Session 1: Role of the Sun in Climate Change During the SORCE Mission

Panel Discussion: Current & Future Plans for Sun-Climate Research

Session	**SORCE Top Ten Achievements** (*EOS*, **25**, Jan-Feb 2013)
Wed. S4	1. New TSI Level
Tue. S2	2. New SSI Record for 115-2400 nm range
Tue. S2	3. New SSI Reference Spectra
Tue. S1 & Wed. S3	4. Use of SORCE SSI & TSI in Climate Modeling
Fri. S6	5. Next-generation, highly-accurate Radiometers
Thur. S5	6. Extension of NOAA Mg II Solar Proxy
Tue. S2	7. Large Flare Measurements in SSI and TSI
Wed. S4 & Thur. S5	8. Advanced Models of the TSI and SSI
	9. Venus and Mercury Transit Observations
	10. Improved Calibrations for Stars and Lunar Reflectance

Wednesday Poster Session includes most of these topics.

After 11 years with SORCE – What's new? What's next?

Robert F. Cahalan

Climate & Radiation Laboratory, NASA-Goddard

SORCE, TCTE & Free Flyer-TSIS Project Scientist

Peter Pilewskie, TSIS PI
Tom Woods, SORCE PI
University of Colorado - LASP

Thanks also to Greg Kopp, Jerry Harder, and other LASP colleagues & to others at GSFC and NIST

– Changes in estimates of the Total Solar Irradiance (TSI), Earth's albedo, and Earth's outgoing longwave radiation
– Historic closing of calibration gap between the suite of TSI instruments, with Transfer Radiometer Facility (TRF)
– Climate models sensitive not only to TSI, but to variations in the *Spectral* Solar Irradiance (SSI) & vertical profiles of temperature and ozone are especially sensitive to SSI.
– SIM indicates multiyear changes at visible and near-infrared wavelengths *out of phase* with TSI,
– Out-of-phase SSI forcing can lead to larger temperature variations in the upper stratosphere, but smaller variations in troposphere and upper ocean.
– Variations in SSI need further study before they may be considered firmly established.
– TSIS SIM has recently undergone comprehensive end-to-end calibration in the LASP SSI Radiometry Facility (SRF) utilizing the NIST SIRCUS system covering 210 – 2400 nm for SSI, not yet available when SORCE launched.
– SORCE follow-on mission Total and Spectral Solar Irradiance Sensor (TSIS), could reduce uncertainty in SSI variability
– Long-term goal of improving the ability to monitor Earth's energy balance, and energy *imbalance* that drives global warming, requires improved measurements of both shortwave and longwave earth-emitted radiation.
– *Lunar Borehole Experiment* has potential to recover changes in TSI over past 400 years; could clarify "Little Ice Age."

SORCE has logged more than 1.6 billion miles!

WolframAlpha PRO

2Pi*(4344 miles)*59716

Examples Random

Input interpretation:

$2\pi \times 4344$ miles $\times 59\,716$

Result:

1.63 billion miles

Unit conversions:

2.623×10^9 km (kilometers)

2.623×10^{12} meters

2.43 light hours

Comparison as length:

$\approx 4.6 \times$ length of the longest observed comet tail (Hyakutake 1996) ($\approx 5.7 \times 10^{11}$ m)

Comparison as diameter:

$\approx 3 \times$ optical diameter of Betelgeuse ($\approx$ 900 Gm)

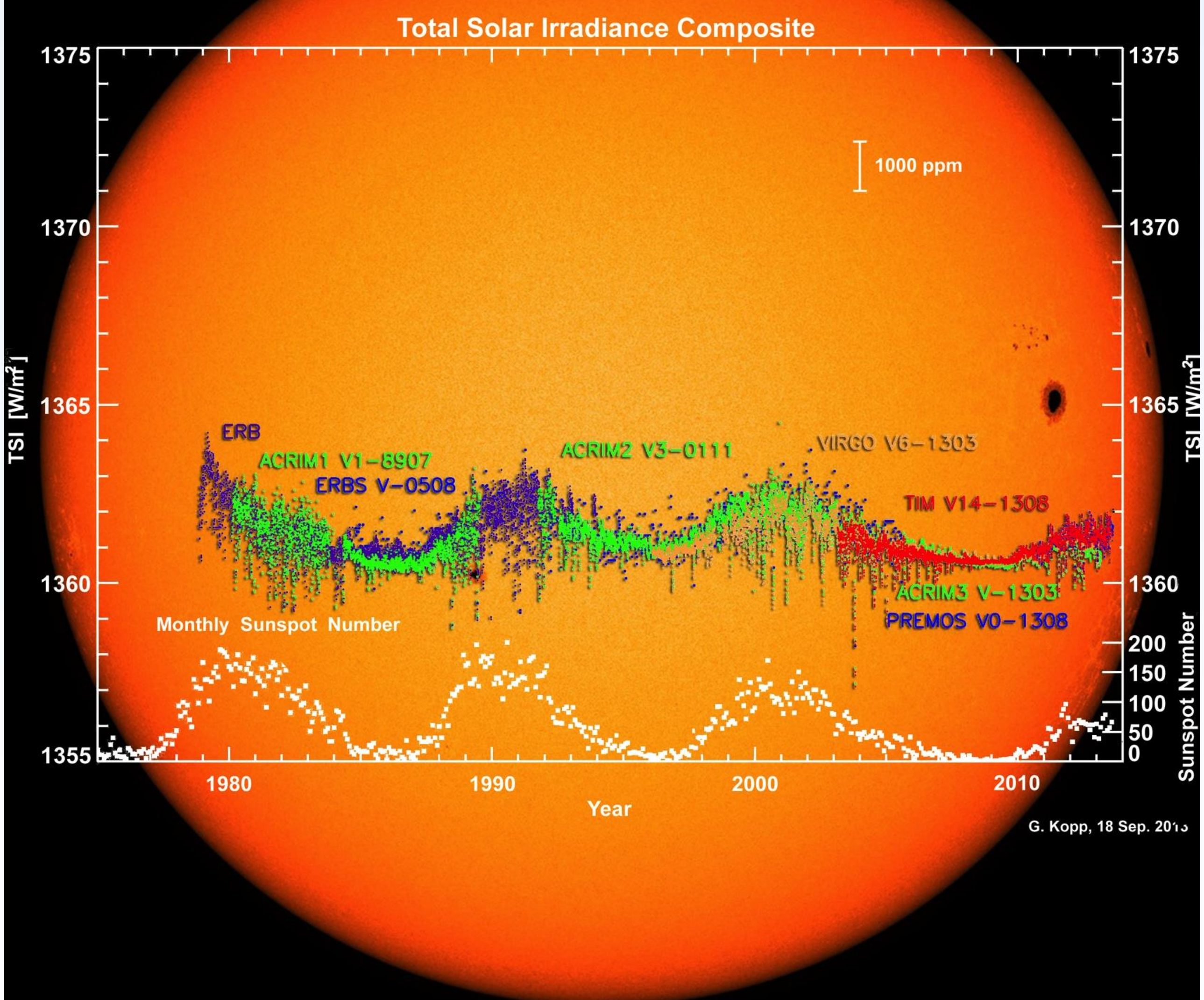
Comparisons as distance:

$\approx 0.2 \times$ smallest distance from the Sun to the heliosheath (79 to 100 au)

$\approx 0.35 \times$ distance from the Sun to the Kuiper cliff ($\approx 7.48 \times 10^{12}$ m)

$\approx 0.44 \times$ semimajor axis of Pluto's orbit ($5.906376272 \times 10^{12}$ m)

TSI “outlier” has become the “standard”



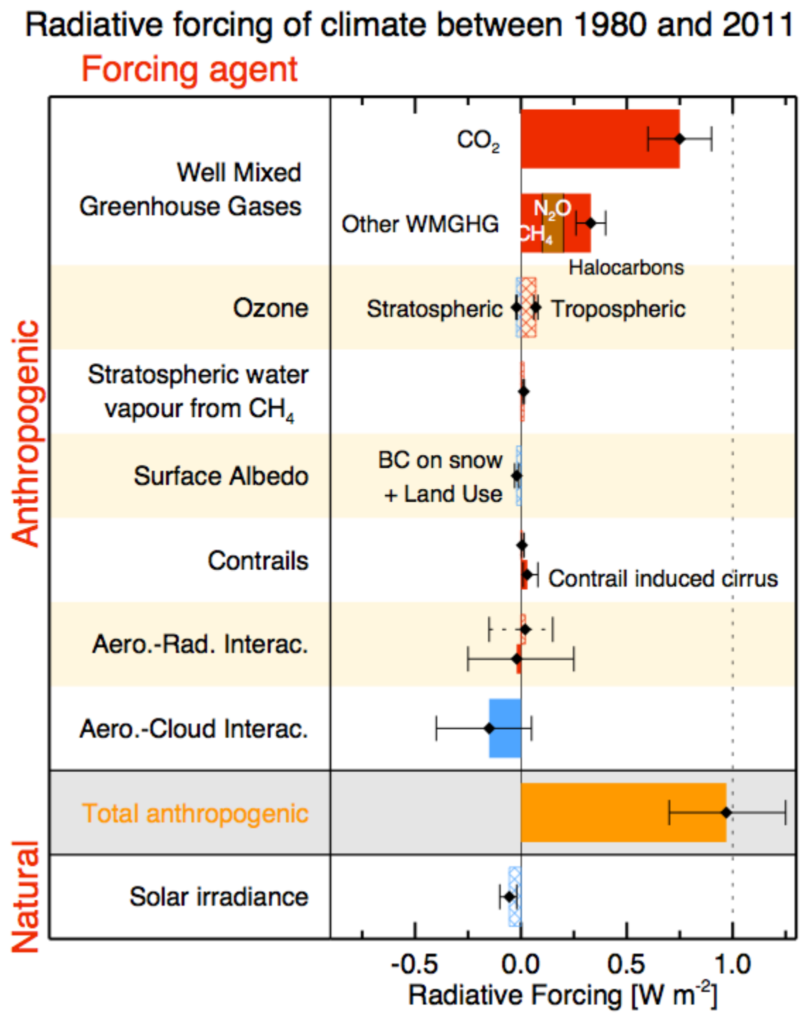
Total solar irradiance (shown in color) over the past three solar cycles since 1978 adjusted to a ground-based cryogenic instrument funded by NASA in collaboration with the National Institute of Standards and Technology (NIST).

Image Credit: Greg Kopp, LASP, University of Colorado / NASA

TCTE launched on November 19, 2013 from NASA Wallops Flight Facility

"We're at Cocoa Beach FL this week to celebrate 11th birthday of SORCE, launched from Kennedy Jan 25 2003 & still after 60,000 Earth orbits is measuring our Sun's total energy & energy spectrum for wavelengths from 1 to 2400 nanometers."

TCTE & TSIS to continue solar irradiance needed by IPCC



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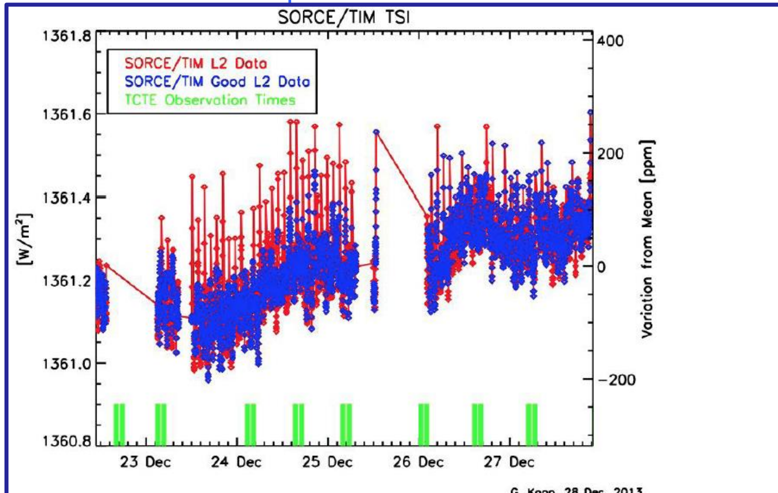


Fig. 5.1.2: The TCTE/TIM acquired overlapping measurements at the times shown in green with the SORCE/TIM (TSI measurements shown in red and blue) throughout the campaign.

Figure 8.20: Bar chart for RF (hatched) and ERF (solid) for the period 1980–2011, where the total anthropogenic ERF are derived from Monte-Carlo simulations similar to Figure 8.16. Uncertainties (5–95% confidence range) are given for RF (dotted lines) and ERF (solid lines).

Robert F. Cahalan

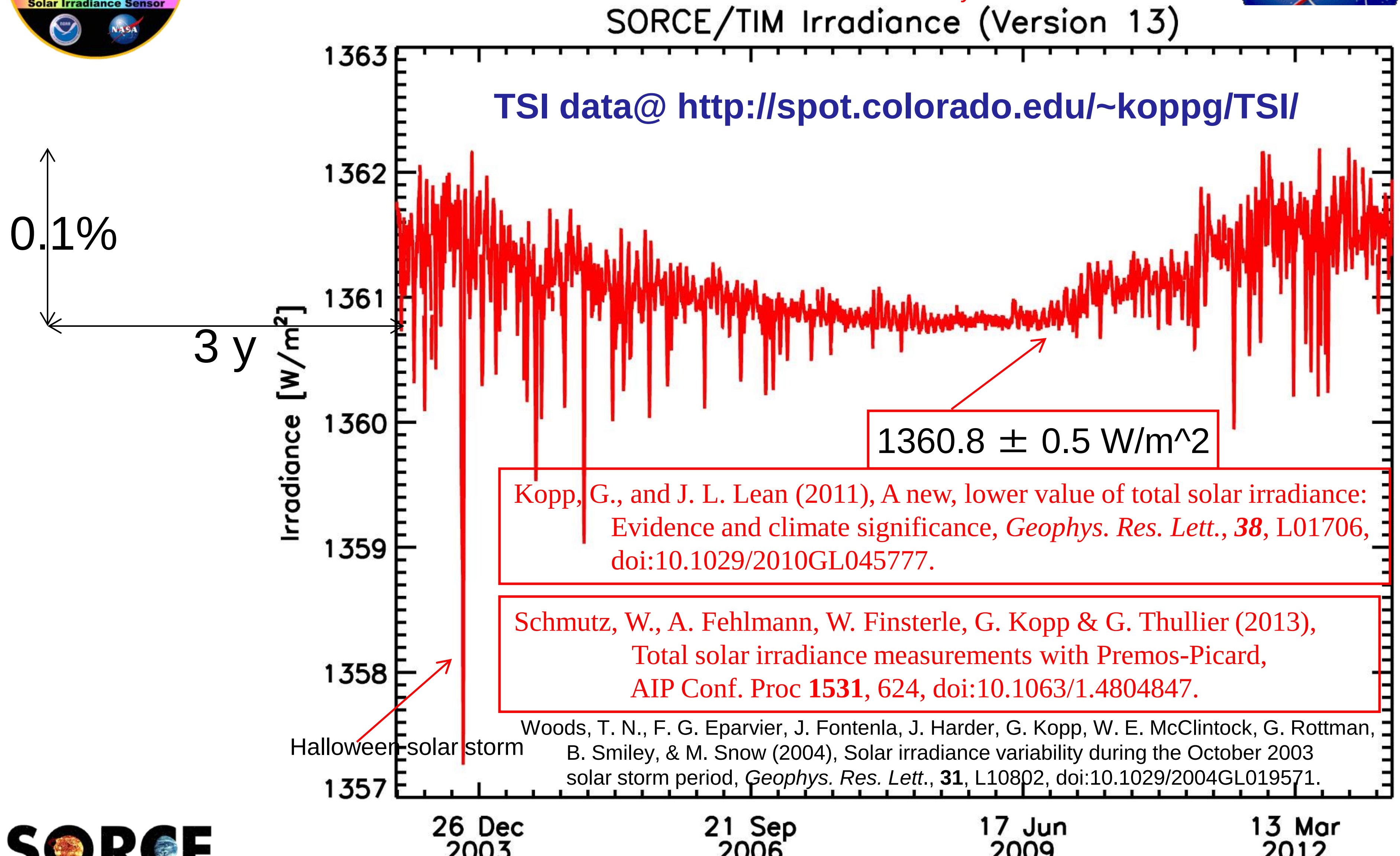
TSI Record: Total Irradiance Monitor (TIM) (daily)

University of Colorado, Boulder

TSIS Total and Spectral Solar Irradiance Sensor

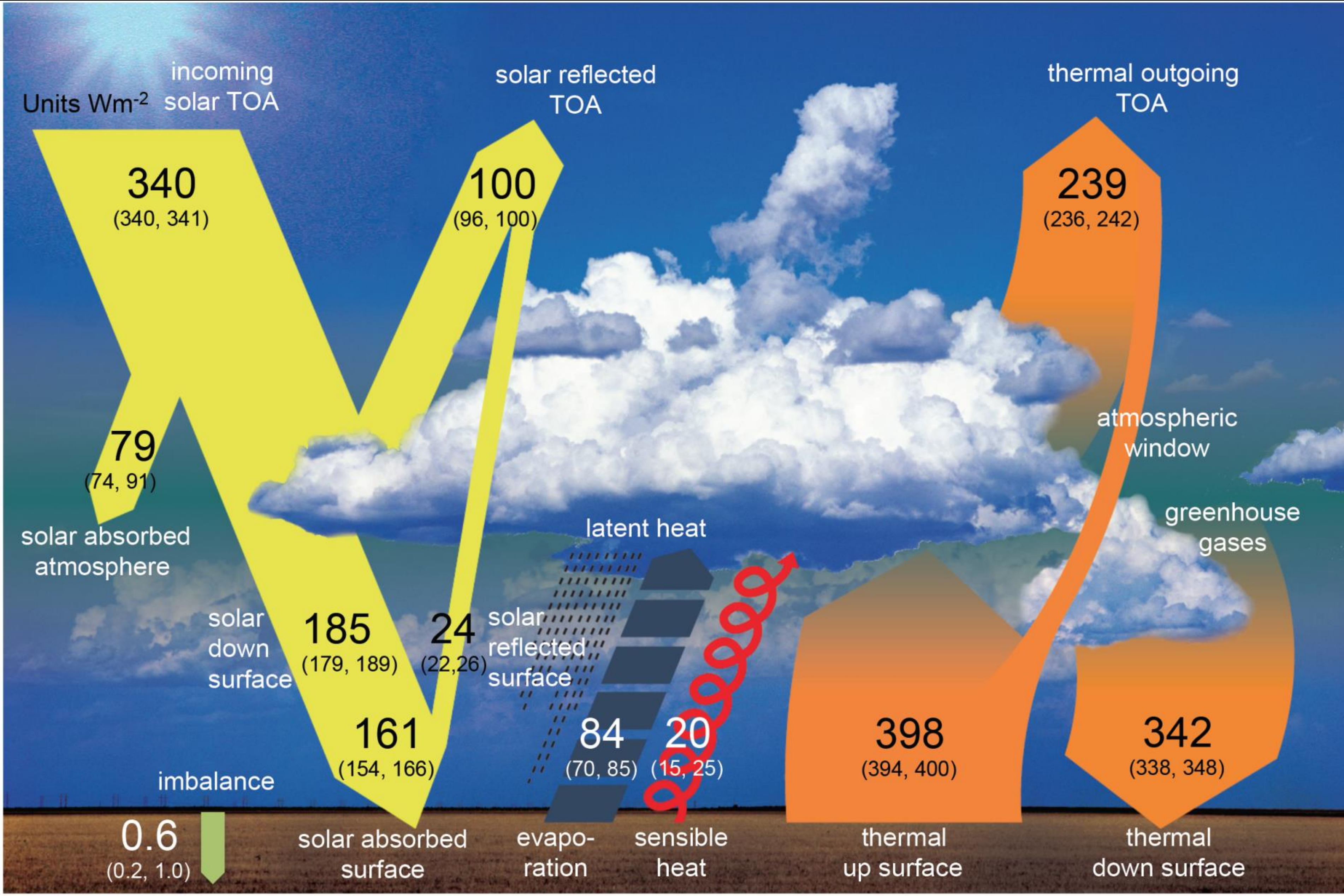
The Climate "Gold Standard" →

20thC estimates varied from 1340 to 1420, i.e. ± 3 %. Today we know TSI to ~0.03%



Plot Courtesy Greg Kopp

Earth's Planetary Energy Balance (Wild et al, 2013)



What have we learned during solar cycle 23?

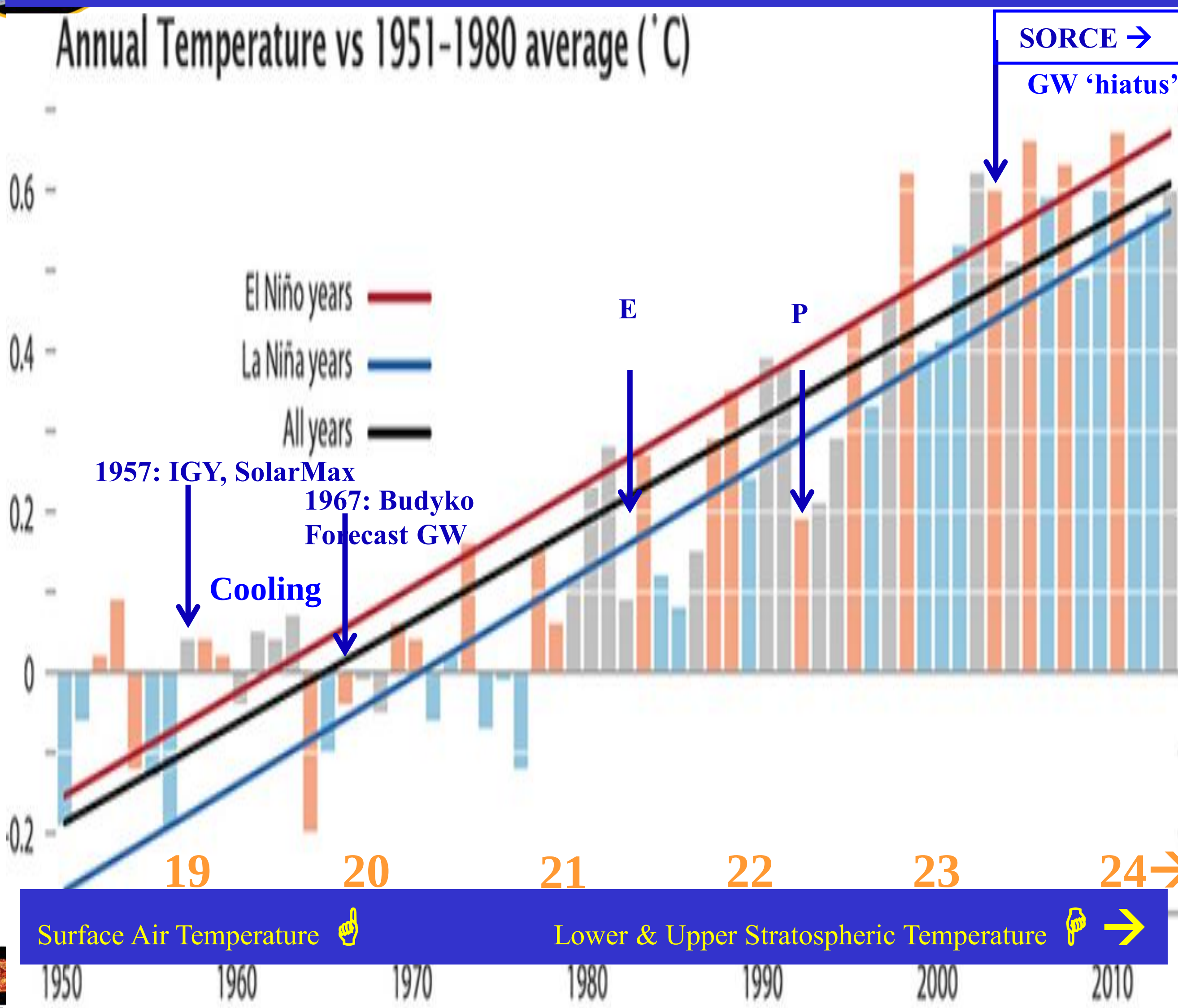
- **TSI = 1360.8 ± 0.5 W/m^2, ~ 4.5 W/m^2 (0.33%) lower than previously accepted**
  - 1360.8/4 ~= 340; Reflected ~= 100 W/m^2, and Emitted ~= 240 W/m^2
  - Net Imbalance ~ 0.5 W/m^2 – based on ocean heat storage estimate. (Estimates vary.)
  - Imbalance implies continued warming – Greenhouse dominates, Sun a player.
  - Cycle 23 Minimum TSI slightly lower than Cycle 22 Minimum, offsets some warming
- **Albedo smaller, ~29% (vs ~31%) – more solar absorbed than previously accepted**
- **Atmospheric Absorption larger ~23% (vs ~20%) due to Aerosol & H20 Continuum**
- Sun's Spectral shape may change, as does Earth's (***Controversial***.)
  - Near-Ultraviolet changes may be large enough to give 1.0 K variations at ~40 km
  - Visible and Near-Infrared changes may be out-of-phase with TSI.
  - TSI, integral of spectrum, may consist of spectral regions with compensating effects.
  - Surface solar forcing very small, direct surface response < 0.1 K in 11-year cycle

Between 2000 & 2012, during cycle 23, Earth's human population increased from 6 billion to 7 billion.

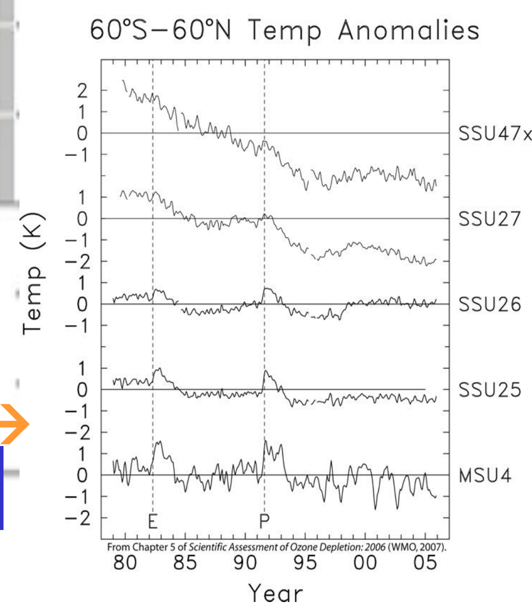
In 2013, atmospheric CO_2 reached 400 ppm, 43% above a pre-industrial 280 ppm, constant to 10% for 10,000 years.

Temperatures are rising ☝

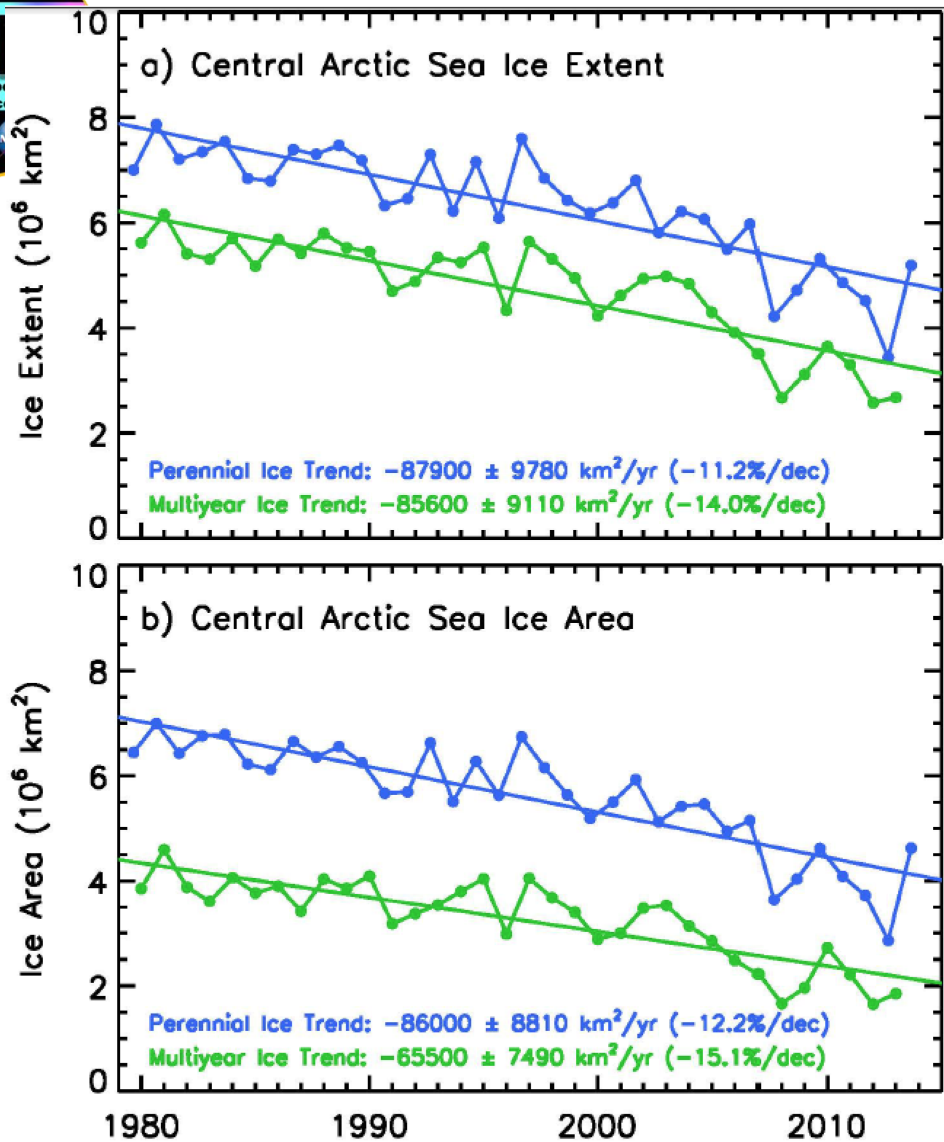
Earth's surface temperature has risen 0.6°C~1.1˚ F since 1950. The three major surface temperature data sets (NCDC, GISS, and HadCRU) all show global temperatures have warmed by 0.16 – 0.17°C (0.28 – 0.30°F) per decade since satellite measurements began in 1979.



Departure from average of annual global temperatures between 1950 – 2013, classified by phase of the El Niño-Southern Oscillation (ENSO). The year 2009 was the warmest year on record when a La Niña event was present. ENSO is a natural episodic fluctuation in sea surface temperature (El Niño/La Niña) and the air pressure of the overlying atmosphere (Southern Oscillation) across the equatorial Pacific Ocean. Over a period of months to a few years, ENSO fluctuates between warmer-than-average ocean surface waters (El Niño) and cooler-than-average ocean surface waters (La Niña) in that region.(source: G. Schmidt, NASA–GISS)



Arctic Ice is melting



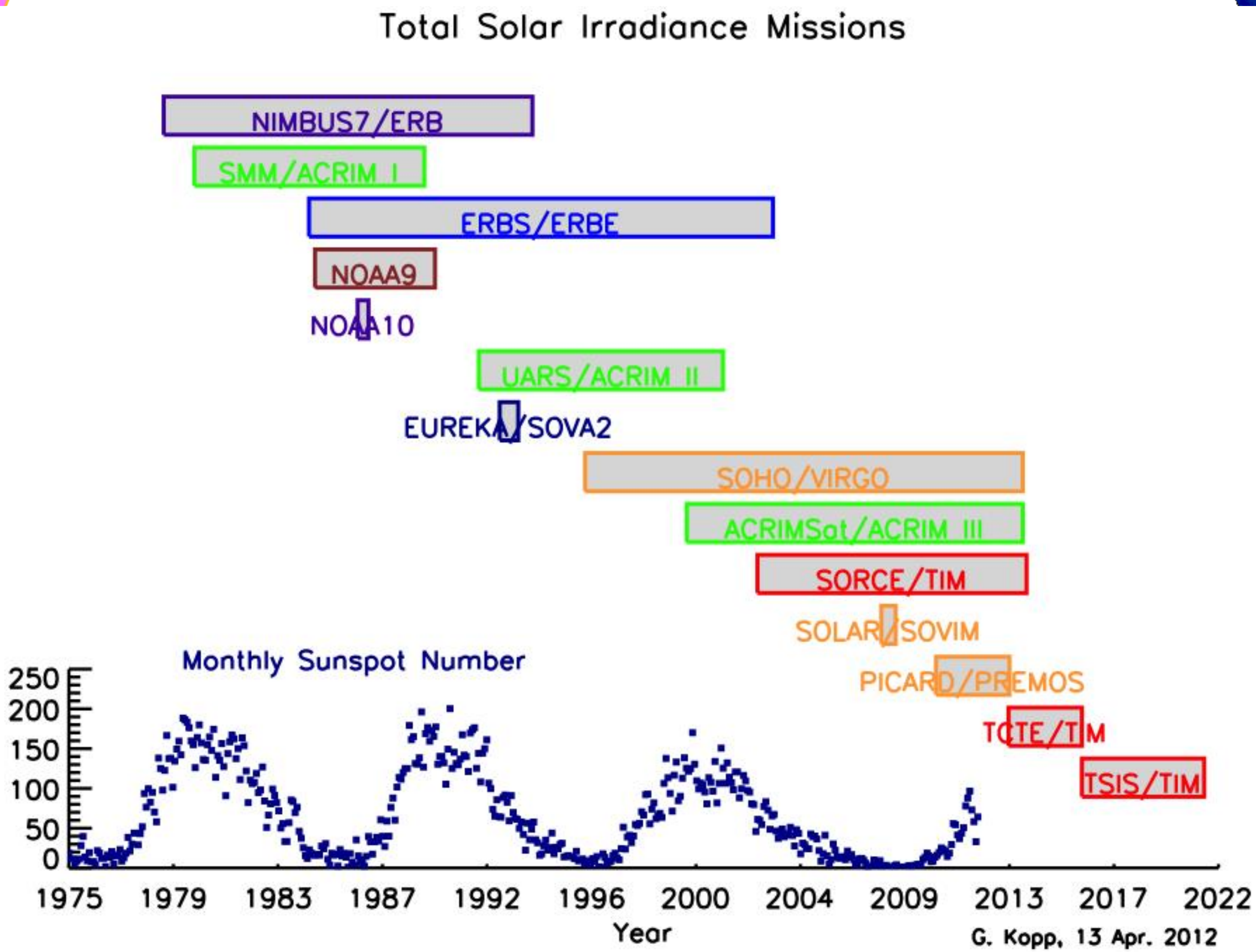
21 22 23 24

Warming and Melting are both raising sea level.

Actic Sea Ice

Global Sea Level →

- **Future TCTE-TSIS overlap *could* plug TSI time gap.**



Continuity of 35+year TSI Record

- Loss of Glory-TIM at launch on March 4, 2011
- Delay of TSIS Flight Opportunity to 2016+

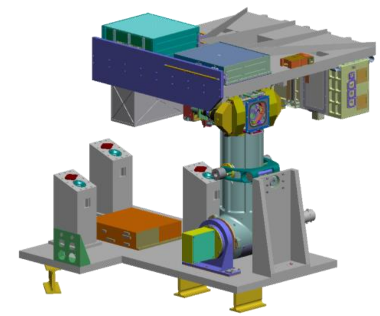
SORCE/TIM

SORCE : 2003 – 2015 ??

Glory/TIM

2011 - 2014 (failed)

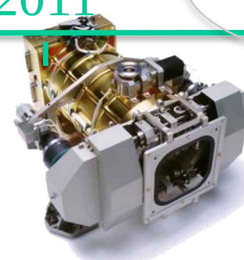
JPSS Free Flyer/TSIS



TSIS : July, 2016 LRD

1978 2003 2011 Gap Risk 2016 2021

TSI record continued since 1978



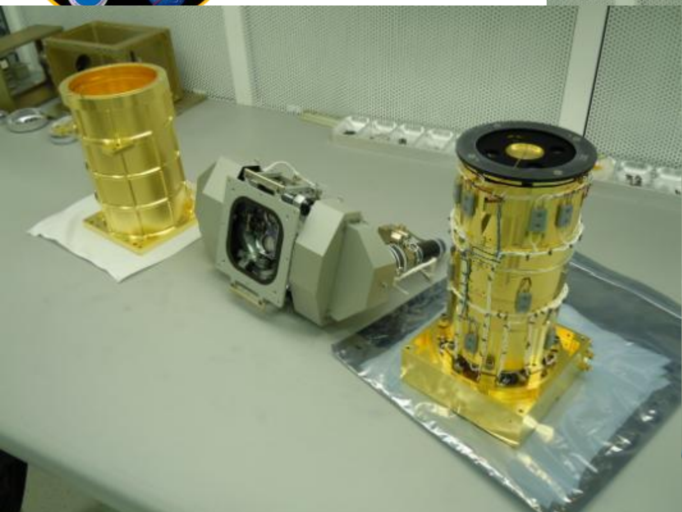
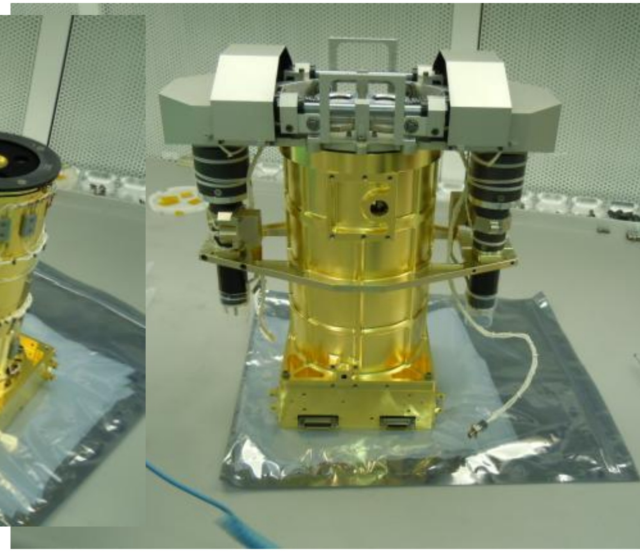
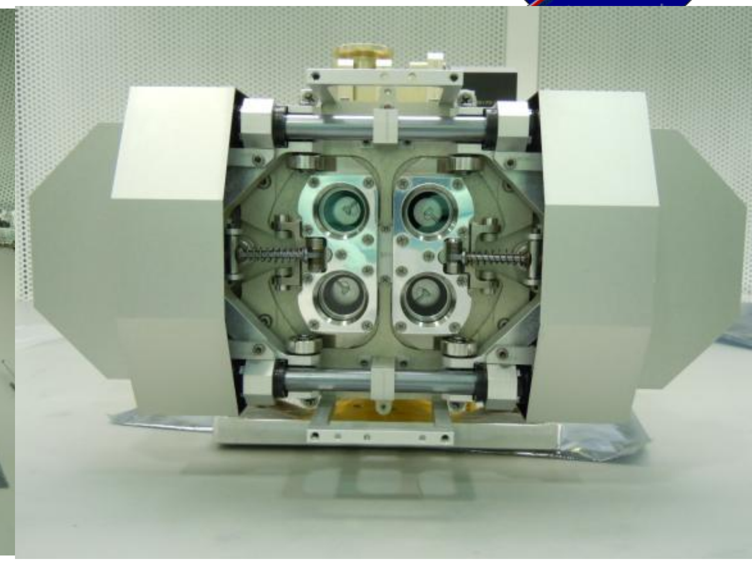
TCTE : 2013-2016 (expected)

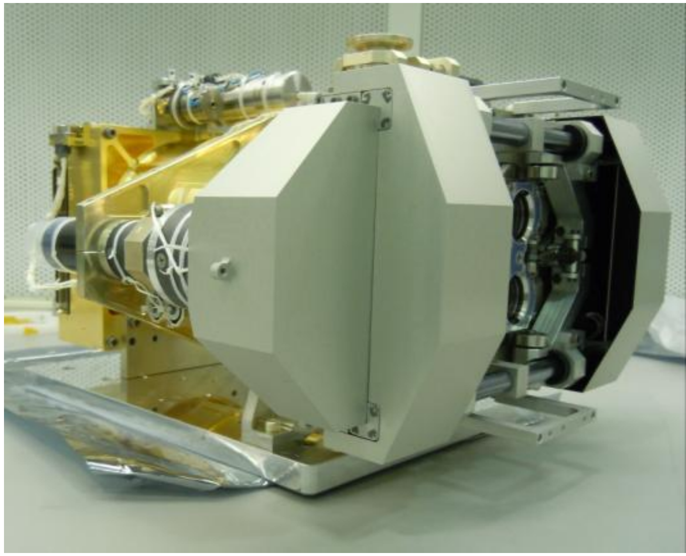
- **To bridge continuity gap in 35 year TSI record continuity, SORCE-TIM Calibration Transfer Exp't (TCTE) is selected -Air Force STPSat3 — Dec 2013.**

SORCE

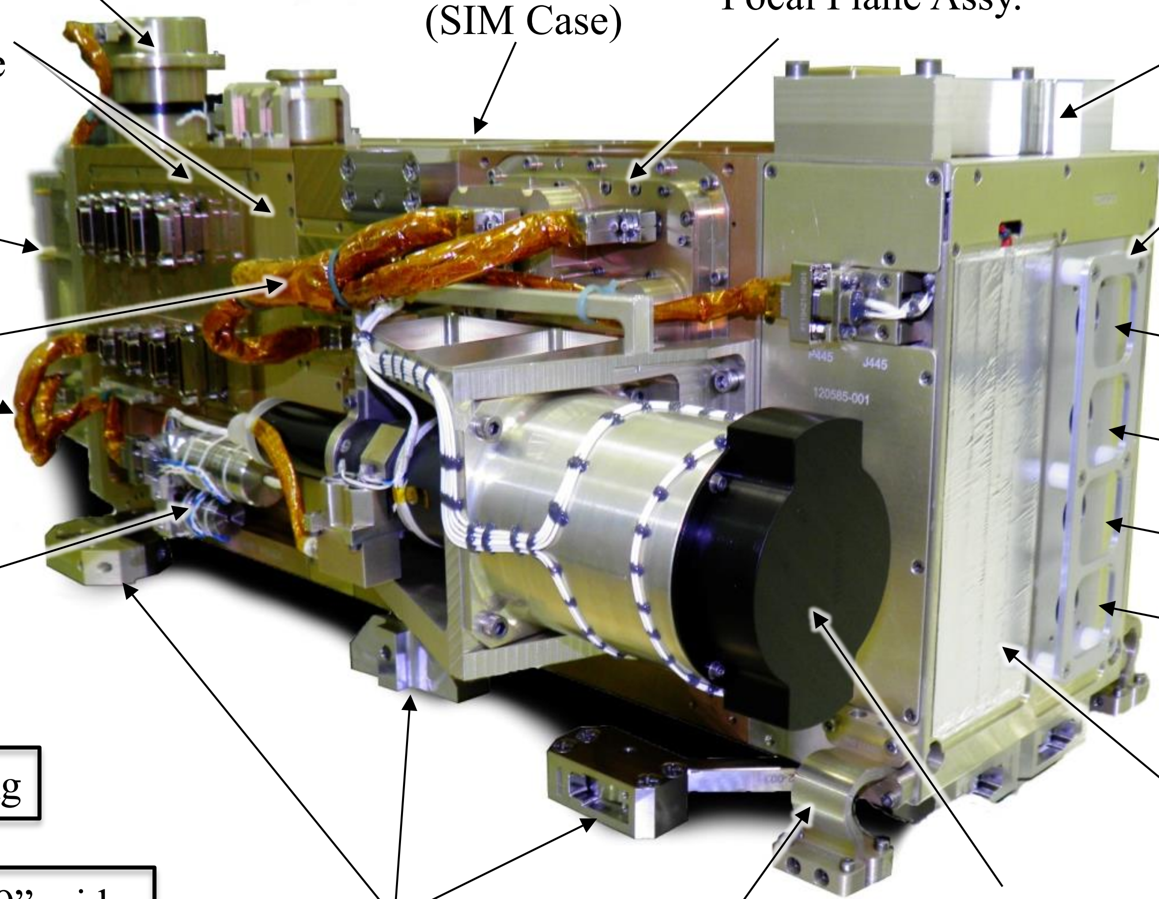
TSIS FM-1 delivered Dec 2013 !

TSIS TIM Assembly:

TSIS TIM & ***SIM*** now in storage



Mass = 14.5 kg

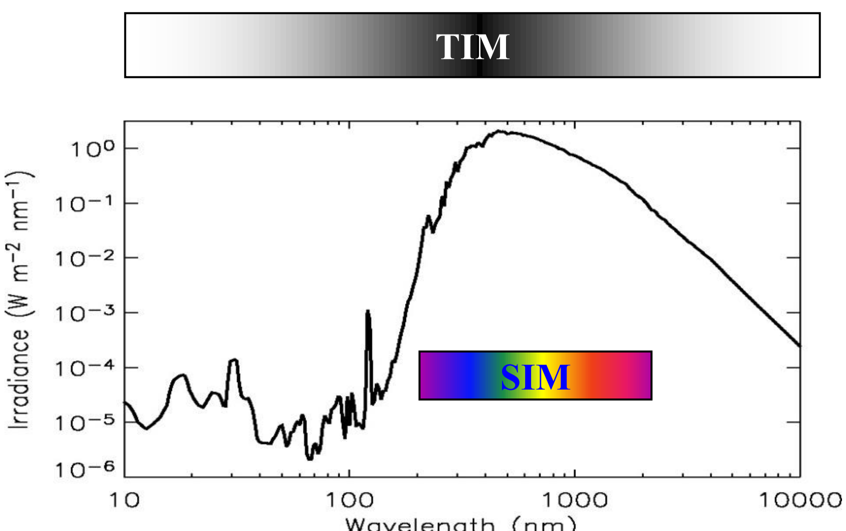
Size: 10.9” wide
10.1” tall
24.3” long

TSIS Top Level Requirements

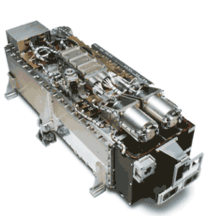
Level 1 Performance Requirement Parameter	TIM Requirement	SIM Requirement
Measured Spectrum	Total solar spectrum	200-2400 nm
Measurement Accuracy	0.01% with noise $\leq$ 0.001%	0.2%
Measurement Stability (long term)	0.001% per year	0.05%/yr (<400 nm) 0.01%/yr (>400 nm)
Spectral Resolution	n/a	1 nm: (< 280 nm) 5 nm: (280 to 400 nm) 35nm: (>400 nm)
Reporting Frequency	4 six hourly averages per day	2 spectra per day
Data processing approach	Consistent with SORCE approach for continuity	Consistent with SORCE approach for continuity

Summary – TSI / SSI Continuity

- **TCTE launch June 2013 *intended to* maintain TSI Data Record Continuity**
  - Glory loss threatened gap in solar irradiance record, but …
  - TCTE overlapped SORCE by 7 days; hope for overlap with TSIS by 50+ days
- **TCTE *lacks* the *Spectral* Irradiance Monitor (*SIM*), but *TSIS* will include *SIM***
  - *SORCE age means likely **gap*** in 10+ year record of SORCE-SIM Solar ***Spectral*** Irradiance
- **TSIS Free Flyer launch expected 2017, but 2014 budget allocated <u>$00M</u>**
  - "NOAA received no funding of the $62M requested for the Polar Free Flyer program. The budget language indicates that NOAA should work with the FY 2015 budget and develop a strategy to address short- and long-term challenges associated with the possible gap in polar data, including reexamining the Polar Free Flyer program." –Mary E. Kicza



TIM



SIM

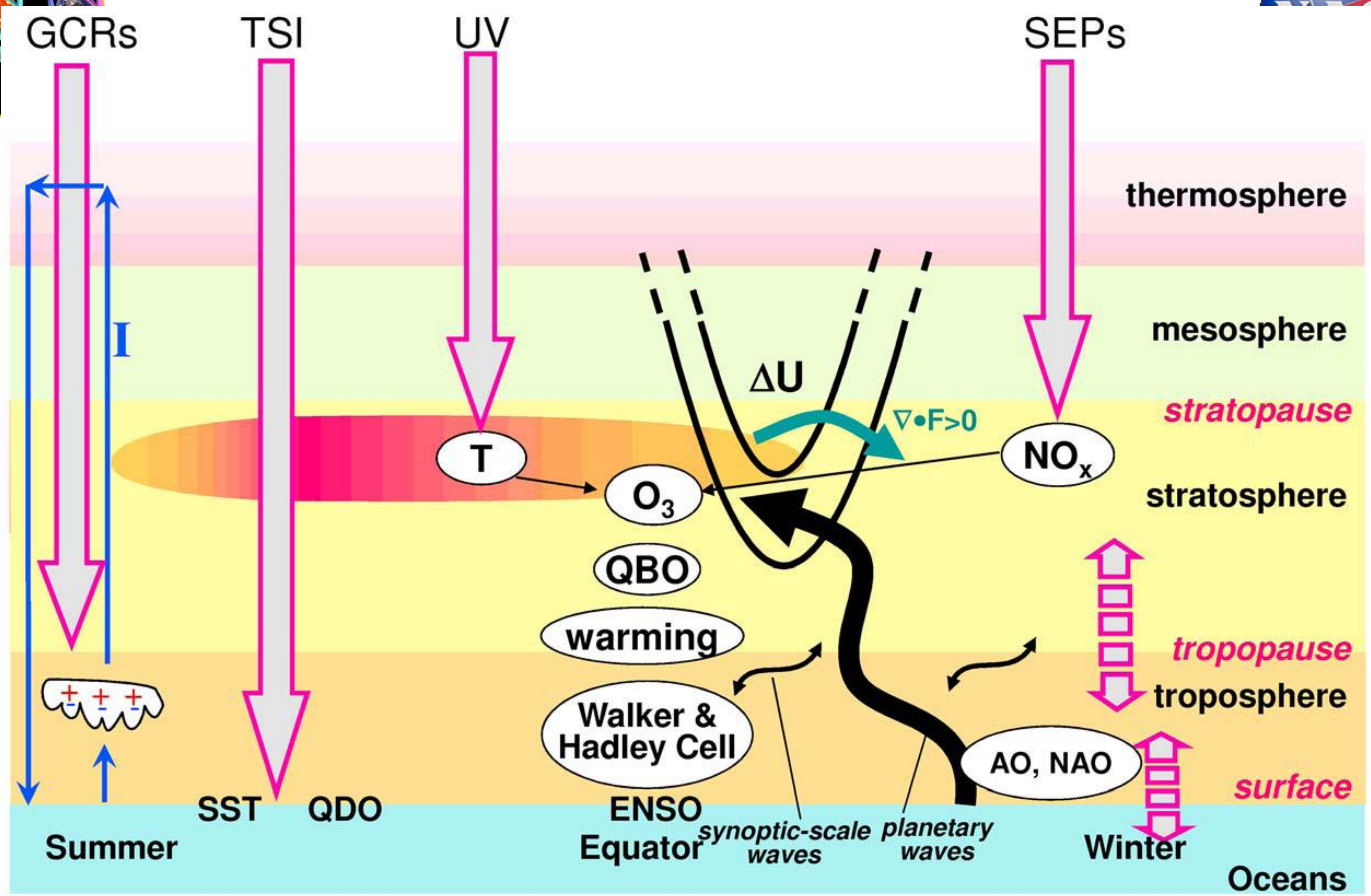
Sun-Climate Questions

- What is the solar forcing at decadal and longer time scales?
  - Solar Irradiance Climate Data Record (CDR): time series of measurements of sufficient length, consistency, and continuity to determine climate variability and change.
- How does the climate system respond?
  - What are the mechanisms of climate response? Requires measurement of wavelength-dependent irradiance variability.
  - Can a solar climate signal be attributed to unique mechanisms?
  - How does the climate response to solar forcing differ from other forcings, for example, greenhouse gas forcing?

Attribution

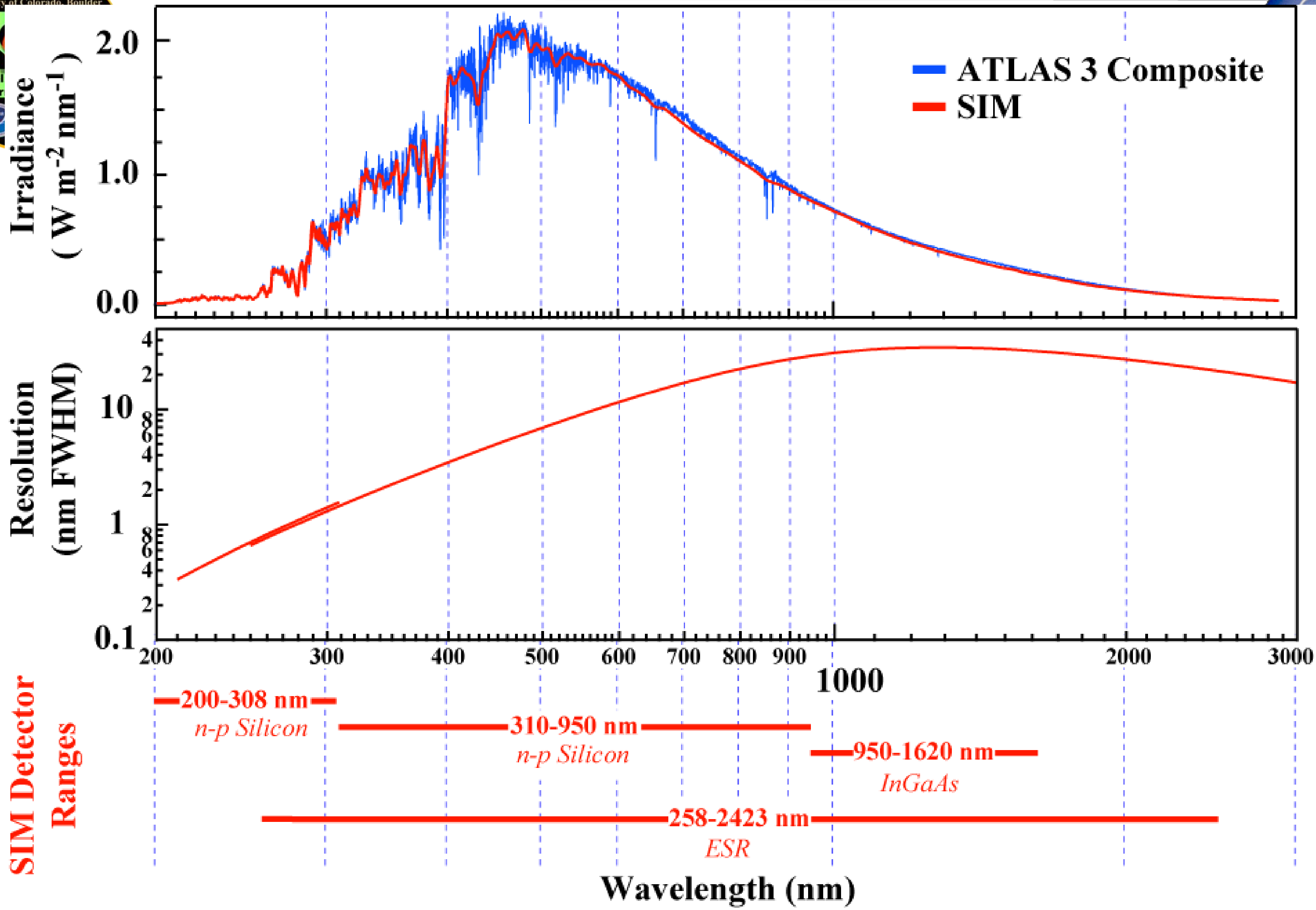
- How much of the 20th-century warming trend was due to anthropogenic forcing?
  - Requires rigorous probabilistic analysis and highly accurate forcings.
- What are the expected climate changes for the 21st century?

Solar Influences on Climate



Gray, L. J., et al. (2010), Solar influences on climate, *Rev. Geophys.*, 48, RG4001, 2009.

SIM and SOLSPEC Irradiance Spectra

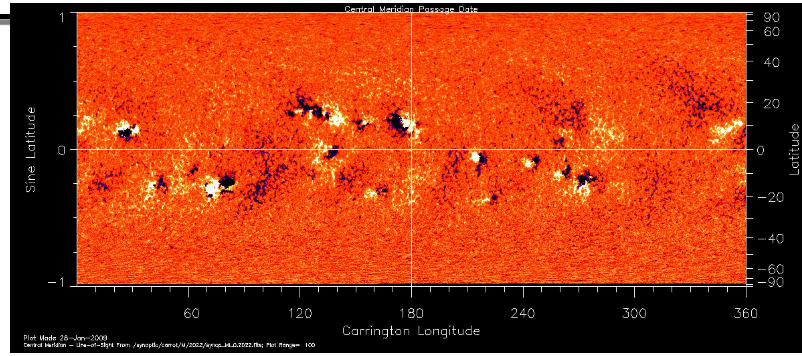


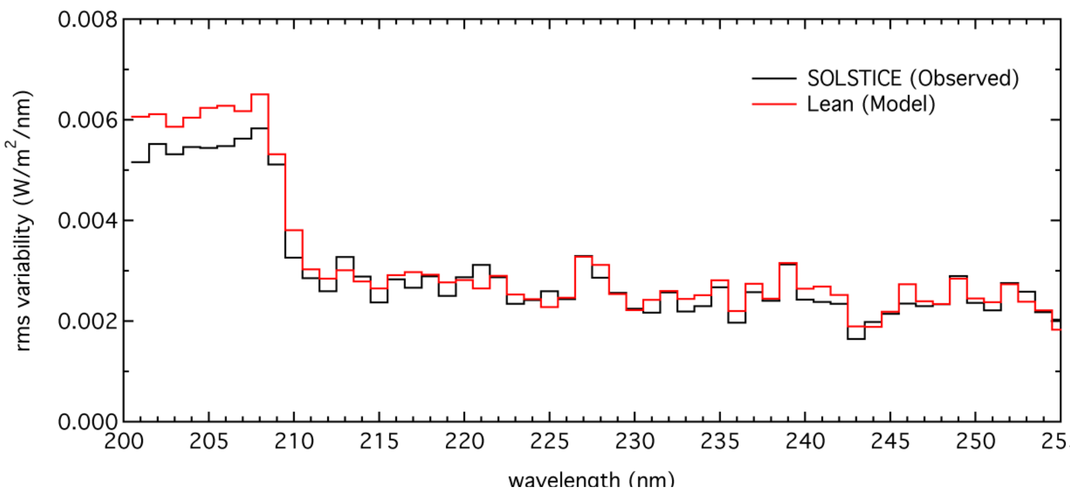
J.W. Harder, G. Thuillier, E.C. Richard, S.W. Brown, K.R. Lykke, M. Snow, W.E. McClintock, J.M. Fontenla, T.N. Woods, P. Pilewskie, 'The SORCE SIM Solar Spectrum: Comparison with Recent Observations' ,*Solar Physics*, 263, Issue 1 (2010), pp 3, doi:10.1007/s11207-010-9555-y

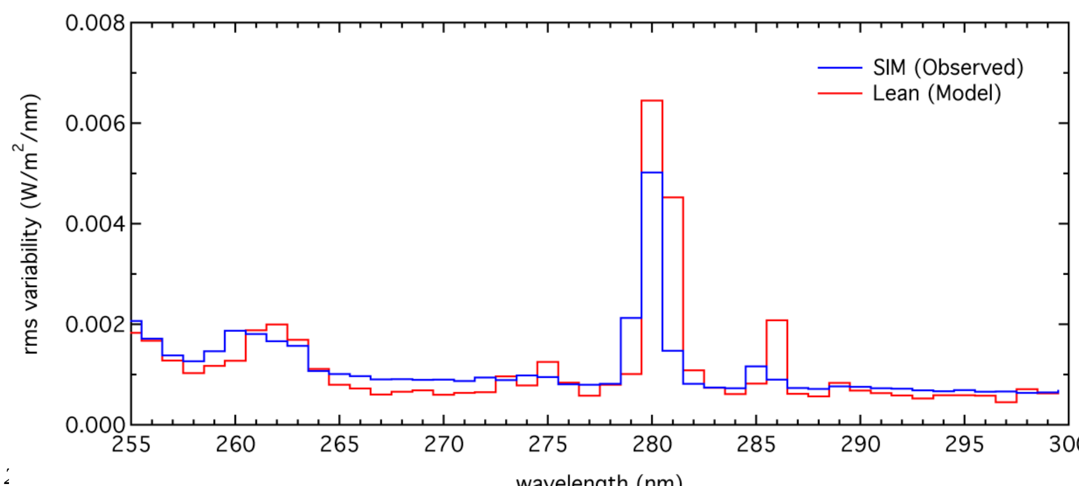
Ongoing solar spectra issues

- Solar Irradiance: how is it dispersed spectrally and where is it deposited into the atmosphere and ocean?
- How does the solar spectral irradiance vary in time?

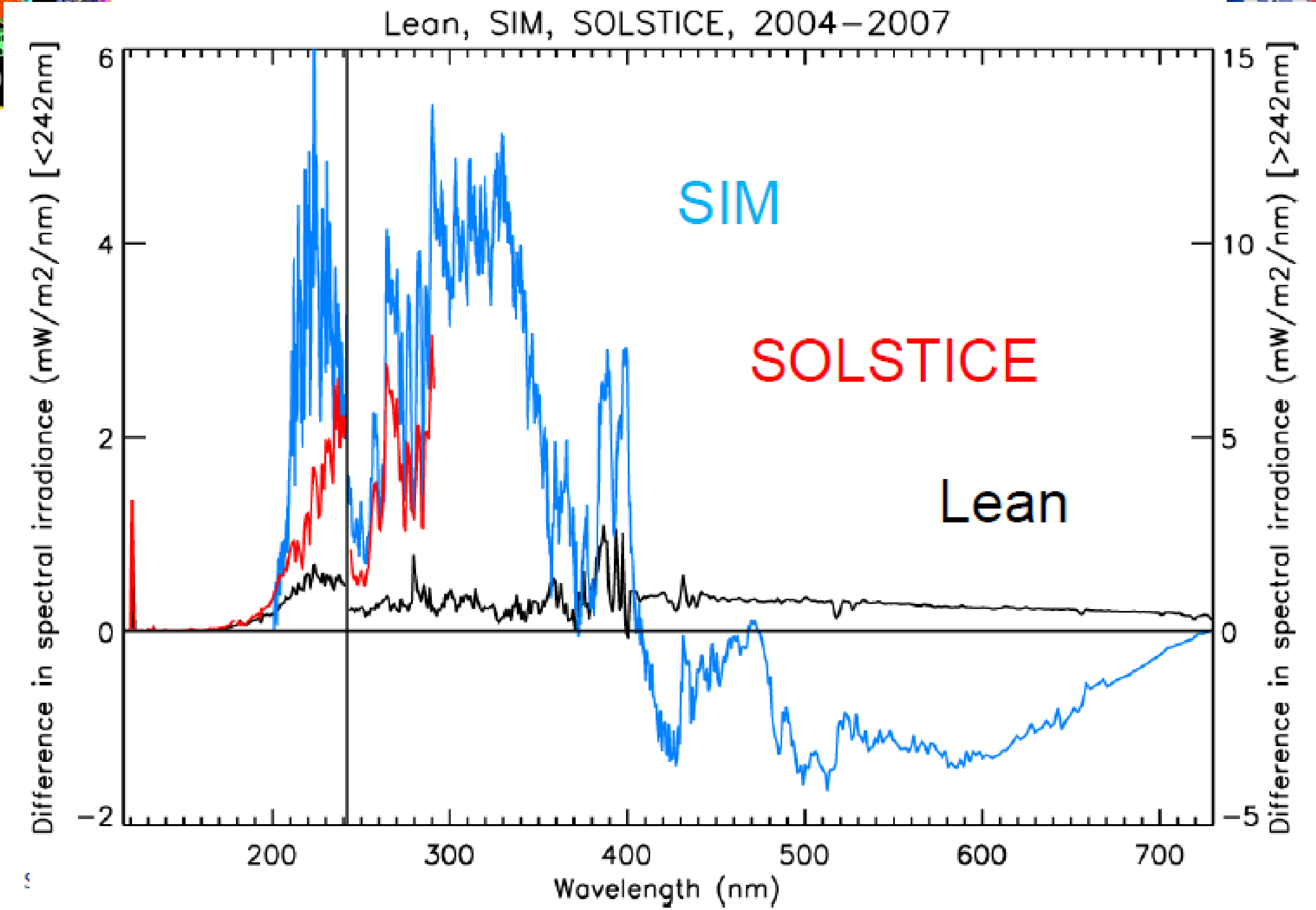
Solar Rotational Variability







(near) Solar Cycle Variability



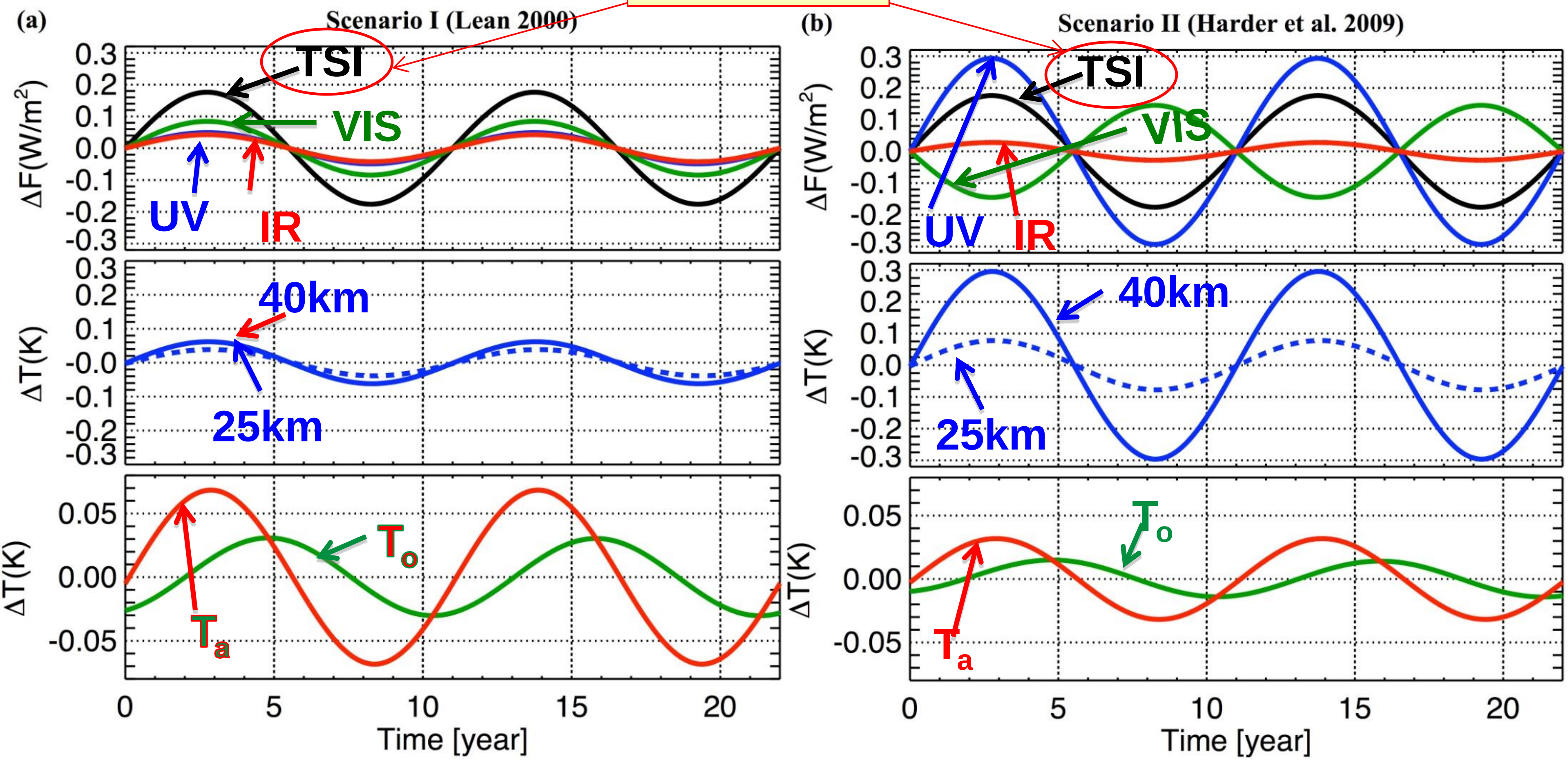
What impact does this have on the atmosphere?

Cahalan R., G. Wen, J. Harder & P. Pilewskie, *GRL*, 2010

Solar Variations (Lean 2000)
And RCM Response

Identical TSI

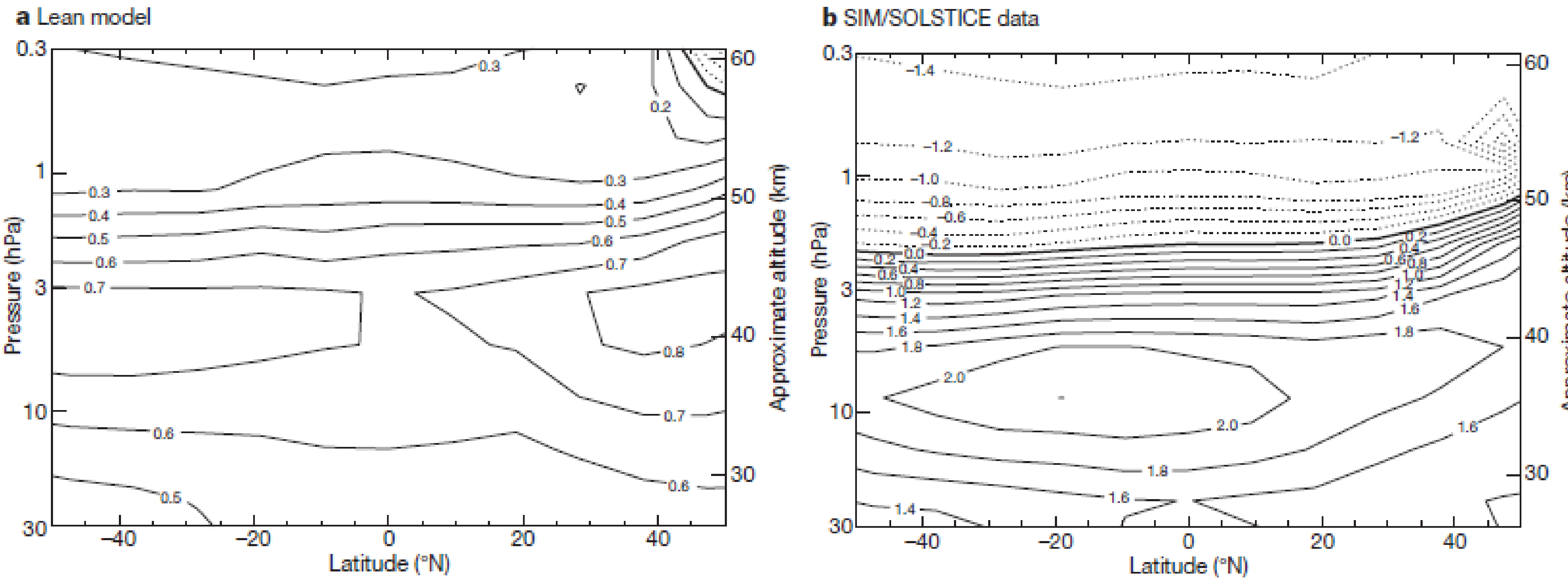
Solar Variations (Harder et al 2009)
And RCM Response



Increased 11-yr in Stratosphere ☝ Decreased 11-yr At Surface & Oceans 👎

Modeled difference in ozone between December 2004 and December 2007

Haigh, J., A. Winning, R. Toumi & J. Harder, *Nature*, 2010



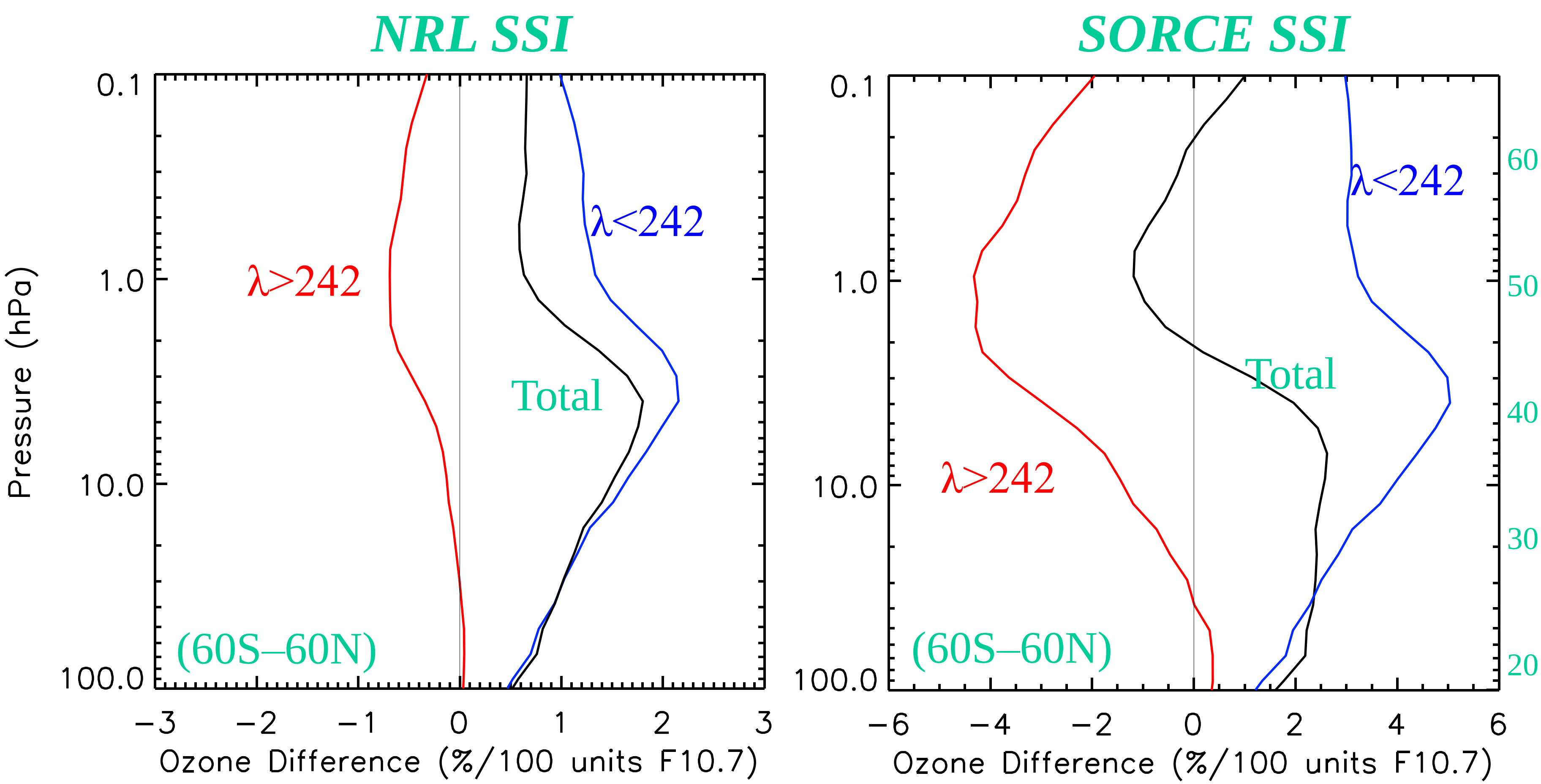
"…consistent with contemporaneous measurements of ozone from the Aura-MLS satellite…"

Table 1 | Difference in global average downward radiative flux

Wavelength	200–310 nm		310–500 nm		500–700 nm		700–1,600 nm		Total solar 200–1,600 nm		Thermal		Net	
Level	TOA	TPS	TOA	TPS	TOA	TPS	TOA	TPS*	TOA	TPS	TOA	TPS	TOA	TPS
Lean data ($W m^{-2}$)	0.02	0.00	0.04	0.03	0.03	0.01	0.02	0.02	0.11	0.06	0	0.02	0.11	0.08
SIM data ($W m^{-2}$)	0.16	0.00	0.11	0.06	−0.13	−0.17	−0.05	−0.05	0.09	−0.16	0	0.06	0.09	−0.10

UV Variability : Direct Heating vs. Photolysis

Responses from **λ < 242**, **> 242** nm compete



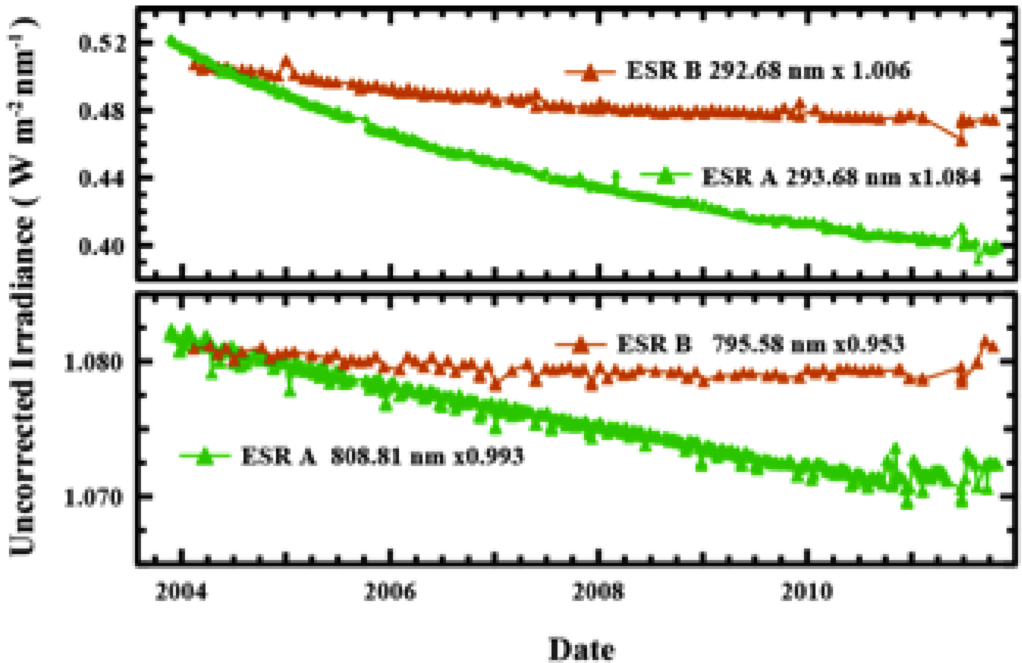
Swartz et al. 2010 – GEOS-5 CCM

SIM Degradation Trending Challenges

- What is the reference with only two SIM channels and both are degrading?
  – SIM previous results are derived with assumption that both channels degrade at same rate as a function of exposure time

$$Degrade_A = 1 - kt_A$$

$$Degrade_B = 1 - kt_B$$



Key result from SSI Validation Workshop at NIST in Feb. 2012: degradation scales with *dose*

New SIM analysis in progress

$$Dose = \int_t \int_\lambda E(\lambda,t) R_A(\lambda,t) \sigma(\lambda) d\lambda dt$$

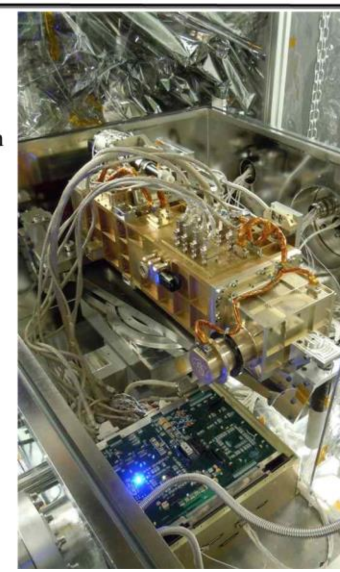
$$If\ E\&R \neq f(t),\ Dose = kt$$

Hope: SRF to replicate TRF success for SSI at key wavelengths

SIM Instrument Level Calibration in SRF

✓ Instrument-level calibration complete (all in vacuum; all channels):

- SIRCUS laser wavelength calibration
- Spectral instrument function measurements
  - ESR and Photodiodes
- Channel to channel boresight alignment calibration
- Pointing and FOV mapping
- Absolute spectral irradiance calibration tied to NIST L1 Cryo
  - ESR (all channels)



Summary of SSI

- SIM and SOLSPEC agree to within 1% over most of spectrum.
- Models can adequately reproduce rotational SSI variability.
- Solar-cycle variability in some SIM spectral bands exhibits out-of phase trends with TSI.
  - Climate implications? Observations require further validation.
  - Continued validation efforts underway
  - New *dose* models of SORCE SIM degradation
  - New measurement-based degradation studies
  - SORCE SIM in the present solar cycle? SORCE/TSIS SIM overlap?
- TSIS SIM will have enhanced degradation tracking capability, lower noise ESR, ultra-clean optical environment to mitigate contamination, first end-to-end cal/val using cryogenic radiometer and SIRCUS sources.

What is the recent history of our Sun's TSI?

Sunspot Cycles

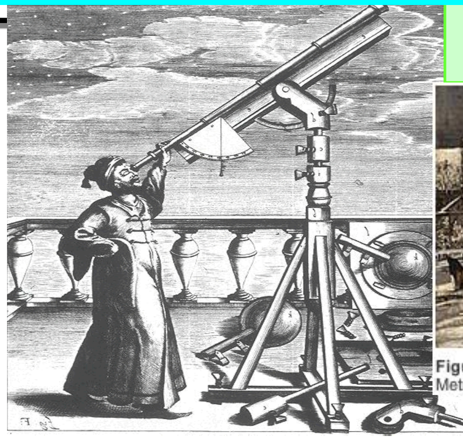
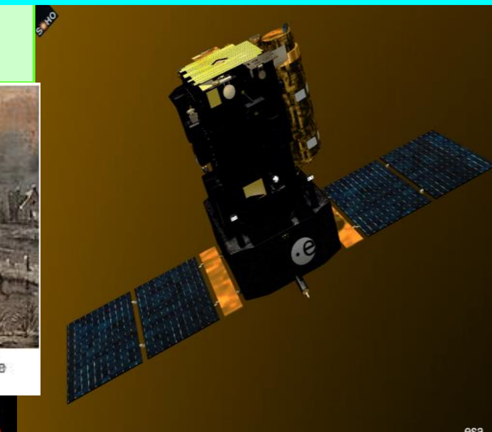


Figure 1: Sports on a Frozen River, by Aert van der Neer (courtesy The Metropolitan Museum of Art).

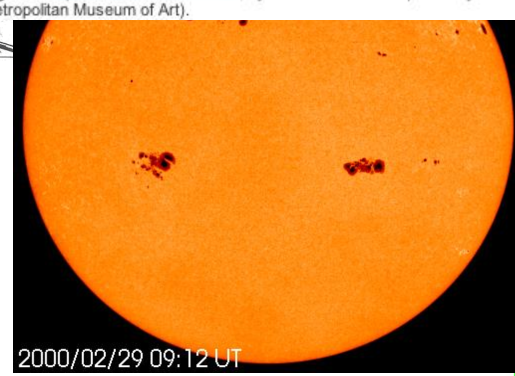


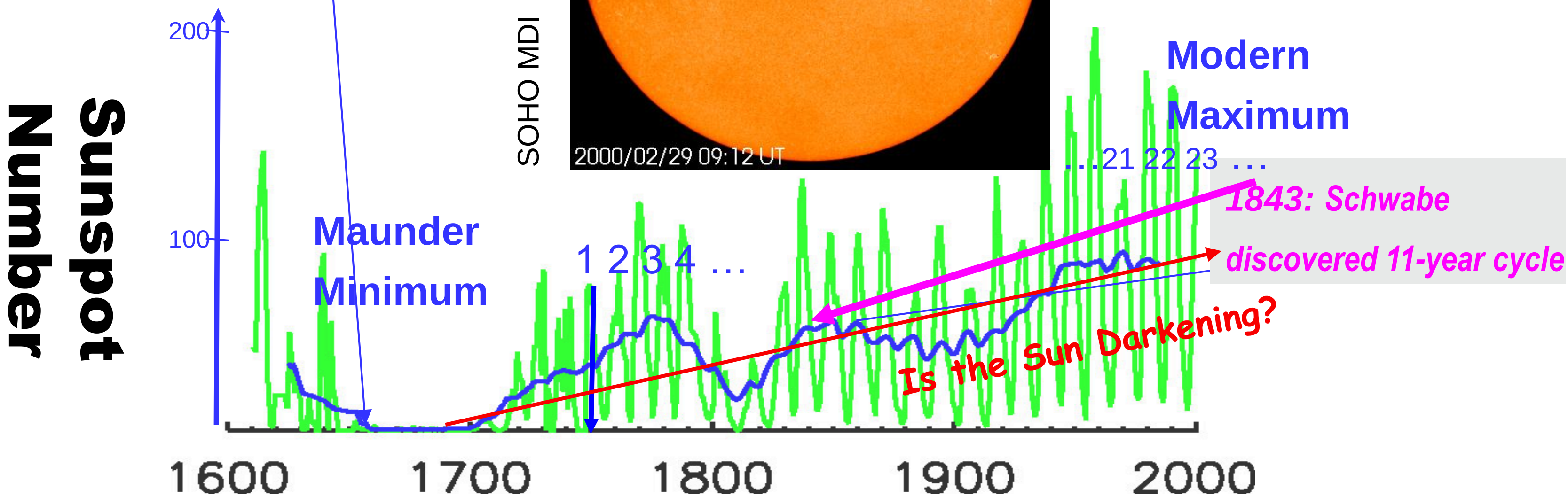
Johannes Hevelius: *1647*

www.sr.bham.ac.uk

SOHO (L1): *launched 1995*

sohowww.estec.esa.nl

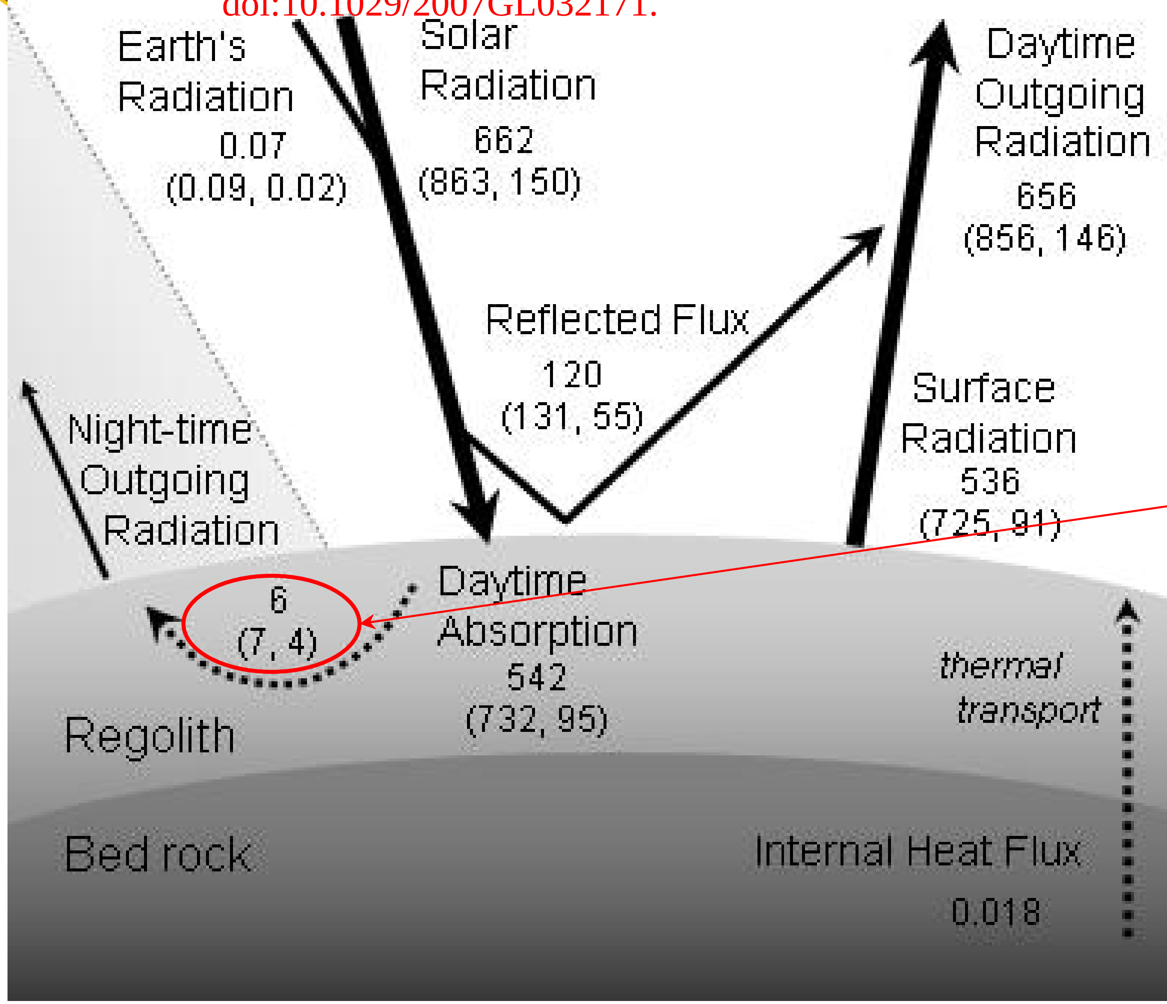




Sun's TSI *highly uncertain* due to <u>unknown</u> faculae!

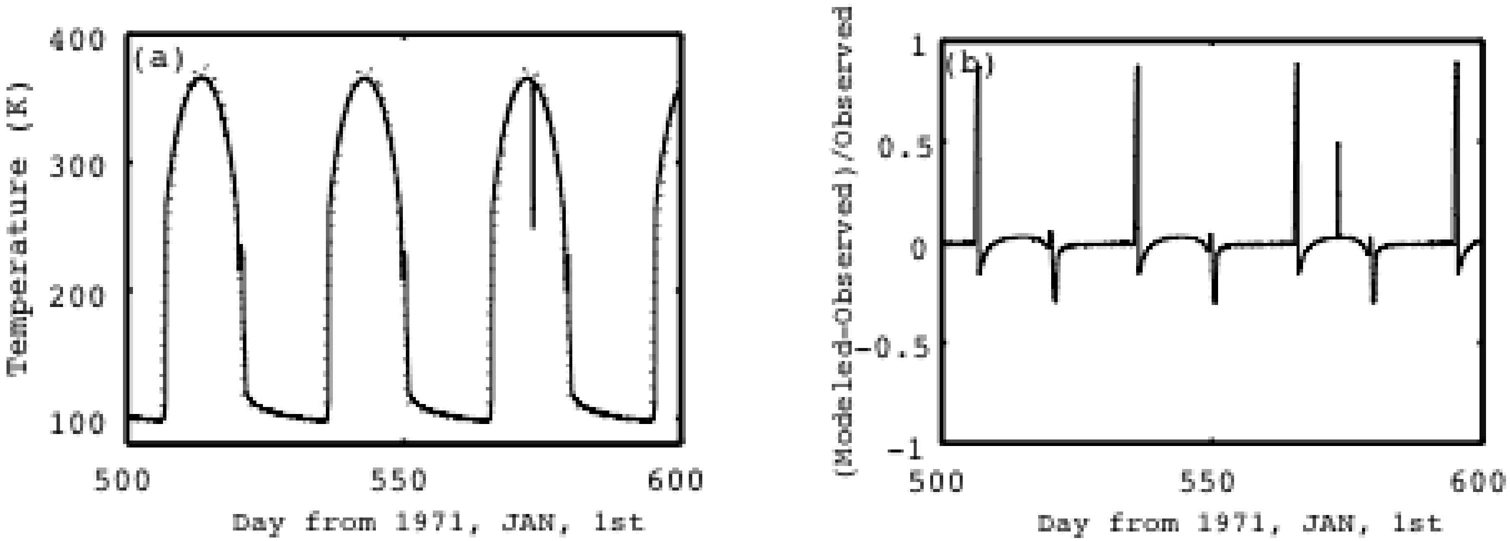
Energy Budgets of Lunar Surface Climate

Miyahara, H., G. Wen, R. Cahalan & A. Ohmura (2008), Deriving historical total solar irradiance from lunar borehole temperatures, *Geophys. Res. Lett.*, ***35***, L02716, doi:10.1029/2007GL032171.



1. Daytime absorption of solar radiation is the driving force.
2. Daytime absorbed solar (542W/m^2) is not balanced by emitted infrared (536W/m^2).
3. Daytime net flux at the surface is stored as heat (6W/m^2). This energy storage is released during lunar night.
4. Terrestrial radiation from the Earth (0.09W/m^2). is about two orders of magnitude less than the heat storage (6W/m^2), and can be ignored at Apollo sites

Model Results vs Observations at the surface @ Apollo 15 latitude



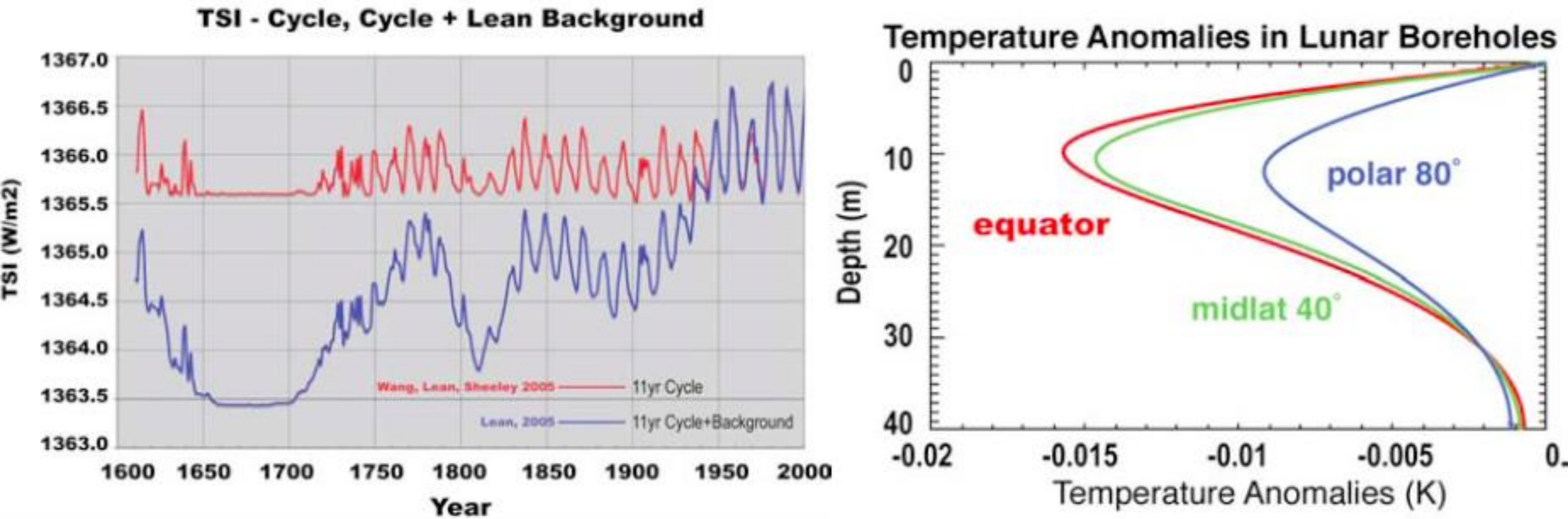


Figure 1. Using two scenarios of reconstructed TSI in IPCC [2007] (left panel) as driving forces, lunar borehole temperature anomalies (right panel) distinguish between historical TSI scenarios of Lean (2000) and that of Wang, Lean, and Sheeley (2005). For latitudes from 0-80°, the anomaly peaks at a depth about 10 m [From Miyahara et al, 2008, Fig 3].

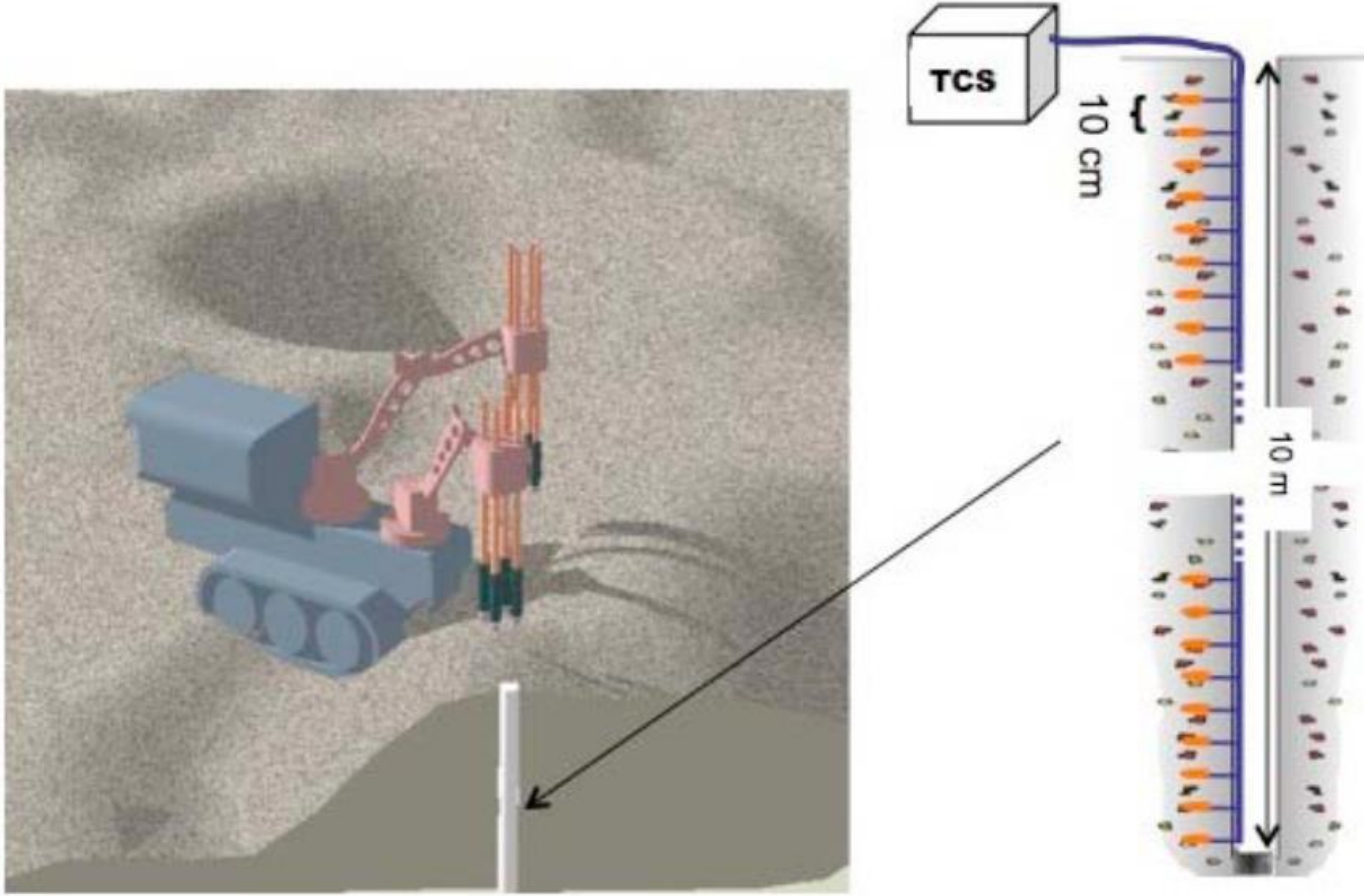


Figure 2. Left: sketch shows schematic of drilling operation. Right: shows the thermometer side branch (dark blue wire in vertical) that supports the PRT probes (orange round heads) that are inserted horizontally into lunar regolith at depth intervals of 10 cm, down to a total depth of 10 m. The thermometry control system (TCS) is used to control, acquire and store temperature measurements.

Lunar Borehole Experiment to Derive the History of Total Solar Irradiance Variations Since Galileo's 1610 Sunspot Observations for Earth's Climate Study

Submitted in response to NNH08ZDA001N-LASER

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Lunar Borehole Summary

1. Two scenarios of the Sun's luminosity (TSI) differing by ≈ 2 W/m^2 over 300 years can be distinguished by the lunar regolith temperature profiles that they produce, with peak difference ≈ 10 mK at depth ≈ 10 m. Paper in GRL, available at: *GRL* **35**, L02716, doi:10.1029/2007GL032171, online at:
http://climate.gsfc.nasa.gov/viewPaperAbstract.php?id=1098

2. The Moon's surface is NOT in radiative thermodynamic equilibrium during day or night. "Turning off" the Sun in a time dependent thermal model demonstrates that it would take ≈ 1000 years to reach a nearly constant equilibrium temperature of about 24-38 K. However, equilibrium *may* be a good first-order approximation to surface temperature in a permanently shadowed region.

After 11 years with SORCE – What's new? What's next?

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Thanks also to Greg Kopp, Jerry Harder, and other LASP colleagues & to others at GSFC and NIST

– Changes in estimates of the Total Solar Irradiance (TSI), Earth's albedo, and Earth's outgoing longwave radiation
– Historic closing of calibration gap between the suite of TSI instruments, with Transfer Radiometer Facility (TRF)
– Climate models sensitive not only to TSI, but to variations in the *Spectral* Solar Irradiance (SSI)
& vertical profiles of temperature and ozone are especially sensitive to SSI.
– SIM indicates multiyear changes at visible and near-infrared wavelengths *out of phase* with TSI,
– Out-of-phase SSI forcing can lead to larger temperature variations in the upper stratosphere,
but smaller variations in troposphere and upper ocean.
– Variations in SSI need further study before they may be considered firmly established.
– TSIS SIM has recently undergone comprehensive end-to-end calibration in the LASP SSI Radiometry Facility (SRF)
utilizing the NIST SIRCUS system covering 210 – 2400 nm for SSI, not yet available when SORCE launched.
– SORCE follow-on mission Total and Spectral Solar Irradiance Sensor (TSIS), could reduce uncertainty in SSI variability
– Long-term goal of improving the ability to monitor Earth's energy balance, and energy *imbalance* that drives
global warming, requires improved measurements of both shortwave and longwave earth-emitted radiation.
– Lunar Borehole Experiment has potential to recover changes in TSI over past 400 years; could clarify "Little Ice Age."

Backup Slides

Need SORCE follow-On TSIS launched in time to overlap with TCTE

*Since 2005 we've closed the solar irradiance **calibration** gap, and…*

… now NASA & NOAA are planning "operational" solar irradiance mission, TSIS, but

- ***IPCC*** AR5 WG1 summary report, now in draft, shows that solar forcing changes are believed to have partly *offset* greenhouse gas global warming during 1980-2011, a result that depends critically on continuity of the Total Solar Irradiance (TSI) record. This result is *opposite* to the longer time change, as solar forcing is thought to have added to the warming since pre-industrial times, but with less confidence since solar irradiance was not measured with enough accuracy prior to the satellite era.

- SORCE and TCTE had a successful 2013 Christmas Campaign to ensure continuity of the Total Solar Irradiance Climate Data Record. All instruments collected science data for 7 days, 22-28 Dec inclusive. This will allow the new improved calibration of the Total Irradiance Monitor (TIM) onboard TCTE to be transferred to the SORCE TIM, and subsequently to the whole TSI record back to 1980.

- TCTE will carry forward the TSI record, and SORCE will attempt to continue the Spectral Solar Irradiance (SSI) record with the Spectral Irradiance Monitor (SIM). While TIM is needed to know the total "energy income" for Earth's energy budget, SIM is needed to know where this energy is deposited, at what altitude for various seasons, and thus how it impacts ozone, temperature, sea ice, etc.

- TSIS instruments were built, tested, and in 2013 stored in preparation for launch. **TSIS needs to be launched in time to overlap with TCTE's TIM, and preferably also with the SORCE SIM.**

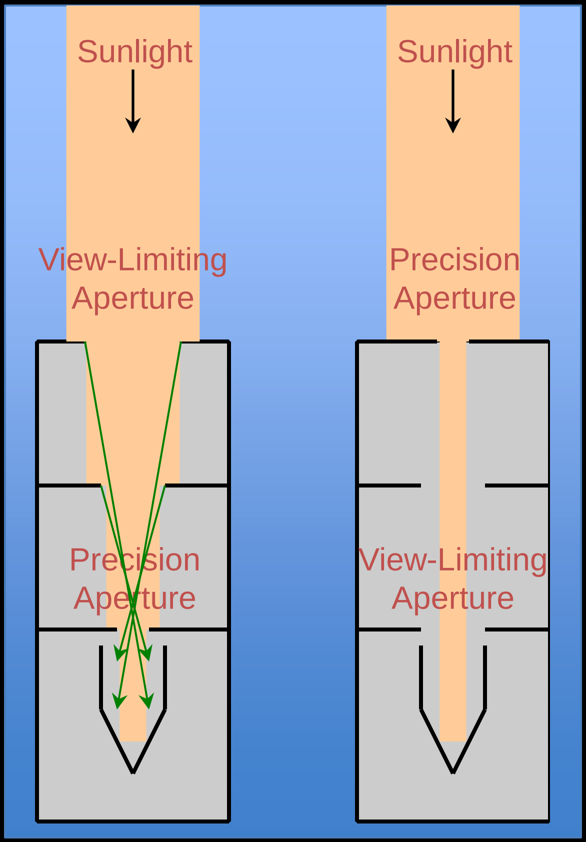
- SORCE & TSIS teams, and the climate community, await news from NOAA about the 2014 budget "passback" and future plans.

Diffraction & Scatter Erroneously Increase Signal

All instruments except the TIM put primary aperture close to the cavity

Expanding TRF beam from filling precision aperture while underfilling view-limiting aperture to overfilling view-limiting aperture causes increase in signal due to scatter and diffraction from front and interior sections of instrument

all other TSI instrument geometries



TIM geometry

Additional light allowed into instrument can scatter into cavity

Majority of light is blocked before entering instrument

Measured increases due to uncorrected scatter/diffraction are surprisingly large

Instrument	Increase
PREMOS-1	0.10%
PREMOS-3	0.04%
VIRGO	0.15%
ACRIM-3	0.69%

TSIS SIM Calibration Error Budget

Instrument uncertainties determined at the component level --> characterization of error budget

Complete

In-progress

Measurement Correction	Origin	Value (ppm)	1σ (ppm)	Status
Distance to Sun, Earth & S/C	Analysis	33,537	0.1	
Doppler Velocity	Analysis	43	1	
Pointing	Analysis	0	100	
Shutter Waveform	Component	100	10	Complete
Slit Area	Component	1,000,000	300	Complete
Diffraction	Component	5,000-62,000	500	In-progress
Prism Transmittance	Component	230,000-450,000	1,000	Complete
ESR Efficiency	Component	1,000,000	1,000	Complete
Standard Volt + DAC	Component	1,000,000	50	Complete
Pulse Width Linearity	Component	0	50	Complete
Standard Ohm + Leads	Component	1,000,000	50	Complete
Instrument Function Area	Instrument	1,000,000	1,000	In-progress
Wavelength ($\Delta\lambda/\lambda$ = 150 ppm)	Instrument	1,000,000	750	In-progress
Non-Equivalence, Z_H/Z_R-1	Instrument	2,000	100	In-progress
Servo Gain	Instrument	2,000	100	Complete
Dark Signal	Instrument	0	100	In-progress
Scattered Light	Instrument	0	200	Complete
Noise	Instrument	-	100	Complete
Combined Rel. Std. Uncertainty			*2000*	

S/C

Component-Level

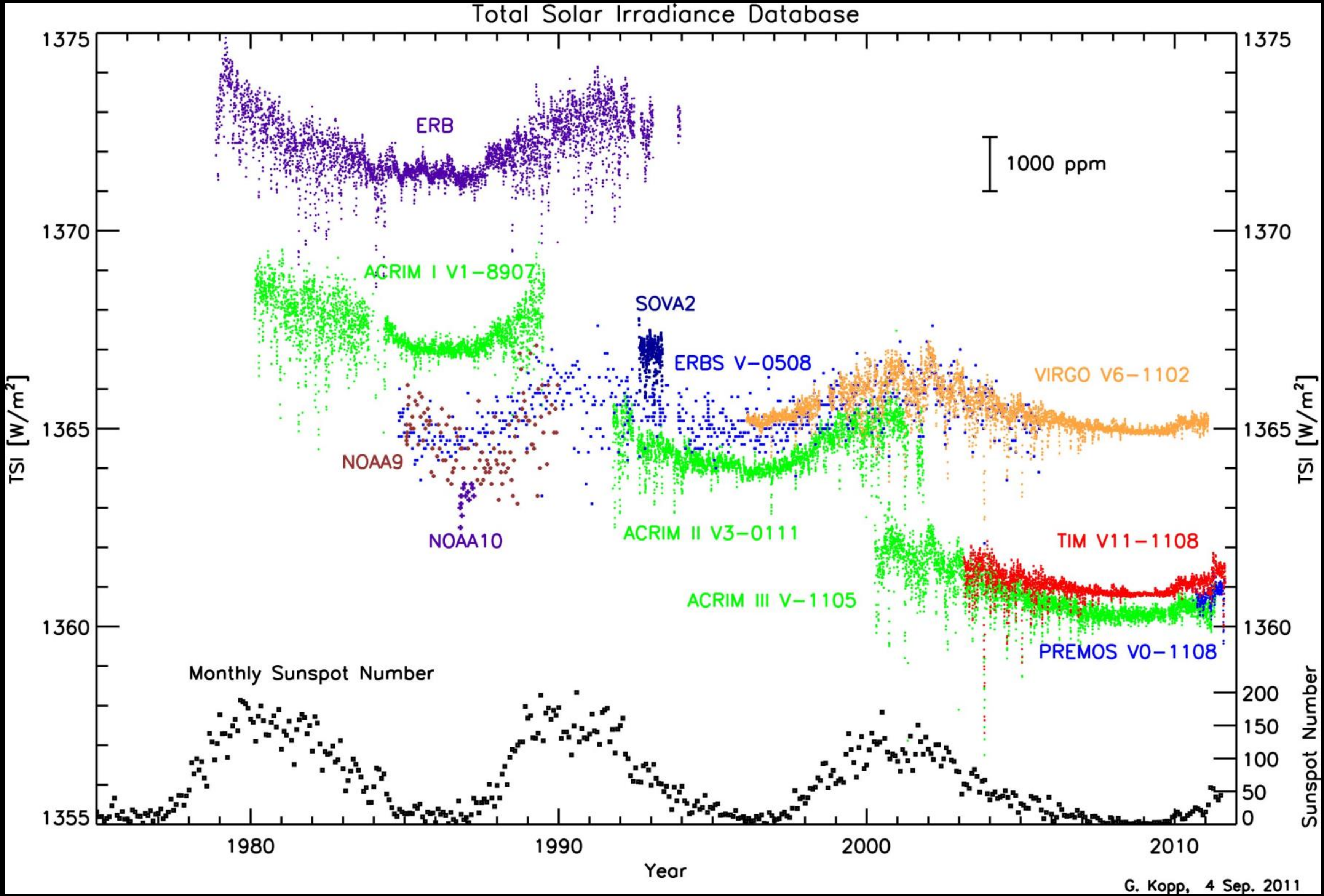
Instrument-Level

Dominant uncertainties are λ-dependent

Calibration and Verification

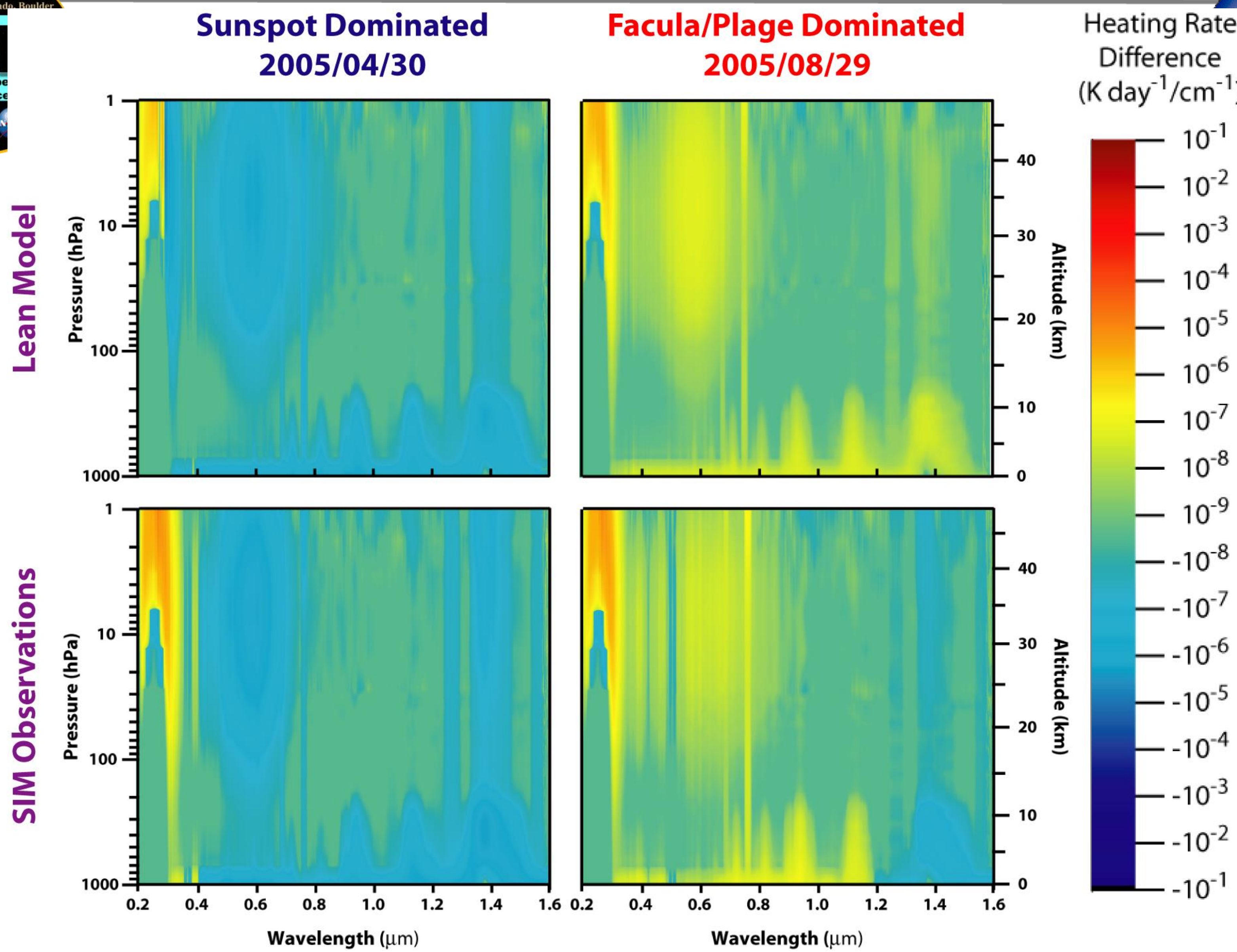
- SIM traces its calibrations to the standard Watt.
- All elements of SIM instrument equations are calibrated at either the component or instrument level.
- Analog to the TSI Radiometer Facility: end-to-end verification of SIM with NIST Spectral Irradiance and Radiance Responsivity Calibrations using Uniform Sources (SIRCUS) and a new LASP SSI Radiation Facility.

... And PREMOS Data Are Recently Available



Robert F. Cahalan

Spectral Heating Rate Differences



Lunar Borehole Model (Keihm 1984)

Paper in press in GRL & available at:
http://climate.gsfc.nasa.gov/viewPaperAbstract.php?id=1098

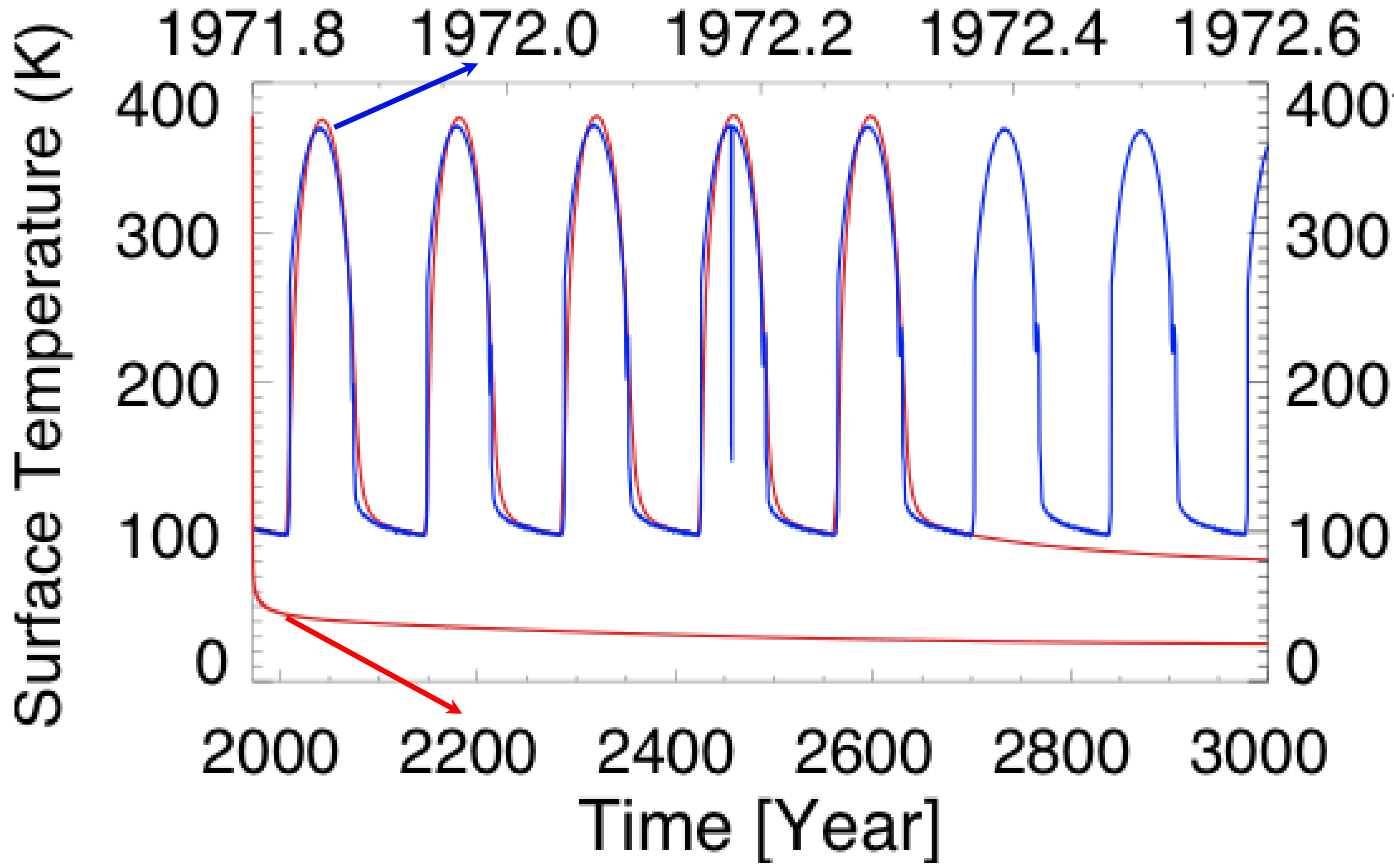
$$\rho C_p \frac{\partial T(z,t)}{\partial t} = \frac{\partial}{\partial z}\left(k \frac{\partial T(z,t)}{\partial z}\right) \quad (1)$$

with boundary conditions

$$k \frac{\partial T(z,t)}{\partial z}\Big|_{z=0} = \varepsilon \sigma T(z,t)^4 - (1-\alpha)\cos(\theta_0) F(t) \quad (2)$$

$$k \frac{\partial T(z,t)}{\partial z}\Big|_{z=z_b} = H \quad (3)$$

Parameters	Formula
$\rho(z)$: *density* (kg/m^3)	$\rho(z) = 1250 \quad (z \le 0.02m)$ $= 1900 - 650\exp[\frac{200-z}{400}] \quad (z > 0.02m)$
$k(z,T)$: *thermal conductivity* $(W/m \cdot K)$	$k(z,t) = k_1(z) + k_2 \cdot T^3$ $k_1(z) = k_s \quad (z \le 0.02m)$ $= k_d - (k_d - k_s) \cdot \exp(\frac{0.2-z}{0.4})$ $k_s = 6 \times 10^{-4} W/m \cdot K$ $k_d = 8.25 \times 10^{-3} W/m \cdot K$ $k_2 = 3.78 \times 10^{-11} W/m \cdot K^4$
$C(T)$: *specific heat* $(J/kg \cdot K)$	$C(T) = 670 + (\frac{T-250}{530.6}) \cdot 10^3 - (\frac{T-250}{498.7})^2 \cdot 10^3$
$\varepsilon(T_s)$: *emissivity*	$\varepsilon(T_s) = a + bT_s + cT_s^2 + dT_s^3$ $a = 0.9696, b = 0.9664 \times 10^{-4}$ $c = -0.31674 \times 10^{-6}, d = -0.9664 \times 10^{-9}$ where T_s is surface temperature
$\alpha(\theta_0)$: *albedo*	$\alpha(\theta_0) = a + b(\theta_0/45)^3 + c(\theta_0/90)^8$ $a = 0.12, b = 0.03, c = 0.14$ Solar zenith angle (θ_0) is computed from JPL ephemerides
H : *internal heat flux* (W/m^2)	$H = 0.018 W/m^2$
$d(t)$: distance (AU)	Moon-Sun distance in astronomical unit (AU) computed from JPL ephemerides
$TSI(t)$: Total Solar Irradiance (W/m^2)	Total solar irradiance at 1 AU



1. "Turning off" the Sun in the time dependent model shows that it would take ≈ 1000 years to reach a nearly constant equilibrium surface temperature in the range 24-38 K.

2. Simple radiative equilibrium (e.g. Huang 2007) is inappropriate to relate Apollo-observed nighttime temperature to Earth's radiation budget.

3. Thermal equilibrium is a good first-order approximation for temperature in permanently shadowed regions where terrestrial radiation from the Earth does become important.