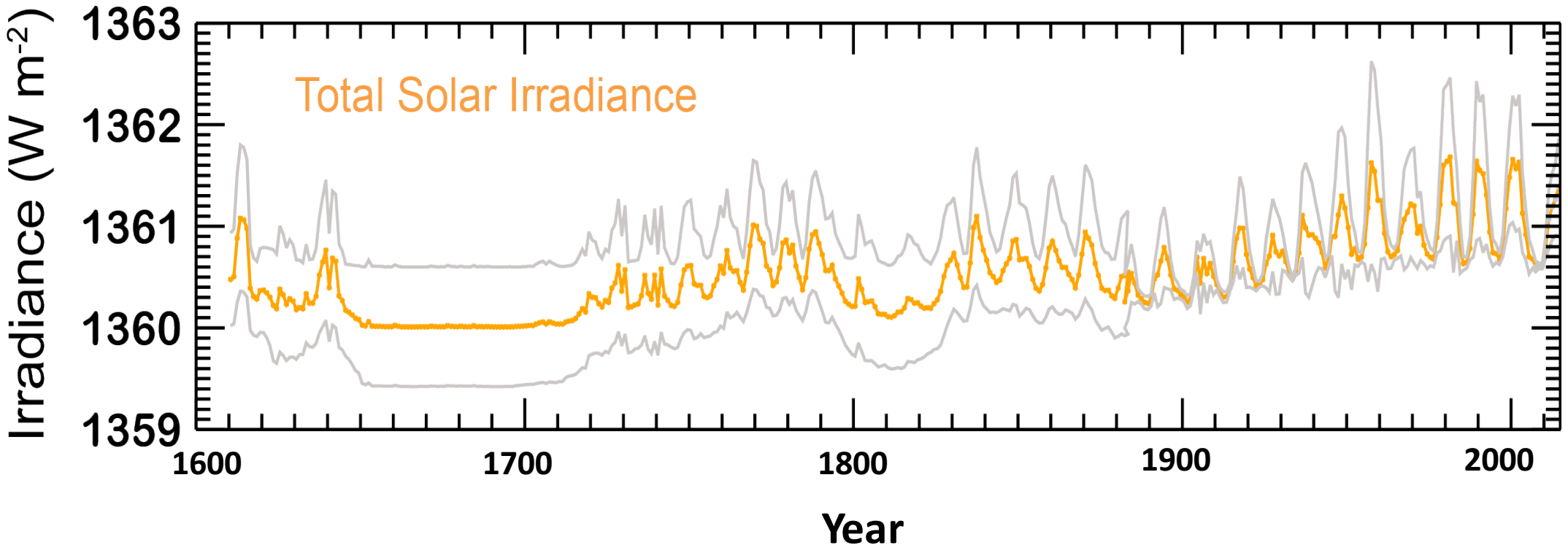
A New Record of Total Solar Irradiance from 1610 to Present

Odele Coddington, Judith Lean, Peter Pilewskie, Martin Snow, Doug Lindholm, and Greg Kopp

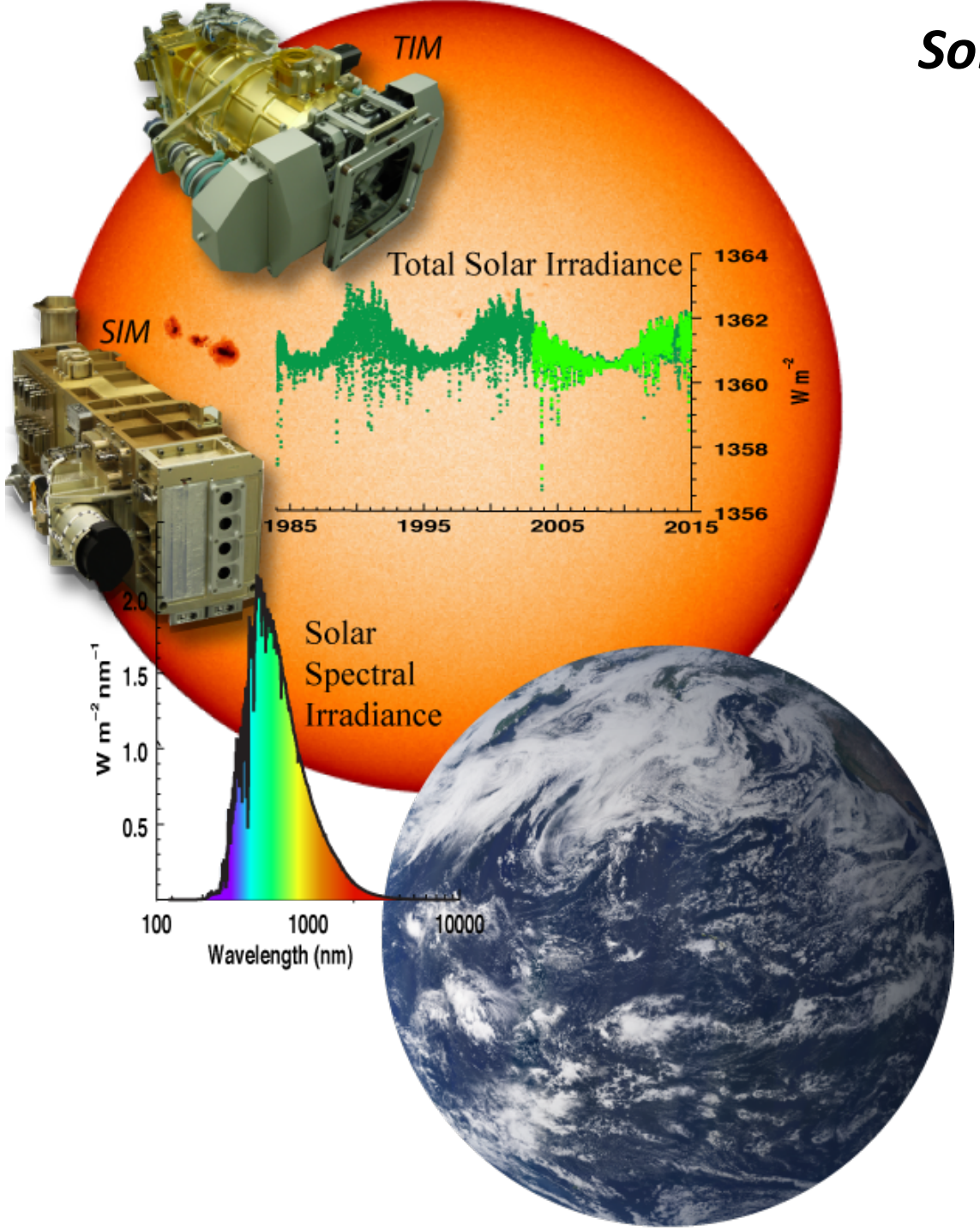


Outline

- NOAA NCEI Climate Data Record (CDR) Program
  - Motivation & Participation Requirements ("Deliverables").
- Naval Research Laboratory TSI (NRLTSI, version 2) Model Formulation
  - Algorithm, inputs, error estimates, differences from original model
- Operational Implementation and Quality Assurance
  - Update cadence, statistical comparisons with measurements, other models, other proxies of solar activity
- Ongoing improvements

The NOAA National Centers for Environmental Information (NCEI) Climate Data Record (CDR) program

- *Formerly the National Climatic Data Center (NCDC)…*
- A CDR is a data record of sufficient length, consistency, and continuity to determine climate variability and change [*National Research Council*, 2004].
- NOAA operational CDR's are:
  - systematically generated,
  - assessed for quality,
  - robust, sustainable, and scientifically defensible,
  - for use in climate studies on multiple time scales, and
  - relevant for broad user groups.
- The *Solar Irradiance Climate Data Record* is a joint effort of the Naval Research Laboratory (NRL) and the Laboratory for Atmospheric and Space Physics (LASP).
  - NRLSSI2 and NRLTSI2 ('2' for version 2) are the current versions of the Naval Research Laboratory (NRL) solar variability models.



Solar Irradiance CDR Deliverables

- **Total Solar Irradiance** (TSI) & **Solar Spectral Irradiance** (SSI) from 115 to 100,000 nm
  - Time Period:
    - 1610 to present (annual averages)
    - 1882 to present (daily and monthly averages)
  - Uncertainties: Wavelength and Time-dependent
  - Format: NetCDF4 with metadata at international standards
- **TSI observational composite** from 1978 to present
- **Documentation**
  - Climate Algorithm Theoretical Basis Document
  - Source Code
  - Supporting Documents and Data (reference solar spectra, model input time series)
- **Stewardship**
  - Periodic preliminary (quarterly) updates for the foreseeable future.
  - Yearly Quality Assurance reports & replacement of preliminary data with final data.
  - Periodic updates to the TSI observational composite with measured data (SORCE/TCTE TIM, transitioning to TSIS TIM in future).

Data Access

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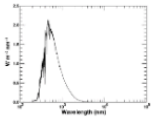
NOAA Climate Data Record (CDR) of Solar Spectral Irradiance (SSI), NRLSSI Version 2

Solar Spectral Irradiance



The Solar Spectral Irradiance (SSI) produced for this Climate Data Record (CDR) for 1 January 2014.

This Climate Data Record (CDR) contains solar spectral irradiance (SSI) as a function of time and wavelength created with the Naval Research Laboratory model for spectral and total irradiance (version 2). Solar spectral irradiance is the wavelength-dependent energy input to the top of the Earth's atmosphere, at a standard distance of one Astronomical Unit from the Sun. Its units are W per m2 per nm. Also included is the value of total (spectrally integrated) solar irradiance in units W per m2. The dataset was created by Judith Lean (Space Science Division, Naval Research Laboratory), Odele Coddington and Peter Pilewskie (Laboratory for Atmospheric and Space Science, University of Colorado). The daily- and monthly-

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Dataset Citation

Cite this dataset when used as a source: Odele Coddington, Judith L. Lean, Doug Lindholm, Peter Pilewskie, Martin Snow, and NOAA CDR Program (2015): NOAA Climate Data Record (CDR) of Solar Spectral Irradiance (SSI), NRLSSI Version 2. [indicate subset used]. NOAA National Centers for Environmental Information. doi:10.7289/V51J97P6 [access date].

Dataset Identifier(s)

ISO 19115-2 Metadata

Access | Documentation | Description | Coverage | Keywords | Constraints | Lineage

Lineage Statement	The data were produced by the Naval Research Laboratory and the University of Colorado, and are archived at the NOAA National Centers for Environmental Information (NCEI). Version 2 indicates the current version of the Naval Research Laboratory solar variability models, denoted NRLTSI2 and NRLSSI2, for total solar irradiance and solar spectral irradiance, respectively. This version labeling distinguishes the models from their original formulation, NRLTSI and NRLSSI (i.e,. Version 1, or original version). The Solar Irradiance Climate Data Record transitioned to the NOAA CDR program is specific to Version 2, although the original formulation of the model has created solar irradiance records used in many previous climate modeling studies, including for the IPCC.
Processor	UCO/LASP > Laboratory for Atmospheric and Space Physics, University of Colorado
Processing Steps	• For a complete description of the processing steps, see the Algorithm Theoretical Basis Document and Data Flow Diagram.

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The process that delivers new Daily Summary (GHCN-D) data in custom PDF or comma delimited output formats is unavailable. However, GHCN-D data updates will continue and data remain available via FTP access.

Operational CDRs

- Atmospheric
- Oceanic
- Terrestrial
- Fundamental

CDR Information

- Guidelines
- Developmental CDRs
- Opportunities

Climate Data Record Program

Welcome to NOAA's CDR Program

The mission of NOAA's Climate Data Record Program is to develop and implement a robust, sustainable, and scientifically defensible approach to producing and preserving climate records from satellite data.

CDR Program: https://www.ncdc.noaa.gov/cdr

Geographic Information System (GIS) Portal

SSI: http://gis.ncdc.noaa.gov/all-records/catalog/search/resource/details.page?id=gov.noaa.ncdc:C00899

TSI: http://gis.ncdc.noaa.gov/all-records/catalog/search/resource/details.page?id=gov.noaa.ncdc:C00828

Algorithm Overview

- NRLTSI2 is a proxy model that determines changes from quiet Sun conditions due to bright faculae (F) and dark sunspots (S) on the solar disk.

$$T(t) = T_Q + \Delta T_F(t) + \Delta T_S(t)$$

- Multiple linear regression analysis of the proxy indices of 'F' and 'S' with irradiance measurements determine the magnitude of irradiance change from background.

$$T_{mod}(t) = T_Q + a + b_F \times \left[F(t) - F_Q\right] + b_S \times \left[S(t) - S_Q\right]$$

Error Estimation: Putting some numbers to it

$$T_{mod}(t) = T_Q + a + b_F \times [F(t) - F_Q] + b_S \times [S(t) - S_Q]$$

- The precision and accuracy of NRLTSI2 depends on:
  - Uncertainty in the absolute scale of the reference Quiet Sun.
  - Statistical uncertainties in the scaling coefficients.
  - Uncertainties in the facular brightening and sunspot darkening values.

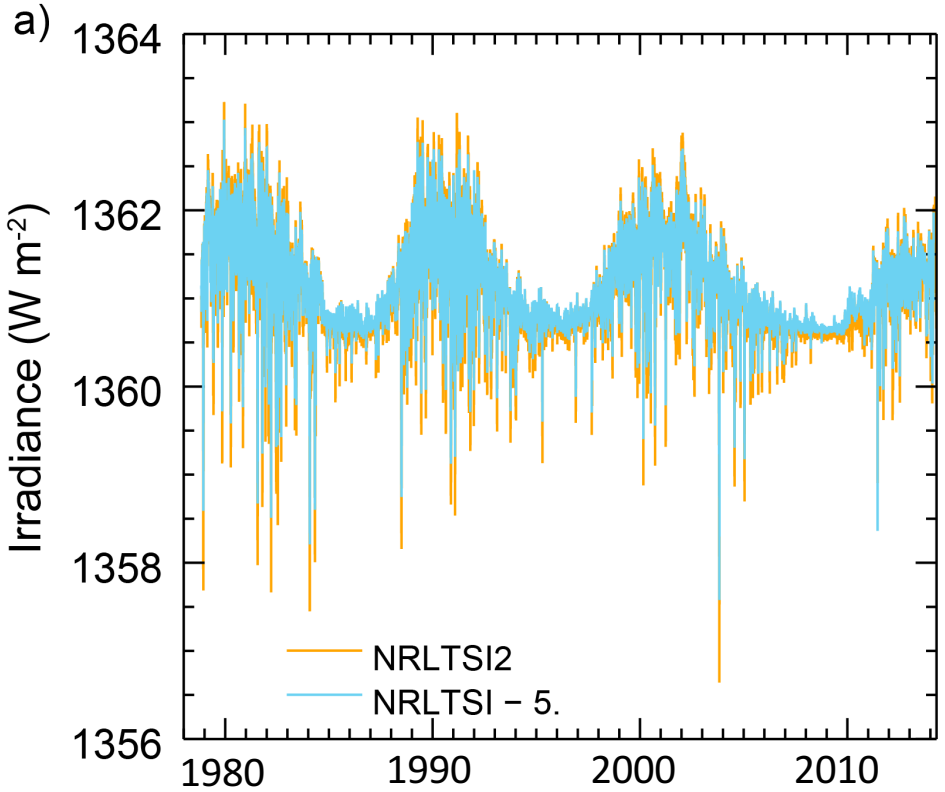
Quantity	Value and Uncertainty
T_Q	1360.45 +/- 0.5 W m^{-2}
a	0.091 +/- 0.006 W m^{-2}
b_F	139.66 +/- 1.12
b_S	-0.000564 +/- 0.000005
$F(t) - F_Q$	0.0151 +/- 0.003 (20%)
$S(t) - S_Q$	10647 +/- 2129 (20%)
$b_F \times [F(t) - F_Q]$	2.2 +/- 0.4 W m^{-2}
$b_S \times [S(t) - S_Q]$	-6.0 +/- 1.2 W m^{-2}
$T_{mod}(t) - T_Q$	-3.8 +/- 1.6 Wm^{-2}
$T_{mod}(t)$	1356.64 +/- 2.1 Wm^{-2}

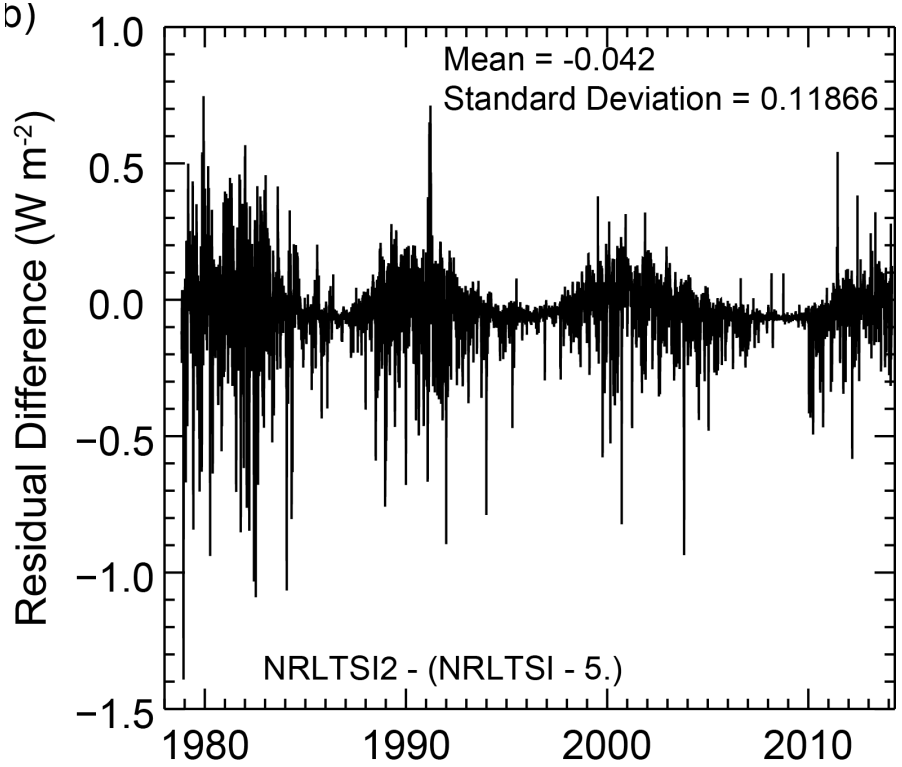
Example specific to 30 Oct 2003….

* Modeled TSI uncertainties exceed SORCE TIM measurement uncertainties by ~ a factor of 4.
** The uncertainties in modeled TSI scale with solar activity.

Differences in NRLTSI2 and original NRLTSI.

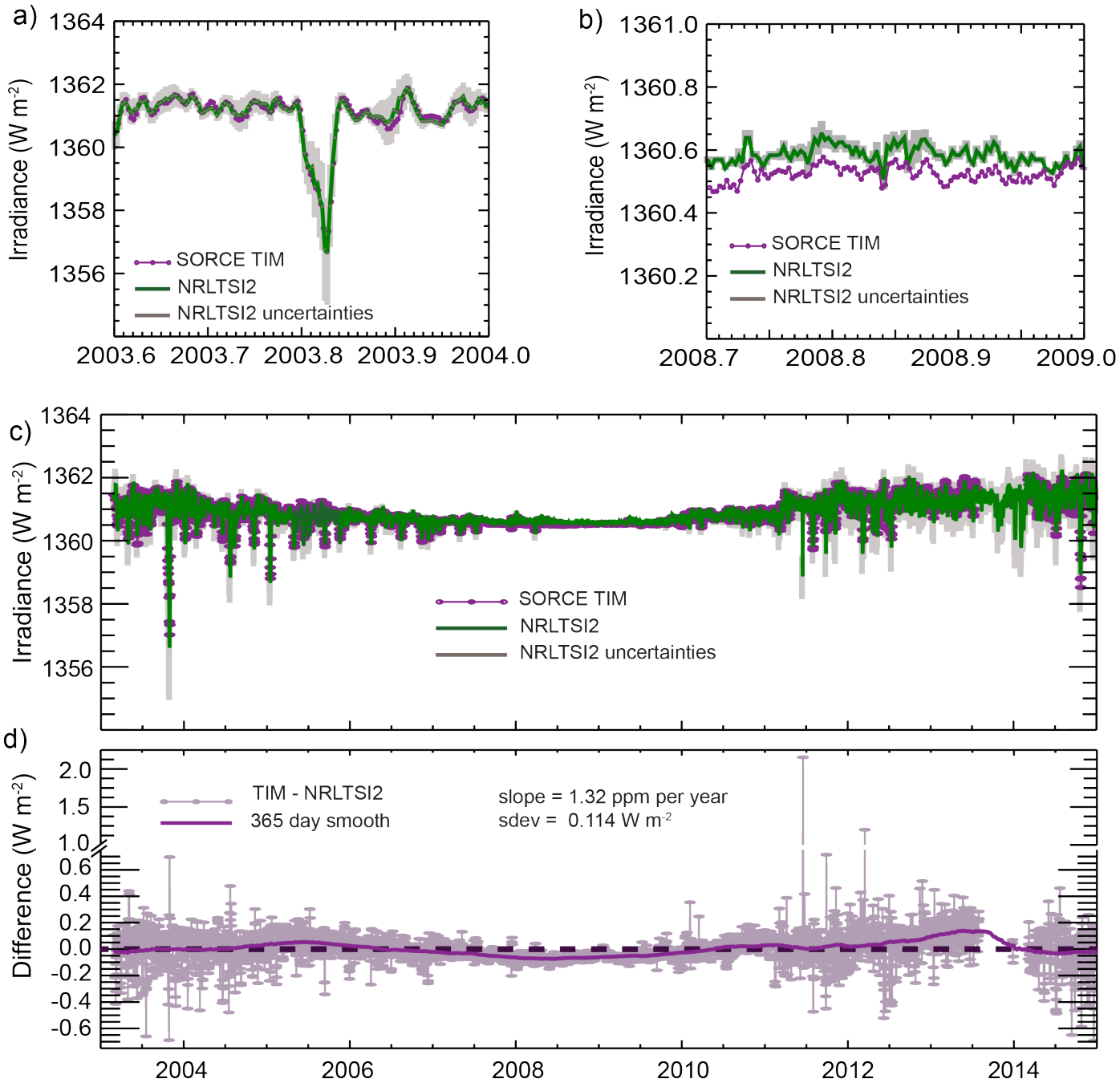
Model Inputs	NRLTSI	NRLTSI2
Quiet sun reference	1365.5 W m-2	1360.45 W m-2
Measurement record	Composite TSI record: 1978-2003 [Frohlich and Lean, 2004]	SORCE TIM TSI measurements: 2003-2014
Proxy Input record	[Hoyt and Eddy, 1982] sunspot area record [Viereck et al., 2003] Mg II composite extended with SORCE	[Hoyt and Eddy, 1982] sunspot area record Univ. of Bremen Mg II index composite





[Coddington et al., *BAMS*, 2015 *under review*]

Comparisons with SORCE TIM: 2003-2014



[Coddington et al., *BAMS*, 2015 *under review*]

Comparison with *observational* TSI composite: 1978-2014

Creation Details:

PMOD Composite [Frohlich and Lean, 1998]

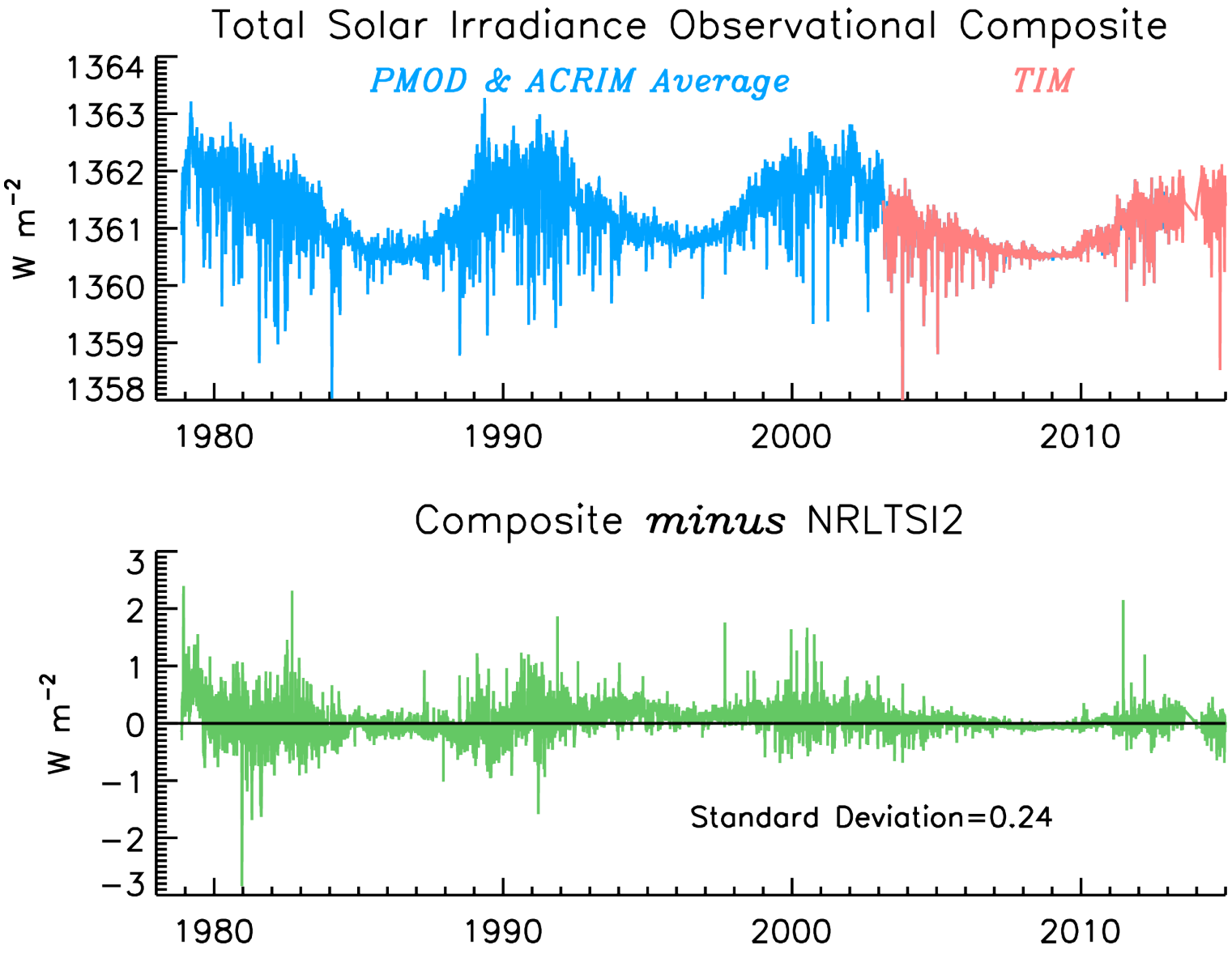
ACRIM composite [Willson and Mordinov, 2003]

a) normalized to SORCE TIM scale

b) averaged together

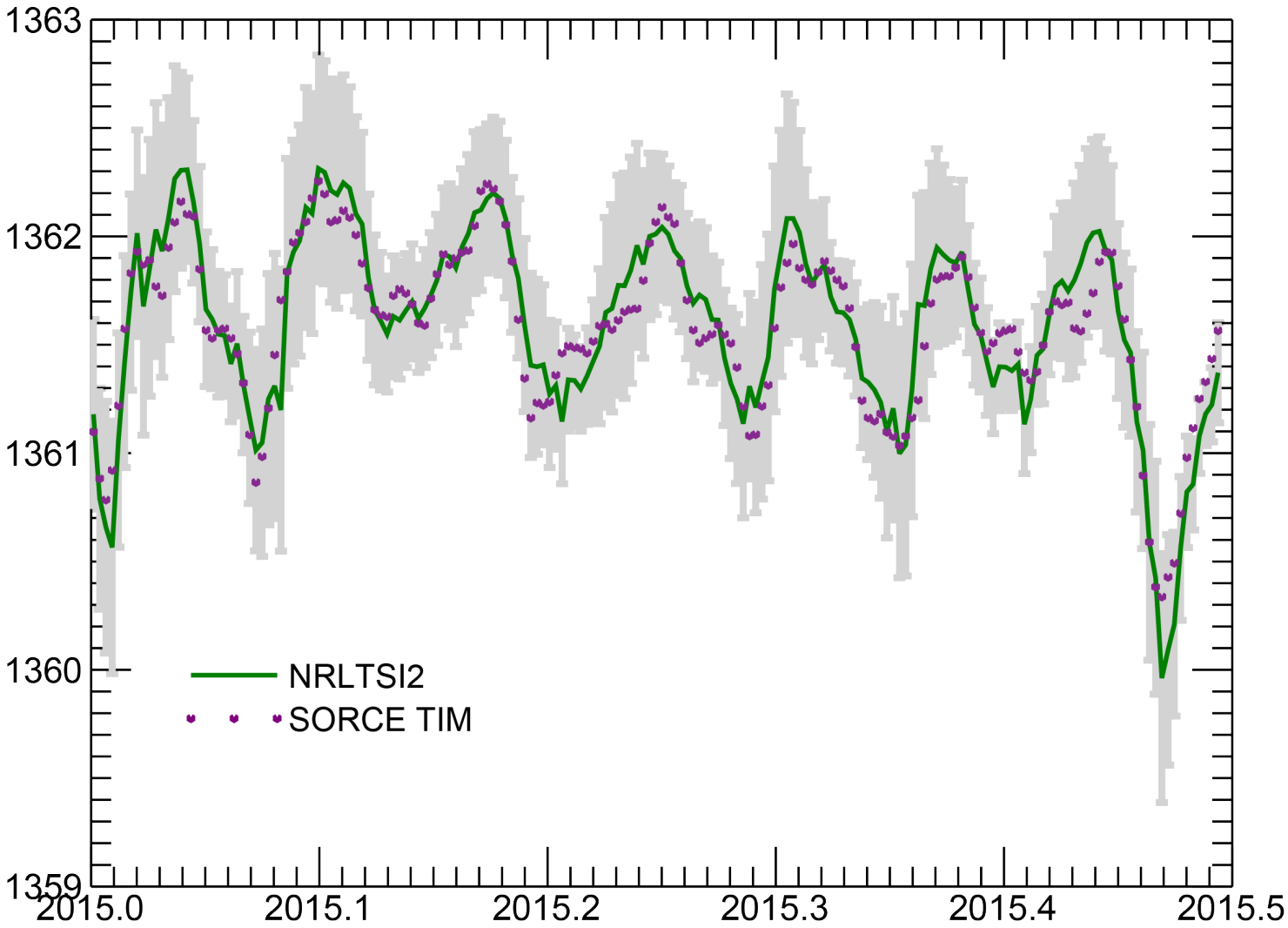
c) period that overlaps with SORCE is replaced by TIM measurements.

d) appended in future with SORCE TIM observations.



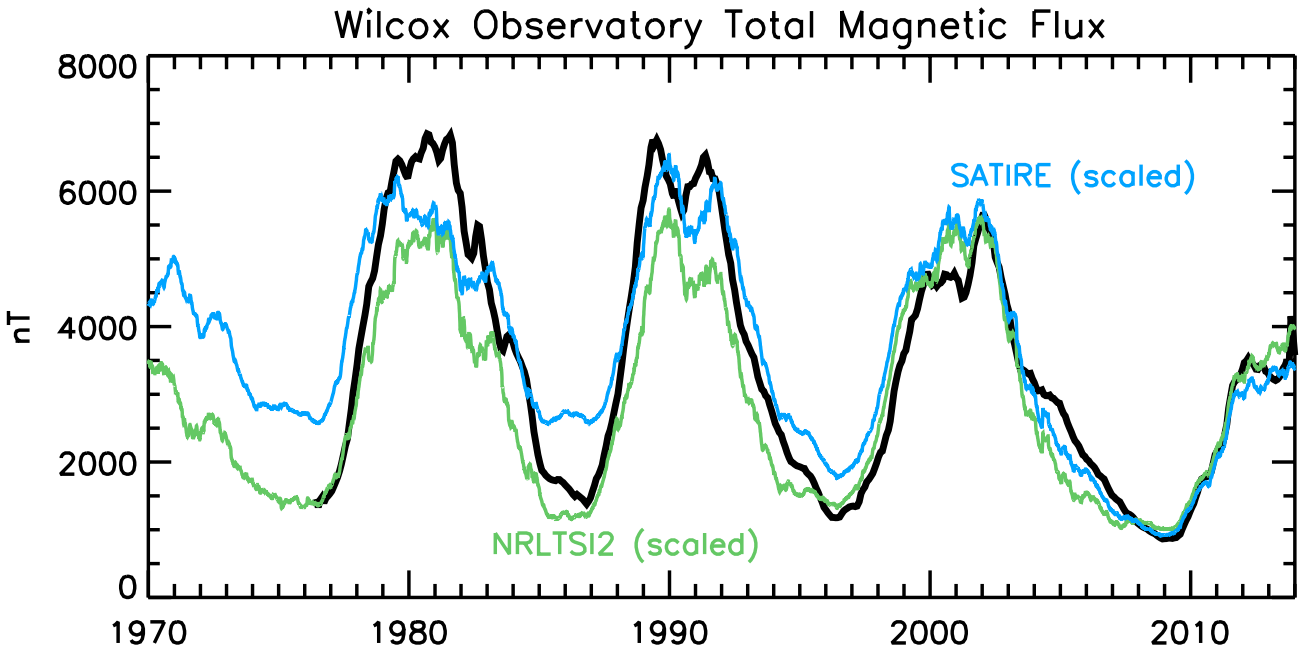
[Coddington et al., *BAMS*, 2015 *under review*]

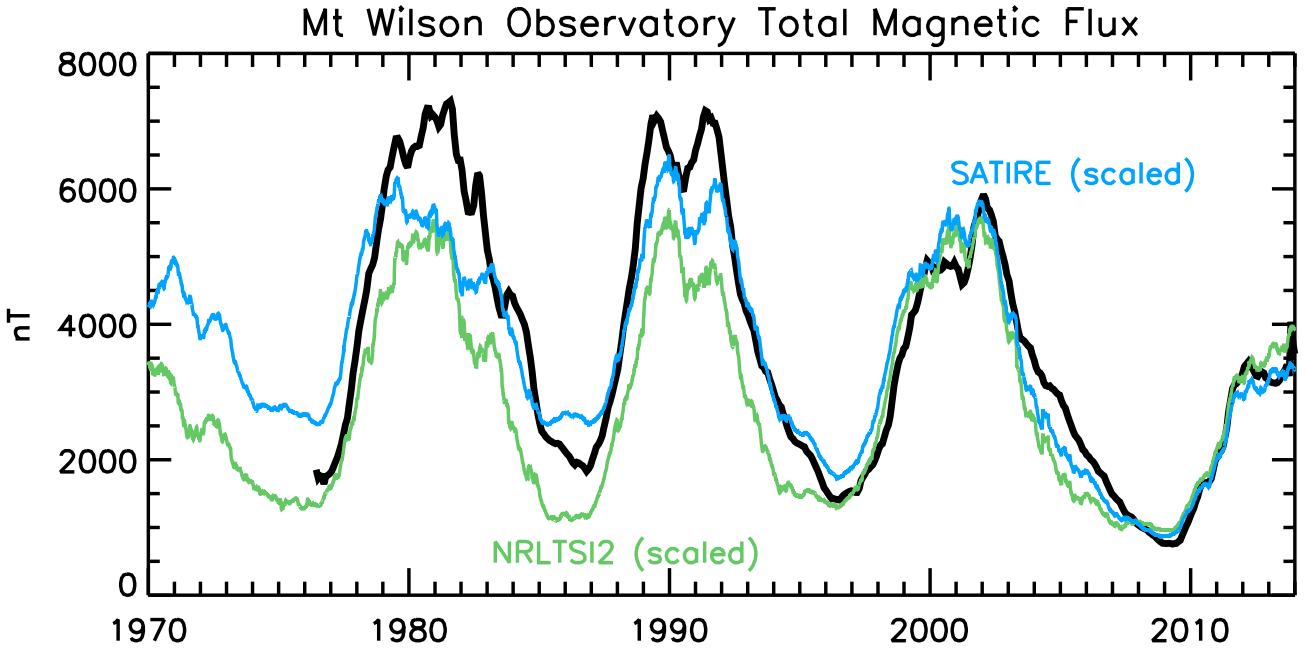
Comparisons with SORCE TIM: Since 2014



Comparisons with other Models and Solar Activity Proxies

The total magnetic flux time series is derived from magnetograms, by adding the absolute values of the magnetic flux at all locations over the solar disk [*Y. Wang,* NRL].

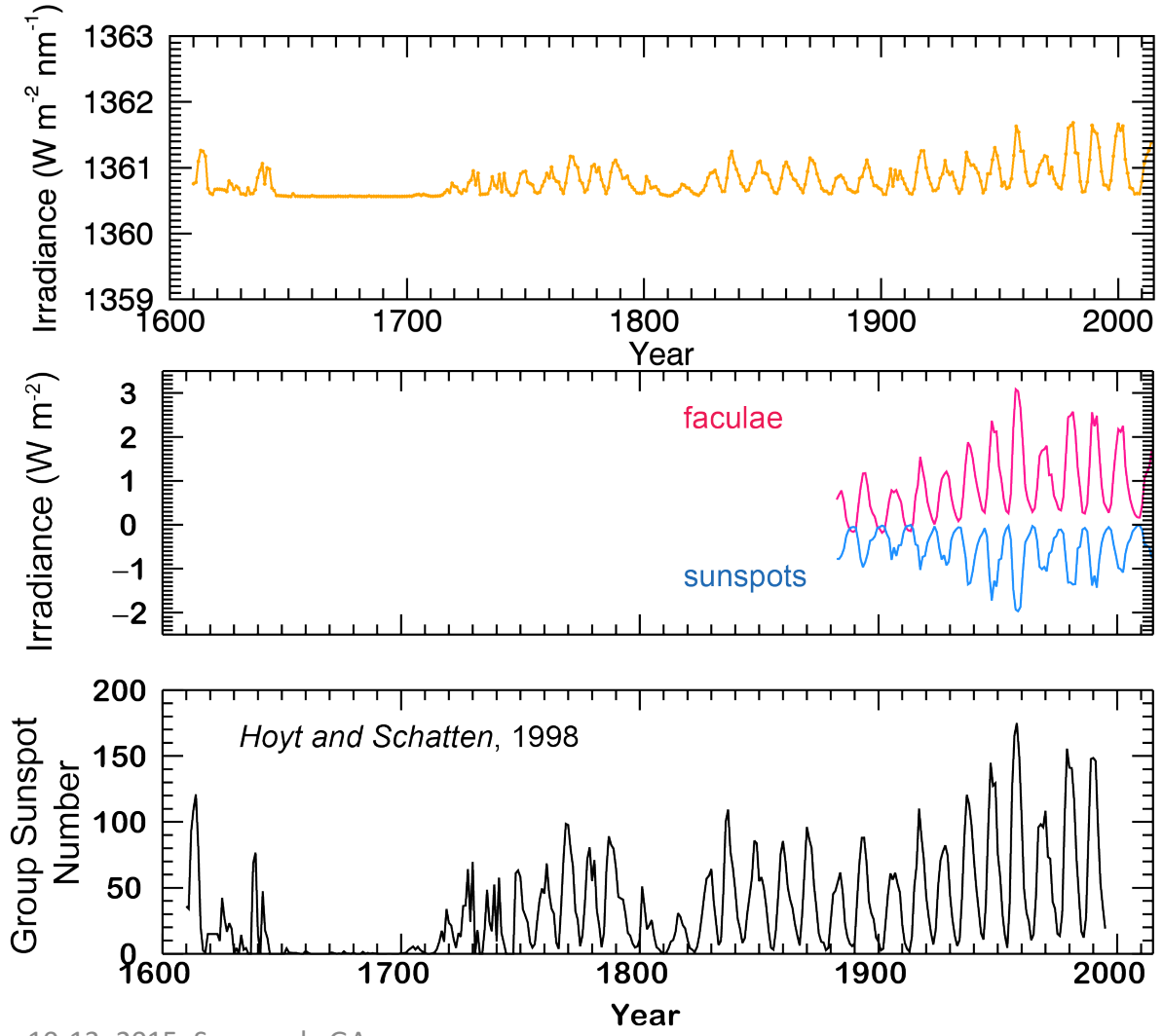




Courtesy J. Lean

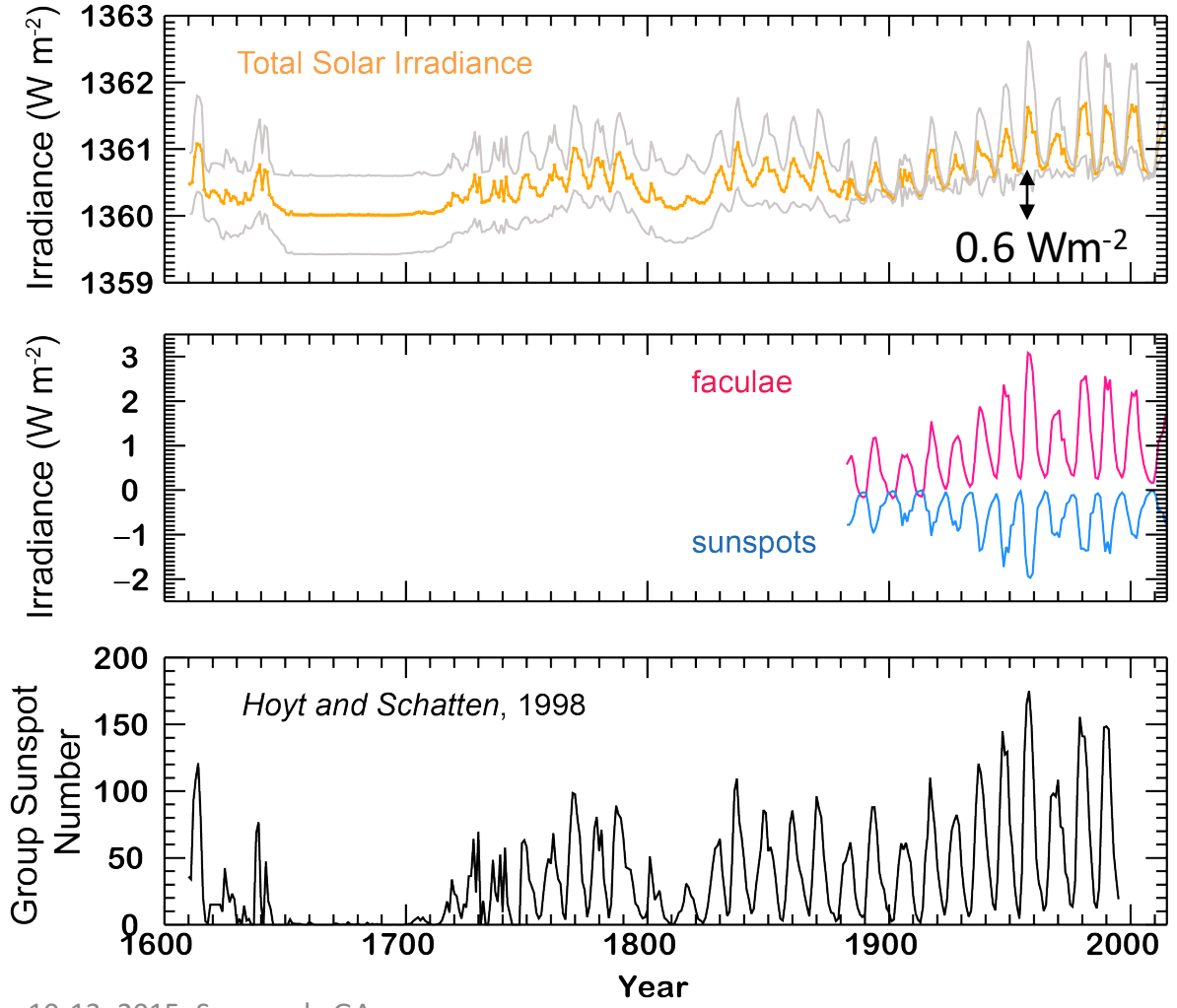
Reconstructing Historical TSI: “Cycle”

- Lean et al. [2001] detail the various proxy indicators of solar magnetic variability used as inputs to the NRL models.
  - Facular Brightening
    - Mg II index: 1978 onward
    - Ca II K index: 1974 onward
    - He I Index: 1974 onward
    - F10.7-cm flux: 1974 onward
    - Plage index: 1944-1987
    - Visible solar images: prior to 1940
    - Group Sunspot Number: 1610 onward
  - Sunspot Darkening
    - USAF SOON:1982 onward
    - RGO: 1882-1982.
    - Group Sunspot Number: 1610 onward



Reconstructing Historical TSI: “Background”

- A long-term secular component in facular brightening is speculative
  - Chromospheric emission in “cycling” stars is higher than in “non-cycling” stars [Baliunas and Jastrow, 1990; Lean et al., 2001; Lean et al., 2005].
  - In NRLTSI2, the increase in Maunder Minimum to present-day quiet Sun is ~ 0.04% (0.6 W m^{-2}).
  - Various estimates exist
    - Lean [2002]: ~ double
    - Wang et.al [2005]: similar
    - Krivova et al. [2010]: similar
    - Shapiro et al. [2011]: order of magnitude larger
    - Judge et al. [2012]: indicate Shapiro et al. [2011] too large by factor or 2
    - Feulner [2011]: < 1 Wm-2, possibly 0 to 0.3 W m-2



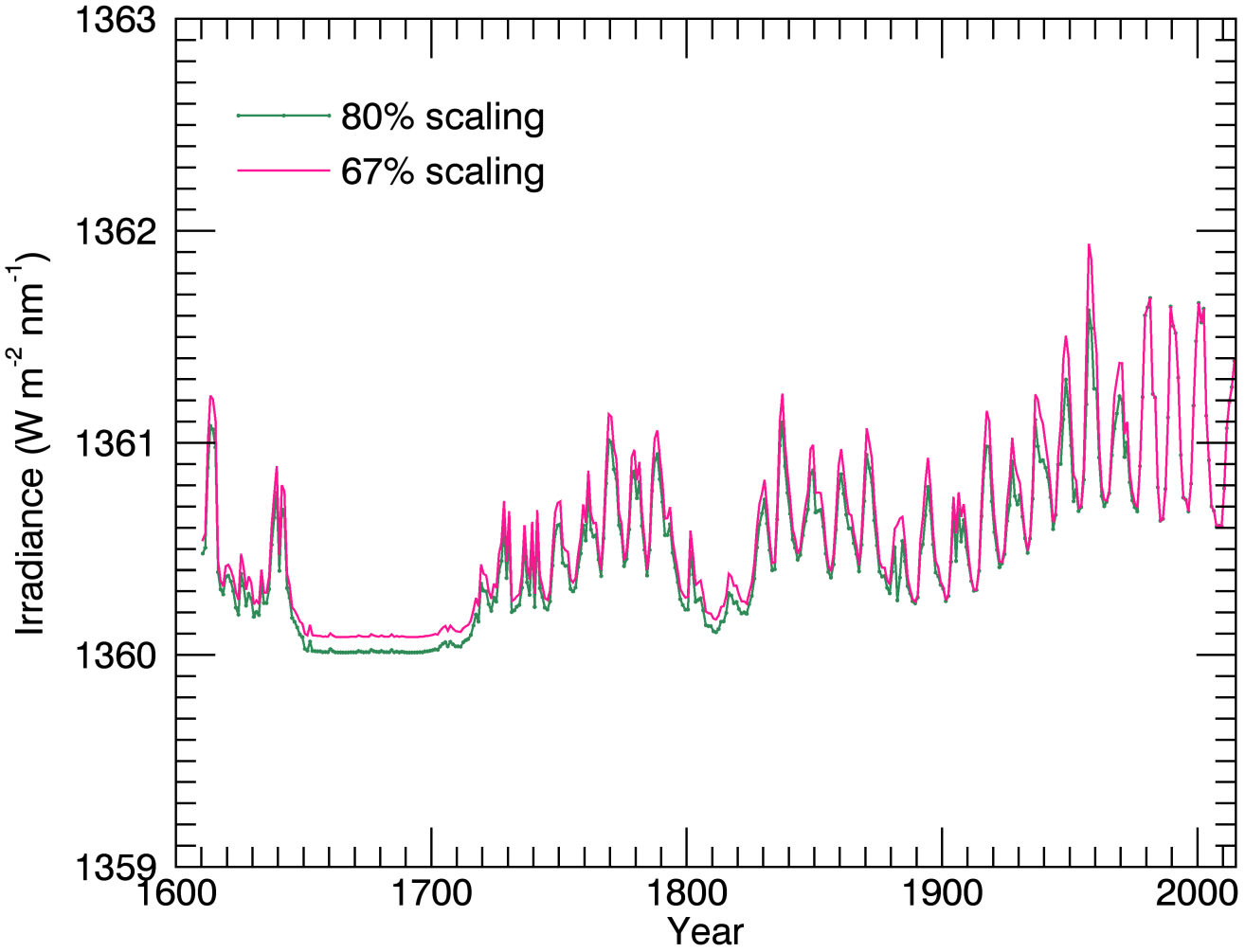
Impacts of Sunspot Area Scaling on Historical TSI

- How do sunspot areas observed by different observatories relate?
- Sunspot Area and Location records:
  - USAF SOON:1982 onward
  - RGO: 1882-1982.

Magnitude of scaling affects the relative roles of sunspots and faculae

Foukal (2014) – 1.2
Fligge and Solanki (1997) – 1.25
Hathaway (2010) – 1.48
Balmaceda et al. (2009) – 1.49

- Willis et al. (2013) – summary of errors in RGO; future paper will provide corrected record.



Ongoing and Anticipated Improvements

1. Sunspot darkening index improvements

- Improve parameterization of sunspot contrast with area.
- Consider weighted average of USAF sunspot region information.

2. Facular brightening index improvements

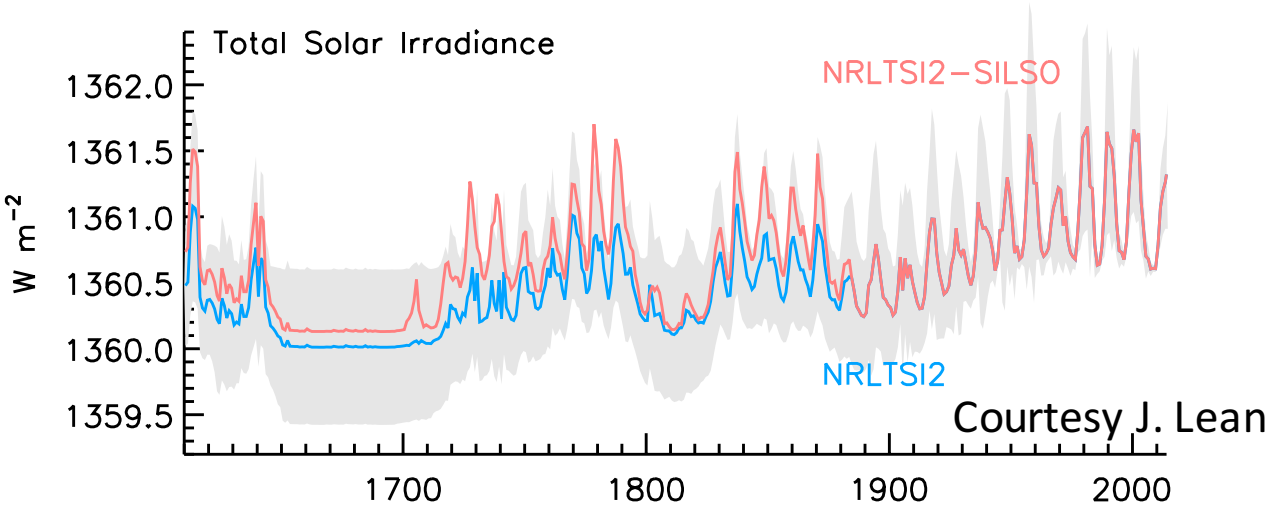
- Analyze residuals between observed irradiance and modeled irradiance (with improved sunspot darkening index).
- Collaborate with science community to understand differences in measured Mg II record.
- Compare different indices of facular brightening.

3. Quantify uncertainties due to model assumptions.

4. Construct the NRLTSI2 model using SOLID TSI and Mg II composites.

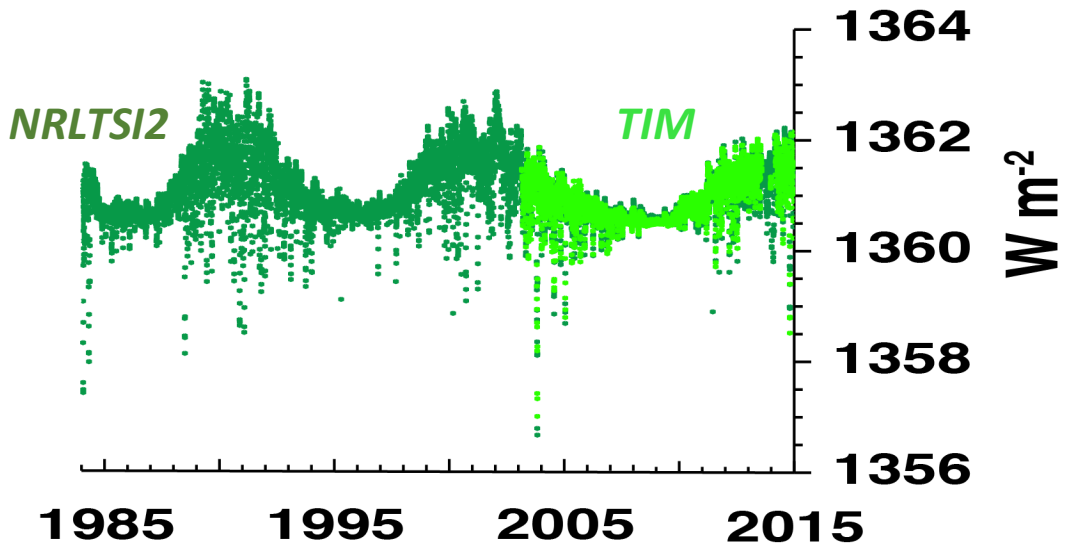
5. Investigate impact of "new" sunspot number record (with ISSI group, Greg Kopp)

The new sunspot Group Number time series (Clette et al., 2013; Svalgaard et al. 2015) compared against original series (Hoyt and Schatten 1998) in NRLTSI2.



SILSO = Sunspot Index and Long-term Solar Observations

Conclusions



- Measurements are invaluable:
  - The improvements in NRLTSI2 & NRLSSI2 are possible due to the SORCE measurement record.
  - Future versions of the NRL models will also be improved by the higher accuracy TSIS irradiance measurements with improved understanding of instrument degradation and on orbit stability.
- Improvements in the models' representativeness of facular brightening and sunspot darkening will be guided by research and comparisons with irradiance observations and other solar proxy observations.
- NRLTSI2 data is publicly available and…*improvements will be ultimately incorporated into a new version of the Solar Irradiance Climate Data Record.*

Thank you!