The NOAA MSU/AMSU/SSU CDR Project: Team, Methods, Current Status, and Future Plan

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With many help from Dr. Wenhui Wang, IMSG at NESDIS/STAR

Outline

- NOAA MSU/AMSU/SSU Project Team
- General Information on the MSU/AMSU CDR Development
- Methodologies for MSU/AMSU CDR Development
  - Inter-satellite calibration to remove non-climate instrument signals
  - Diurnal drift correction
  - Residual bias correction
- Merged MSU/AMSU Products
- CDR Inter-Comparison
- CDR Consistency Test
- Data Set Archive and Web Service
- Summary and Future Plans

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NOAA MSU/AMSU/SSU CDR Project– CDR Development Team

MSU/AMSU

Cheng-Zhi Zou/STAR
Wenhui Wang/IMSG

SSU

Cheng-Zhi Zou/STAR
Likun Wang/QSS
Haifeng Qian/IMSG
Tom Kleespies/STAR

Yong Han/STAR
Yong Chen/CIRA

NOAA MSU/AMSU/SSU CDR Project– SDS Science Team

Cheng-Zhi Zou/STAR, CDR development, Team Lead

Carl Mears/Remote Sensing Systems, Inter-comparison

Qiang Fu/U. Washington, Inter-comparison, Science application

Tom Kleespies/STAR, Instrument characteristics

Lidia Cucurull/STAR, GPS-RO

Sid Boukabara/STAR, RAOB/satellite inter-comparison

Dick Dee, Paul Poli/ECMWF, ECMWF Reanalysis

Jack Woollen/NCEP, NCEP Reanalysis

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Fuzhong Weng/STAR

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Zhaohui Cheng
Mei Gao
Changyong Cao
Bob Iacovazzi
Dan Tarpley

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NOAA MSU/AMSU Pre-launch Calibration

- NOAA Pre-launch Calibration and Processing
  - NESDIS STAR provides pre-launch operational calibration support for level-1c data, including lunar contamination correction, antenna pattern correction, determine nonlinearity using pre-launch lab testing data …(Fuzhong's talk)
  - NESDIS Office of Satellite Data Processing and Distribution (OSDPD) distributes pre-launch calibrated level-1c data to users; most NWP centers and early-generation reanalysis use these level-1c data for data assimilation; This set of data is referred to as NOAA operational calibrated data in this talk
  - NESDIS NCDC and other NWP/data centers archive these level-1c data for climate applications

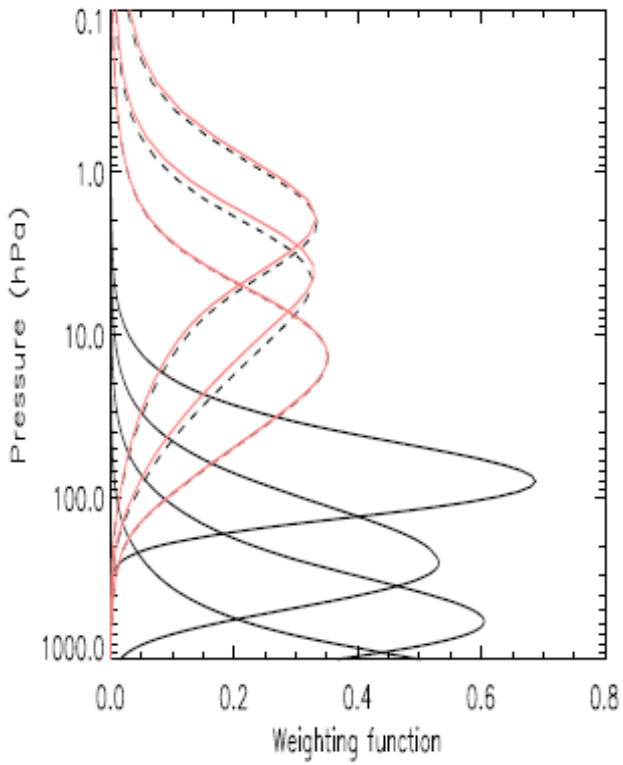
Purposes for CDR Project

- Develop consistent radiance Fundamental Climate Data Record (FCDR) to support consistent modeling reanalysis activities and consistent satellite retrievals

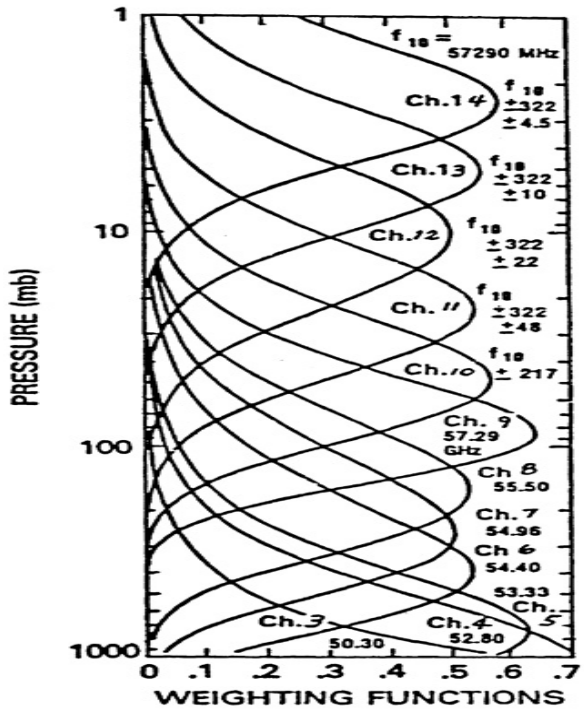
- Develop consistent atmospheric temperature thematic climate data record (TCDR) for climate service support – climate change research, climate change monitoring, validating climate model simulation…

MSU/AMSU/SSU channels

MSU+SSU; 1978-2007



AMSU; 1998-present



MSU/AMSU/SSU

Total 22 channels

15 atmospheric channels

Left: Weighting functions for the MSU and SSU instruments, where the black curve represent the MSU weighting functions and the dashed and red curves are the SSU weighting functions for different time period, showing a shift due to an instrument CO_2 cell pressure change; Right: Weighting functions for AMSU-A. All weighting functions are corresponding to nadir or near-nadir observations.

MSU/AMSU Advantages

- No cloud contamination, all weather measurements except heavy precipitation
- Continuity
- Global coverage
- Frequency believed to be stable
- Community acceptance

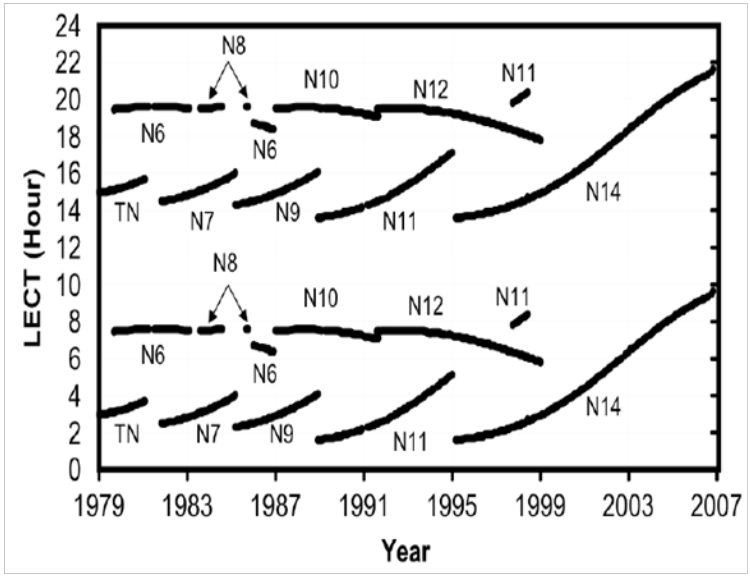
Fundamental Challenges

- No SI-traceable standards
- No stable microwave target to verify results
- No other observations for global validation (need to discuss RAOB, GPSRO)

➢ Need to develop consensus, self-consistent, best-practice algorithms for CDR development based on physical and engineering understanding of the instrument and sampling issues

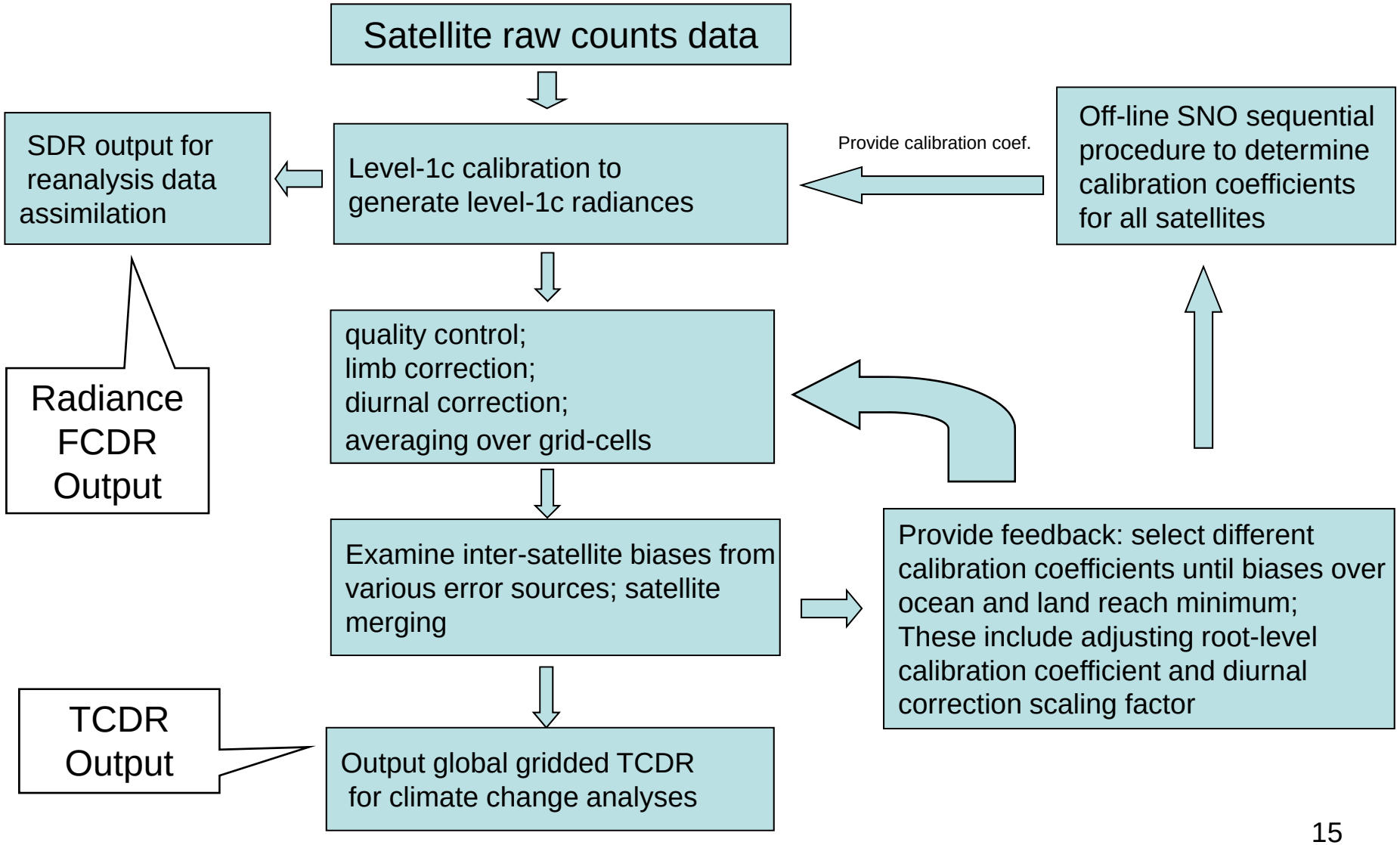
Known Issues on MSU/AMSU CDR Development (contributions from many investigators)

- Uncertainty 0.3-0.7K
- Atmospheric O_2 decreasing? (not considered yet)
- Short overlaps between NOAA-9 and NOAA-10
- Lat/Lon and time dependency in biases
- Orbital-decay
- Antenna pattern correction
- Incident angle errors
- Stratospheric effect on MSU ch2
- Noises in TLT
- Instrument signal contamination on radiances
- Diurnal drift effect
- Residual bias correction



Local Equator Crossing Time for NOAA POES satellites

NOAA MSU/AMSU CDR Development System



Key points

- Ocean and land processed separately to decouple instrument and diurnal drift errors
- Ocean for instrument errors
- Land for sampling diurnal drift errors
- Reference satellite is NOT a big problem: NOAA-10 is selected as a reference in a sense that only its constant offset is assumed to be zero; all other parameters (e.g., nonlinear coefficients) were determined from inter-calibration procedure that is independent from reference satellite

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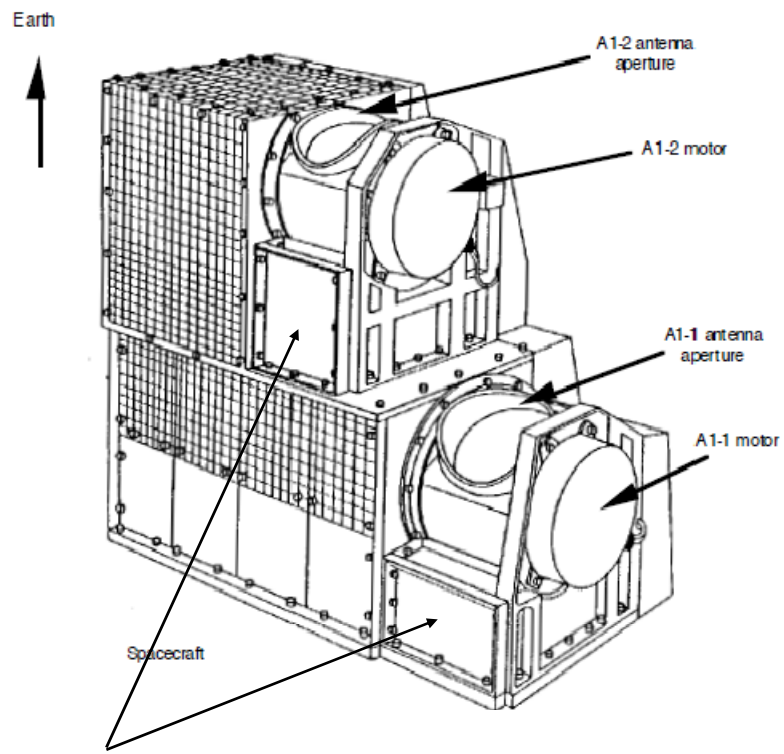
Instrument Calibration Principles

- Motor rotates in x-axis when satellite orbits the Earth
- 8 seconds per cycle
- Each scan cycle contain

30 Earth views:	Raw Counts	C_e
2 warm target views:	Raw Counts	C_w
2 cold space views:	Raw Counts	C_c

- Use these measurements to determine level-1c radiance

AMSU-A1 physical configuration



Warm Target Inside

Level-1c Calibration Equation

Nonlinear Calibration: one set of calibration coefficients for all scan positions

$$R = R_L - \delta R + \mu Z$$

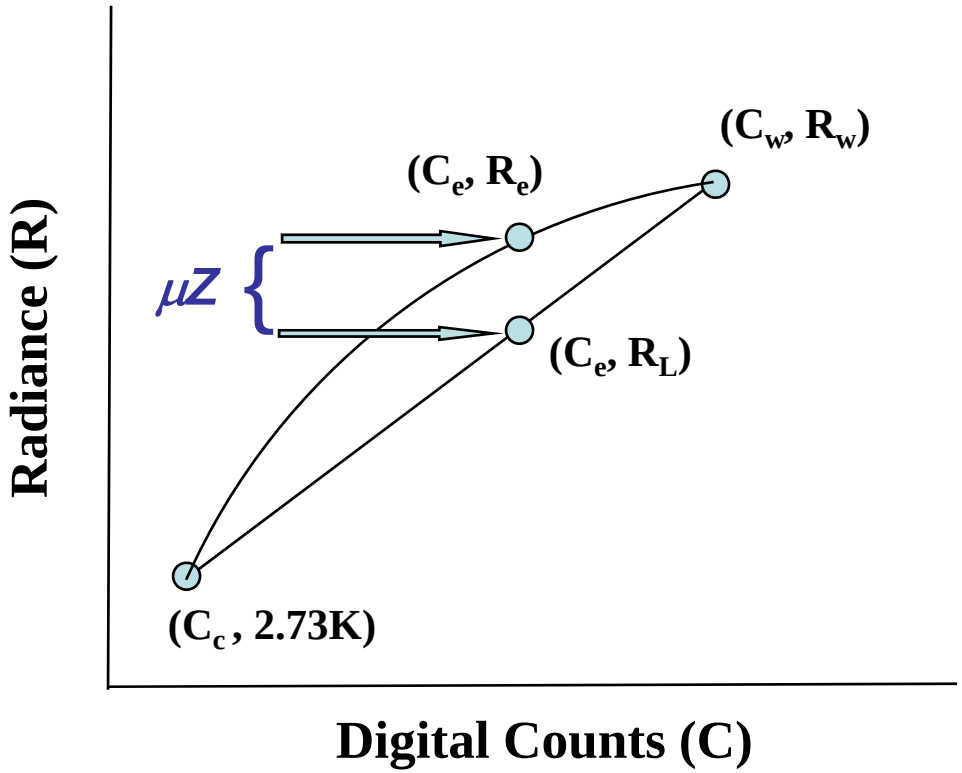
***R_L* is the linear calibration term**

$$R_L = R_c + S(C_e - C_c)$$

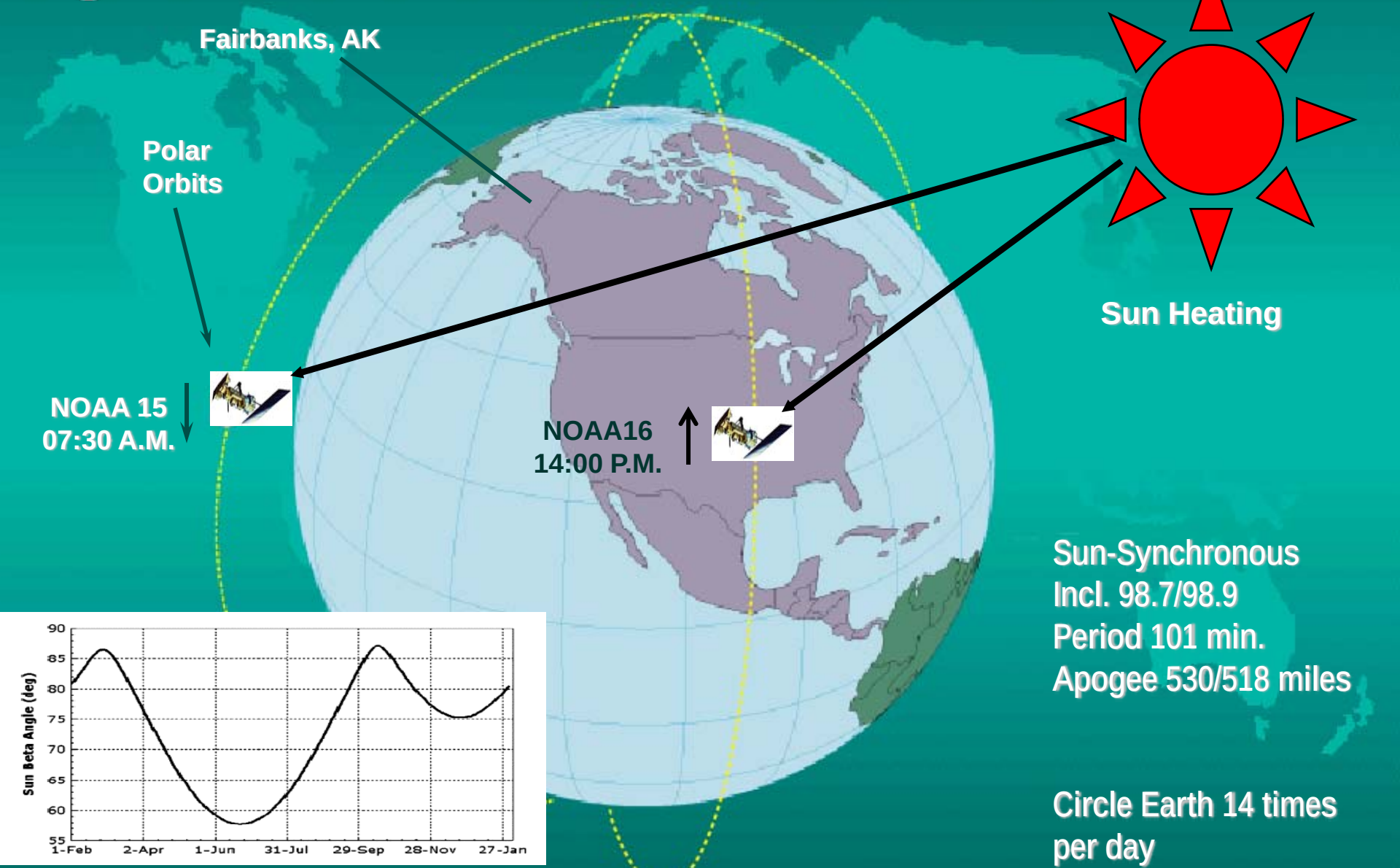
S ⟶ Slope

***Z* is the quadratic nonlinear term**

$$Z = S^2 (C_e - C_c)(C_e - C_w)$$



NOAA POES Satellite System



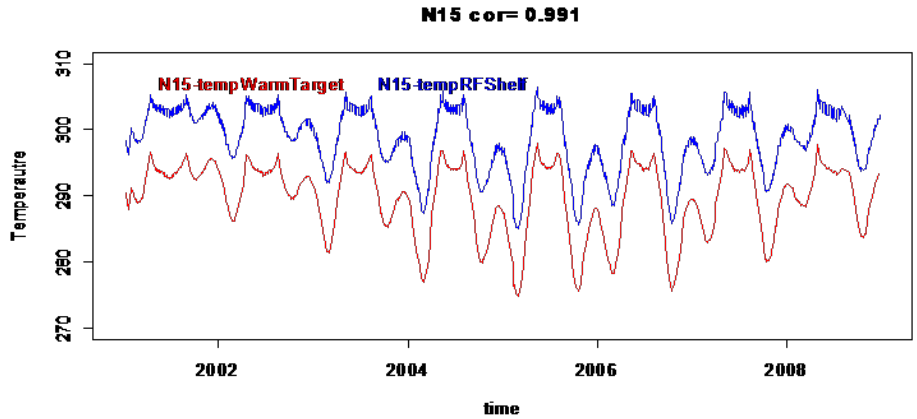
Sun-Synchronous
Incl. 98.7/98.9
Period 101 min.
Apogee 530/518 miles

Circle Earth 14 times per day

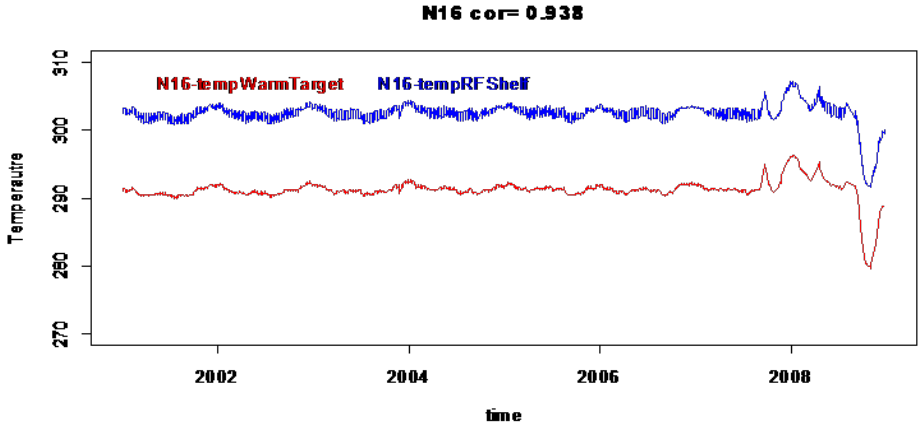
Sun Beta Angle Variation (Twarog et al. 2006)

Sun Heating Related Instrument Temperature Variability

NOAA-15 instrument body (blue) and warm target (red) temperatures



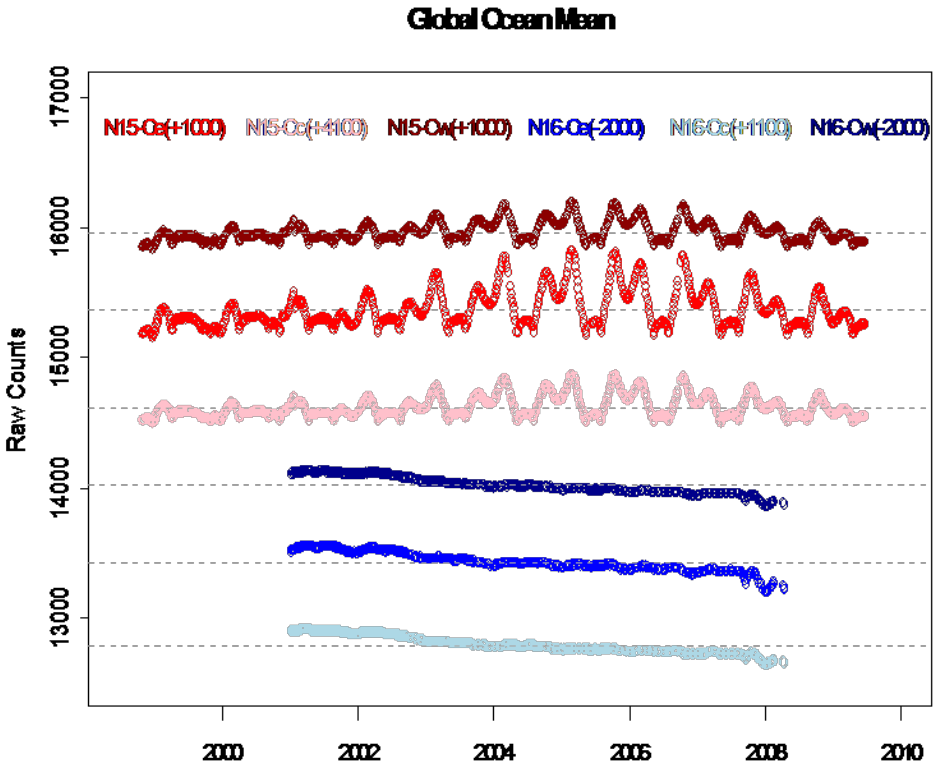
NOAA-16 instrument body (blue) and warm target (red) temperatures



Time series of instrument body and warm target temperatures for NOAA-15 and NOAA-16

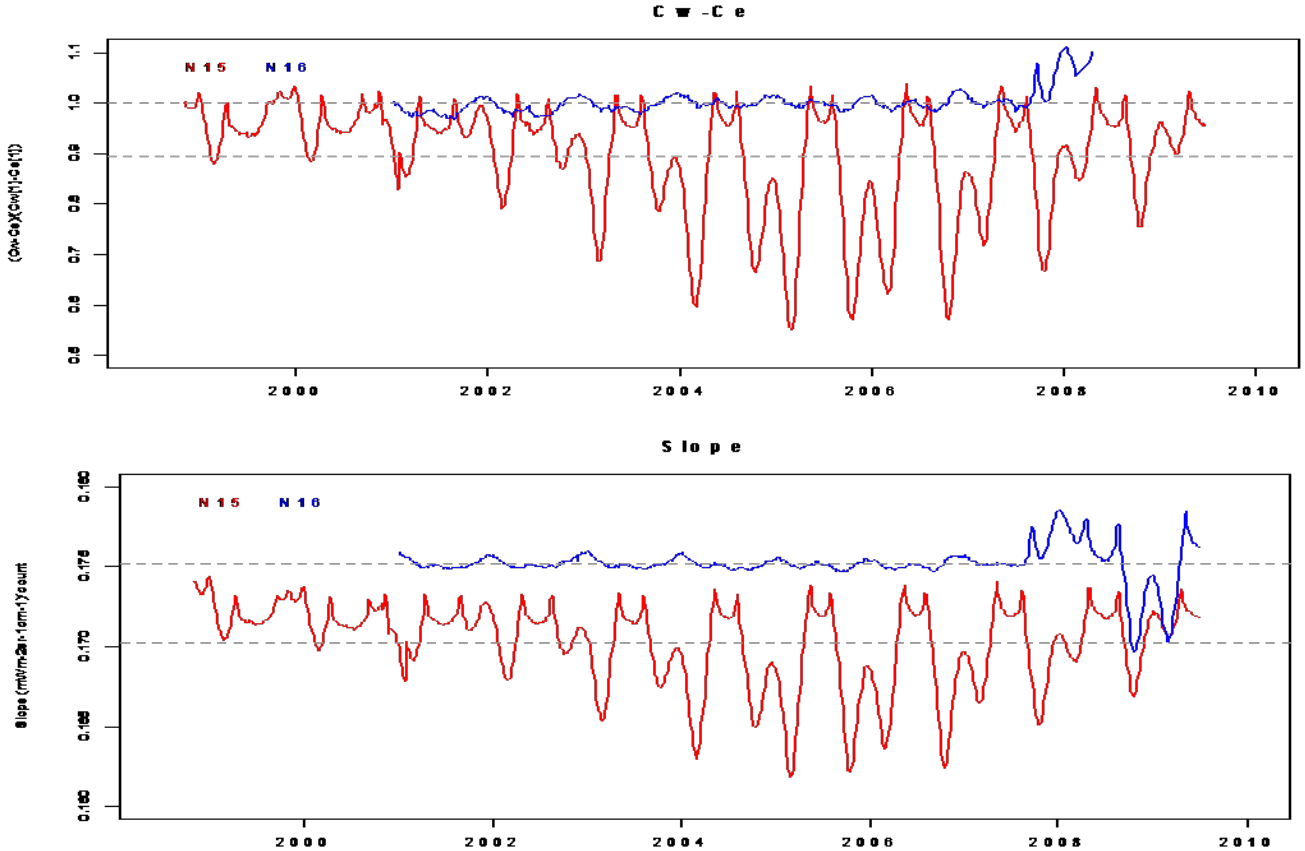
Raw Counts Examination – Global Mean

- Atmospheric climate characteristics cancel out between Northern and Southern Hemispheres
- Only instrument sun heating signals remain
- NOAA-16 showing a steady decrease in all raw counts data
- NOAA-15 showing a solar heating activity



Global ocean mean time series of the raw counts data for Earth view, warm target view, and cold space view for channel 5 on NOAA-15 and NOAA-16, respectively

Gain Variability



Time series of the Delta Counts (top) and Slope (bottom) for channel 5 on NOAA-15 (red) and NOAA-16 (blue), respectively

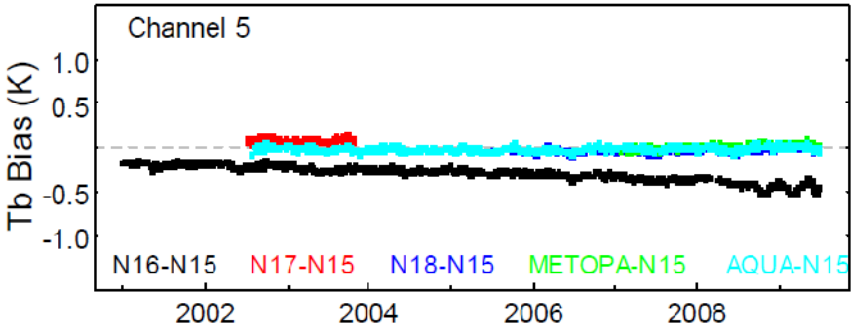
Weak vs Strong Nonlinearities in AMSU-A channels

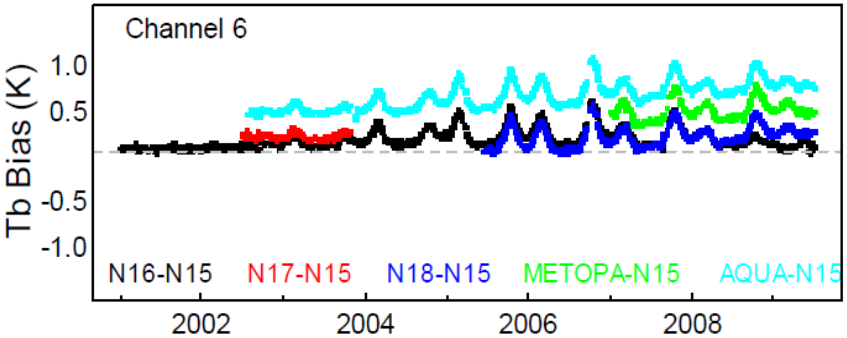
- ❑ NOAA-15 sun heating signals do not show up in channel 5 and other inter-satellite difference time series-- suggesting weak calibration nonlinearity

- ❑ NOAA-15 sun heating signals show up in channel 6 inter-satellite difference time series—suggesting strong nonlinearity

- • NOAA-16 has large long-term Tb bias drift, also channel dependent

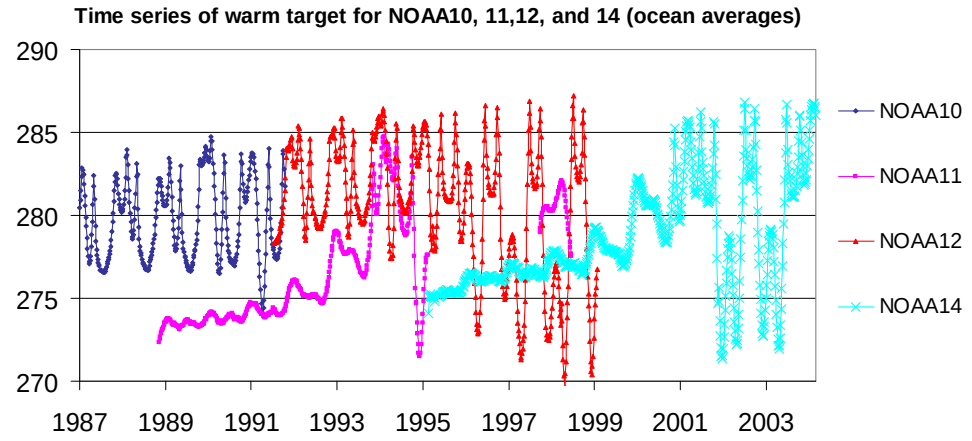
Ocean mean, consider as differences of level-1c radiances

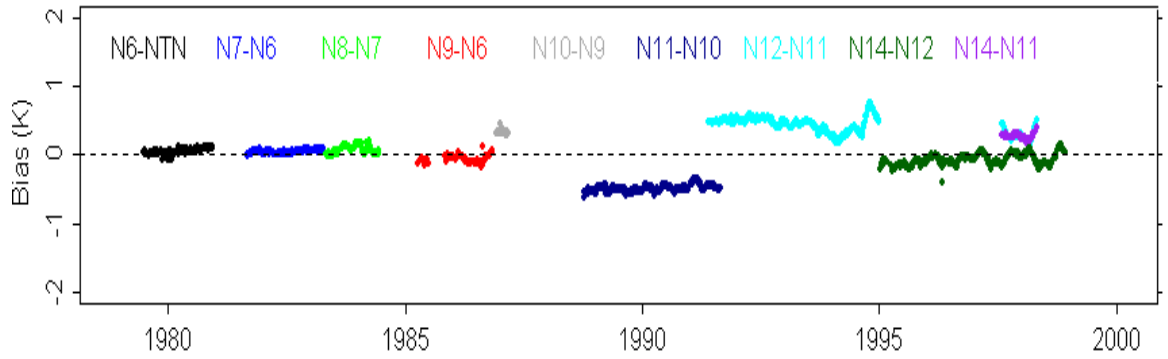




Warm Target Signals in MSU Tb Time Series

Warm target temperature time series for MSU satellites

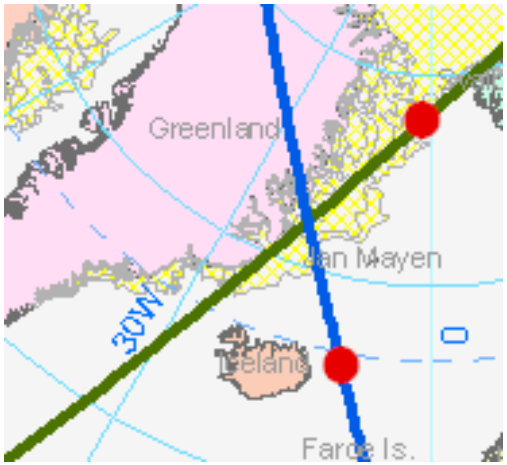


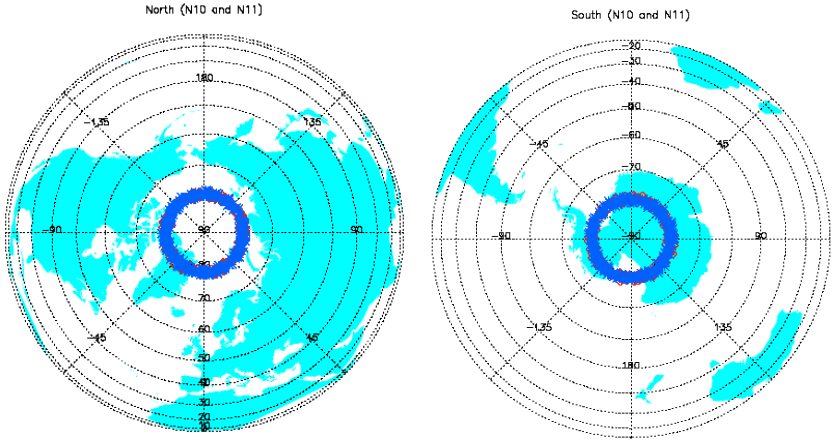


MSU Ch2 global ocean mean Tb difference time series

SNO Datasets

- Use Cao's (2004) orbital method to find SNO datasets
- SNO events are generally found over the polar region
- SNO Temperature range for MSU CH2: 200-250 K
- Global temperature range for MSU CH2: 200-260 K
- SNO dynamic range IS NOT a big issue for temperature channels
- SNO dynamic range IS a big problem for water vapor channels



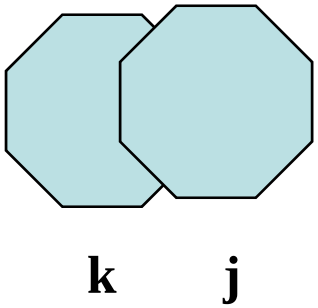


Schematic viewing SNO and its locations

SNO Radiance Error Model

$$R_k = R_{L,k} - R_{0k} + \mu_k Z_k$$

$$R_j = R_{L,j} - R_{0j} + \mu_j Z_j$$



$$\Delta R = \Delta R_L - \delta R_0 + \mu_k Z_k - \mu_j Z_j$$

Radiance Error Model for SNO Matchup K and J

$$\delta R_0 \approx R_{0k} - R_{0j}$$

Remove mean inter-satellite biases

$$\delta\mu \approx \mu_j - \mu_k$$

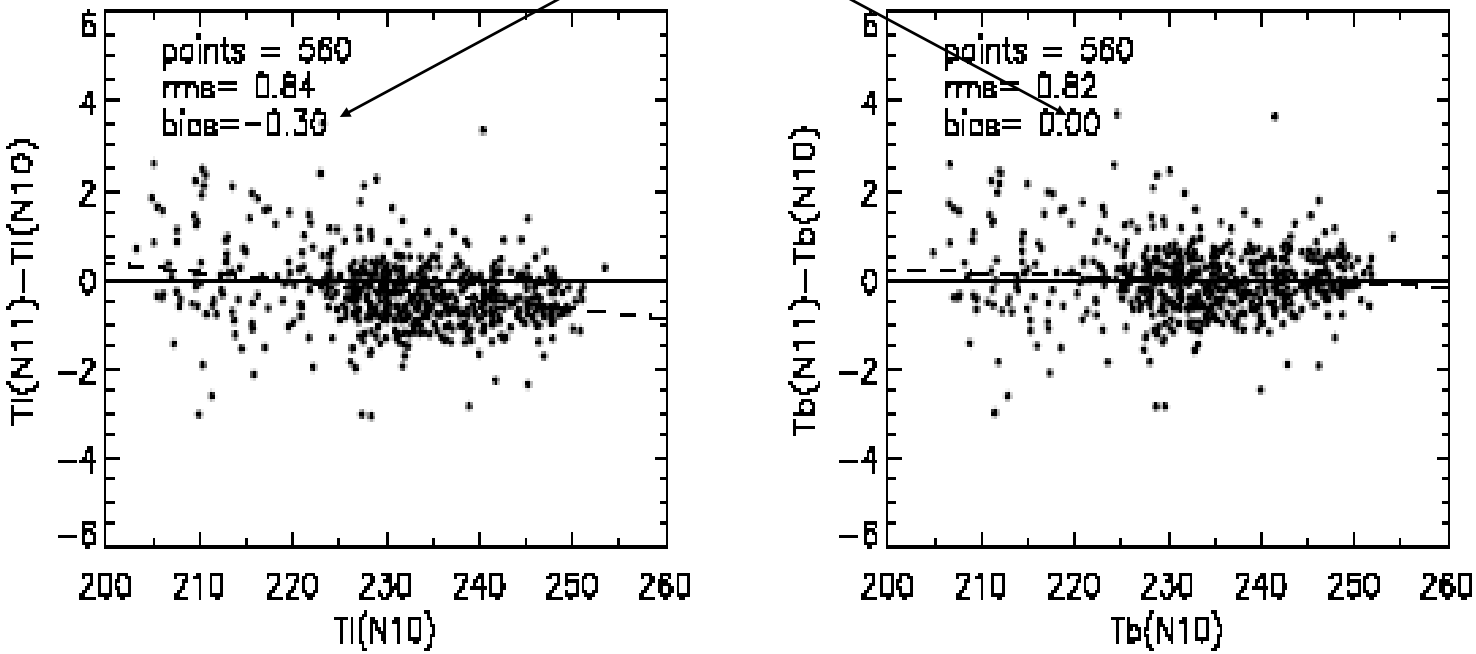
Remove non-uniformity in inter-satellite biases

$$\mu_j$$

Remove instrument non-climate signals

SNO removal of mean and temperature-dependent biases

mean biases reduced to zero



Scatter plots showing effects of the nonlinear calibration on distribution of the brightness temperature difference between NOAA 10 and NOAA 11: i) mean biases reduced to zero; ii) bias non-uniformity significantly reduced

Animation showing removal of instrument temperature signals using SNO calibration

- Theoretically, one specific value of μ exist that can completely remove instrument temperature signals:

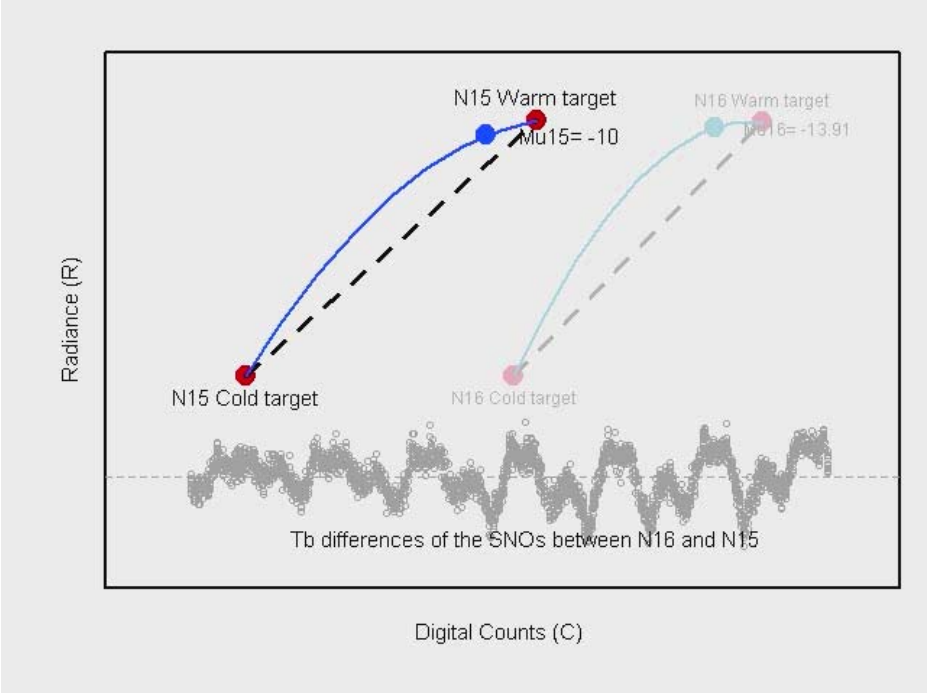
$$R = R_L - \delta R + \mu Z$$

$$\Downarrow$$

$$\overline{R'T'_w} = \overline{R'_L T'_w} + \mu \overline{Z'T'_w}$$

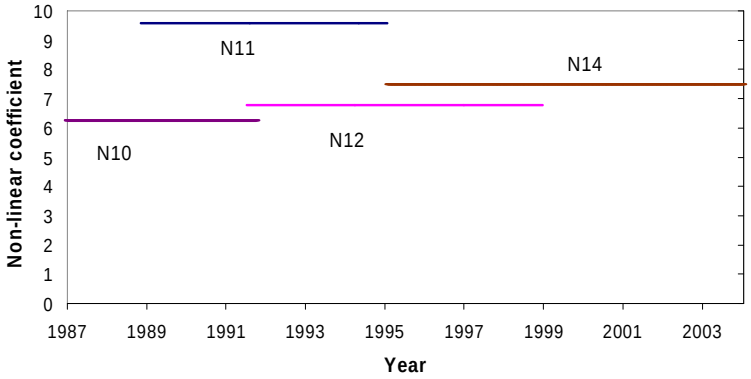
$$\Downarrow$$

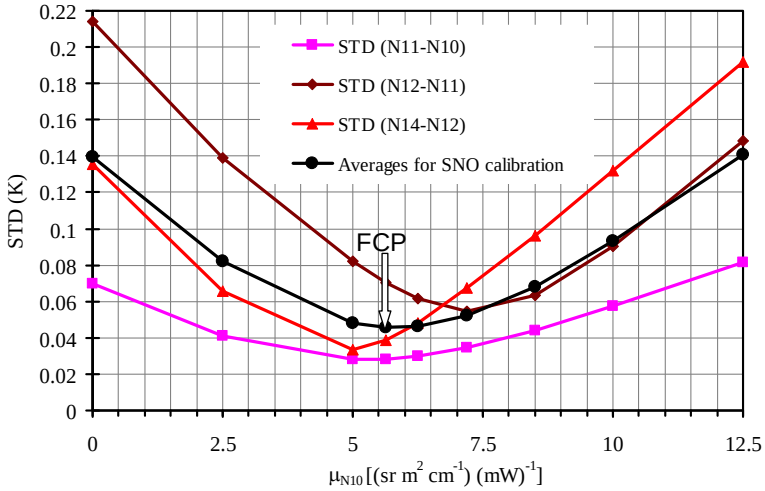
$$\mu = \mu_c = -\frac{\overline{R'_L T'_w}}{\overline{Z'T'_w}}$$



Sequential procedure for multi-satellite pairs

- Select an arbitrary satellite as the reference satellite – e.g., assuming NOAA-10 coefficients are known
- Compute NOAA-10 radiance
- Obtain coefficients of neighbor satellite from regressions of their SNOs and compute the radiance of the neighbor satellite
- Use the adjusted neighbor satellite as new reference and repeat the above procedure until coefficients of all satellites are obtained
- Repeat the above procedure by changing μ of the reference satellite until minimum standard deviation of the difference time series are obtained





SNO vs NOAA Operational Calibrations

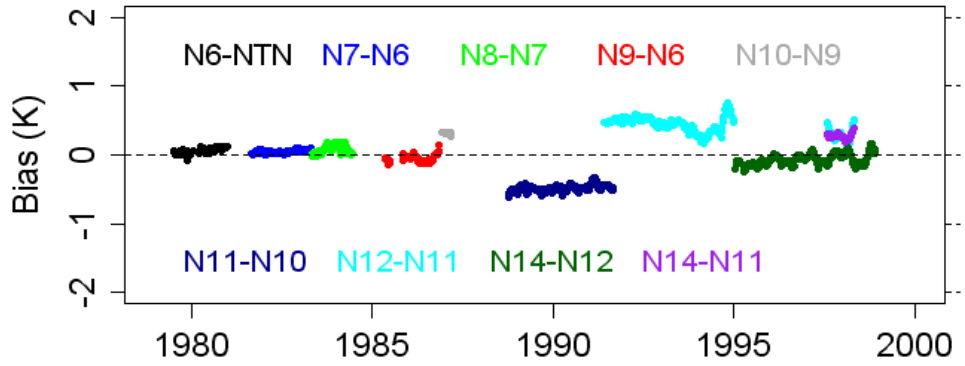
- **One coefficient for one channel, applicable to all scan positions**

Ch2 examples

satellites	Nonlinear calibration coefficients determined by post-launch SNOs (Zou et al. 2006)	Nonlinear calibration coefficients determined by pre-launch lab testing data (Mo et al. 2001)
N10	6.25	4.9-5.1
N11	9.59	6.6-7.7
N12	6.77	3.1-3.3
N14	7.46	3.2-3.4

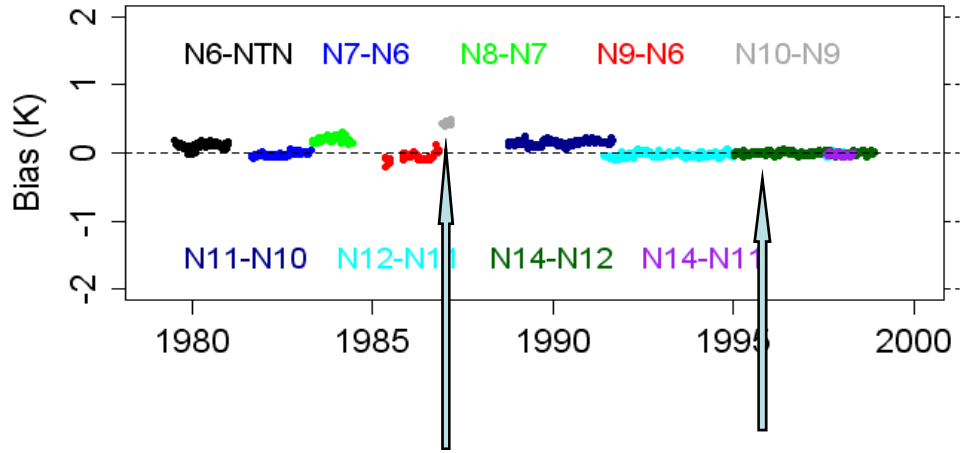
Impact on inter-satellite differences—global ocean mean

Intersatellite biases for NOAA operational calibration (ch2 5-day and global ocean-mean)



STD=0.10K

Intersatellite biases after SNO calibration



STD=0.03K

Short overlap problem

Inter-satellite differences dramatically reduced

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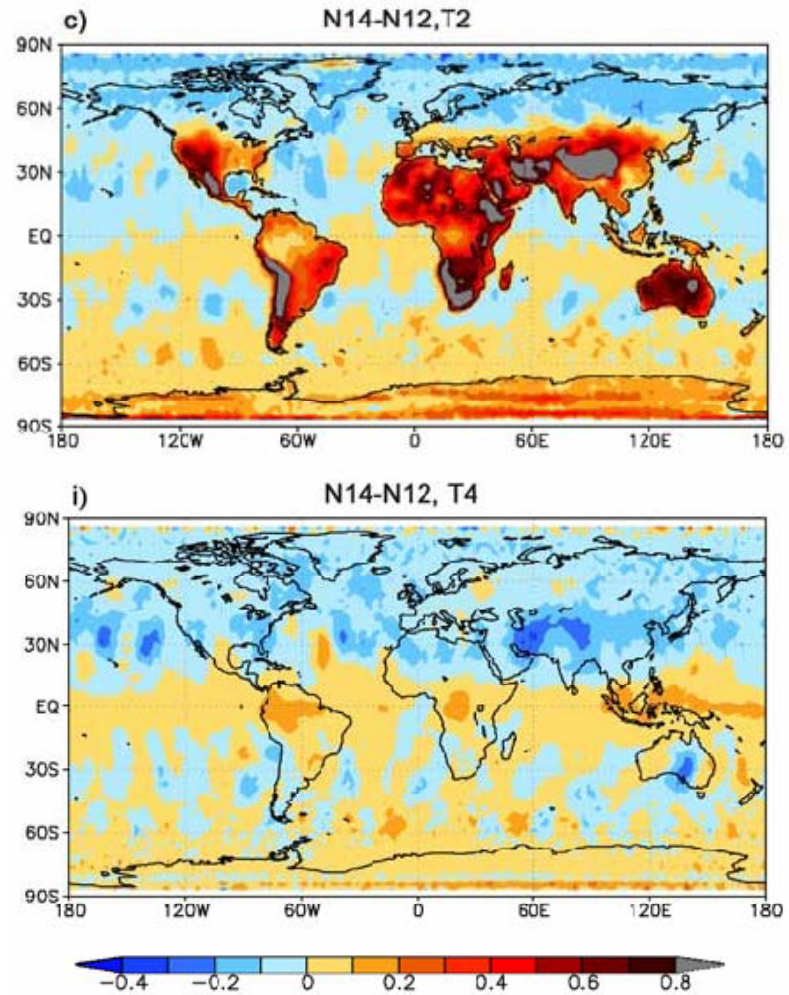
Inter-Satellite Bias Pattern After SNO Calibration

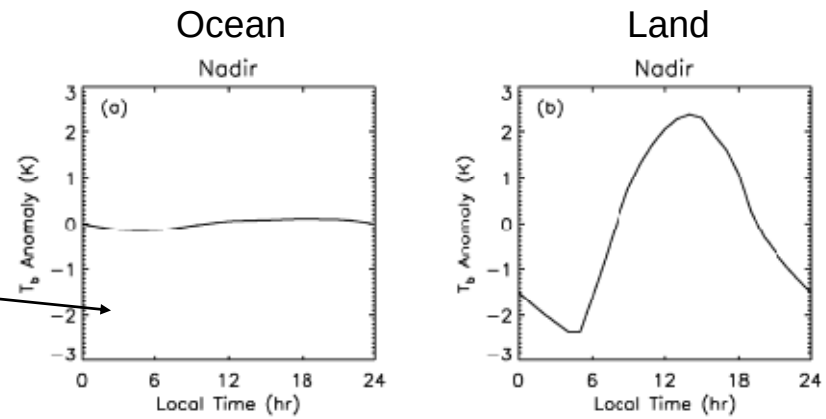
- For well calibrated channels, inter-satellite biases are within 0.1 K at grid-cells
- After instrument errors are removed, inter-satellite bias patterns show diurnal drift errors over land
- Diurnal drift over oceans are NOT important for ch2
- Diurnal drift for ch4 are NOT important globally
- Certain satellite pairs show latitudinal-dependent bias patterns; may need high order calibration nonlinearity



Diurnal Drift Correction

- Adjust observations at different time to a standard local noon time using diurnal anomaly dataset developed by Remote Sensing Systems (RSS), which is based on NCAR community climate model simulation

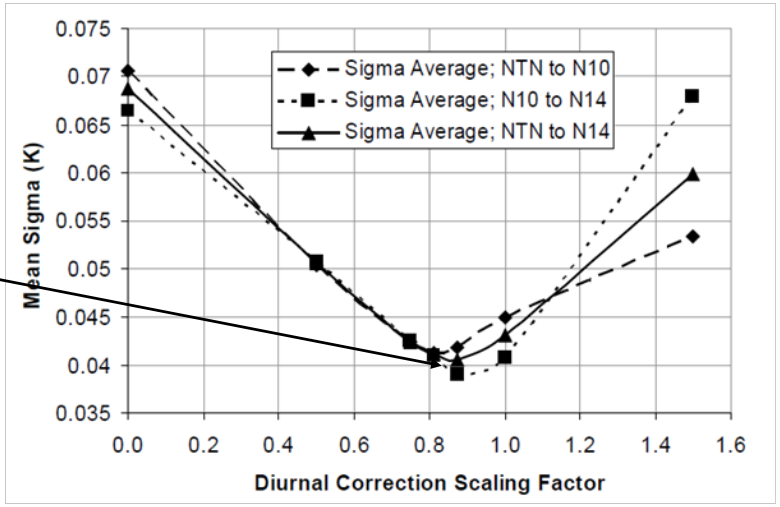
$R_{dc}(\text{noon time})=R_c(t)-\delta R*f$



(Mears et al. 2003)

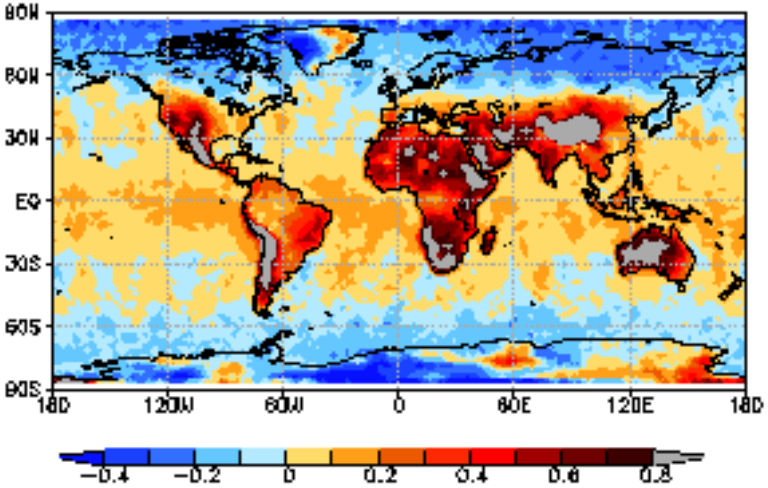
- A scaling factor is introduced to take into account the uncertainty in the simulated diurnal anomaly magnitude. The scaling factor was determined by minimizing inter-satellite differences over land

- Scaling factor=0.875, which is slightly smaller than RSS dataset

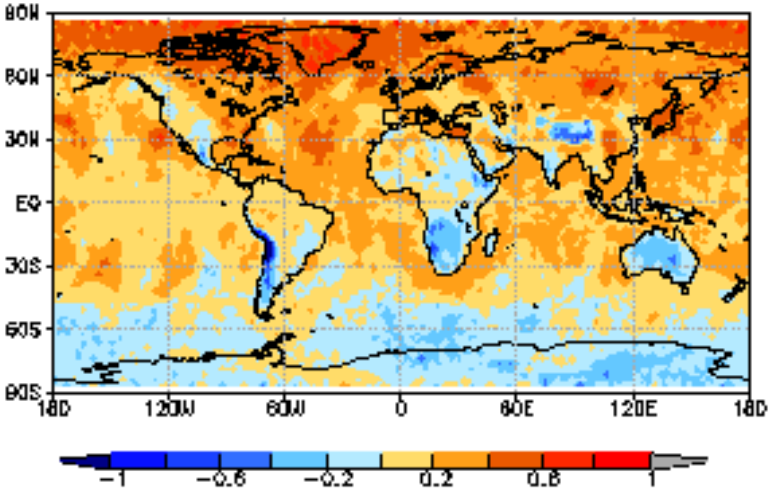


Impact of Diurnal Drift Correction on Bias Patterns

No diurnal drift correction



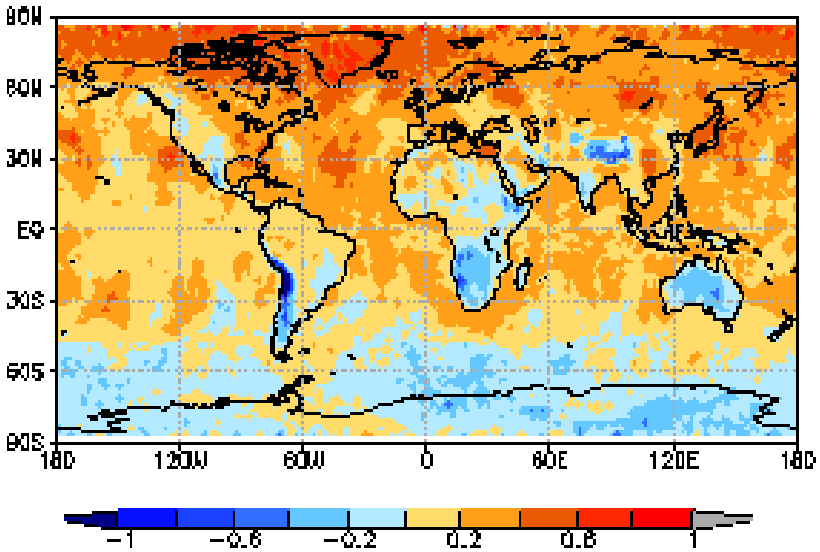
With diurnal drift correction



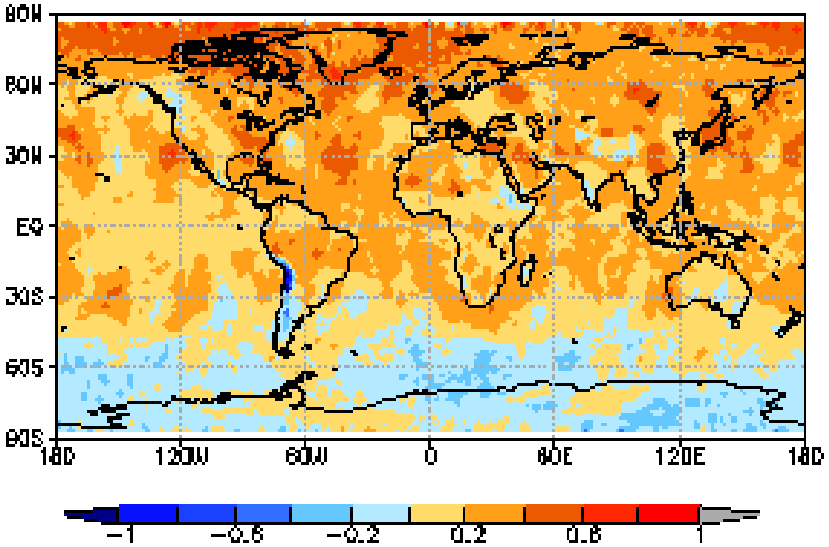
Channel 2 intersatellite bias pattern between NOAA-11 and NOAA-10 (NOAA-11 minus NOAA-10) during 10/1988-08/1991 with and without diurnal drift correction

Diurnal drift effect on spatial trend pattern

28-year (1979-2006) MSU2 mid-tropospheric temperature trends (K/Decade)



No diurnal-drift correction



With diurnal-drift correction

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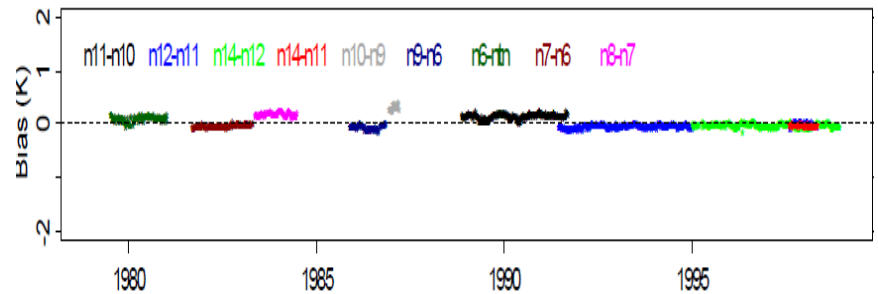
Residual Bias Correction

- Constant bias correction
- Christy Correction: Relate the inter-satellite biases linearly to warm target temperature variation

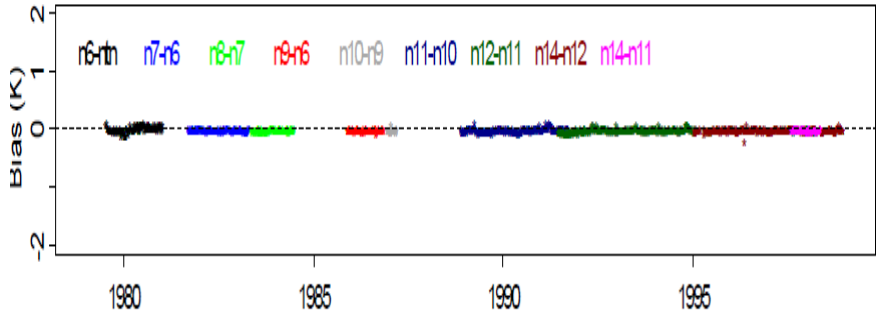
$$< \Delta T_{j,k} >= bias_{j,k} + a_j T_w^{'}(j) + a_k T_w^{'}(k)$$

- Simultaneously solve multi-satellite regression equations to obtain correction coefficients; Then correct the unadjusted time series

After SNO calibration but before residual bias correction



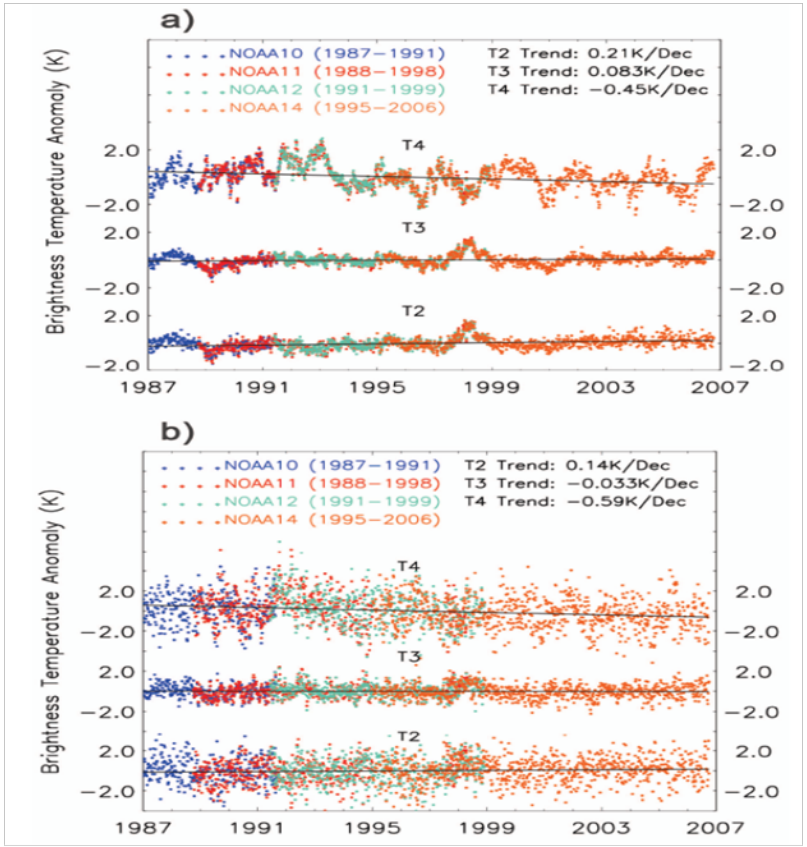
After residual bias correction



MSU Channel 2 Tb difference time series over ocean

Recalibrated MSU TCDR, Version 1.2

- Christy type residual bias correction applied globally to remove remaining biases related to warm target variability
- After all calibration and adjustments are made, constant bias correction are applied as a default at each grid-cell to remove any remaining errors at each grid-cell
- Temperature time series are generated by averaging available Satellites



Temperature anomaly time series and trends for geographic locations of (a) (6.250W, 6.250S) and (b) (6.250W, 31.250S) after various bias corrections were made. See text for definition of T_2, T_3, and T_4.

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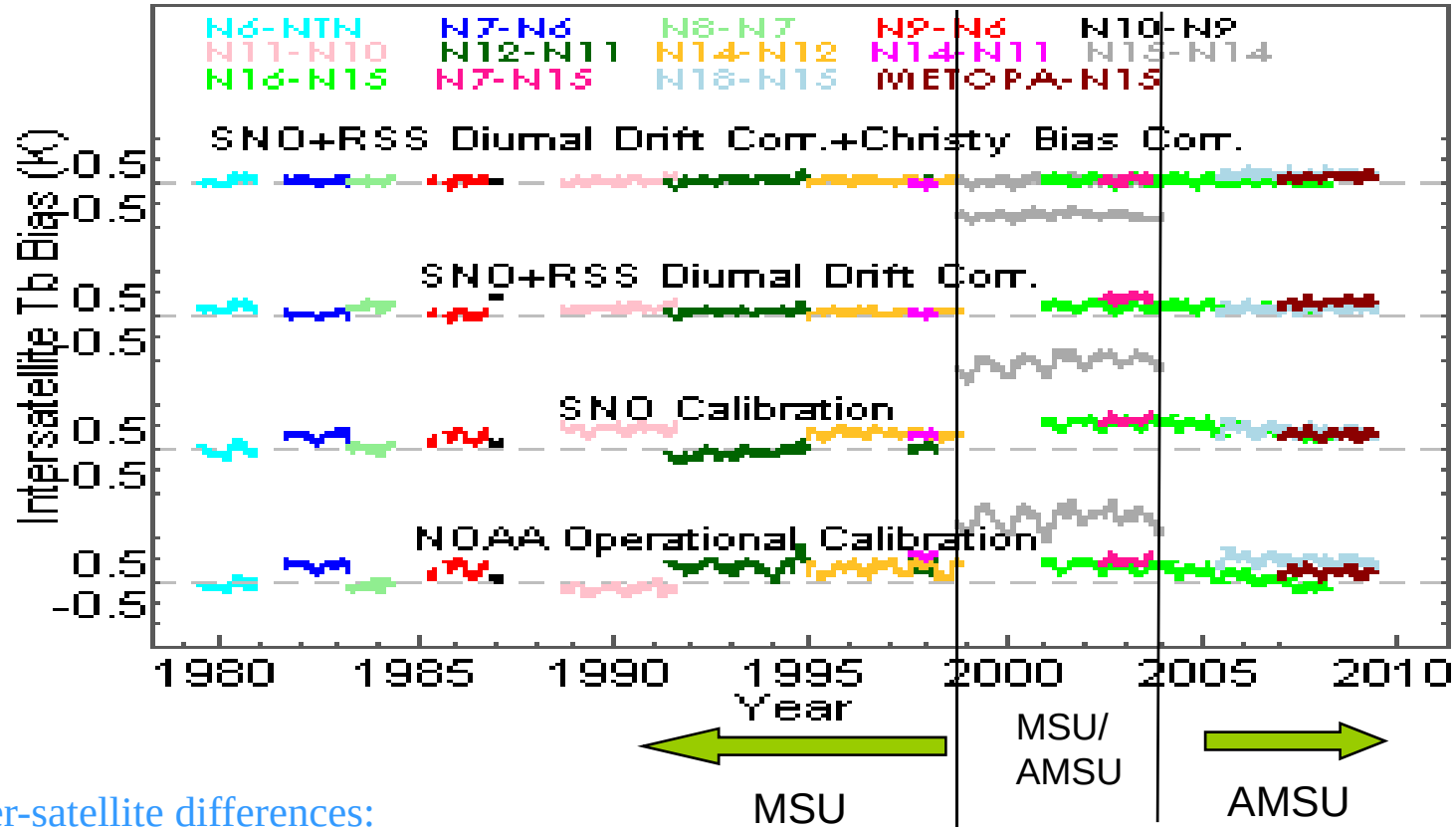
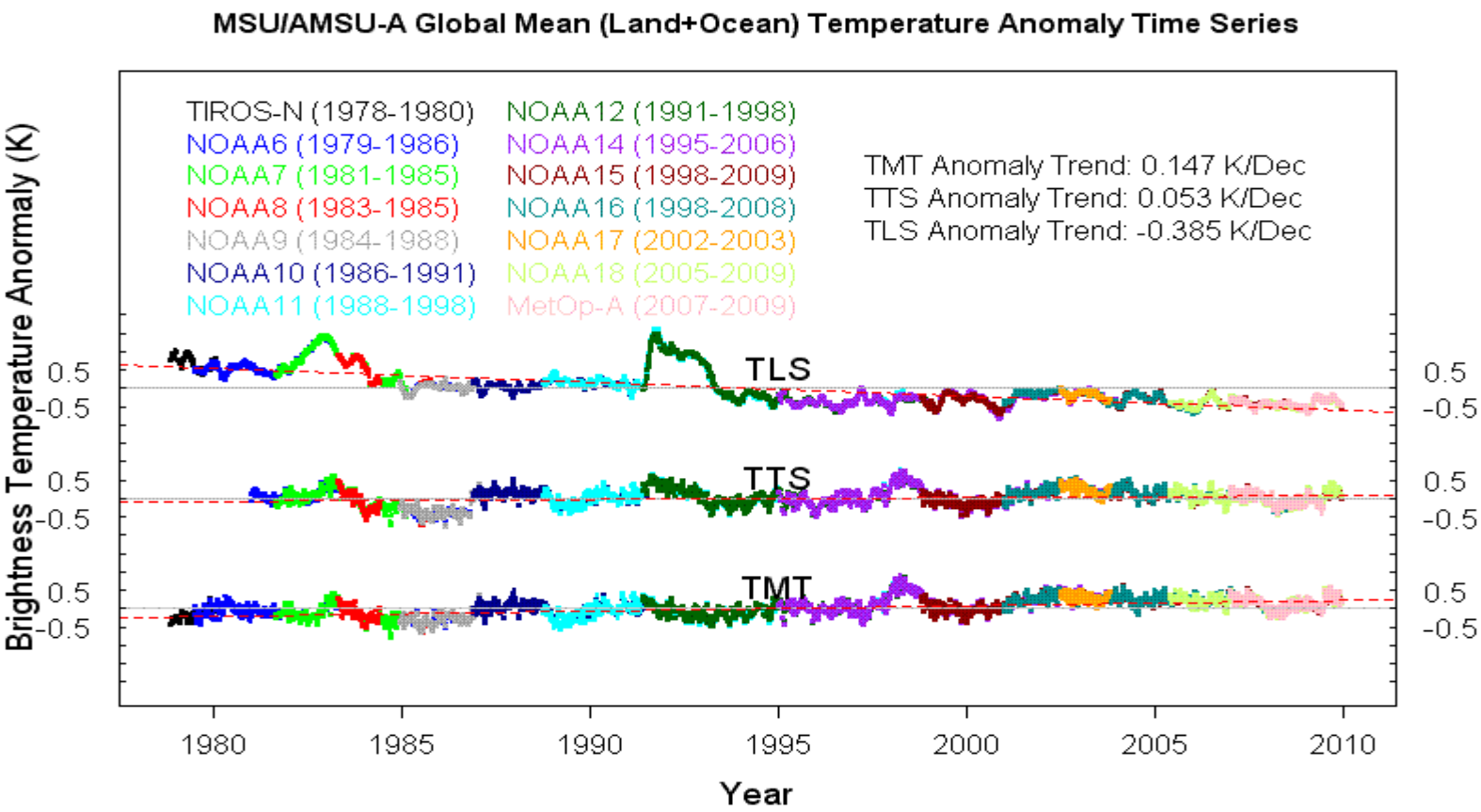
Merging of MSU and AMSU channels

Inter-satellite differences over land for MSU ch2 and AMSU ch5



inter-satellite differences:
Pre-launch: Biases=0.5-1K; sigma=0.1-0.15 K
Post-launch: Biases=0; sigma=0.02-0.03 K

Merged MSU/AMSU time series, Version 2.0



Five-day and global-mean temperature anomaly time series

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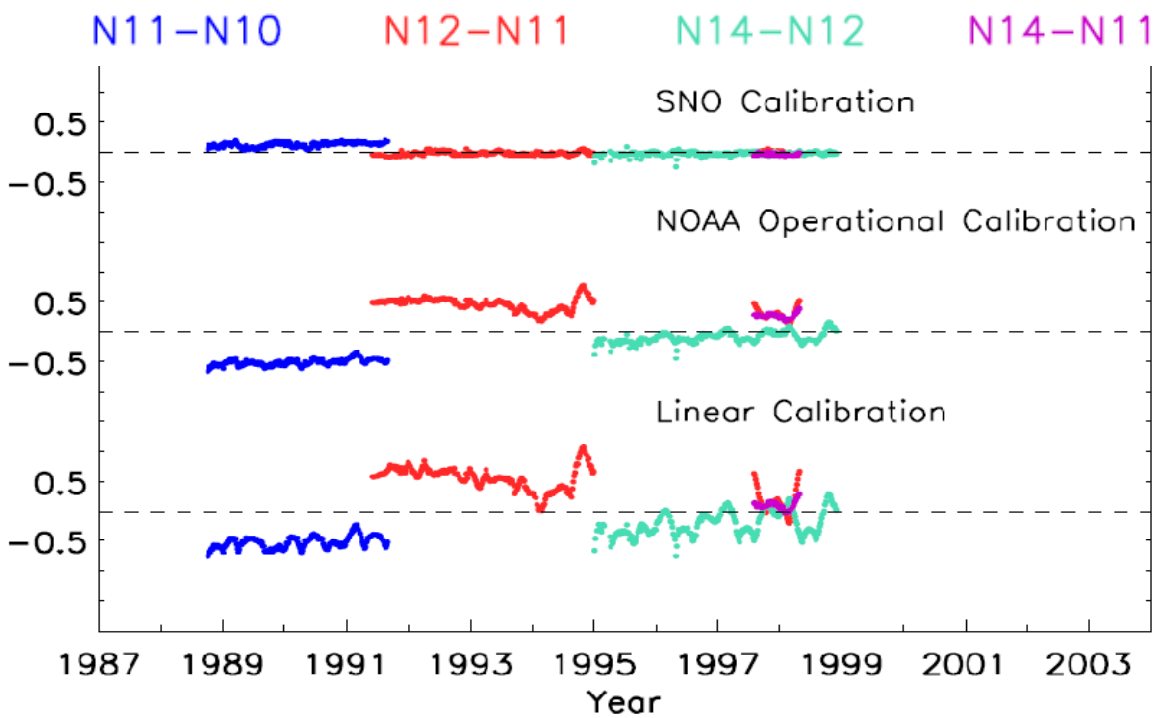
Inter-Comparison

- Same CDR but developed by different groups
- Same CDR but from other satellite observations
- Reanalysis
- Radiosonde
- Climate model simulations
- Observations of other variables

Residual Bias Correction Can Be Applied to Time Series from Different Level-1c Calibration



STD=0.03K

STD=0.10K

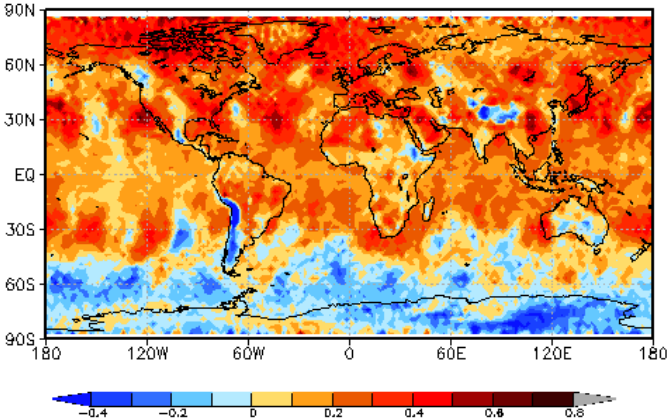
STD=0.20K

Note: UAH and RSS use NOAA operational calibration
STAR uses SNO calibration

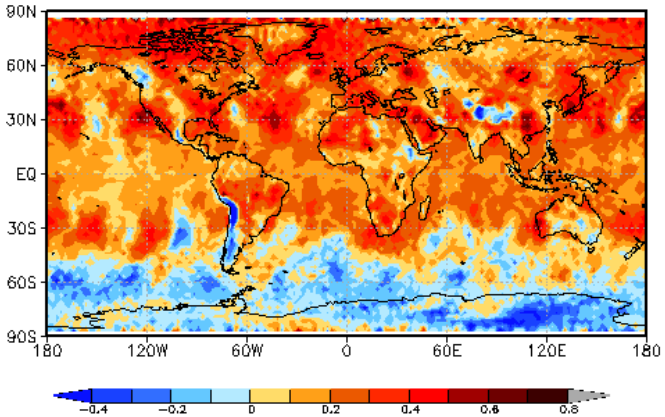
Spatial Trend Pattern: SNO vs NOAA Operational Calibrations

- Using NOAA operational calibrated dataset plus Christy residual bias correction, we obtained the same trend as that from the SNO calibration plus Christy correction
- Over global oceans, **ch2 trend = 0.173 K/Dec**
- If using zonal-mean bias correction, **ch2 trend=0.117 K/Dec**; possible reasons for trend differences between RSS and STAR

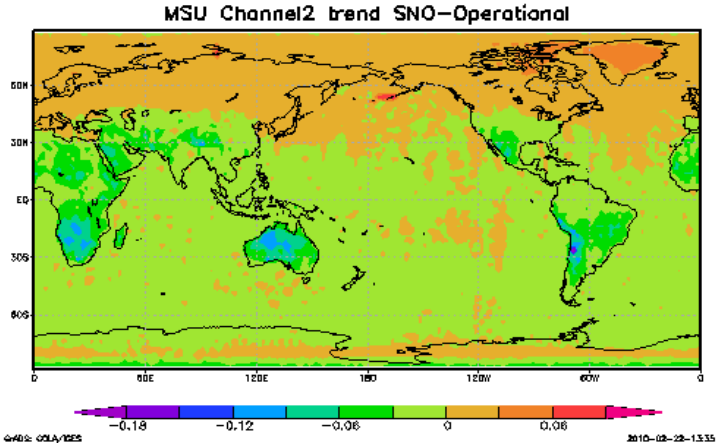
SNO calibration plus Christy Correction 1979-2006, MSU-only TMT trends



NOAA operational calibration calibration plus Christy Correction 1979-2006, MSU-only TMT trends



Difference between top and bottom of the right figures



Same CDR but developed by different groups

	UAH	RSS	NOAA/STAR	Comments
Raw counts	Same	same	same	In NOAA 1b files, lunar contamination corrected?
Warm Target Calibration	NOAA algorithm	NOAA algorithm	NOAA algorithm	Computed as means of good PRTs, Thermal gradient problem not Considered
Level-1c Calibration	NESDIS Algorithm	Quadratic nonlinear, NOAA operational calibration (nonlinear coefficients determined by lab testing data)	Quadratic nonlinear, SNO Calibration (offsets and nonlinear calibration coefficients determined by SNO matchups)	Mean STD of inter-satellite Difference time series: Linear CAL: 0.20K NOAA OPT CAL: 0.10K SNO CAL: 0.03K
Diurnal drift correction	Use local MSU or AMSU observations from different scan positions at different local times	Use CCM model simulated diurnal anomalies for adjustment; minimizing inter-satellite biases	Use RSS diurnal anomalies, but with reduced diurnal amplitude for adjustment; minimizing inter-satellite biases	
Residual bias correction 1	Christy correction; ocean data applied to both ocean and land	Christy correction; ocean data applied to both ocean and land	Ocean data determined Christy correction applied globally	
Residual bias correction 2	Remove a zonal mean inter-satellite biases	Remove a zonal mean inter-satellite biases	Remove grid-cell inter-satellite biases	Zonal-mean and grid-cell corrections cause trend differences
Gap filling	Yes	No	No	

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CDR Consistency Test

- Ocean-mean trend should be most reliable – diurnal drift errors are negligible, only instrument signals need to be corrected
- Robust scheme for instrument signal removal – double correction
- Trends over land should be compatible with ocean – the atmosphere should be well mixed in long-term climate change process
- Average of the spatial trend pattern should be consistent with global-mean merging – a test if spatial bias correction procedure works well
- Adding more satellites should not affect the trend

Trends Over Land and Ocean

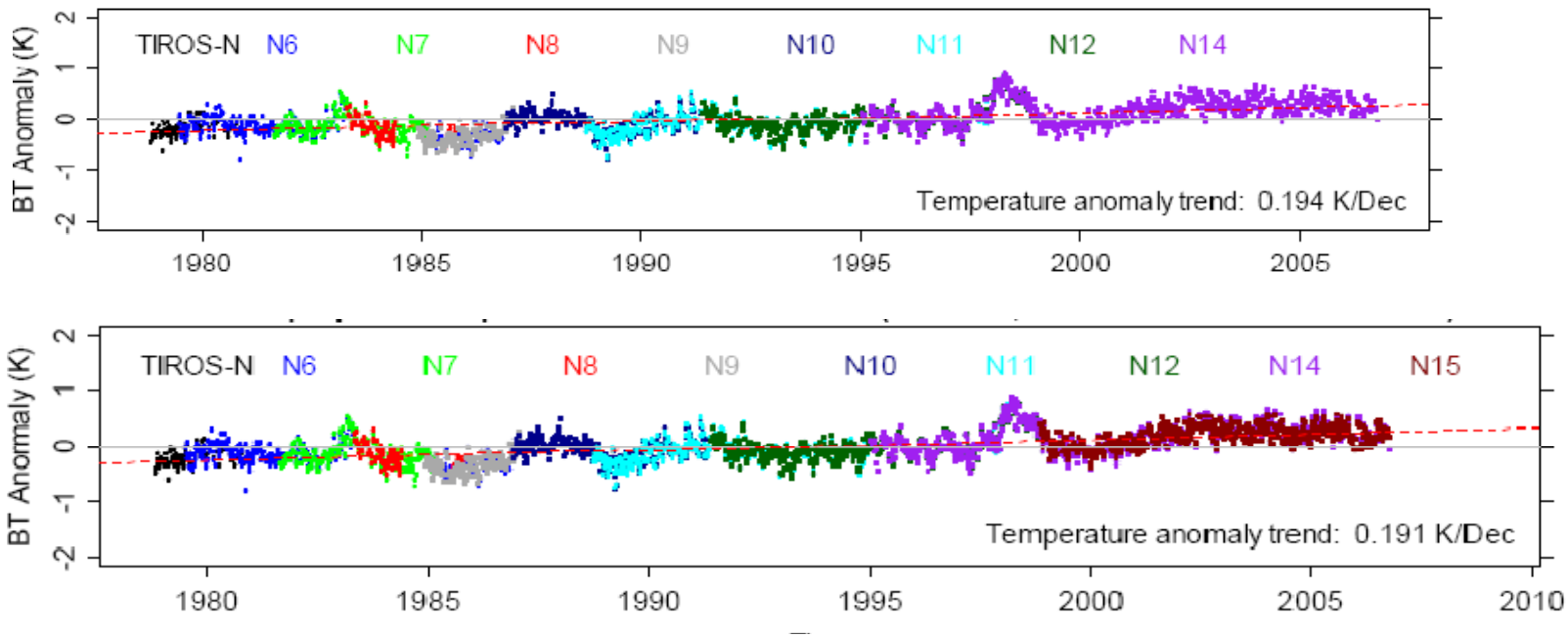
Channel 2 trend from 1978.11-2006.9, Unit in K/decade

Without diurnal correction	Global Mean	0.149
	Ocean Mean	0.172
	Land Mean	0.093
With diurnal correction	Global Mean	0.184
	Ocean Mean	0.180
	Land Mean	0.194

- Trend over land is compatible with ocean
- Diurnal adjustment has negligible effect on trend over ocean

Consistency Test by Adding AMSU

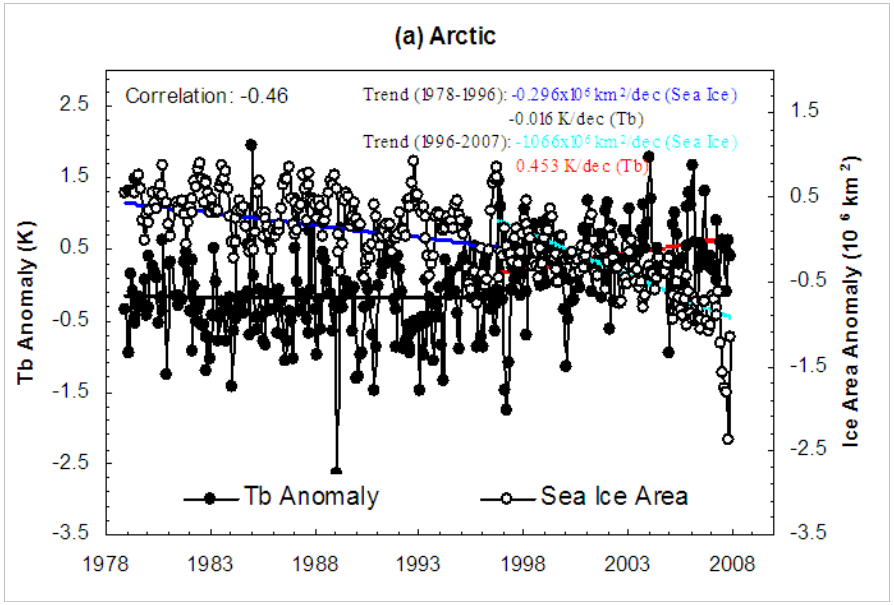
MSU2/AMSU5—mid-tropospheric temperature



Compare with Observations of Other Variables

- Sea ice melting time series and temperature time series show good correlation (-0.46)
- Before 1998, temperature trend is flat, corresponding to slow melting trend
- After 1998, large temperature trend corresponds to accelerated melting trend

Comparisons with sea ice melting trend (Wang and Zou, 2010)



Sea ice observations are from Comiso et al, 2008, which are derived from SMMR/SSMI/AMSR-E observations

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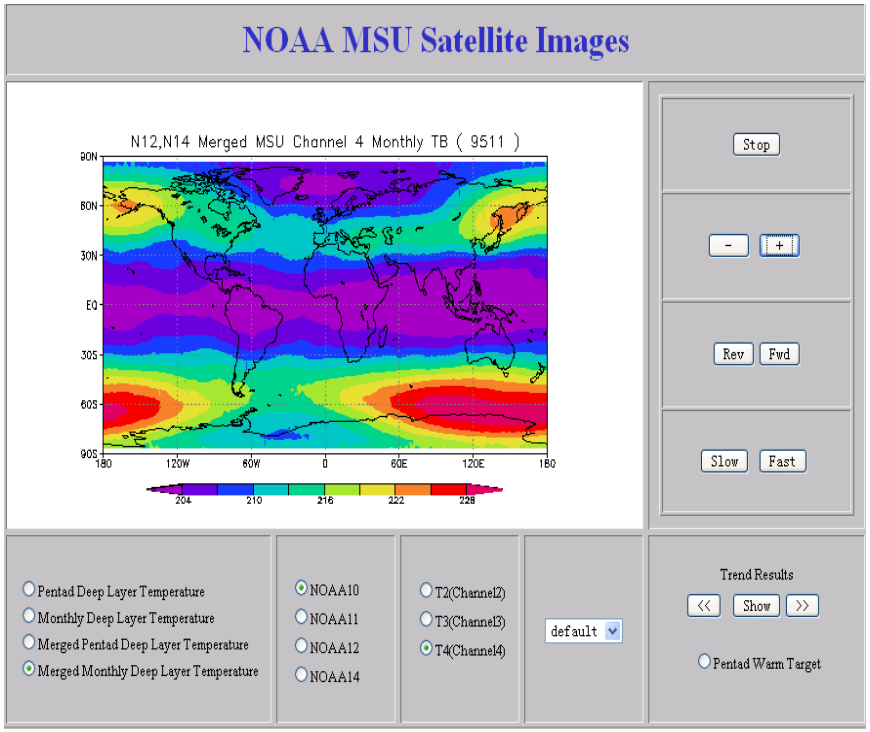
Data Archive and Download

- Website address:
http://www.orbit.nesdis.noaa.gov/smcd/emb/mscat/mscatmain.htm

- Datasets for public access:

- Level -1b calibration coefficients
- Level -1c radiance:
  - SNO calibrated
  - pre-launch (operationally) calibrated
- Level 3 gridded products: $2.5^0 \times 2.5^0$
  - MSU/AMSU merged pentad and monthly TMT, TTS, and TLS, Version 1.2 and 2.0
- Continue to add more channels when available



Data Format

- **Calibration coefficients provided in Tables on website**
- **Level-1c format options**:
  - Current radiance data stored in monthly file
  - Subroutine codes to process original level-1b file
- **Level-3 grid temperature TCDR**
  - ASCII text file
  - NetCDF
- **Will talk with GSICS, NCDC on appropriate format**

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Summary

- Well-intercalibrated 28-year (1978-2006) MSU-only radiance CDR is generated for reanalysis data assimilation which accounts for sun heating variability on instrument
- NCEP CFSR and NASA MERRA have already assimilated 20-year (1987-2006) recalibrated MSU level-1c data
- Version 1.2 well-merged 28-year MSU-only deep-layer atmospheric temperature TCDR is generated for climate change research
- AMSU channels 4, 5, 6, 7, 8, 9, 10 from NOAA-15 to NOAA-18 and MetOp-A have been inter-calibrated
- Version 2.0 merged MSU/AMSU (1978-present) deep-layer atmospheric temperature TCDR have been created and put online; merging include MSU2/AMSU5, MSU3/AMSU7; MSU4/AMSU9
- SSU recalibration and CDR development is ongoing

Future Plans

- Generate recalibrated SSU CDR
- Working on intercalibration of AMSU channels 11-14
- Working on MSU/AMSU TLT channel using recalibrated MSU2/AMSU5 data
- Routinely update online dataset and trend (make merged MSU/AMSU date set operational)
- Working with reanalysis community to assimilate recalibrated MSU/AMSU in future reanalysis systems (long term goals)
- Working with team members to understand differences between different observation systems
- Discuss with NCDC on dataset transition to better serve the community

Available Documentation

- Zou, C.-Z., M. Goldberg, Z. Cheng, N. Grody, J. Sullivan, C. Cao, and D. Tarpley (2006), Recalibration of microwave sounding unit for climate studies using simultaneous nadir overpasses, J. Geophys. Res., 111, D19114, doi:10.1029/2005JD006798
- Zou, C.-Z., M. Gao, 2007, A 20-year MSU dataset for atmospheric temperature change studies, SPIE Conference: Atmospheric and Environmental Remote Sensing Data Processing and Utilization III: Readiness for GEOSS, San Diego, CA, August 26 – 30, 2007, Paper number 6684-02.
- Zou, C.-Z. (2008), Intercalibration of microwave sounding unit with short overlaps, Proc. SPIE, Vol. *7085*, 708506; DOI:10.1117/12.798116
- Zou, C.-Z. and W. Wang (2009), Diurnal drift correction in the NESDIS/STAR MSU/AMSU atmospheric temperature climate data record, Proc. SPIE, Vol. *7456*, 745616
- Zou, C.-Z., M. Gao, M.Goldberg, 2009, Error structure and atmospheric temperature trends in observations of the microwave sounding unit, *J. Climate*, 22, 1661-1681, DOI: 10.1175/2008JCLI2233.1
- Zou, C. Z., and W. Wang (2009), Stability of MSU derived atmospheric temperature trend, *J. Atmos. Oceanic Tech*, In press.

Future Documentation Plans

- Technical report on MSU recalibration, provide detailed calibration coefficients
- Technical report on AMSU recalibration, provide detailed calibration coefficients
- Description of Version 2.0 MSU/AMSU products
- Report on comparisons between reanalysis and MSU/AMSU recalibration
- SSU CDR development report

Questions and Recommendations

- If we have a MSU perfectly inter-calibrated (e.g., NOAA-14 versus NOAA-12, do we still need a SI-traceable standard? Can we declare a victory?

- If not, what else should we do?

- Instrument calibration:

  - warm target calibration: gradient problem-- difficult for MSU since only two PRTs were used to measure warm target temperature; AMSU plausible since there are 5 to 7 PRTs on blackbody

  - high order nonlinearity

  - accuracy of band frequency?

  - cold target calibration? Cosmic ray effect?

Questions and Recommendations

- Empirical bias correction: recommended excise
  - Global ocean mean merging should be tested by different groups
  - Which of the following correction approaches provide trend consistent to global ocean mean merging: zonal mean or grid-cell dependent bias correction?
  - Compare trends derived from NOAA operational and SNO calibrated radiances

Questions?