Climate Data Records for
Total and Spectral Solar Irradiance:

Solar Irradiance, Climate Impact

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- **Project Description, Production (& QA)**
  - *solar total and spectral irradiance variations*
  - *global and regional climate response patterns*
- **Applications, Schedule – *Decadal Climate Forecasts***
  - *projected solar and anthropogenic variations*
  - *near term surface & atmosphere temperature, ozone projections*

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LASP, University of Colorado, Boulder, CO
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Project Description

TSI = Total Solar Irradiance
SSI = Solar Spectral Irradiance

Extend, advance, improve instrument TSI and SSI records

- assess absolute accuracies and instrument stabilities with time
- cross calibrate independent measurements
- construct composite TSI (& SSI?) record
- seek consistency among measurements and models

What are TSI & SSI changes on climate time scales?

Extend, advance and improve models of TSI & SSI variability

- facular brightening functions *(from ground- and space based data)*
- sunspot darkening functions *(from ground- and space based data)*
- historical solar irradiance reconstructions using solar activity indices

Utilize TSI & SSI in studies of climate change and short- and long-term solar and climate processes

- provide records to scientific community for climate attribution studies
- assess Sun's role in present, past and future climate and atmospheric change

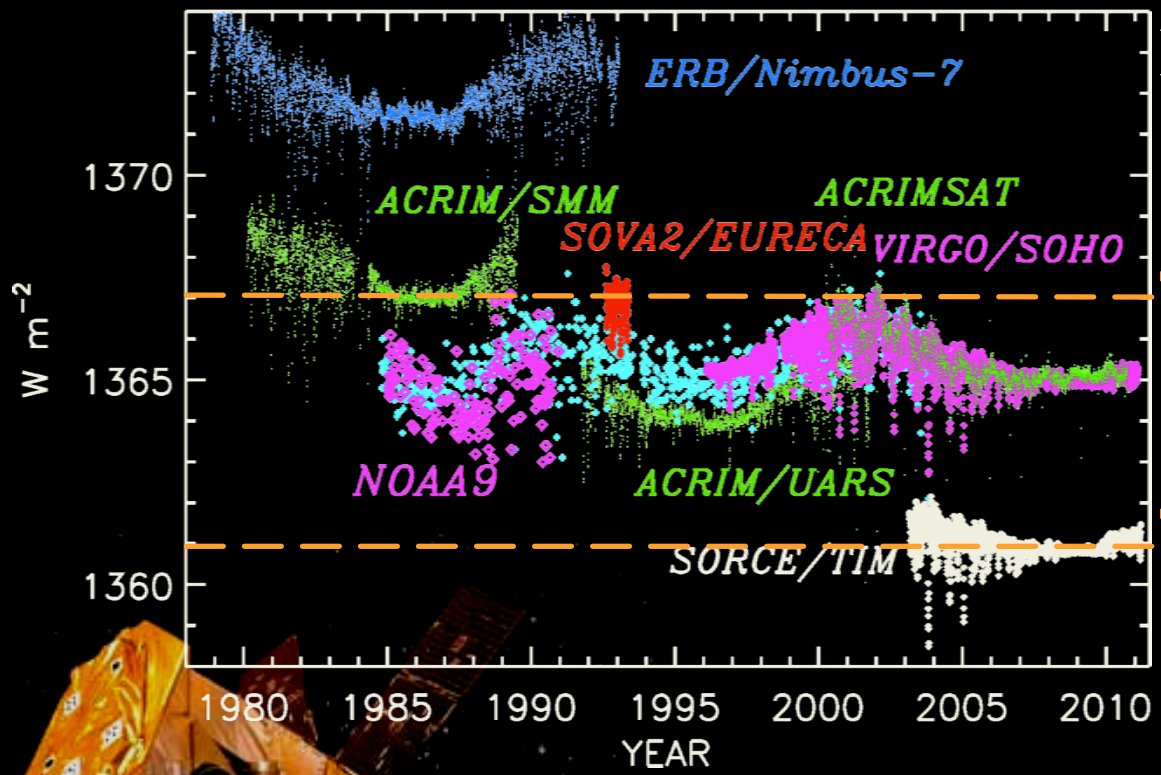
Project Description

CDR(s) (Validated Outputs)	Period of Record	Spatial Resolution; Projection information	Time Step	Data format	Inputs	Uncertainty Estimates (in percent or error)	Collateral Products (unofficial and/or unvalidated)
Total Solar Irradiance	1978 – present	N/A	1 day	SORCE: ASCII and IDL save, and HDF5. Similar data formats are planned for TSIS. LASP can produce in NetCDF if needed.	Raw satellite sensor telemetry data; composites from individual sensor level 3 irradiance data. TSI: ERB, ACRIM-I,II,&III, ERBS, SOVA, VIRGO, and TIM SSI: SIM, SOLSPEC, SCIAMACHY	0.01-0.035%	N/A
Solar Spectral Irradiance	2002-present	N/A	1 day			0.2-1%	N/A

TSI & SSI reconstructions
Decadal climate forecasts

- Solar Irradiance CDR Development Team maintains several of the duties of the former NPOESS Operations and Algorithms Team (OAT)
- Ensures effective and technically robust utility of solar irradiance CDRs
  - *Collaborate with user community and other CDR Teams*
- Ensures data stewardship of TSI and SSI through:
  - *Develop TSIS Algorithm Theoretical Basis Document*
  - *Develop CDR from current and heritage satellite instruments*
  - *Construct irradiance composites for user applications*
  - *Develop related solar irradiance products & algorithms for community application.*
- Rapid and reliable generation of Solar Irradiance CDRs following TSIS launch

Production Approach: Total Solar Irradiance Measurements



↕ 0.1%

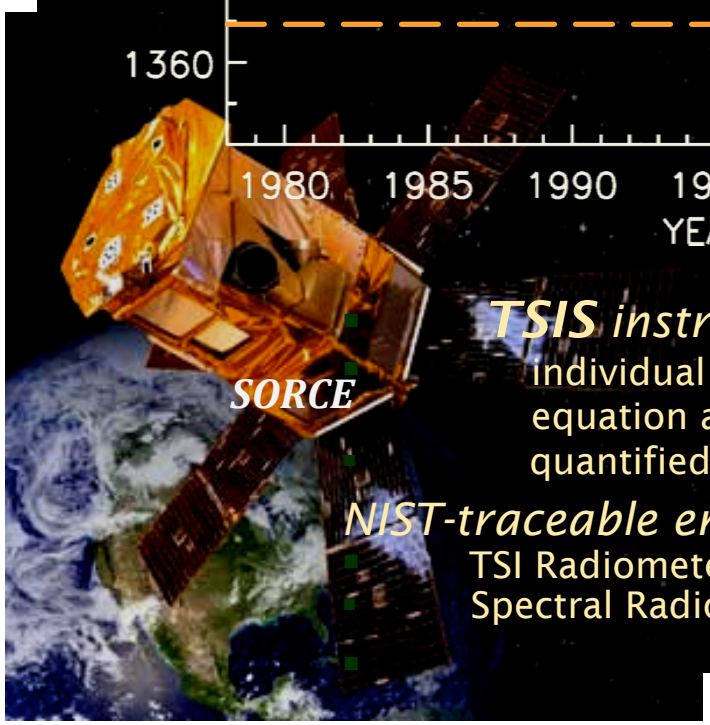
1367 ?

1361 ✔

Kopp & Lean, GRL, 2011

Current, heritage and future satellite instruments including TIM on SORCE, TCTE, and TIM and SIM on TSIS

TSIS/TIM
0.01% accuracy
0.001%/yr precision

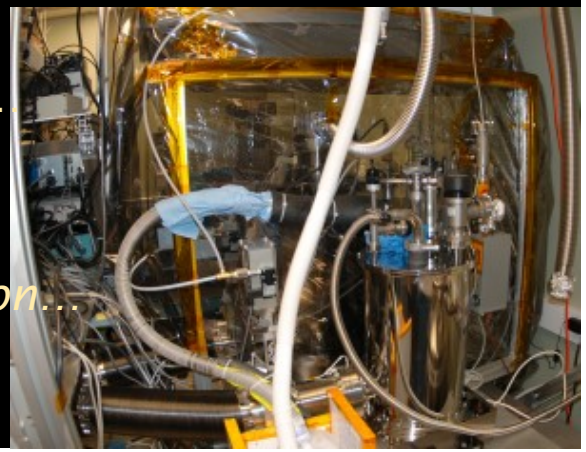


***TSIS** instruments are absolute sensors…*

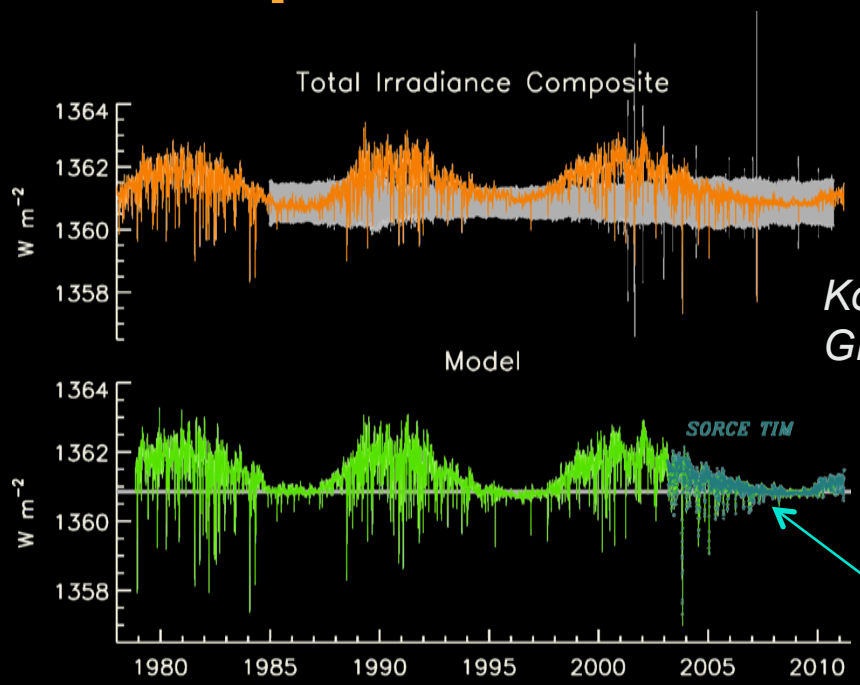
individual components of the measurement equation are calibrated and uncertainties quantified; onboard calibration tracking

NIST-traceable end-to-end calibration, validation…

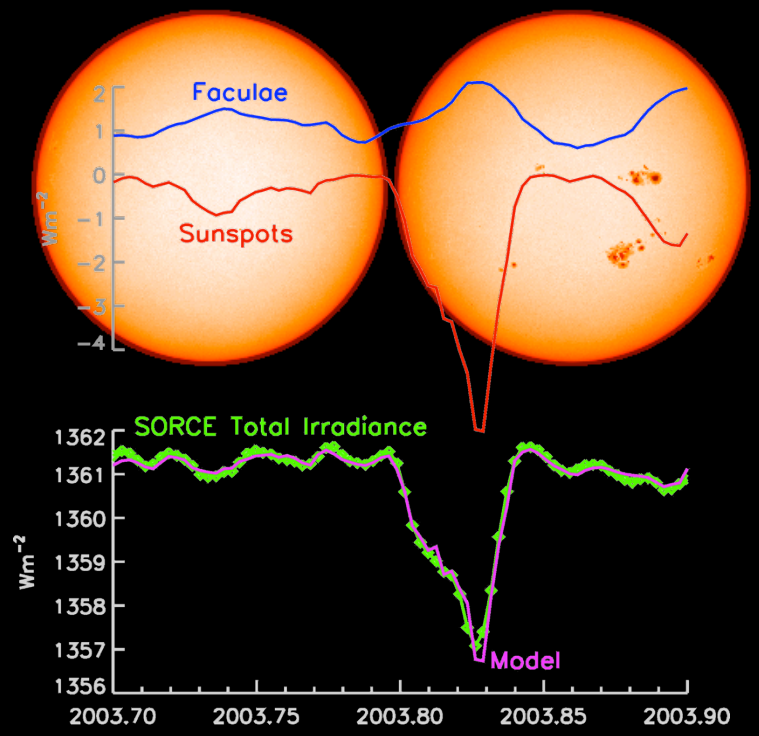
TSI Radiometer Facility (TRF)
Spectral Radiometer Facility (SRF) at LASP

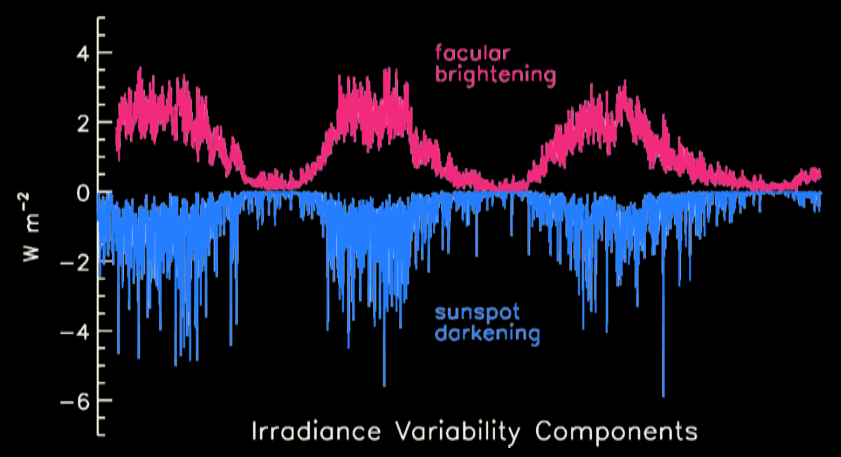


Production Approach: Total Solar Irradiance Composite and Model



Kopp & Lean, GRL, 2011

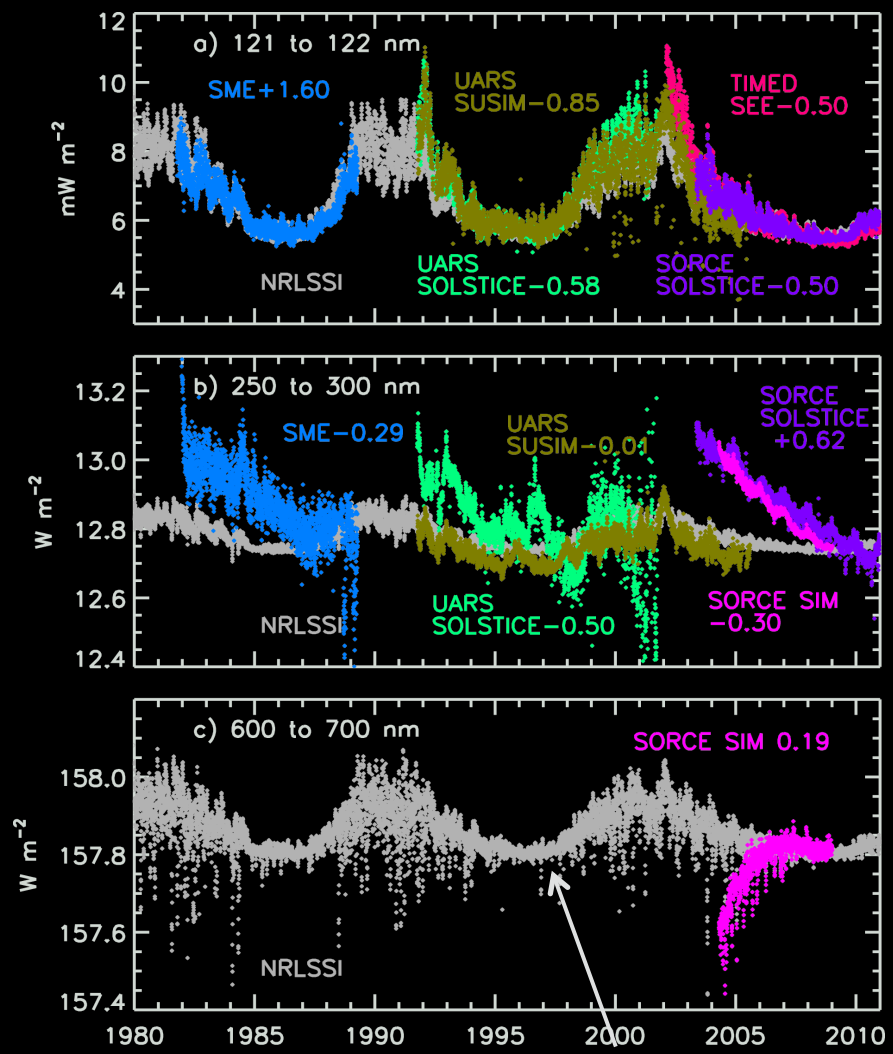




Long-term trend (2003-2010) in Model/TIM ratios is 0.0003% (3 ppm) per year– which is within the SORCE TIM long-term repeatability of 10 ppm per year: differences are larger on shorter time scales

NOAA Report:
Uncertainties Spanning Potential SORCE/TIM to JPSS/TIM Gap
G. Kopp & J. Lean, Sept 2011

Production Approach: Solar Spectral Irradiance Measurements and Models



individual measurements are offset-adjusted

NRLSSI model of faculae and sunspot influences

SSI are less accurate and less repeatable than TSI

- *wavelength dependence*
- *reduced signal*
- *more optical elements*
- *fewer observations, minimal overlap*

Compared with NRLSSI model SORCE/SIM solar cycle variations are:

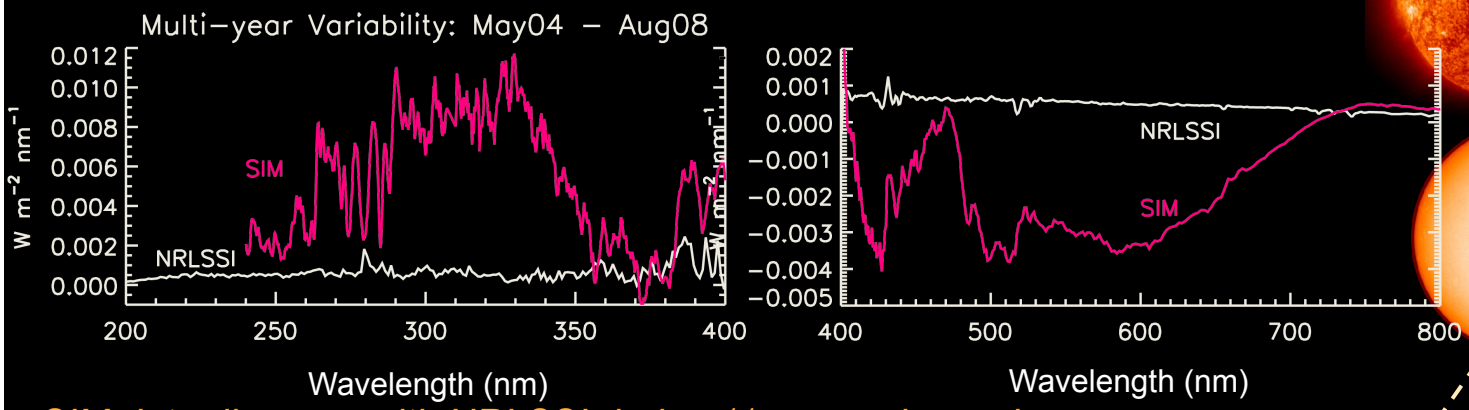
- in-phase and larger at UV wavelengths

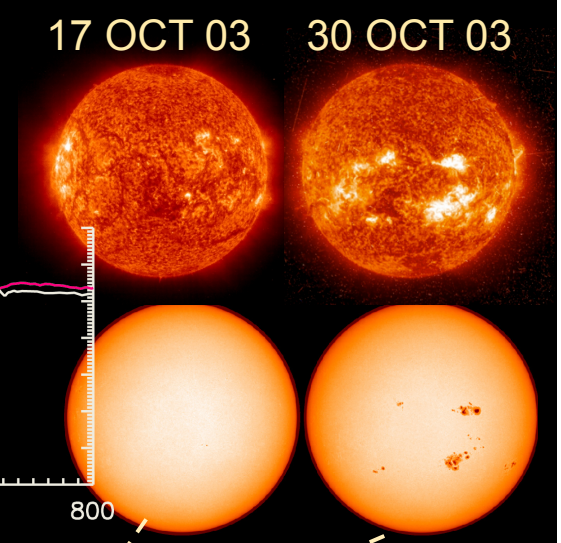
- out-of-phase and larger at VIS wavelengths

IPCC AR5 GCMs are using NRLSSI *(with Wang, Lean, Sheeley, 2005 background)*

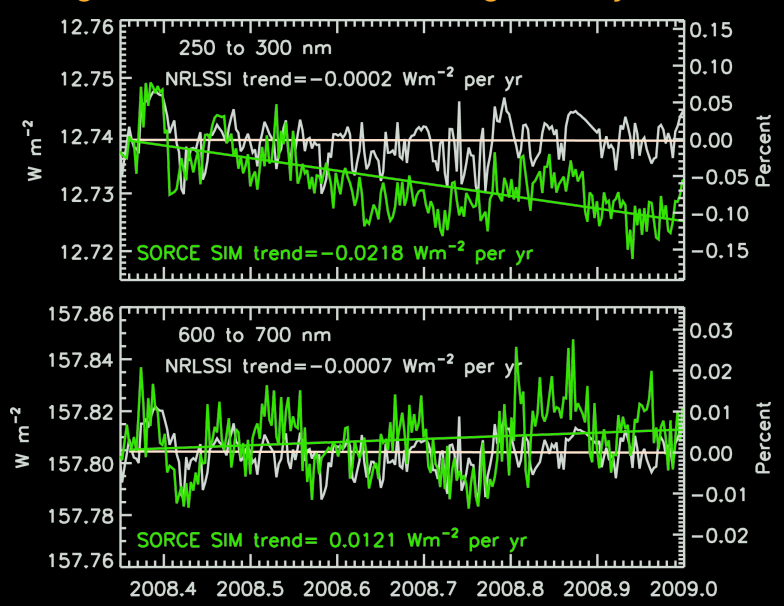
Paper in Progress with Gerard Thuillier (CNES): Analyses of Different Solar Spectral Irradiance Reconstructions for Atmospheric and Climate Modeling

Quality Assurance: Compare Measurements and Models





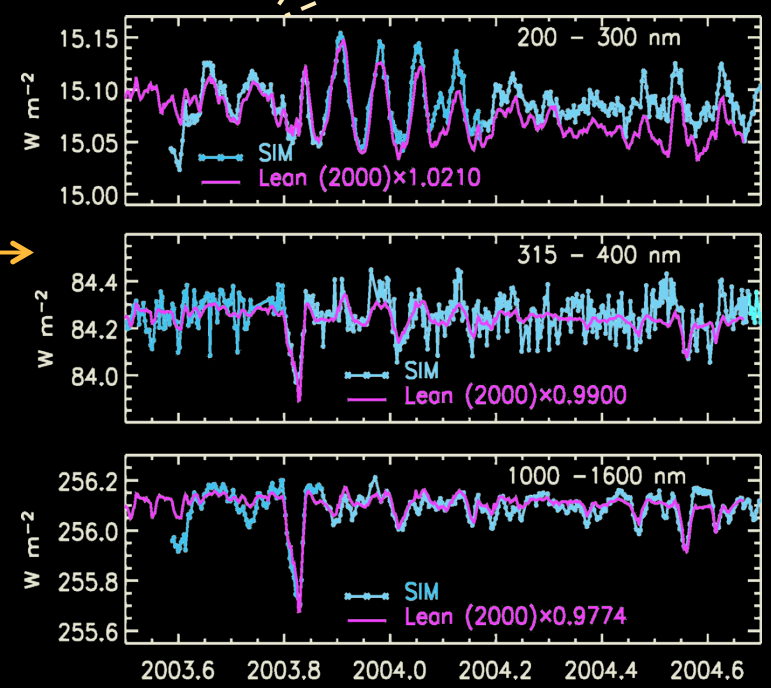
SIM data disagree with NRLSSI during 11-year solar cycle
BUT agree with NRLSSI during 27-day solar rotation at both



SOLAR MAX

and

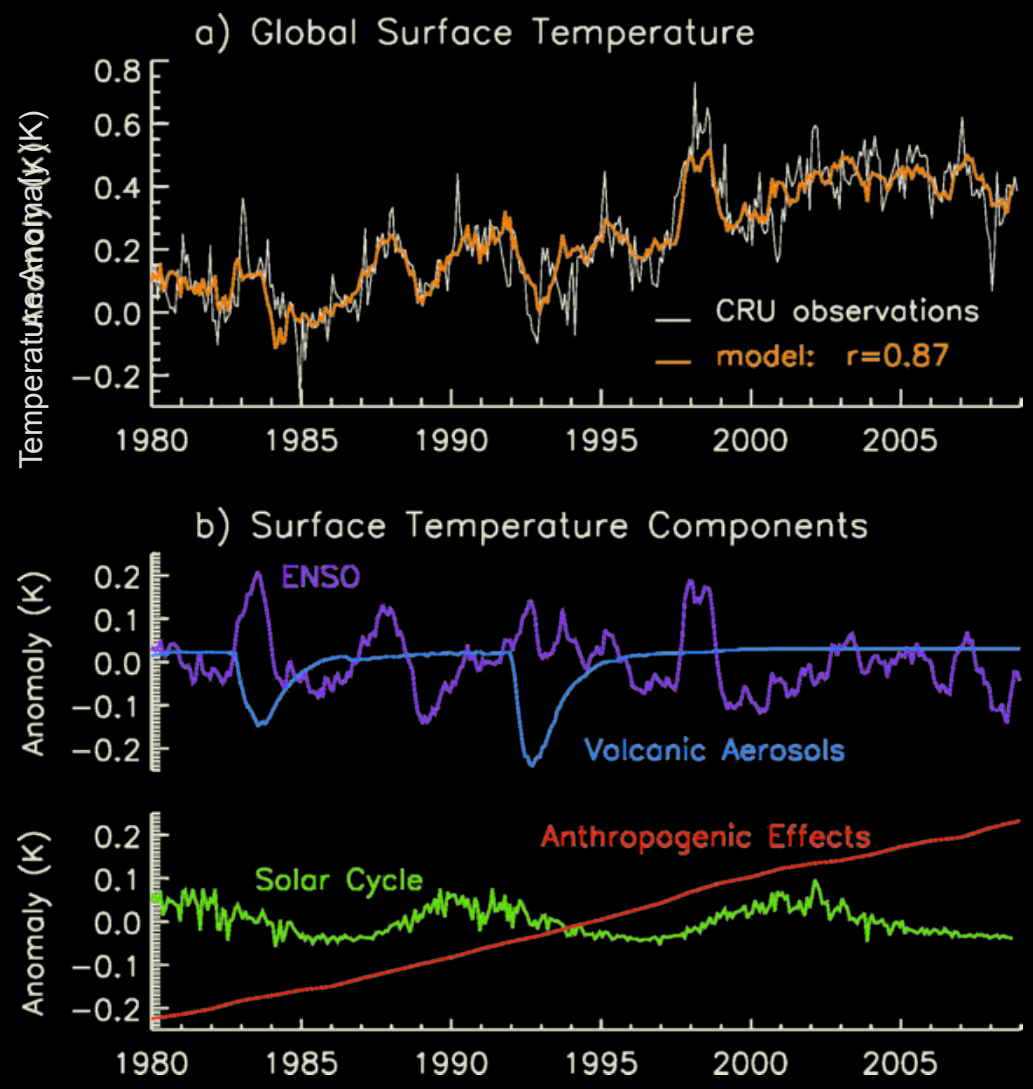
SOLAR MIN



Lean and DeLand, J. Clim, (2012) identify instrumental effects in SIM SSI from trends during solar minimum

Production Approach: Linear Model of Climate Change including Solar Irradiance

Lean and Rind GRL, 2008, 2009



… CRU temperature data, Univ. East Anglia, UK

NRL's Linear Climate Model (NRLLCM):
ENSO + volcanic aerosols + solar activity + anthropogenic effects explain 76% of observed temperature variance

+0.2°C 1997-98 "super" ENSO

-0.3°C Pinatubo Volcano

+0.1°C Solar cycle 23

+0.4°C Anthropogenic effects 1980-2006

Applications: Is Climate (Really, Still) Changing? Why? (the media perspective)

Washington Po
30 March 2009

GTON POST

"Few
the worl
climat
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—PRESIDEN

With
Mr. Presi

We, the undersigned scientists,
Surface temperature changes
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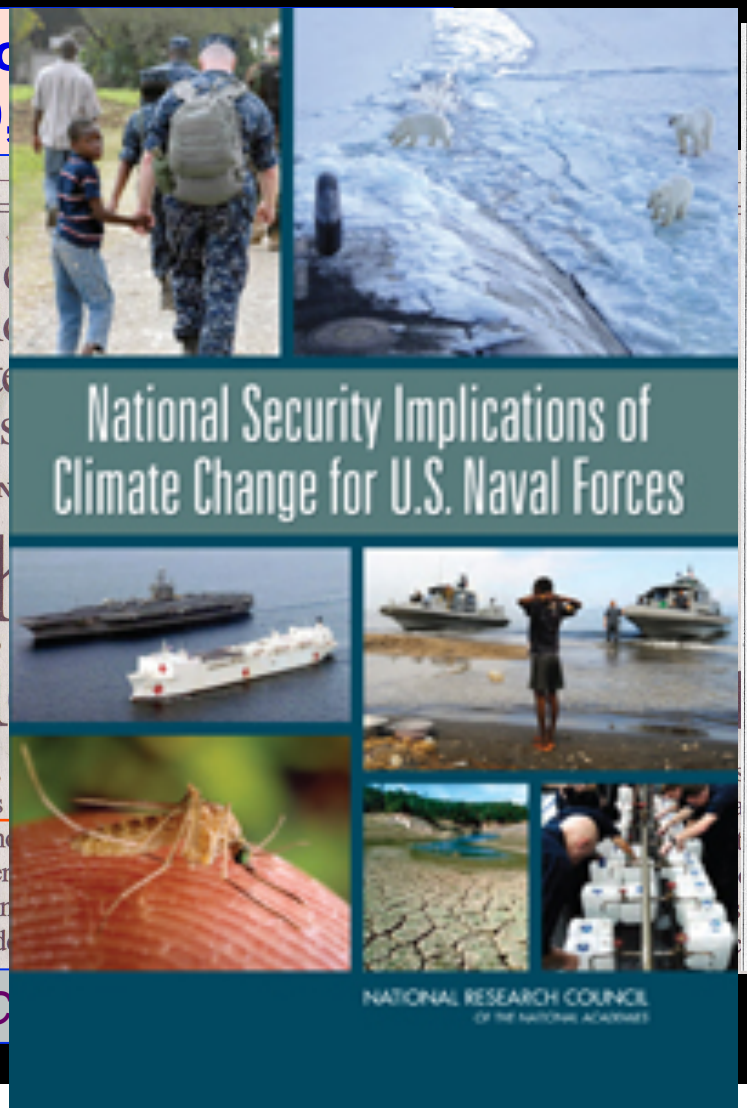


Washington Post 8 Sept 2010

A19

If climate skeptics win . . .

Stephen Stromberg's Sept. 3 PostPartisan commentary, "A downside to Murkowski's exit," hit the nail on the head about a disturbing trend that has emerged this year among almost a dozen Republican Senate candidates. These candidates are full-fledged global-warming deniers. If they win, the number of card-carrying members of the Flat Earth Society will rise exponentially in the world's greatest deliberative body.

Wisconsin candidate Ron Johnson said, "I think it is far more likely it is just sunspots" rather than human actions causing global warming. Nevada candidate Sharron Angle said, "I don't . . . buy into the whole man-caused global warming . . . mantra of the left." Colorado candidate Ken Buck admitted, "I am one of those people that Al Gore refers to as a skeptic," and Missouri Rep. Roy Blunt said, "There isn't any real science to say we are altering the climate path of the Earth."

If candidates like these replace climate champions in November, we will feel more than just the loss of a few elected officials. We will lose out on a clean energy future that creates jobs, increases our national security and protects the planet for future generations.

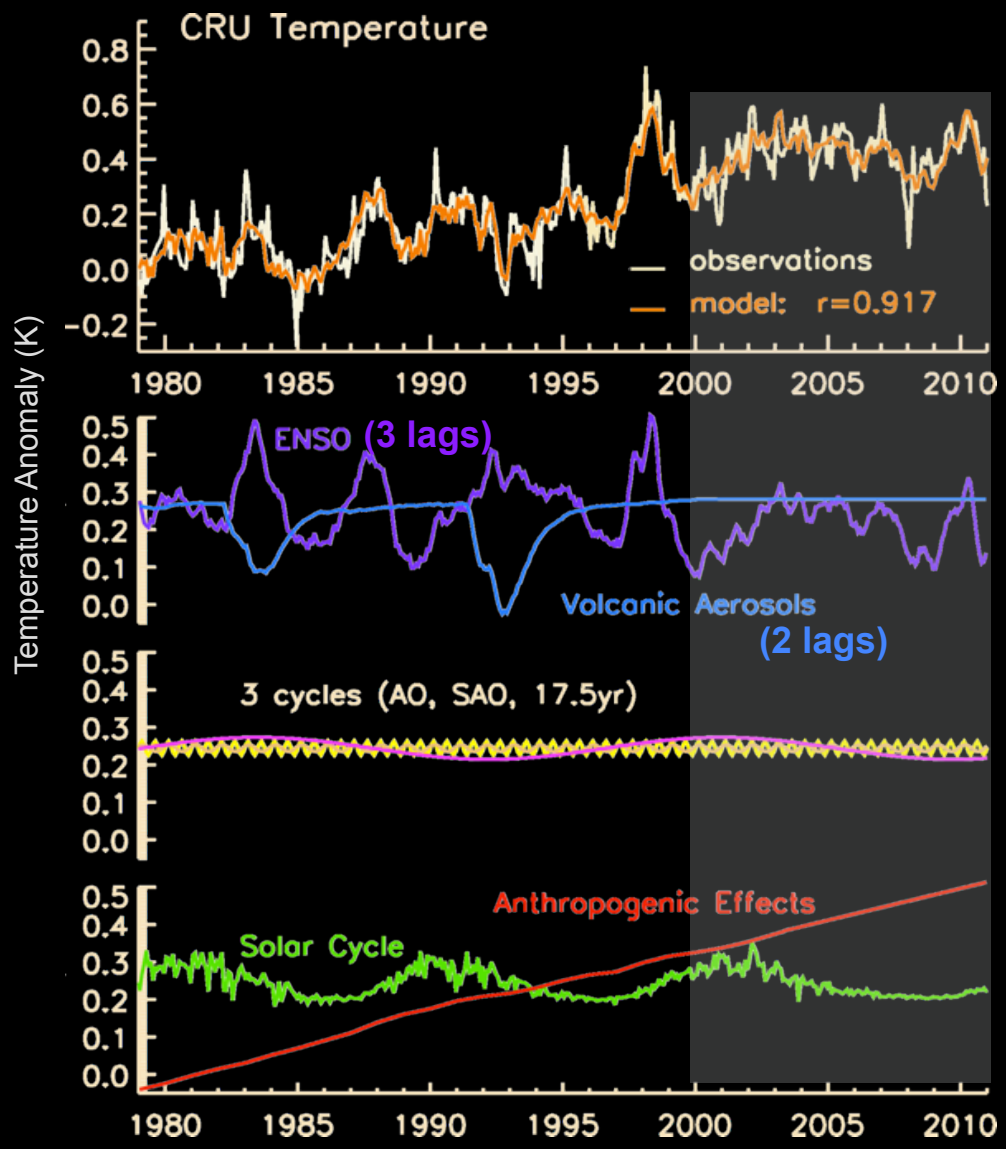
GENE KARPINSKI, *Washington*

The writer is president of the League of Conservation Voters.

relatively stable for a decade and may even drop in the next few years." That was in the Times's first paragraph.

Applications: Causes of Global Surface Temperature Change, 1979-2011

(Kopp and Lean, GRL, 2011)



… CRU temperature data, Univ. East Anglia, UK

NRL's Linear Climate Model (NRLLCM):
ENSO + volcanic aerosols + solar activity + anthropogenic effects explain 85% of observed temperature variance

QA

…update, improve, compare
…repeat, repeat, repeat

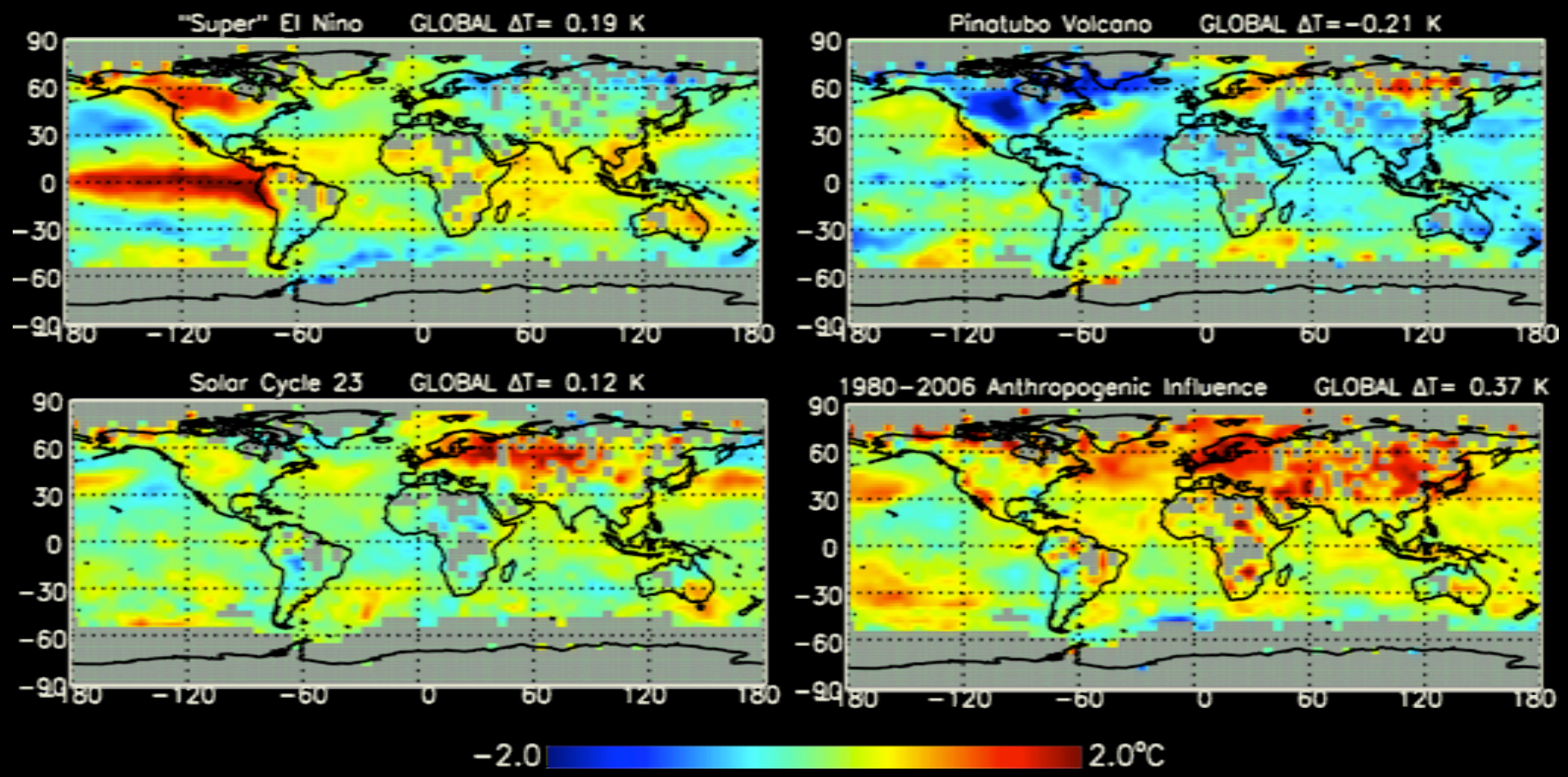
+0.2°C 1997-98 "super" ENSO

-0.3°C Pinatubo Volcano

+0.1°C Solar cycle 23

+0.4°C Anthropogenic effects 1980-2006

Applications: Surface Temperature Responses Regional Response Patterns



(5°×5° lat-long)

Lean, WIRE, 2011

Applications: Relative Climate Forcing of Solar Irradiance, ENSO and Aerosols

"The new study (Kaufmann et al., PNAS, 2011) shows that while greenhouse gas emissions continued to rise, their warming effect on the climate was offset by the cooling produced by the rise in sulphur pollution."

http://environmentalresearchweb.org/

Did China's coal burning REALLY offset global warming in the past decade? (No)

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5 July 2011 Last updated at 04:16 ET

714 Share

Global warming lull down to China's coal growth

By Richard Black
Environment correspondent, BBC News

The lull in global warming from 1998 to 2008 was mainly caused by a sharp rise in China's coal use, a study suggests.

The absence of a temperature rise over that decade is often used by "climate sceptics" as grounds for denying the existence of man-made global warming.

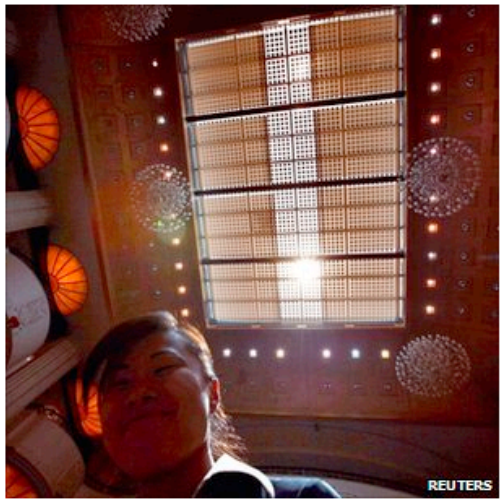
But the new study, in **Proceedings of the National Academy of Sciences**, concludes that smog from the extra coal acted to mask greenhouse warming.

China's coal use doubled 2002-2007, according to US government figures.

Although burning the coal produced more warming carbon dioxide, it also put more tiny sulphate aerosol particles into the atmosphere which cool the planet by reflecting solar energy back into space.

The researchers conclude that declining solar activity over the period and an overall change from El Nino to La Nina conditions in the Pacific Ocean also contributed to the temperature plateau.

Lead researcher Robert Kaufmann from Boston University, whose research interests span climate change and world oil markets, said the study was inspired by "sceptical" questioning.



Solar power is coming to China - but coal-burning grew amazingly quickly a few years back

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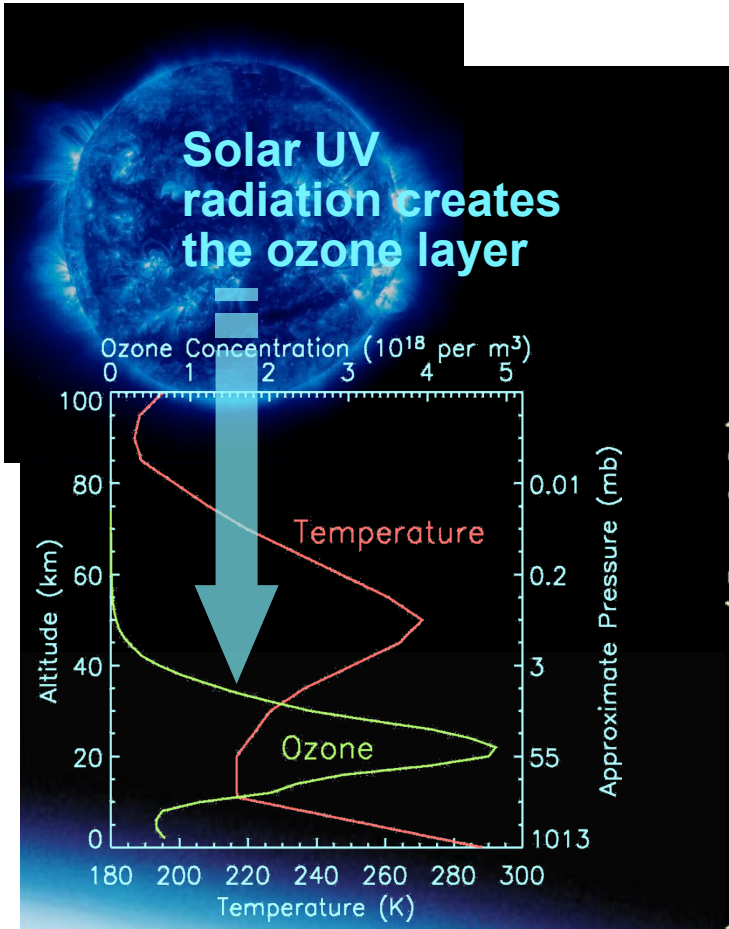
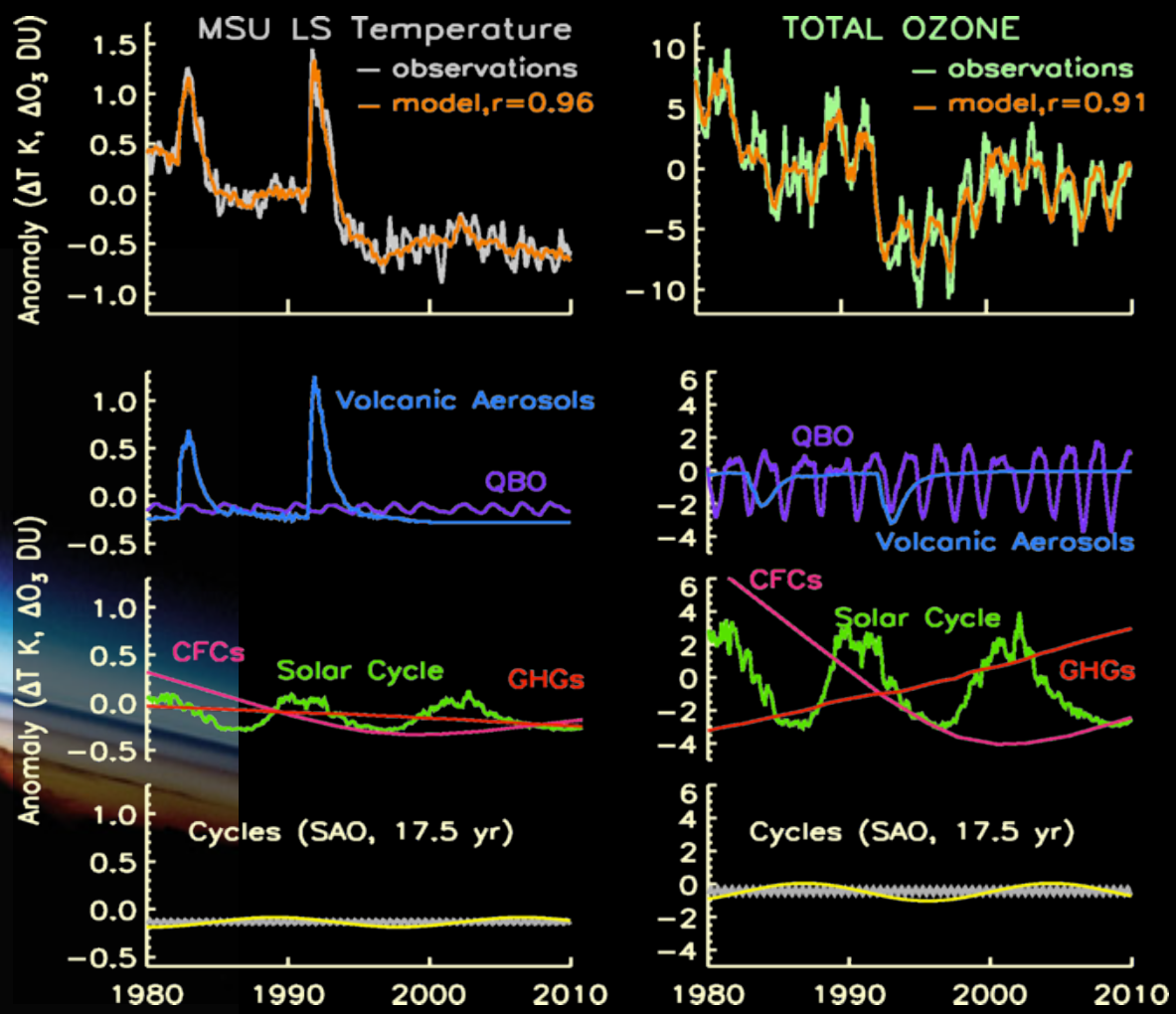
Solar predictions bring heat and light

Solar surprise for climate issue

Climate science, from Bali to Copenhagen

Applications: Stratospheric Temperature and Ozone Climatology





Regression Model Analysis:

Volcano:
$\Delta T = +1.5^{o}C$ $\Delta O_3 = -3$ DU

Solar cycle:
$\Delta T = +0.3^{o}C$ $\Delta O_3 = +6$ DU

Long-term Trend: (1980 - 2010)
$\Delta T = -0.7^{o}C$ $\Delta O_3 = -5$ DU

Applications: Climate, The Next 10 Years

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Climate change: The next ten years

- 13 August 2008 by Fred Pearce and Michael Le Page
- Magazine issue 2669. Subscribe and get 4 free issues.
- For similar stories, visit the Climate Change Topic Guide

WHAT's going to happen to the climate over the next 10 years or so? Is it time to buy that air conditioner you considered during the last heatwave? Should you rip up your garden and replant it with drought-resistant plants, or can you expect more rain - perhaps even floods - in your part of world? The other possibility, of course, is that your local climate will change little in the near future.

On the one hand we have weather predictions for the next few days. On the other we have climate forecasts for the very distant future. But what happens in the middle? Why don't we have forecasts for, say, 2010 or 2018? Knowing how temperature and rainfall will change over the next few years would be invaluable to many people, from farmers to the tourism industry to those in charge of our water supplies. Yet while you might think predicting how the climate will change over the next few years would be a lot easier than saying what it will be like in 2030 or 2050, it's actually harder.

Improved Surface Temperature Prediction for the Coming Decade from a Global Climate Model

Smith et al., Science, 2007

… climate will continue to warm, with at least half of the years after 2009 predicted to exceed the warmest year currently on record…..ΔT=0.3°C from 2004-2014

Advancing decadal-scale climate prediction in the North Atlantic sector

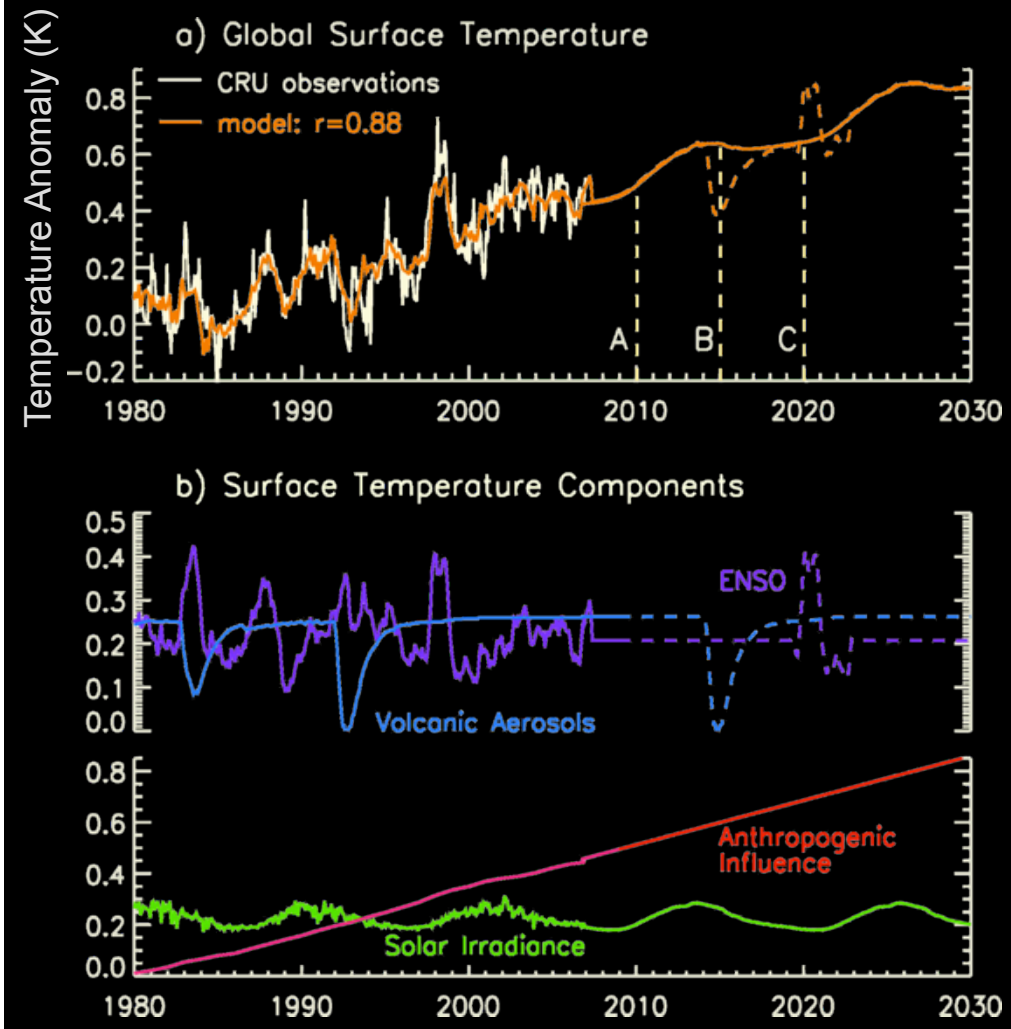
Keenlyside et al., Nature, 2008

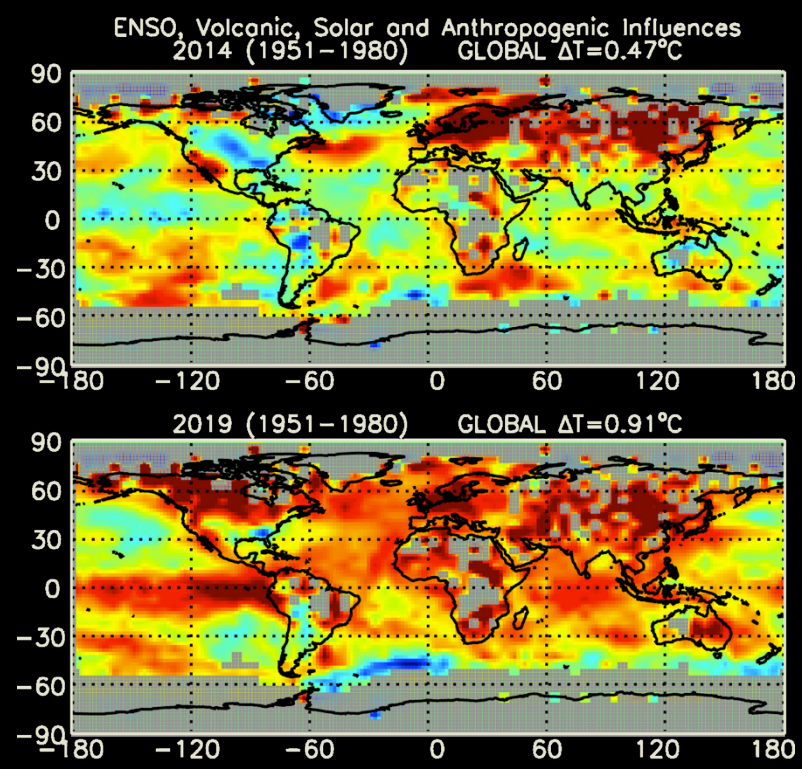
….global surface temperature may not increase over the next decade, as natural climate variations in the North Atlantic and tropical Pacific temporarily offset the projected anthropogenic warming.

- 2 more images

Applications: How – and Why - will Climate Change?

Assuming Past is Prologue…. future near-term climate change will vary because of both natural and anthropogenic influences





There will be both warming and cooling in the next few decades

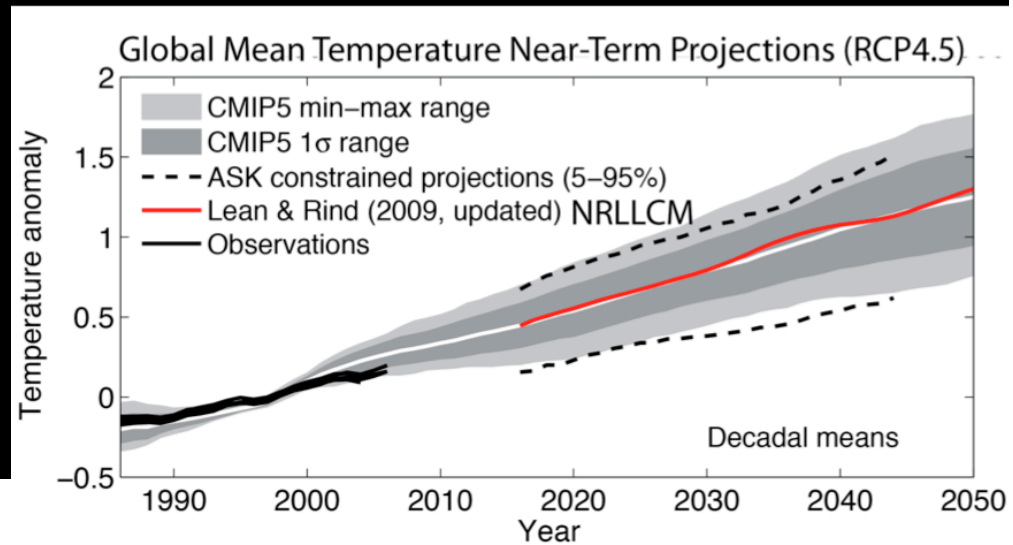
Applications: Near-Term Annual Mean Surface Temperature Forecasts

Courtesy of Ed Hawkins, University of Reading……

Modeled and statistical projections using specified GHG scenario (RCP4.5)

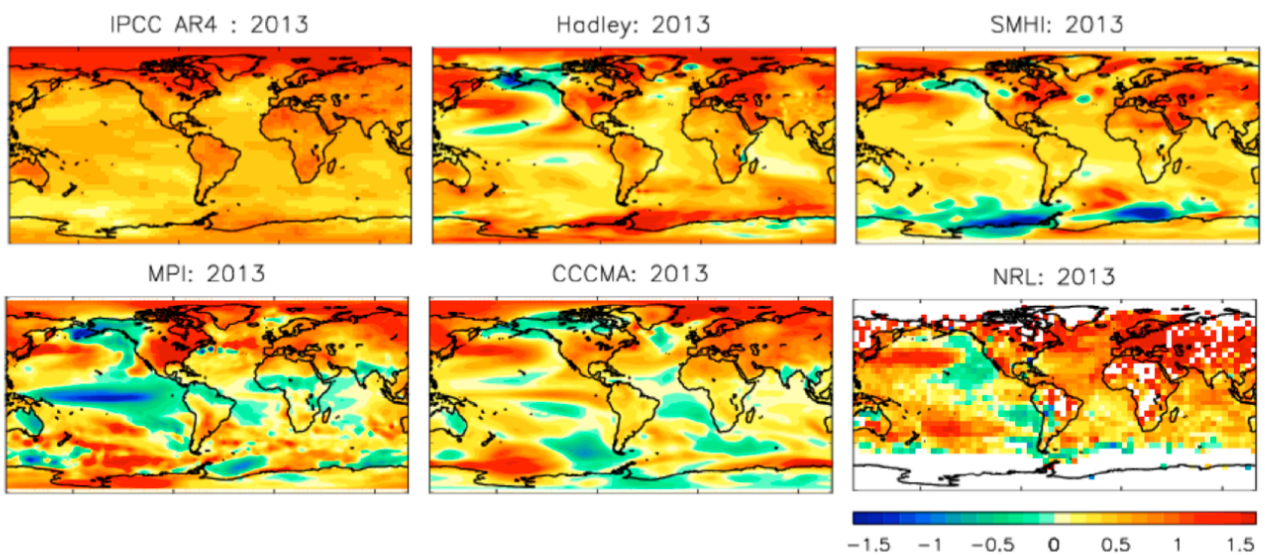
CMIP5 … Coupled Model Intercomparison Project

- 20 international climate modeling groups



Decadal Climate Forecasting Exchange
Surface Temperature Projections for 2013

Courtesy of Douglas Smith and Adam Scaife, UK Met Office

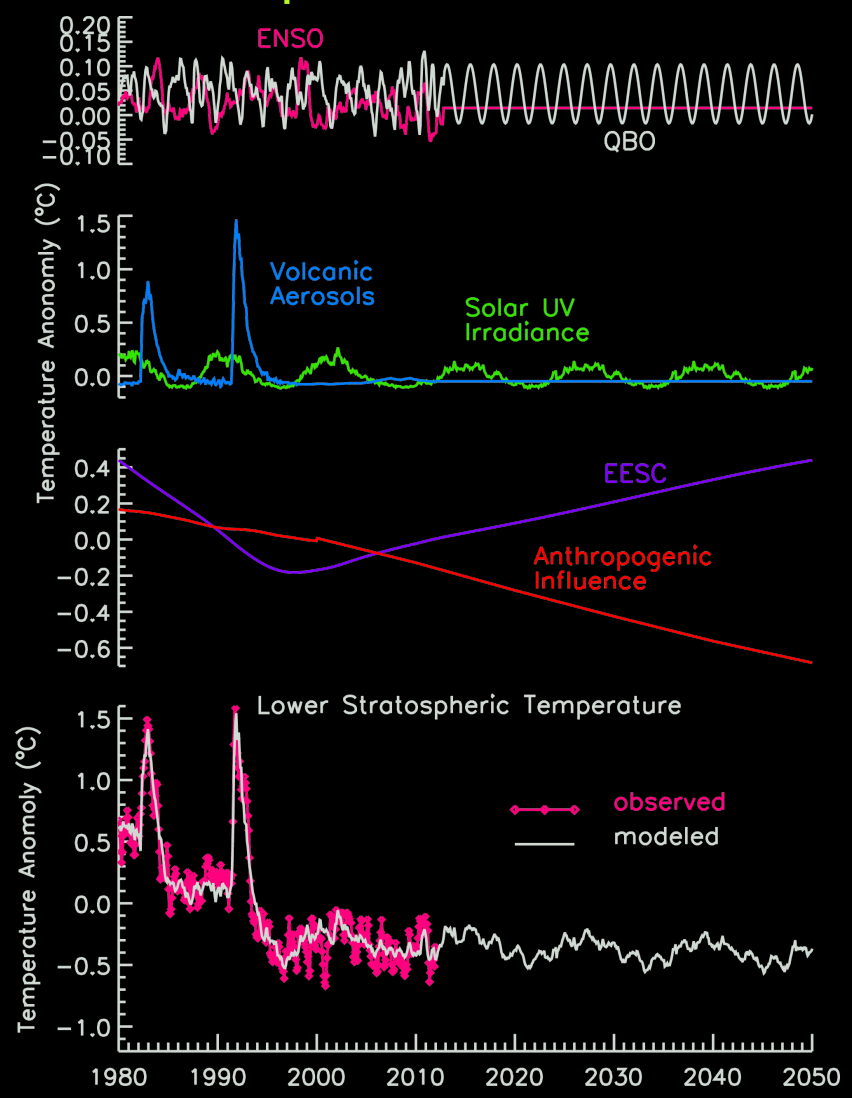


Quality Assurance:
Comparison with future observations

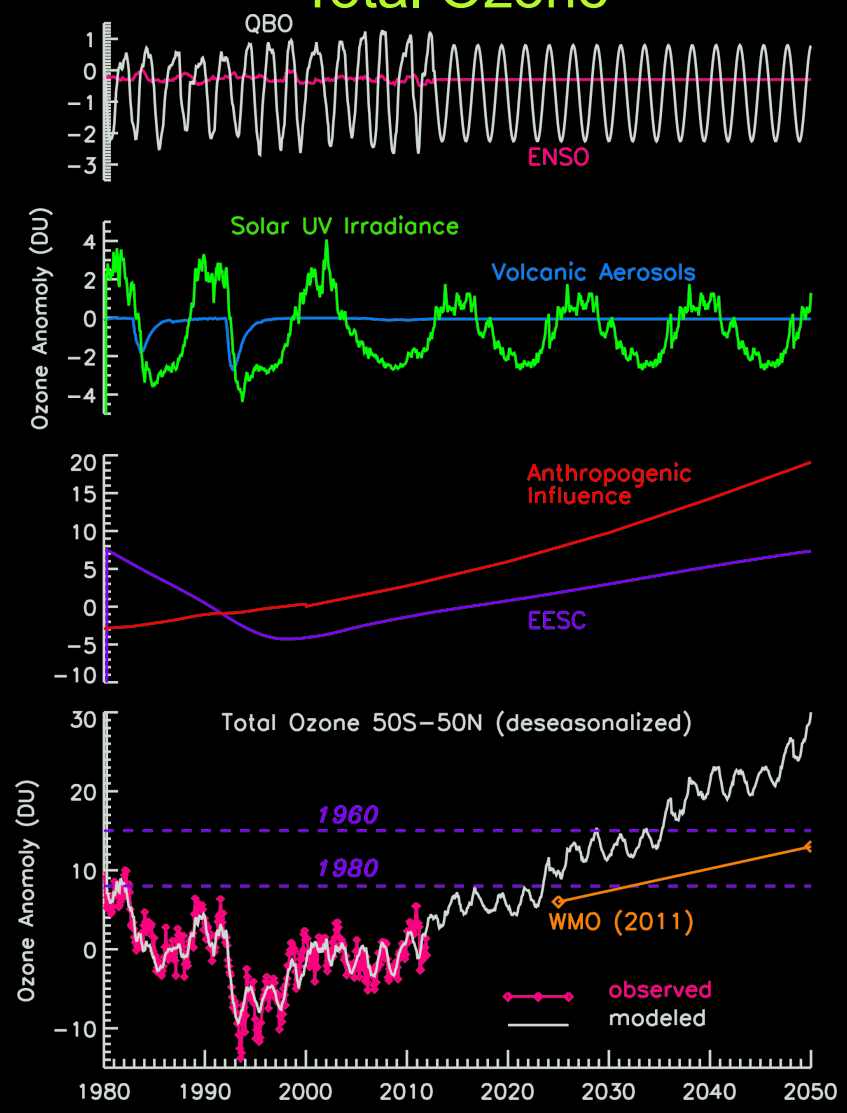
Schedule:
Ongoing !! ??

Applications:
Future Lower Stratospheric Changes

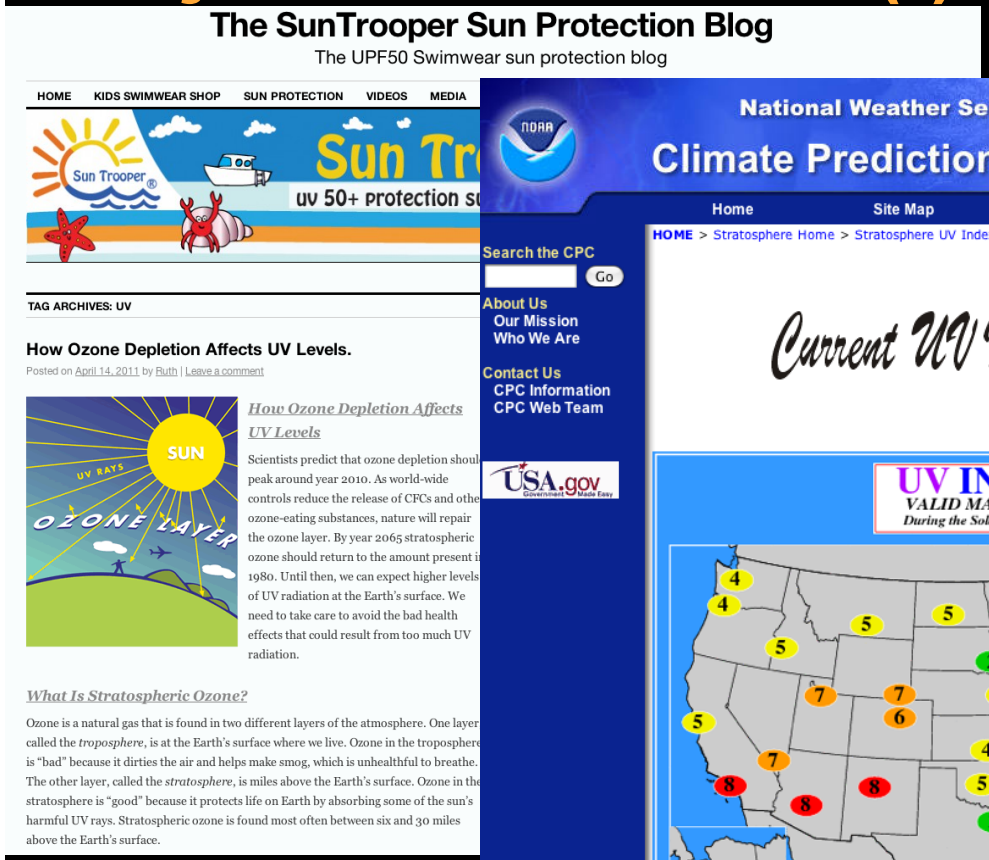
Temperature at 19 km

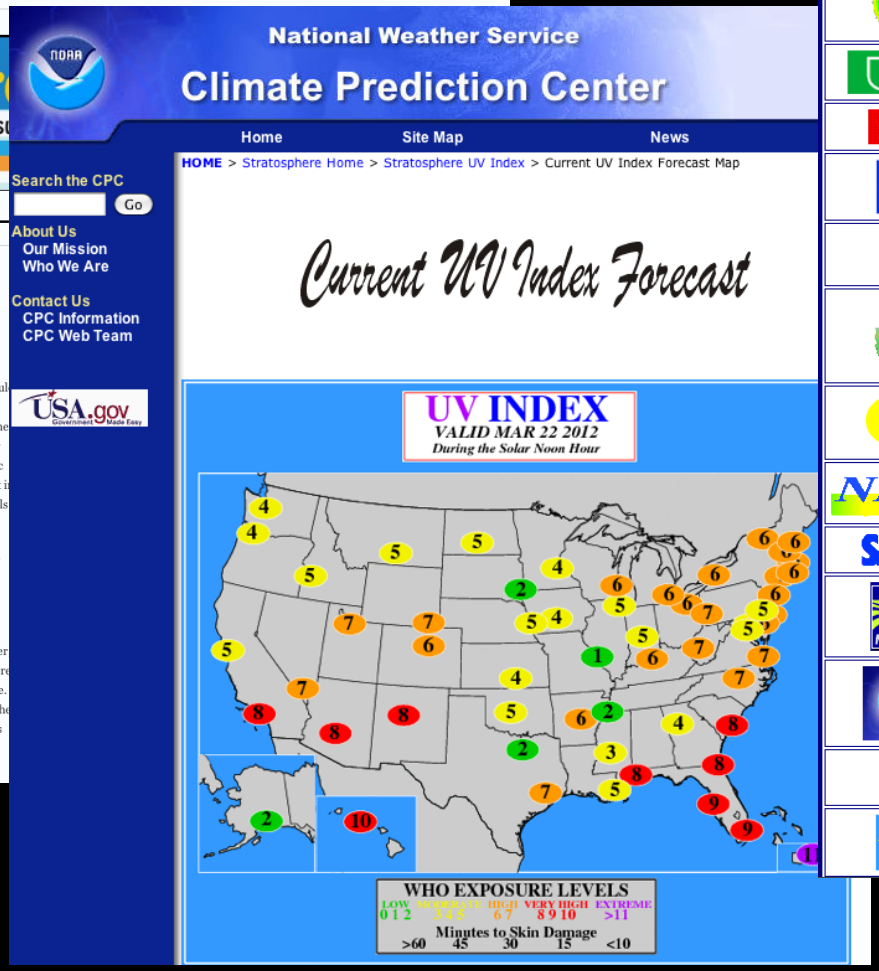


Total Ozone



Applications: UV Index Projected Decrease (!)





UV Index: 0-10+

The U.S. National Weather Service calculates UV Index using a computer model that relates the ground-level strength of solar ultraviolet (UV) radiation to forecasted stratospheric ozone concentration, forecasted cloud amounts, and elevation of the ground.

Solar Irradiance, Climate Impact: Summary

- **Longer, continuous high precision records of TSI and SSI are crucial on climate time scales**

  - long-term trends not yet detectable from instrumental instabilities in observations

- **Natural influences, including solar irradiance, alter Earth's surface temperature, atmosphere and ozone**

  - evident in recent past and in future decades, superimposed on warming trend

- **Decadal climate projection is an emerging crucial capability**

  - needs solar irradiance inputs; needs accurate and precise climate models

  - ongoing evaluation, improvement, revised projection ...UKMO "Decadal Exchange"

Work in Progress with David Rind using GISS Middle Atmosphere General Circulation Climate Model3:

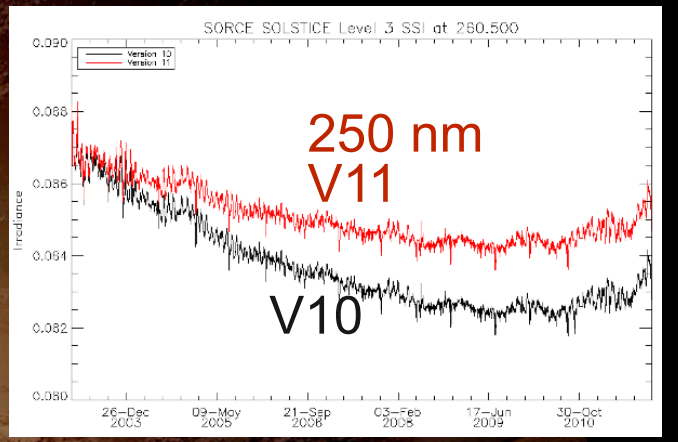
What difference does the new lower TSI values make in general circulation model climate simulations?

Climate models are "calibrated" to ensure that net radiation at the top of the atmosphere is small: Model 3 achieves this by adjusting its paramaterization of cloud formation.

Climate Data Records for Total and Spectral Solar Irradiance:

Schedule

- **Extend and improve the long-term TSI records**
  - *TSI gap mitigation*
  - *SSI validation and improvements*
- **Extend and improve the long-term SSI records**
  - *SSI validation and improvements*
  - *Ongoing reanalysis of SORCE SIM & SOLSTICE SSI*
  - *New degradation models for SORCE SIM & SOLSTICE*
  - *SSI workshop 13 September, Annapolis, MD.*
- **Assess, validate, improve decadal climate forecasts**
  - *improve TSI and SSI and climate model inputs*
  - *improve climate model capabilities & application to assessments, vulnerabilities, users*
- **Complete and Review TSIS ATBD**



An error in the version 10 degradation correction in the A/B transfer is now believed to have produced the unusually large variation at some wavelengths in the MUV data. SNS Jan 2012

Production Approach

- Converting from Instrument signal to irradiance follows a "Measurement Equation Approach"

$$\mathcal{E}_\lambda(\lambda_s) = \frac{\mathcal{P}_{\mathrm{ESR}}(\lambda_s)}{A_{slit} \cdot \int \alpha_\lambda \cdot T_\lambda \cdot \phi_\lambda \cdot S(\lambda, \lambda_s)\, d\lambda}$$

ESR detected power

Aperture area

ESR Absorptance

prism transmission

slit diffraction

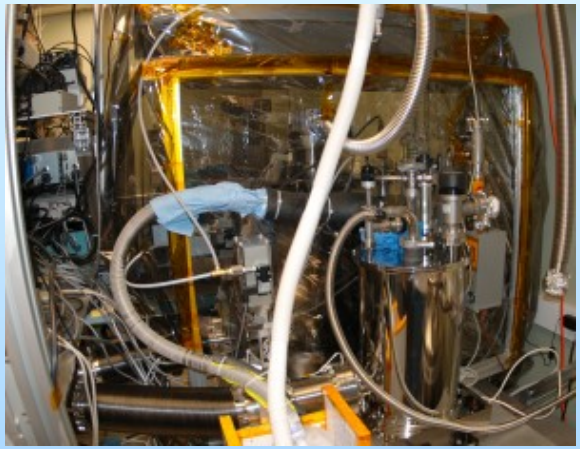
instrument function

Measurement equation for the SIM instrument

- Measurement and characterization/calibration of all terms on the right-hand-size of equation are performed
  - shutter waveform factor, entrance aperture/slit, bolometer absorption, equivalence ratio, loop gain, diffraction correction, prism transmission, exit slits, instrument function convolution, photodiode radiant responsivity…

Production Approach: Determining Accuracy and Precision

- The TSIS instruments are characterized to be *absolute sensors*.
  - Each term in the measurement equation is calibrated and the overall measurement uncertainty is a root sum square error of the individual uncertainties.
- End-to-end validation:
  - The TSI Radiometer Facility (TRF) and Spectral Radiometer Facility (SRF) at LASP tie irradiance comparisons to a NIST L-1reference cryogenic radiometer at power levels typical of the Sun and under flight-like vacuum conditions



A NIST-calibrated cryogenic radiometer (foreground) accurately measures input light at solar power levels in the TRF. Instruments are tested in the vacuum chamber enclosed by the clean tent toward the rear.

Production Approach: Calibration and Verification

- Both TIM and SIM trace their calibrations to the standard Watt.
- All elements of TIM and SIM instrument equations are calibrated at either the component or instrument level.
- End-to-end verification of TIM via the TSI Radiation Facility (TRF)
  - Kopp, MO3.1/27102: *Total Solar Irradiance Measurements from the Total Irradiance Monitor*
- End-to-end verification of the SIM instrument using the NIST Spectral Irradiance and Radiance Responsivity Calibrations using Uniform Sources (SIRCUS) facility

TSIS TIM Uncertainty Budget

Correction	Origin	Value [PPM]	1σ [PPM]
Distance to Sun, Earth & S/C	Analysis	33,537	0.1
Doppler Velocity	Analysis	57	0.7
Shutter Waveform	Component	100	1.0
Aperture	Component	1,000,000	28
Diffraction	Component	452	46
Cone Reflectance	Component	182	35
Non-Equivalence, ZH/ZR-1	Instrument	782	43
Servo Gain	Instrument	2,115	0.0
Standard Volt +DAC	Component	1,000,000	15
Pulse Width Linearity	Component	800	3
Standard Ohm + Leads	Component	1,000,000	25
Dark Signal	Instrument	1,645	14
Pointing	Analysis	100	10
Measurement Repeatability (Noise)	Instrument	-	4
Uncertainty due to Sampling	Analysis	-	12
Total RSS			85.5

TSIS SIM Uncertainty Budget

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

Instrument-Level Component-Level S/C

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*	

Complete

In-progress

Dominant uncertainties are I-dependent

QA Approach: Long Term Stability Requirement Met Through On-Orbit Degradation Correction

On-orbit interchannel transmission comparisons track wavelength and exposure time dependent transmission loss

$$\mathcal{T}(\lambda, t - t_0) = \mathcal{T}(\lambda, t_0)\, e^{-\tau(\lambda, t - t_0)}$$

$$\tau(\lambda, t) = \kappa(\lambda) \cdot c(t)$$

κ(λ) evaluated by periodic ESR measurements between separate channels

The degradation correction determined using the Channel A to Channel B ratio data measured twice per month

The Channel A to Channel C comparison (~1 per year) verifies the degradation correction

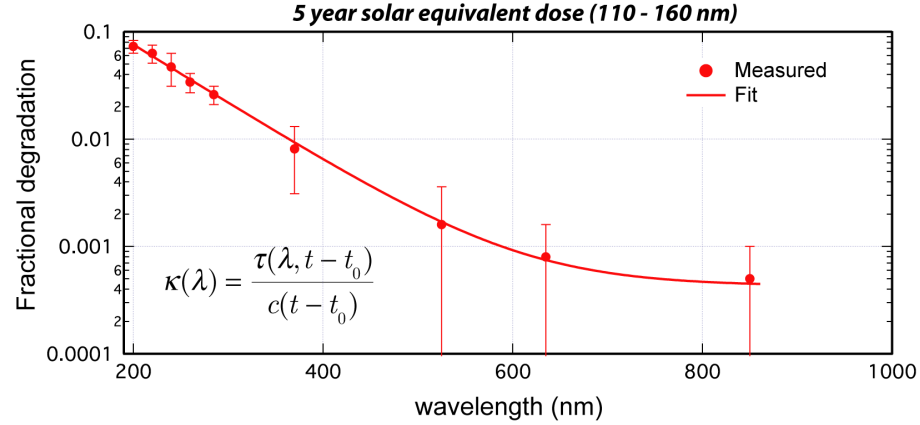
Channel C is to be used infrequently enough so that it can be considered "pristine" (less than 0.01%/year of degradation)

We must be able to measure trends < 0.01% (0.05%) / year in this Channel A to Channel C ratio data for Vis/IR (UV)

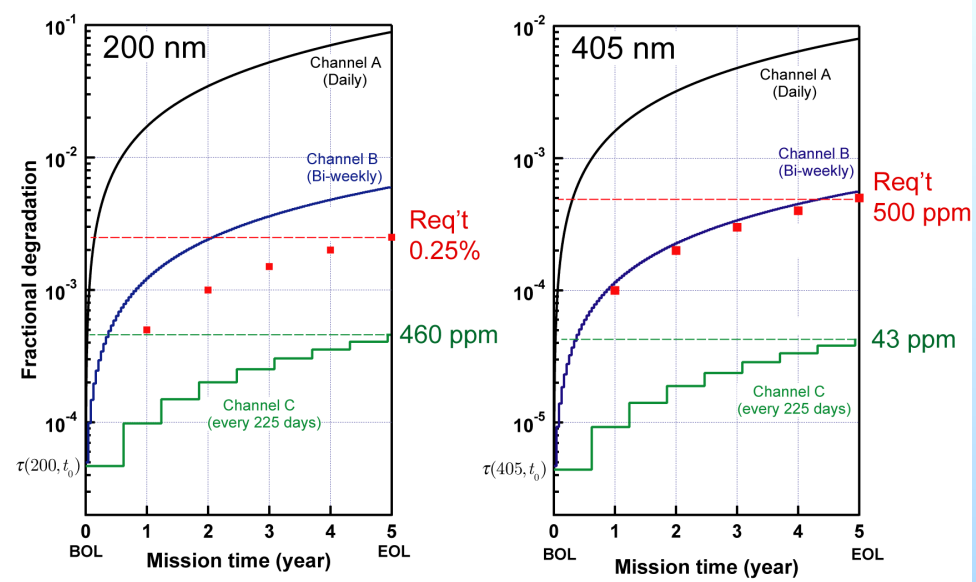
This puts a limit on the spectra to spectra repeatability

Fractional degradation vs. wavelength

5 year solar equivalent dose (110 - 160 nm)



Fractional degradation vs. exposure time



Schedule: Status of TSIS ATBD

Complete *In progress*

** Out for Internal Review.*

- Section 1: Introduction *
- Section 2: Overview and Background Information *
- Section 3: Instrument Design *
- Section 4: Algorithm Description
- Section 5: Calibration and Characterization *
- Section 6: Degradation Correction & Uncertainty Estimates
- Section 7: Validation
- Section 8: Data Product Requirements and Description
- Section 9: Production of Science Data