The solar and geomagnetic inputs into the JB2008 thermospheric density model for use by CIRA08 and ISO 14222

COSPAR 2010 Session C0.1
Paper C01-0003-10 July 20, 2010

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What is the difference between CIRA08 and ISO 14222?

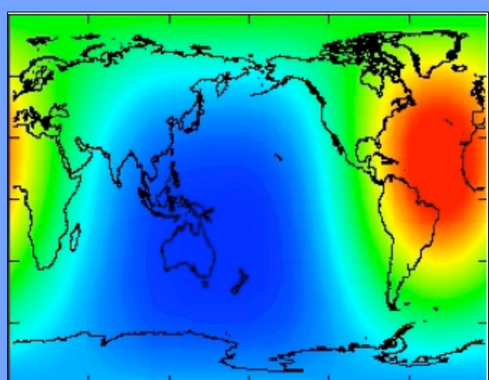
- **CIRA08** is the **scientific publication** describing the Earth's neutral atmosphere, especially above 120 km, and is compiled by authors in the COSPAR CIRA task group
- **ISO 14222** is the Earth atmosphere density >120 km **international standard** developed by ISO TC20/SC14/WG4 project leads

CIRA08 and ISO 14222 similarities

- **Both documents describe the same models and information but for different audiences**
- **CIRA08** is being published by JASR and will describe the NRLMSIS-00 and JB2008 models, parameters, and **scientific** basis
- **ISO 14222** is being published by ISO and will describe the NRLMSIS-00 and JB2008 models, parameters, and **engineering** uses

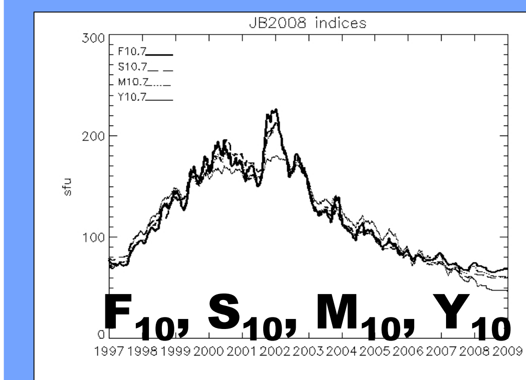
JB2008 overview

JB2008 output



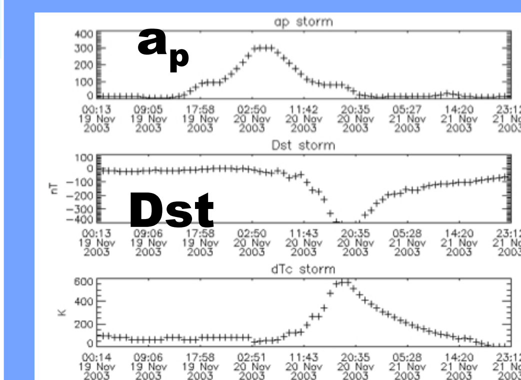
neutral atmosphere

JB2008 solar inputs



solar EUV & FUV indices

JB2008 geo-mag inputs



a_p and Dst indices

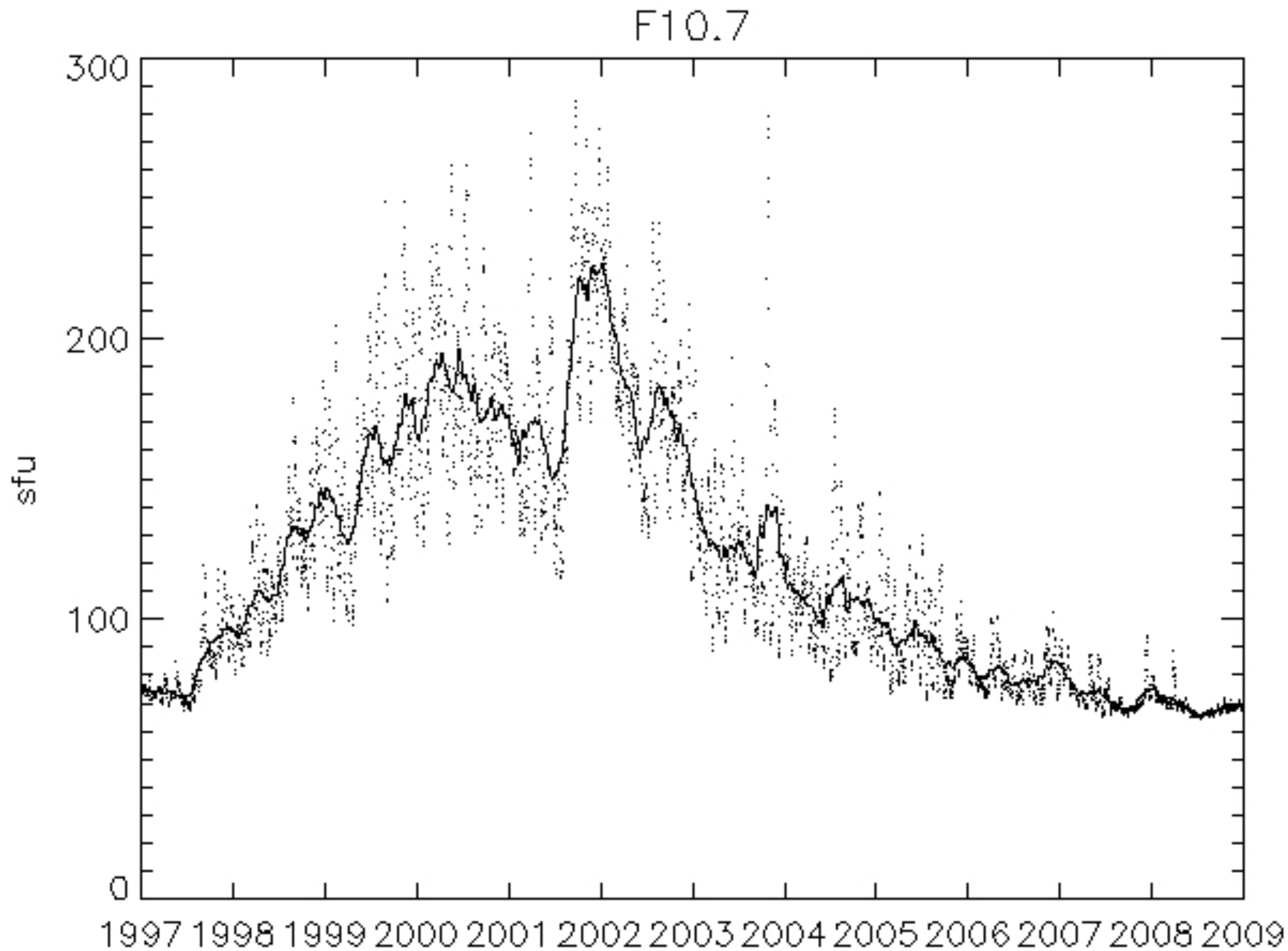
F10 proxy

- First daily measurements began February 14, 1947 – **high value for legacy time series**
- Measured by DRAO National Research Council Solar Radio Monitoring Programme in Penticton
- Observations of flux density values made at 17, 20 and 23 UTC each day
- 20 UTC observed values (not 1 AU) archived at World Data Center were used in JB2008 derivation
- Physical units are $\times 10^{-22}$ W m^{-2} Hz^{-1} and their numerical value is used without the multiplier and called solar flux units (sfu); **this has become defacto standard unit for solar indices**
- $F_{10.7}$ a useful proxy for the combination of **chromospheric, transition region, and coronal** solar EUV emissions modulated by bright solar active regions whose energies at Earth are deposited in the thermosphere
- It originates mostly in the solar cool (low) corona by electrons in thermal free-free (bremsstrahlung) emission in the vicinity of sunspots and in widely distributed areas associated with the hot complexes of solar activity

F10 proxy

- The dependence on few processes, combined with its localized formation in the cool corona, i.e., a region that is closely coupled with magnetic structures responsible for creating the XUV–EUV irradiances, makes this a **good generalized solar proxy** for thermospheric heating
- The running 81-day centered smoothed $F_{10.7}$ values, using the moving boxcar method, are referred to as F_{81}
- The observed archival daily $F_{10.7}$ values and their 81-day running center-smoothed values, F_{81}, with a **1-day lag** are used in JB2008
- The 1-day lag had the best correlation with satellite-derived density residuals
- A linear regression is used with daily $F_{10.7}$ to scale and **report all other JB2008 solar indices in units of sfu**
- $F_{10.7}$ is the **recognized historical EUV proxy** and, by reporting other proxies or indices in sfu, it is very easy to qualitatively identify similarities and differences between them
- For solar energy inputs, it is **desirable to have solar indices and proxies that vary differently through time**; this strategy of using multiple solar indices has significantly improved the accuracy of density modeling in JB2008

F10 proxy



$F_{10.7}$ daily and 81-day smoothed values for use by the JB2008 model from January 1, 1997 to January 1, 2009

S10 index

• $S_{10.7}$ index is an activity indicator of the integrated 26–34 nm solar irradiance measured by the Solar Extreme-ultraviolet Monitor (SEM) instrument on the NASA/ESA Solar and Heliospheric Observatory (SOHO) satellite

• SEM has been making observations since December 16, 1995 for the 26–34 nm solar EUV emission with 15-second time resolution in this first order broadband wavelength range

• $S_{10.7}$ index is created by first normalizing the data, then converting it to sfu via a first degree polynomial fit with $F_{10.7}$; spikes from abnormal flares and missing data were excluded from the fitting vectors; normalization is achieved using a mean value = 1.9955×10^{10} photons cm^{-2} s^{-1} for the time frame December 16, 1995 to June 12, 2005 (solar cycle 23)

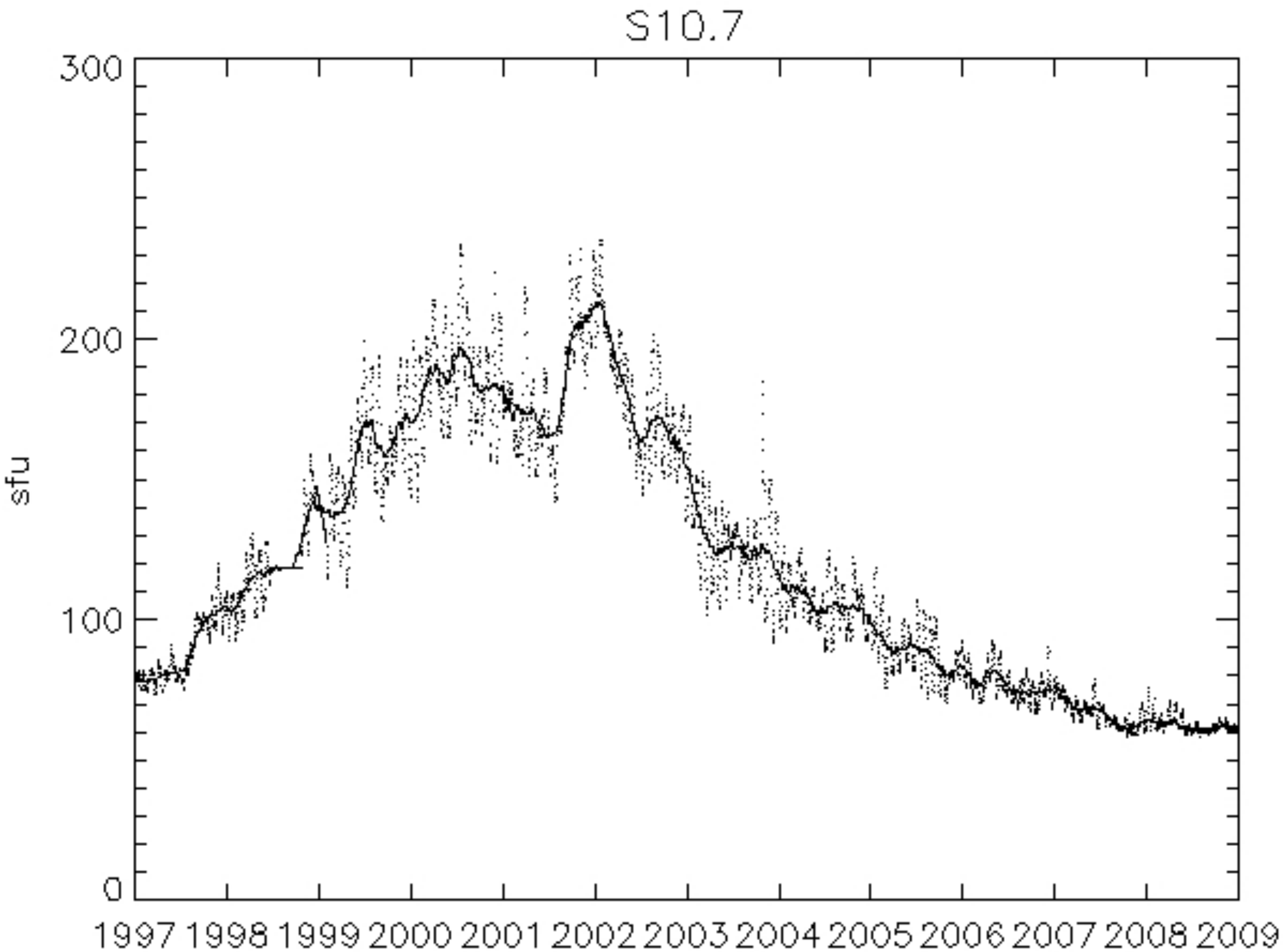
• Corrections to $S_{10.7}$ are made and identified with versions: versions 3.0–3.9 are used by JB2006 and after June 12, 2005 include a slight long-term trend removal to ensure that similar values at the minima of solar cycles 22 and 23 were achieved

• For JB2008, ($S_{10.7}$ v4.0 and higher) a new derivation was completed using the equation as follows: $S_{10.7} = (-2.90193) + (118.512) * (SOHO\_SEM_{26\_34}/1.9955\times10^{10})$

S10 index

- Chromospheric He II at 30.4 nm and coronal Fe XV at 28.4 nm dominate the broadband SEM 26-34 nm irradiances but that bandpass includes contributions from other chromospheric, transition region, and coronal lines
- When the SOHO SEM and TIMED SEE 26–34 nm integrated data are compared, there are differences in the time series particularly during active solar conditions; it is possible that the SOHO SEM measurements are slightly contaminated with 2nd order emissions from the coronal 17.1 nm Fe IX line that have not been removed; however, this topic needs further investigation
- The energy in this bandpass principally comes from solar active regions, plage, and network
- Once the photons reach the Earth, they are deposited (absorbed) in the terrestrial thermosphere mostly by atomic oxygen above 200 km
- We use the daily $S_{10.7}$ index and it’s 81-day running center-smoothed values, S_{81}, with a 1-day lag (the best correlation with satellite density residuals) in JB2008
- We infer the 1-day lag is consistent with the average atomic oxygen thermal conduction timescale in the thermosphere above 180 km

S10 index



$S_{10.7}$ (v4.0) daily and 81-day smoothed values for use by the JB2008 model from January 1, 1997 to January 1, 2009

M10 proxy

• The $M_{10.7}$ index is derived from the Mg II core-to-wing ratio that originated from the NOAA series operational satellites, e.g., NOAA-16,-17,-18, which host the Solar Backscatter Ultraviolet (SBUV) spectrometer

• Although the NOAA data are from operational satellites, the SORCE/SOLSTICE and ERS-2/GOME research satellites also make the Mg II cwr measurements

• The 280 nm solar spectral band contains photospheric continuum and chromospheric line emissions; the Mg II *h* and *k* lines at 279.56 and 280.27 nm are chromospheric in origin while the weakly varying wings or continuum longward and shortward of the core line emission are photospheric in origin; the instruments from all satellites observe both features

• The ratio of the Mg II variable core lines to the nearly non-varying wings is calculated to provide a measure of chromospheric solar active region emission that is theoretically independent of instrument sensitivity change through time; however, long-term changes can occur in the index if instrument wavelength calibrations change in-flight or the solar incidence angle into the instrument changes

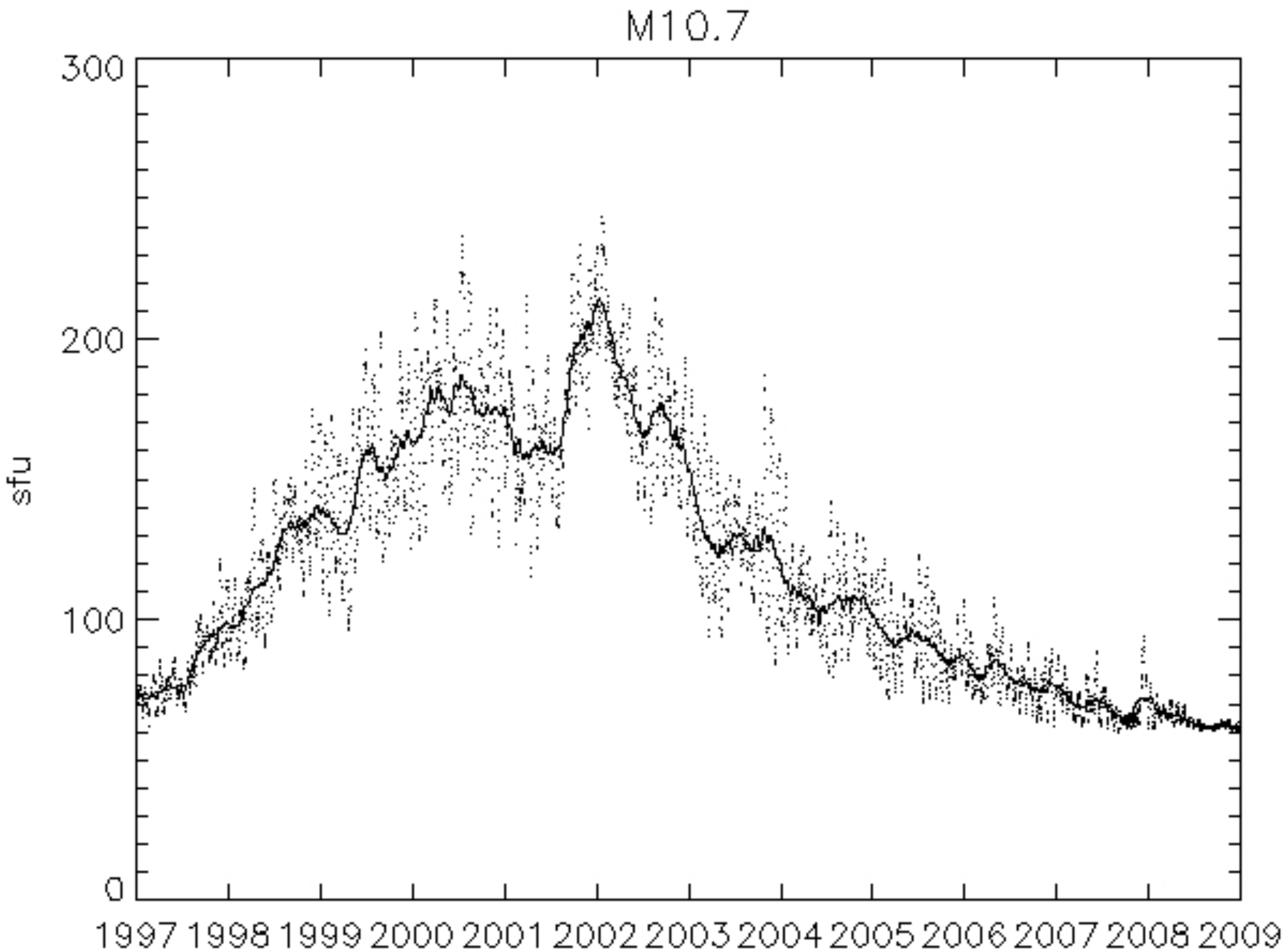
M10 proxy

- The daily Mg II core-to-wing ratio (cwr) has historically been provided through the NOAA Space Weather Prediction Center (SWPC); SET has developed and provides an operational Mg II cwr data product ($MgII_{cwr\_SET}$) available at the Products menu link of http://spacewx.com that uses the NOAA-16,-17-18, SORCE/SOLSTICE, and ERS-2/GOME data sources
- SET uses the DeLand algorithm to create the index
- The Mg II cwr is an especially good proxy for some solar FUV and EUV emissions; it well represents photospheric and lower chromospheric solar FUV Schumann-Runge Continuum emission near 160 nm that maps into lower thermosphere heating due to O_2 photodissociation; since a 160 nm solar FUV emission photosphere index is not produced operationally, the $MgII_{cwr\_SET}$ proxy is used and modified into the $M_{10.7}$ index for comparison with the other solar indices
- This derivation is performed by finding the relationship between long-term (multiple solar cycle) daily $MgII_{cwr\_SET}$ and $F_{10.7}$ using a first-degree polynomial fit to produce a coefficient set that can translate Mg II cwr into sfu; the result is $M^*_{10.7}$

M10 proxy

- Next, a correction is added for the decline of solar cycle 23 to account for NOAA 16 instrument degradation that may be related to its diffuser screen illumination geometry changing with time; this cause is unconfirmed; the correction is accomplished by using another first degree polynomial fit between a trend ratio and day number starting 2448542.0 JD (October 12, 1991 12:00 UT) near the peak of solar cycle 22; the trend ratio is formed from the 365-day center smoothed $M^*_{10.7}$ divided by the 365-day center smoothed $F_{10.7}$
- The v4.0 formulation of the $M_{10.7}$ index in sfu is: $M_{10.7} = [-2107.6186 + (8203.0537)^* (MgII_{cwr\_SET})] + [(M^*_{10.7})^*(1.2890589 + (-8.3777235\times10^{-5})^*x - 1)]$
- The day number x = 0, 1, 2, ... with x = 0 equivalent to starting on 2448542.0 JD
- The daily $M_{10.7}$ and its 81-day running center-smoothed values, M_{81}, are used with a 2-day lag in JB2008 as a proxy for the Schumann-Runge continuum FUV emission
- A 2-day lag time is appropriate for $M_{10.7}$, which represents O_2 photodissociation, recombination, conduction, and transport processes at the 95–110 km level
- We infer this lag is consistent with the average molecular oxygen dissociation and thermal conduction timescale in the thermosphere above 95 km, although eddy and turbulent conduction processes may play a role

M10 proxy



$M_{10.7}$ (v4.0) daily and 81-day smoothed values for use by the JB2008 model from January 1, 1997 to January 1, 2009

Y10 index

- The $XL_{10.7}$ index was developed as a candidate index for the JB2006 model but was unused; while developing the JB2008 model, it was determined that a thermospheric energy contribution to satellite drag from the 80–95 km region was significantly correlated with the composite $XL_{10.7}$ solar index
- Solar X-rays in the 0.1–0.8 nm wavelength range come from the cool and hot corona and are typically a combination of both very bright solar active region background that varies slowly (days to months) plus flares that vary rapidly (minutes to hours), respectively
- The photons arriving at Earth are absorbed in the lower thermosphere to mesopause and (85–100 km) by molecular oxygen (O_2) and molecular nitrogen (N_2) where they ionize those neutral constituents to create the ionospheric D-region
- The X-ray Spectrometer (XRS) instrument is part of the instrument package on the GOES series operational spacecraft. The GOES/XRS provides the historical through current epoch 0.1–0.8 nm solar X-ray emission data with a 1-minute cadence and as low as 5-minute latency. These data, which are particularly useful for flare detection, are continuously reported by NOAA SWPC at their website of http://www.swpc.noaa.gov/

Y10 index

• SET uses the GOES/XRS 0.1–0.8 nm data for an index of the solar X-ray active region background, without the flare component, for operational use; this is called the X_{b10} index and is used to represent the daily energy that is deposited into the mesosphere and lower thermosphere

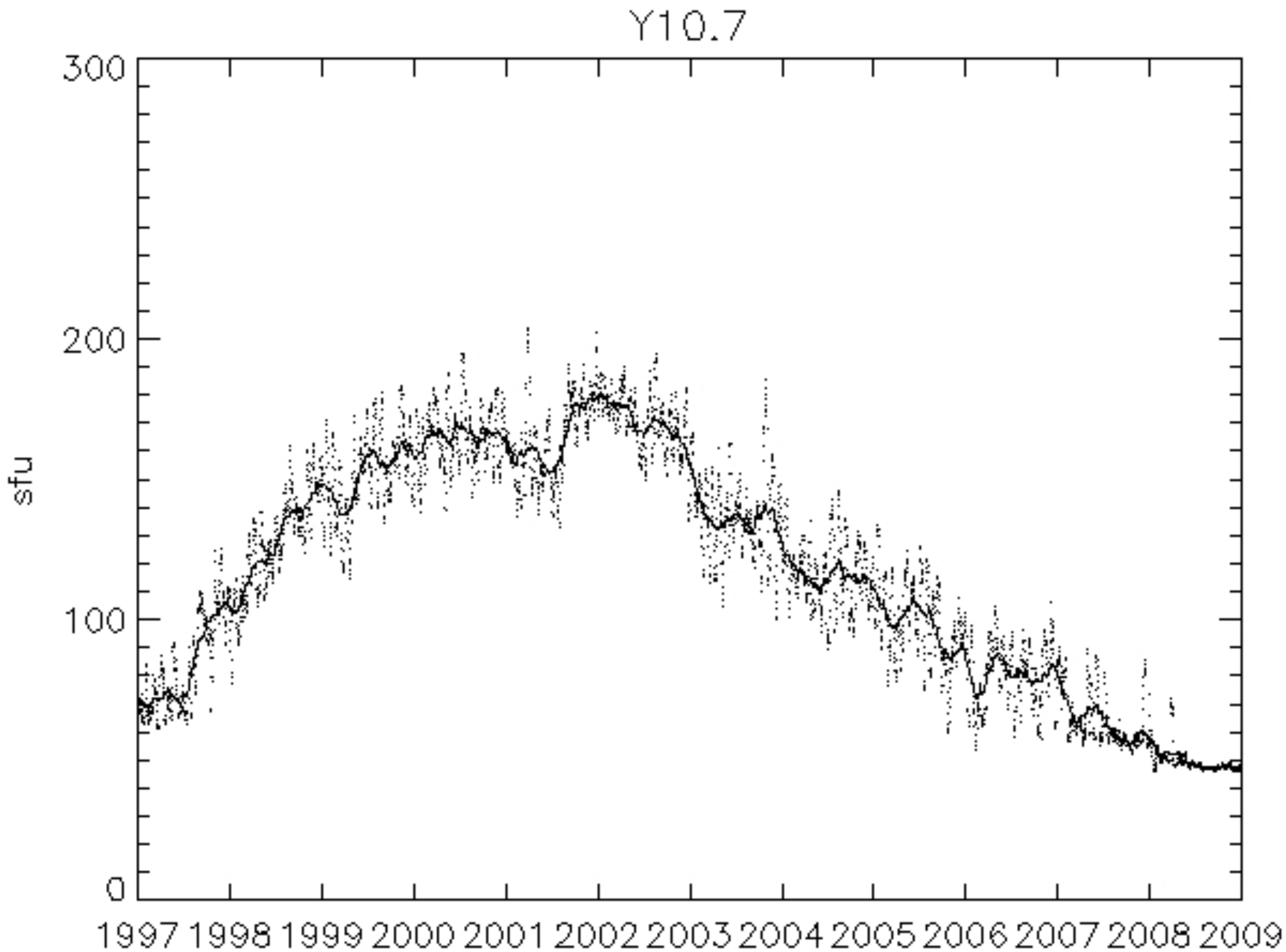
• While the 0.1-0.8 nm X-rays are a major energy source in these atmospheric regions during high solar activity, they relinquish their dominance to another emission that reaches the same optical depth, i.e., the competing hydrogen (H) Lyman-α emission that is the major energy source in this atmosphere region during moderate and low solar activity

• Lyman-α is created in the solar upper chromosphere and transition region and demarcates the EUV from the FUV spectral regions; it is formed primarily in solar active regions, plage, and network; the photons, arriving at Earth, are absorbed in the mesosphere and lower thermosphere where they dissociate nitric oxide (NO) and participate in water (H_2O) chemistry; Lyman-α is regularly observed by the SOLSTICE instrument on the UARS and SORCE satellites as well as by the SEE instrument on TIMED and the EVE instrument on SDO

Y10 index

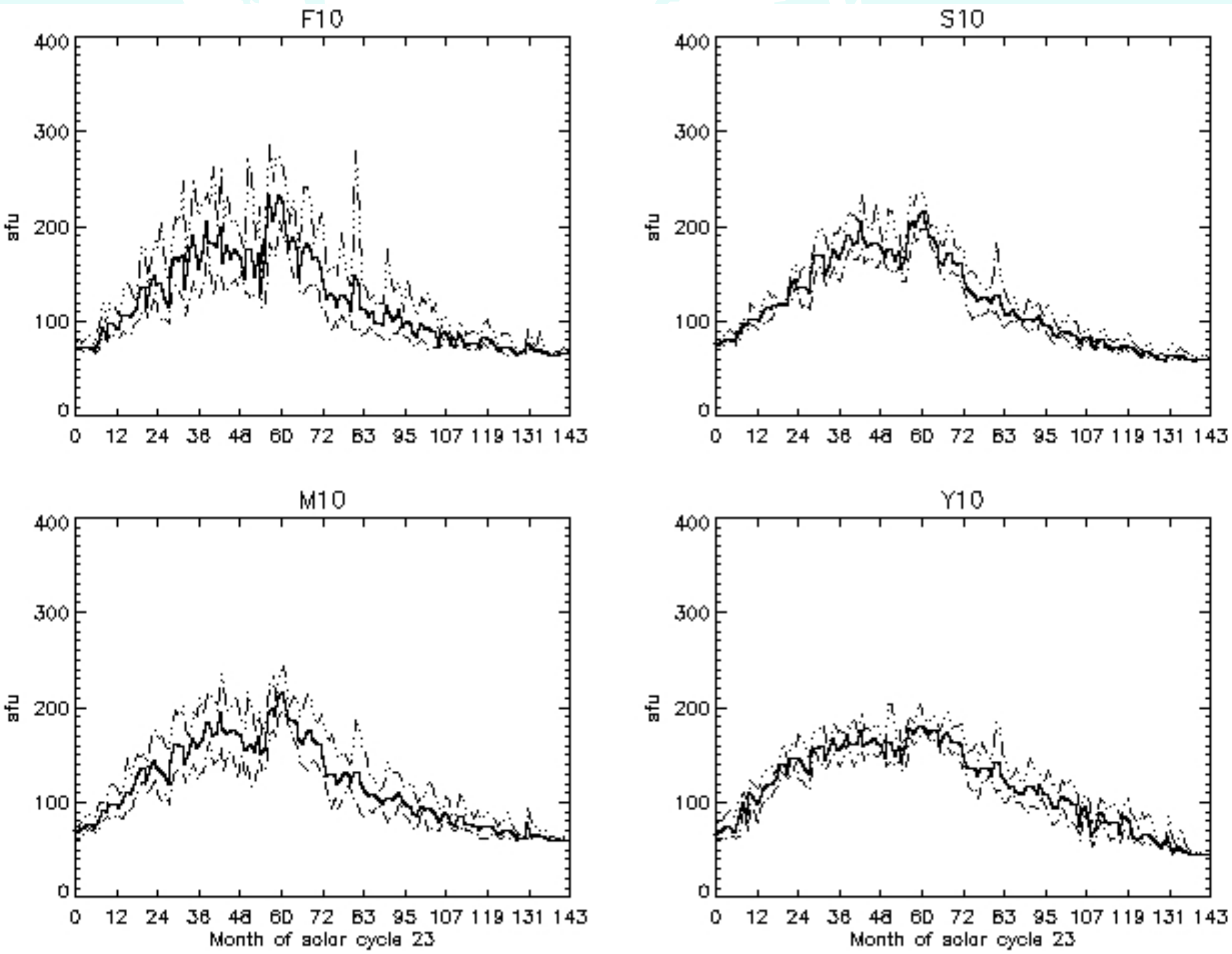
- Since these two solar emissions are competing drivers to the mesosphere and lower thermosphere, we have developed a composite solar index of the X_{b10} and Lyman-α; it does not contain a flare component and is weighted to represent mostly X_{b10} during solar maximum and to represent mostly Lyman-α during moderate and low solar activity
- A normalized F_{81}, F_{81norm}, consisting of the 81-day centered smoothed $F_{10.7}$ divided by it's mean value for the time frame of January 1, 1991 through February 16, 2008 is used as the weighting function and multiplied with the X_{b10} and Lyman-α (Lya) expressed as ratios to their solar maximum values; the resulting index is called $Y_{10.7}$ in sfu
- $Y_{10.7} = F_{81norm} * X10 + [(1- F_{81norm}) * L10]$
- $L10 = -88.3926 + (3.35891\times10^{-10} * Lya) + (2.40481\times10^{-22} * Lya^2)$
- $X10 = [(-42.5991 + (0.533669 * X_{b10})]$
- This daily index has a 5-day lag strongly correlated with the satellite drag density residuals after modeled density variations due to the other solar indices were removed; the 81-day running center-smoothed values, Y_{81}, are also used with the 5-day lag
- We infer the 5-day lag is consistent with the average molecular oxygen and molecular nitrogen thermal conduction timescales in the lower thermosphere above 85 km, although eddy and turbulent conduction may also play a role

Y10 index



$Y_{10.7}$ (v4.0) daily and 81-day smoothed values for use by the JB2008 model from January 1, 1997 to January 1, 2009

Comparison between indices



$F_{10.7}$, $S_{10.7}$, $M_{10.7}$, $Y_{10.7}$ (v4.0) monthly minimum, mean, and maximum values for use by the JB2008 model from January 1, 1997 to January 1, 2009

Table A. Solar indices related to atmospheric heating

Index	IS 21348 Spectral category	IS 21348 Spectral sub-category	Wavelength range (nm)	Solar source temperature region[1]	Solar source feature[1]	Atmosphere absorption (unit optical depth, km)[2]	Terrestrial atmosphere absorption (thermal region)[2]
*$F_{10.7}$	Radio	Radio	10.7E7	Transition region, cool corona	Active region	90-500	Thermosphere with 1-day lag; 9.8% daily variability contribution
*$S_{10.7}$	UV	EUV	26-34	Chromosphere, corona	Active region, plage, network	200-300	Thermosphere with 1-day lag; 74.1% daily variability contribution
*$M_{10.7}$	UV	FUV	160	Photosphere-lower chromosphere	SRC	95-110	Lower thermosphere with 2-day lag; 10.3% daily variability contribution
$MgII_{cwr}$	UV	MUV	280[3]	Chromosphere	Active region, plage, network	200-300	Thermosphere
*$Y_{10.7}$	X-rays and UV	X-rays+H Lyman-α	0.1-0.8, 121	Chromosphere, transition region, hot corona	Active region, plage, network	85-100	Mesopause-lower thermosphere with 5-day lag; 5.8% daily variability contribution
H Lya	UV	H Lyman-α	121	Transition region, chromosphere	Active region, plage, network	85-100	Mesopause-lower thermosphere
X_{b10}	X-rays	X-rays	0.1-0.8	Hot corona	Active region background	85-100	Mesopause-lower thermosphere

*Index or proxy is used in the JB2008 model exospheric temperature equation.
[1]Vernazza *et al.*, 1976; Vernazza *et al.*, 1981.
[2]Banks, P. and G. Kockarts, 1973.
[3]The *h* & *k* lines at the band center are chromospheric and are referenced to blackbody continuum wings at edges of bandpass.

Indices' characteristics

- By expressing the proxies and indices in common units, their contribution to the daily density variability in the JB2008 exospheric temperature equation for Tc can be determined; the $F_{10.7}$ contribution to Tc daily variability is 9.8%, $S_{10.7}$ is 74.1%, $M_{10.7}$ is 10.3%, and $Y_{10.7}$ is 5.8%

Table B. Characteristics of daily JB2008 solar indices

Index or proxy	Observing facility	Instrument	Observation time frame	Measurement cadence	Measurement latency	Operational availability
$F_{10.7}$	Penticton ground observatory	Radio telescope	1947-2009	3 times/day	Up to 24 hours	yes
$S_{10.7}$	SOHO, GOES	SEM, EUVS	1996-2009	15-second	Up to 24 hours	(a)
$M_{10.7}$	NOAA-16,17,18, SORCE, ERS-2	SBUV, SOLSTICE, GOME	1991-2009	2 times/day	Up to 24 hours	yes
$Y_{10.7}$	GOES-12, UARS, SORCE, TIMED	XRS, SOLSTICE (2), SEE	1991-2009	1-minute, 16 times/day	Up to 10 minutes, up to 48 hours	(b)

(a) SOHO/SEM is a NASA research instrument but provides daily irradiances on an operational cadence; GOES 13 EUVS B channel makes measurements in the same bandpass as SOHO SEM.

(b) GOES XRS is a NOAA operational instrument whereas TIMED/SEE and SORCE/SOLSTICE are NASA research instruments providing daily irradiances on an operational measurement cadence.

(c) UARS/SOLSTICE stopped in 2005; SORCE/SOLSTICE intends to provide data for several years.

Indices for different solar activity conditions

Table A4. Reference values for intermediate- and short-term solar variability

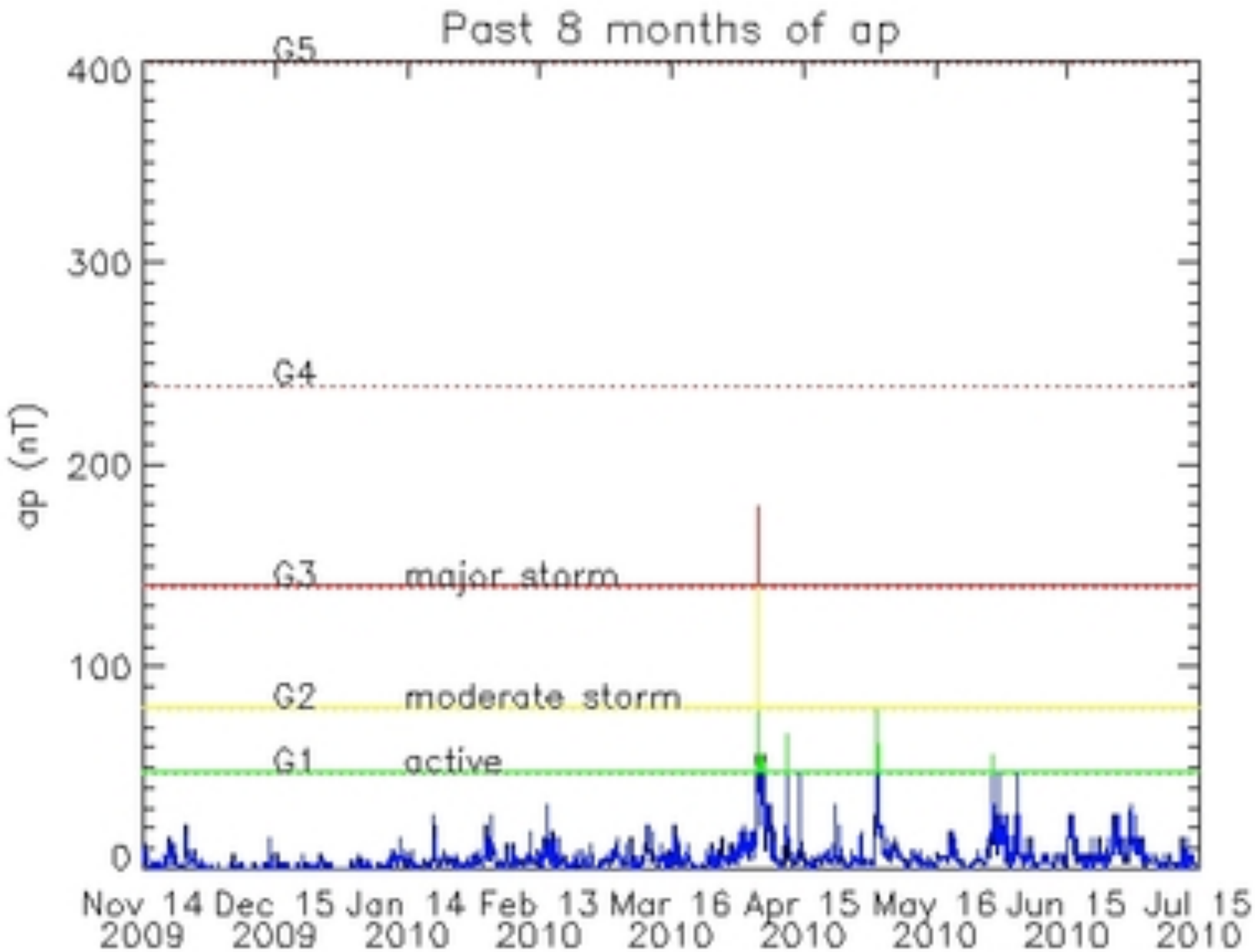
	Case 1: Intermediate-term (81 days)			Case 2: Short-term (27 days high activity)			Case 3: Short-term (27 days low activity)		
Daily	Low	Moderate	High	Low	Moderate	High	Low	Moderate	High
$F_{10.7}$	65	120	225	90	165	280	80	105	145
$S_{10.7}$	60	120	215	105	135	185	85	100	120
$M_{10.7}$	60	115	215	95	135	185	80	95	115
$Y_{10.7}$	50	115	180	110	150	185	90	110	135

Daily updated values are found at the JB2008 menu link on the SET http://spacewx.com website

a_p index

- The a_p index reports the amplitude of planetary geomagnetic activity for a given day (Mayaud, 1980); the official a_p values are calculated at the GeoForschungsZentrum Potsdam Adolf-Schmidt-Observatory for Geomagnetism in Germany
- It is translated from the K_p index, which is derived from geomagnetic field measurements made at several locations around the world
- The daily A_p is obtained by averaging the eight 3-hour values of a_p for each day. The U.S. Air Force Weather Agency also calculates an estimated a_p from a different, smaller set of stations than are used in calculating the official a_p values
- The AFWA a_p index values are available through several products issued by NOAA SPWC
- Daily Ap and 3-hour ap indices were used in early orbit analyses and it was determined that the time scales of geomagnetically-induced variability represented by these indices were on the order of a few hours

Ap index


Past 8 months of ap
ap (nT)
400
300
200
100
0
G5
G4
G3 major storm
G2 moderate storm
G1 active
Nov 14 2009
Dec 15 2009
Jan 14 2010
Feb 13 2010
Mar 16 2010
Apr 15 2010
May 16 2010
Jun 15 2010
Jul 15 2010

Dst index

- The Disturbance Storm Time (Dst) index is an indicator of the strength of the storm-time ring current in the inner magnetosphere
- During the main phase of geomagnetic storms, the ring current becomes highly energized and produces a southward-directed magnetic field perturbation at low latitudes on the Earth's surface; this is opposite to the normal northward-directed main field
- The quick-look Dst index is calculated hourly and released through the World Data Center (WDC) in Kyoto, Japan using measurements from four off-equatorial magnetic observatories
- Dst is an 'absolute' index and is reported in units of nT; magnetic observatory data are required for its calculation; magnetic observatories are specially designed and carefully operated facilities that provide stable-baseline magnetometer data over long periods of time; typically, an observatory supports the operation of fluxgate, proton-precession, and declination-inclination (theodolite) magnetometer systems; measurements from the various sensor systems can be combined to produce data that are extremely accurate
- Traditionally, four stations have been used for the Dst calculation: Hermanus (HER), South Africa; Kakioka (KAK), Japan; Honolulu (HON), Hawaii; and San Juan (SJG), Puerto Rico

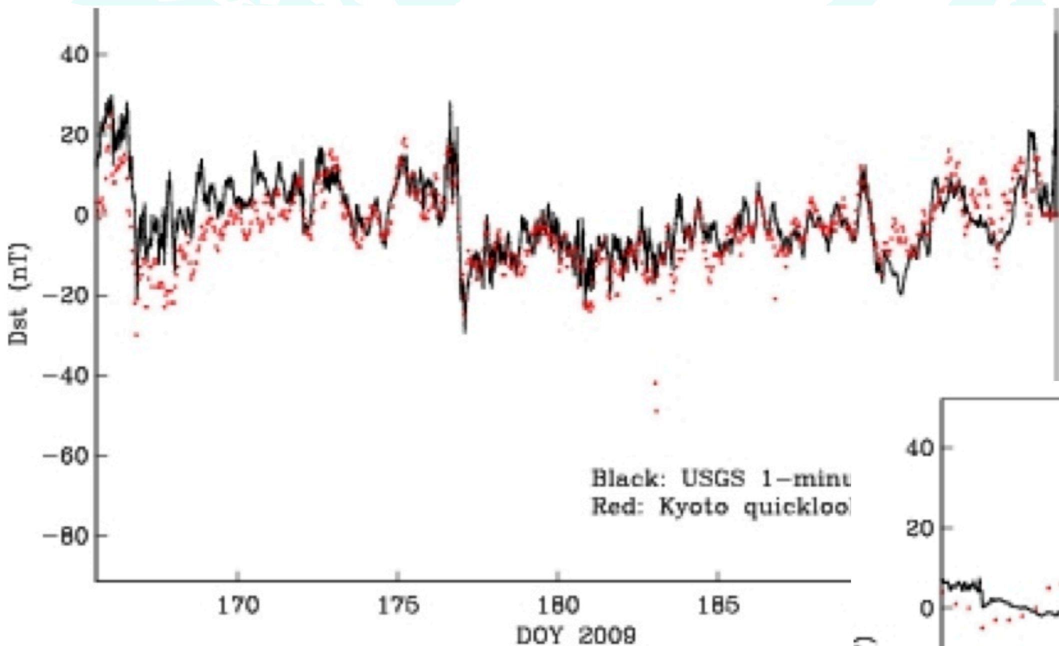
Dst index

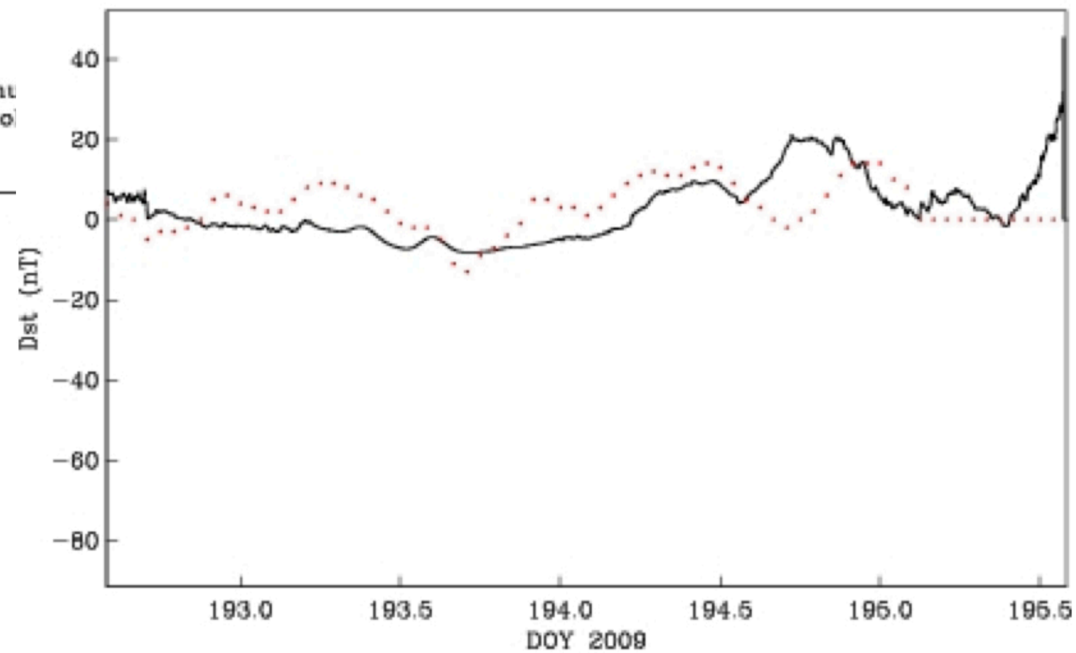
- Most magnetic storms begin with sharp decreases (southward-directed negative values) in Dst, called the storm sudden commencement, in response to increased solar wind pressure. Following a southward turning of the interplanetary magnetic field, Dst decreases as ring current energy increases during the storm's main phase. During the recovery phase the ring current energy decreases and Dst increases until the storm's end when the magnetic field perturbation has ceased

- Use of Dst as an index for the energy deposited in the thermosphere during magnetic storms is more accurate than the use of the a_p index. This is because Dst has higher temporal resolution with an ability to segregate storm phases with their corresponding magnitudes. On the other hand, the 3-hour a_p index is an indicator of general magnetic activity over the Earth and responds primarily to currents flowing in the ionosphere and only secondarily to magnetospheric variations. The a_p index is derived from measurements by observatories at high latitudes that can be blind to energy input during large storms and it can underestimate the effects of storms on the thermosphere

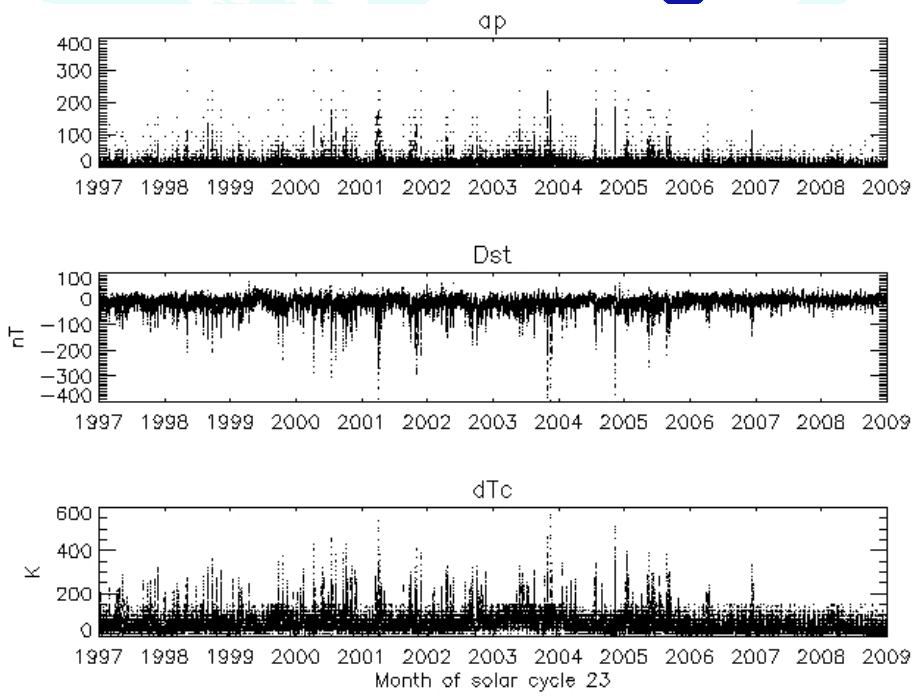
- An algorithm for determining the storm events was developed in JB2008 that locates the temporal start, minimum, recovery slope change, and final end of the storm as reflected in the Dst index

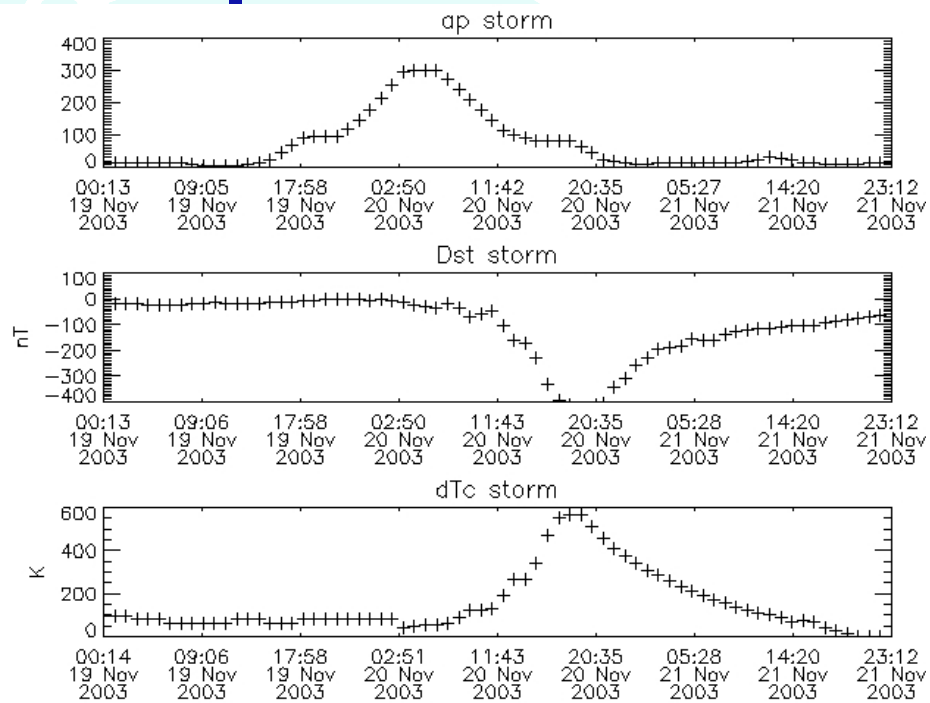
Dst index


Dst (nT)
40
20
0
-20
-40
-60
-80
Black: USGS 1-minu
Red: Kyoto quickloo
170
175
180
185
DOY 2009


Dst (nT)
40
20
0
-20
-40
-60
-80
193.0
193.5
194.0
194.5
195.0
195.5
DOY 2009

Geomagnetic comparisons

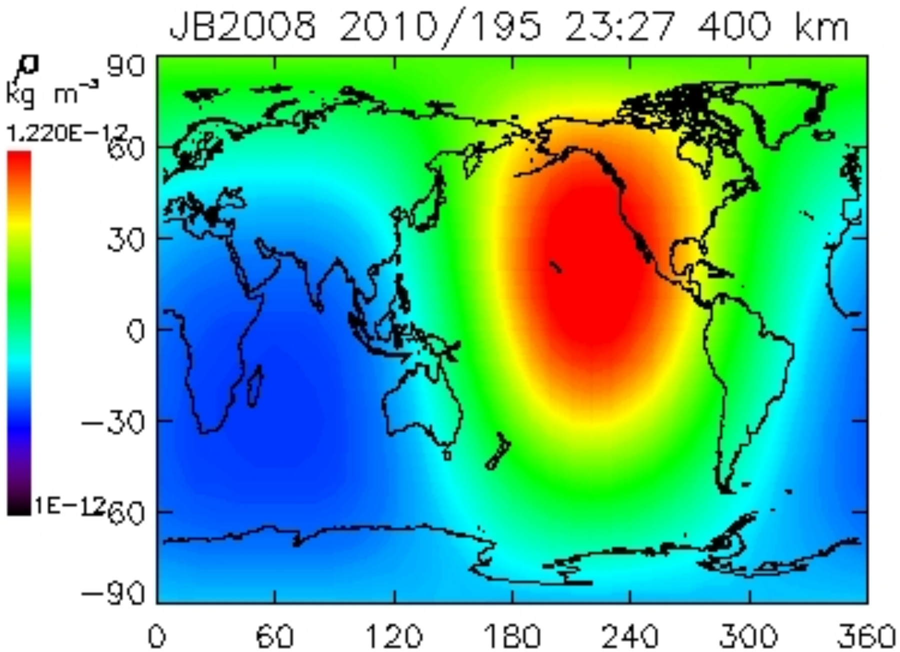


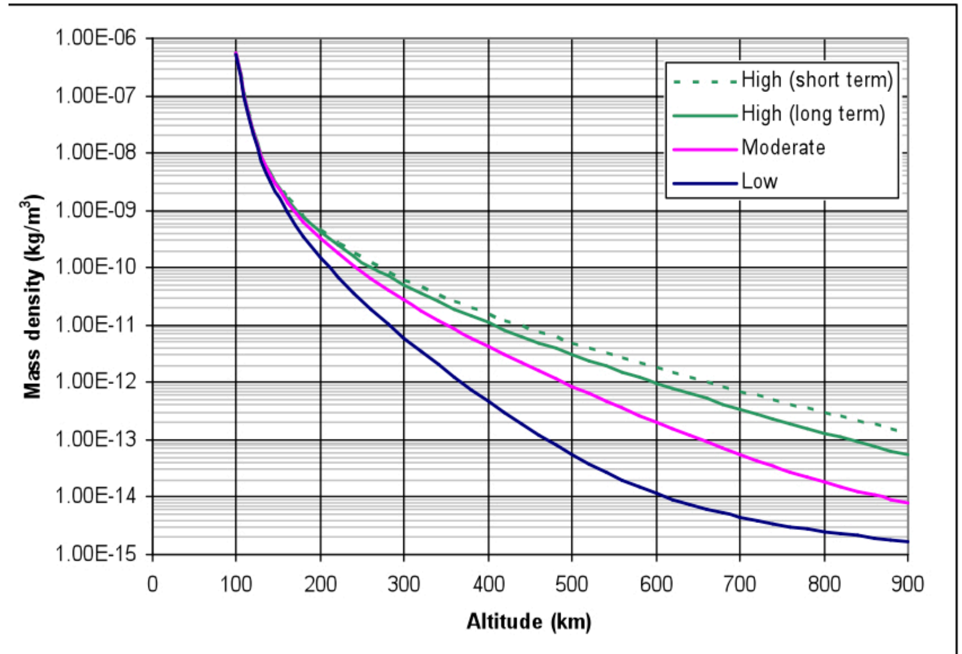


The a_p, Dst, and dTc geomagnetic, ring current, and delta temperature indices for use by the JB2008 model in solar cycle 23

The a_p, Dst, and dTc geomagnetic, ring current, and delta temperature indices for use by the JB2008 model in a storm period between November 19–22, 2003

JB2008 output





JB2008 density at 400 km altitude for low solar and quiet geomagnetic activity on July 14, 2010

JB2008 mean air density with altitude for low, moderate, and high long- and short-term solar and geomagnetic activity