New solar indices for improved thermospheric densities

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Overview

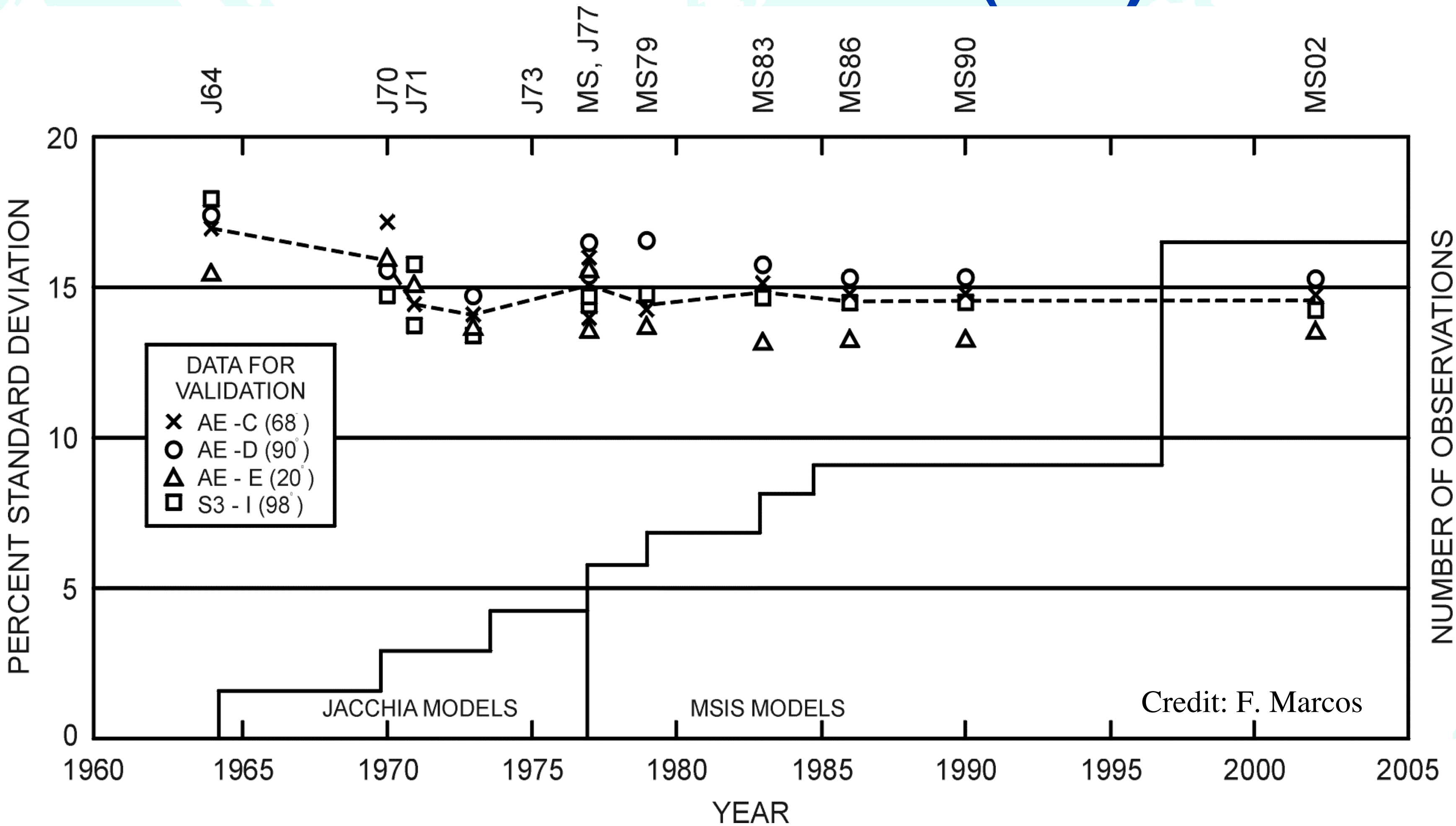
Solar proxies for thermospheric density modeling (JB2006)

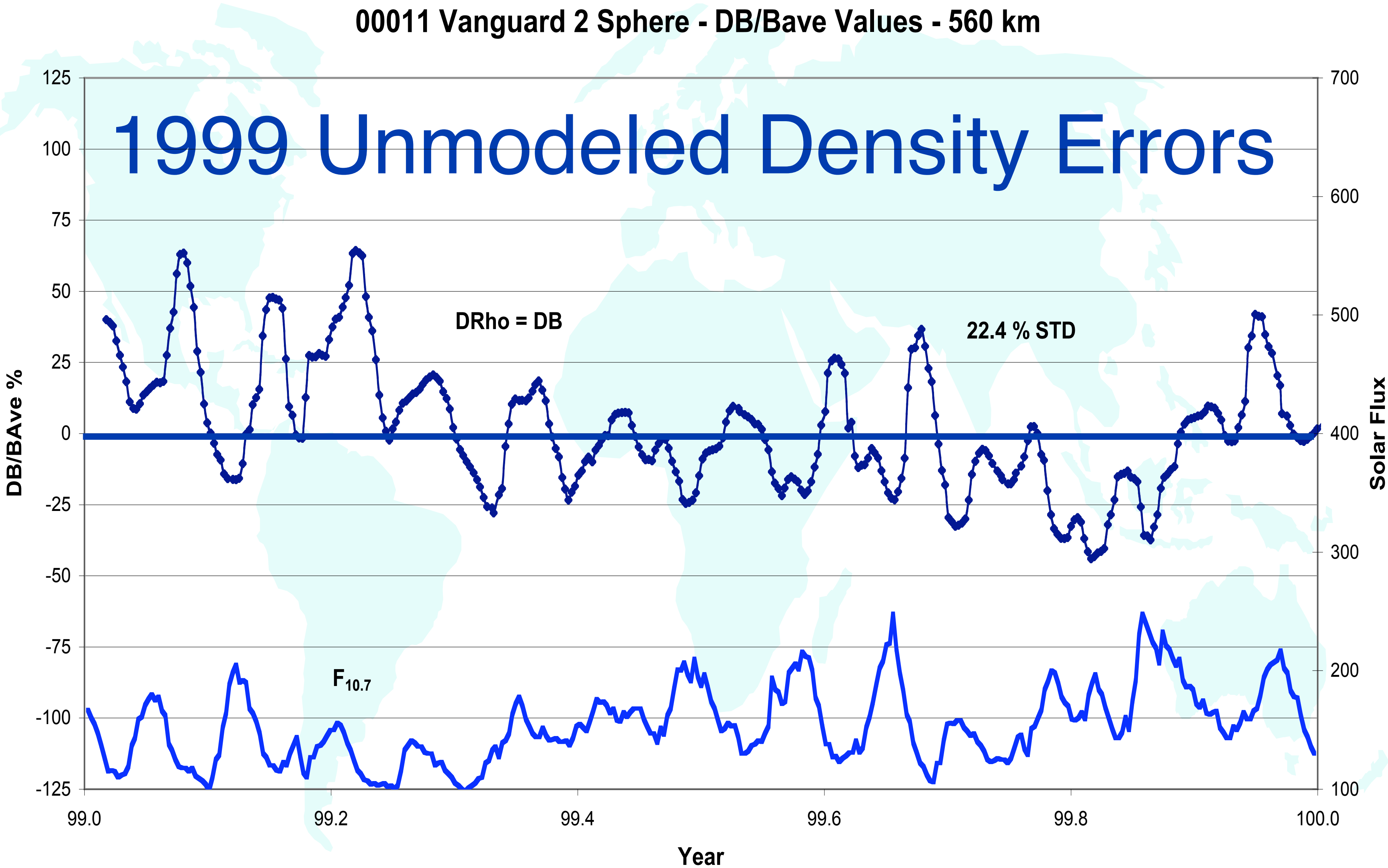
- comparisons with previous models
- solar proxy selection and development

Solar and geomagnetic forecasts

- Integrated solar irradiances proxies – F10, S10, Mg10

Historical Density Model Errors at 350 km (1-σ)





00011 Vanguard 2 Sphere - DB/Bave Values - 560 km
1999 Unmodeled Density Errors
DRho = DB
22.4 % STD
F10.7
DB/BAve %
Solar Flux
Year
125
100
75
50
25
0
-25
-50
-75
-100
-125
700
600
500
400
300
200
100
99.0
99.2
99.4
99.6
99.8
100.0

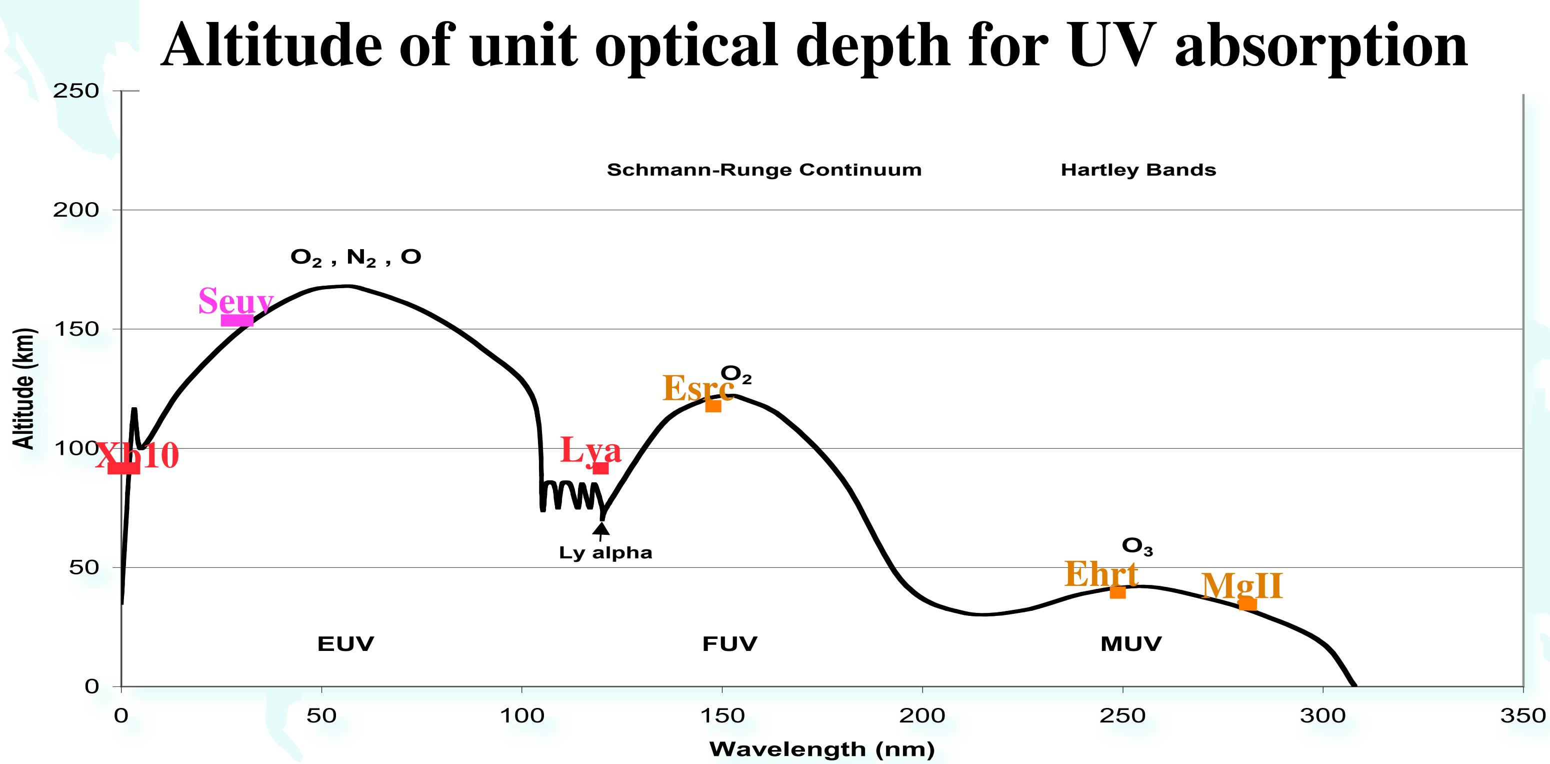
Jacchia-Bowman 2006 thermospheric density model

- Motivation: significantly reduce 1-σ error
- Improvements
  1) uses the CIRA72 (Jacchia 71) model diffusion equations
  2) new solar indices in the extreme and far ultraviolet wavelengths
  3) new exospheric temperature and semiannual density equations
  4) temperature correction equations for diurnal and latitudinal effects
  5) density correction factors at high altitude (1500- 4000 km)
- Bowman, Tobiska, and Marcos, AIAA-2006-6166

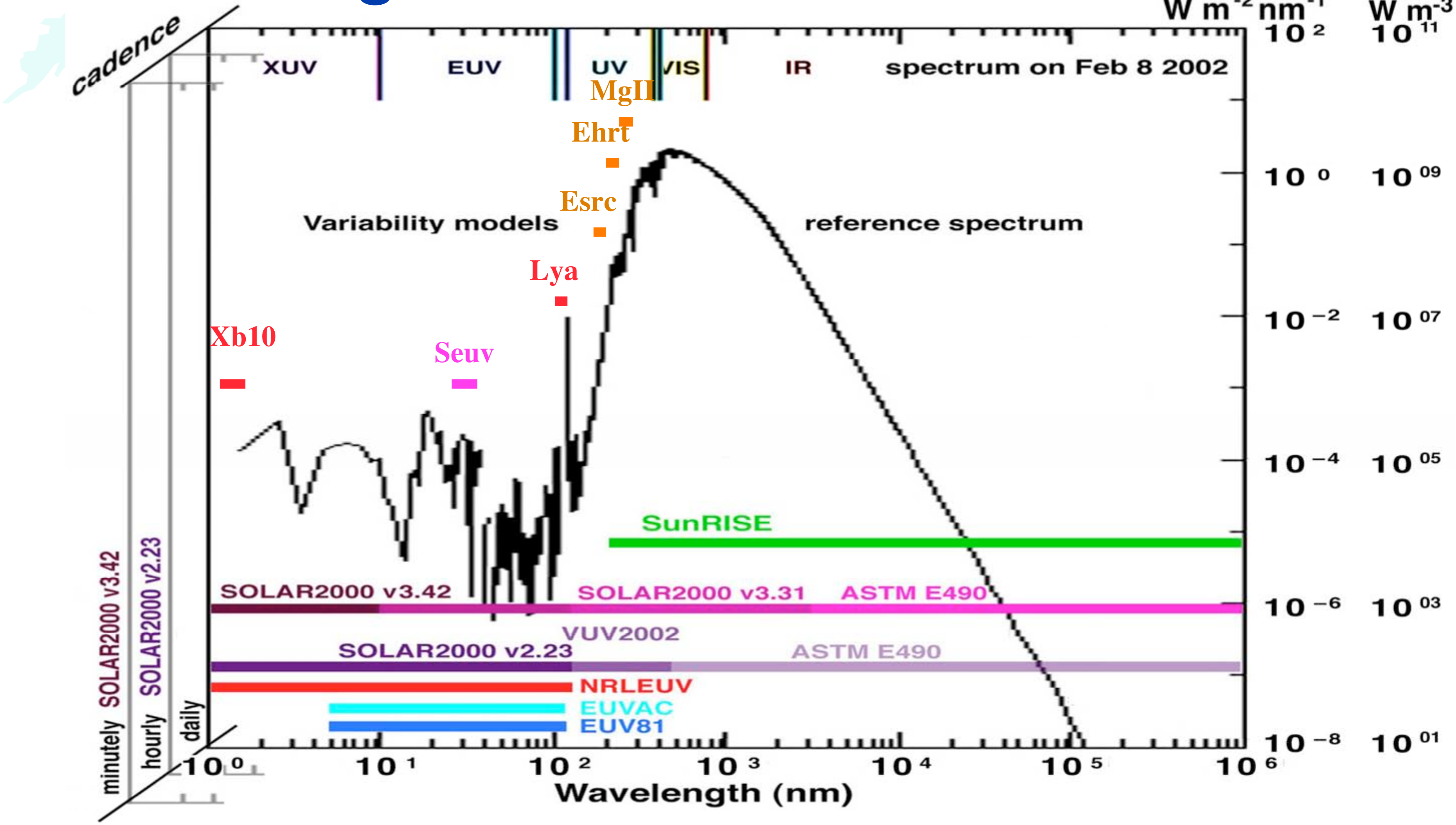
Jacchia-Bowman 2006

- JB2006 is validated through comparisons of accurate daily density drag data that are previously computed for numerous satellites
- For the 400 km altitude, the Jacchia 1971 16% standard deviation is reduced to 10% during periods of low geomagnetic storm activity

Motivation for new solar indices … capture maximum UV absorption, including SRC in FUV



Integrated irradiance indices



Solar index candidates

Index	ISO 21348 Spectral category	ISO 21348 Spectral sub-category	Wavelength range (nm)	Solar source temperature region	Solar source feature	Atmosphere absorption (unit optical depth, km)	Atmosphere absorption (thermal region)
X_{hf}	X-rays	X-rays	0.1-0.8	Hot corona	Flare	70-90	Mesosphere
X_{b10}	X-rays	X-rays	0.1-0.8	Corona	Active region background	70-90	Mesosphere
$XE_{10.7}$	X-rays and UV	XUV+EUV	1-40	Chromosphere, corona	Active region	90-200	Lower, mid thermosphere
$E_{10.7}$	X-rays and ultraviolet	XUV+EUV	1-105	Chromosphere, corona	Active region	90-500	Thermosphere
*$F_{10.7}$	Radio	Radio	10.7E7	Transition region, cool corona	Active region	90-500	Thermosphere
*S_{EUV}	UV	EUV	26-34	Chromosphere, corona	Active region, plage, network	200-300	Thermosphere
$XL_{10.7}$	X-rays and UV	X-rays+H Lyman-α	0.1-0.8,121	Chromosphere, transition region, corona	Active region background, plage, network	70-90	Mesosphere
H Lya	UV	H Lyman-α	121	Transition region, chromosphere	Active region, plage, network	70-90	Mesosphere
E_{SRC0}	UV	FUV	125-175	Photosphere, chromosphere	Plage and network	90-125	Mesosphere, lower thermosphere
E_{SRC1}	UV	FUV	151-152	Chromosphere	Plage and network	125	Lower thermosphere
E_{SRC2}	UV	FUV	144-145	Chromosphere	Plage and network	125	Lower thermosphere
E_{SRC3} = E_{SRC}	UV	FUV	145-165	Photosphere, chromosphere	Plage and network	125	Lower thermosphere
*Mg_{10}	UV	MUV	280	Chromosphere	Active region	20	Stratosphere
E_{SRB}	UV	FUV+MUV	175-205	Photosphere	Plage and network	50-70	Mesosphere
E_{HRT}	UV	MUV	245-254	Photosphere	Network	25	Stratosphere

Solar index selections

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Solar index characteristics

Index	Observing facility	Instrument	Observation time frame	Measurement cadence	Measurement latency	Operational availability
$F_{10.7}$	Penticton ground observatory	Radio telescope	1947-2005	3 times/day	Up to 24 hours	yes
S_{EUV}	SOHO	SEM	1996-2005	15-second	Up to 24 hours	(a)
$XL_{10.7}$	GOES-12, UARS, SORCE, TIMED	XRS, SOLSTICE (2), SEE	1991-2005	1-minute, 16 times/day	Up to 10 minutes, up to 48 hours	(b)
E_{SRC}	UARS, SORCE	SOLSTICE (2)	1991-2005	16 times/day	Up to 48i hours	(c)
Mg_{10}	NOAA-16,17	SBUV	1991-2005	2 times/day	Up to 24 hours	yes
E_{HRT}	UARS, SORCE	SOLSTICE (2)	1991-2005	16 times/day	Up to 48 hours	(c)

(a) SOHO is a NASA research satellite but provides daily irradiances on an operational measurement cadence.
(b) GOES XRS is a NO AA operational instrument whereas TIMED/SEE and SORCE/SOLSTICE are NASA research satellites providing daily irradiances on an operational measurement cadence.
(c) UARS/SOLSTICE is no longer active; SORCE/SOLSTICE is intended to provide data for several years.

Solar index selection - F10

- $F_{10.7}$
  - the traditional coronal solar energy proxy in units of sfu
  - represents XUV-EUV broadband
  - τ > 180 km
  - 13% of thermospheric response comes from $F_{10.7}$
  - provided by Penticton
  - we use the observed archival daily values, with a 1-day lag, over the common time frame of January 1, 1996 – June 12, 2005
  - make a running 81-day centered smoothed set of values (F_{81})
  - we perform linear regression with daily $F_{10.7}$ to scale and report all other solar indices in units of sfu

Solar index selection - S10

- S_{EUV}
  - chromospheric index converted to sfu
  - τ > 180 km
  - 75% of thermospheric response comes from this emission
  - SOHO SEM instrument measures the 26–34 nm emission with 15-sec time resolution; TIMED SEE has 96-min resolution
  - SEM 26-34 nm irradiances are EUV line emissions dominated by the chromospheric 30.4 nm He II line from active regions & plage
  - photons are absorbed mostly by atomic oxygen above 180 km
  - the integrated 26–34 nm emission (SOHO_SEM26-34) is normalized by dividing the daily value by the common time frame mean value
  - the normalized value is converted to sfu through linear regression with F10.7 over the common time frame
  - resulting index is called S10 with a 1-day lag

Solar index selection - Mg10

- E_{SRC}
  - solar FUV Schumann-Runge Continuum (SRC) contains emission between 125–175 nm from the photosphere and lower chromosphere
  - FUV near 145-165 nm is center of SRC; photospheric proxy (sfu)
  - 100 < τ < 125 km
  - 12% of thermospheric response comes from these emissions
  - solar energy is deposited in the terrestrial mesosphere and lower thermosphere (80–125 km) primarily through the energy released from the dissociation of molecular oxygen
  - we integrate the daily SOLSTICE 145–165 nm emission and created a normalized value
  - divide the daily value by the common time frame mean value
  - perform linear regression with $F_{10.7}$ to report the index in sfu
  - E_{SRC} is used with a 5-day lag but IS NOT operationally available

Steps to create Mg_{10}

- a substitute for E_{SRC} is needed and we use Mg II in sfu
- our analysis has found that it represents very well the photospheric and lower chromospheric solar FUV Schumann-Runge Continuum emission (E_{SRC})
- we created a new composite Lyman-alpha from UARS & SORCE SOLSTICE data by scaling each dataset to 365-day smoothed F10.7 to establish the long-term trend
- Next, we scaled the Mg II from NOAA 16 SBUV instrument to the new composite Lyman-alpha
- we created a function to scale Mg II beyond the research data (after July 2005)
- we created a modified Mg II by linear regression with $F_{10.7}$ and report as Mg_{10}
- Mg II is operationally provided by NOAA 16,17 SBUV and SORCE SOLSTICE

Solar indices tested

$Tc = a_0 + a_1 \overline{F}_{10.7}$	
$+ a_{i+1}\Delta F_{10.7}$	10.7 cm - Cool Corona/TR Proxy
$+ a_{i+2}\Delta MgII$	280 nm - Chromosphere Proxy
$+ a_{i+3}\Delta E_{10}$	SOLAR2000 - $F_{10.7}$ + MgII
$+ a_{i+4}\Delta XE_{10}$	SOLAR2000 - EUV 1-40 nm
$+ a_{i+5}\Delta XB_{10}$	SOLAR2000 - XUV Background Xray
$+ a_{i+6}\Delta$Lyá	SOLAR2000 - Lyman-alpha
$+ a_{i+7}\Delta S_{EUV}$	SOHO EUV - Chromosphere 26-34 nm
$+ a_{i+8}\Delta SRC$	SRC Continuum - Lower chromosphere FUV 145-165 nm
$+ a_{i+9}\Delta Hart$	Hartley Bands - Photosphere MUV 245-254 nm

Daily Density Data – 18 Sats

Ht (km)	1996-99	2000-04	Type	Shape
175		26692	PAM-D	Spheriod
		25935	PAM-D	Spheriod
200	22781	22781	PAM-D	Spheriod
	06073	06073	Venus Lander	Spheriod
250	22277	22277	PAM-D	Spheriod
	04053	04053	IntelSat 3	Cylinder
300	14694	14694	R/B	Cylinder
	08063	08063	R/B	Cylinder
350	02150	02150	OV3-1	Cylinder
	02389	02389	OV3-3	Cylinder
400	12388	12388	RadarCal	Sphere
	14483	14483	RadarCal	Sphere
	04382	04382	DFH-1	~Sphere
500				
	00011	00011	Vanguard 2	Sphere
600	00047	00047	R/B	Cylinder
700				
	02909	02909	Calsphere	Sphere
800	02826	02826	Calsphere	Sphere
1000	00900	00900	Calsphere	Sphere

Red	Low i	<35 Deg
Yellow	Mid i	~50 Deg
Green	Crit i	~63 Deg
Blue	High i	>70 Deg

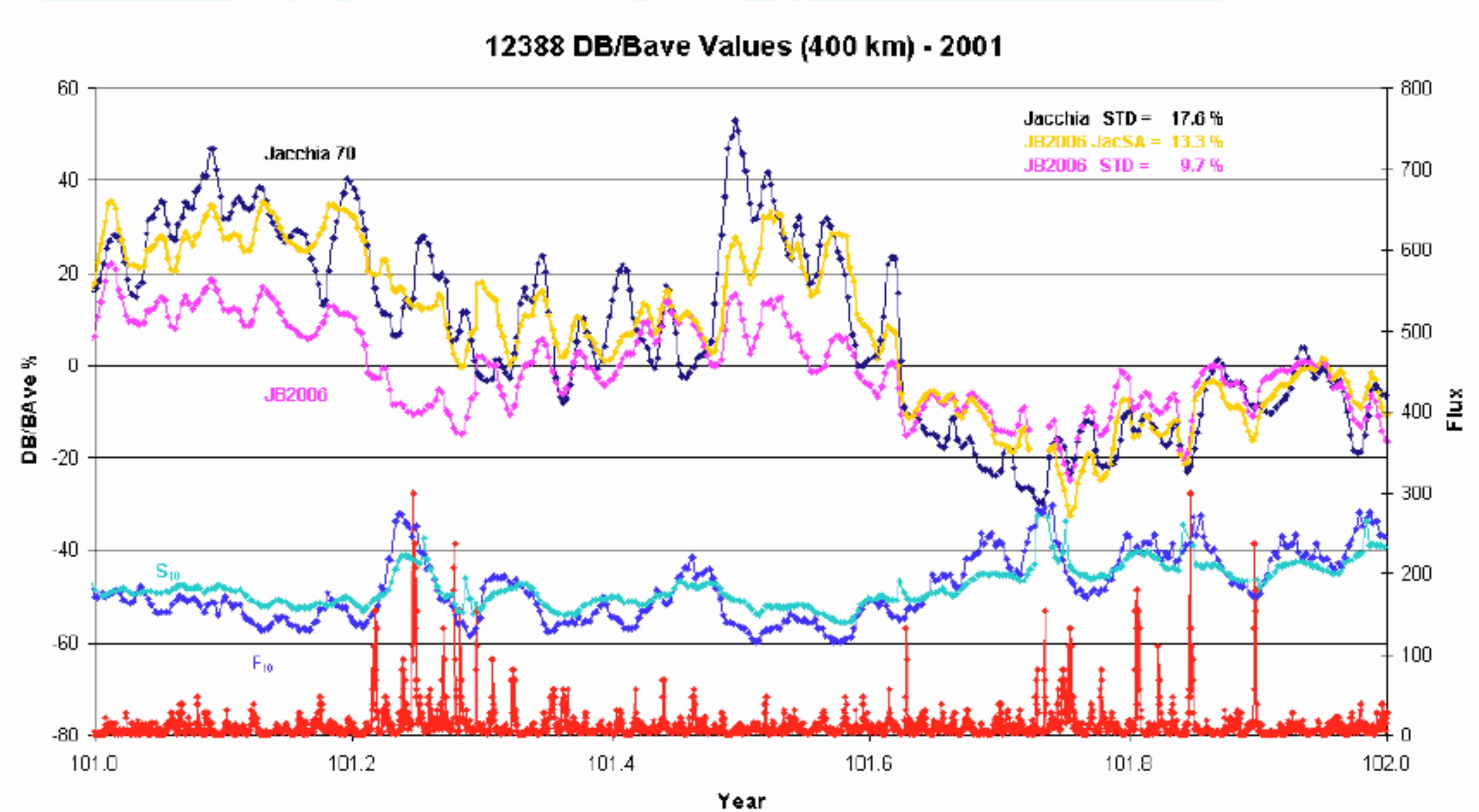
Exosphereric temperature

RMS (ΔTc K)	$\Delta F_{10.7}$	$\Delta S_{10.7}$	ΔE_{SRC} ($\Delta Mg_{10.7}$)	% Uncertainty reduce
19.9	1.405	–	–	0
17.4	0.552	–	–	13
15.7	0.606	–	0.918	21
14.8	0.172	2.604	–	26
14.7	–	2.835	–	26
14.3	–	2.299	0.564	28
14.1	**0.255**	**1.914**	**0.615**	**29**
Lag	1 day	1 day	5 days	

- Analysis also performed for n-day centered averaged values and other indices
- All satellite data sets were used in Tc fits
- All coefficient values are in sfu
- $\Delta Mg_{10.7}$ was substituted for ΔE_{SRC} at a small penalty of uncertainty
- **29% uncertainty reduction due to solar (semi-annual improved separately)**

$$Tc = 379.0 + 3.353\ F_{81} + 0.358\ \Delta F_{10.7} + 2.094\ \Delta S_{10.7} + 0.343\ \Delta Mg_{10.7}$$

Reduced error in JB2006

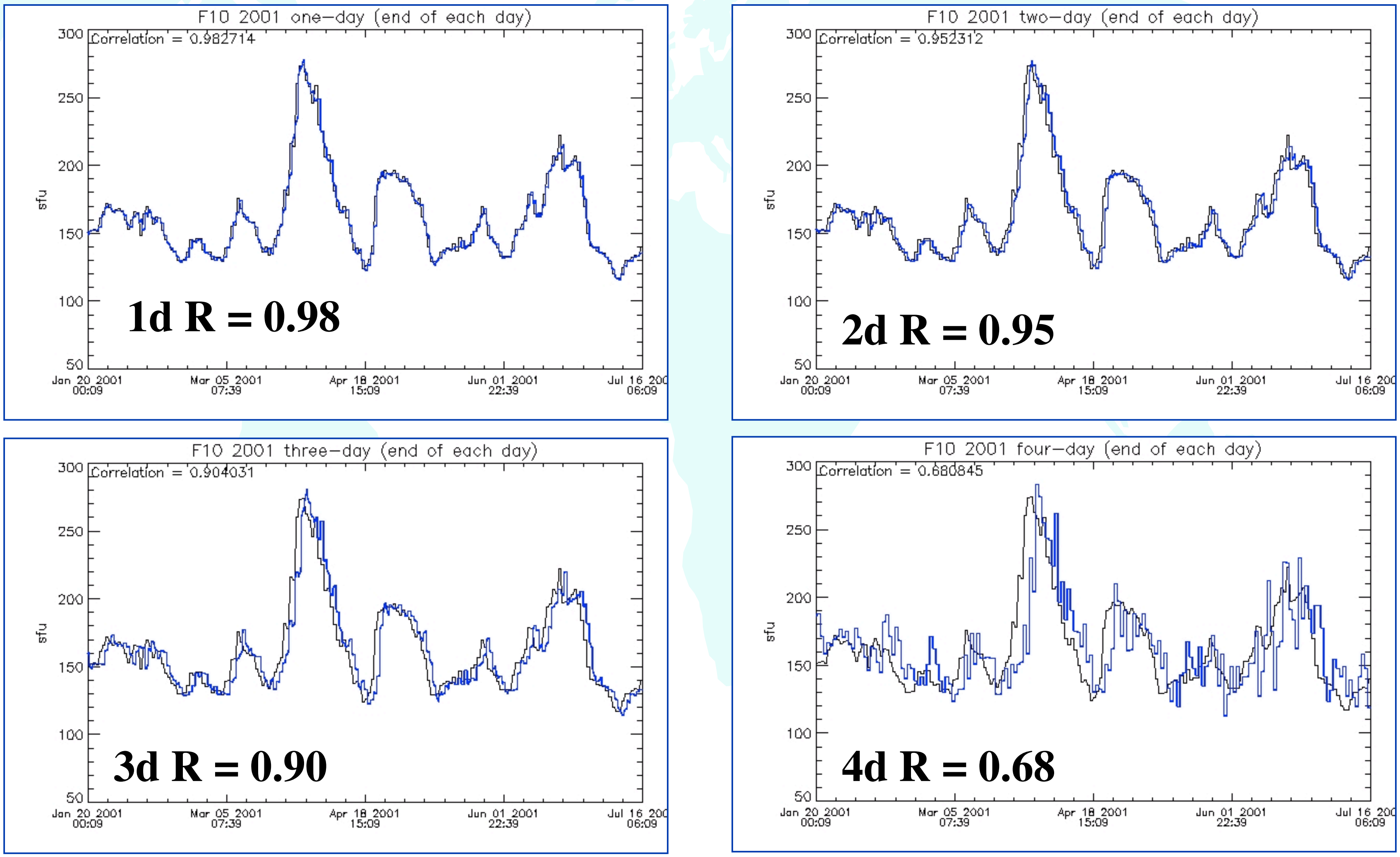


SET's new operational indices

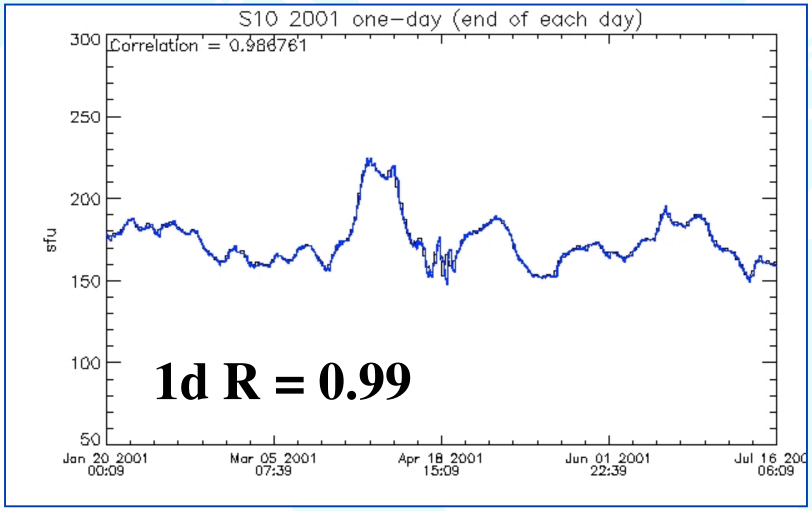
- **Persistence and recurrence** is achieved using linear prediction for S_{10}, Mg_{10}, F_{10}
- $x_t = \phi_1 x_{t-1} + \phi_2 x_{t-2} \ldots + \phi_P x_{t-P} + w_t$ (P is previous values to be used, t is number of values to forecast)
- Day 2 forecast is additionally adjusted using a modified slope algorithm (MSd2)
- **Time period (type) algorithm**

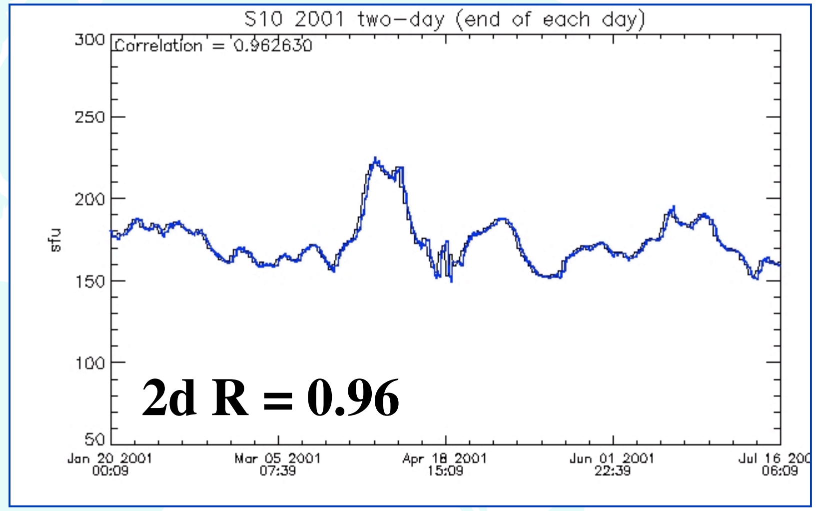
Time period	(type)	algorithm
-24 to 0 hours	(nowcast)	linear prediction (t = 3; P=3)
0 to 48 hours	(forecast)	linear prediction (t = 3; P=3) + MSd2
48 to 96 hours	(forecast)	linear prediction (t = 5; P=137)

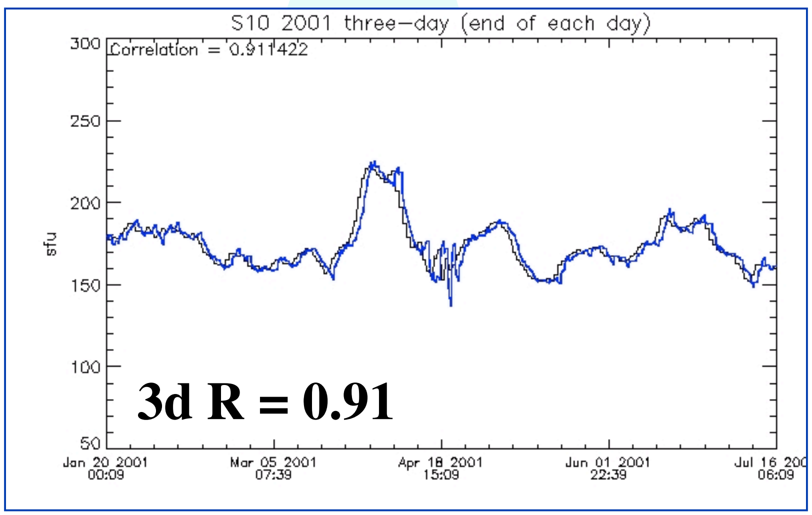
2001 EOD forecast: 1-4 day F_{10}

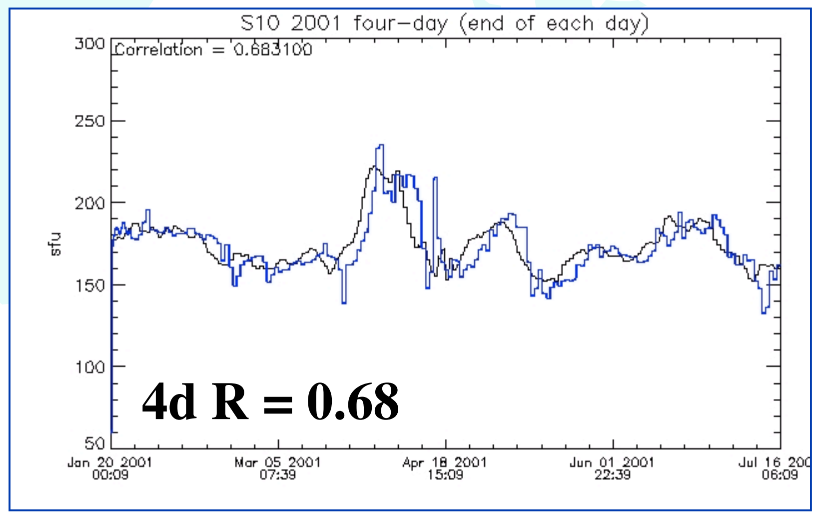


2001 EOD forecast: 1-4 day S_{10}

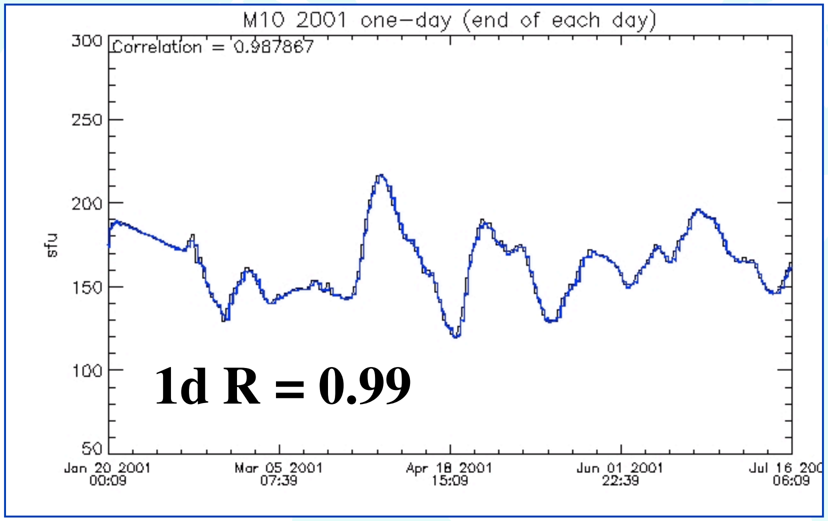


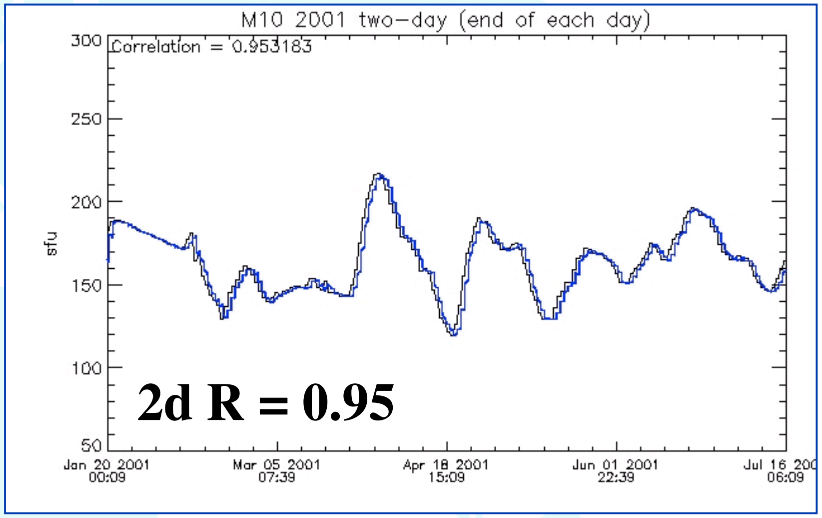


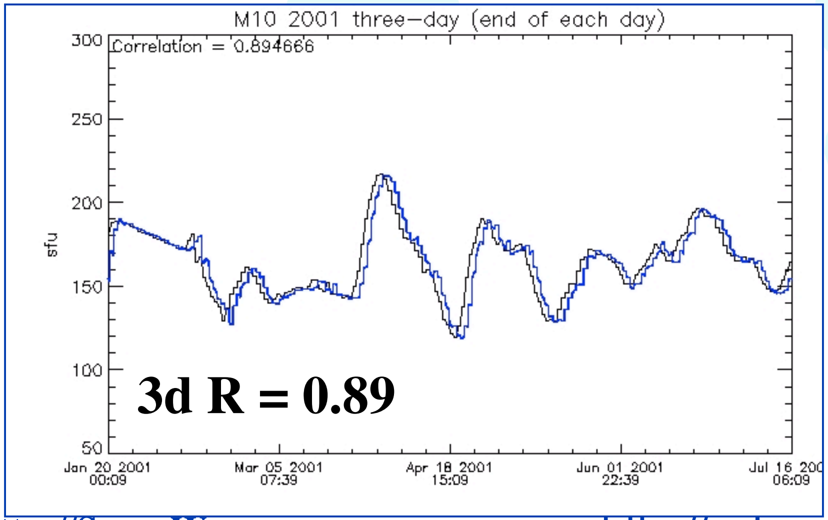


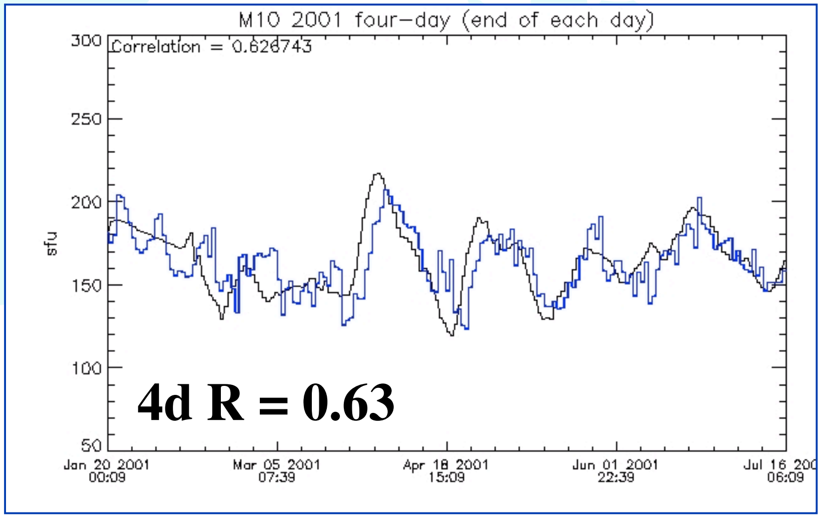


2001 EOD forecast: 1-4 day Mg_{10}









Conclusions

New solar energy terms provide 60% of the improvement

- 29% uncertainty reduction in delta-exospheric temperatures, ΔTc
- *Combined with semiannual, the uncertainty reduction is ~50%*

Solar indices capture previously unmodeled energy

- *Selection based on considerations of availability and simplicity*
- 3 indices and proxies were selected
  - $F_{10.7}$, $S_{10.7}$, $Mg_{10.7}$
- 2 indices ($XL_{10.7}$, E_{SRC}) gave slight improvements but were not used

Lag analyses suggest bounded vertical transport velocities

- **1 day:** O (200 km at unit optical depth driven by chromo. EUV)
- **5 days:** N_2 (also O_2, O, NO at 125 km unit optical depth driven by chromo./photo. FUV SRC)
- **8 days:** N_2 (also O_2, NO, H_2O at 80 km unit optical depth driven by chromo Lyα + coronal X-ray)
- **n-days:** N_2 (also O_2, O_3, H_2O, CO_2 at 25 km unit optical depth driven by photospheric Hartley Band not found to be significant)

Forecasts out to 96-hours

- **1 day:** 98-99% correlation coefficients
- **2 day:** 95-96% correlation coefficients
- **3 day:** 89-91% correlation coefficients
- **4 day:** 63-68% correlation coefficients