How Does the Sun's Spectrum Vary?

Rotational to Multi-Decadal Solar Irradiance Variations

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Solar Rotation – days to months, multiple "realizations"

- Marchenko, DeLand & Lean, Space Weather & Climate, 2017

- issues ~~remain~~ resolved about spectral dependencies – UV vs IR

(Lean et al. Earth & Space Science, draft manuscript)

Solar Cycle – years to decades

- challenged by instrument sensitivity drifts; SIST COMPOSITES

- disagreement quantified/evaluated among observations and models

Long Term – multiple decades

- speculative; depends on constraining & understanding solar cycle variations

- new reconstructions since 850 CE differ from PMIP4 recommendations

(Lean, Earth & Space Science, 2018)

1st Year

2nd Year

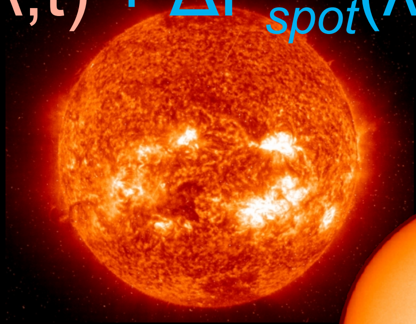
3rd Year

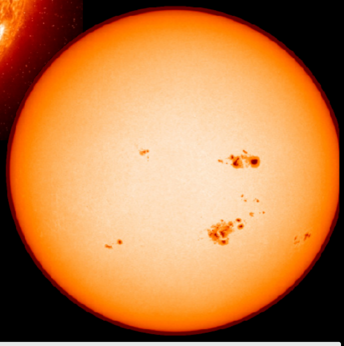
Funded by NASA

New Models of Contemporary Solar Irradiance Variability

$\Delta TSI(t) = TSI(t) - TSI_{quiet} = \Delta TSI_{faculae}(t) + \Delta TSI_{spot}(t)$

$\Delta F(\lambda,t) = F(\lambda,t) - F_{quiet}(\lambda) = \Delta F_{faculae}(\lambda,t) + \Delta F_{spot}(\lambda,t)$





NRLTSI3:

$\Delta TSI_{faculae}(t) \propto a \times Mg(t)$, $Mg > 0.011$

$\Delta TSI_{faculae}(t) \propto a \times Mg(t) + b \times Mg(t)^{1.1}$, $Mg < 0.011$

$\Delta TSI_{spot}(t) \propto \Sigma A_s C_s \, \mu(3\mu+2)/2$

NRLSSI3:

$\Delta SSI_{faculae}(\lambda,t) \propto \Delta TSI_{faculae}(t)$

$\Delta SSI_{spot}(t) \propto \Delta TSI_{spot}(t)$

Numerical constraints:

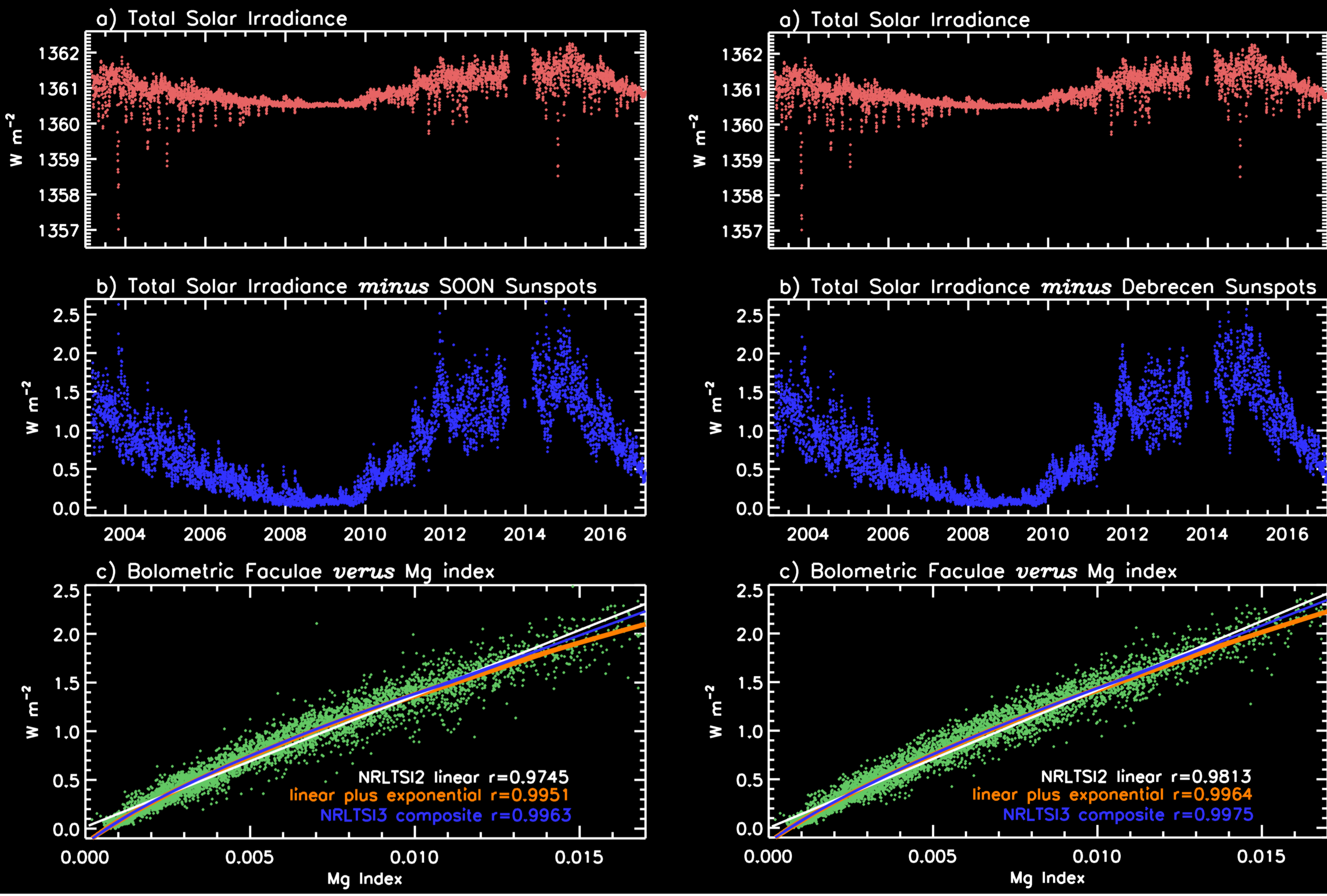
$TSI_{quiet} = \int SSI_{quiet}(\lambda) d\lambda$

$TSI(t) = \int SSI(\lambda,t) d\lambda$

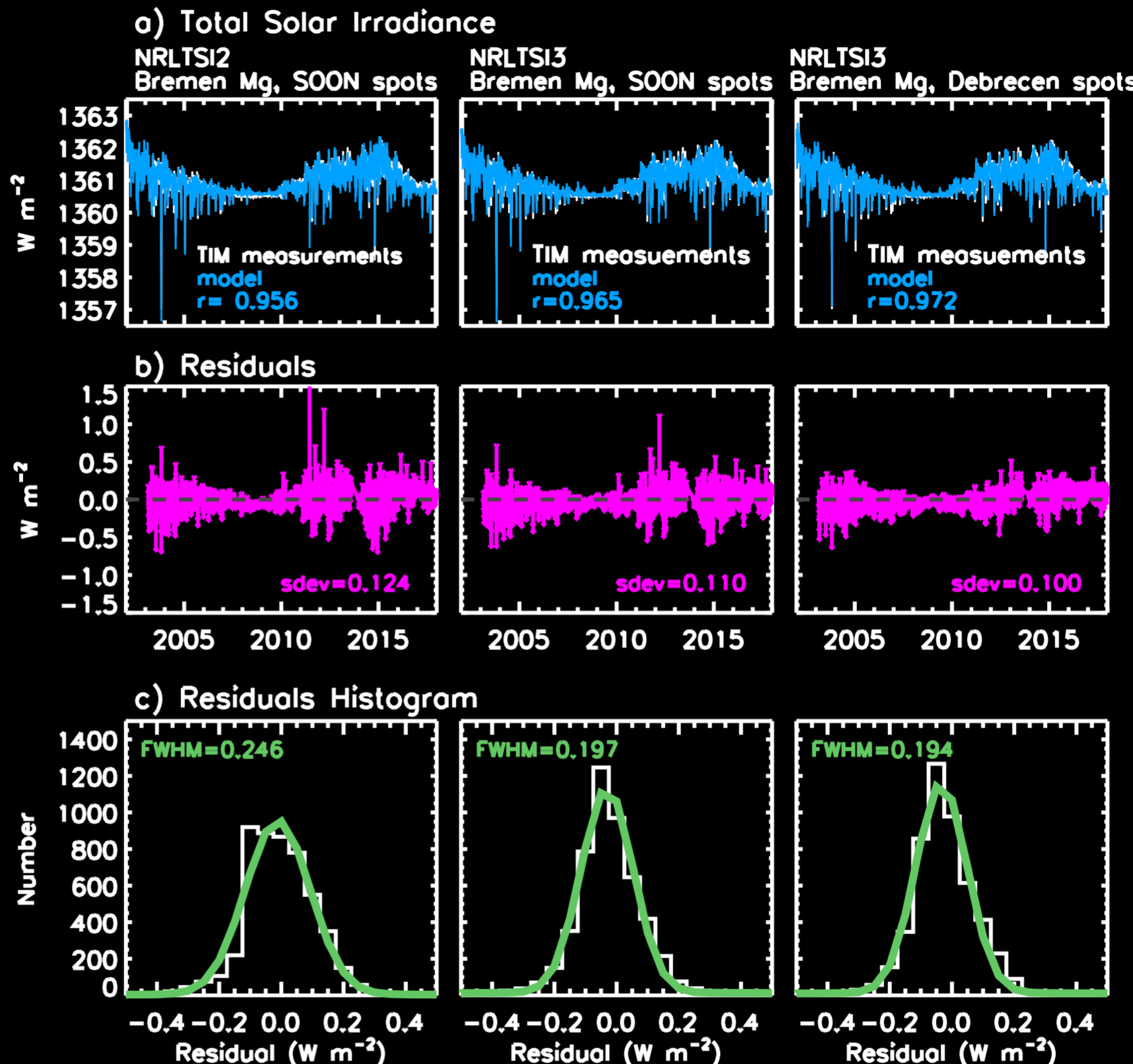
$\Delta TSI_{fac}(t) = \int SSI_{fac}(\lambda,t) d\lambda$

$\Delta TSI_{spot}(t) = \int SSI_{spot}(\lambda,t) d\lambda$

Relationship of Irradiance Faculae & Mg Index



NRLTSI3 reproduces TIM TSI observations better than NRLTSI2 (NOAA CDR)



NRLTSI2 →

Use of adjusted Mg(t) index is 100% significant →

Substitution of Debracen for SOON spots is 100% significant

Quantitative Determination of Statistical Significance using the F-test

Statistical Analysis in Climate Research
(von Storch and Zwiers, 1999)

$$F_{repl} = df\left(\frac{SSR_{Madj} - SSR_M}{SSE_{Madj}}\right)$$

$$F_{repl} = df\left(\frac{SSR_{SOON} - SSR_{DEB}}{SSE_{SOON}}\right)$$

SSR= sum of squares of regression
$= \sum(y_{mod}(t) - \overline{y}_{obs})^2$

SSE= sum of square errors
$= \sum(y_{obs}(t) - y_{mod}(t))^2$

df = degrees of freedom

SST=SSR+SSE, r^2=SSR/SST

TSI model constructed from TIM observations:
SSR_{Madj} = 830
SSR_M = 820
SSE_{Madj} = 60, *df* = 1130

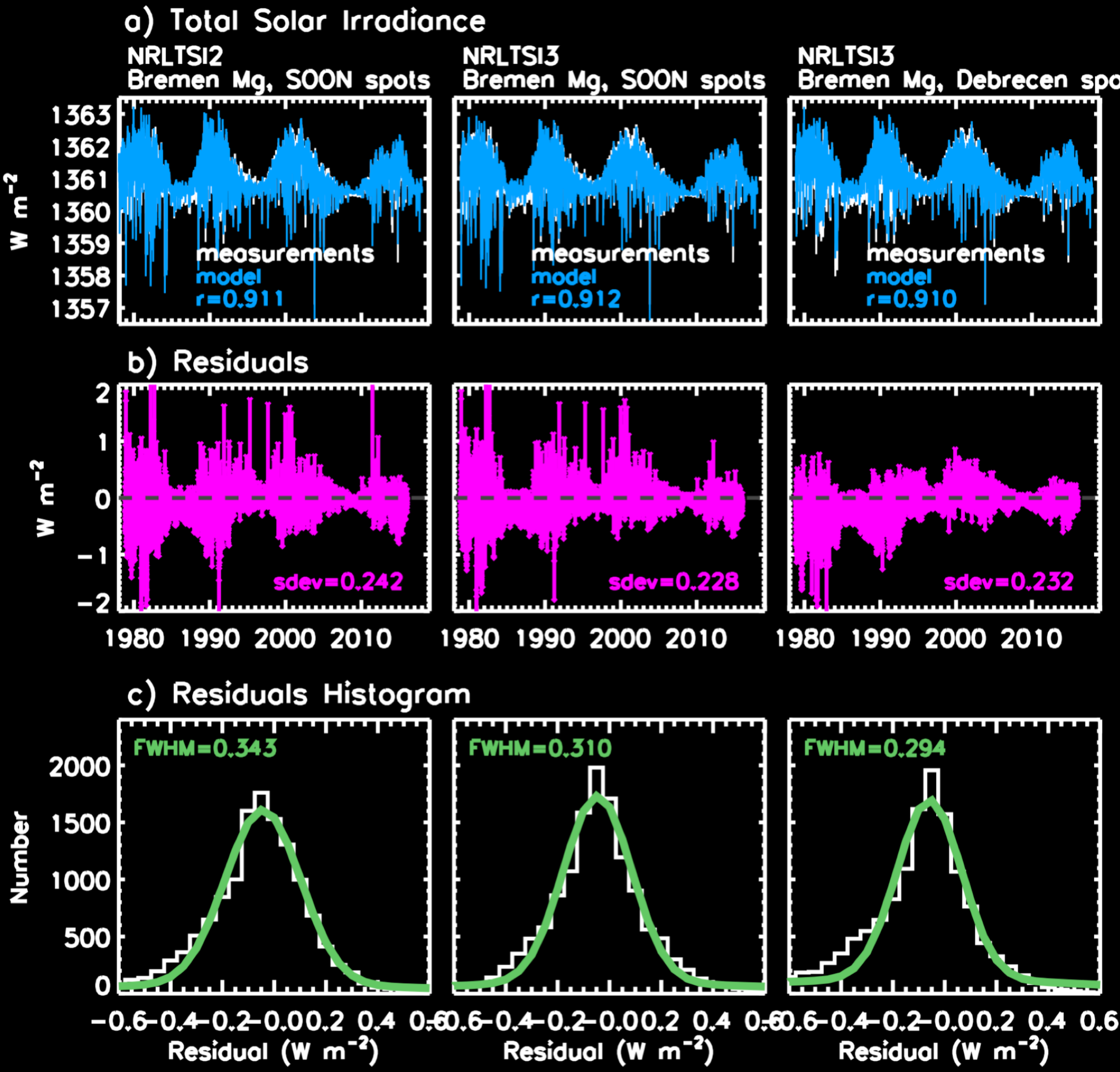
$$\frac{(SSR_{Madj} - SSR_M)}{SSE_{Madj}} = \frac{10}{60}$$

Use of Adjusted of Mg(t)
F_{add}= 188

Replacement of SOON with Debrecen spots *F_{repl}=148*

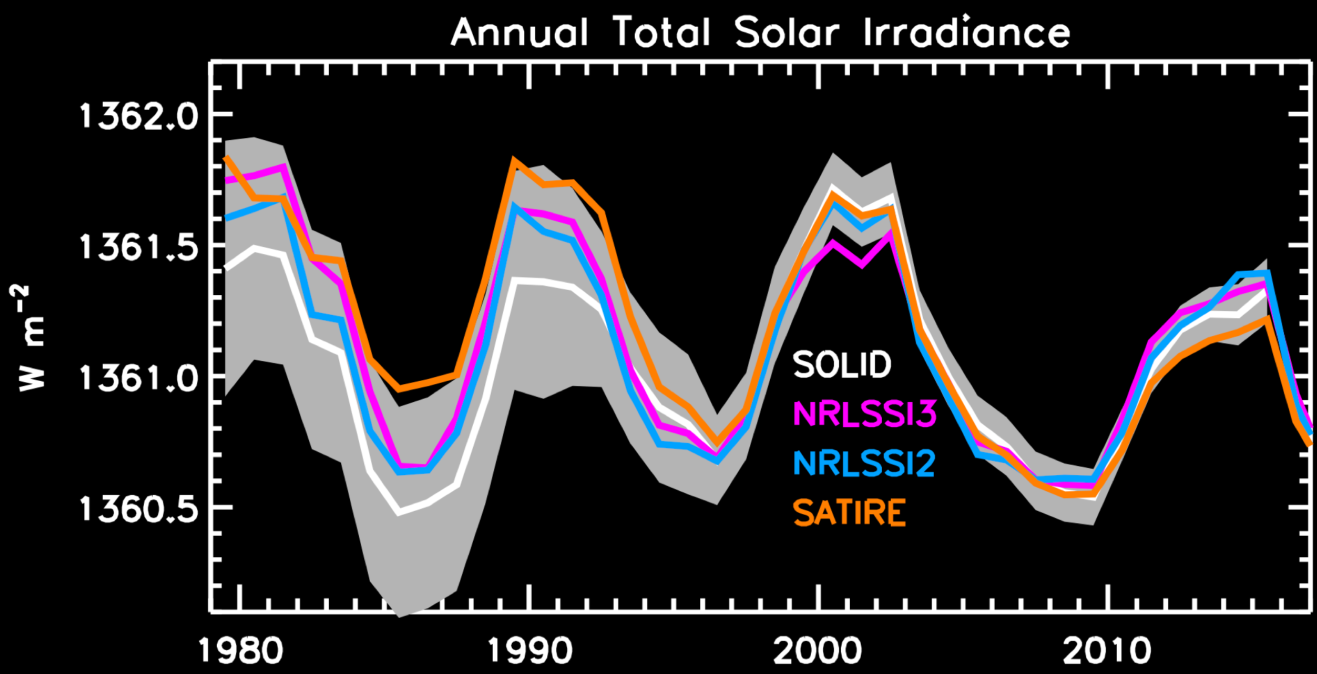
F(1,60) of 7 is 99% significant

Composite TSI record (de Wit et al., 2017) lacks sufficient long-term repeatability to confirm NRLTSI3 improvements over NRLTSI2



New SIST TSI & Mg Composites?

Uncertainties in TSI Composite Preclude Differentiation Among Models



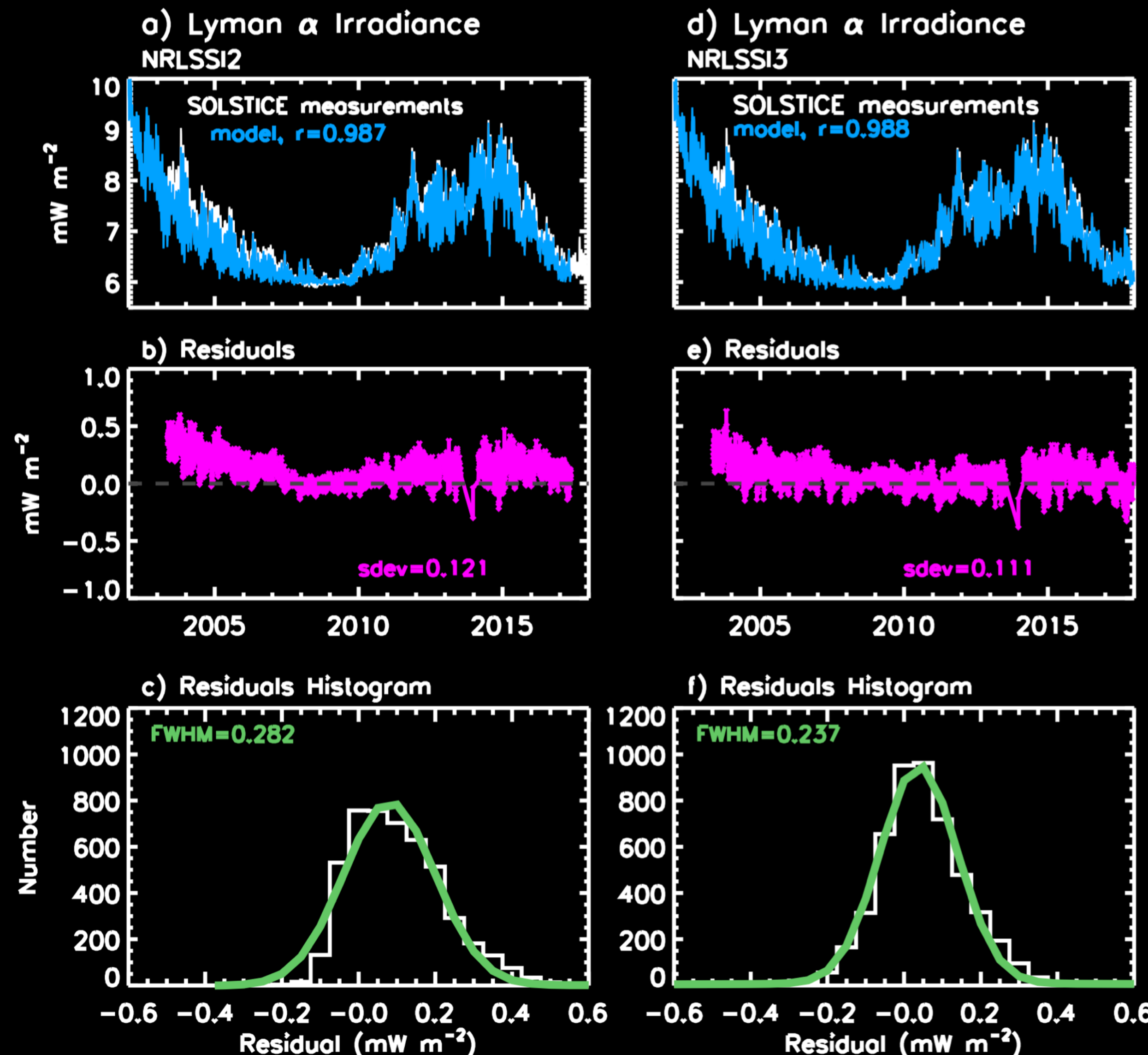
adding even a modest nonlinear Mg component alters annual values …affects historical reconstructions

Why are composite uncertainties not larger prior to SORCE TSI observations?

NOTE: NRLTSI3 and SATIRE agree better at cycle maximum than at minimum…. is this a result of SATIRE's use of magnetograms at solar minimum, when active region features are minimal?

NRLSSI3 reproduces SOLSTICE Lyman α observations better than NRLSSI2 (NOAA CDR)

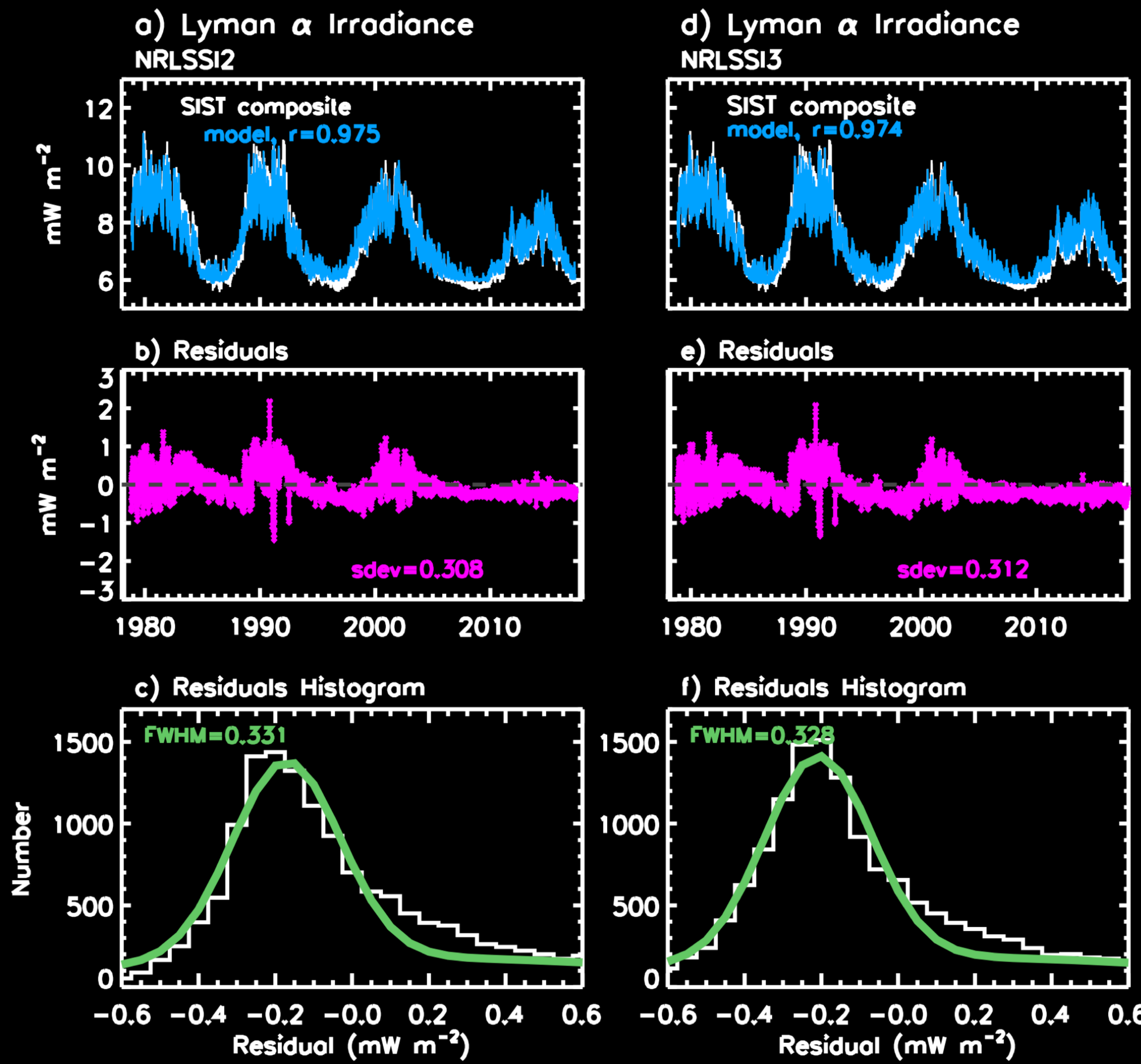
adj Mg:
F_{repl}= 100% sig



SSR=0.00230
SSE=0.00015

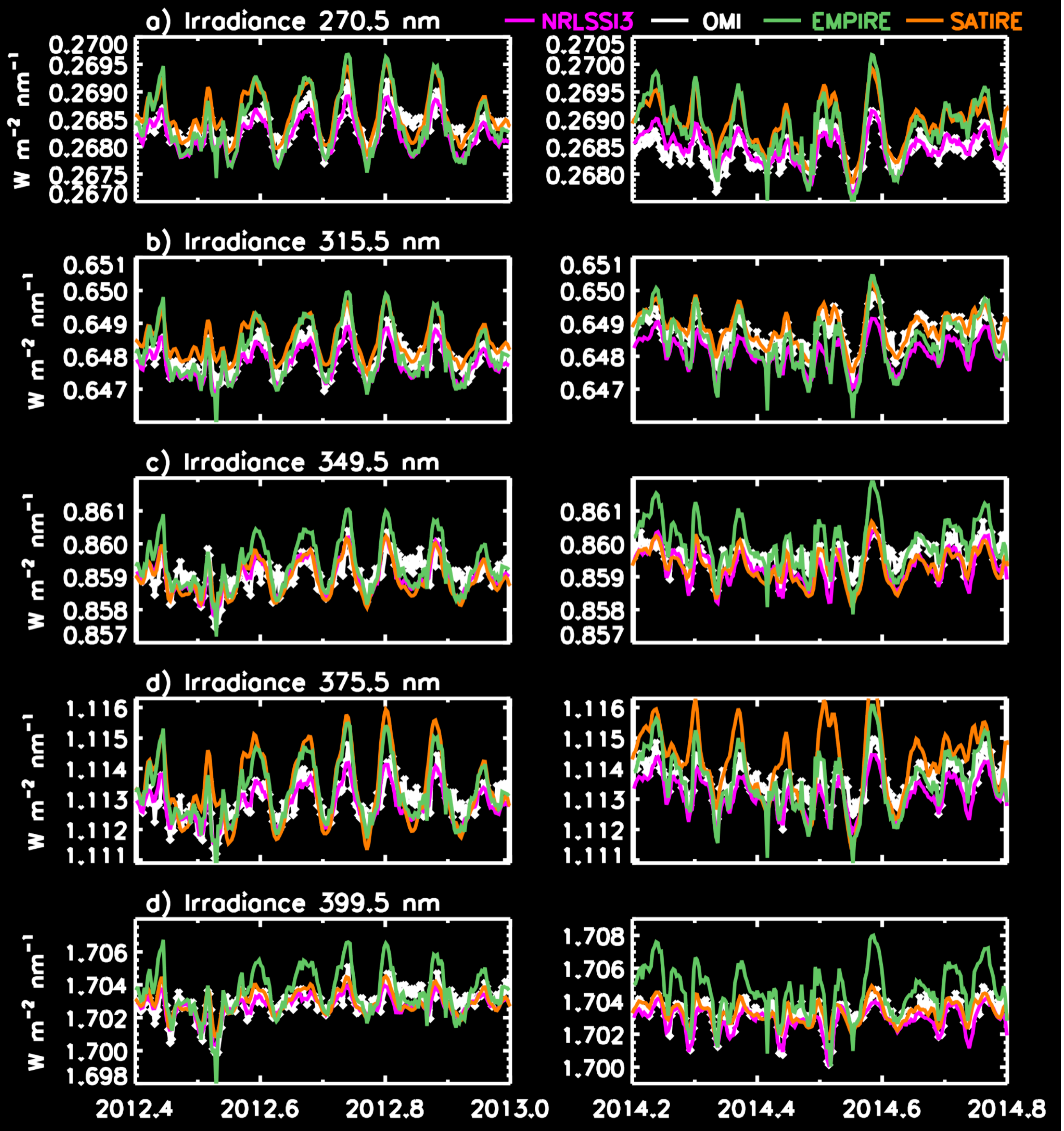
SSR=0.00241
SSE=0.00008

Composite Lyman α (LASP) record lacks repeatability to quantify NRLSSI3 improvements over NRLSSI2



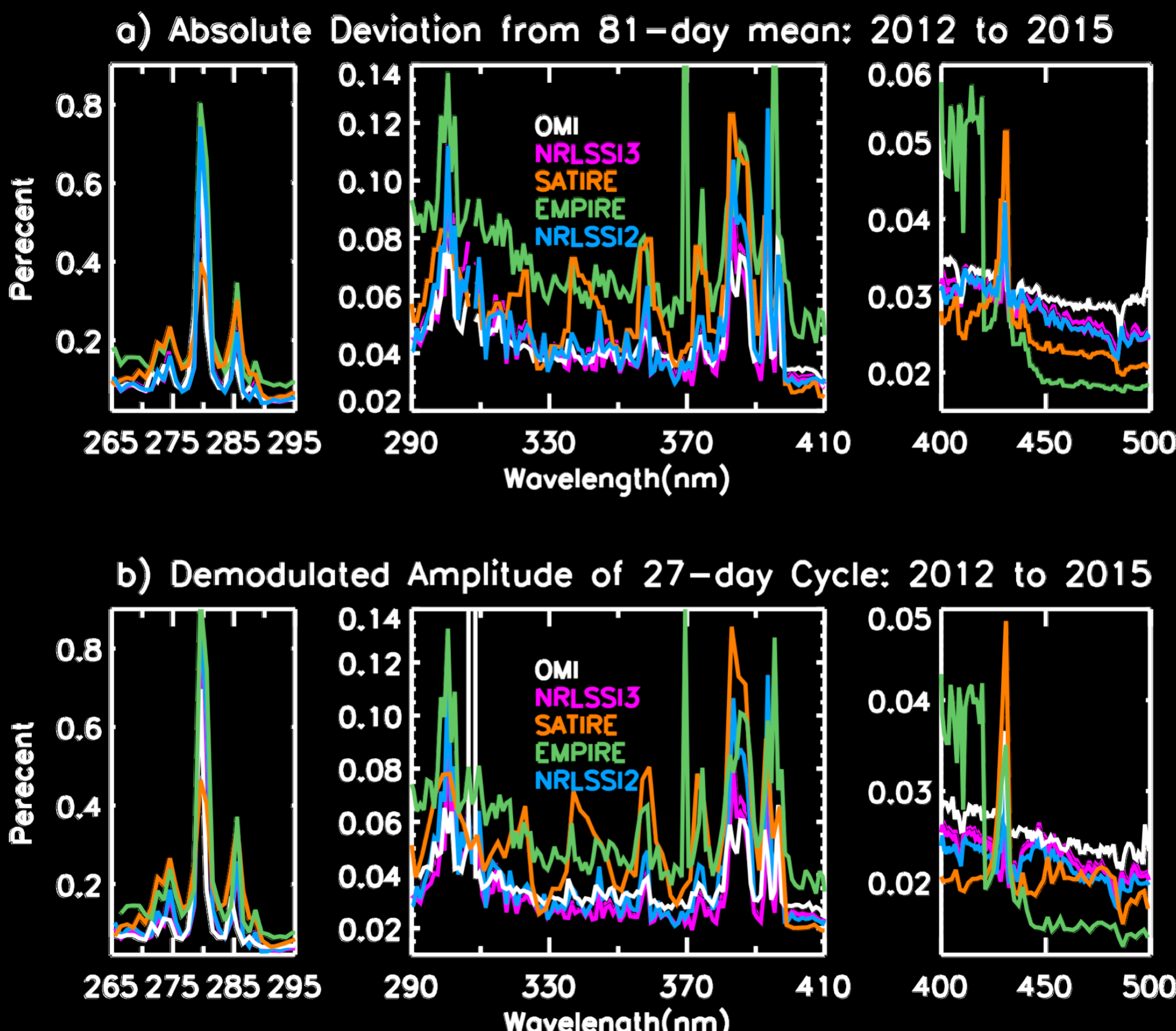
New SIST Ly α & Mg Composites?

OMI observations provide independent validation of spectral irradiance variability models on rotational time scales



all time series detrended with 81-day running means

OMI observations provide independent validation of spectral irradiance variability models



NRLSSI3 tracks OMI rotational modulation better than SATIRE and EMPIRE

SATIRE: *significantly overestimates width & variability of Fraunhofer lines & blends 290-400 nm; underestimates variability 400-500 nm*

EMPIRE: *overestimates all variability 290-420 nm; Dramatically underestimates all variability 430-500 nm*

Origin of spectral irradiance variability differences between NRLSSI3 & SATIRE:

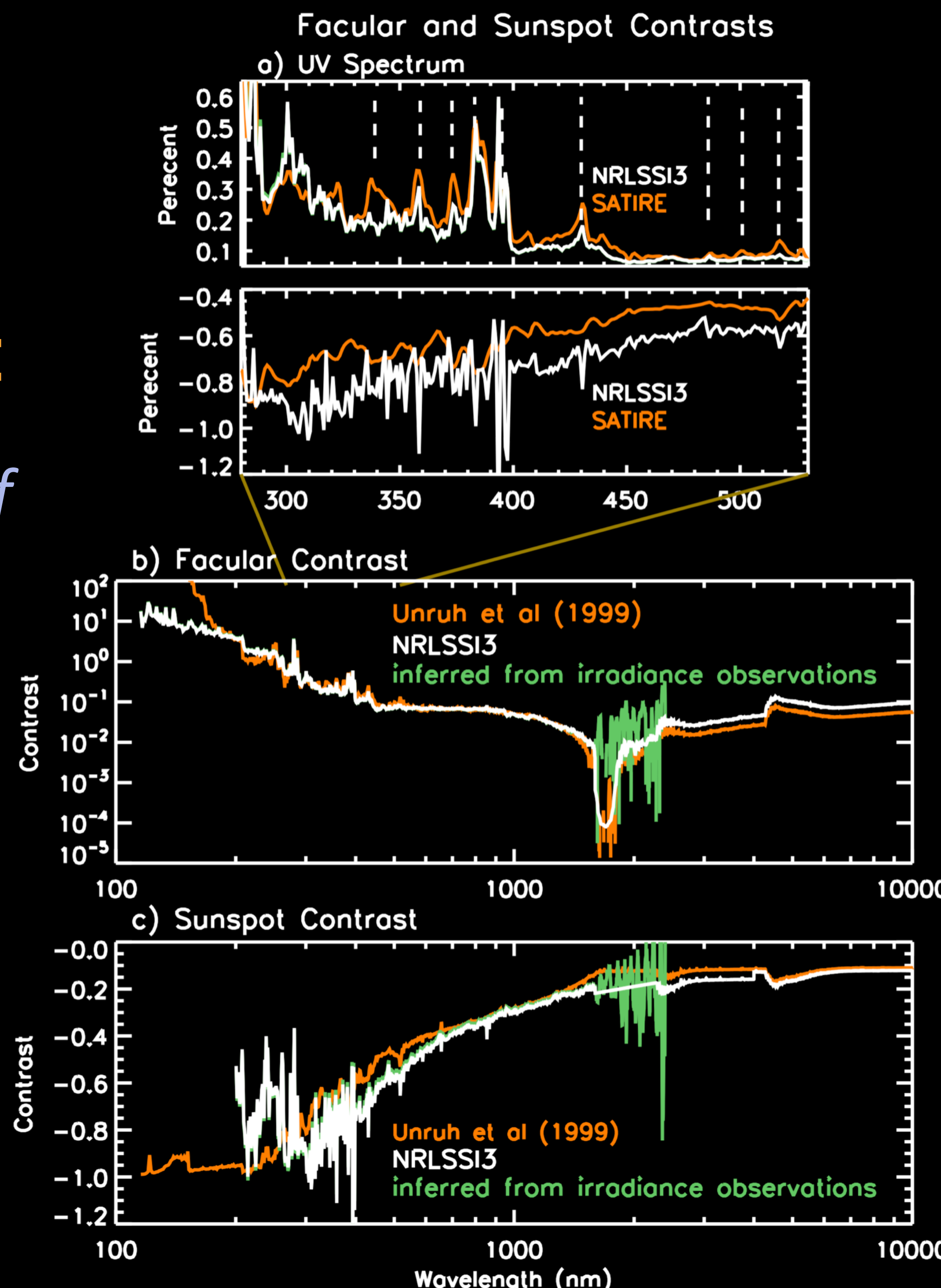
wavelength-dependence of facular and sunspot contrasts differ

NRLSSI3: inferred from SORCE observations

SATIRE: specified with theoretical stellar atmosphere model

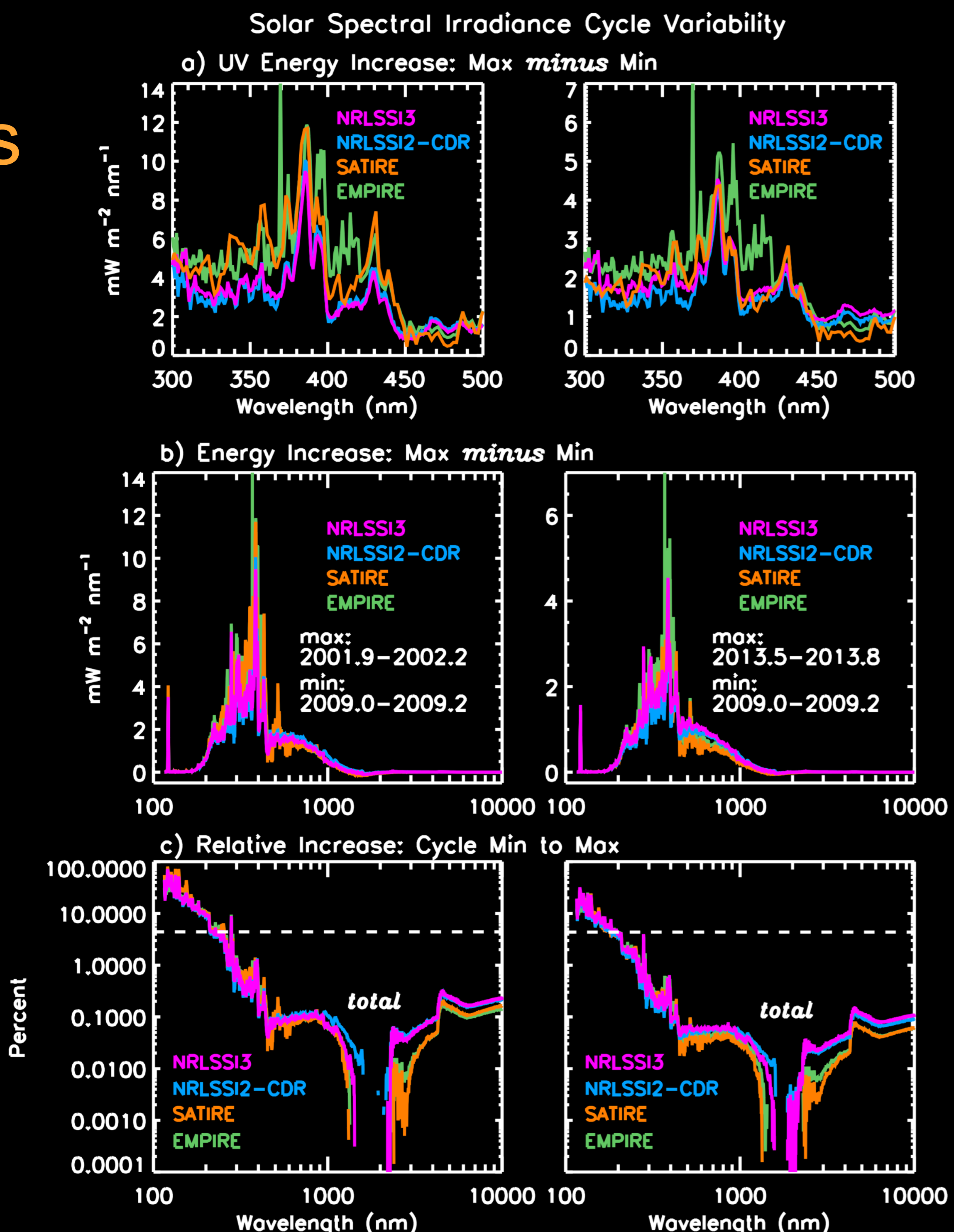
facular contrast too high in Fraunhofer lines and blends, and also too broad

Sunspot contrast systematically not dark enough

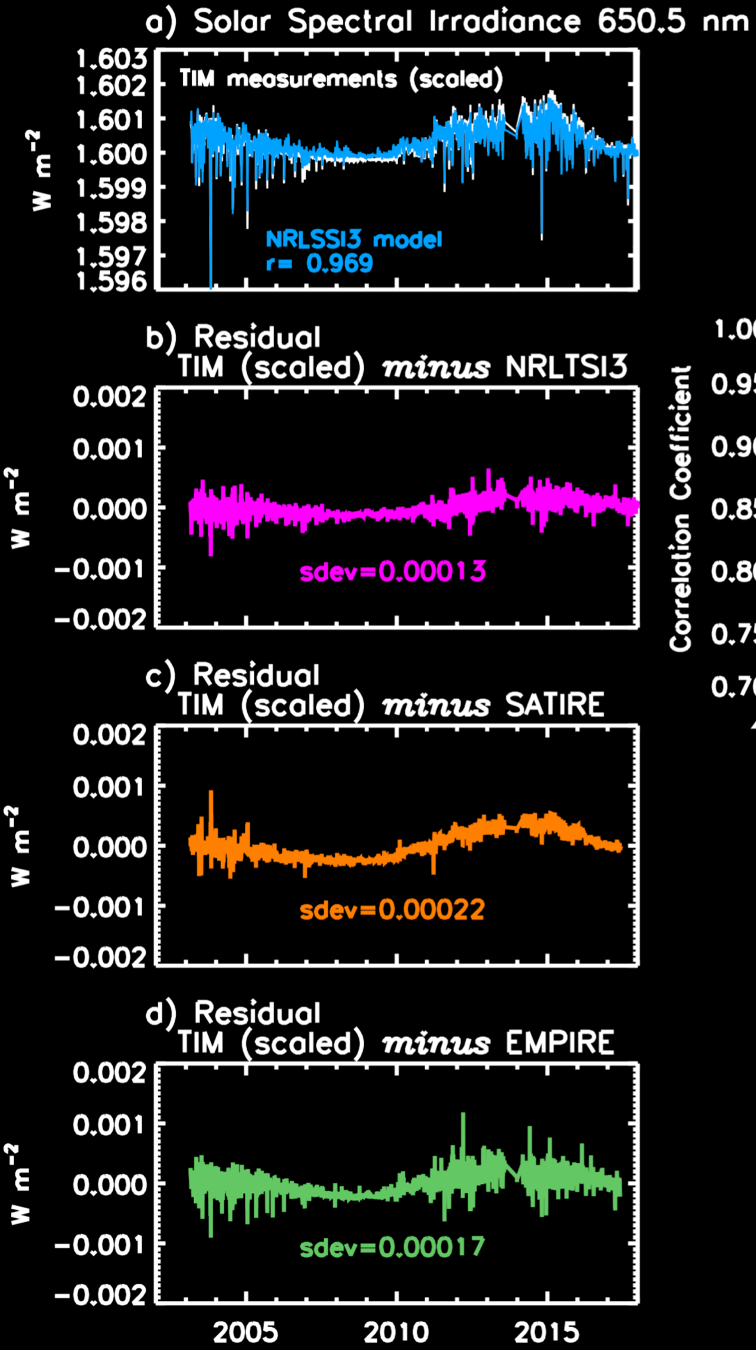


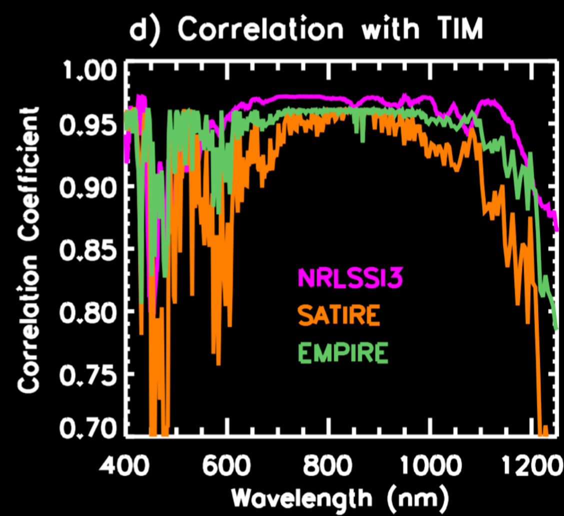
Solar Cycle Irradiance Variations

- NRLSSI3 changes are slightly larger than NRSSI2 because NRLTSI3 has slightly larger solar cycle change than NRLTSI2 (due to additional facular term)
- NRL3SSI and SATIRE changes agree better in NUV continuum than lines
- SATIRE changes larger than NRLSSI3 in NUV spectral features
- SATIRE (& EMPIRE) changes smaller than NRLSSI3 in visible spectrum



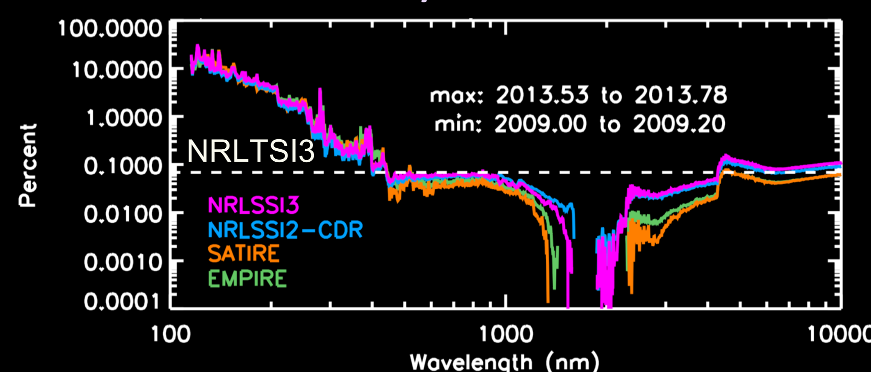
TSIS observations are expected to have improved repeatabily to better clarify relationship of TSI and SSI



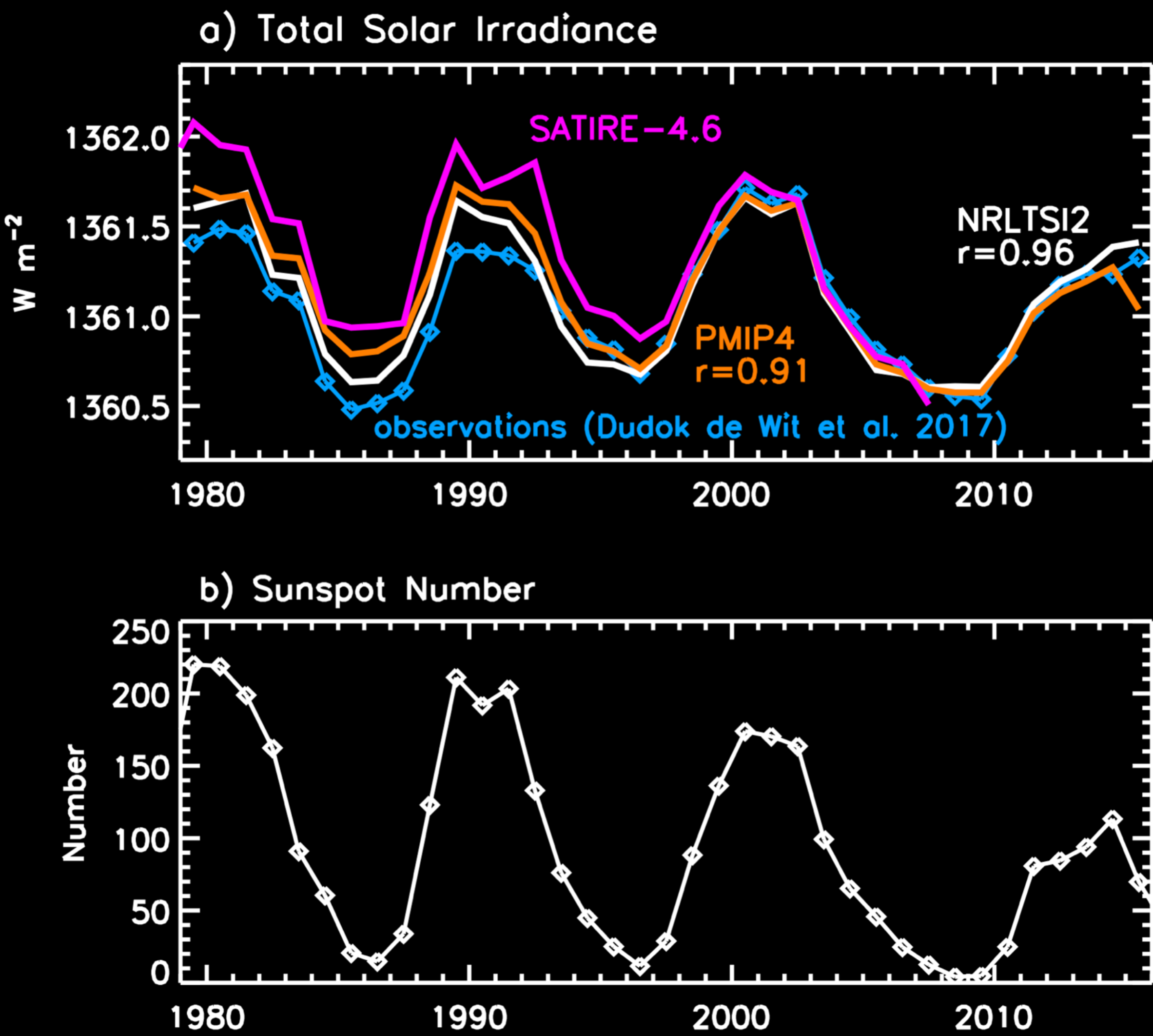


Indirect validation of visible wavelength SSI solar cycle variability using TIM?

TSI & SSI at 600-700 nm have similar variability



New Estimates of Solar Irradiance Variability in the Pre-Industrial Millennium

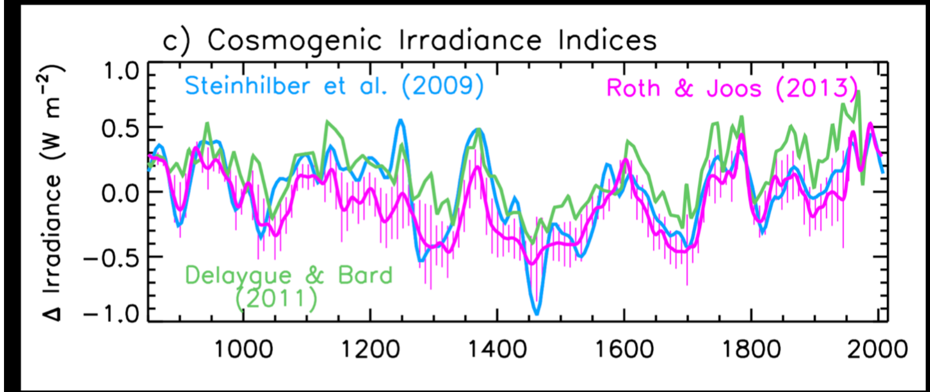


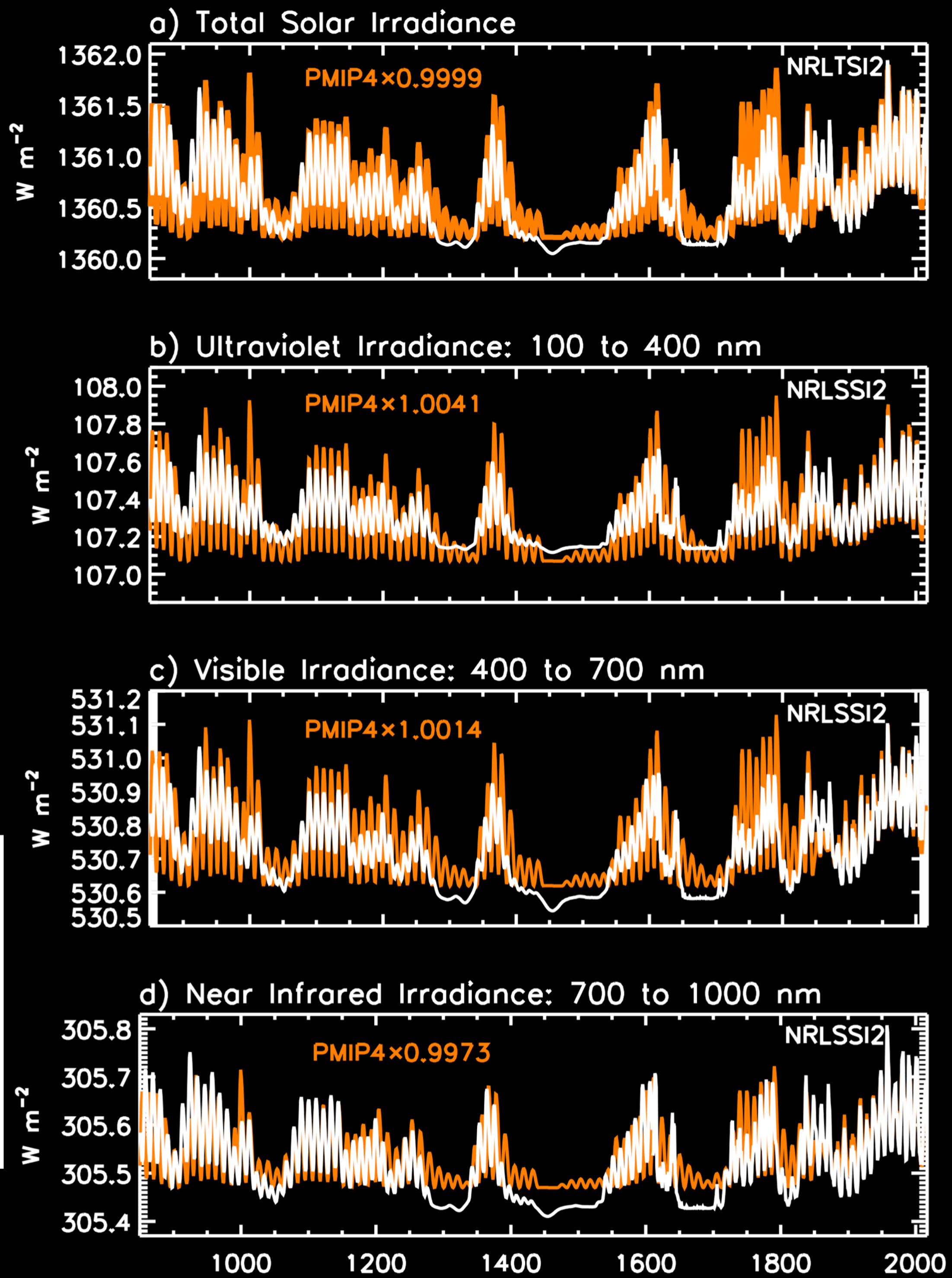
Estimating Solar Irradiance Since 850 CE
J. Lean, Earth & Space Science, 2018

Solar irradiance reconstructions in the space era are the foundation for historical reconstructions: significant differences exist among different reconstructions

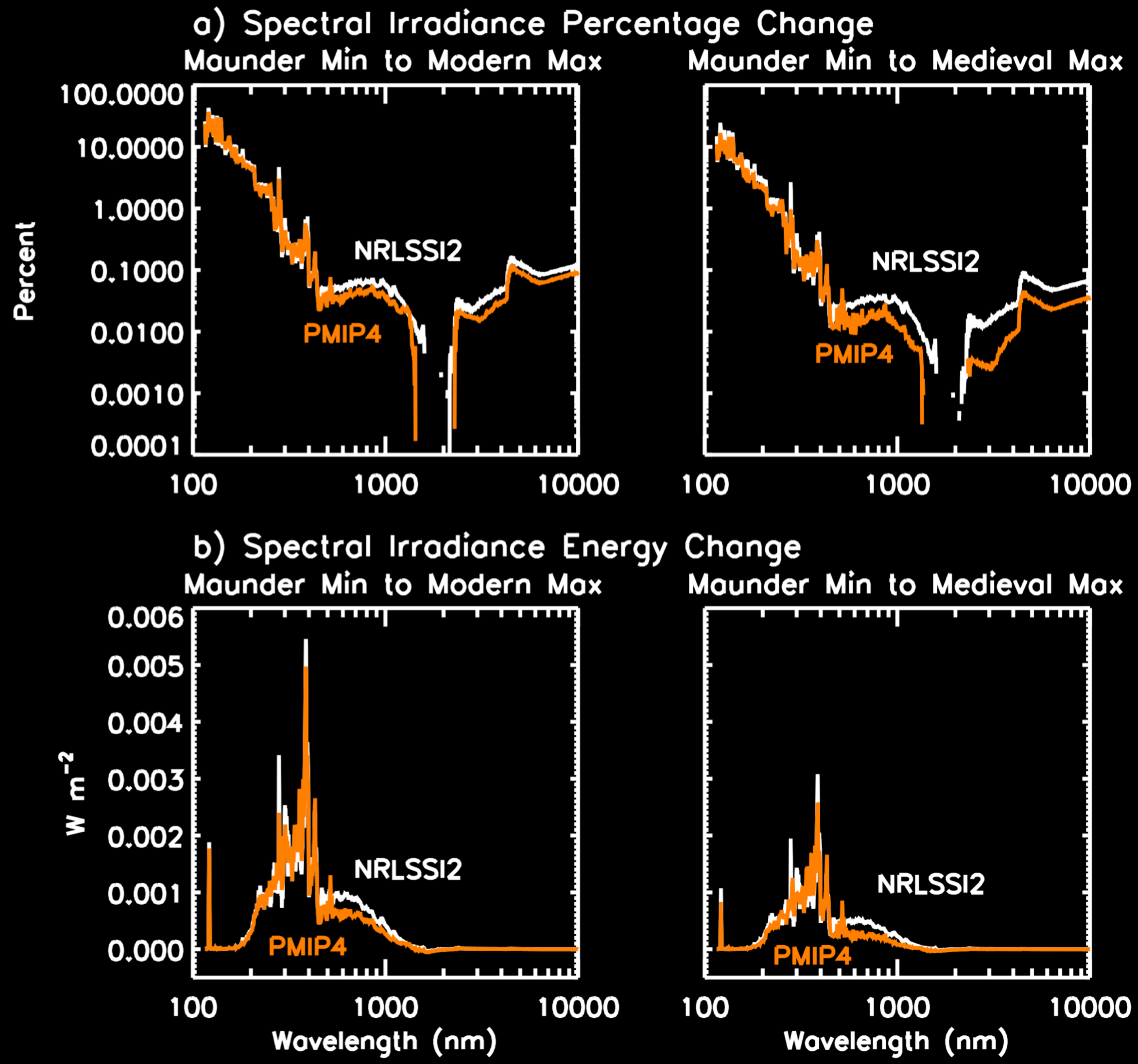
NRLTSI2 and NRLSSI2 differ from PMIP4 on multiple time scales

- *NRLSSI2 cycle cycle amplitudes are smaller than in PMIP4*
- *NRLSSI2 multi-decadal changes are larger than in PMIP4*





Solar Irradiance in Medieval Maximum not as high as Modern Maximum?



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SUMMARY, Year 3

Solar Rotation

- OMI validates NRLSSI3 rotational modulation

- SATIRE overestimates NUV rotation in lines and blends because facular contrasts in these features are too high in theoretical stellar atmosphere models

- EMPIRE overestimates NUV rotational variability across the entire NUV spectrum – likely misuse of ODR?

Solar Cycle

- demonstrated mutual consistency of SORCE TIM TSI and SOLSTICE Lyman a SSI observations over the 11-year cycle, and relationship to Bremen Mg index

- existing TSI & Lyman a composite unable to validate NRLTSI3/NRLSSI3 improvements

- awaiting new TSI, Lyman a and Mg composites from SIST

- overestimation of SATIRE and EMPIRE NUV variability, and underestimation of visible variability during solar rotation, likely extends to solar cycle & multi-decadal

Multi Decadal

- new irradiance reconstruction from 850-1610 CE, consistent with NOAA CDR 1610-present – notable differences from PMIP4 recommendations

How Does the Sun's Spectrum Vary?

Publications and Products

New NRLTSI3 (total) and NRLSSI3 (spectral) irradiance variability models (and uncertainties), formulated and implemented using improved facular and sunspot indices
- 1978-2017 files available
- Earth & Space Science papers (2) underway for SIST special edition

Reanalysis of SME observations provides new database for extending extant observations, and model validation
- multiple talks at meetings (AGU, EUG, SORCE) comparing models and observations (Odele)

New estimates of historical TSI & SSI irradiance in pre-industrial millennium, consistent with NOAA CDR irradiance in past four centuries – differ from PMIP4 recommendations
- 850-2017 files available
- Earth & Space Science paper published 2018

In collaboration with other SIST members:.

- Incorporate new composites of total solar irradiance, Lyman α irradiance and Mg index composite to additionally constrain solar cycle changes