Stratospheric Temperature Trends

Our Evolving Understanding

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with contributions from many colleagues,
particularly SPARC Temperature Trends Activity
(SPARC Stratospheric Temperature Trends Assessment Panel)

SPARC General Assembly, Queenstown NZ, 12 January 2014

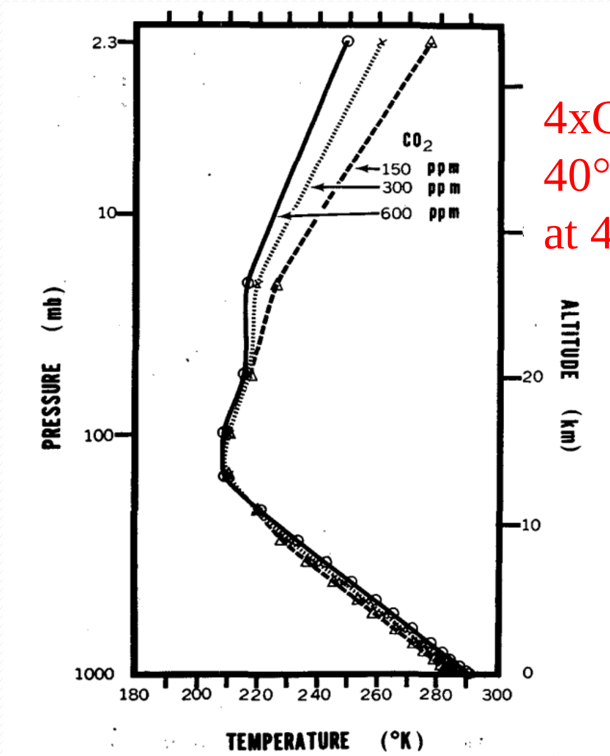
Objectives

- Review 4 decades of research, 2 decades of SPARC contributions
- Emphasize observations
- Summarize the evolution of our understanding
- Highlight current areas of uncertainty

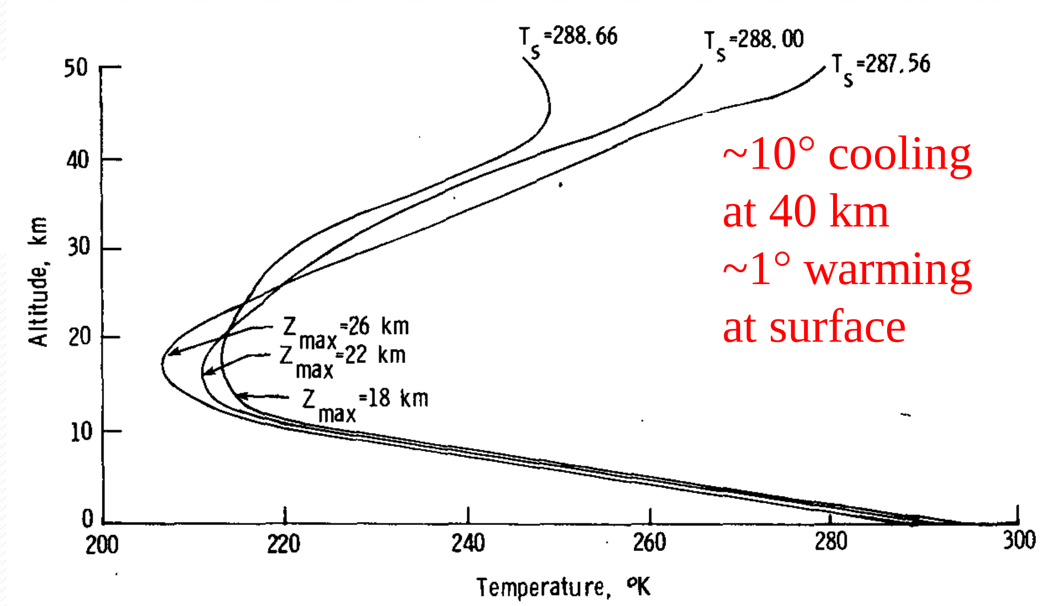
Focus

- Global T changes
- Radiosonde and MSU observations of lower strat. T
- SSU observations of upper strat. T
- Post-Pinatubo stratospheric T evolution
- Reanalyses
- Emerging global observational datasets
- Not focusing on
  - Spotty observations (rocketsonde, lidar)
  - Modeling developments and intercomparisons
  - Causes of trends (GHG, O_3, H_2O, aerosols, …)
  - Relation to dynamical changes (overturning circulation)
  - Seasonal or 3-D structure of trends
  - Interannual signals (solar, QBO, ENSO, …)

Two Pioneering Model Studies



4xCO_2
40°cooling
at 40 km

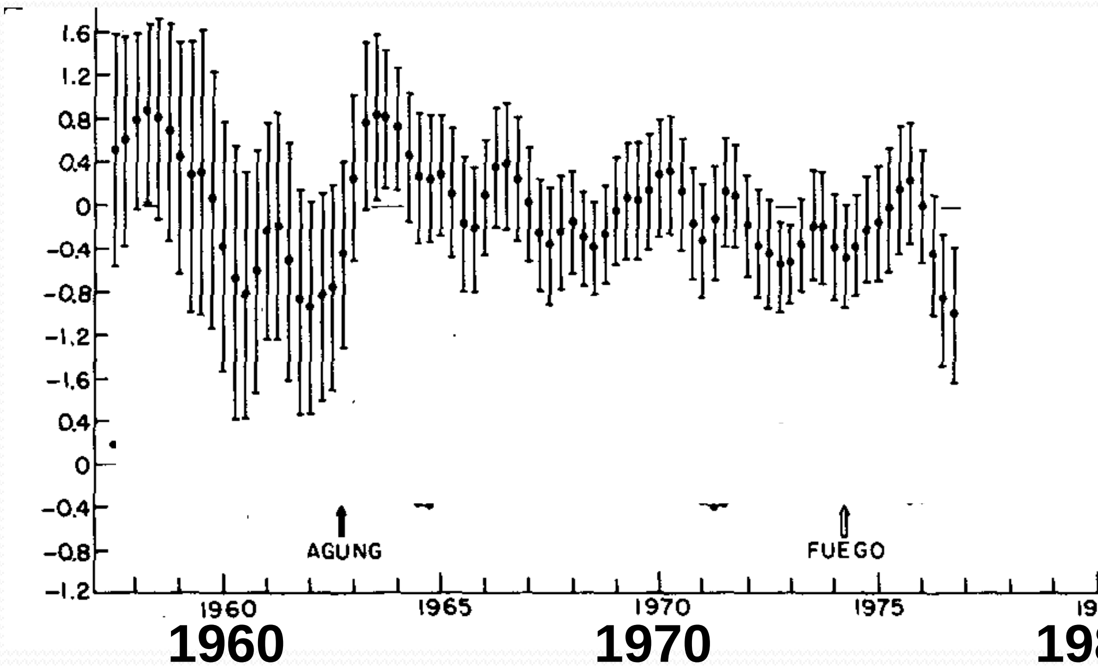


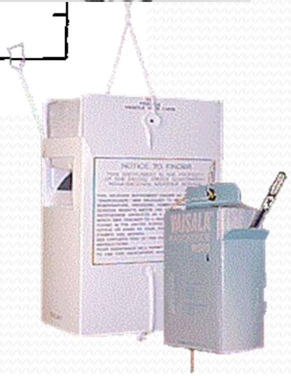
~10° cooling
at 40 km
~1° warming
at surface

- *Manabe and Wetherald* (JAS, 1967)
- Increasing CO_2 cools stratosphere in 1D RCM
- Also addressed: Ozone, Solar variations, Water vapor

- *Ramanathan et al.* (JAS, 1976)
- O_3 loss cools stratosphere in 1D RCM
- Discussed tropical tropopause cooling effect on stratospheric water vapor

Early Radiosonde Study – Lower Stratosphere

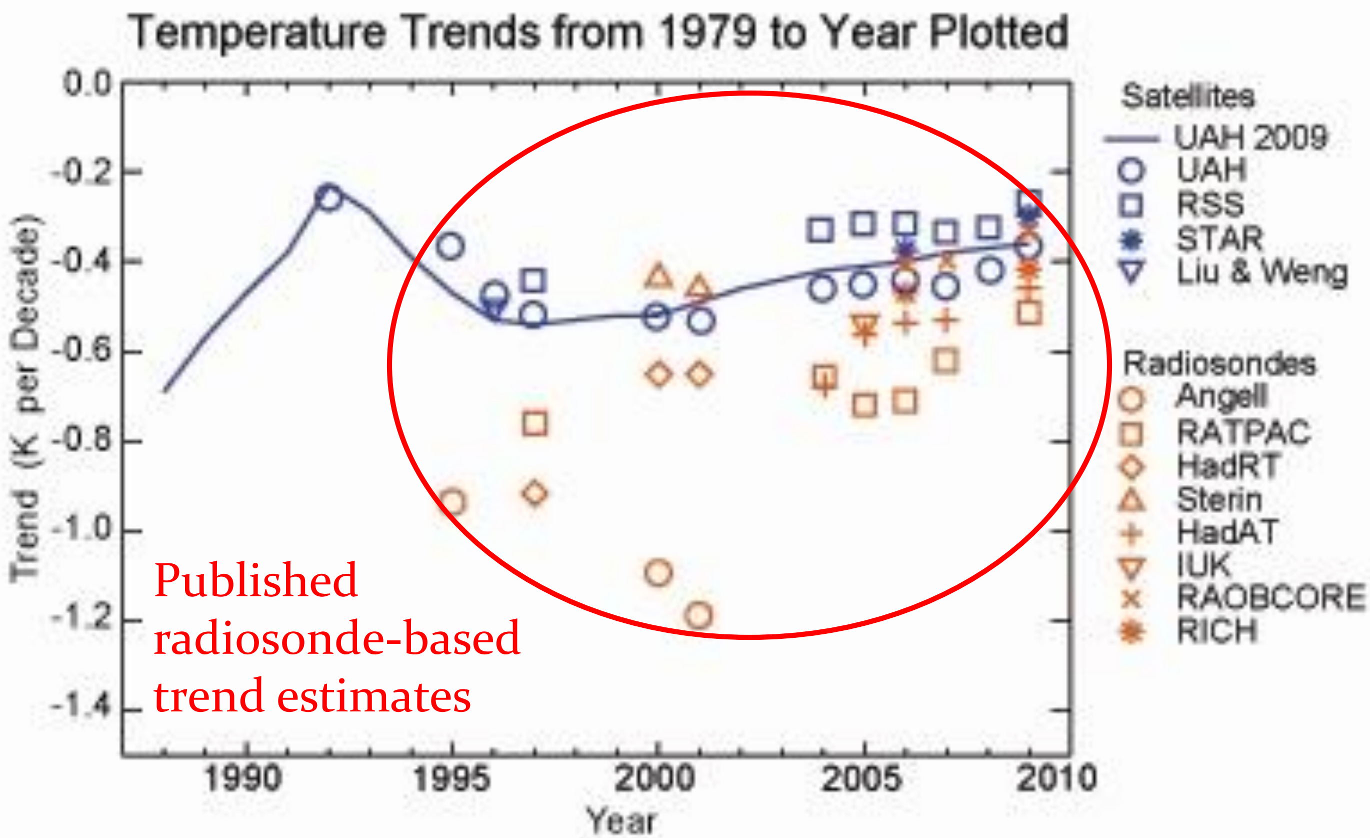




Global 100-30 hPa T Anomalies

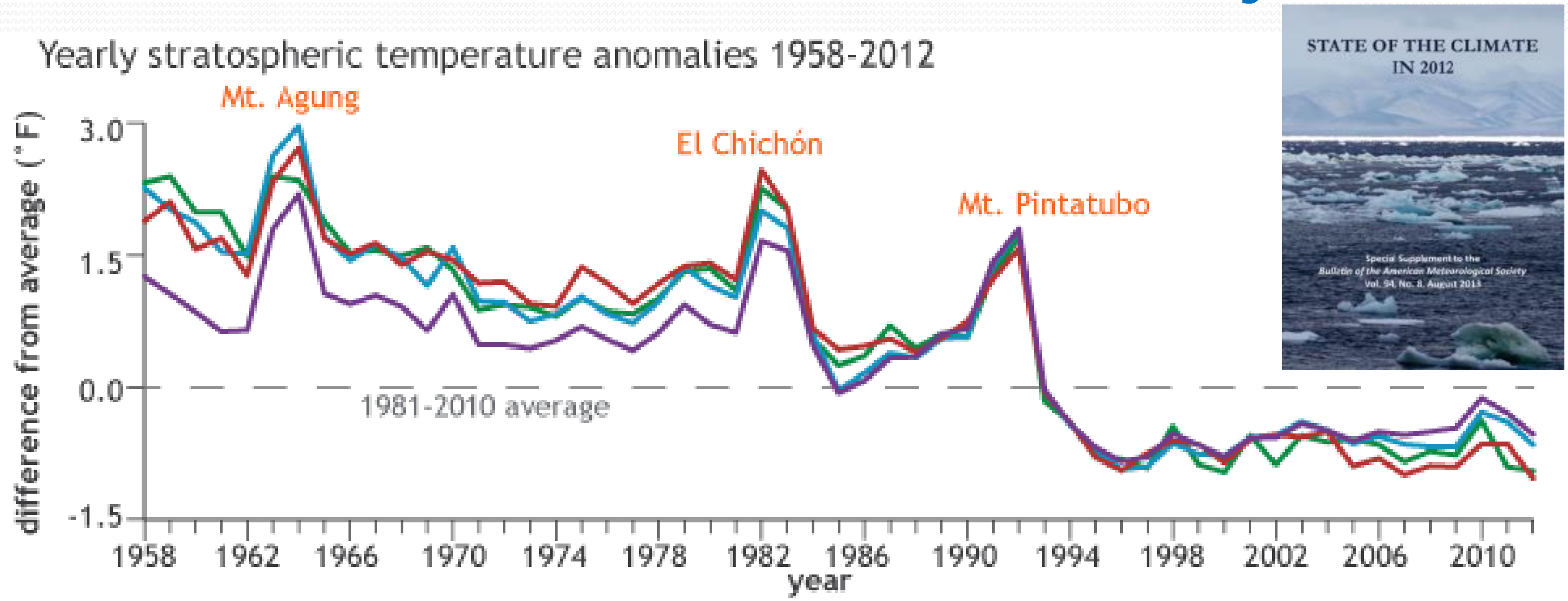
- *Angell and Korshover* (MWR, 1978)
- 42-station radiosonde network, 20-yr record
- Identified volcanic warming, QBO signal, ENSO signal, solar signal, <u>cooling trend</u>, sampling uncertainties

Trend Uncertainties in 1990s and 2000s



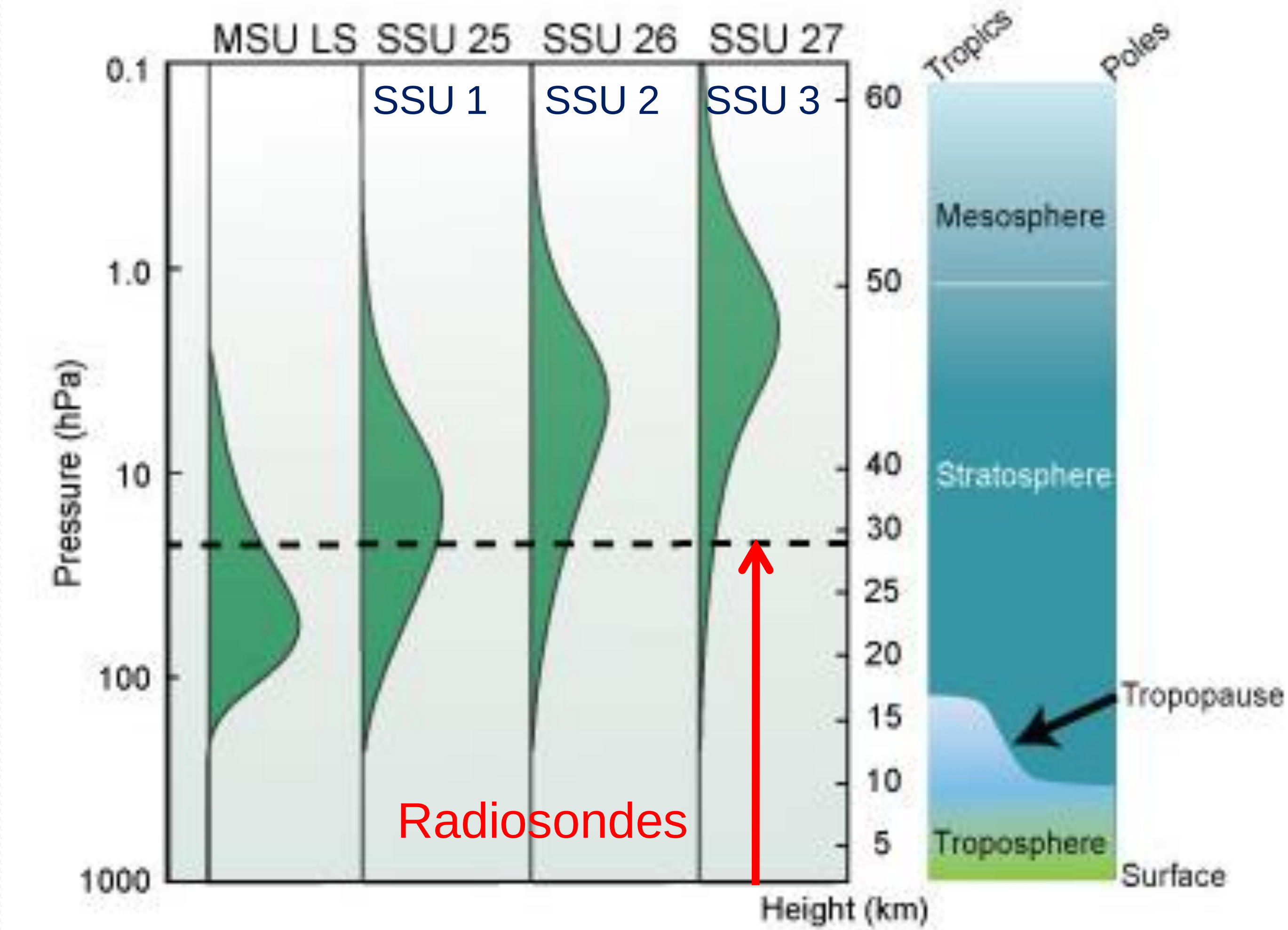
- All data points are PUBLISHED trend estimates
- Large spurious cooling in early radiosonde estimates
- Adjusted radiosonde data show less cooling
- Spread among trends comparable to trend magnitudes
- *Seidel et al.* (WIREs Climate Change 2011)

Current Radiosonde Analyses

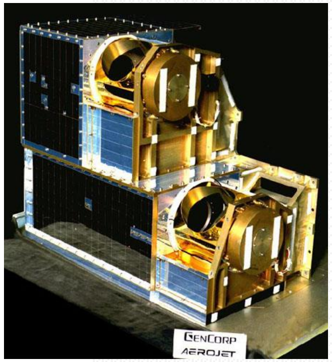


- 55-yr record … and continuing
- Time-varying biases removed in data from several teams
- Different approaches help quantify structural uncertainty
- ~ 2K cooling since 1958; Little change since 1995
- *Bull. Amer. Meteor. Soc.* supplement (2012)

“Early” Satellite Observations

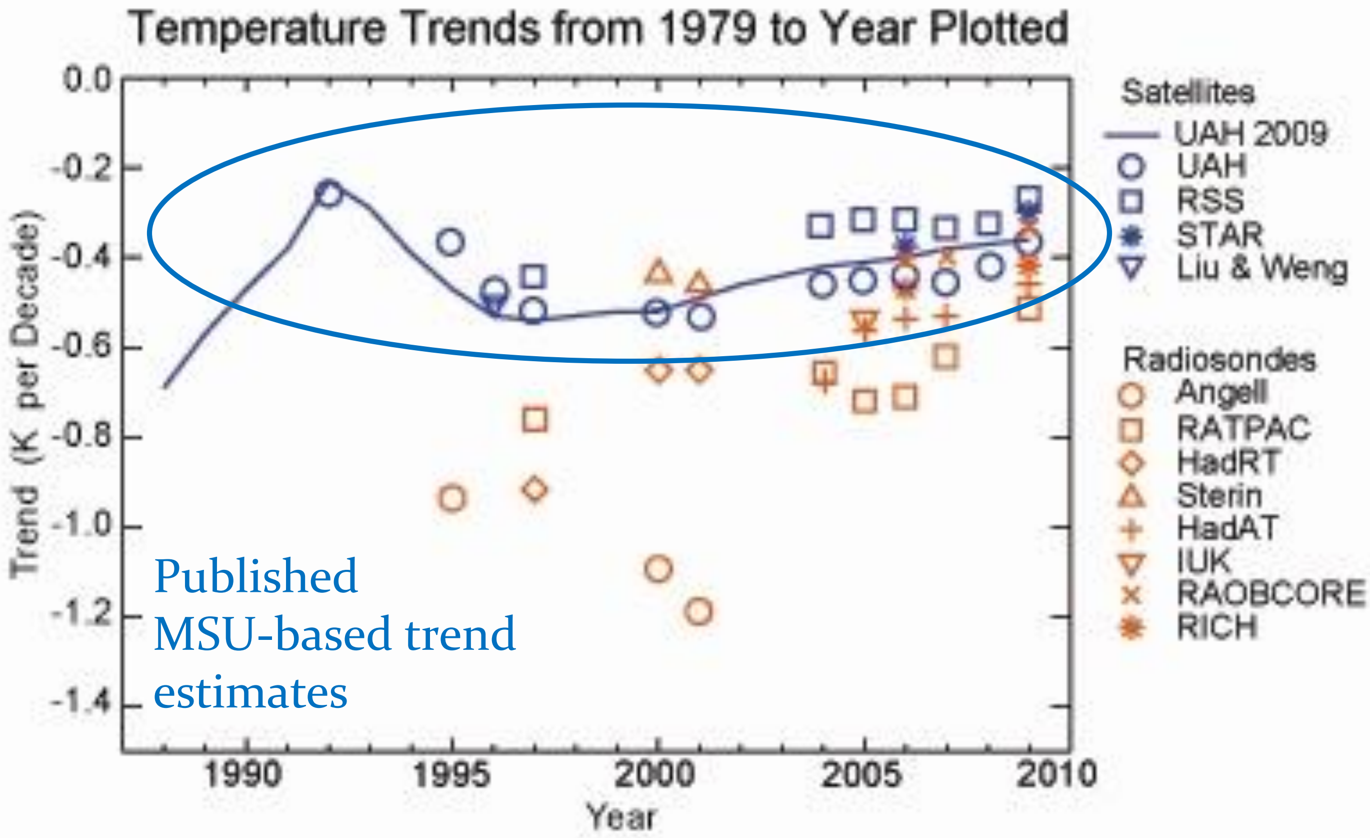


MSU



SSU

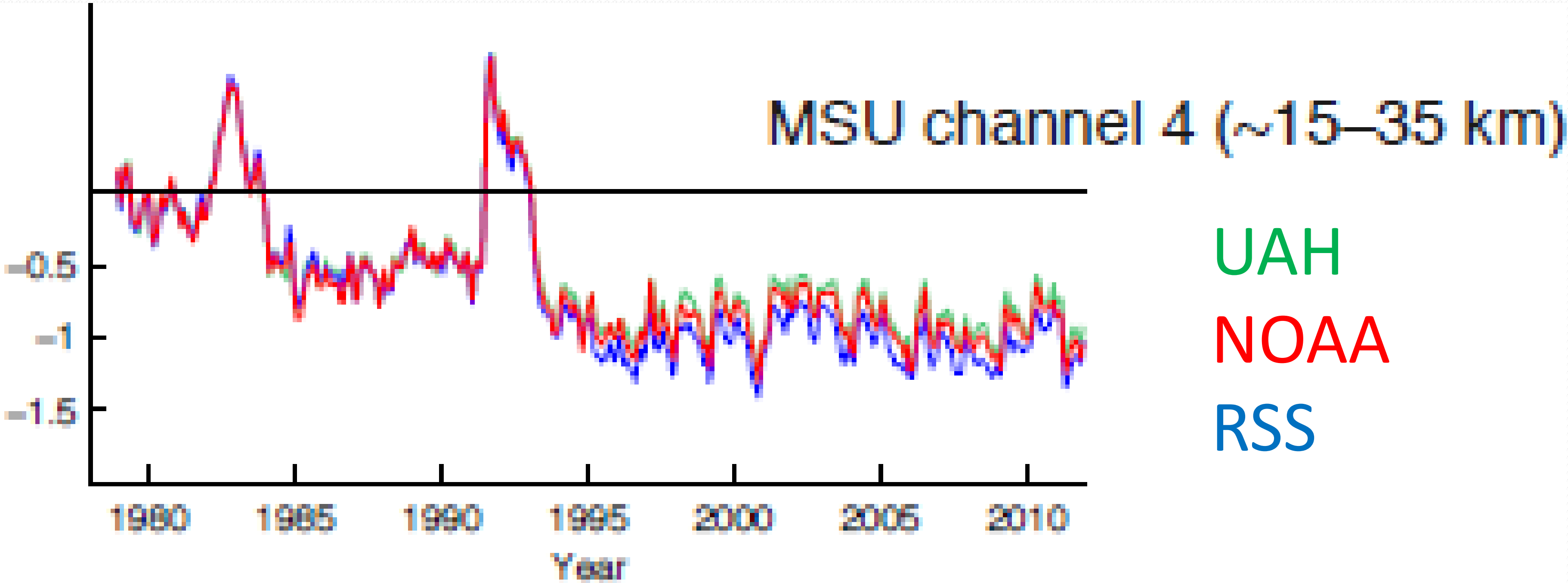
Trend Uncertainties in 1990s and 2000s



- MSU shows less cooling than radiosondes for the same periods
- Different versions of UAH dataset have different trends
- Spread among trends comparable to trend magnitudes, as with raobs
- *Seidel et al.* (WIREs Climate Change 2011)

Current MSU Analyses

global T anomalies



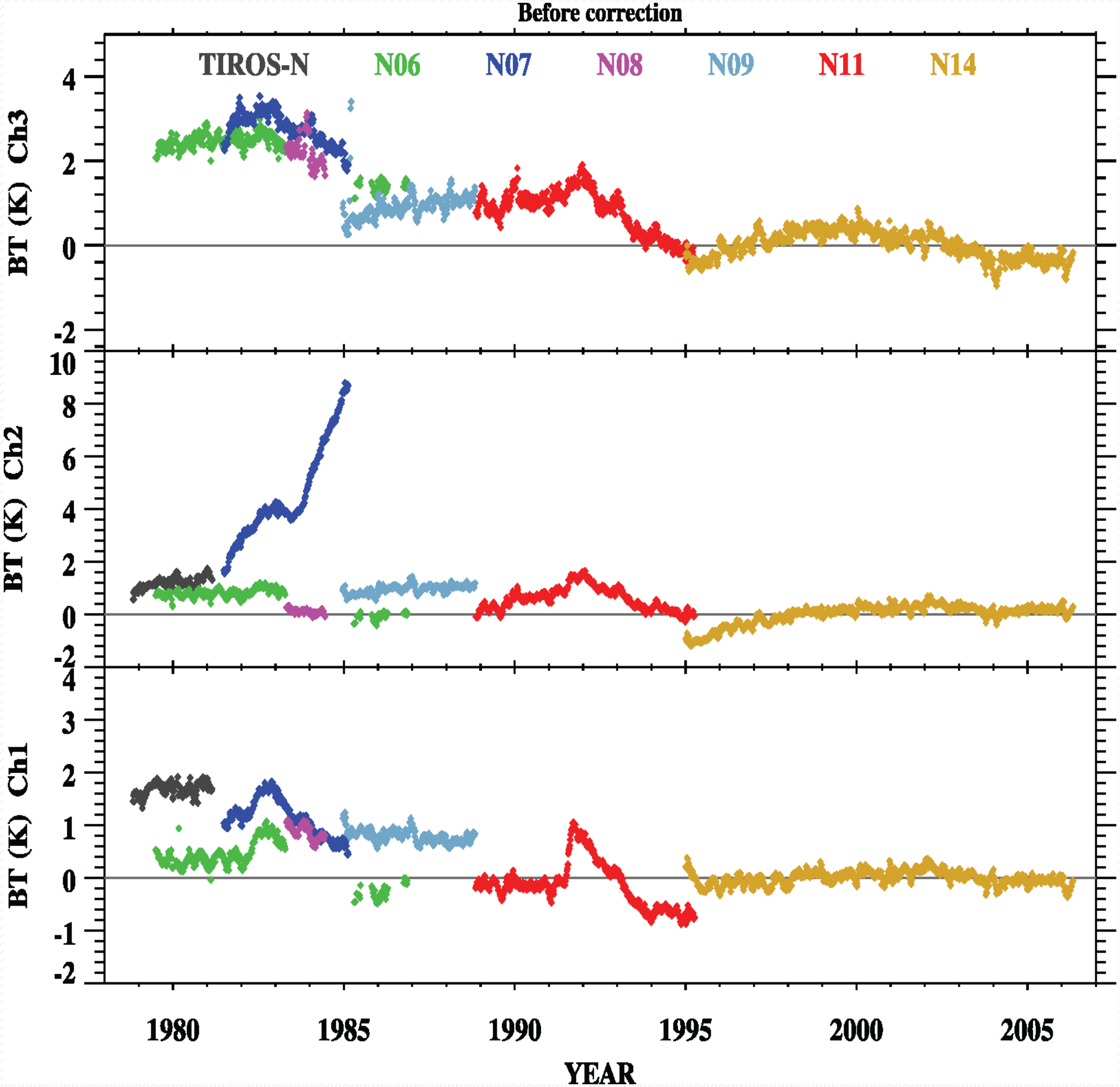
UAH

NOAA

RSS

Stratospheric Sounding Unit (SSU)

on NOAA Polar Orbiters 1979-2005

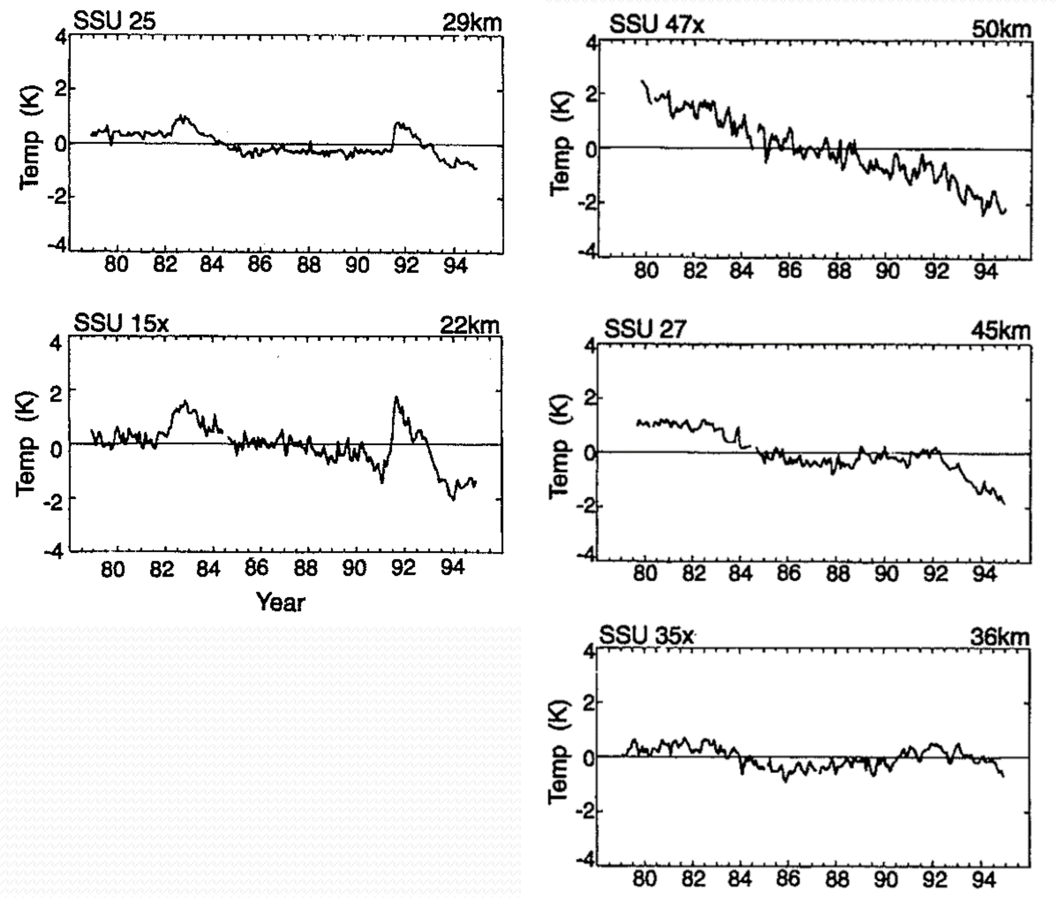


"Raw" brightness temperatures from multiple SSUs

SSU Status circa 2000

SPARC Stratospheric Temperature Trends Assessment Panel

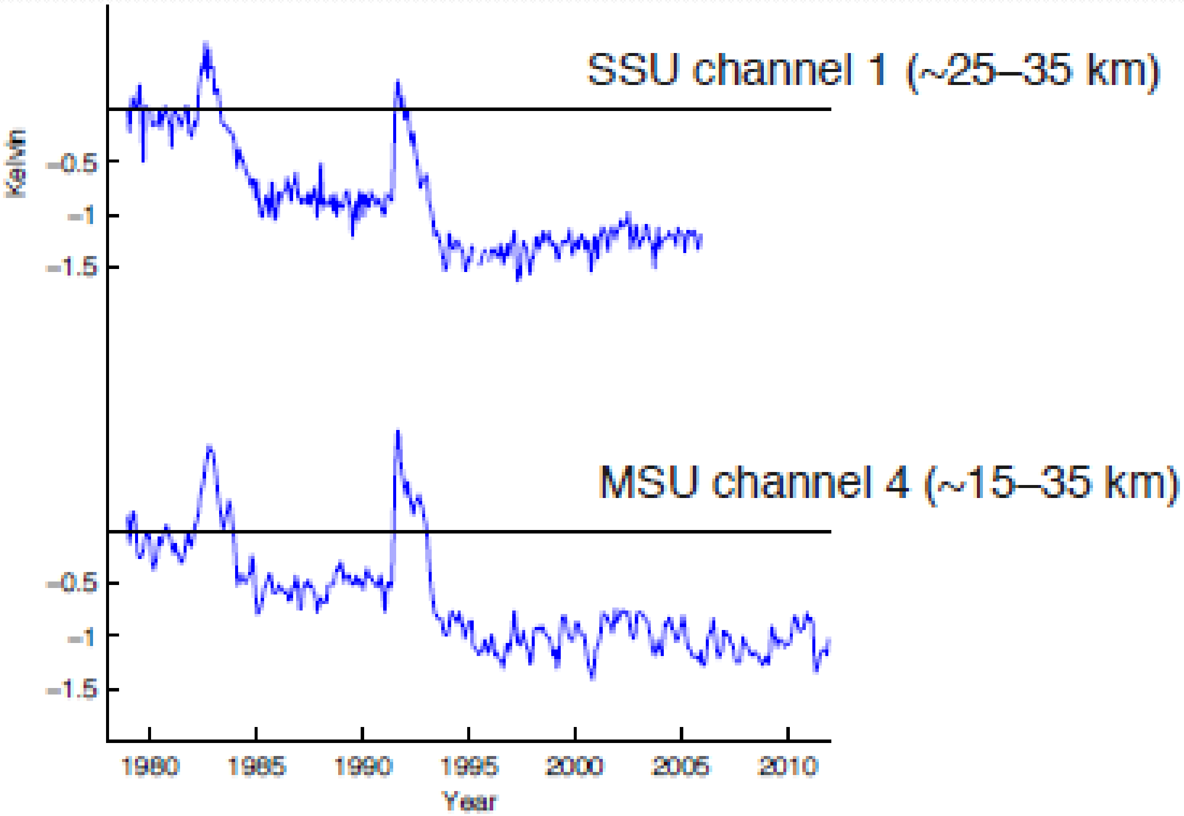
- One dataset from UK Met Office (*Nash and Forster* Adv. Space Res. 1986)
- 3 channels, plus synthetic channels using off-nadir obs
- "While the adjustment process succeeds in resolving one major uncertainty … there may be residual uncertainties du to other factors that necessitate continued analysis of this data." (*Ramaswamy et al.* Rev. Geophys. 2001)



SSU research in 21st century

- SSU record ended in 2005
- SPARC activity remains interested in unique data record
- Effect of atmospheric CO_2 increase on weighting function
  - Recognized (*WMO* 1988, *Brindley et al*. J. Climate 1999)
  - Reconsidered (*Shine et al*. GRL 2008)
  - Removed (*Randel et al*. JGR 2009)
- Concern about X channels (*Randel et al*. 2009) and vertical consistency (*Seidel et al*. 2011)
- NOAA team creates second SSU dataset, different merging and adjustment methods (*Wang et al*. J. Climate 2012) supercedes *Liu and Weng* (2009)
- Differences between of NOAA and UKMO datasets deemed a "mystery" (*Thompson et al*. Nature 2012)
- Re-examination by both NOAA and UKMO. New versions, and papers, forthcoming in 2014.

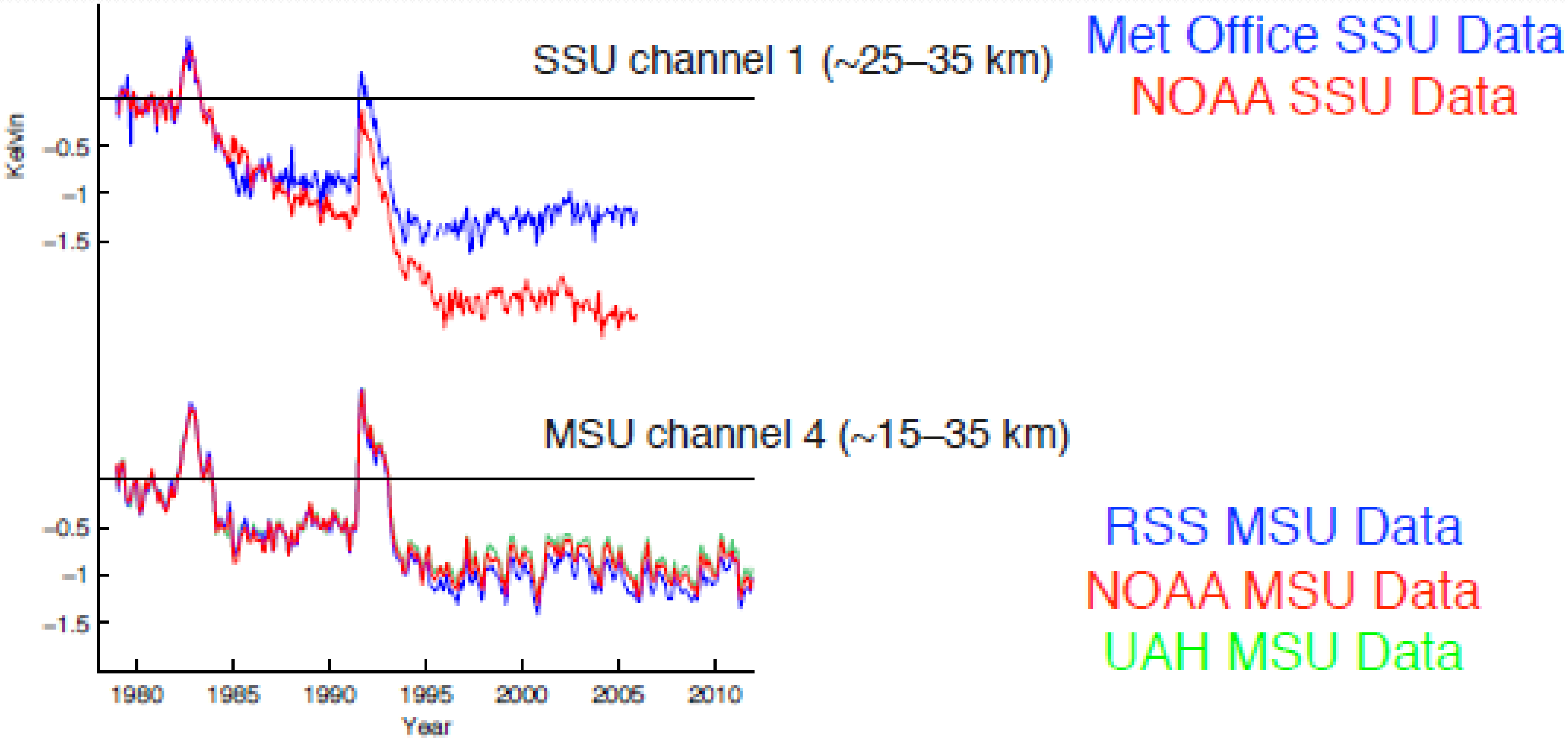
Lower Stratosphere: SSU and MSU



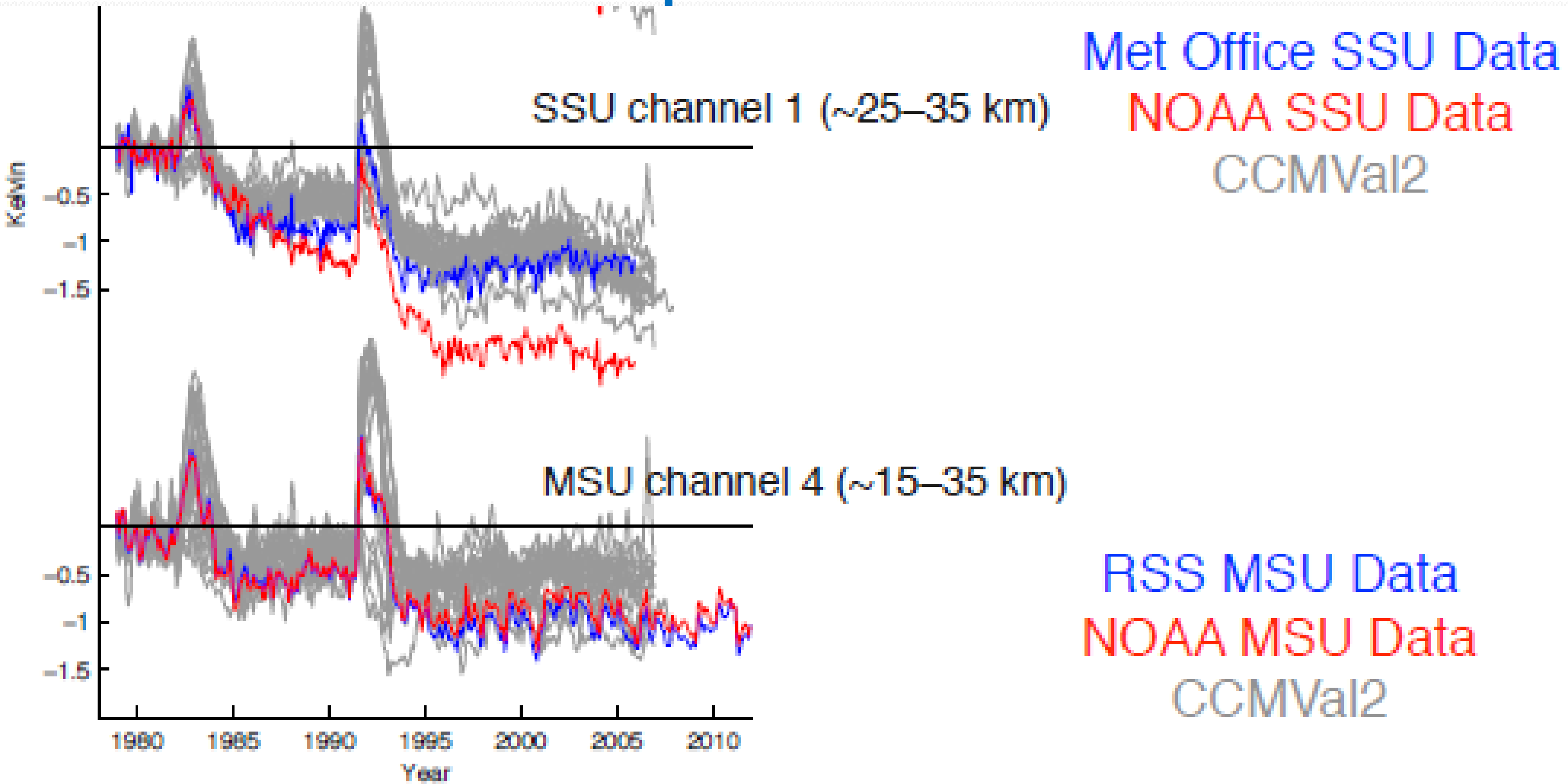
Met Office SSU Data

RSS MSU Data

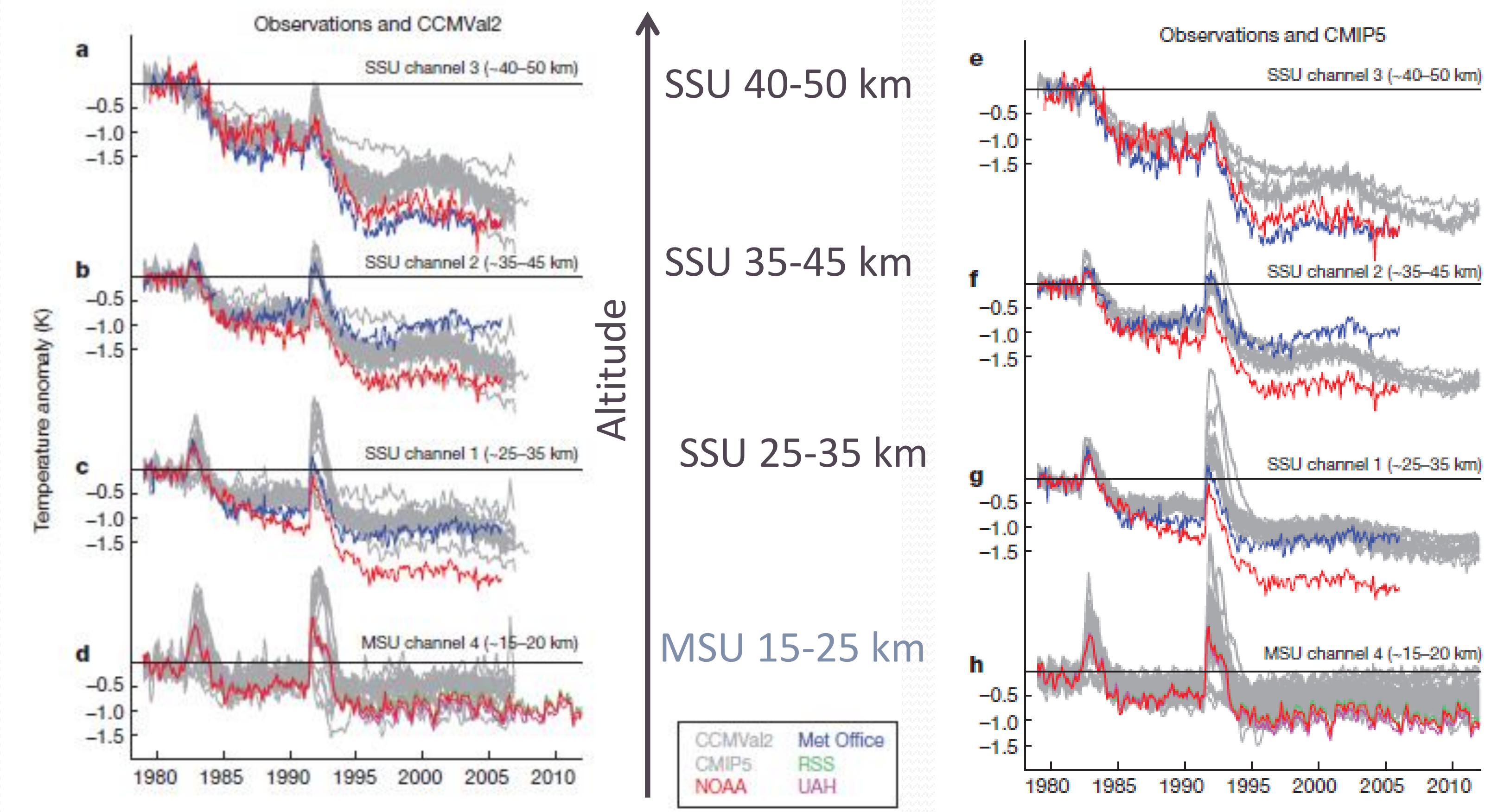
Lower Stratosphere: SSU and MSU



Lower Stratosphere: SSU and MSU

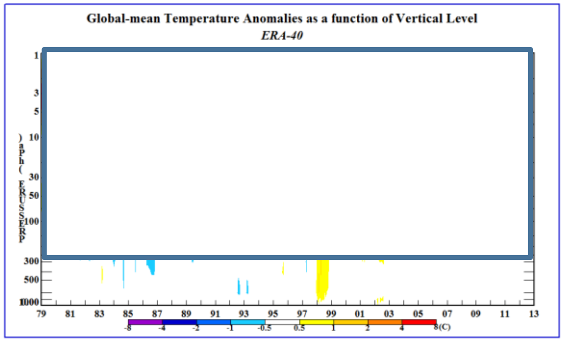


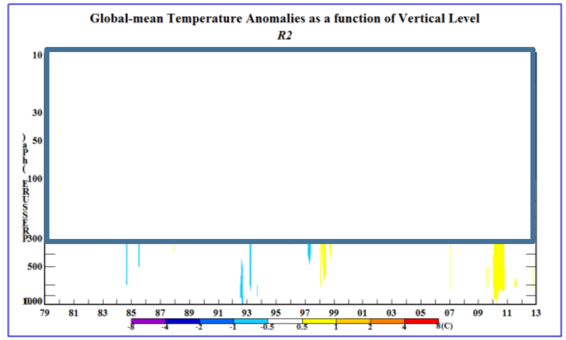
Chemistry-Climate Models   Atmosphere-Ocean Global Climate Models

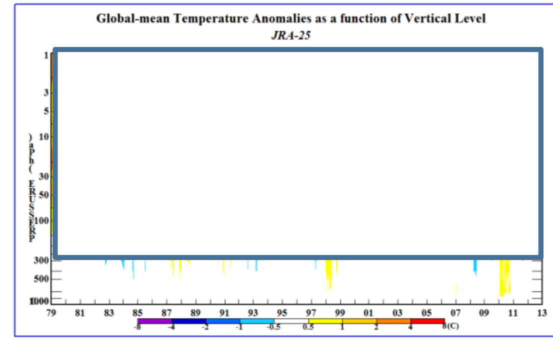


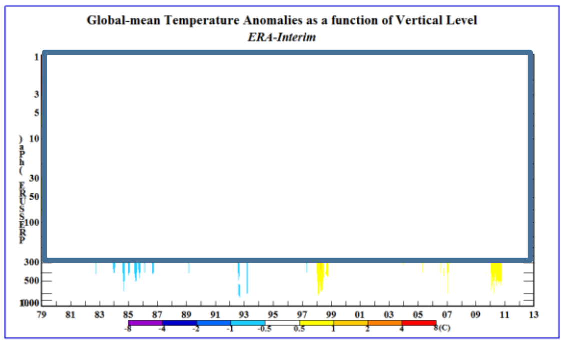
- Differences between SSU versions inconsistent among 3 channels
- Volcanic warming greater in models than observed
- Differences between SSU versions, and with models, in long-term T change

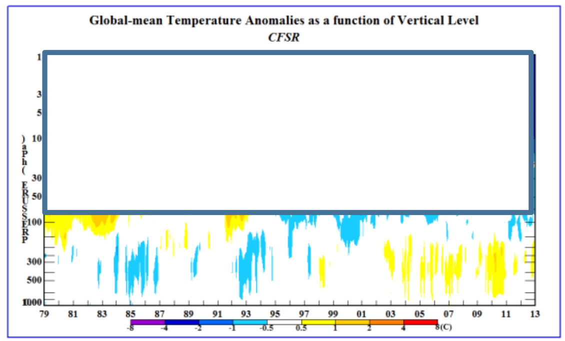
Reanalyses

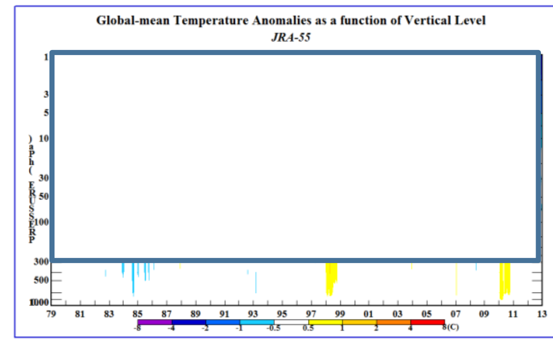




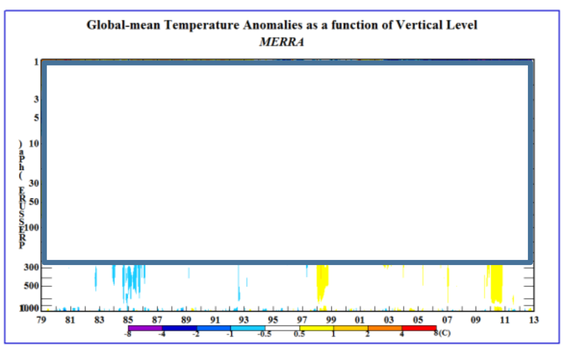








Altitude

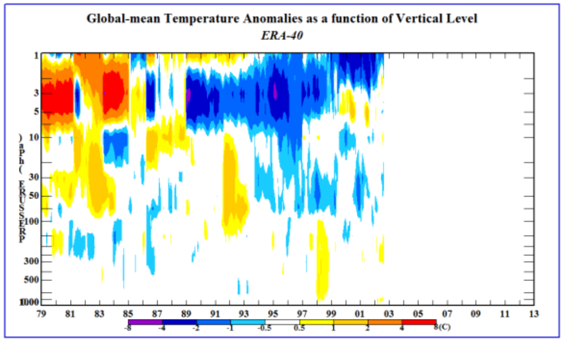


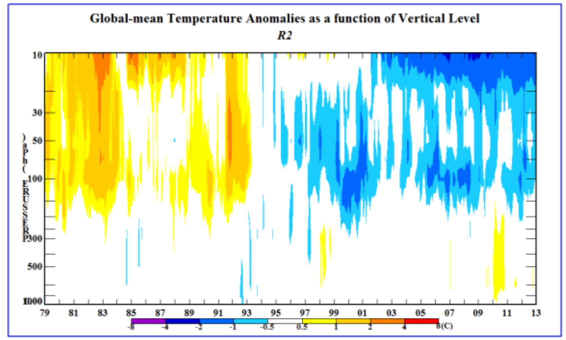
T Anomalies in 7 Reanalyses
1979 – 2012

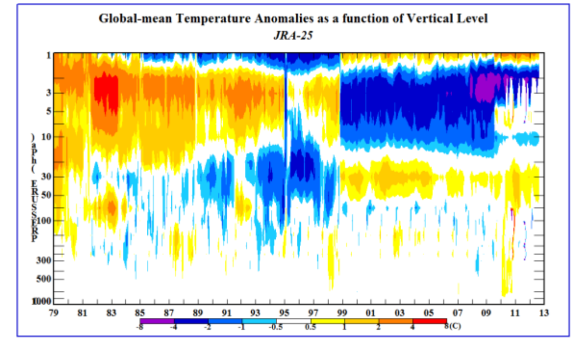
Temperature scale: -8 to +8 K
1000 – 300 hPa

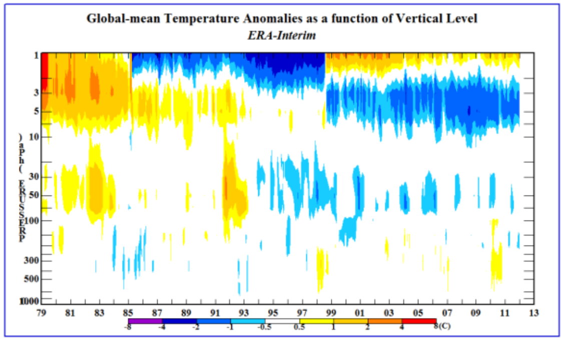
Figure courtesy of Craig Long (S-RIP)

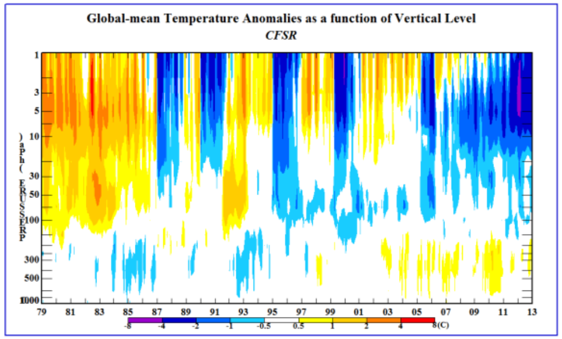
Reanalyses

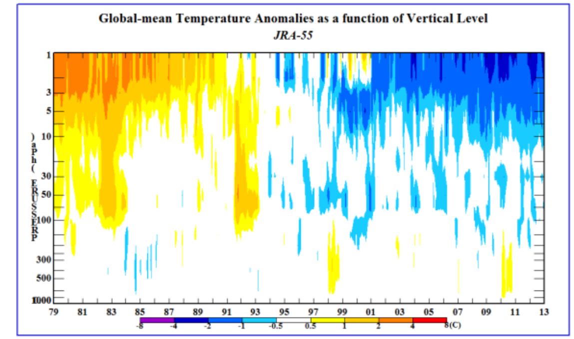


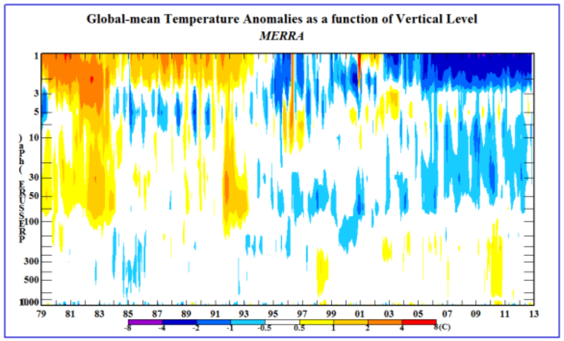












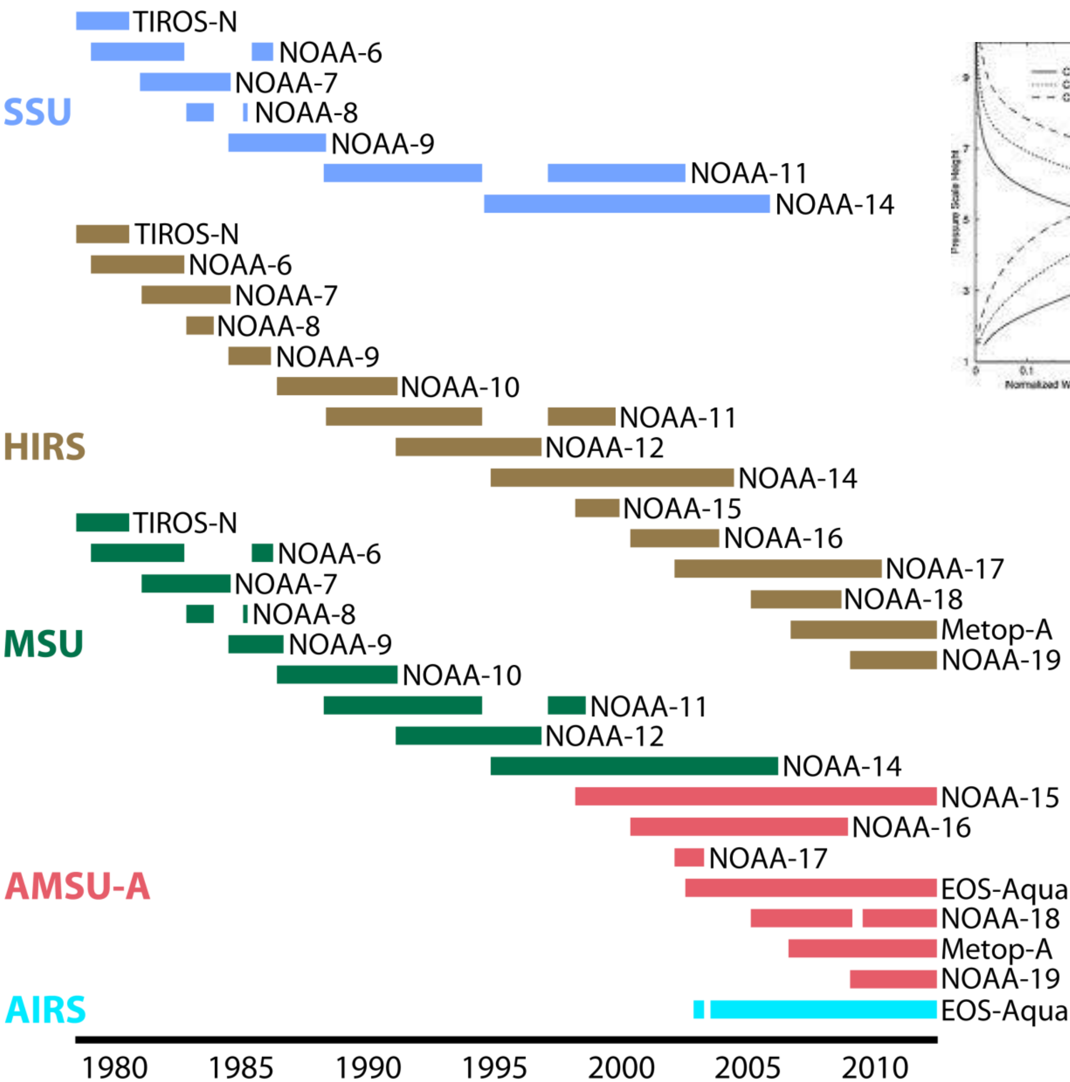
T Anomalies in 7 Reanalyses
1979 – 2012

Temperature scale: -8 to +8 K

1000 hPa - top

Figure courtesy of Craig Long (S-RIP)

21st C. Observations from Polar Orbiters



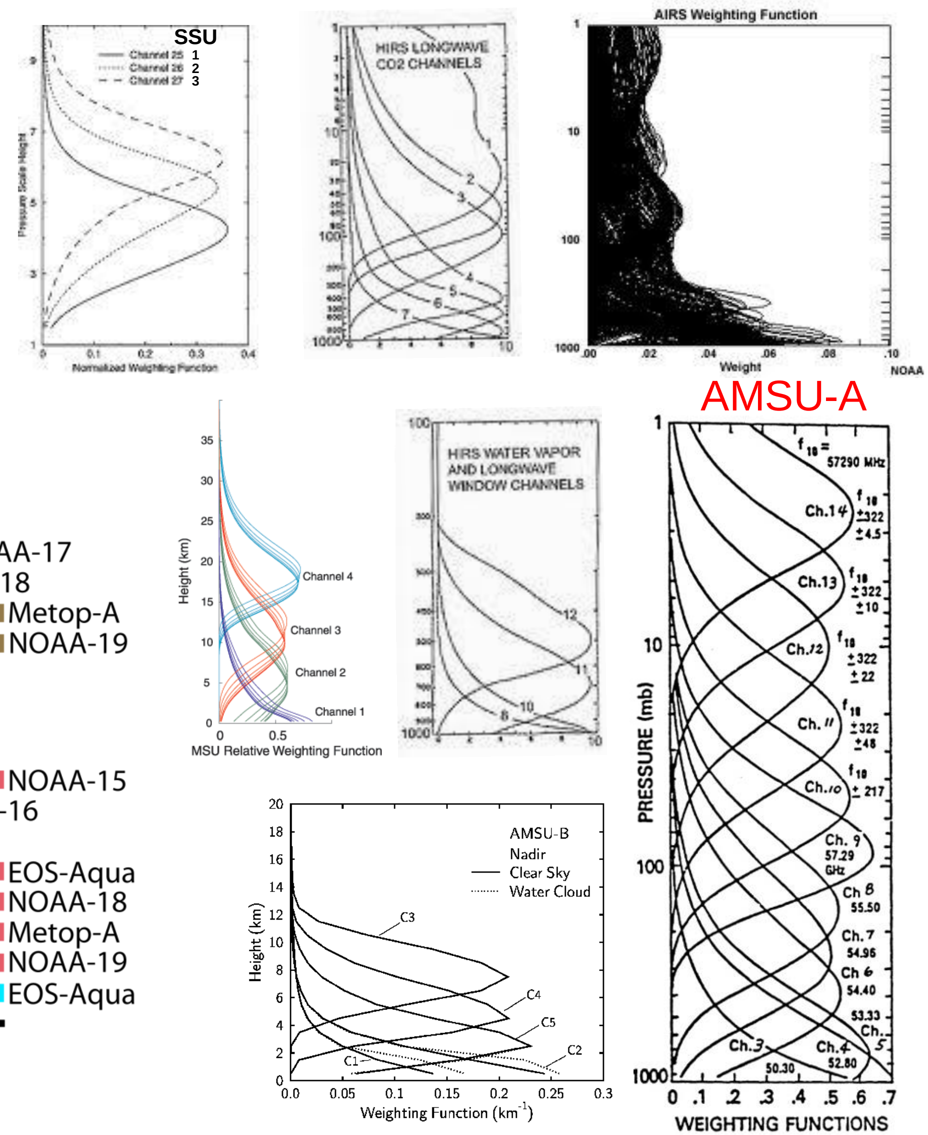
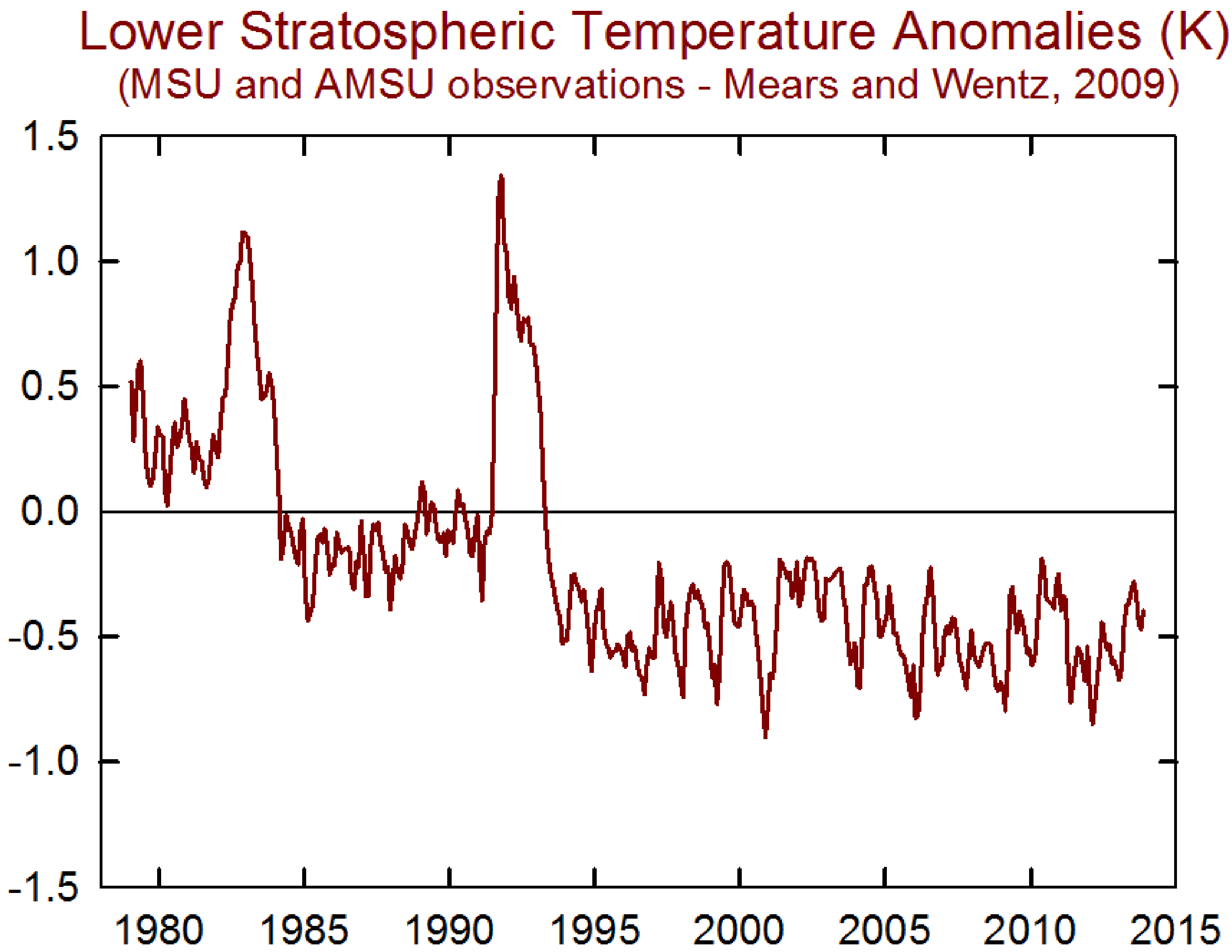


Figure courtesy of A. Simmons


Lower Stratospheric Temperature Anomalies (K)
(MSU and AMSU observations - Mears and Wentz, 2009)
1.5
1.0
0.5
0.0
-0.5
-1.0
-1.5
1980
1985
1990
1995
2000
2005
2010
2015

Other 21st C. Observations

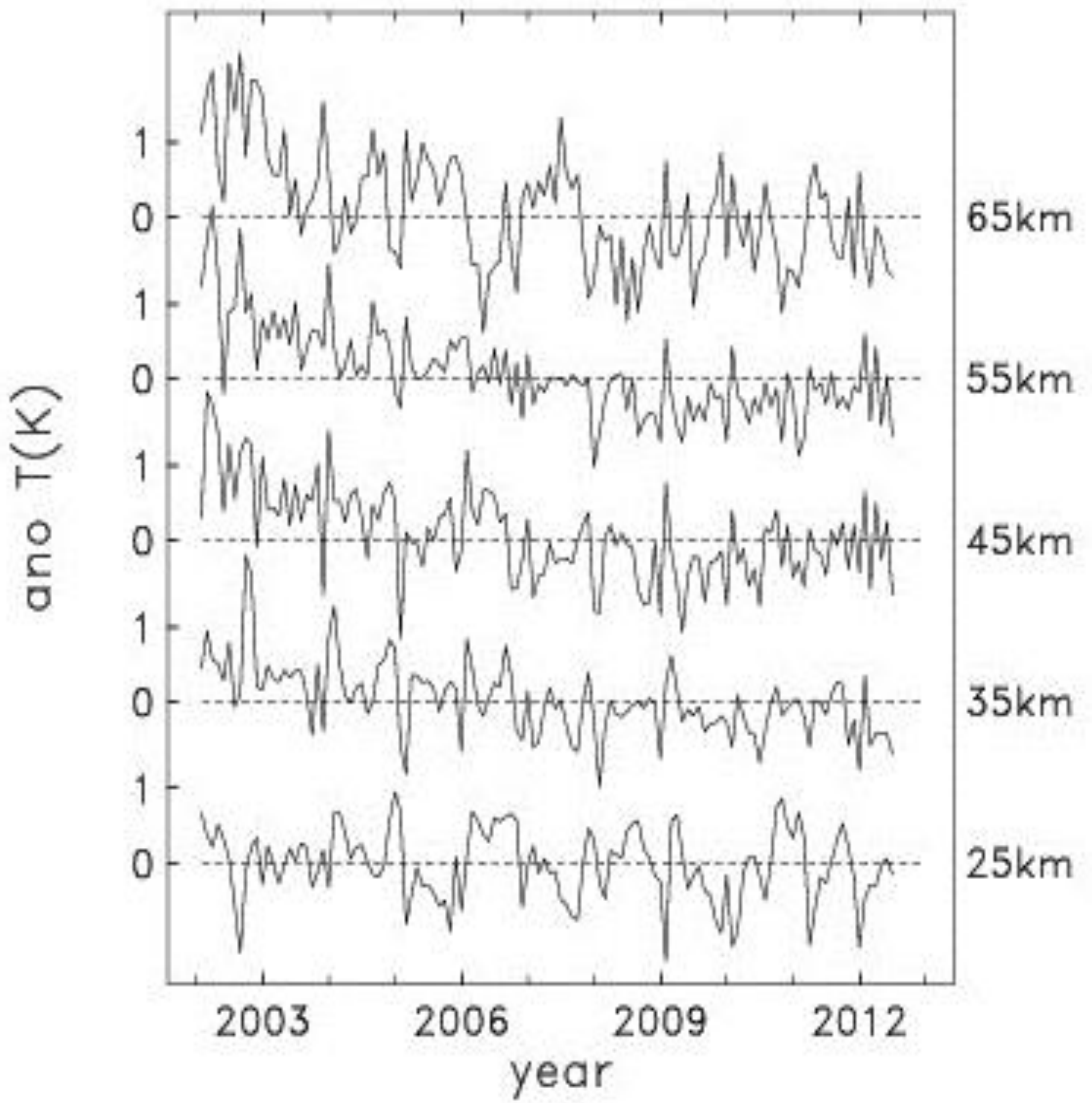
- Satellite:
  - GNSS-RO: Global Navigational Satellite System Radio Occultation
  - SABER: Sounding of the Atmosphere using Broadband Emission Radiometry (NASA)
  - GOMOS: Global Ozone Monitoring by Occultation of Stars (ESA)
- Ground-Based
  - NDACC Lidars
  - GCOS Reference Upper-Air Network

Other 21st C. Observations

	GNSS-RO	SABER	GOMOS
Principle	Refractivity-dependent time delay of radio transmission	Broadband radiometry; CO_2 emissions	Chromatic refractivity; scintillation measurements
Altitude Range (km)	8-25	20-100	15-30
Vertical Resolution (m)	200	2000	200
Period of Obs.	~2006-present	2001-present	2002-2012
Maturity of analysis effort	High	low	low

GNSS-RO: Global Navigational Satellite System Radio Occultation
SABER: Sounding of the Atmosphere using Broadband Emission Radiometry (NASA)
GOMOS: Global Ozone Monitoring by Occultation of Stars (ESA)

SABER T Anomalies (50^{o}N-S)



Unpublished data, courtesy of Bill Randel

Take-home Messages

- Models have long predicted large stratospheric T changes.
  - Stratospheric T should remain a priority for climate change detection.
  - Discrepancies between models and obs need better explanations.
- Observations for detecting changes are not ideal.
  - Progress has been slow.
  - Large uncertainties remain and need to be better quantified.
- Post-volcanic warming is the dominant signal in the lower stratosphere.
- Observations suggest long-term cooling, but
  - Cooling is not monotonic or linear
  - On global-average, there has been little change since 1995.
- Maybe we should stop talking about stratospheric T changes as trends.

SPARC T Trends Activity References

Ramaswamy, V., M.-L. Chanin, J. Angell, J. Barnett, D. Gaffen, M. Gelman, P. Kekhut, Y. Koshelkov, K. Labitzke, J.-J. R. Lin, A. O'Neill, J. Nash, W. Randel, R. Rood, K. Shine, M. Shiotani, and R. Swinbank, 2001: **Stratospheric temperature trends: Observations and model simulations.** *Rev. Geophys., 39, 71-122*.

Shine, K.P., M.S. Bourqui, P.M.de F. Forster, S.H.E. Hare, U. Langematz, P. Braesicke, V. Grewe, C. Schnadt, C.A. Smith, J.D. Haigh, J. Austin, N. Buchart, D. Shindell, W.J. Randel, T. Nagashima, R.W. Portman, S. Solomon, D.J. Seidel, J. Lanzante, S. Klein, V. Ramaswamy, M.D. Schwarzkopf, 2003: **A comparison of model-predicted trends in stratospheric temperatures.** *Quart. J. Royal. Meteor. Soc., 129, 1565-1588. doi: 10.1256/qj.02.186.*

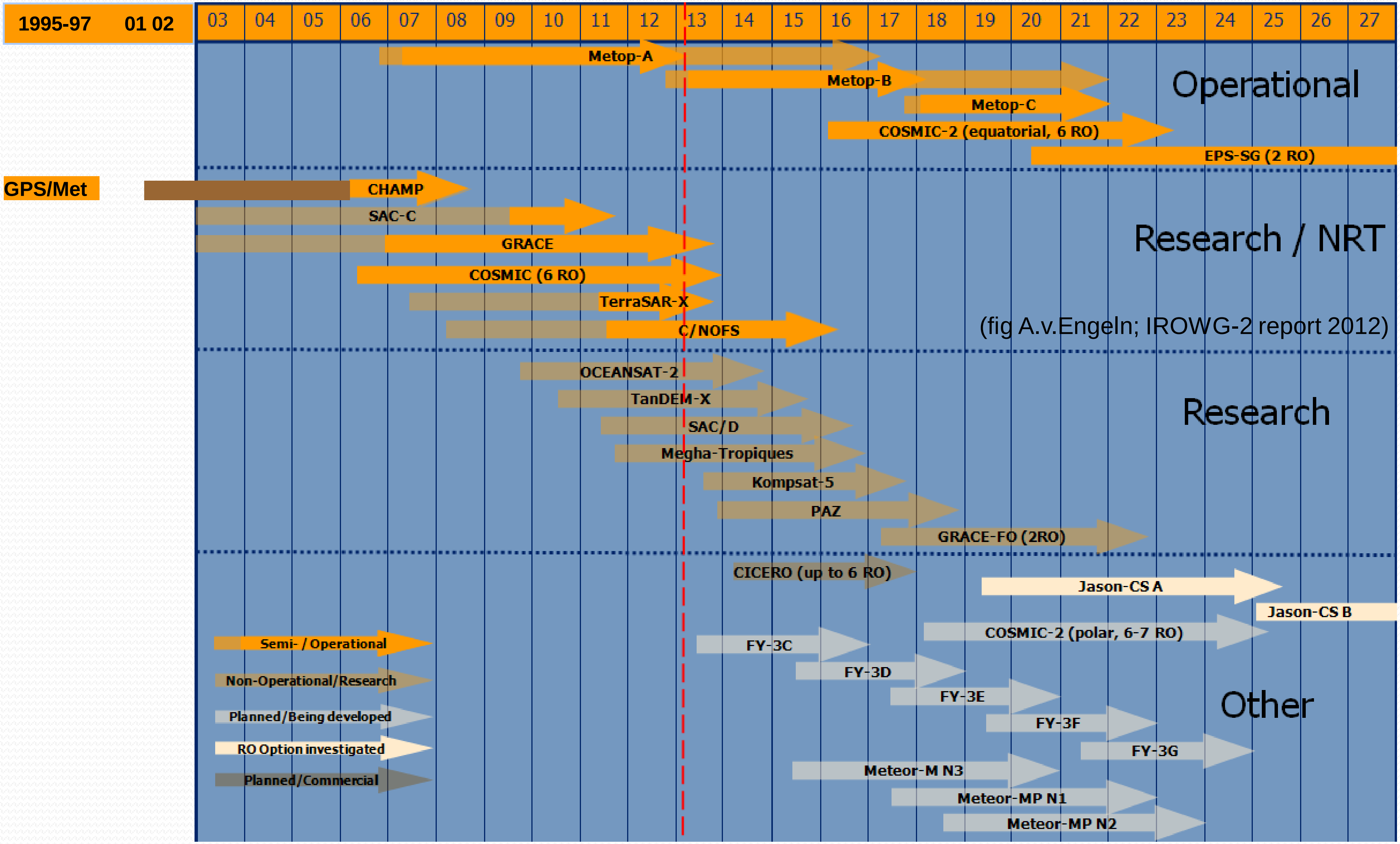
Randel, W.J., K.P. Shine, J. Austin, J. Barnett, C. Claud, N.P. Gillett, P. Keckhut, U. Langematz, R. Lin, C. Long, C. Mears, A. Miller, J. Nash, D.J. Seidel, D.W.J. Thompson, F. Wu and S. Yoden, 2009: **An update of observed stratospheric temperature trends**. *J. Geophys. Res., 114, D02107, doi:10.1029/2008JD010421*.

Seidel, D.J., N.P. Gillett, J.R. Lanzante, K.P. Shine, P.W. Thorne 2011: **Stratospheric temperature trends: Our evolving understanding.** Wiley Interdisciplinary Reviews: Climate Change, 2, 592-616, DOI: 10.1002/wcc.125

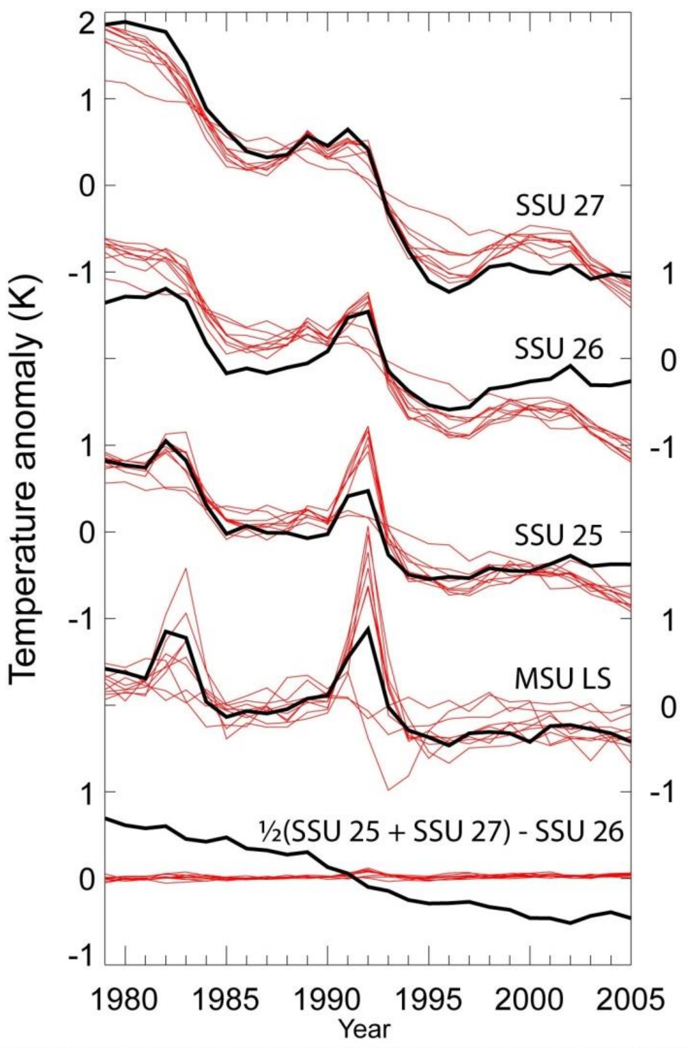
Thompson, D.W.J., D.J. Seidel, W.J. Randel, C.-Z. Zou, A. H. Butler, R. Lin, C. Long, C. Mears, A. Osso, 2012: **The mystery of recent stratospheric temperature trends**. Nature, 491,692-697, doi:10.1038/nature11579.

GNSS radio occultation satellite missions: past, current, planned...

Figure courtesy of Andrea Steiner



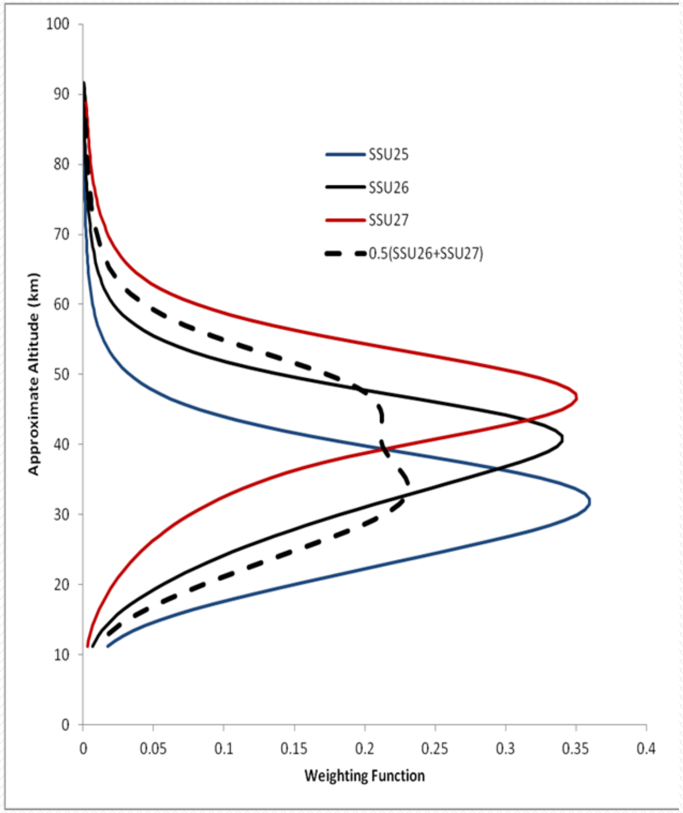
SSU time series comparisons



SSU 27
37-52 km

SSU 26
30-45 km

SSU 25
23-38 km



Comparison of channels
Seidel et al. (2011)

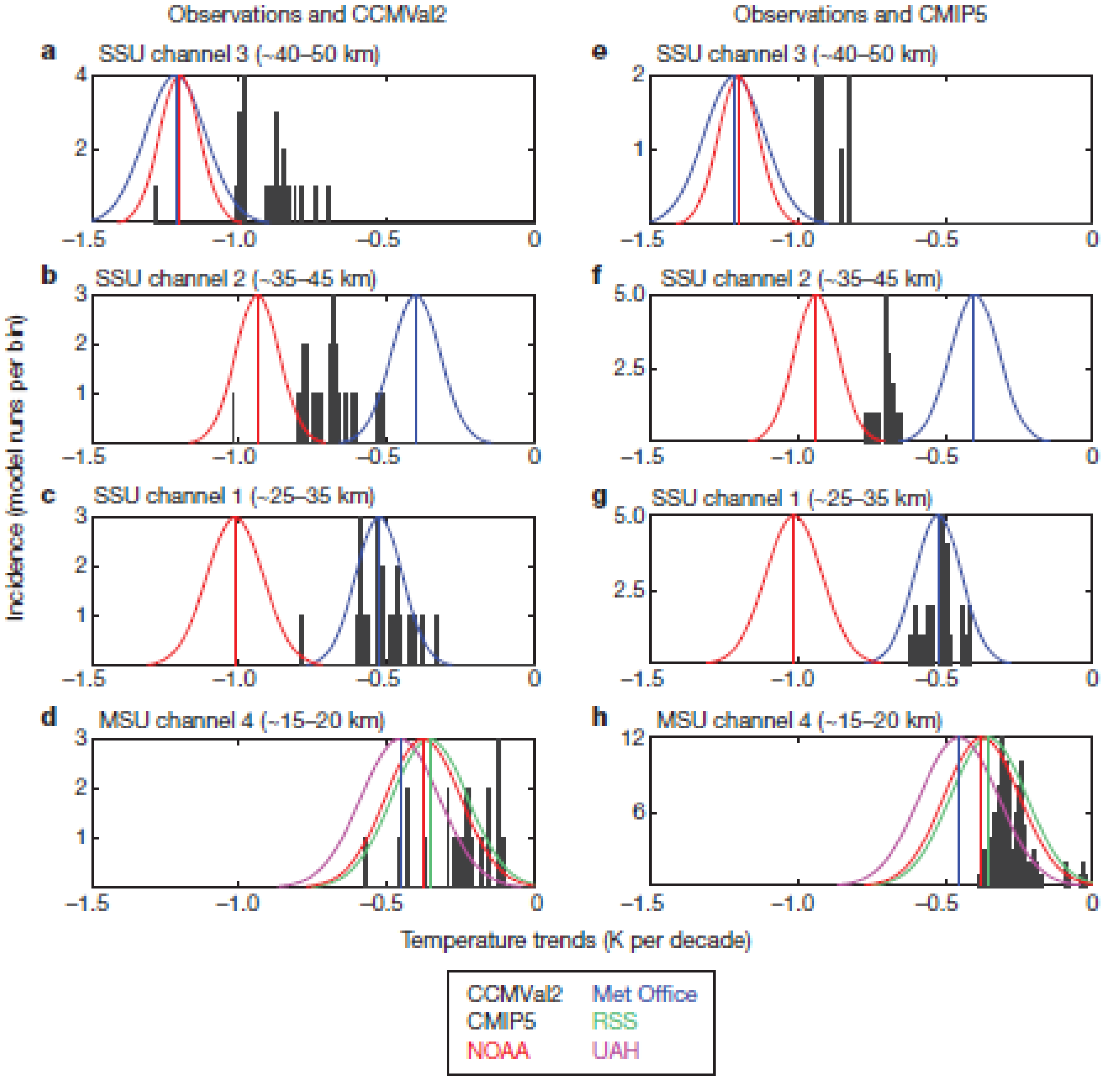
Weighting functions
Courtesy K. Shine

Temperature Trend Comparisons

Chemistry-Climate Models

Atmosphere-Ocean Global Climate Models

Altitude



SSU

trend difference comparable to trend magnitude

MSU

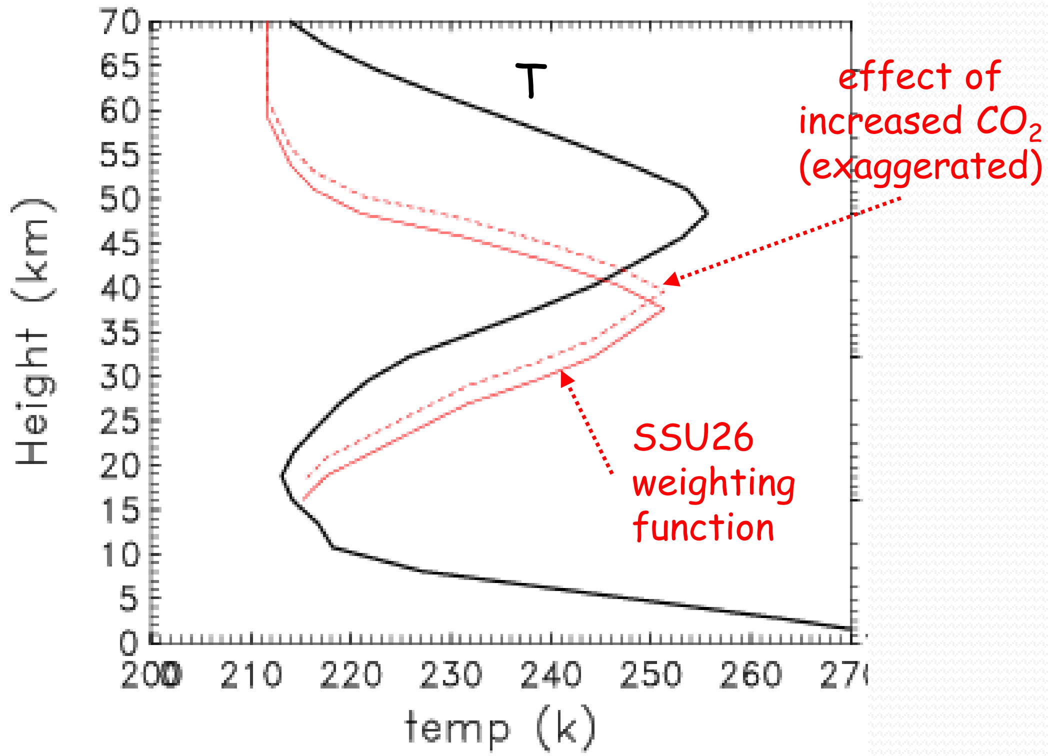
better agreement among obs and with models

SSU Issues

- Pressure cell leakage effects
- “Synthetic” channels (X channels) using off-nadir data
- Tidal effects
- Dataset nomenclature confusion
- Interpretation of radiance changes vs T changes – importance of weighting function
- Complete uncertainty budget analyses
- SSU / AMSU merging
- Utility of early satellite data (Nimbus PMR, VTPR, SAMS, ISAMS) not much investigated

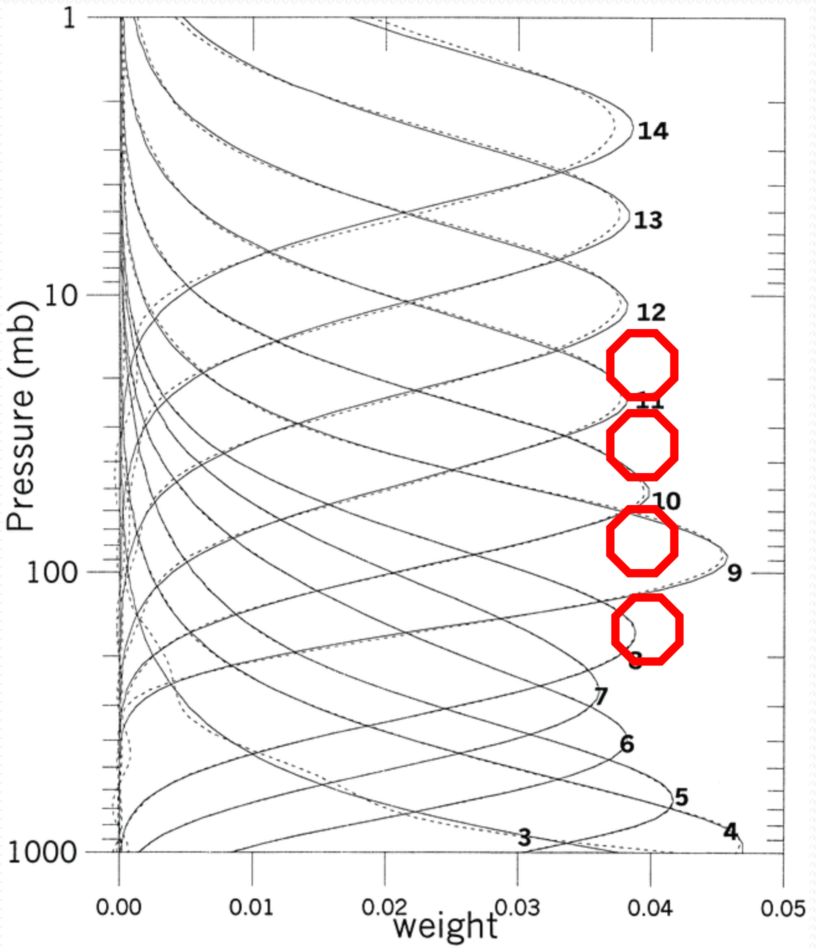
Atmospheric CO_2 increase affects SSU

- Effective elevation of SSU weighting functions
- Apparent warming trends ~0.3 K/decade



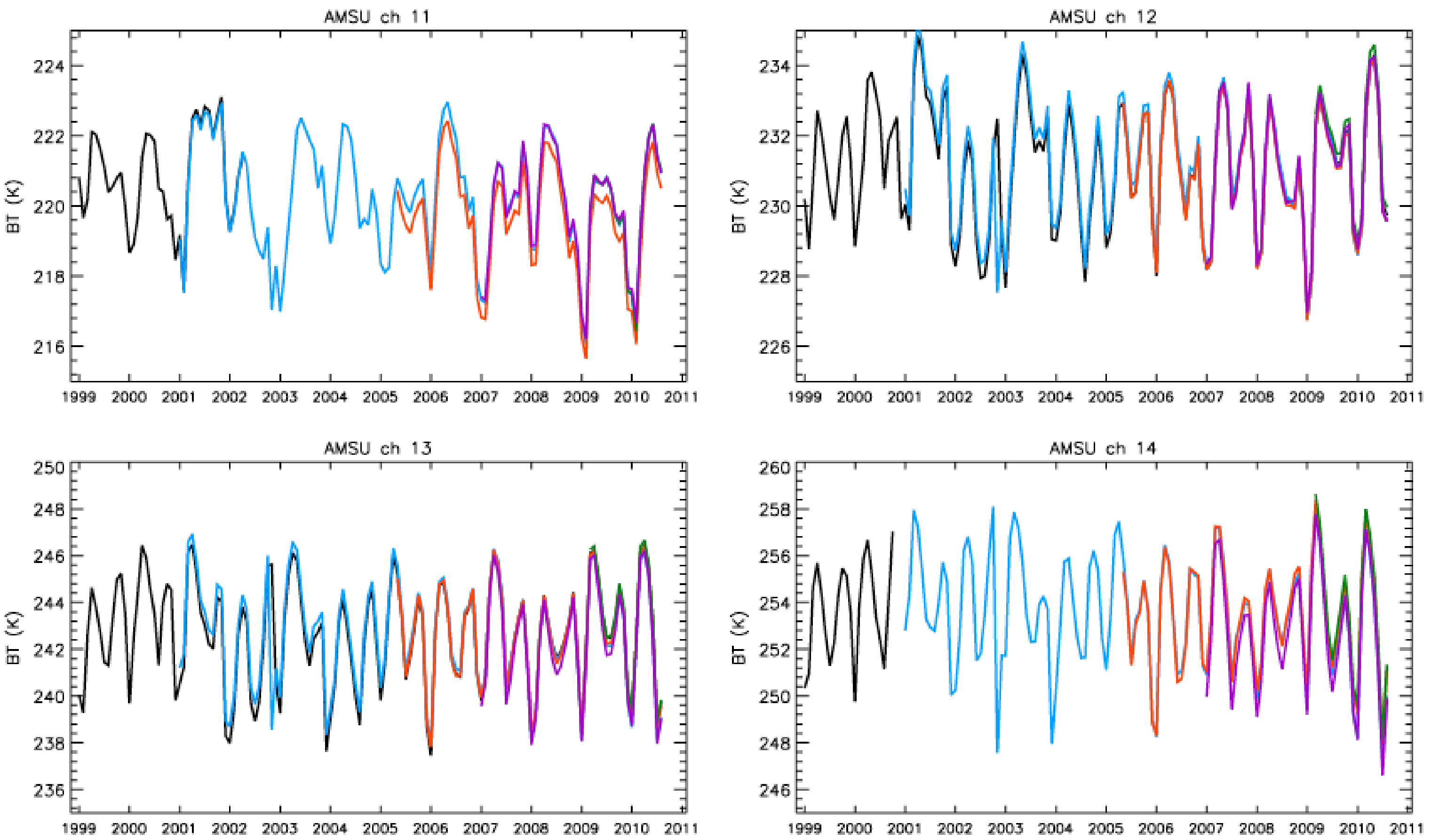
Courtesy W. Randel

AMSU weighting functions



Carl Mears

AMSU series from channels 11-14

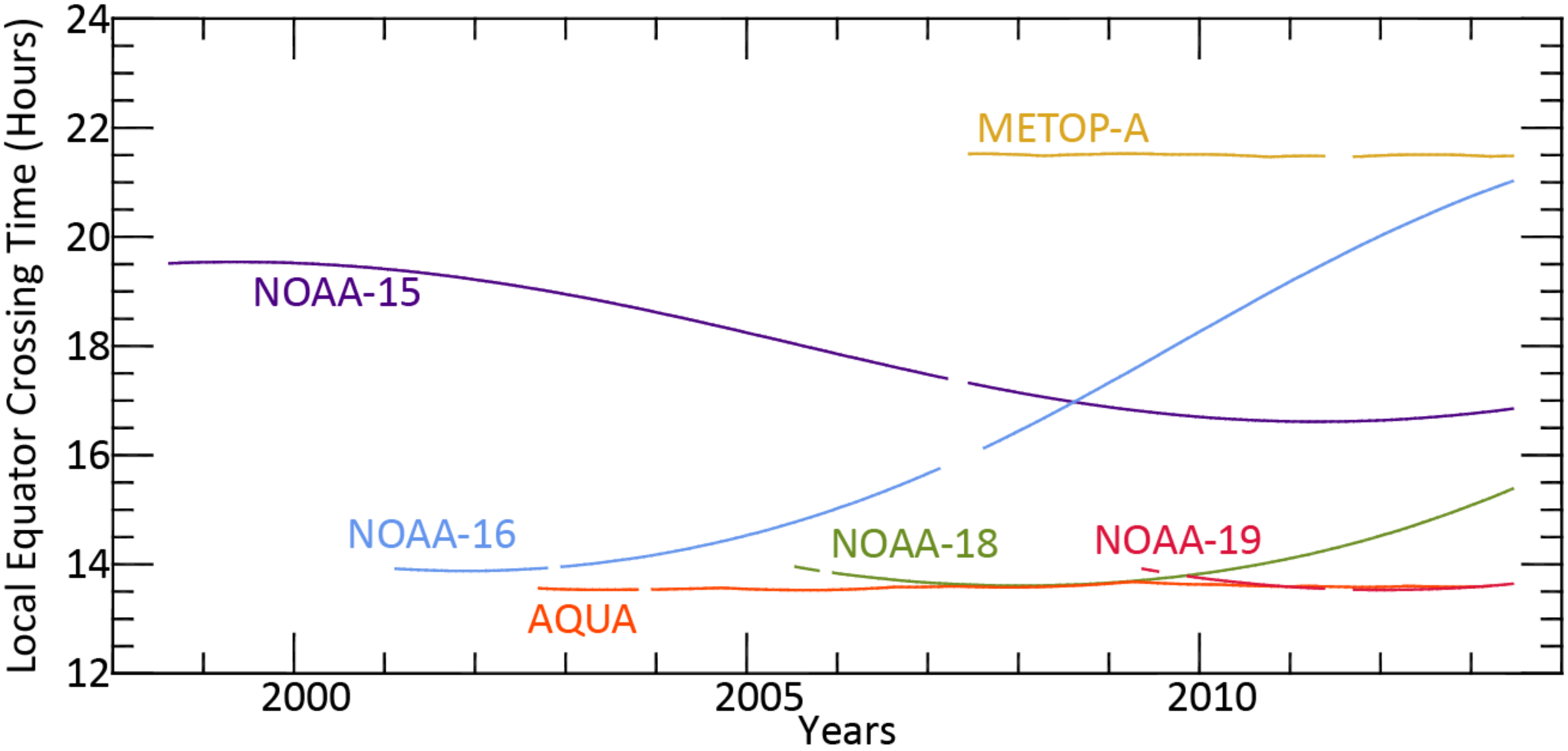


NOAA 15 NOAA 16 NOAA 18 METOP A NOAA 19

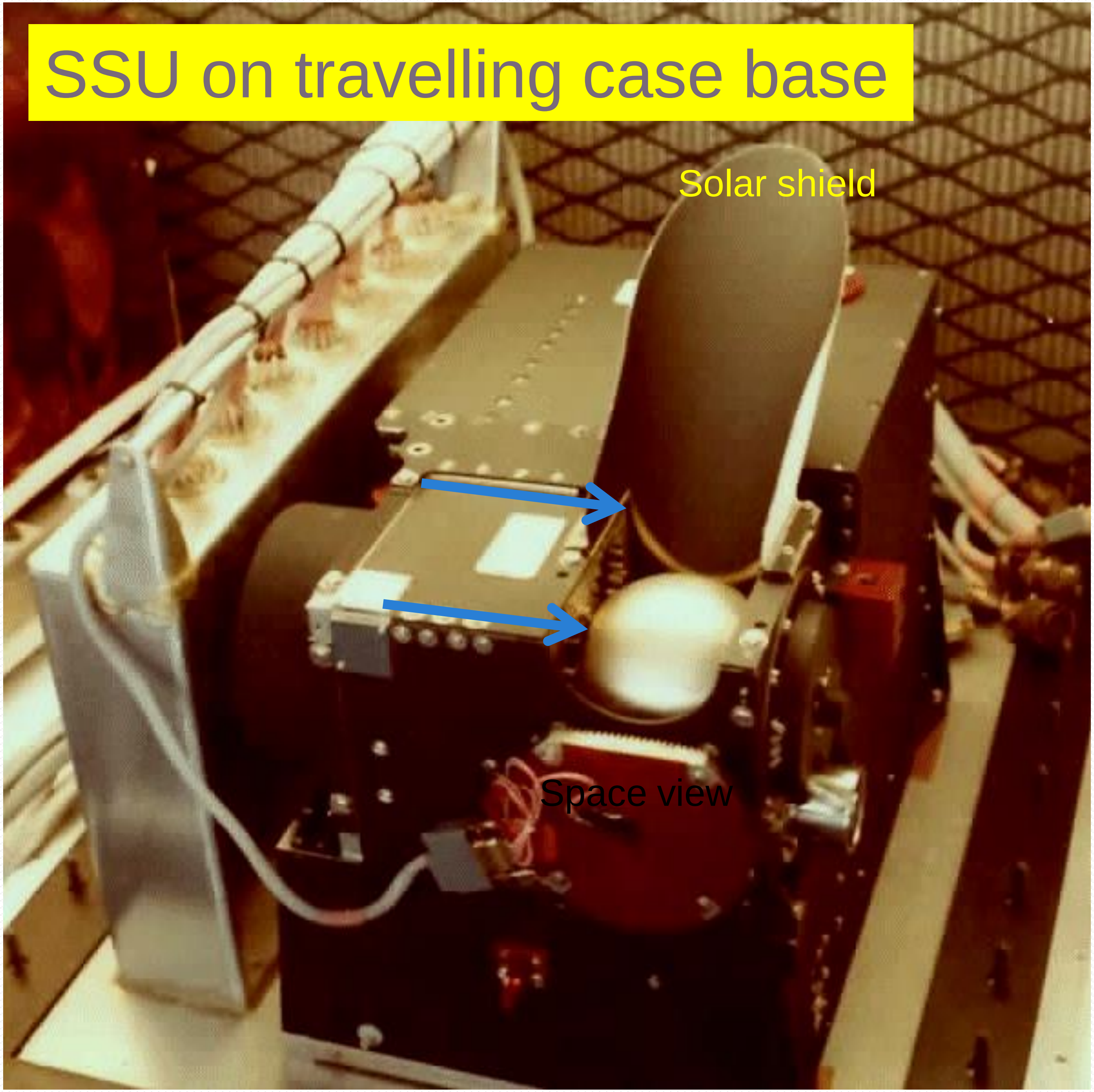
Carl Mears

AMSU LECTs - Channel 13

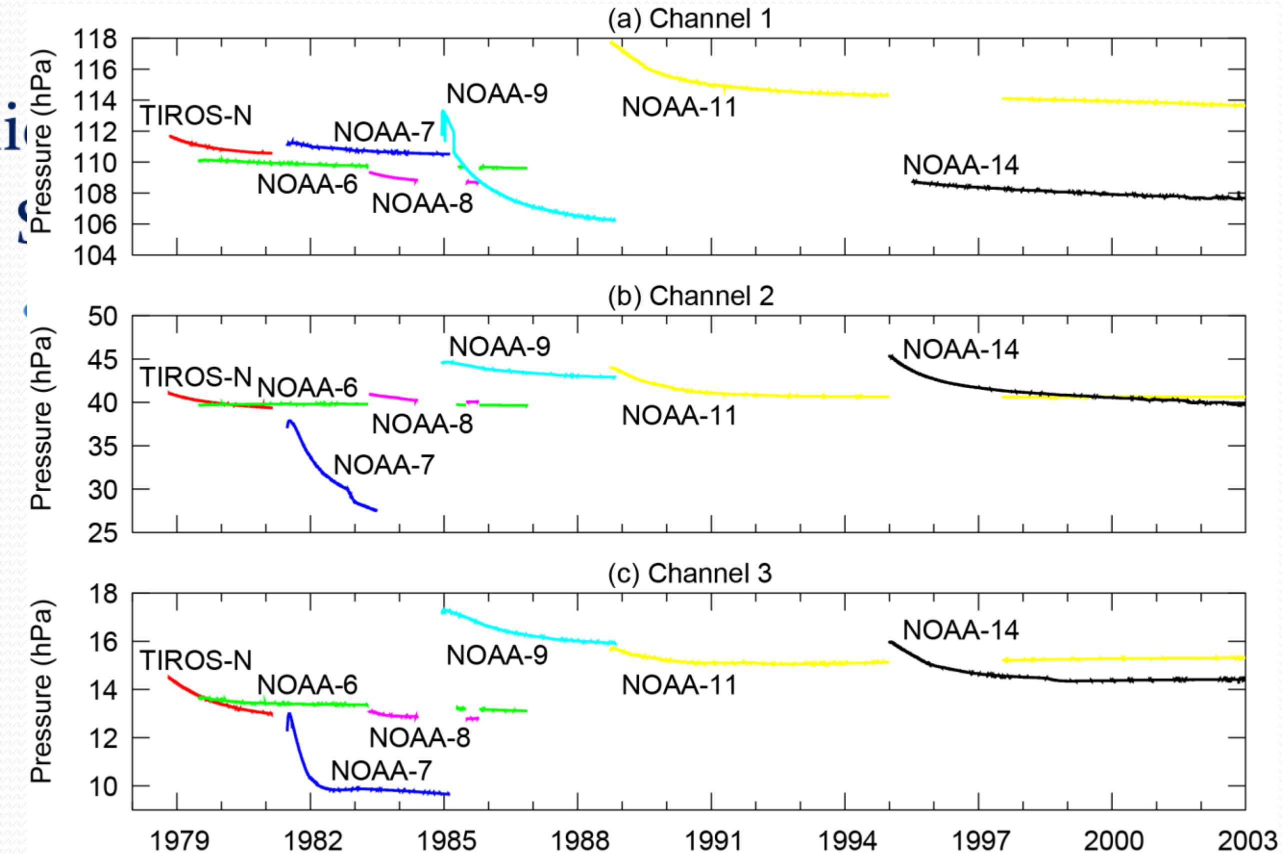
Carl Mears



John Nash



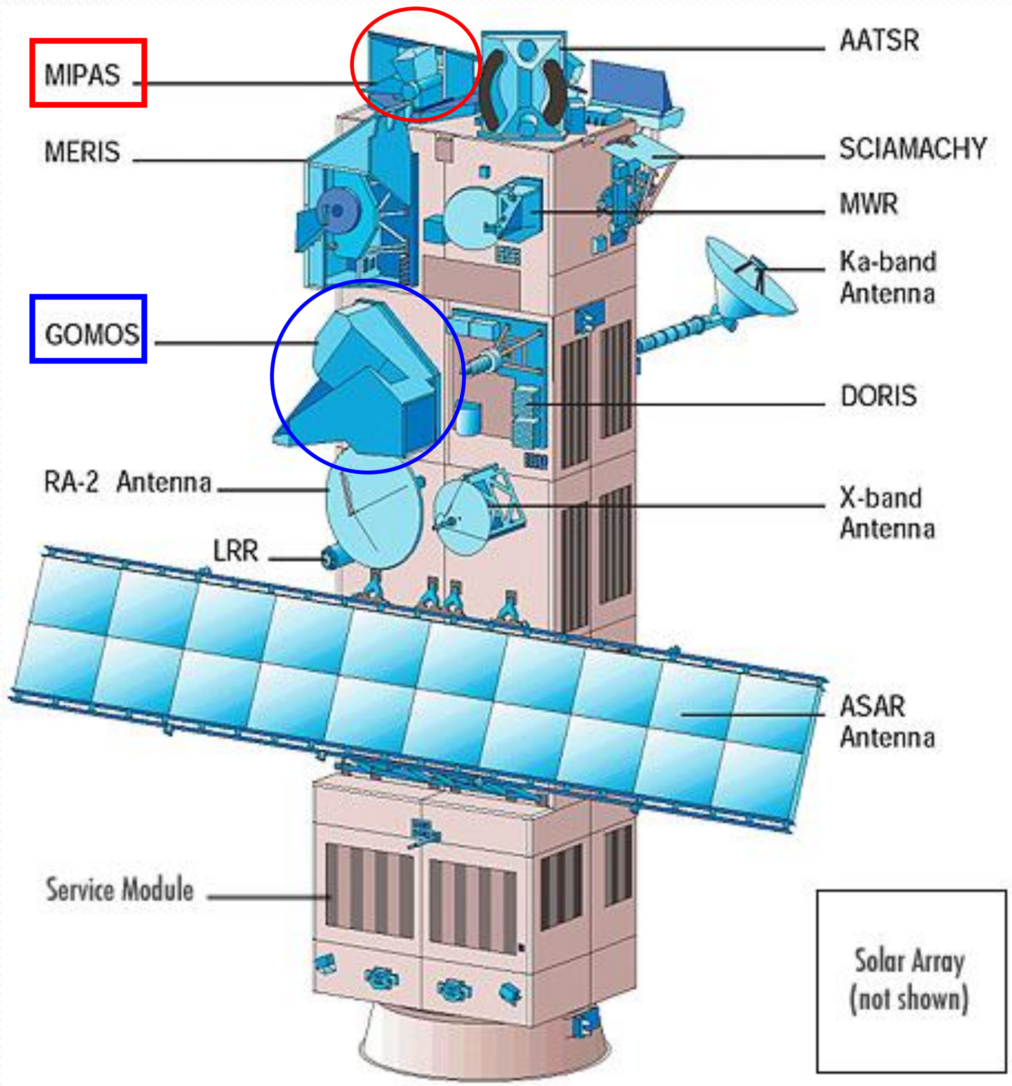
Sealing problem of SSU pressure modulator cell



Time series for "effective" cell pressures deduced from the frequency of oscillation of the modulator cell
Values are adjusted to best fit to the Met Office's 6-monthly estimates.

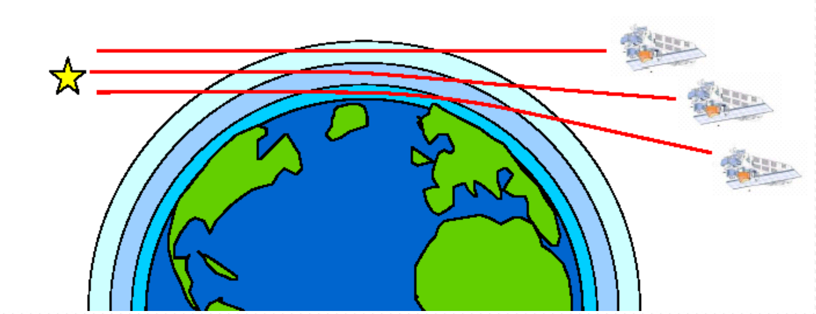
A sealing problem caused cell pressures to increase during storage on the ground and then to decrease after launch.

GOMOS temperature measurements: data updates

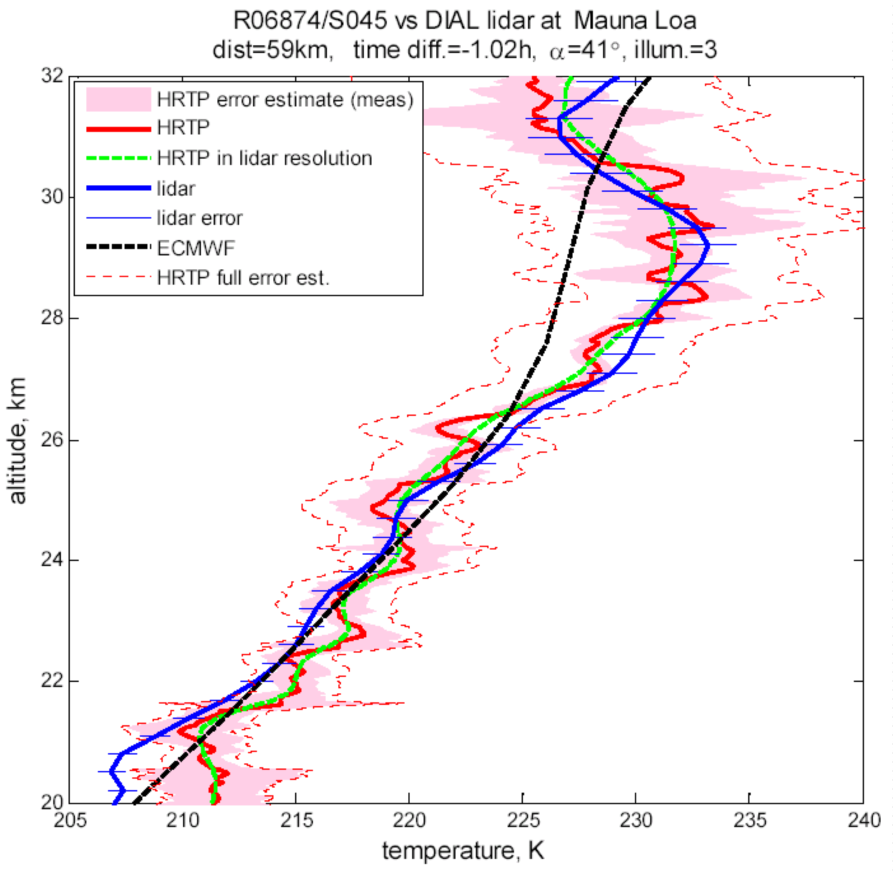


Envisat: 2002 - 2012

High Resolution Temperature Profiles



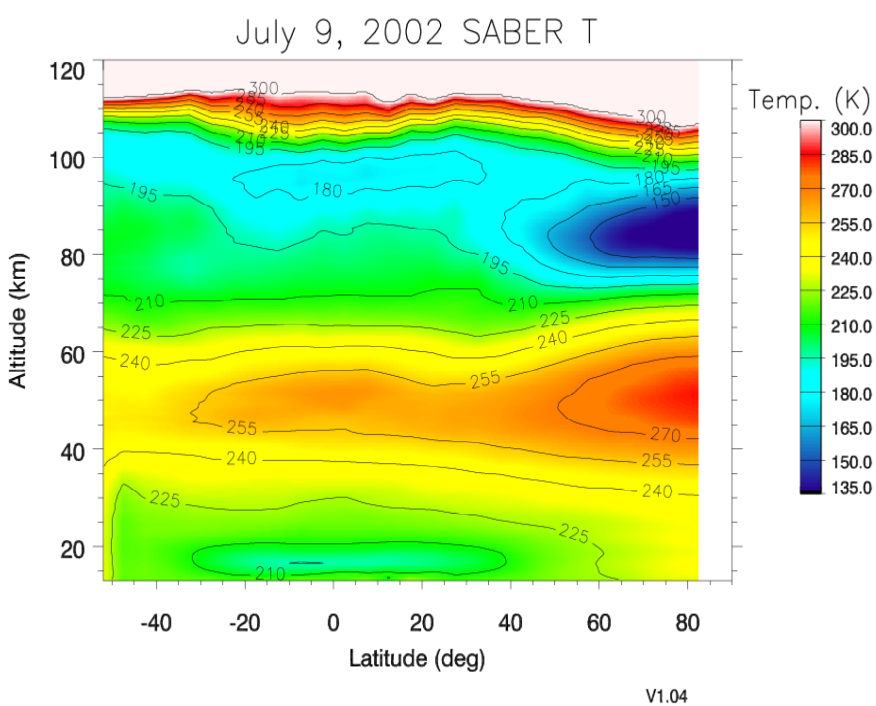
- Unique experiment
  - Based on chromatic refraction
  - Uses scintillation measurements by GOMOS fast photometers
- New reprocessed dataset (with IPF 6.0) is available and under validation
- Main parameters
  - vertical resolution ~200 m
  - precision ~1-2 K
  - Valid altitude range ~15-30 km

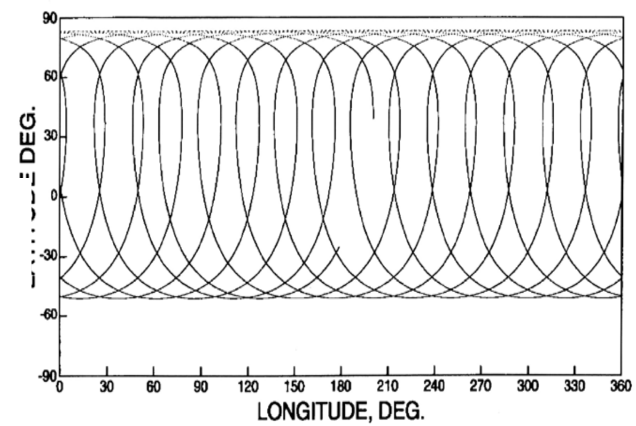


Bill Randel

SABER data details

- Limb emission viewing geometry
- Broadband radiometry, T(p) derived from CO_2 emissions
- Data since late 2001
- Coverage: 50° S – 80° N / 80° S – 50° N (60-day yaw cycles)
- Altitudes ~20-100 km; Vertical resolution ~2 km





Bill Randel

SABER data details

- Limb emission viewing geometry
- Broadband radiometry, T(p) derived from CO_2 emissions
- Data since late 2001
- Coverage: 50° S – 80° N / 80° S – 50° N (60-day yaw cycles)
- Altitudes ~20-100 km; Vertical resolution ~2 km