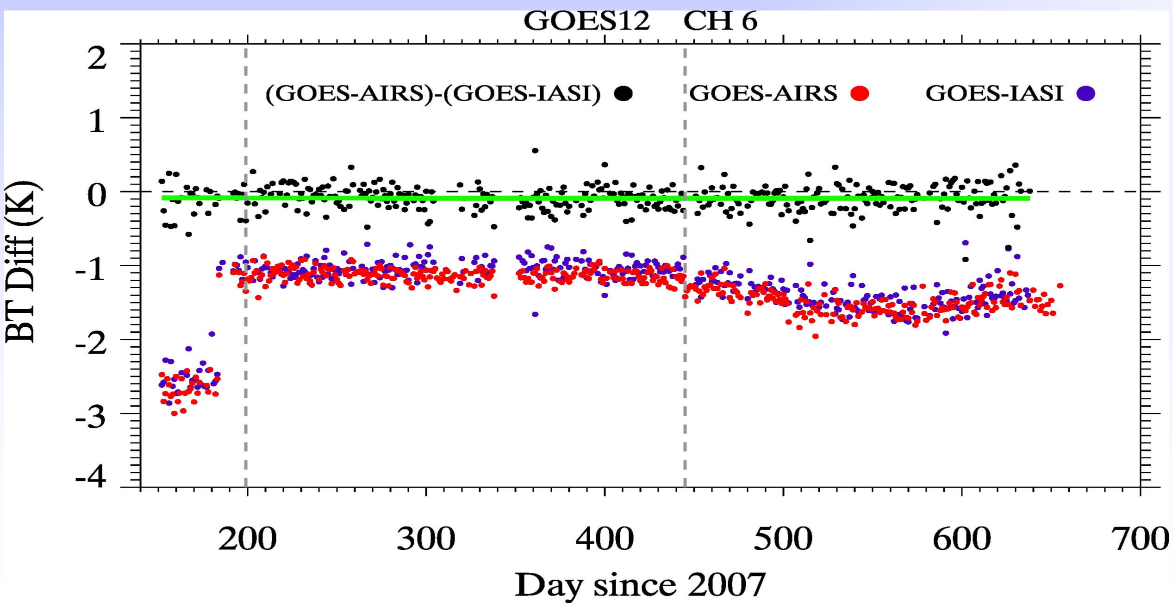
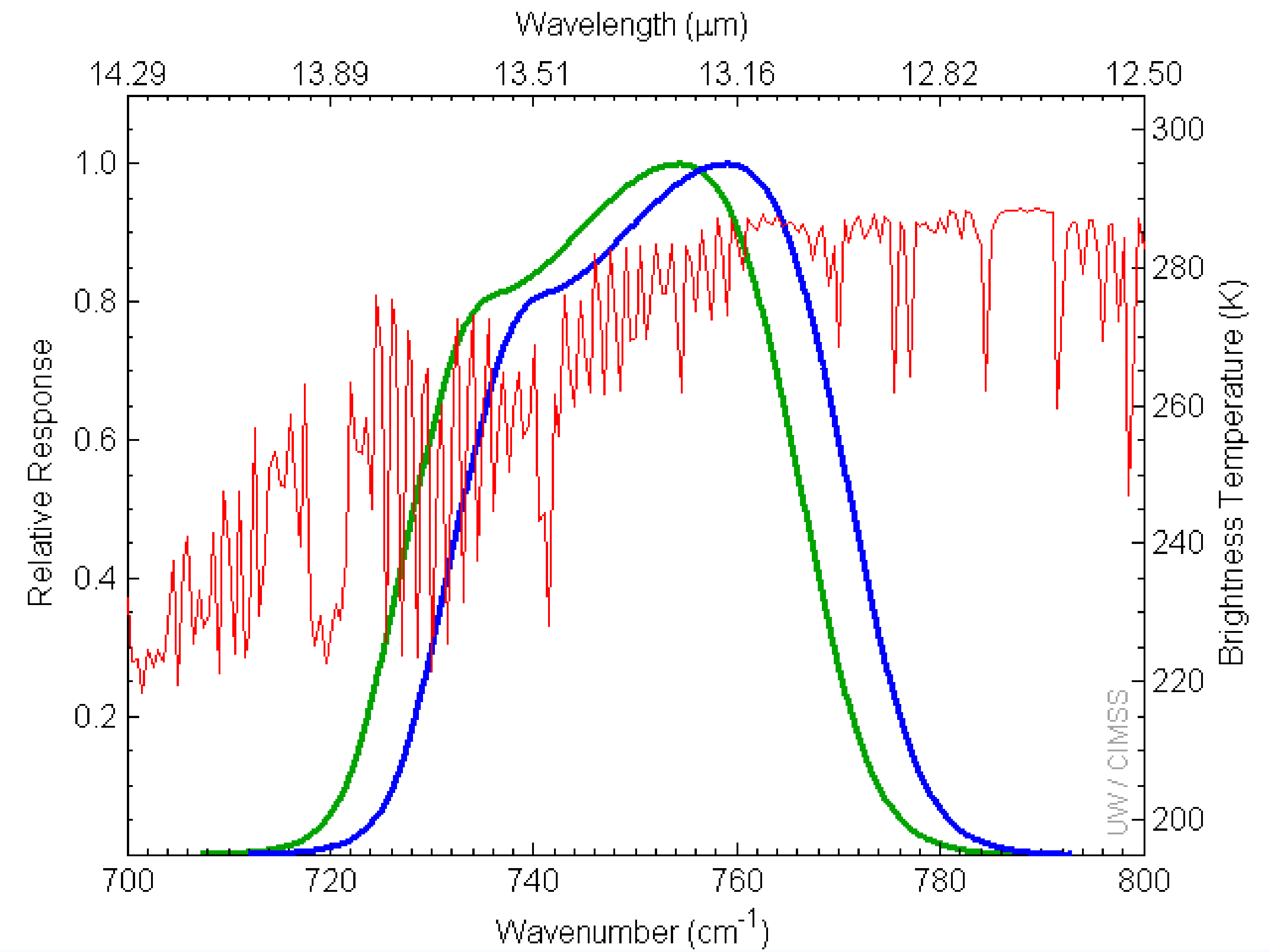
GSICS

# Coordinated international program for sustained operational implementation of satellite intercalibration and characterisation

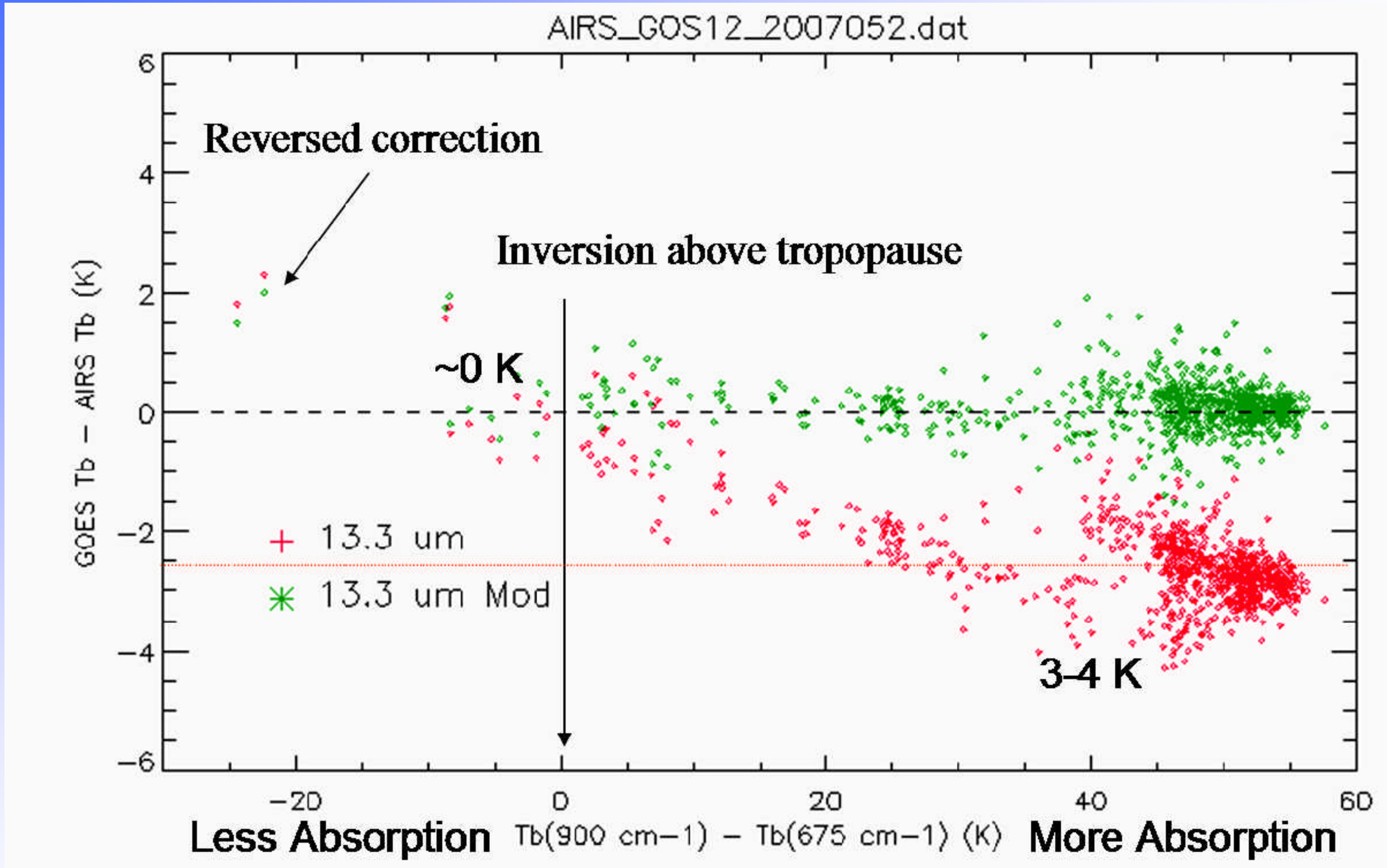





*GOES-13 Imager Band 6 spectral response functions, original (blue) and with a -4.7 cm-1 shift (green), superimposed on spectral radiance for the U. S. Standard Atmosphere (red).*




Adding a constant under-corrects warm scenes and over-corrects cold scenes

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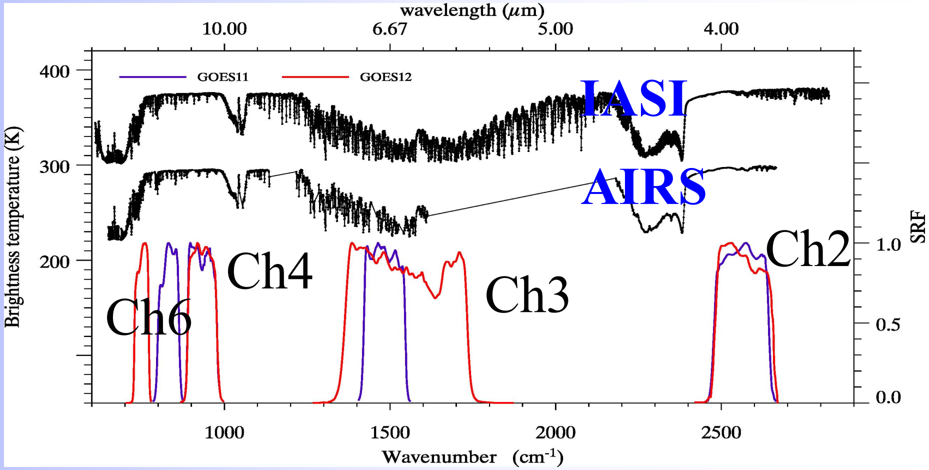
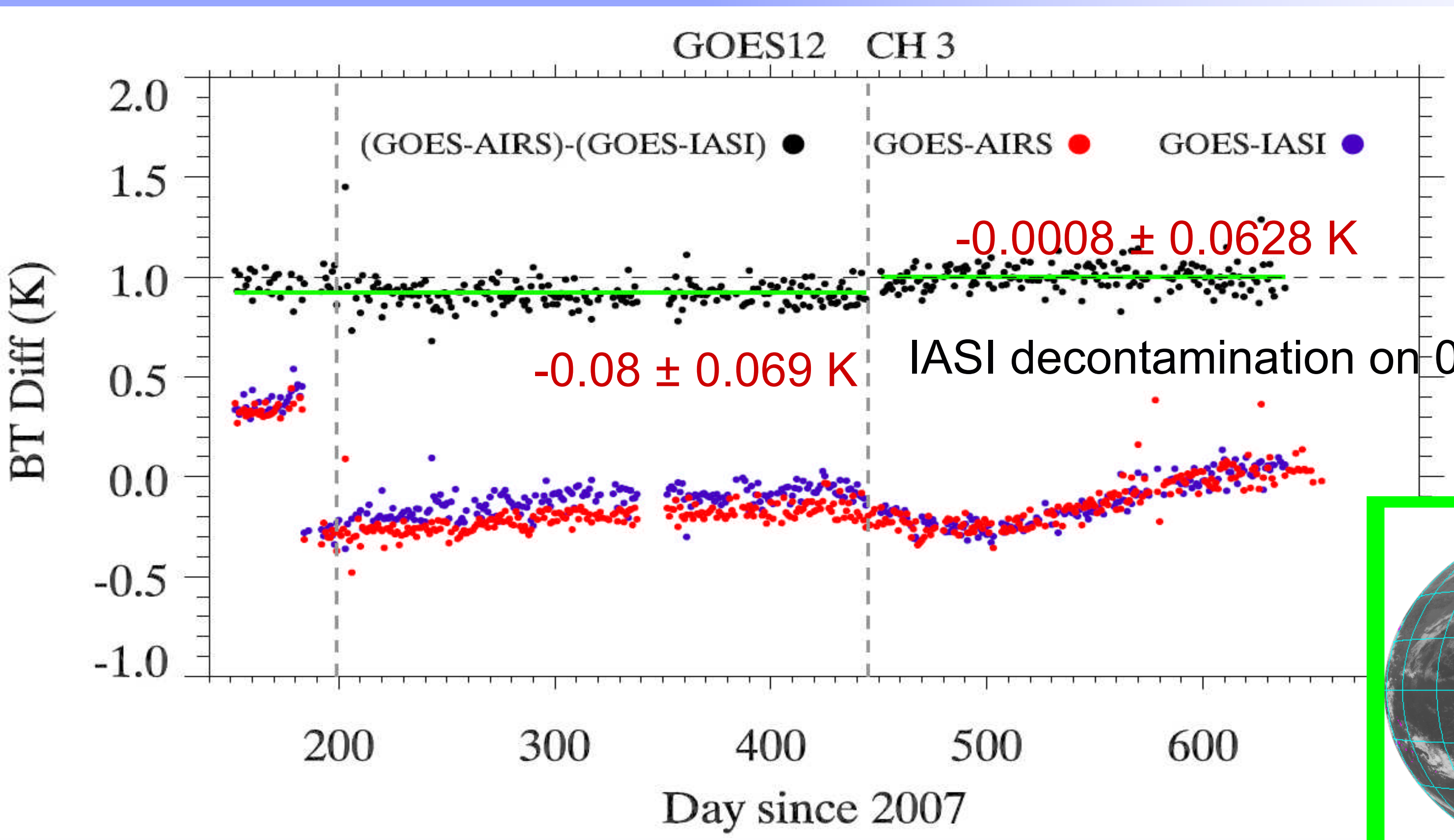
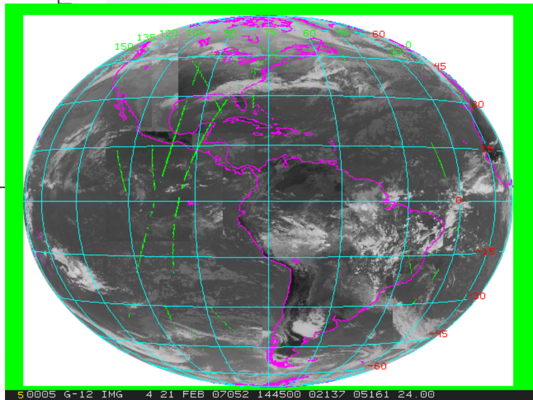
# GOES as transfer radiometer

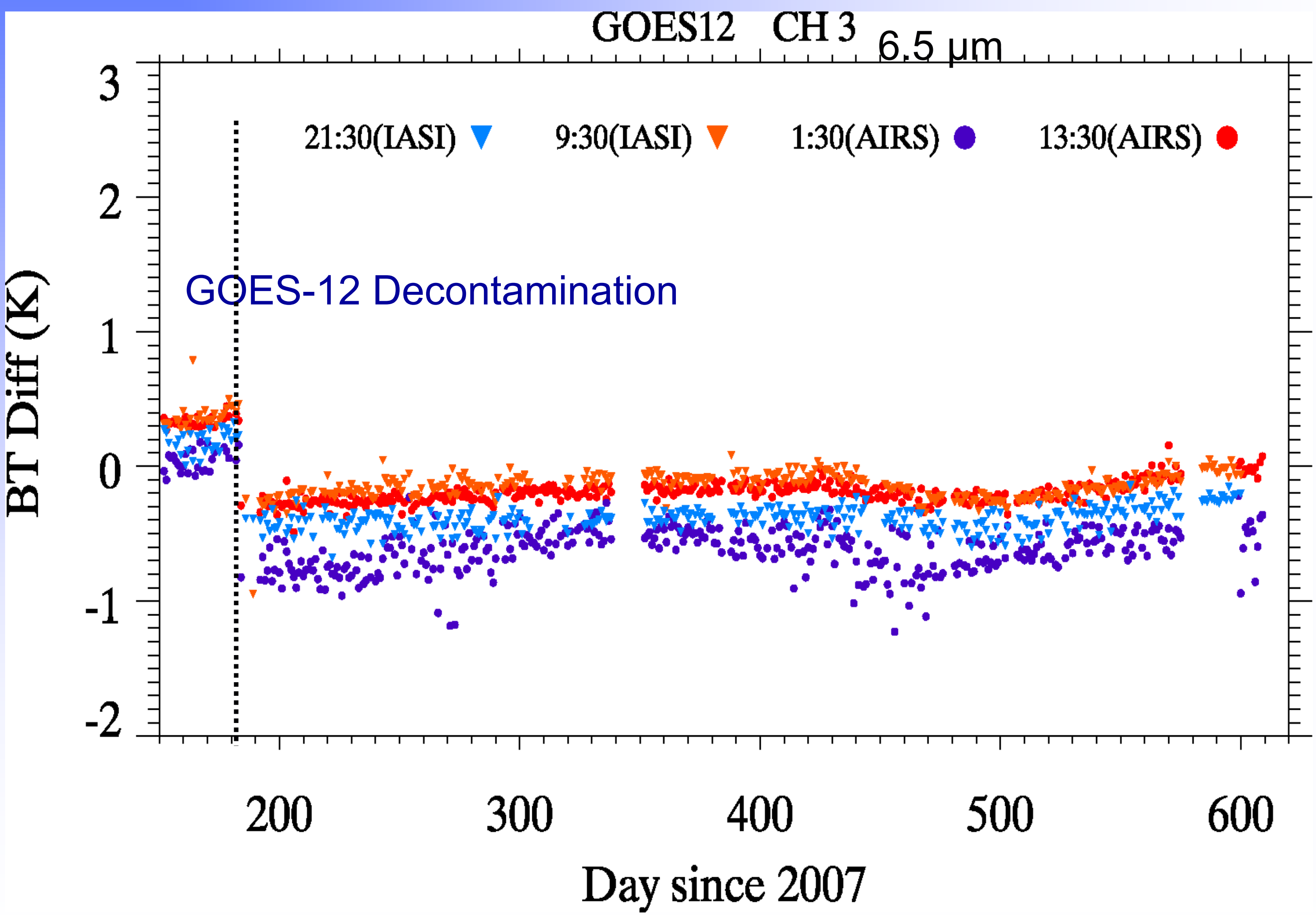
## GOES12: 6.5 µm channel



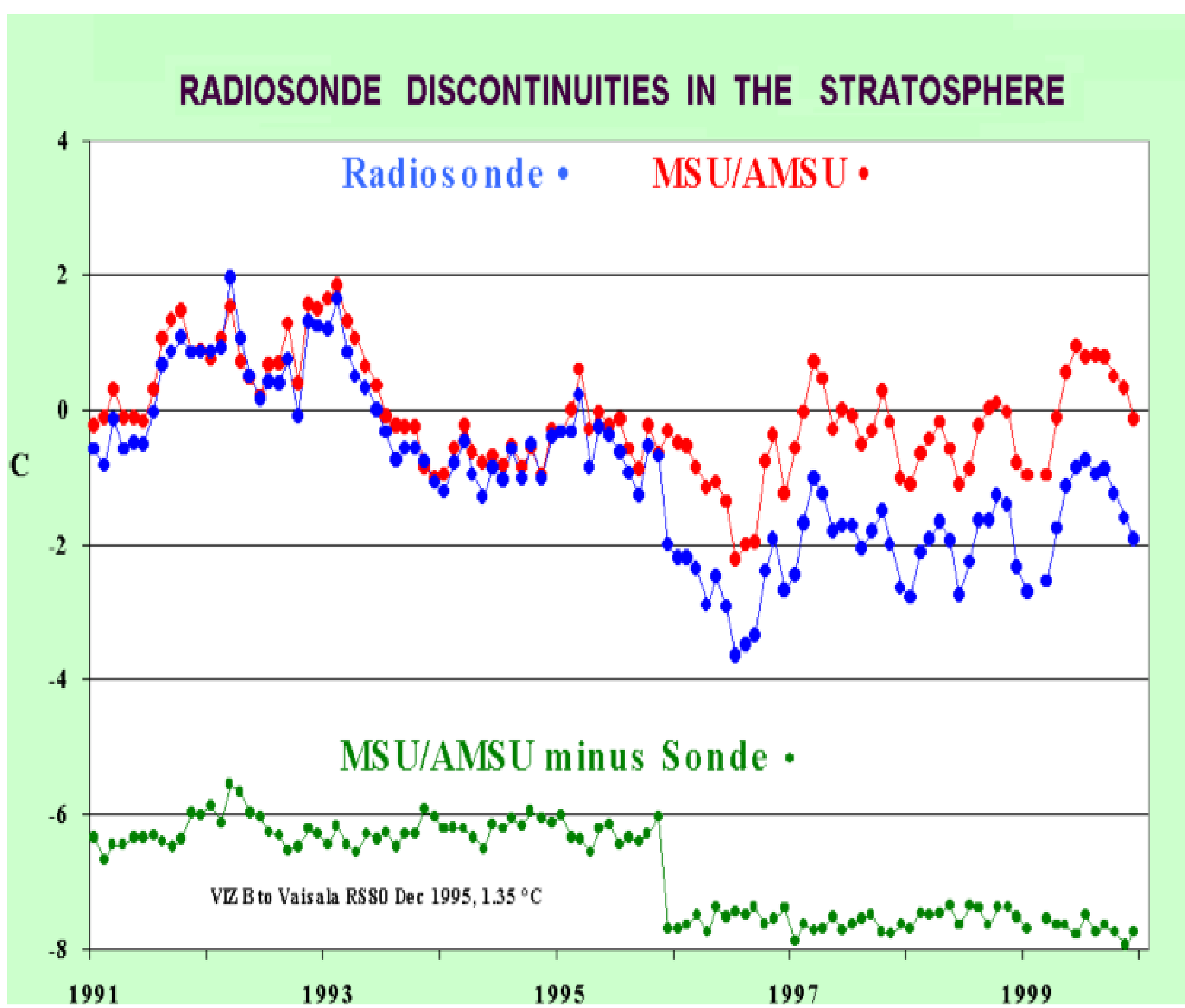



# Assess GOES Calibration Accuracy: 1) Diurnal Bias



# What do you do with an irrefutable data set??

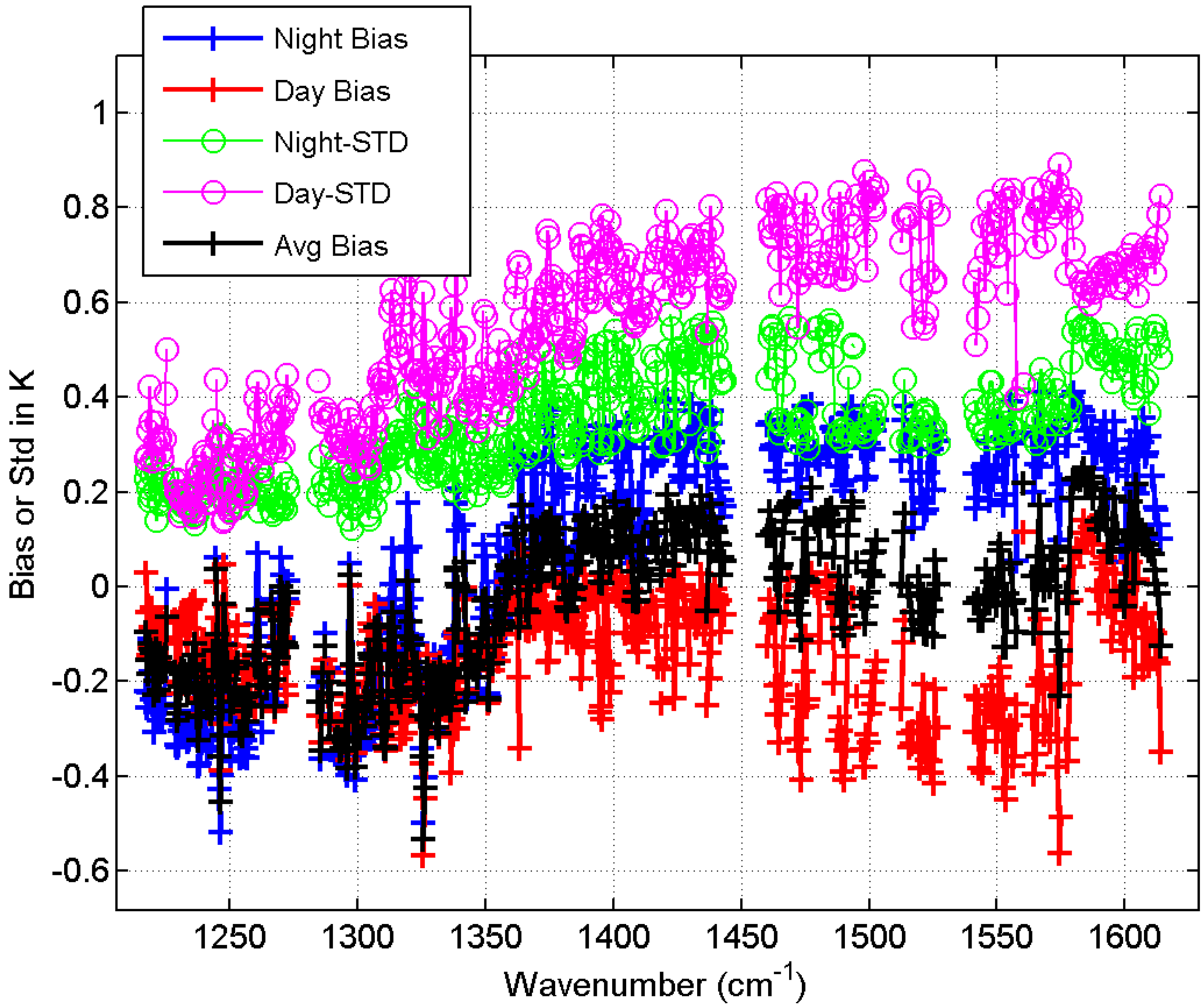
- Monitor change
- Validate other observing systems
- Validate NWP analyses, forecasts, reanalyses, climate projections
- Derive level 2 products but the retrieval process will result in the products not being irrefutable.




Satellites can serve as transfers standards to monitor radiosondes

VIZ B to Vaisala (RS80) at Chuuck Island

# Validation of Mid- to Upper-Trop Water Raobs




Averages over hundreds of sonde launches over 3 years, 5+ sites.

Possible RS-90 day vs night bias

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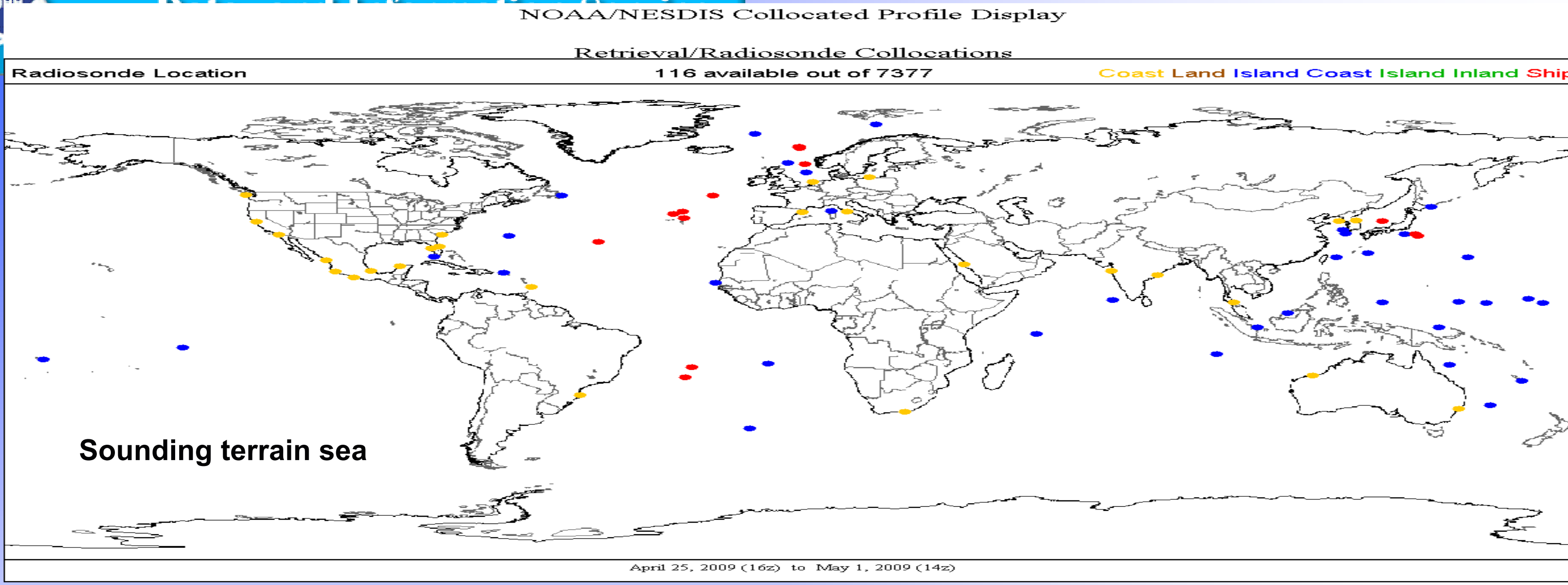
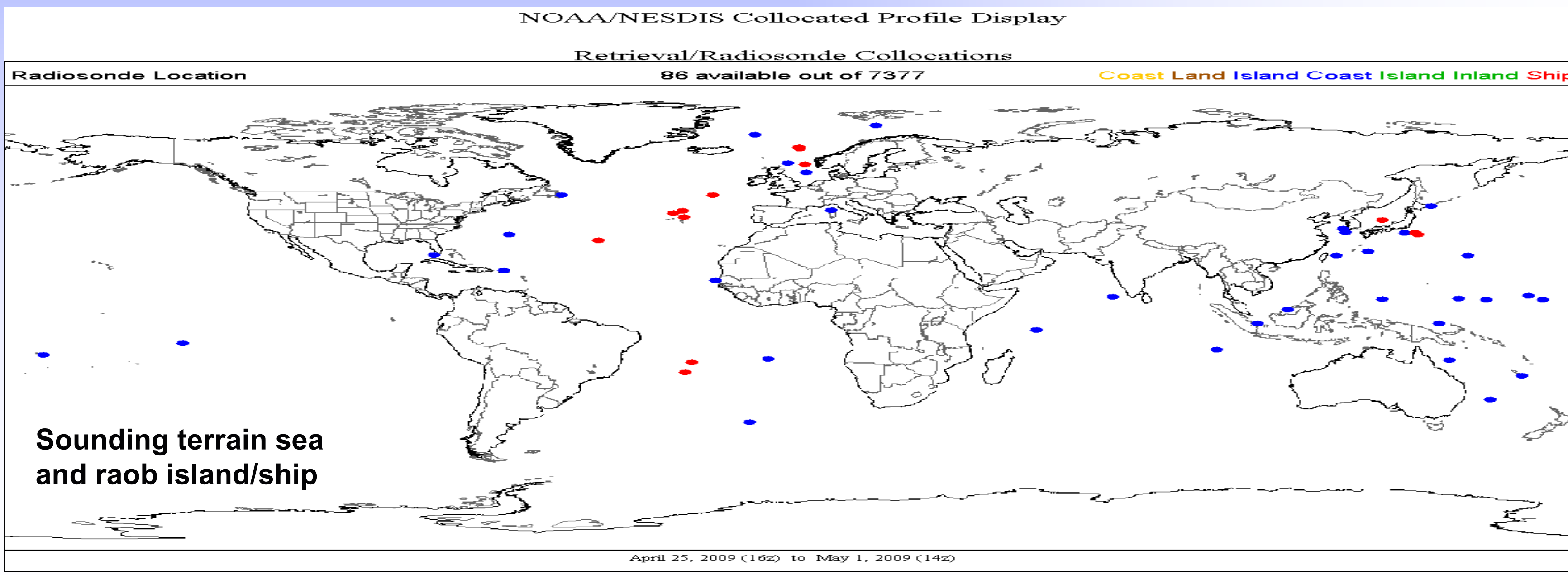
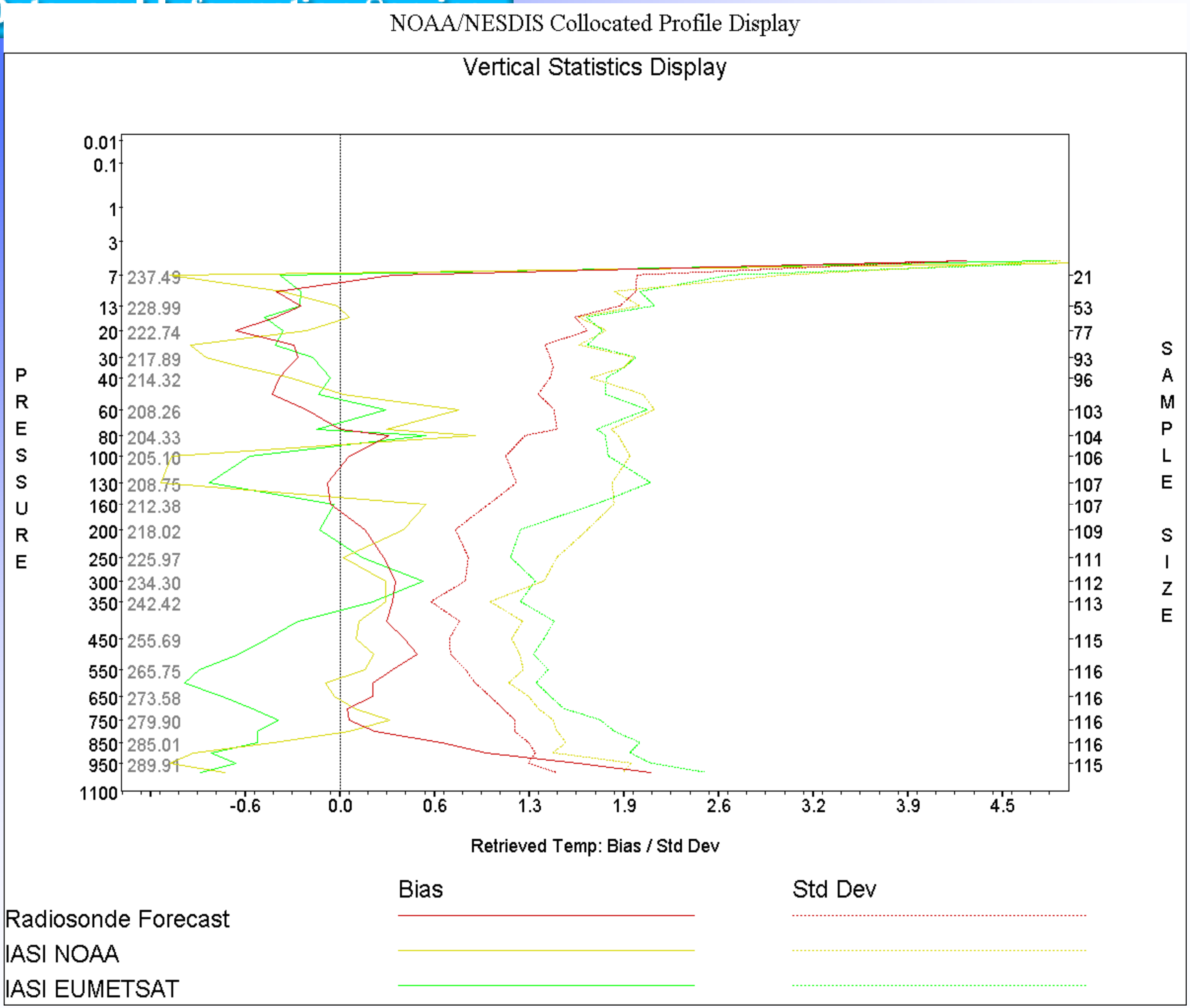


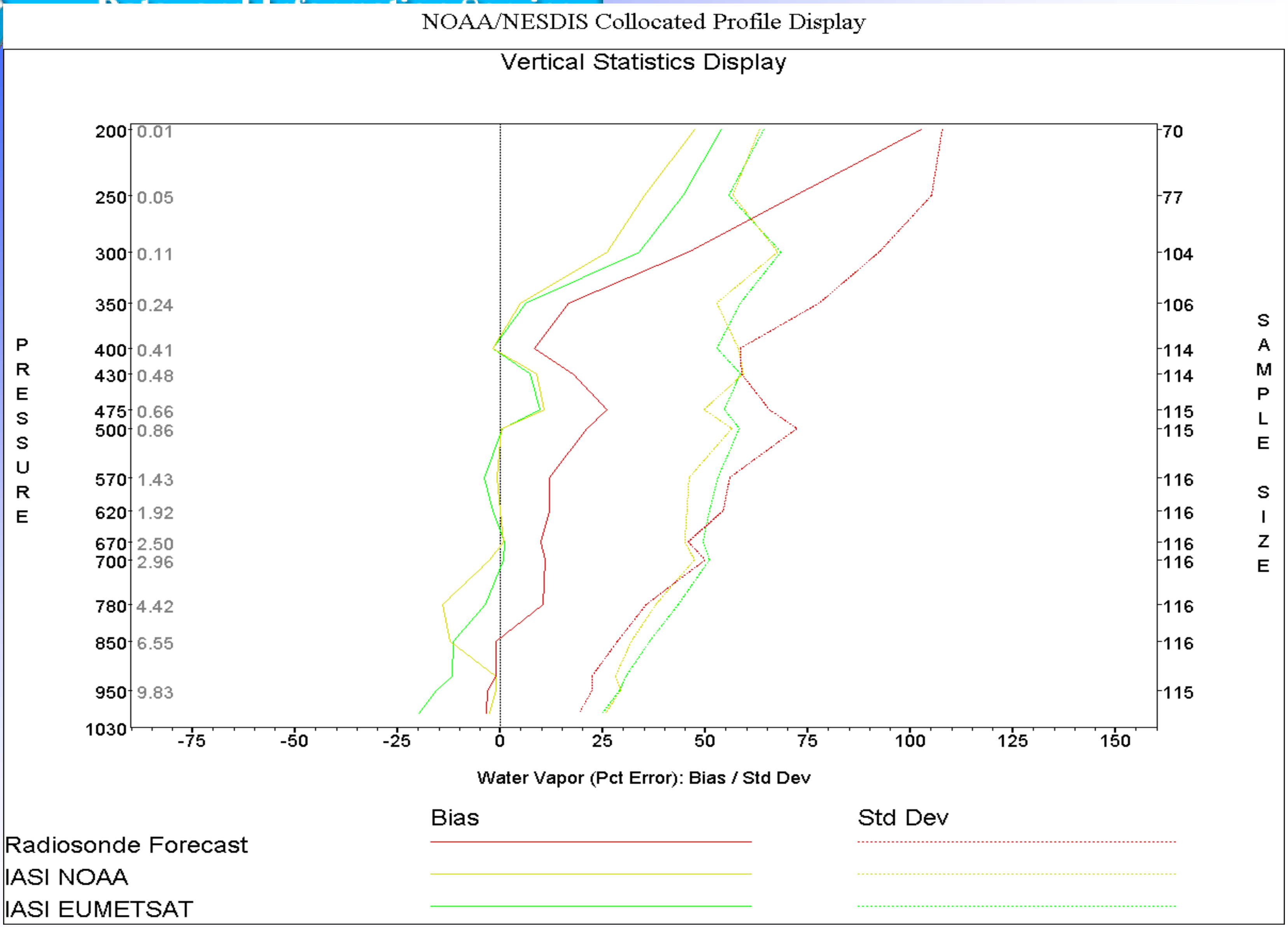

IASI EU and IASI NOAA common denominator sample w/QC over sea

National Environmental Satellite, D...



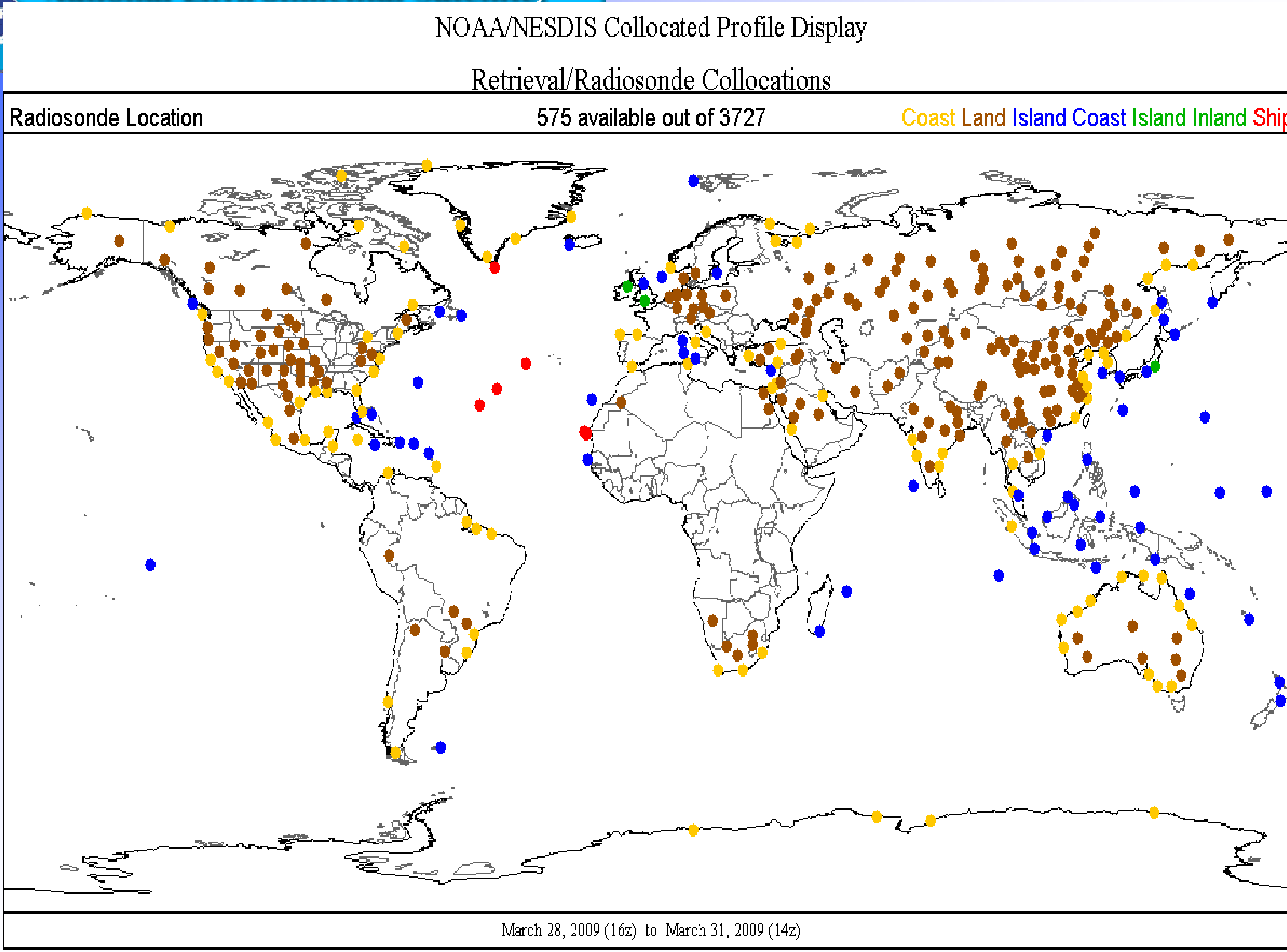

IASI EU and IASI NOAA common denominator sample w QC

National Environmental Satellite,



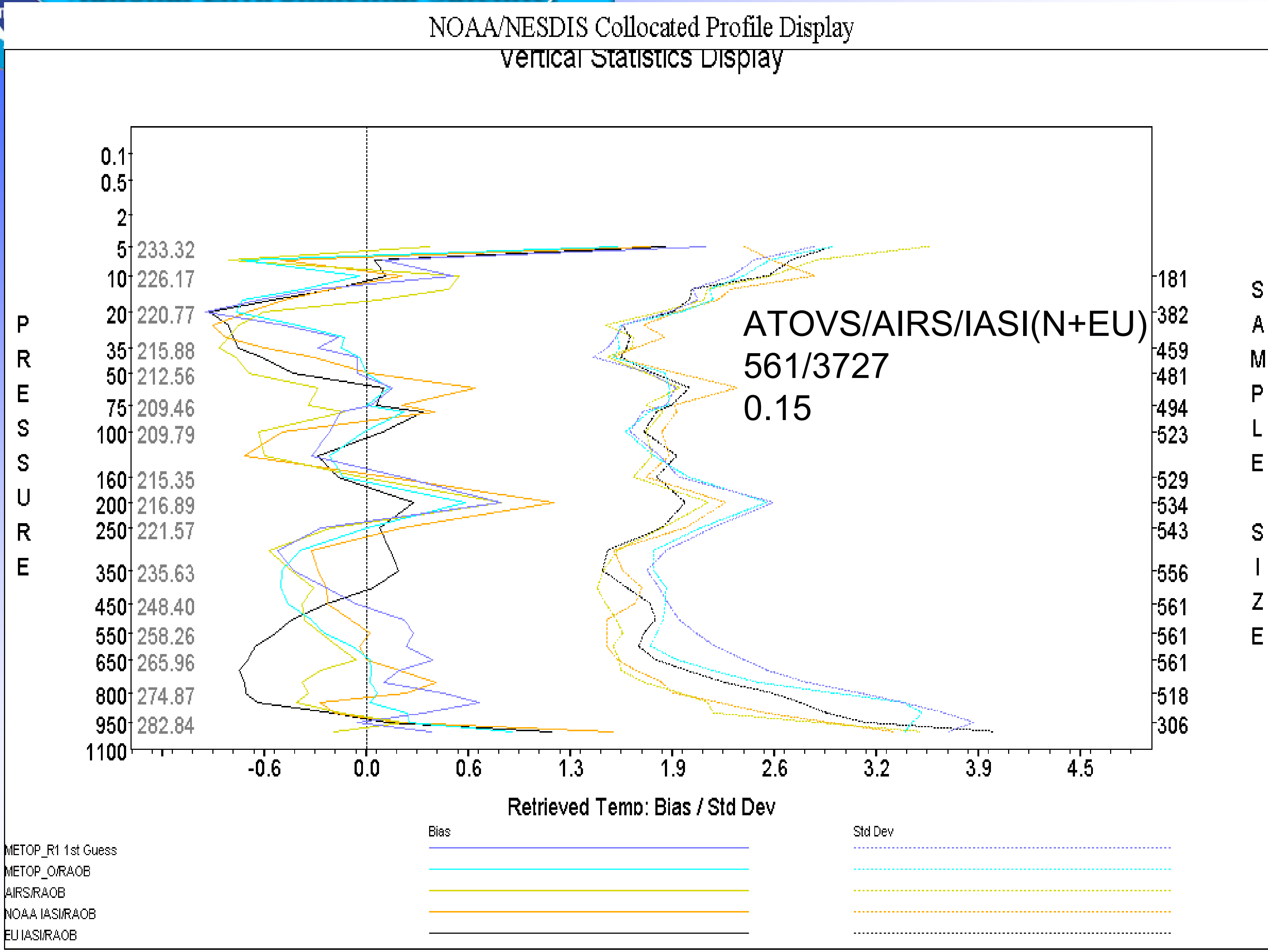

IASI EU and IASI NOAA common denominator sample w QC

National Environmental Satellite,




ATOVS, AIRS, IASI-NOAA and IASI-EU … common denominator sample after respective QC

National Environmental Satellite,




ATOVS, AIRS, IASI-NOAA and IASI-EU … common denominator sample after respective QC

# Motivation

- AIRS and IASI spectrally resolved radiances for the first time provides the capability to produce a climate data record of spectrally resolved infrared radiances (SRIR) with excellent spatial coverage, twice per day coverage with unprecedented accuracy and long-term stability

- We have developed a SRIR climate data record

# Outline

- Overview of the Spectrally Resolved Infrared Radiances (SRIR)
- Approach to derive the SRIR Climate Data Record (CDR)
- Validation of the SRIR CDR
- Validating ECMWF and NCEP analysis fields using the SRIR CDR
  - (mostly using September months for 2003 through 2008)
- Summary and Conclusion

# Spectrally Resolved Infrared Radiances (SRIR) Overview

# AIRS Radiances observes the Signature of Climate Change

- High spectral resolution AIRS radiance provides sensitivity to nearly all climate forcing, responses and feedbacks.

- The AIRS radiances are sensitive to changes in
  - Carbon dioxide
  - Methane
  - Carbon monoxide
  - Ozone
  - Water vapor
  - Temperature
  - Clouds
  - Aerosols
  - Surface characteristics
  - Etc..

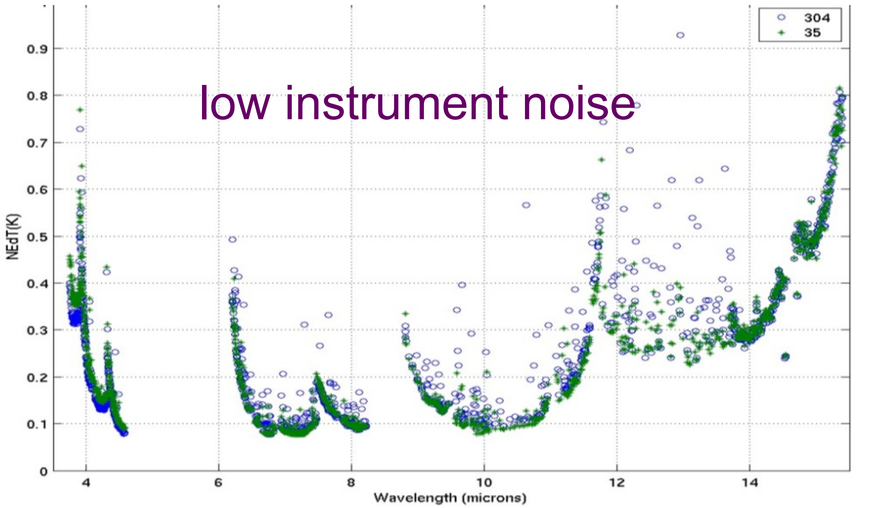
- Spectral Resolved Infrared Radiance datasets allow us to validate the accuracy of the model by directly comparing simulated with observed data.

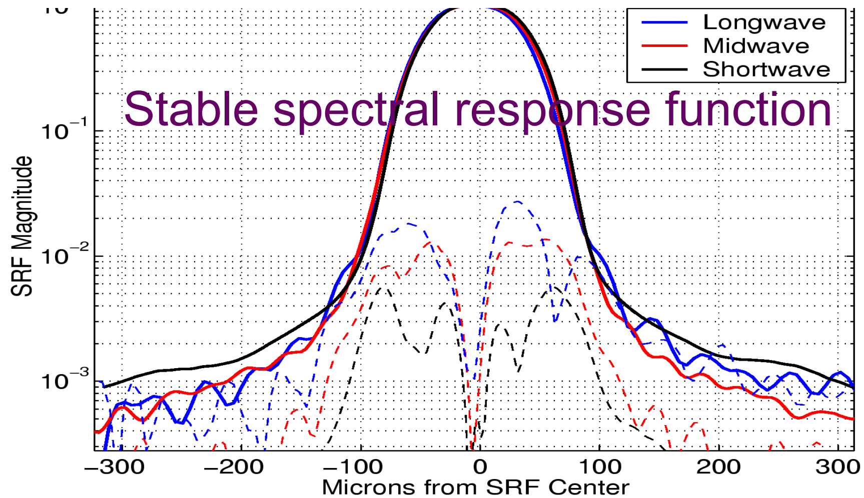
# SRIR Objective

- To develop a very accurate SRIR CDR (with high spatial coverage) from AIRS and demonstrate its utility to:
  - Detect and monitor climate change of temperature, moisture, GHGs and clouds
  - Validate of weather and climate models; to test the realism of the model-derived atmospheric states with very high certainty.
  - Assess changes in model-derived fields due to assimilation of new data or an operational change in processing

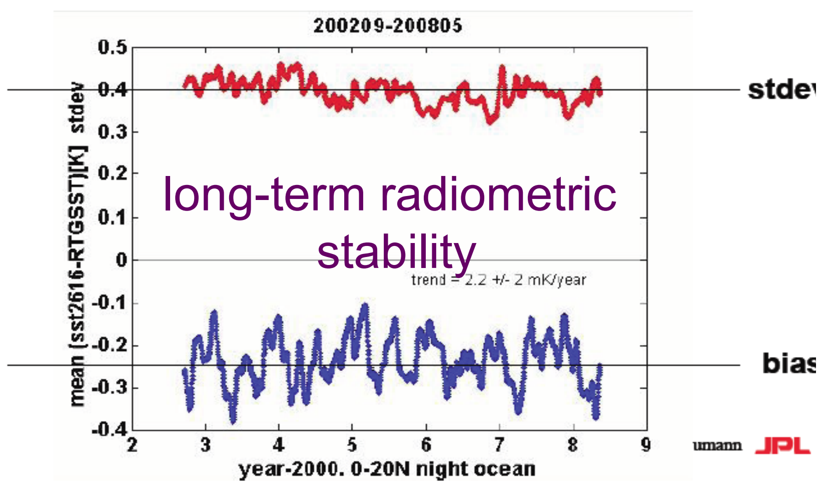
Demonstrated in presentation

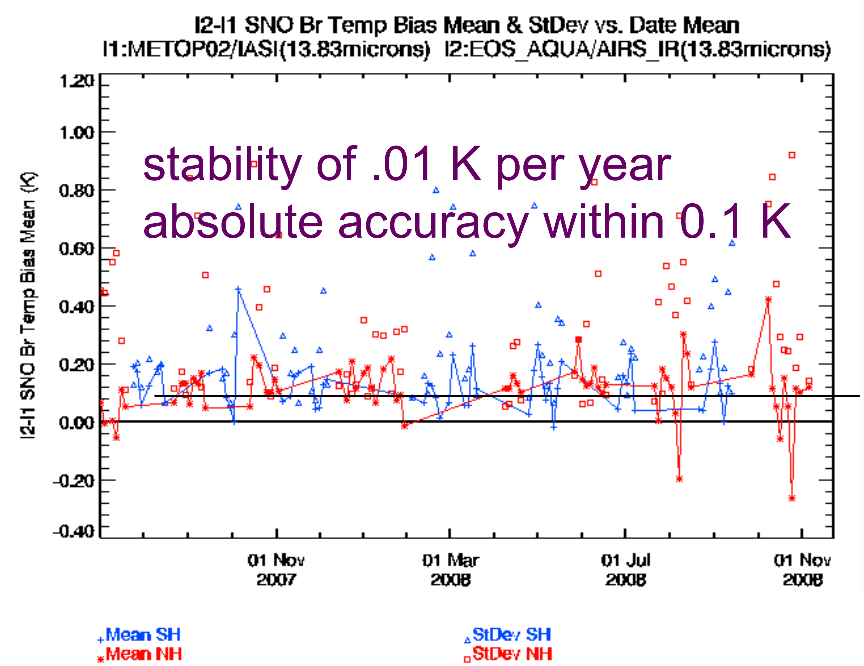
# AIRS has been demonstrated by many investigators to have excellent accuracy, precision and stability (critical requirement to produce a CDR without adding uncertainties using adhoc methods to make a dataset stable)




The analysis of the first 6 years of data show that the AIRS trend for the direct difference (sst2616-rtgsst) is <4 mK/year. Absolute accuracy validation is limited by residual cloud contamination.



# SRIR Climate Data Records from the Advanced IR Sounders 2002-2020++

- AIRS (available from 2002) spectrally resolved radiances for the first time demonstrated the capability to produce a climatology of SRIR with excellent spatial coverage, twice per day coverage, unprecedented accuracy and long-term stability.

- Extended SRIR climate data records can be derived from:
  - NASA AIRS - Atmospheric Infrared Sounder (2002 – 2012 ) (14 km fov)
  - EUMETSAT IASI - Infrared Atmospheric Sounding Interferometer (2006 – 2020's) (12 km)
  - NPP/NPOESS CrIS - Cross-track Infrared Sounder (2011 – 2020's) (15 km)
  - Possible Geostationary Advanced Sounder (2020's) (10 > 5 km)

- Continuous accumulation of the SRIR datasets will enable broad applications of the data set in climate analysis and model verifications.

# Steps to derive the SRIR climatology

# Steps

- Gridded radiances are converted to Principal Component Scores (PCS) and stored into gridded daily datasets (0.5 long x 2.0 lat, ascending and descending).
- PCS are limb adjusted and stored in angle adjusted gridded daily datasets
- Angle adjusted PCS are converted to brightness temperatures and stored in gridded daily datasets.
- Each gridbox for each dataset has a clear flag.
- Compute daily/monthly clear and all-sky gridded datasets of limb adjusted brightness temperatures.

# AIRS Limb Adjustment Methodology:

Step 1) Limb adjust the off-nadir PCS to the nadir PCS.

Use regression to predict the limb adjusted PCS from the first six PCS and the PCS to be limb adjusted

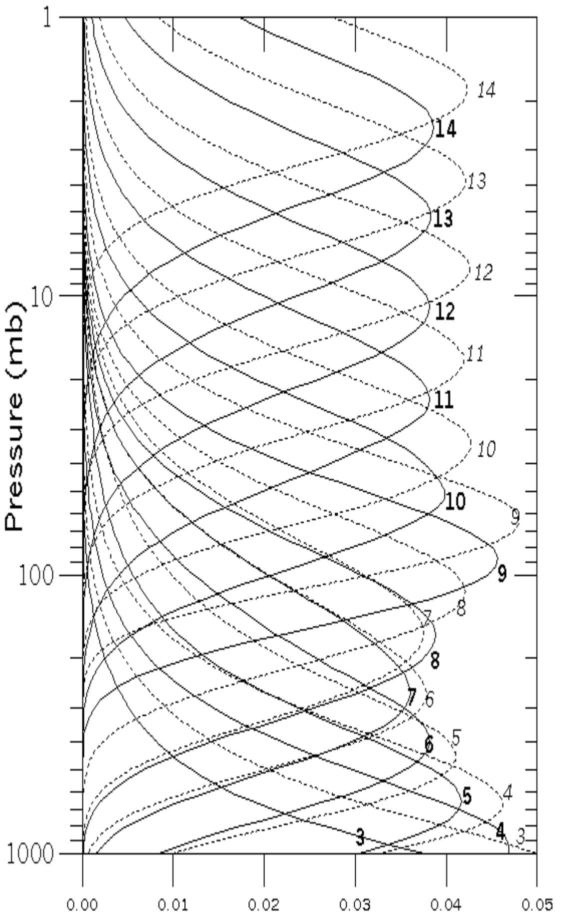
$$\text{Limb-adj PCS}(n,\text{angle}) = \sum_{i=1}^{6} C(i,\text{angle})*\text{PCS}(i,\text{angle}) + C(n,\text{angle})*\text{PCS}(n,\text{angle})$$

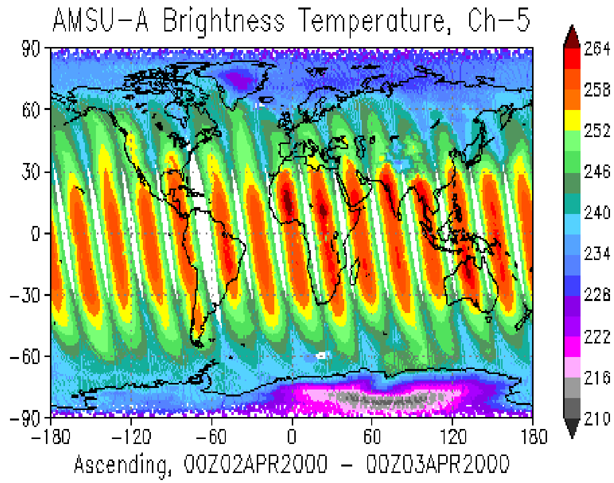
The regression coefficients are generated from six months of data. Averaged PCS as a function of scan angle (90 per scan line) over two degree latitude bands for ocean and non ocean cases.

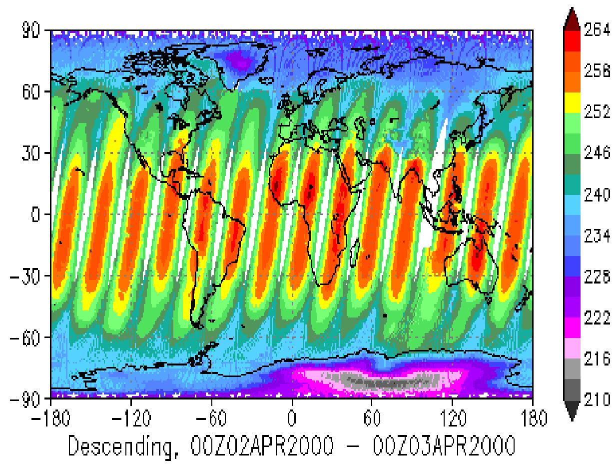
Step 2) Reconstruct the limb adjusted radiance from the limb-adjusted PCS.

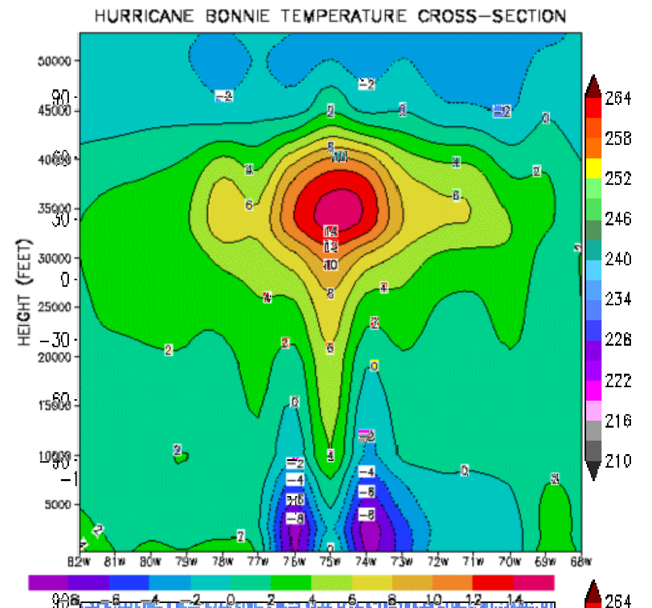
Step 3) Convert the limb adjusted radiances to limb adjusted brightness temperatures

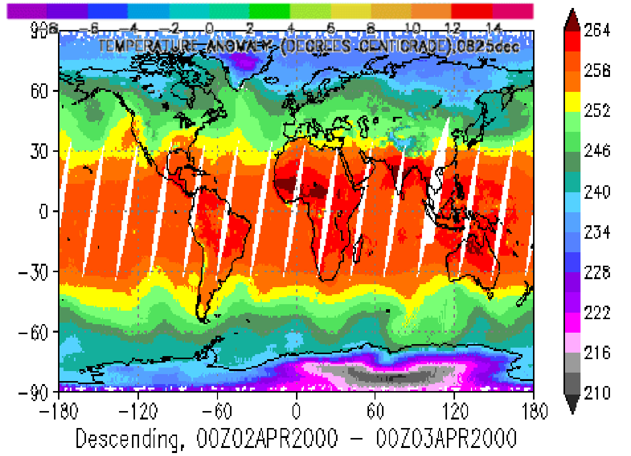
# Need to limb adjust radiances to allow for studies related to spatial patterns (AMSU example)



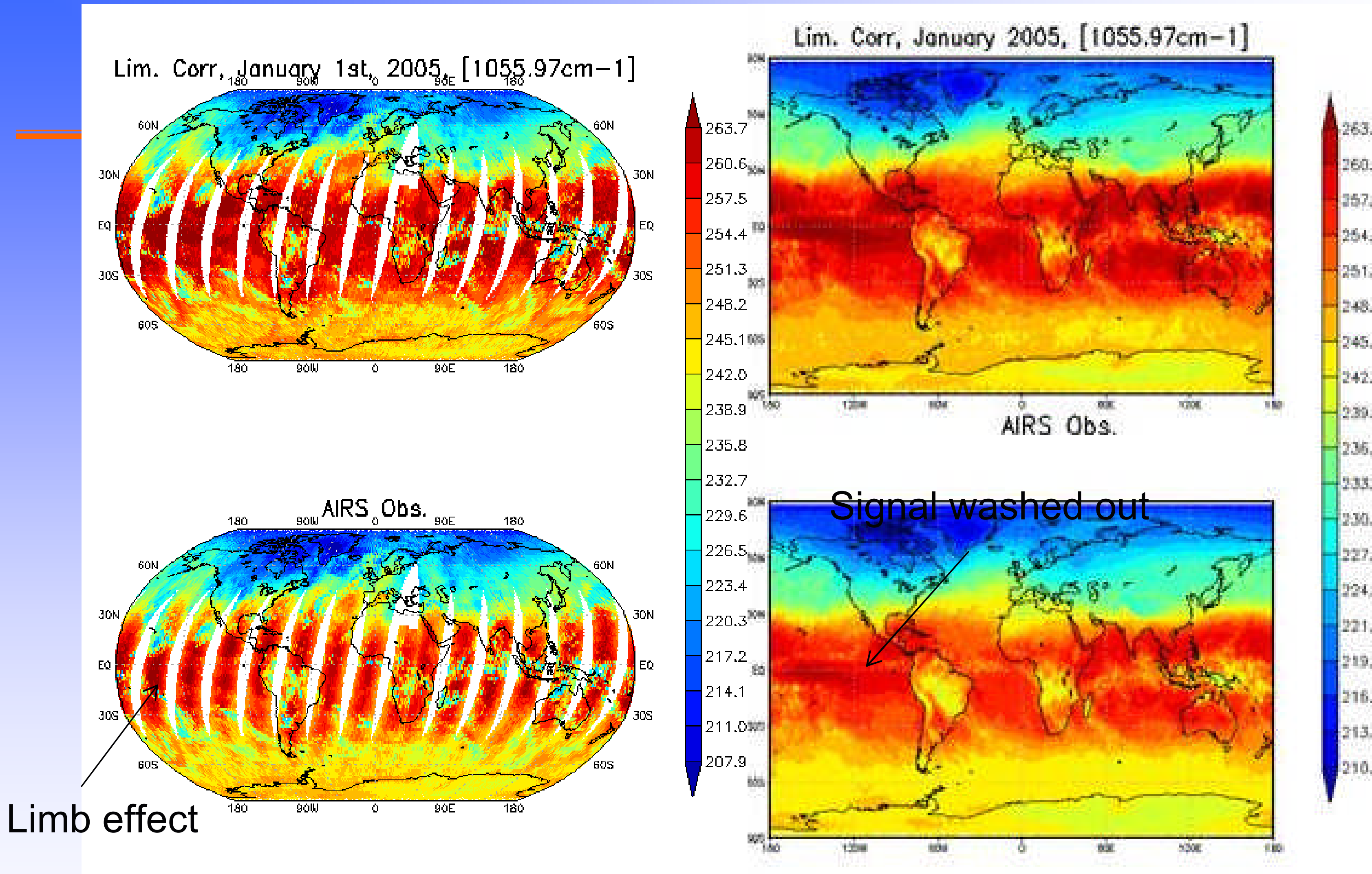




Goldberg, M. D., D. S., Crosby, and L. Zhou, 2001: The limb adjustment of AMSU A observations: methodology and validation. *J. Appl. Meteor.*, **40**, 70-83.

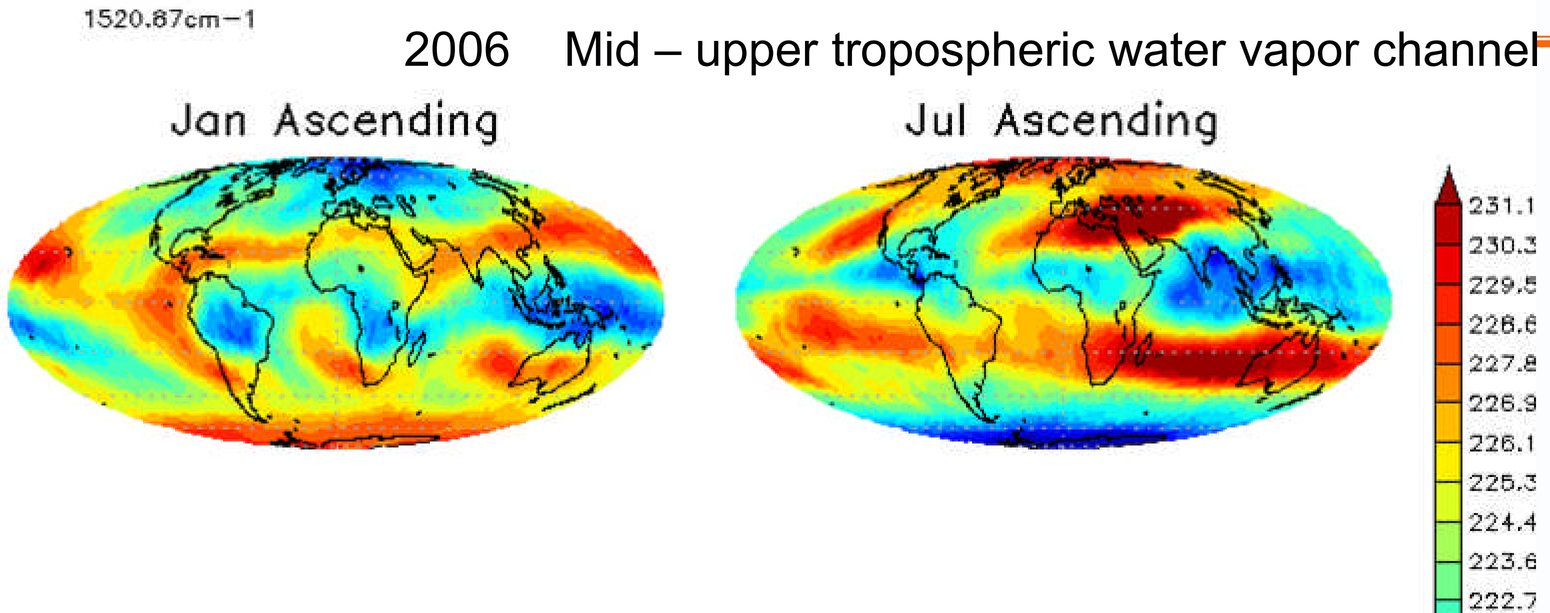
# Example of AIRS limb adjusted data

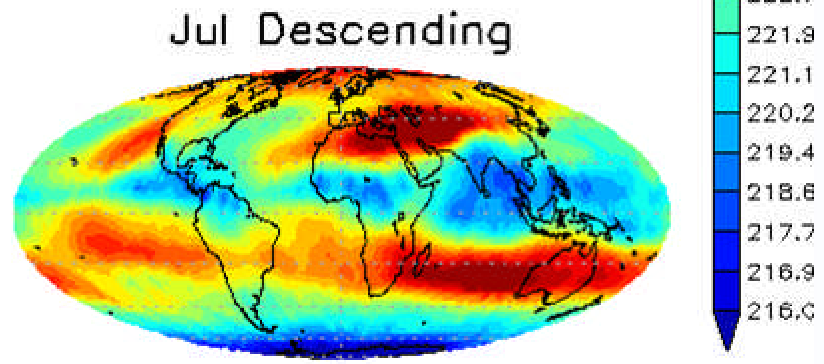


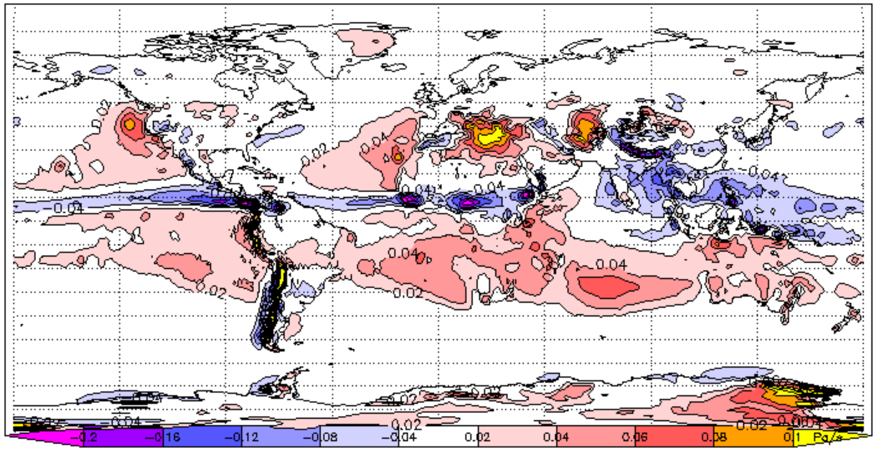

Limb corrected (upper left) and original observed (lower left) AIRS radiance; monthly averaged limb corrected (upper right) and original (lower right) AIRS radiance

**Must limb adjust the data to create meaningful global datasets**

2006 Mid – upper tropospheric water vapor channel



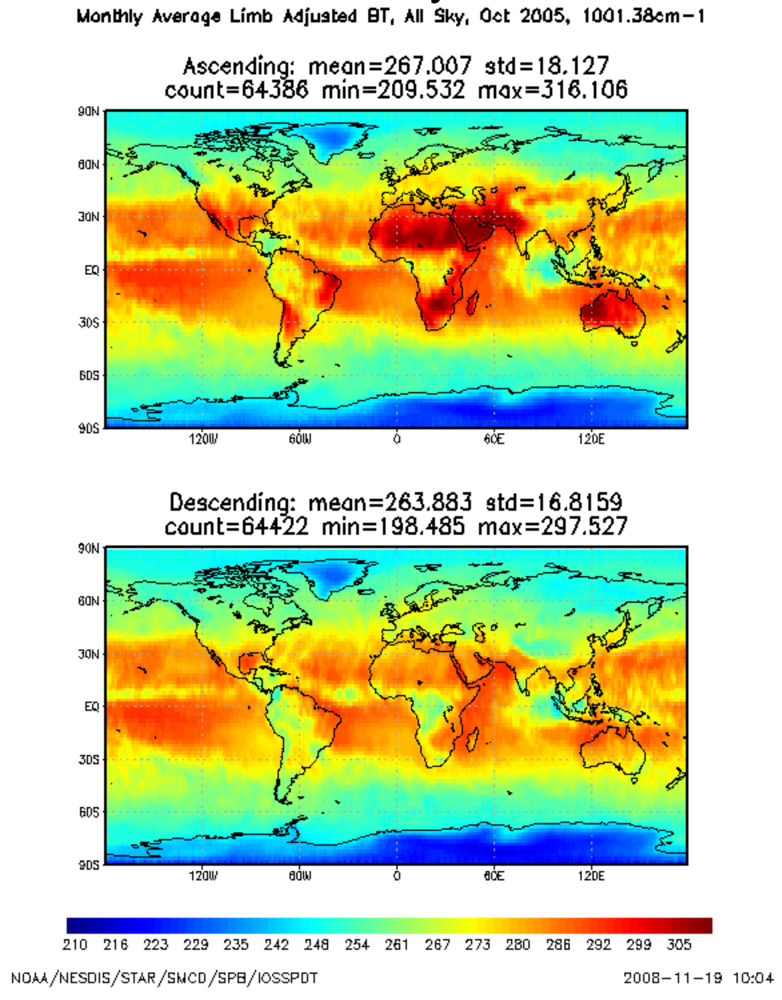

ERA40 July 1979-2001 mean

Warmer brightness temperatures correspond to dryer air and matches areas of descending air from ERA40

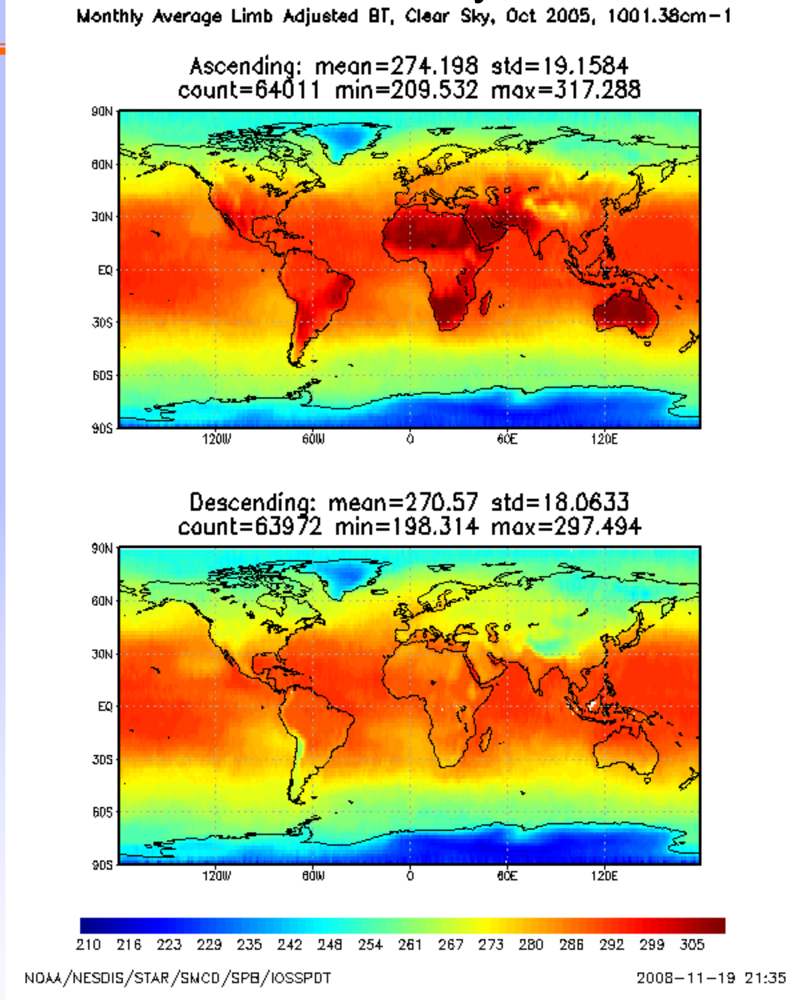
# Clear Flag

- Clear test is described in detail in [*Goldberg et al.*, 2003].
- Predict clear AIRS (2390 cm-1) from AMSU
- Compare predicted AIRS (2390 cm-1) with actual AIRS.
- Predict surface temperature from AIRS and compare with NCEP forecast surface temperature.
- Compute variability of AIRS (2390 cm-1) for 3x3 array of AIRS footprints within the AMSU footprint.

# All Sky



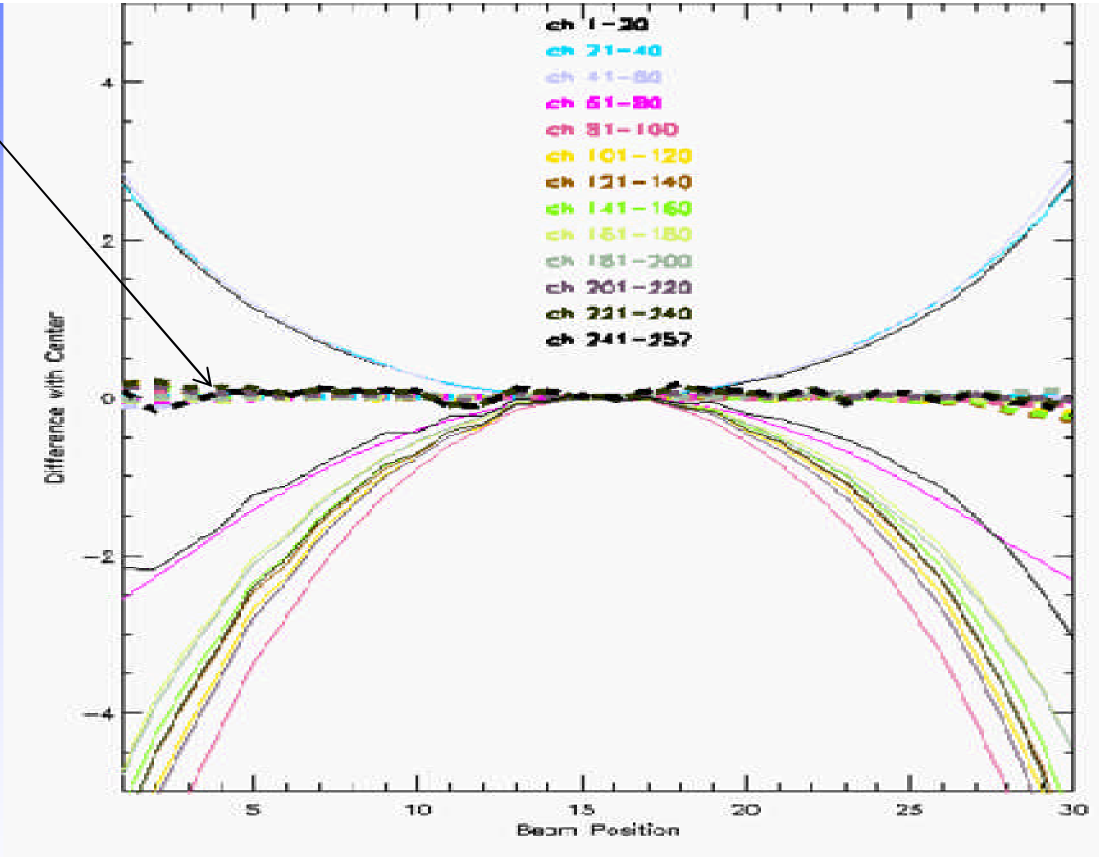

# Clear Sky



# Validation of the SRIR climatology

# Validation of Limb Adjustment

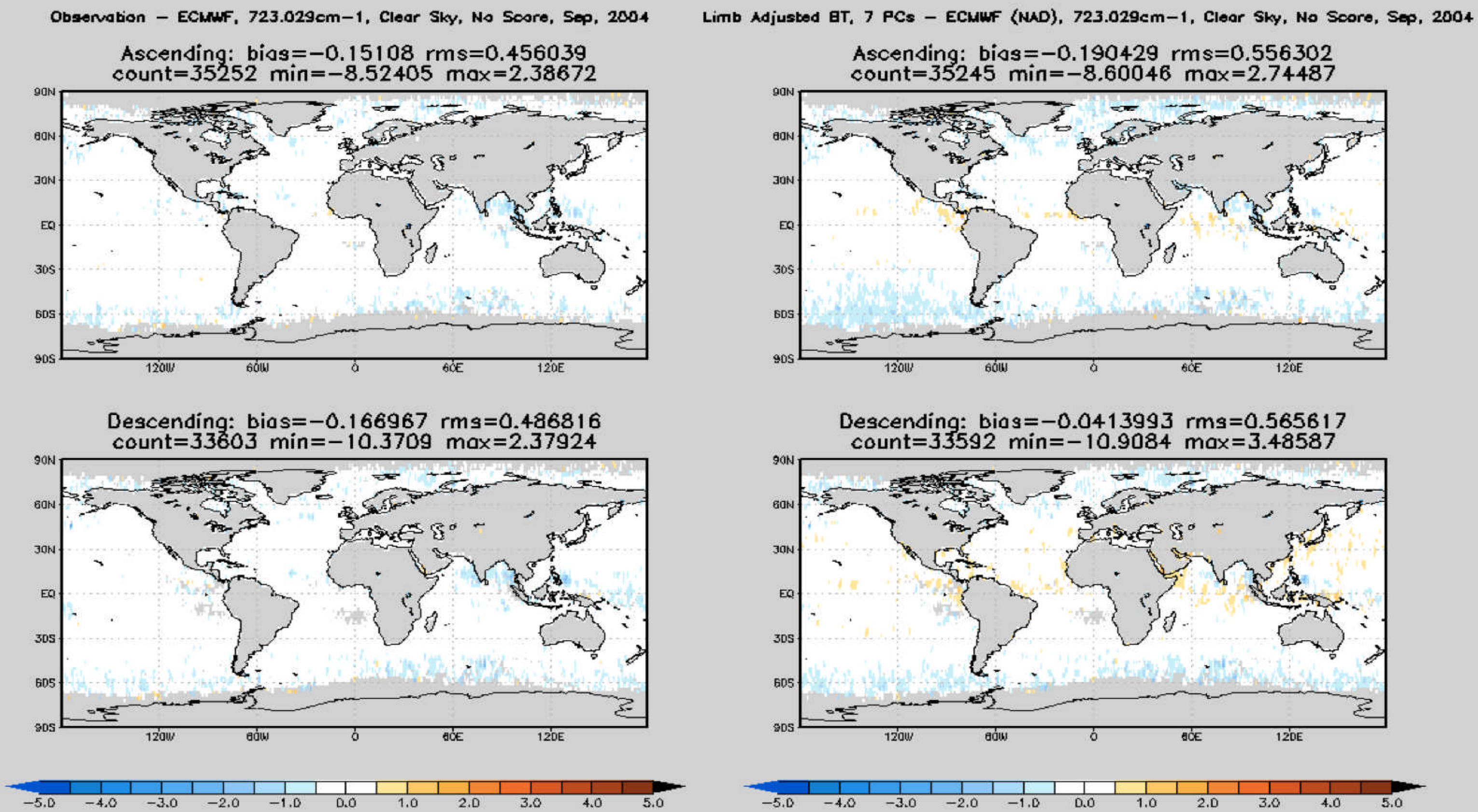
Limb adjustment successfully removes the large scanline dependency




Deviations of averaged original (colored curves) for groups of channels and limb adjusted (heavy dashed curve) brightness temperatures from nadir as a function of beam position

# SRIR validation by comparing measured vs simulated brightness temperatures against ECMWF with and without limb adjustment

Original - EC(sim, f(angle)) | Limb adjusted – EC(sim, f(nadir))




Bias and standard deviation nearly the same, channel peaks near 700 mb

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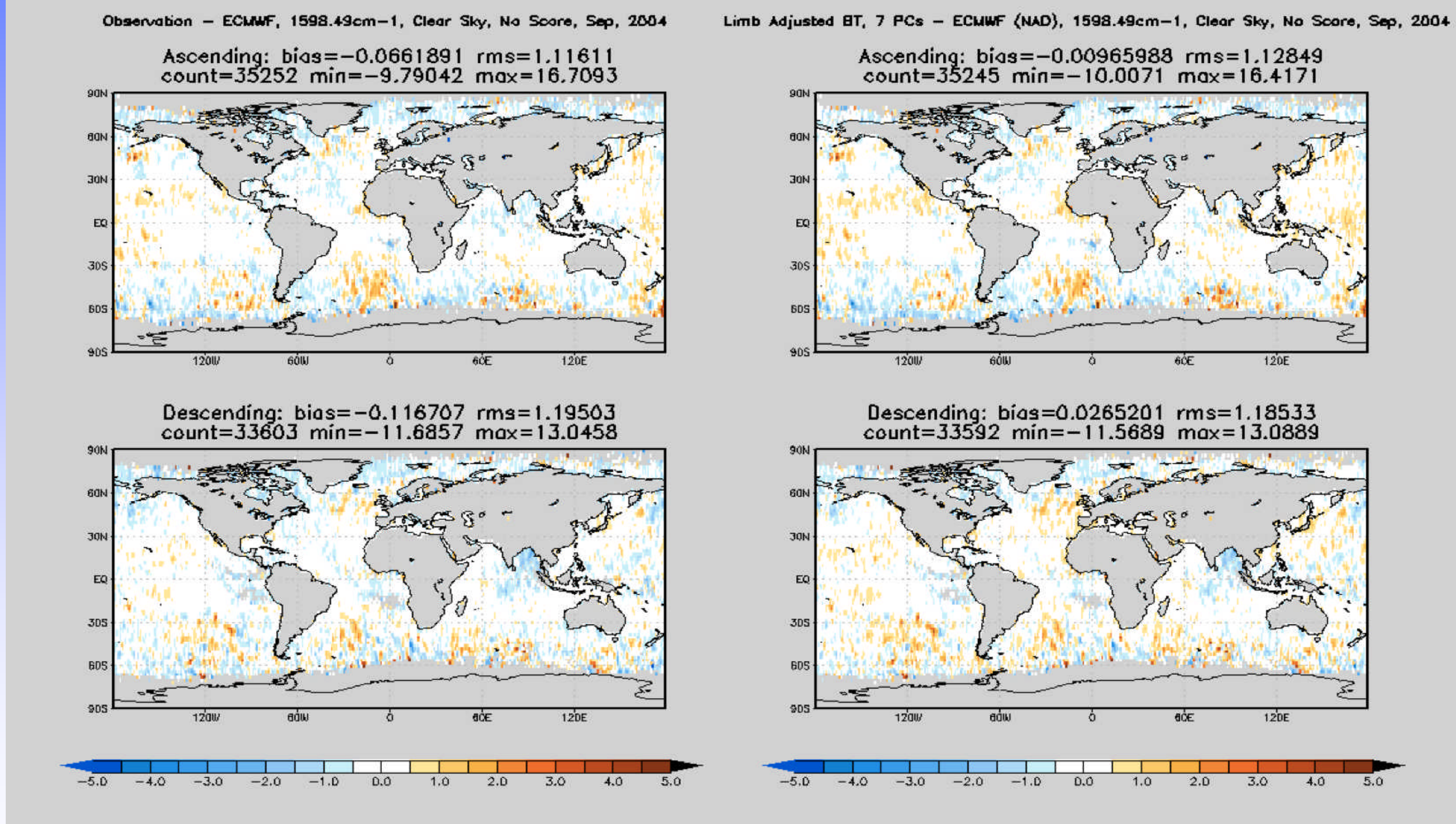
# SRIR validation by comparing measured vs simulated brightness temperatures against ECMWF with and without limb adjustment

Original - EC(sim, f(angle)) Limb adjusted – EC(sim, f(nadir))

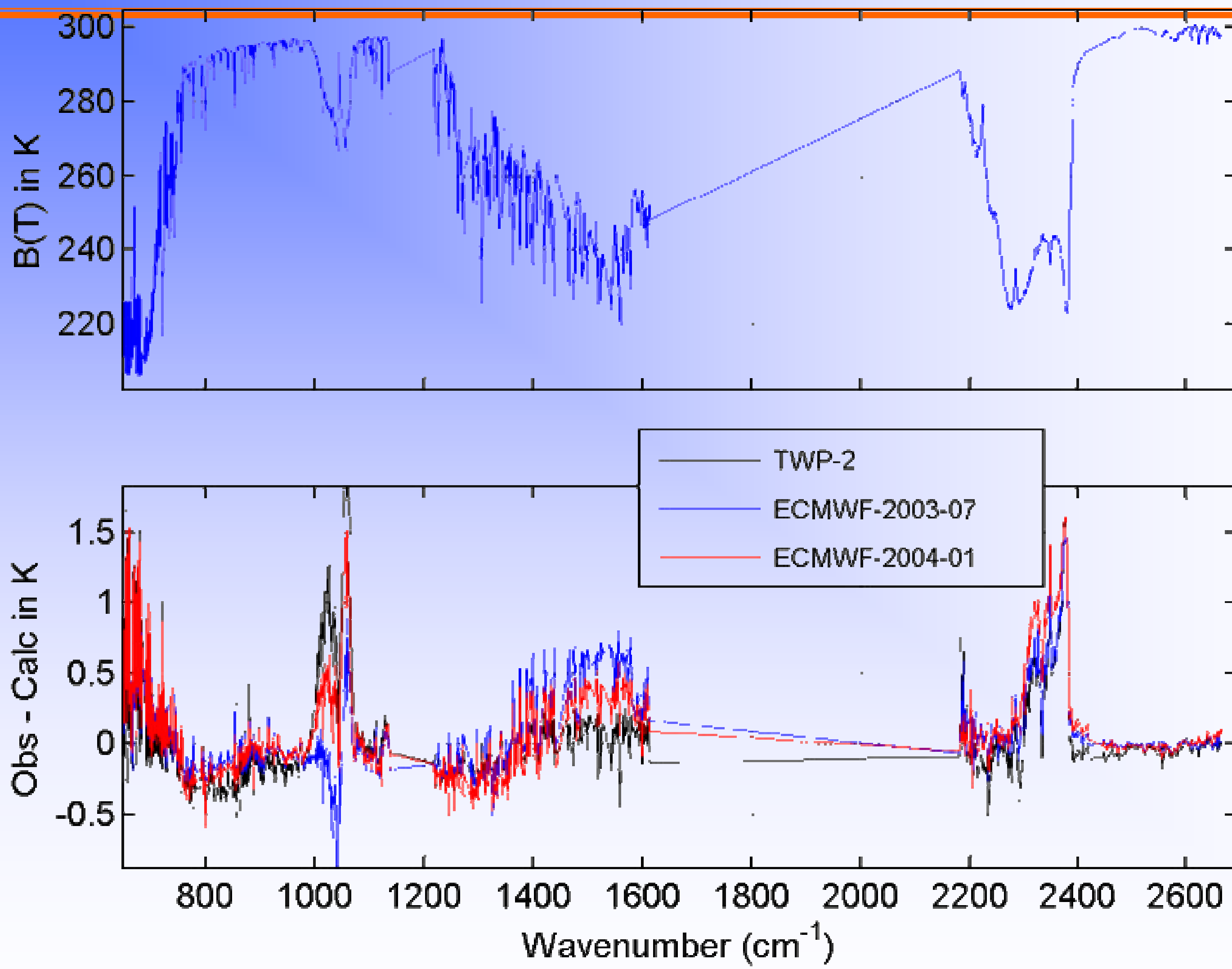



Bias and standard deviation nearly the same, water vapor channel peaking near 500 mb (for mean profile)

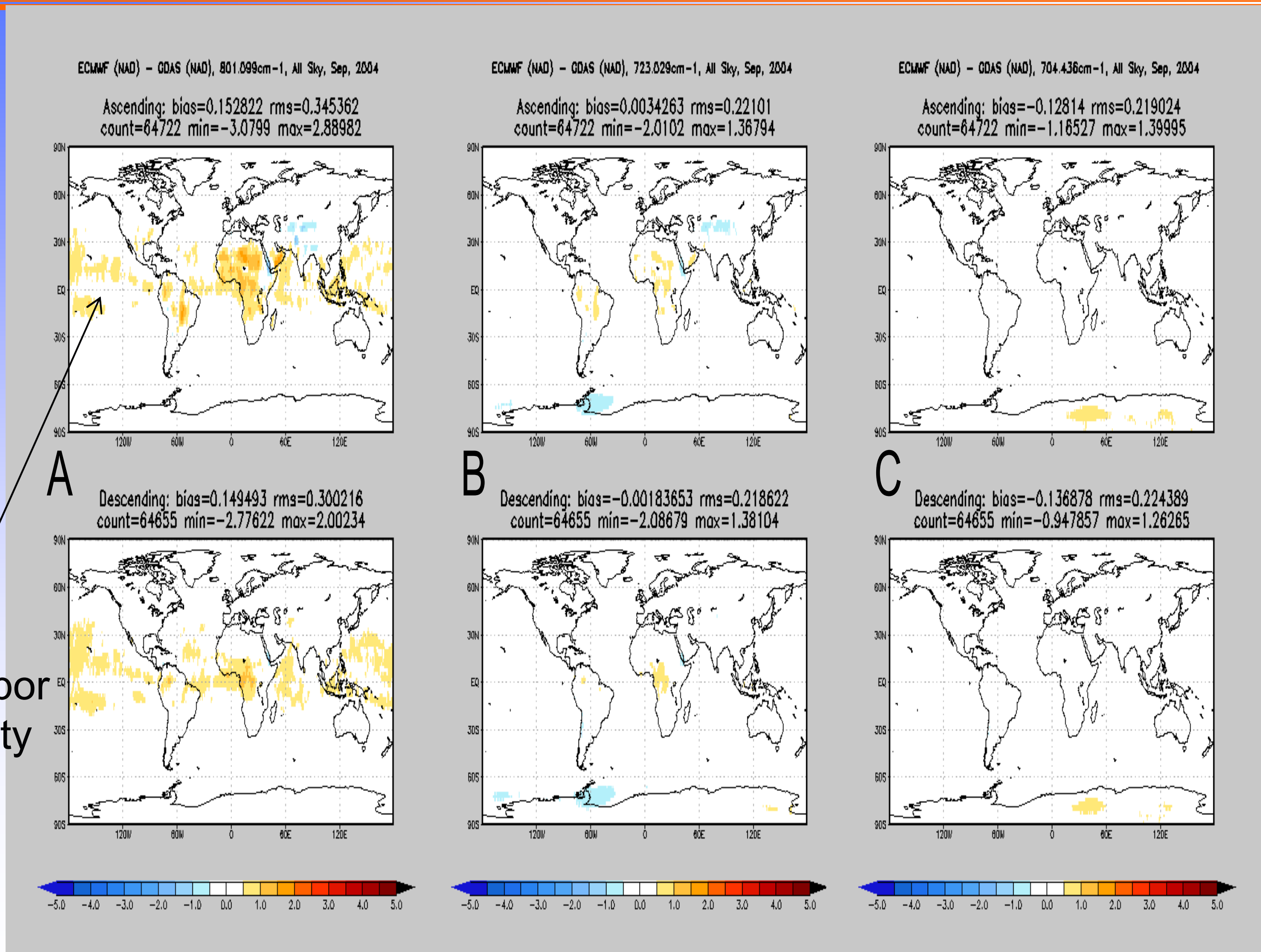
# Validation of model fields using AIRS clear-sky SRIR climatology

# NCEP vs ECMWF

- There are differences between the NCEP and ECMWF analyses
- Mean bias and standard deviations for temperature are nearly the same, except in upper stratosphere.
- Water vapor differences are very large
- Following few slides shows differences of simulated AIRS (ECMWF) – simulated AIRS(NCEP/GDAS) (no measured data are used)


300
280
260
240
220
B(T) in K
TWP-2
ECMWF-2003-07
ECMWF-2004-01
1.5
1
0.5
0
-0.5
Obs - Calc in K
800
1000
1200
1400
1600
1800
2000
2200
2400
2600
Wavenumber (cm$^{-1}$)

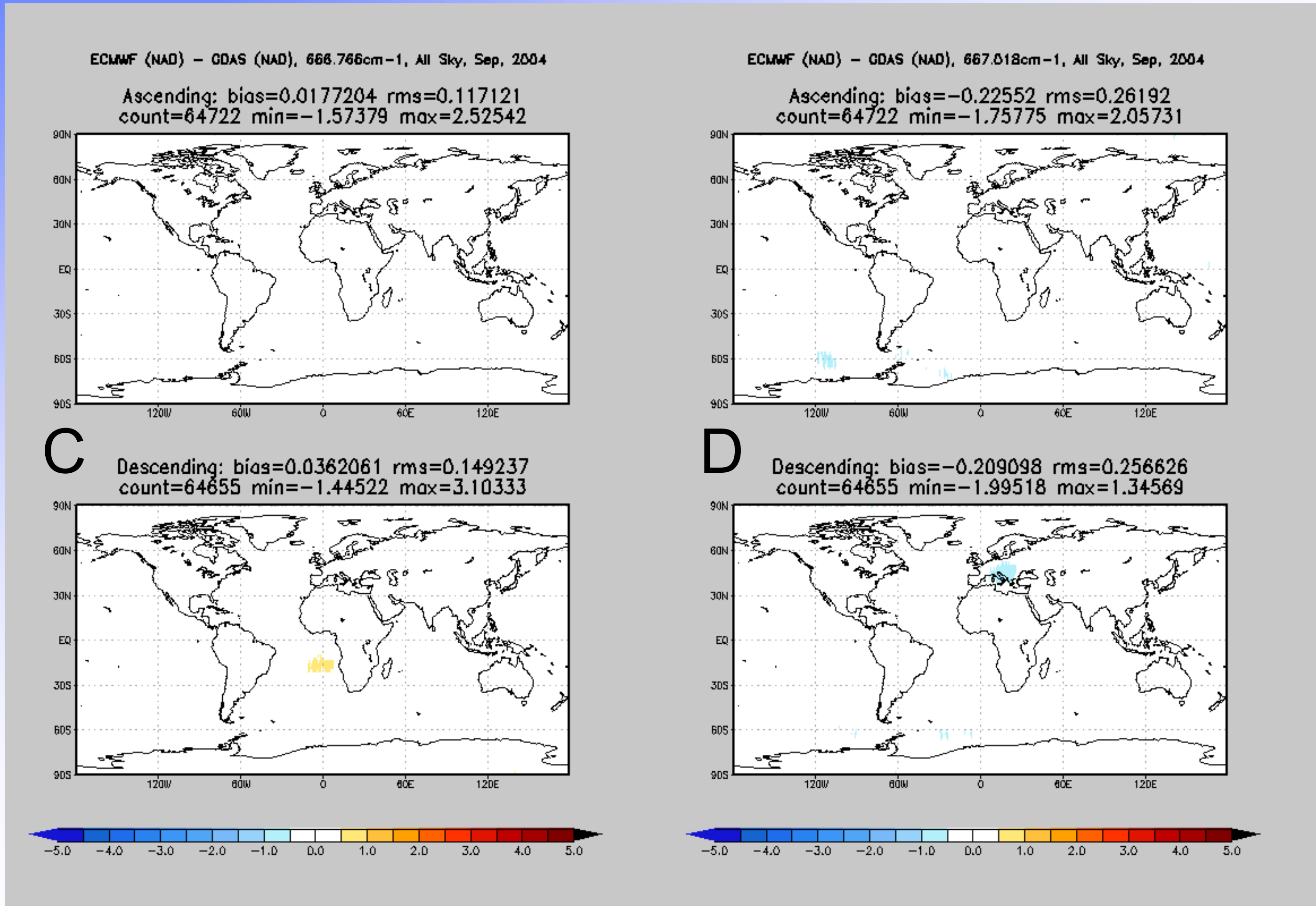
# : ECMWF minus GDAS simulated brightness temperatures for A: 801.09 cm$^{-1}$ (850 mb), B: 723.029 cm$^{-1}$ (700 mb), and C: 704.436 cm$^{-1}$ (350 mb)



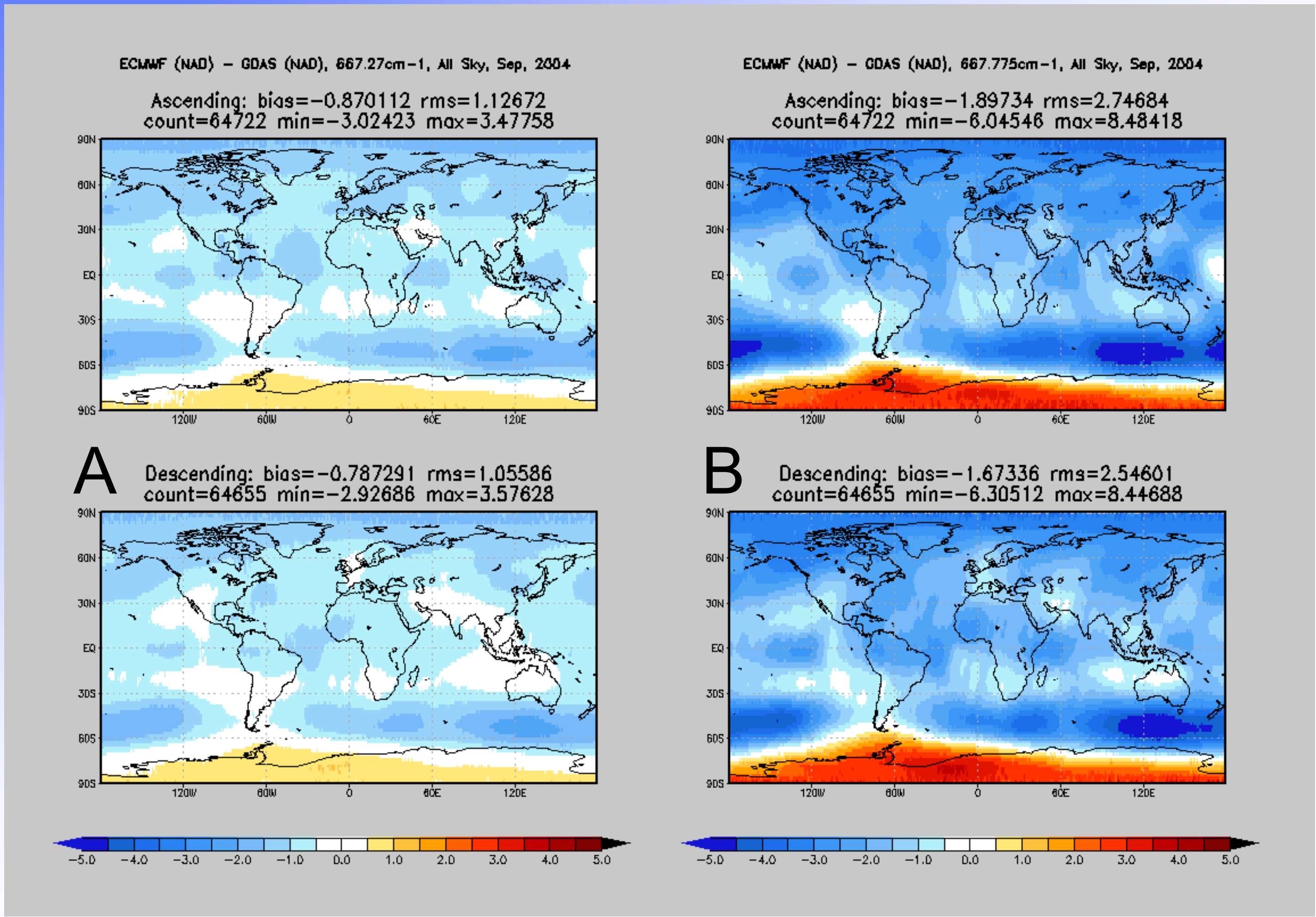

Water vapor sensitivity

Temperature channel differences are very small

# ECMWF minus GDAS simulated brightness temperatures for C: 666.766 $cm^{-1}$ (40 mb), and D: 667.018 $cm^{-1}$ (25 mb)

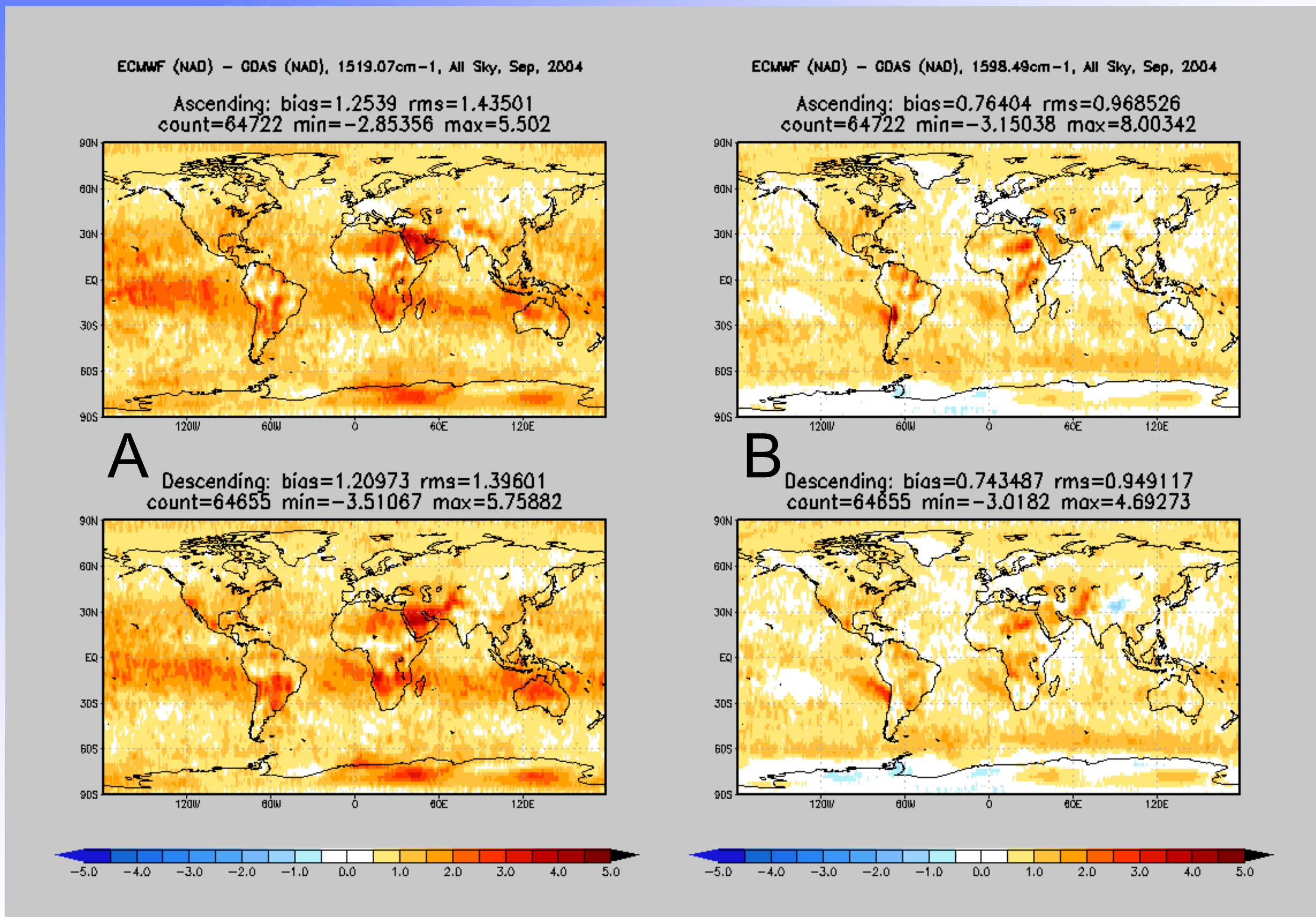


# ECMWF minus GDAS simulated brightness temperatures for A: 667.27 cm-1 (15 mb) and B: 667.775 cm-1 (1.5 mb)



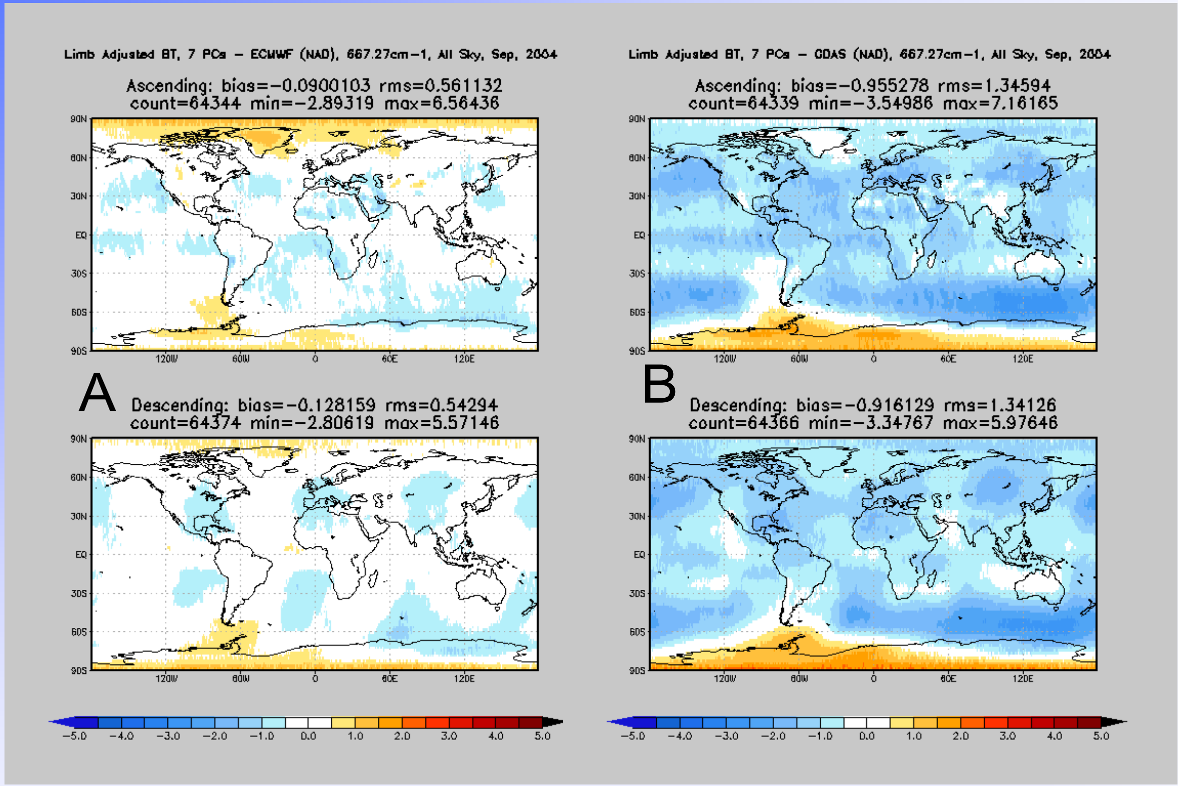

Finally we see large differences at 15 and 1.5 mb

# ECMWF minus GDAS simulated brightness temperatures for A: 1519.07 cm$^{-1}$ (315 mb) and B: 1598.45 cm$^{-1}$ (490 mb)




And large differences in water vapor

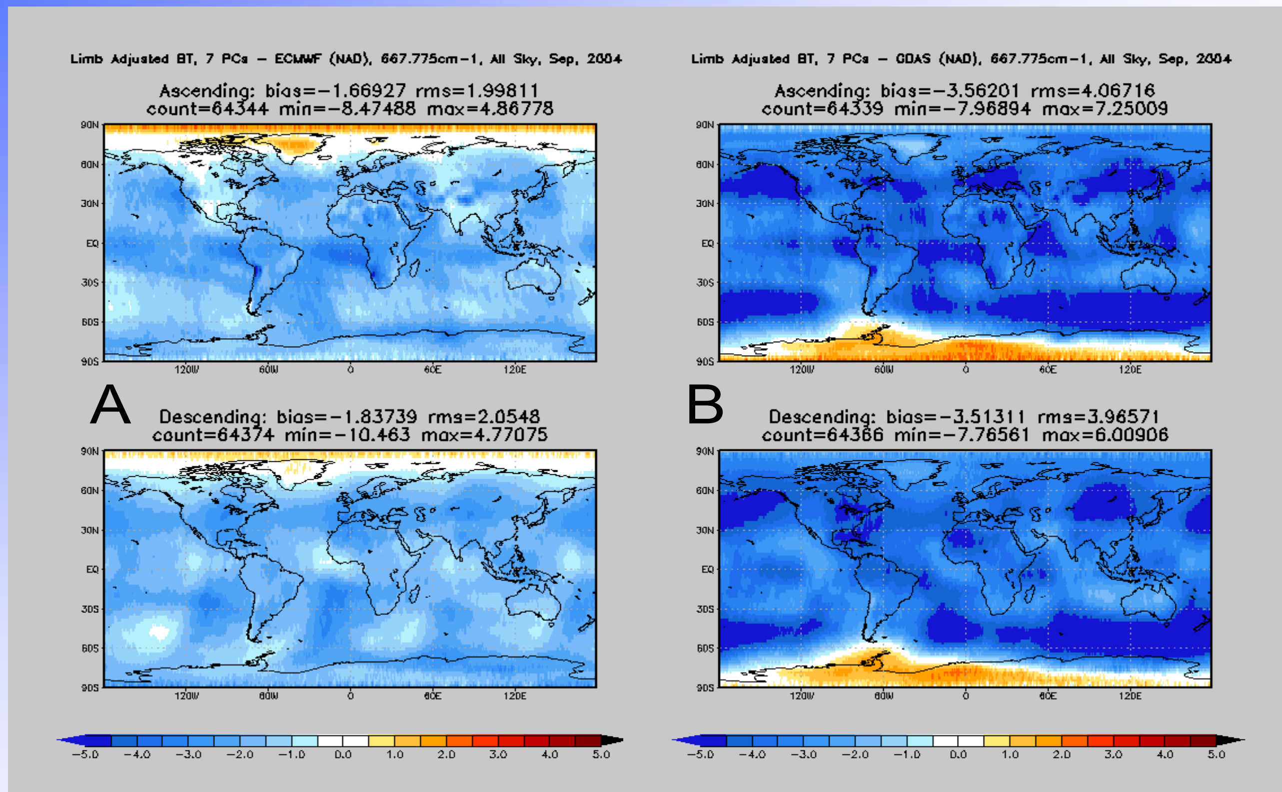
# We use the SRIR as the Jury




Difference between limb adjusted AIRS and simulated ECMWF brightness temperatures (A) and with NCEP (B) for 667.27 $cm^{-1}$ (15 mb)

ECMWF agrees with the AIRS SRIR Climate Data Record , The difference with ECMWF is nearly zero

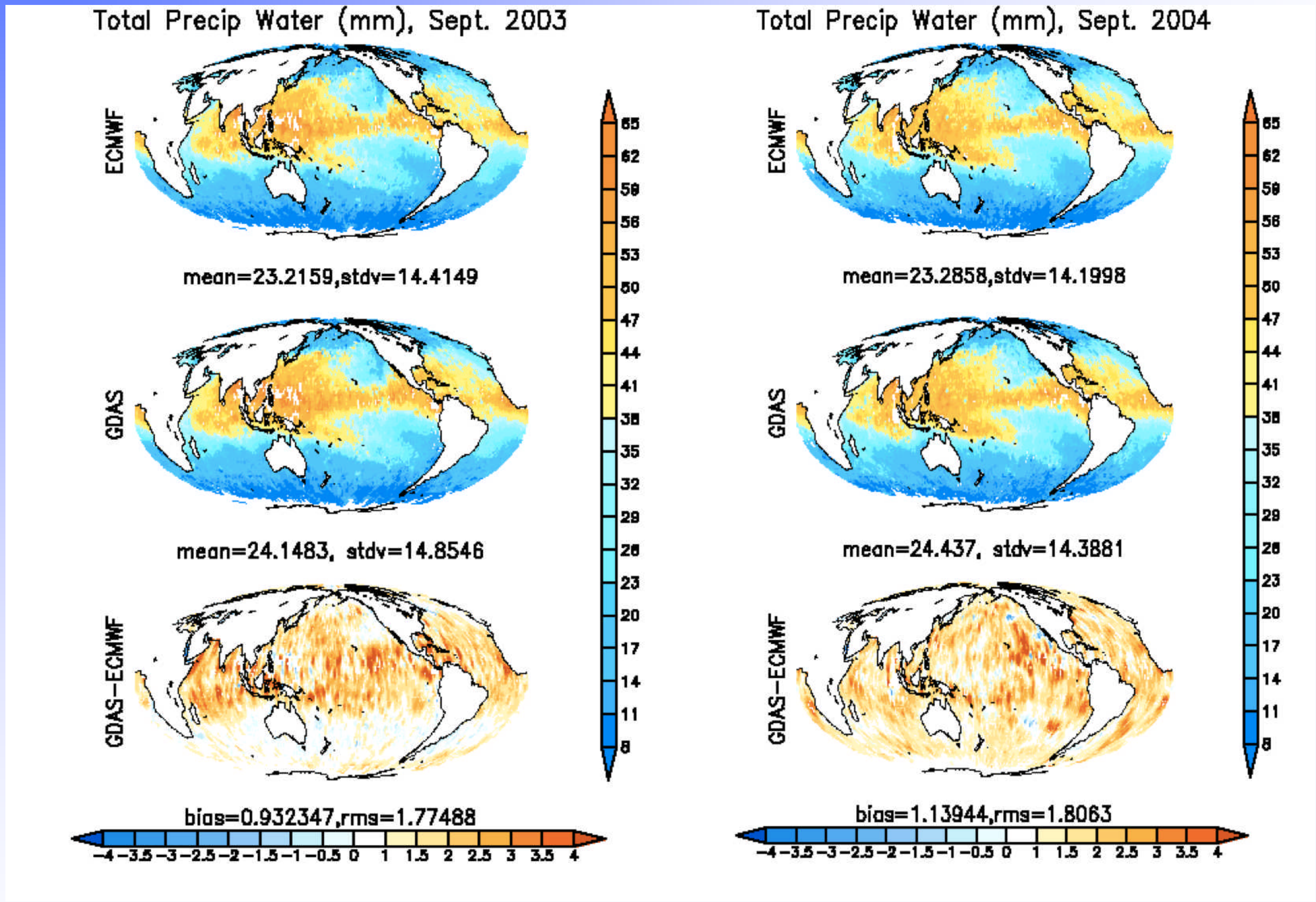
# We use the SRIR as the Jury




Difference between limb adjusted AIRS and simulated ECMWF brightness temperatures (A) and with NCEP (B) for 667.775 $cm^{-1}$ (1.5 mb)

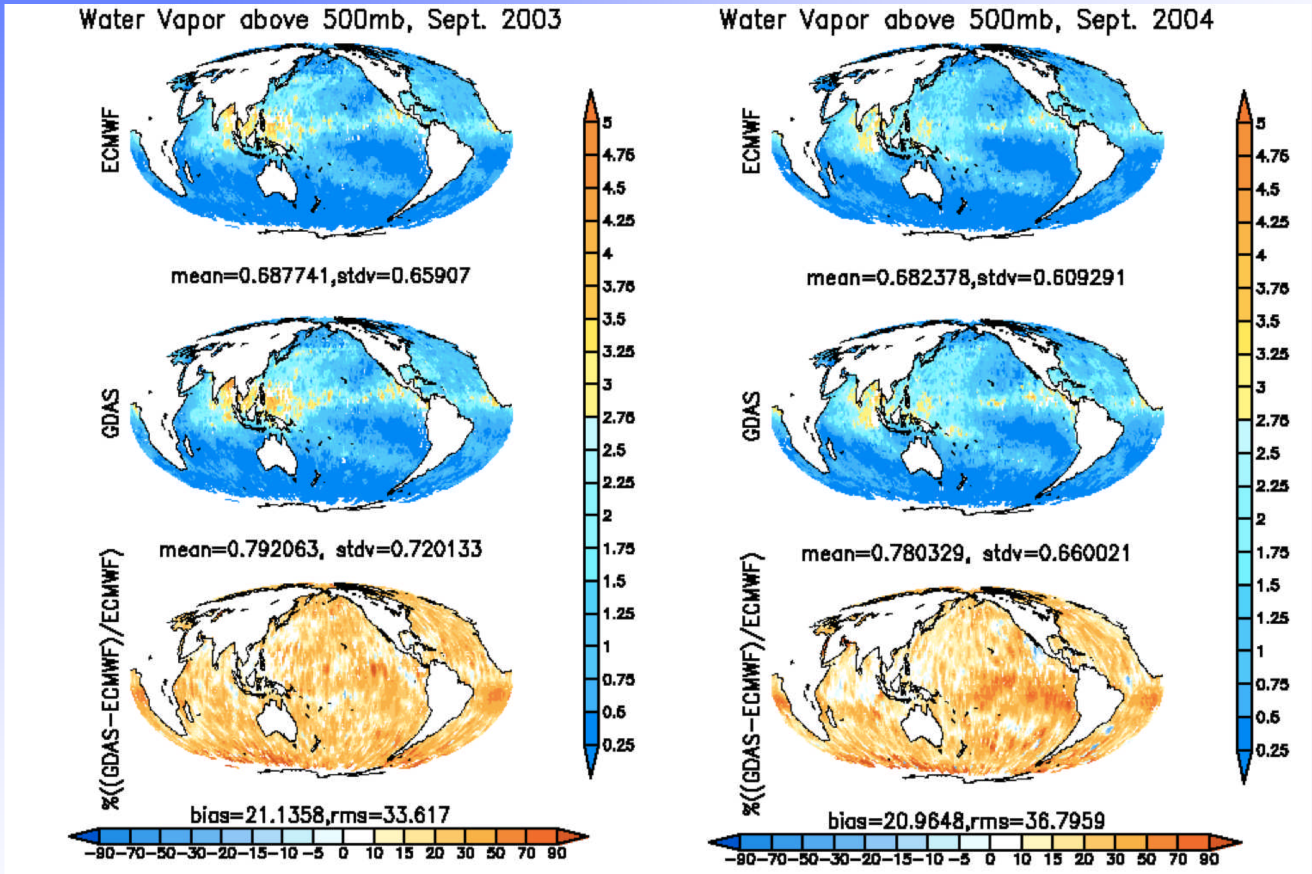
ECMWF agrees better with the AIRS SRIR Climate Data Record , Both model analysis need to improve

# How about water vapor??



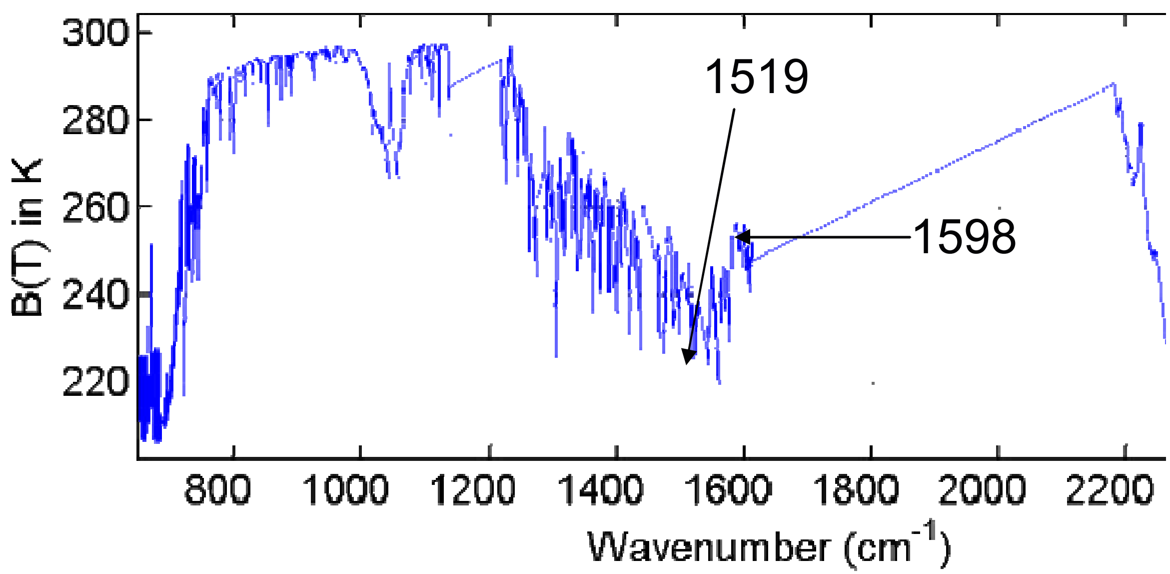

NCEP water vapor (TPW) is consistently higher

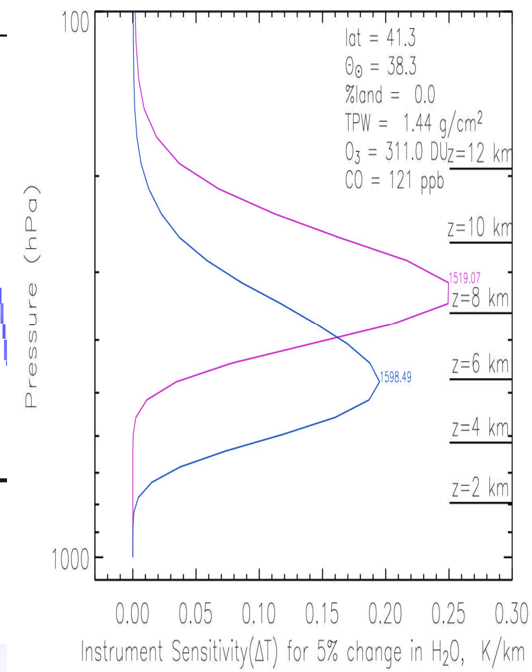
# How about water vapor??



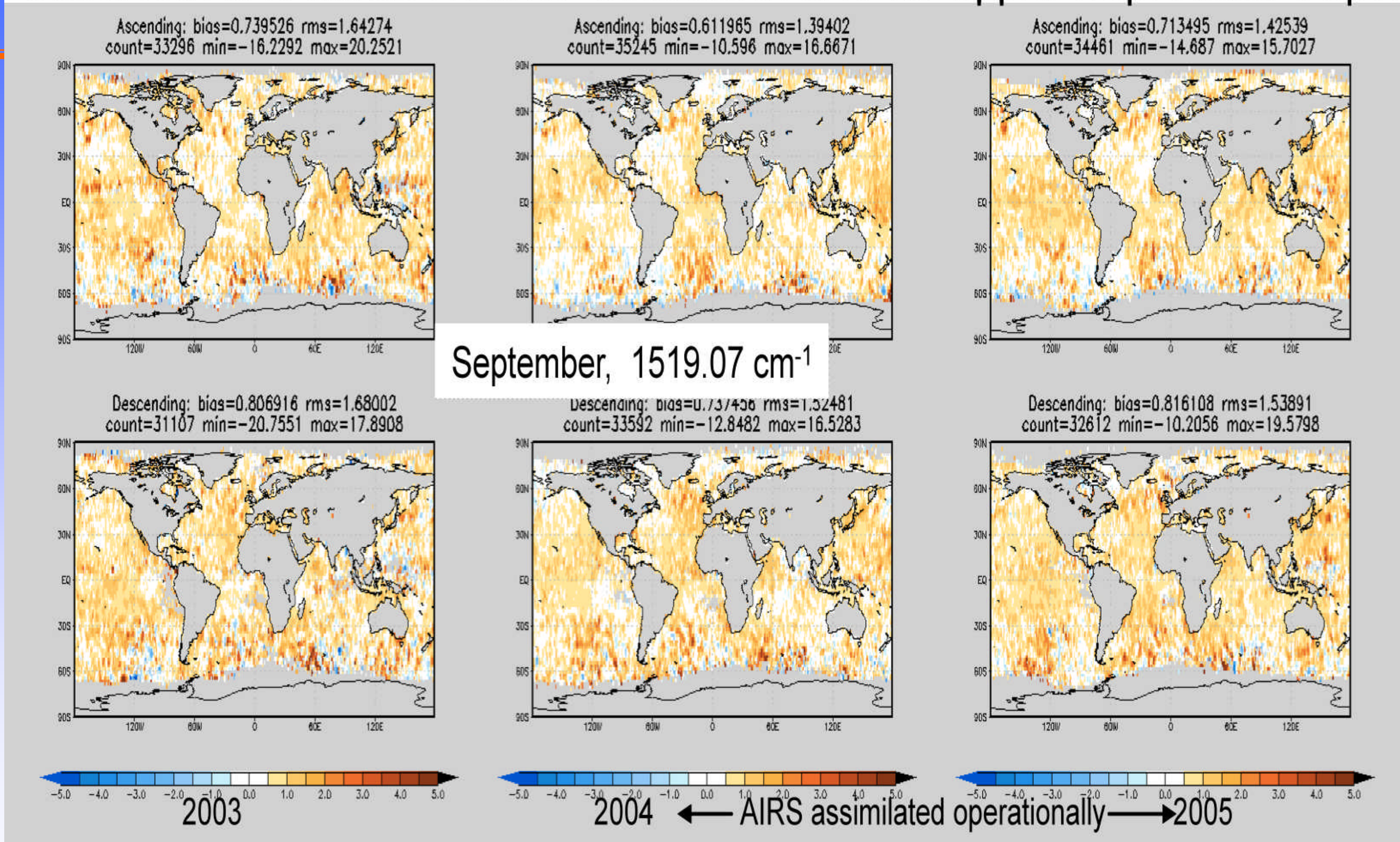

NCEP water vapor above 500 mb (TPW) is consistently higher (20%)

# Which water vapor field more accurate?
# We selected an upper tropospheric water vapor channel (1519 cm-1) and a mid tropospheric water vapor channel (1598 cm-1)



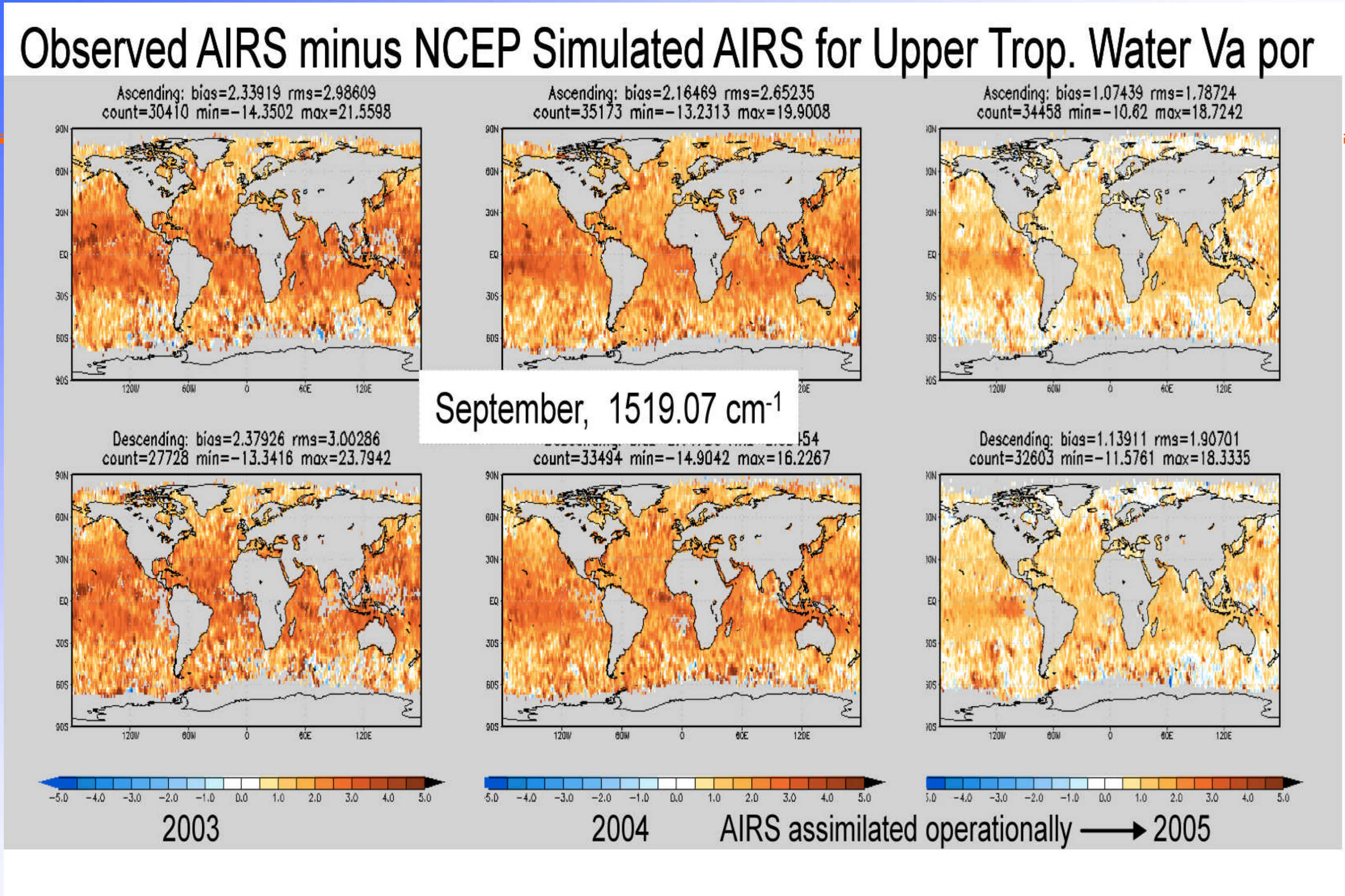



# Observed AIRS minus ECMWF Simulated AIRS for Upper Trop. Water V apor

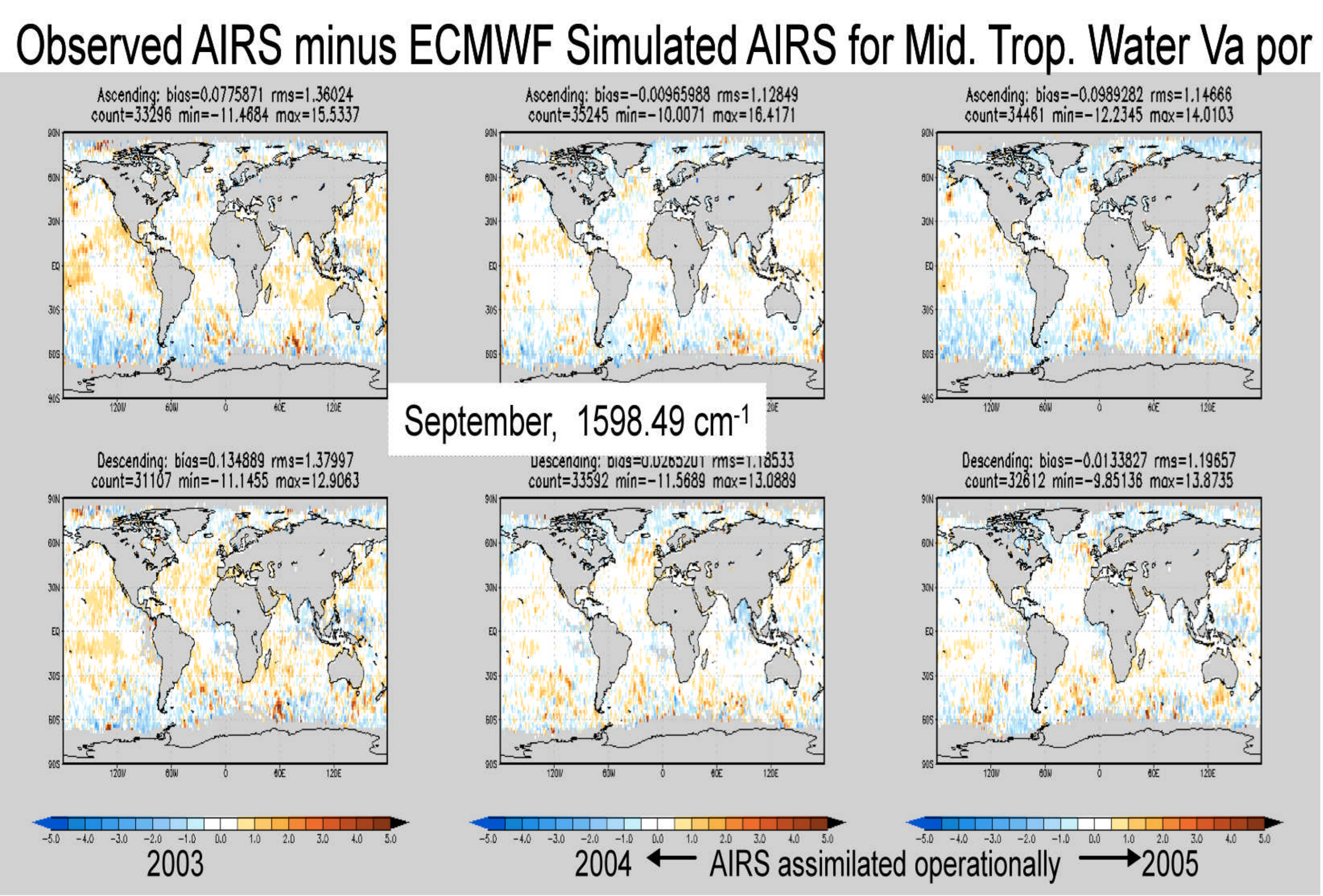



ECMWF bias is about 0.7 K, and seems to be consistent for 2003 – 2005

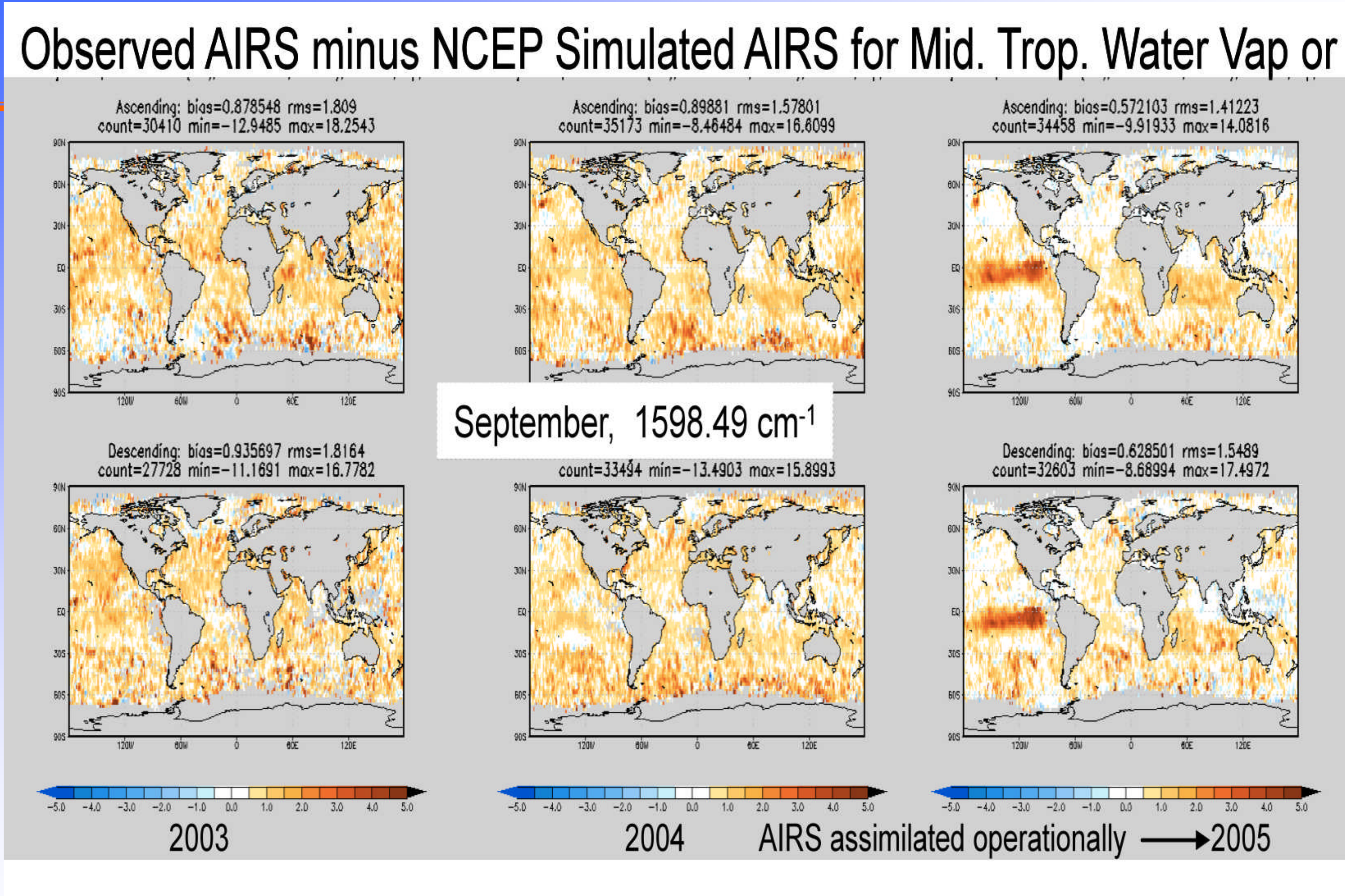
Note 2004 ECMWF assimilated AIRS




NCEP bias is 3 times larger but reduces by half after AIRS is assimilated.

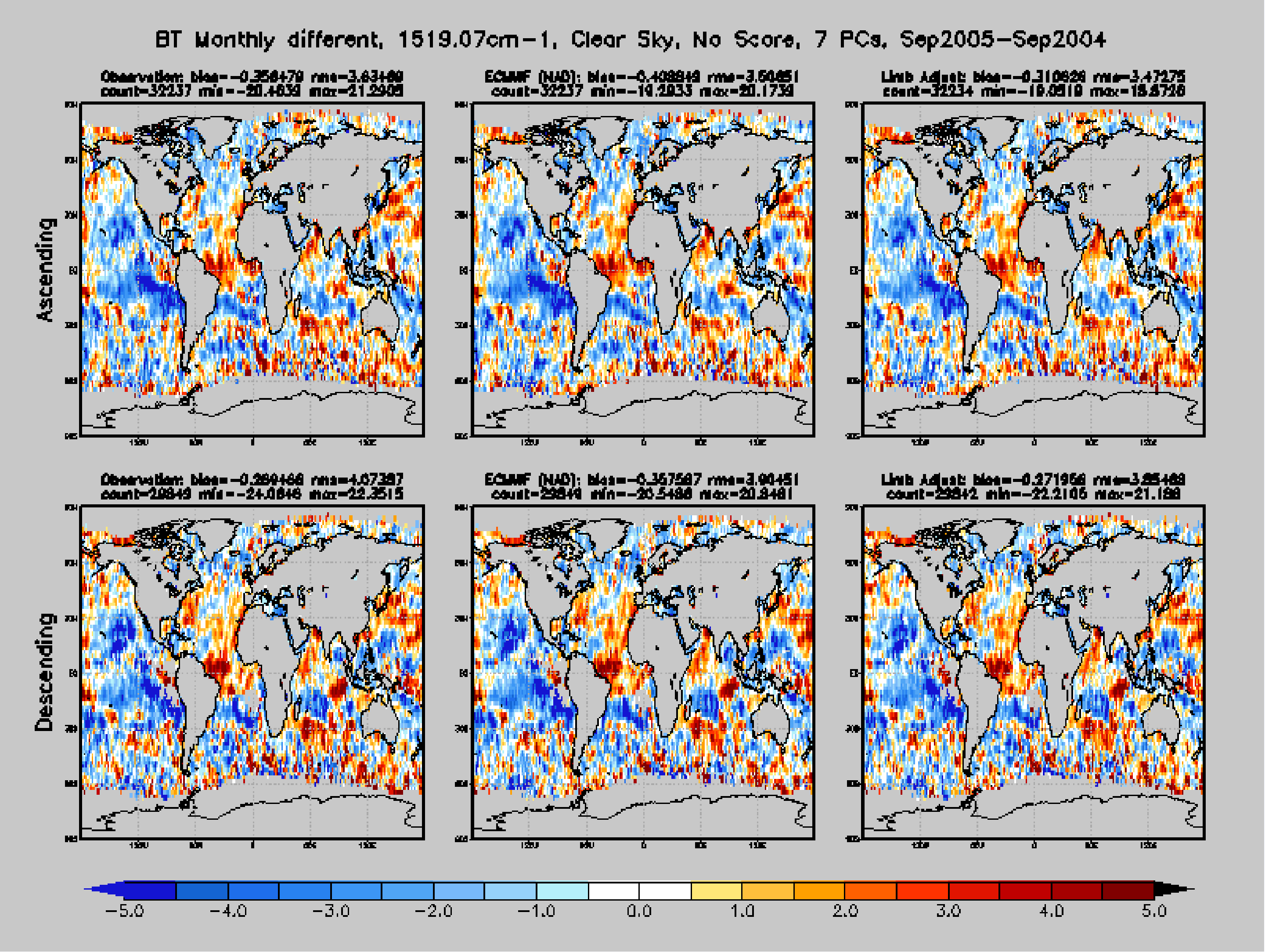



ECMWF bias is nearly zero !!!

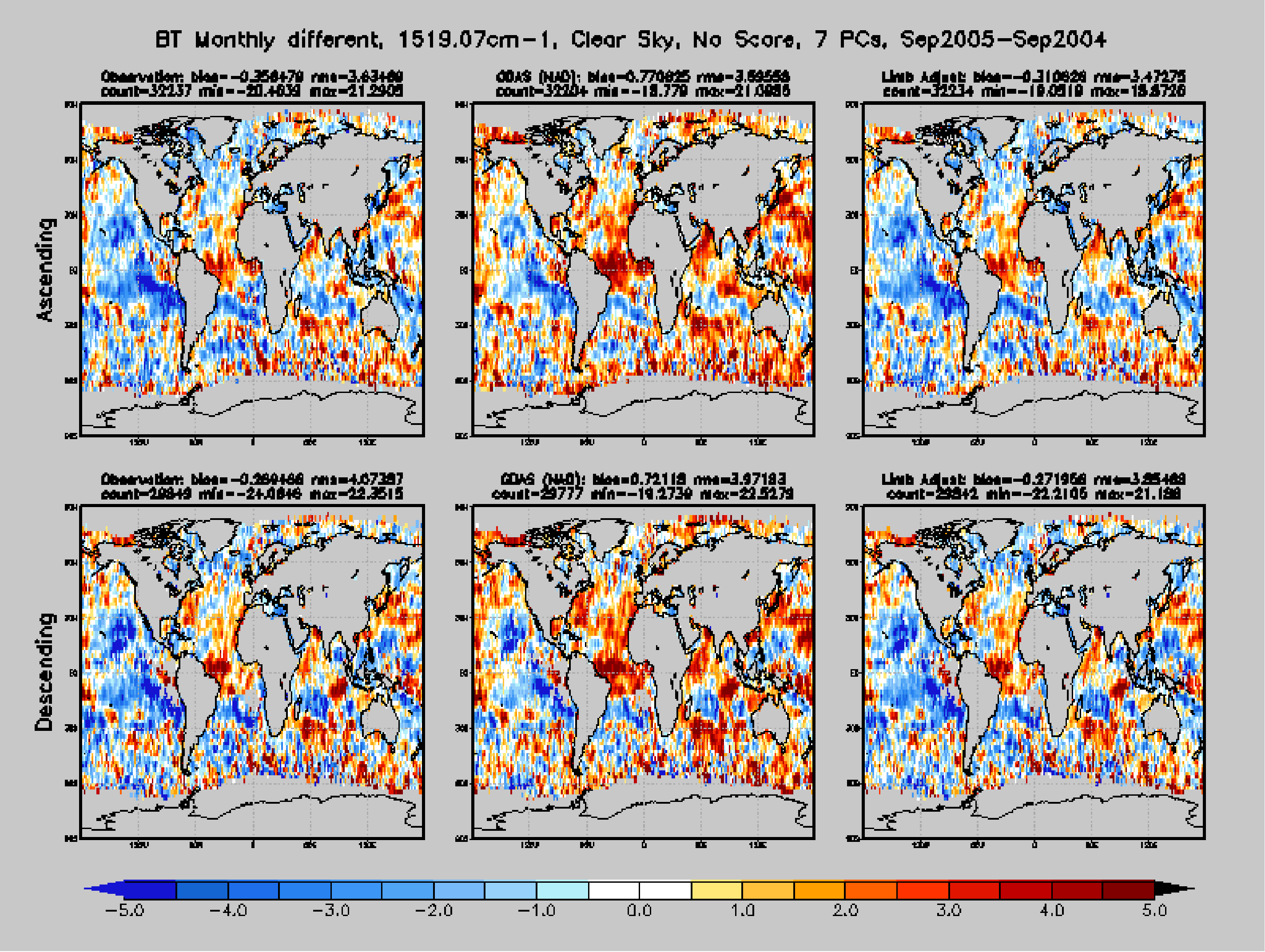



NCEP bias is relatively much larger, reduces after AIRS is assimilated, but large bias over equatorial eastern Pacific

# Interannual difference - EC



# Interannual differences - NCEP



# Jury declares ECMWF water vapor more accurate

- But ………

- Operational change in ECMWF in Sept. 2006 caused an increase in the bias. (e.g. adaptive bias tuning)

- NCEP  above 500 mb TPW in 2003 and 2004 was 20% higher,  then in 2005 just 11% higher because NCEP assimilated AIRS,  and in 2006 the difference is close to 0% because of a change in the ECMWF water vapor field.

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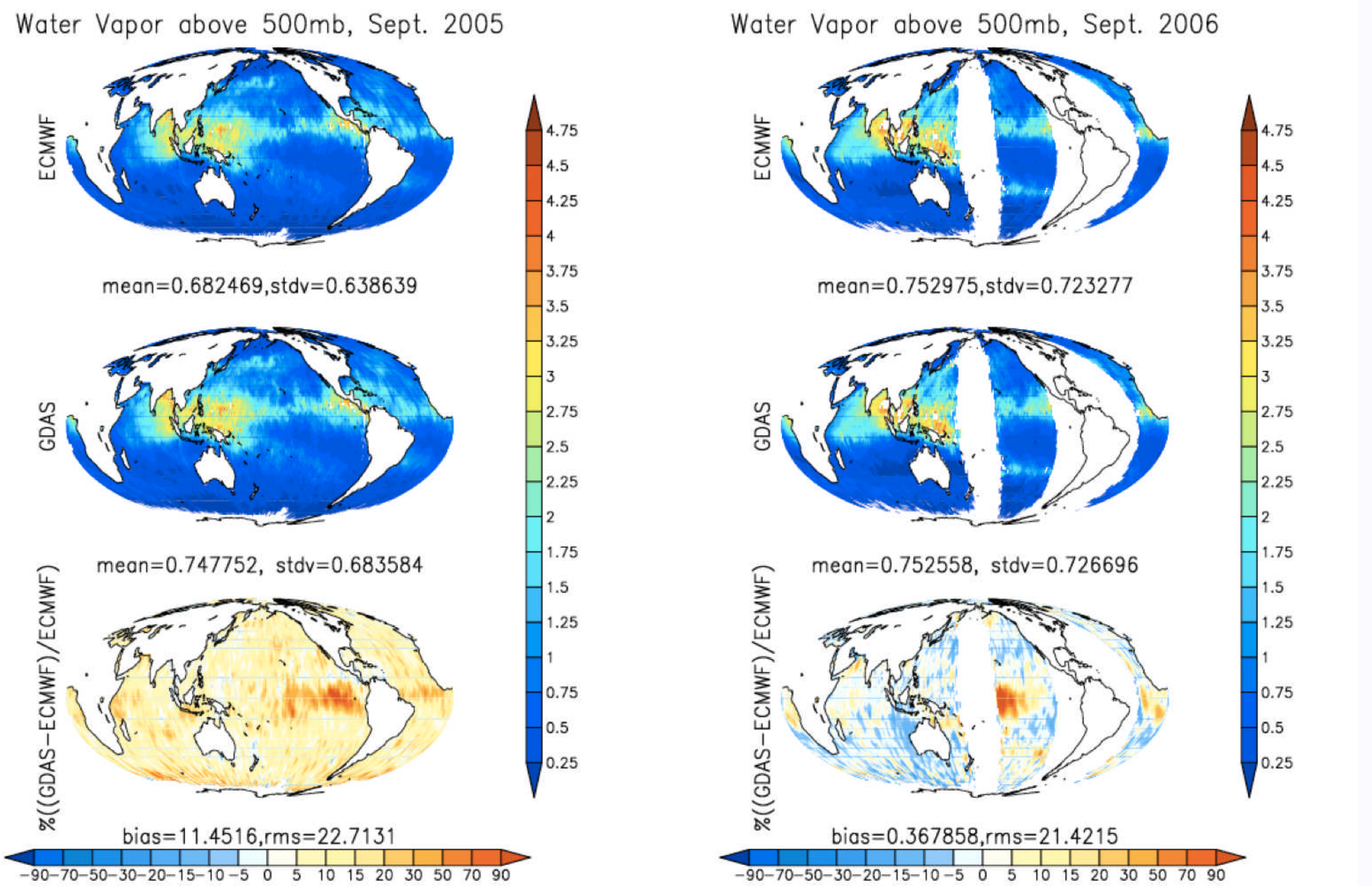
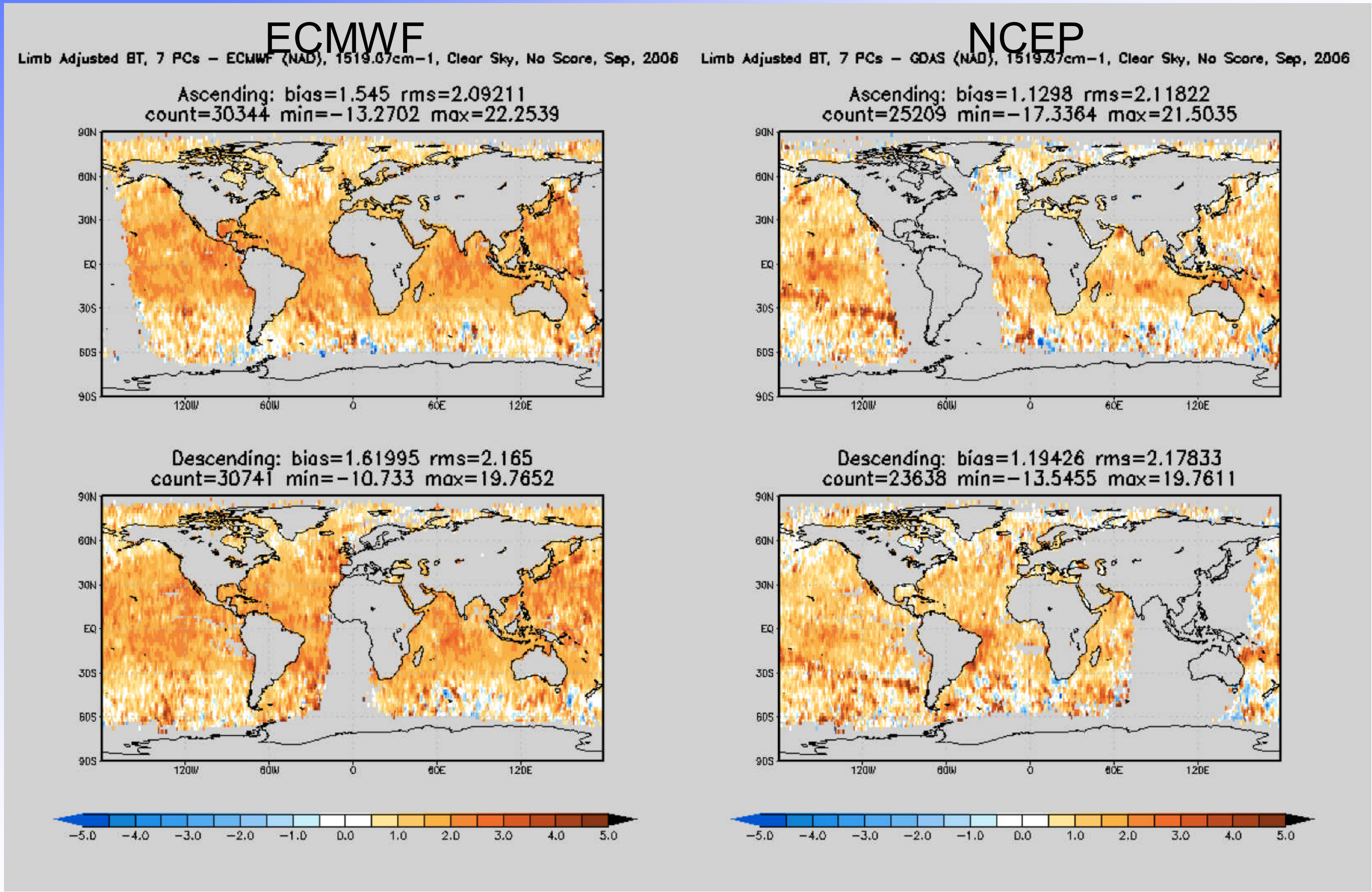
# Note ECMWF TPW above 500 mb in 2006 is now similar with NCEP

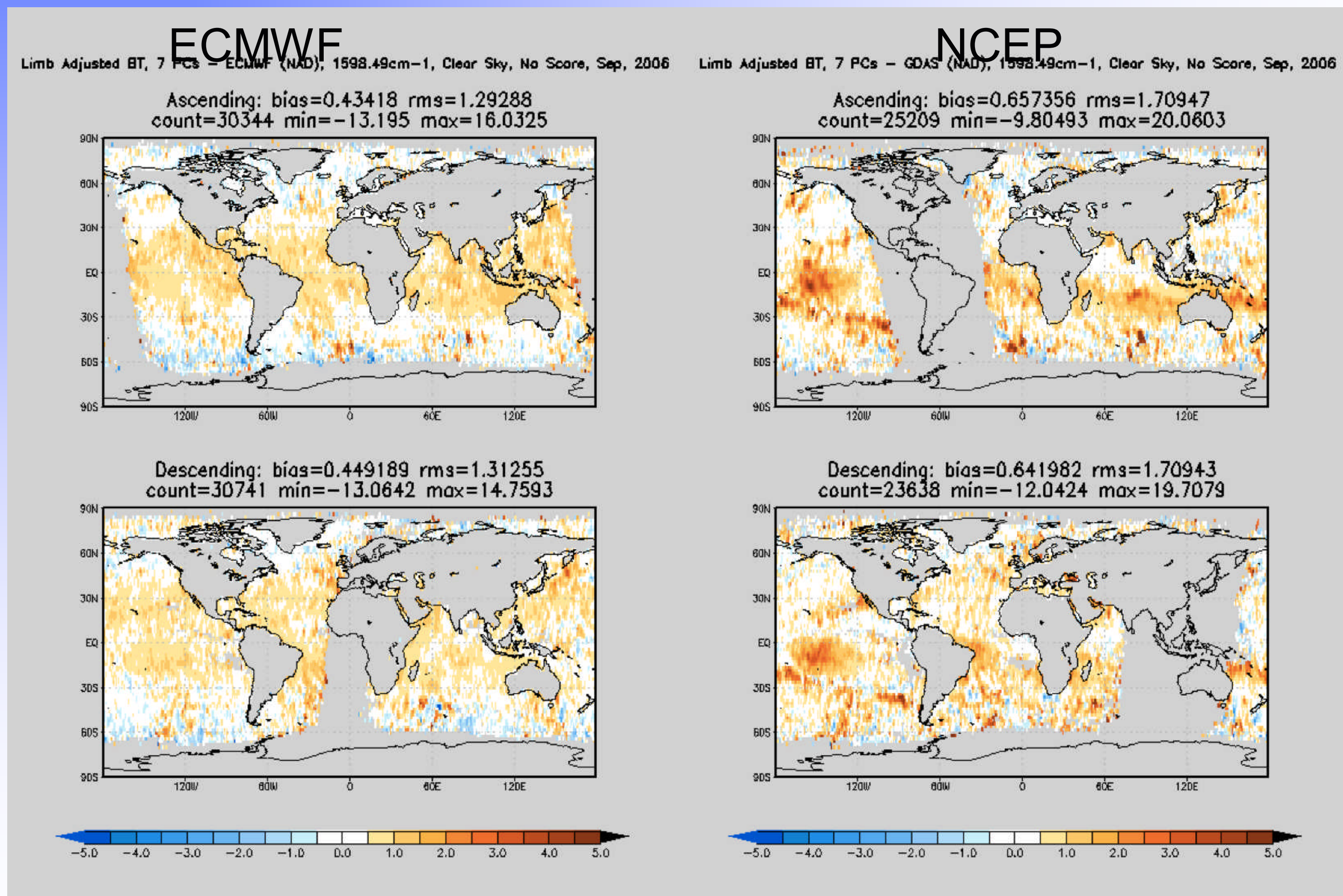


# Upper Tropospheric Water Vapor Channel




ECMWF bias is now larger than NCEP!!! (increased by ~0.8 K)

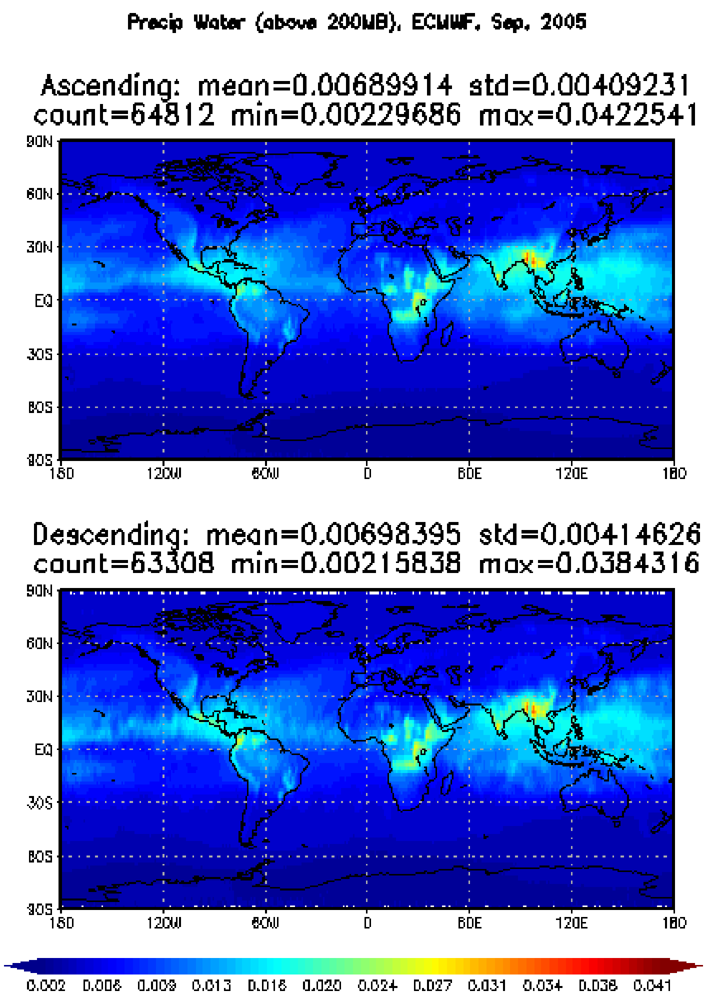
# Mid Tropospheric Water Vapor Channel

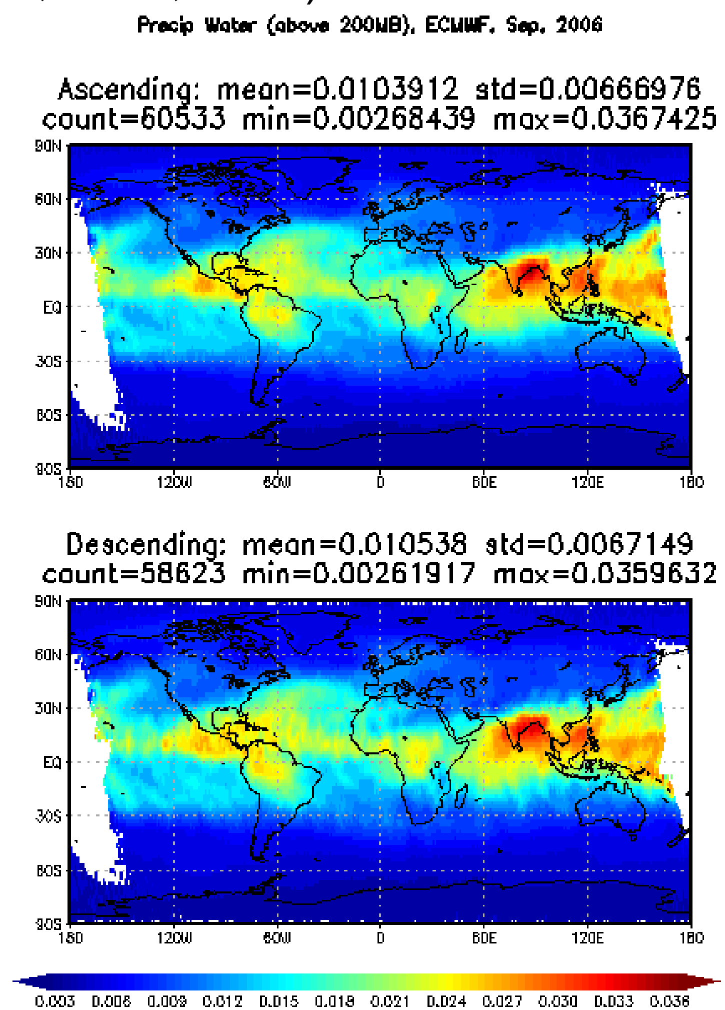



ECMWF bias is nearing NCEP

# So what is the cause??

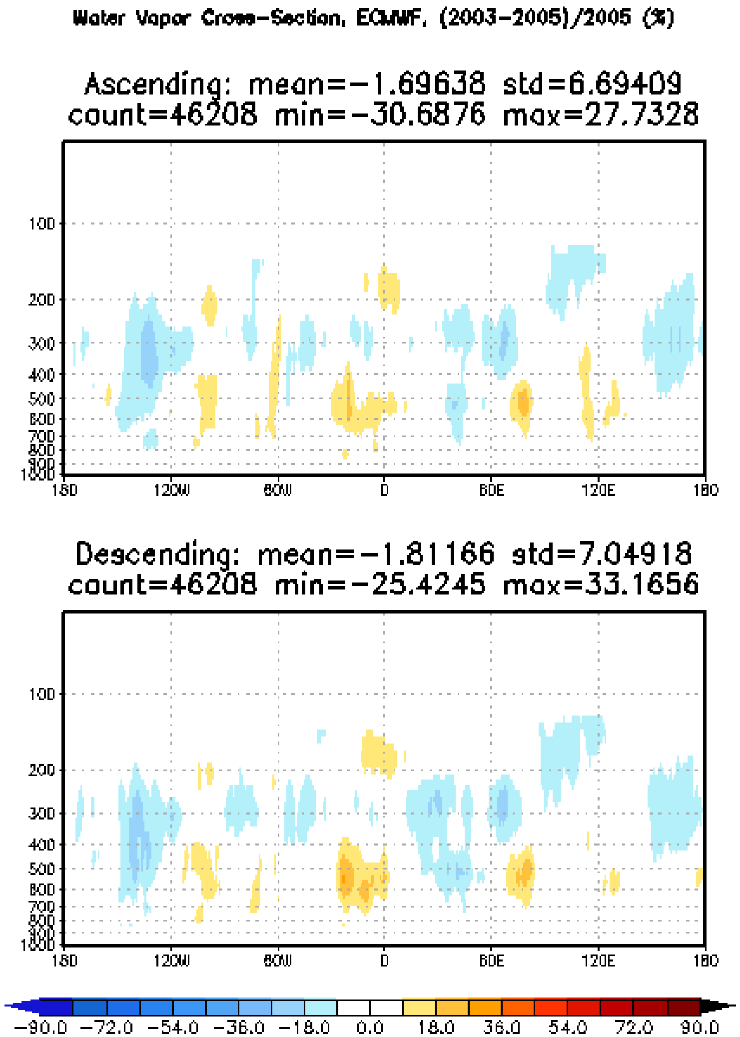
We found the water vapor (TPW) above 200 mb is nearly twice as large (this is consistent for 2006, 2007, 2008)



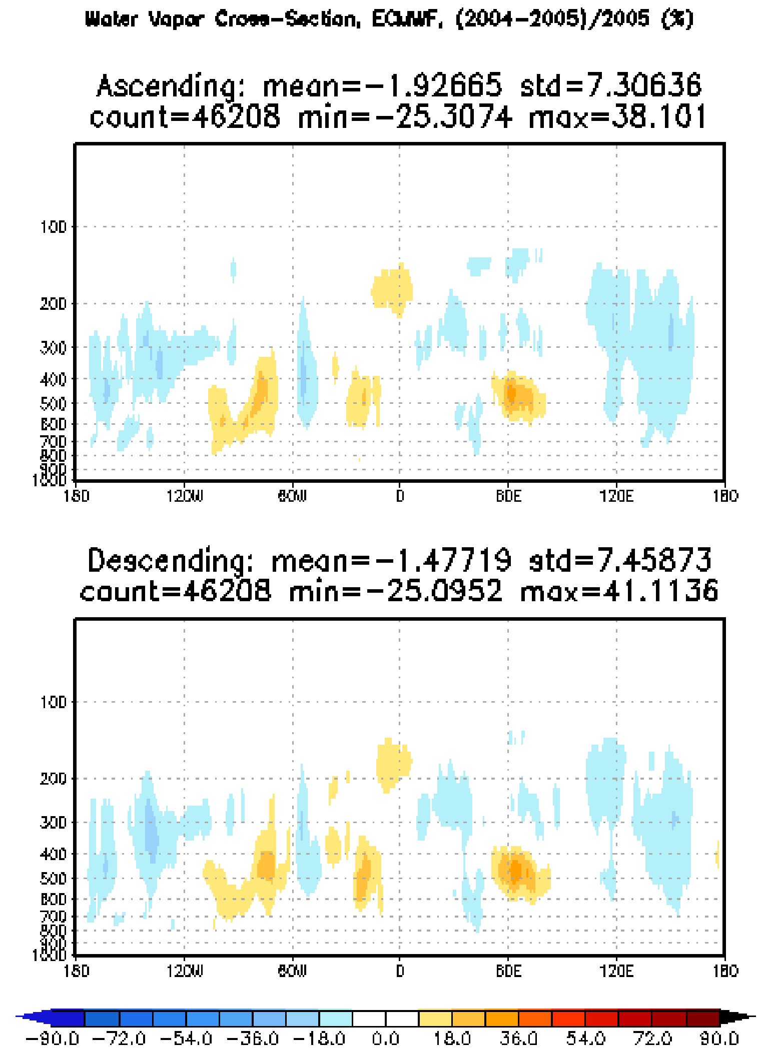



# Compare Annual Difference (%) of ECMWF using 2005 as Base Year

Very small year to year differences (2003 – 2005, 2004 – 2005)




2003




2004

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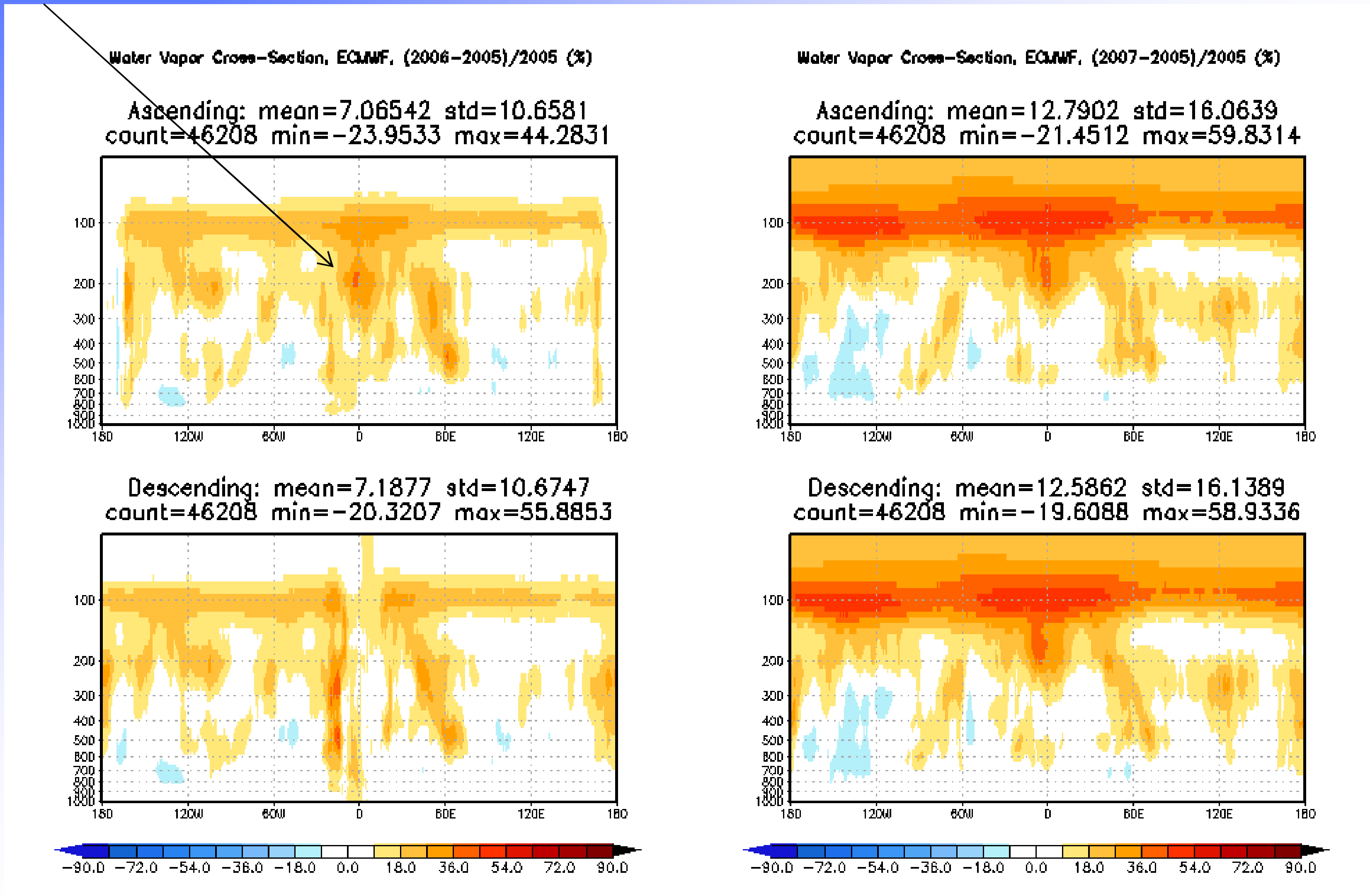
# Compare Annual Difference (%) of ECMWF using 2005 as Base Year

More water from previous years, difference with 2005 is now much larger




2006 2007 (2008 ~ 2007)

| | | 2003 | 2004 | 2005 | 2006 |
|---|---|---|---|---|---|
| a | ECMWF TPW | 23.22 mm | 23.29 | 22.70 | 22.34 |
| b | NCEP TPW | 24.15 mm | 24.44 | 24.02 | 24.01 |
| c | NCEP - ECMWF | 0.93 mm | 1.14 | 1.32 | 1.67 |
| d | ECMWF PW above 500mb | 0.69 mm | 0.68 | 0.68 | 0.75 |
| e | NCEP PW above 500 mb | 0.79 mm | 0.78 | 0.75 | 0.75 |
| f | NCEP - ECMWF | 21.14% | 20.96% | 11.45% | 0.37% |
| g | ECMWF 1519cm$^{-1}$ | 0.73 K | 0.61 | 0.71 | 1.55 |
| h | NCEP 1519cm$^{-1}$ | 2.34 K | 2.16 | 1.06 | 1.13 |
| i | NCEP – ECMWF* | -1.61 K | -1.55 | -0.35 | 0.42 |
| j | ECWMF 1598cm$^{-1}$ | 0.10 K | -0.01 | -0.10 | 0.43 |
| k | NCEP 1598cm$^{-1}$ | 0.86 K | 0.90 | 0.56 | 0.65 |
| l | NCEP – ECMWF* | -0.76 K | -0.91 | -0.66 | -0.22 |
| m | SUM OF DIFF* | -2.37 K | -2.46 | -1.01 | 0.20 |

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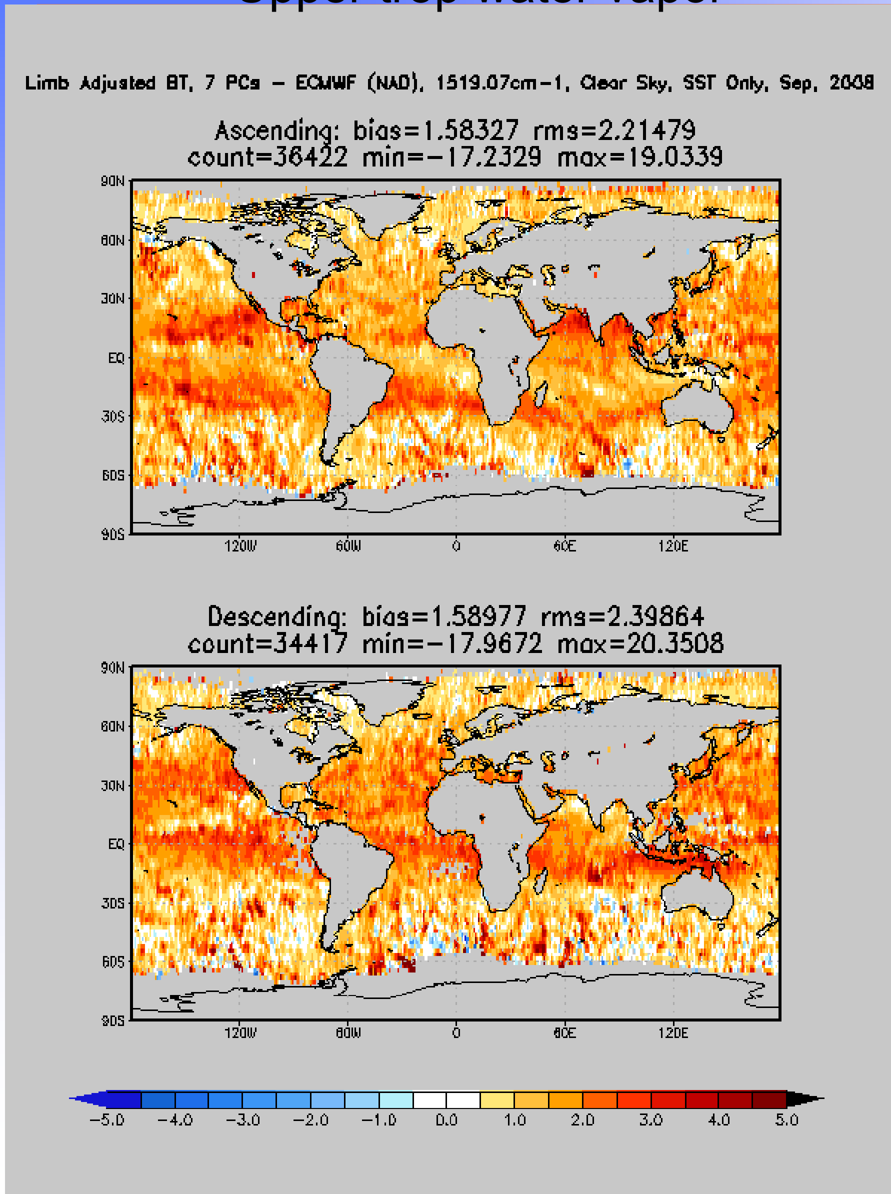
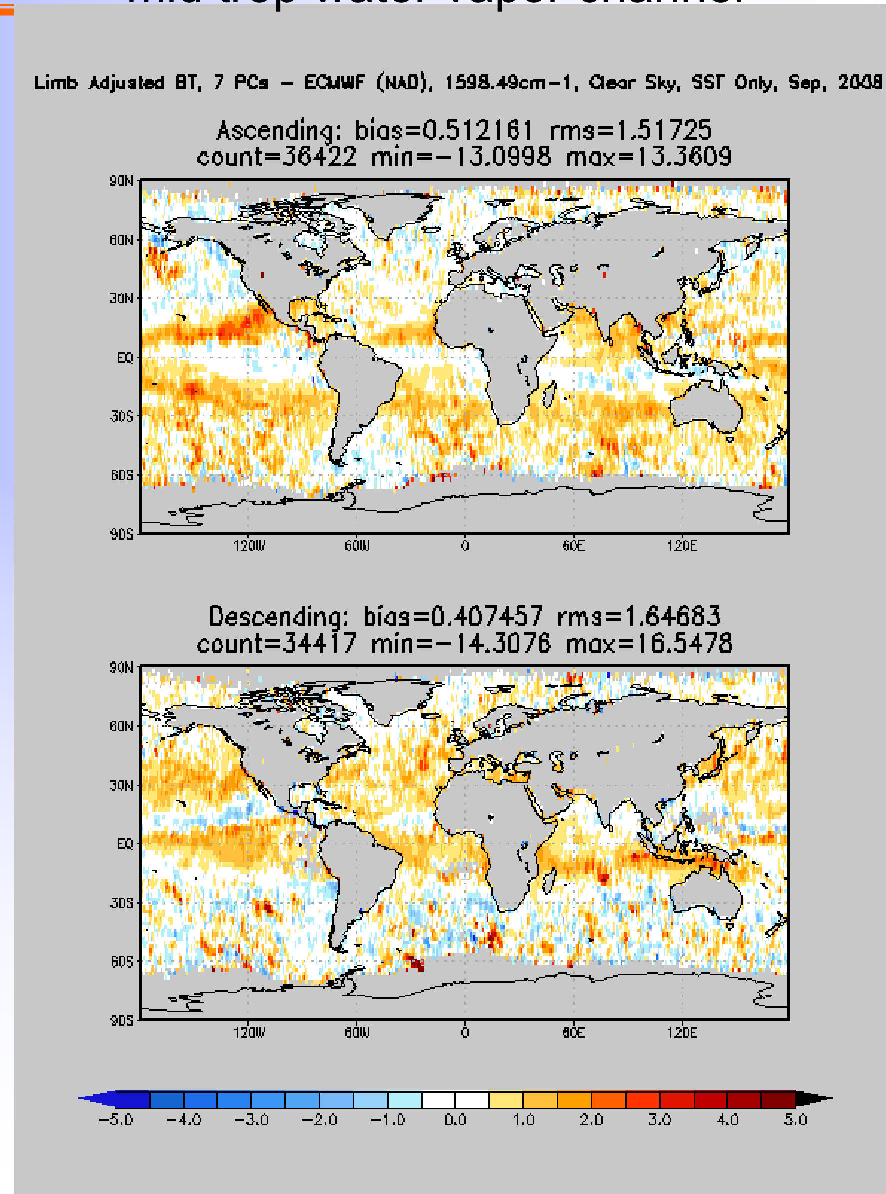
# September 2008 AIRS – EC bias remains consistent with 2006

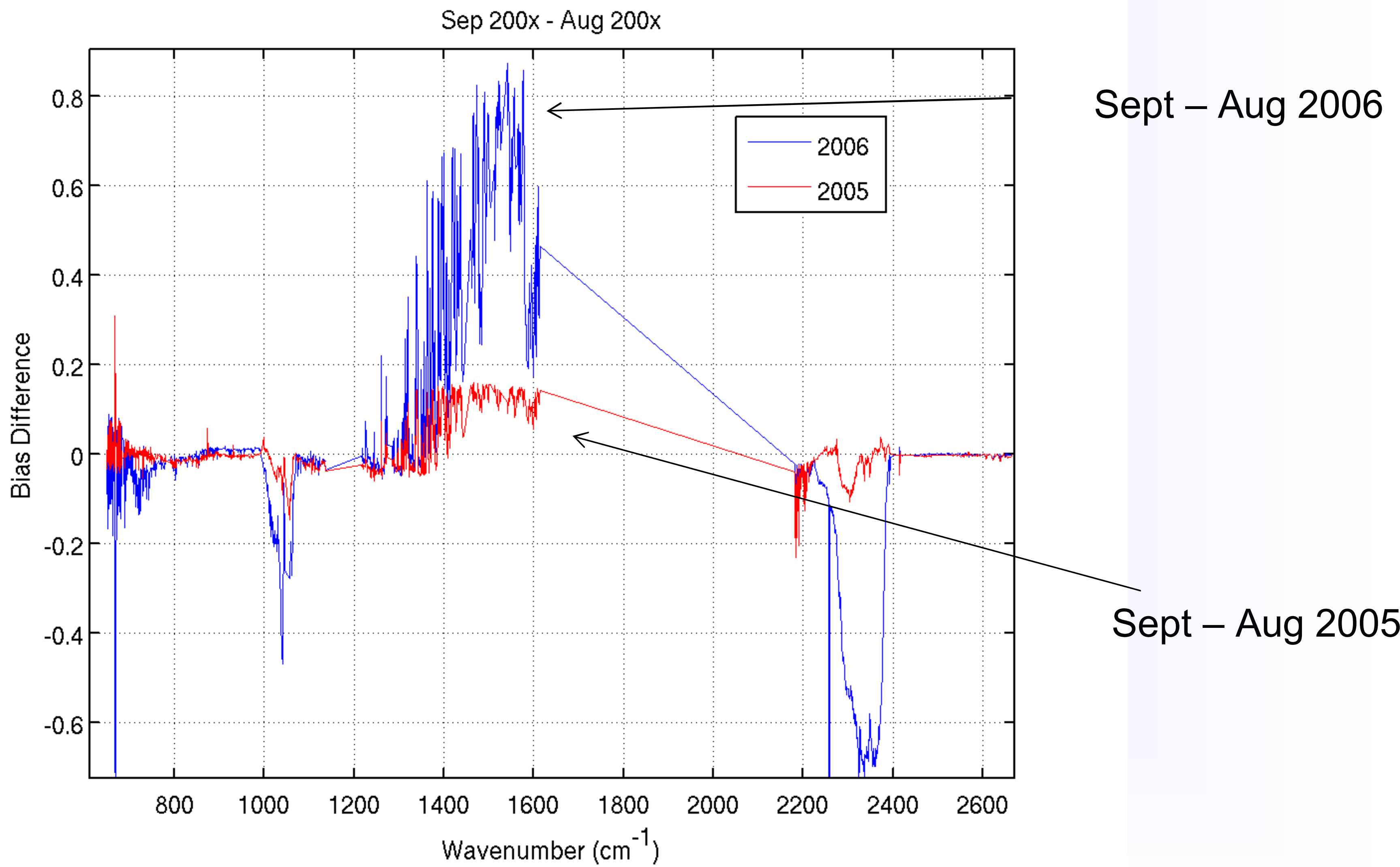
Upper trop water vapor

mid trop water vapor channel



# Our results agree with findings from Larrabee Strow (UMBC) using small datasets of collocated super clear AIRS and ECMWF data




ECMWF added adaptive bias tuning on Sept 12, 2006

# Sept. 2006 Changes

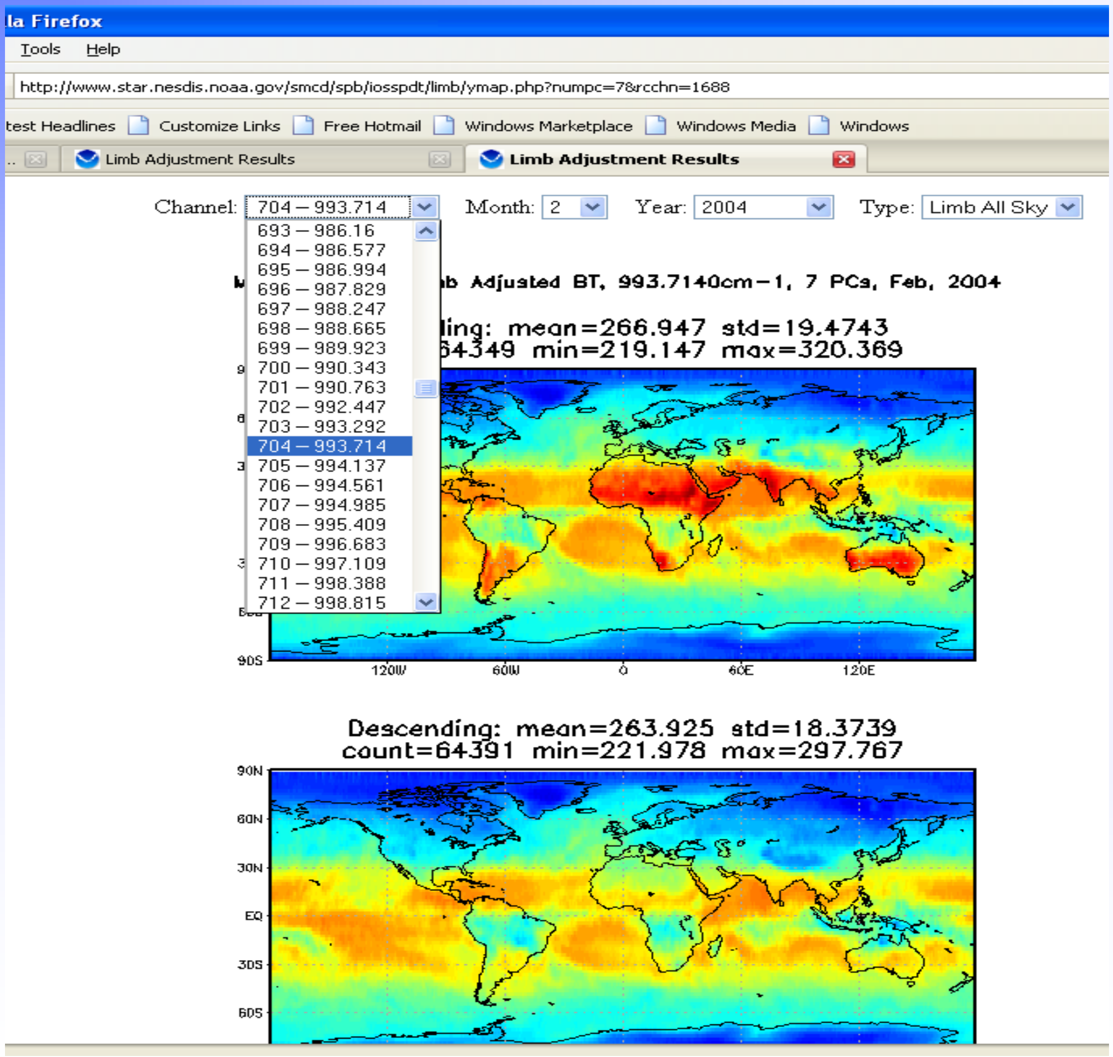
- 12 September 2006 Introduction of Cycle 31r1. This version includes the following changes:
- Revisions to the cloud scheme, including treatment of ice supersaturation and new numerics
- Implicit computation of convective transports
- Introduction of turbulent orographic form drag scheme and revision to sub-grid scale orographic drag scheme
- Gust fix for orography and stochastic physics
- Reduction of ocean surface relative humidity from 100% to 98% (due to salinity effects)
- Revised assimilation of rain-affected radiances
- **Variational bias correction of satellite radiances**
- Thinning of low level AMDAR data (mainly affects Japanese AMDAR network

# Summary

- Developed a SRIR radiance CDR
- The CDR consists of daily/monthly brightness temperatures for all AIRS channels
  - Ascending (day), clear sky
  - Ascending, all sky
  - Descending (night), clear sky
  - Descending, all sky datasets

# Summary

**Datasets have been generated for 5 years data from January 2003:**



# Summary

- First major step towards developing a much longer record of thermal infrared radiances at high spectral resolution and high spatial global coverage to:
  - Monitor climate change
  - Assess the accuracy and realism of weather and climate analyses and forecasts.

# Contribution

- Fundamental dataset for independent and very accurate validation of model reanalyses and climate projections, and for monitoring climate change.

- Climatology will be extended to include IASI and CrIS.