Stratospheric Temperature Trends
Our Evolving Understanding
and
Applications of GNSS-RO Observations

Dian Seidel
NOAA Air Resources Laboratory
College Park, Maryland, USA

ECMWF - ROM SAF Workshop on Applications of GPS-RO Observations
ECMWF, Reading, UK             16-18 June 2014
Objectives

• Review observed long-term stratospheric T changes
  • Radiosondes
  • Microwave Sounding Unit
  • Stratospheric Sounding Unit
  • Reanalyses

• Highlight areas of uncertainty, observational gaps

• Suggest questions for assessing value and limitations of RO observations
Why do we care about stratospheric temperature change?

- Detection and attribution of climate change
  - Greenhouse gases
  - Stratospheric ozone
- Understanding climate processes that are difficult to measure directly
  - Stratospheric water vapor (T changes at tropical tropopause)
  - Stratospheric circulation (latitudinal structure of T changes)
Models predict large stratospheric T changes

Manabe and Wetherald (JAS, 1967)
Increasing CO$_2$ cools stratosphere in 1-D radiative convective model

Ramanathan et al. (JAS, 1976)
O$_3$ depletion cools stratosphere in 1-D radiative convective model

4xCO$_2$
40° cooling at 40 km

~10° cooling at 40 km
~1° warming at surface
Radiosondes: Long-term, legacy observations

Angell and Korshover (MWR, 1978)

- 42-station radiosonde network, 20-yr record
- Identified volcanic warming, QBO signal, ENSO signal, solar signal, cooling trend, sampling uncertainties
Time-varying biases in radiosonde data

- 100 mb monthly temperature anomalies at Bet Dagan, Israel
- 1968 change from French Metox to American VIZ radiosonde
- Spurious temperature decrease ~ 3 K

_Gaffen_ (JGR, 1994)
Stratospheric T trend uncertainties

- All data points are PUBLISHED global lower-stratospheric trend estimates
- Cooling trends are order of magnitude larger than surface warming trend (~1K/century)
- 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 by several teams
- Different approaches help quantify structural uncertainty
- ~ 1-2 K cooling since 1958; Little change since 1995

20th century satellite observations

![Graph depicting atmospheric layers with labels SSU 1, SSU 2, SSU 3, MSU, and Radiosondes.](image)
Stratospheric T trend uncertainties

- MSU shows less cooling than radiosondes for the same periods
- Spread among trends comparable to trend magnitudes

*Seidel et al.* (WIREs Climate Change 2011)
Current MSU analyses

global T anomalies (K)

MSU channel 4 (∼15–35 km)

RSS
NOAA
UAH

Thompson et al. (Nature 2012)
Comparison of MSU analyses
interquartile range of monthly zonal anomalies

<table>
<thead>
<tr>
<th></th>
<th>NOAA</th>
<th>RSS</th>
<th>UAH</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.7</td>
<td>0.6</td>
<td>0.8</td>
<td>Global IQR(K)</td>
</tr>
</tbody>
</table>

![Graph showing comparison of interquartile range (IQR) of monthly zonal anomalies for different datasets: NOAA, RSS, and UAH, with values at specific latitudes. The IQR values range from 0.6 to 1.6 K.]
Lower Stratospheric Temperature Anomalies (K)
(MSU and AMSU observations - Mears and Wentz, 2009)
Stratospheric Sounding Unit (SSU) on NOAA Polar Orbiters 1979-2005

“Raw” brightness temperatures from multiple SSUs
SSU research in 21st century

- SSU record ends in 2005, but community remains interested in unique UKMO dataset
- 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 creates second SSU dataset, different merging and adjustment methods (Wang et al. J. Climate 2012)
- Differences between datasets deemed a “mystery” (Thompson et al. Nature 2012)
- Re-examination by both NOAA and UKMO. New versions forthcoming.
Lower Stratosphere: SSU and MSU

SSU channel 1 (~25–35 km)

Met Office SSU Data

MSU channel 4 (~15–35 km)

RSS MSU Data
Lower Stratosphere: SSU and MSU

SSU channel 1 (~25–35 km)

MSU channel 4 (~15–35 km)

Year


K

-1.5 -1 -0.5

Met Office SSU Data
NOAA SSU Data

RSS MSU Data
NOAA MSU Data
UAH MSU Data
Comparing Models with SSU and MSU

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
Do reanalyses help?

T Anomalies in 6 Reanalyses

1979 – 2012

Temperature scale: -8 to +8 K

1000 – 300 hPa

Figure courtesy of Craig Long
SPARC Analysis-Reanalysis Intercomparison Project
Do reanalyses help?

T Anomalies in 6 Reanalyses
1979 – 2012

Temperature scale: -8 to +8 K
1000 – top

Figure courtesy of Craig Long
SPARC Analysis-Reanalysis Intercomparison Project
Summary of Stratospheric T “Trends”

• 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 (and reanalyses) for detecting changes are not ideal.
  • Progress has been slow.
  • Large uncertainties remain and need to be better quantified.
  • Lack of reference-quality observations a major problem.

• 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.
Questions about the potential value of GPS-RO to the climate observing system (response to 2008 COSMIC workshop at UCAR, Boulder)

1. Comparability of data from different COSMIC satellites
   • Are claims of 0.02-0.05 K precision (surface – 30 km) realistic?
2. Comparability of CHAMP and COSMIC (and other?) GPS satellite systems
3. Reproducibility of refractivity results
   • Source of differences among 4 centers
4. Reproducibility of temperature results
5. Impact of assumptions on both refractivity and retrieved profiles
   • Ionospheric structure, 1st guess temperature and humidity profiles, ...
6. Observed refractivity (or delay) vs. retrieved meteorological profiles
   • Potential value of refractivity as a benchmark climate variable
7. Profiling of the lower troposphere
   • (now I’d add the middle and upper stratosphere as concerns)
8. Impact of observations scattered across space and time
   • Suggested similar sampling of climate model runs to evaluate
9. Potential aliasing by water vapor changes in GPS-RO temperature time series
10. Water vapor retrievals
Current questions for climate applications of GPS RO

- Vertical domain of useful measurements
- Variables of most utility (refractivity, $T_{\text{dry}}$?)
- Expected longevity of measurements
- Ground-based measurements needed to optimize long-term record. Possible coordination with GCOS Reference Upper Air Network (GRUAN)
Thank you!
GNSS radio occultation satellite missions: past, current, planned...

Status of the Global Observing System for Radio Occultation (Update 2013), IROWG/DOC/2013/02

www.irowg.org/workshops.html

Figure courtesy of Andrea Steiner
SPARC T Trends Activity References


### Other 21st C. Observations

<table>
<thead>
<tr>
<th></th>
<th>GNSS-RO</th>
<th>SABER</th>
<th>GOMOS</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Principle</strong></td>
<td>Refractivity-dependent time delay of radio transmission</td>
<td>Broadband radiometry; CO2 emissions</td>
<td>Chromatic refractivity; scintillation measurements</td>
</tr>
<tr>
<td><strong>Altitude Range (km)</strong></td>
<td>8-25</td>
<td>20-100</td>
<td>15-30</td>
</tr>
<tr>
<td><strong>Vertical Resolution (m)</strong></td>
<td>200</td>
<td>2000</td>
<td>200</td>
</tr>
<tr>
<td><strong>Period of Obs.</strong></td>
<td>~2006-present</td>
<td>2001-present</td>
<td>2002-2012</td>
</tr>
<tr>
<td><strong>Maturity of analysis effort</strong></td>
<td>High</td>
<td>low</td>
<td>low</td>
</tr>
</tbody>
</table>

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)
21st C. Observations from Polar Orbiters

Figure courtesy of A. Simmons
AMSU weighting functions

TIDE EFFECTS ON STRATOSPHERIC TEMPERATURE DERIVED FROM SUCCESSIVE ADVANCED MICROWAVE SOUNDING UNITS
AMSU series from channels 11-14

NOAA 15  NOAA 16  NOAA 18  METOP A  NOAA 19

TIDE EFFECTS ON STRATOSPHERIC TEMPERATURE DERIVED FROM SUCCESSIVE ADVANCED MICROWAVE SOUNDING UNITS
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
SABER data details

- Limb emission viewing geometry
- Broadband radiometry, $T(p)$ derived from $\text{CO}_2$ emissions
- Data since late 2001
- Coverage: $50^\circ$ S – $80^\circ$ N / $80^\circ$ S – $50^\circ$ N (60-day yaw cycles)
- Altitudes ~20-100 km; Vertical resolution ~2 km
SABER T Anomalies (50°N-S)

Unpublished data, courtesy of Bill Randel