

International Solar Cycle Studies: Sun as a Climate Driver

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International Solar Cycle Study (ISCS)

THE GOAL of this talk is to describe the organization, goals, achievements and results of the former SCOSTEP program: “International Solar Cycle Study” .

As part of this talk, we will discuss the differences between the various indices used in irradiance modeling and we will examine how they match the observed irradiance data over the last three solar cycles.

The most important environmental problems facing humanity today is to understand and predict global change (both natural and man-induced) as well as the rapid changes in our space environment.

CRITICAL ISSUE: What are the relative impacts of natural and anthropogenic influences on changes in the Earth's atmosphere?

PROBLEM: The time period of interest far exceeds the lifespan of any single experiment, thus composite irradiance time series must be compiled from data of several irradiance experiments.

On time scales longer than the almost three decade long irradiance measurements, surrogates for irradiance have to be used to mimic/model the longer term irradiance changes.

QUESTION: How well these indices used for irradiance modeling are reliable for predicting long-term irradiance changes.

ISCS: Origins and Achievements

To investigate and answer these questions, in 1997 the Scientific Committee On Solar TERrestrial Physics (SCOSTEP) adopted the International Solar Cycle Study (ISCS) program in response to the world-wide solar physics community at Upsala, Sweden. The goal of the ISCS program (1998-2002) was to investigate all aspects of the physics of the Sun in the different layers of the solar atmosphere and various time-scales during the rising phase of Solar Cycle 23.

The kick-off meeting was held at Nagoya, Japan in conjunction with the 1998 COSPAR Plenary meeting. The proceedings were published as a special issue of *Advances in Space Research* (M. A. Shea ed.) in 2002. The second meeting was held in June 2001 at Longmont, Colorado, USA. The content of the Longmont presentations were summarized in AGU Monograph 141 entitled "Solar Variability and Its Effect on Climate" (Judith Pap and Peter Fox, eds.).

ISCS: Conclusion

The ISCS final meeting was held in June 2003 at the Astronomical Institute, Slovak Academy of Sciences, Tatranska, Lomnica, Slovak Republic. The proceedings were published as ESA SP-535 entitled "Solar Variability as an Input to the Earth's Environment" (A. Wilson, ed.) in 2003.

After the completion of ISCS, SCOSTEP has initiated a new comprehensive program named Climate And Weather of the Sun-Earth System (CAWSES) in which the study of solar variability and its effect on climate and space weather is included.

Organization of ISCS

The ISCS program was organized into three working groups according to their physics and the layer of the Sun at various time-scales. These three working groups are:

Working Group 1. “Solar Energy Flux Study: From the Interior to the Outer Layers” (Coordinators: Claus Fröhlich and Judit Pap)

WG1 was concerned about measurements of the solar energy flux which included both electromagnetic as a function of wavelength and integrated over the entire solar spectrum as well as particles. Analyzing the measurements, modeling the observed changes, interpreting the results and studying the climate effects of solar variability were the major activities of this working group.

Organization of ISCS

(continued)

Working Group 2. “Solar Magnetic Field Variability Study: From the Lower Atmosphere through the Inner Corona” (Coordinators: Richard Harrison and Don Michels)

WG2 was concerned with the physics of the solar eruptive phenomena which included the initiation and propagation of coronal mass ejections (CMEs) and flares. Specific topics were: (i) CME occurrence rate during the rising portion of Cycle 23; (ii) characteristics of acceleration and propagation of CMEs; (iii) CME and flare relationship; (iv) the low coronal dimming (EUV/X-ray) under CME events; (v) the relationship between the coronal Moreton waves and CMEs; and (vi) source region of CMEs.

Organization of ISCS

(continued)

Working Group 3. “Solar Emissions: Origins and Transport through the Heliosphere” (Coordinators: George Simnett and David Webb)

WG3 was focused on their studies in five general research topics: (i) origin of solar activity including CMEs, flares and erupting filaments, especially regarding the evolution of solar magnetic fields; (ii) the origin of the solar wind and the propagation of disturbances through it, which included in-situ measurements of magnetic clouds and the plasma and field structures; (iii) studies of the modulation of galactic cosmic ray, of the acceleration and propagation of SEPs, and of interplanetary shock waves; (iv) space weather studies, including the forecasting of geoeffective solar and interplanetary disturbances; and (v) studies involving interplanetary scintillations (IPS) observations.

ISCS HIGHLIGHTS AND ACHIEVEMENTS

1. CME Occurrence Rate during the Rising Cycle 23 (by N. Gopalswamy)

A study given by Gopalswamy *et al.* (2003) on the solar cycle variation properties of CMEs such as daily CME rate, mean and median speeds, and the latitude of solar sources for Cycle 23 (1996-2002) shows the following:

1. There is an order of magnitude increase in CME rate from the solar minimum (0.5/day) to maximum (6/day)
2. The maximum rate is significantly higher than previous estimates
3. The mean and median speeds of CMEs also increase from minimum to maximum by a factor of 2

ISCS HIGHLIGHTS AND ACHIEVEMENTS – continued

1. CME Occurrence Rate during the Rising Cycle 23 (by N. Gopalswamy)

4. The number of metric Type II bursts (summed over CR) track CME rate, but CME speeds seem to be only of secondary importance
5. For Type II bursts originating farther from the Sun, the CME speed is important
6. The latitude distribution of CMEs separate the prominence-associated (high-latitude) and active-region associated CMEs
7. The rate of high-latitude CMEs show north-south asymmetry and cessation eruption in the north and south roughly mark the polarity reversals

ISCS HIGHLIGHTS AND ACHIEVEMENTS – continued

Solar Cycle Variations of Magnetic Clouds and CMEs (by C. C. Wu, R. P. Lepping and N. Gopalswamy)

Utilization of magnetic clouds observed by Wind during November 1994 - May 2002. The average occurrence rate is 9 magnetic clouds per year for the overall period (68 events/7.6 years). It is found that some of the frequency of occurrence anomalies were during the early part of Cycle 23:

1. Only 4 magnetic clouds were observed in 1999, and
2. An unusually large number of magnetic clouds (16 events) were observed in 1997 in which the Sun was beginning the rising of Cycle 23

ISCS HIGHLIGHTS AND ACHIEVEMENTS – continued

Solar Cycle Variations of Magnetic Clouds and CMEs (by C. C. Wu, R. P. Lepping and N. Gopalswamy)

During the period 1996 - 2001, the results show:

1. The occurrence frequency of magnetic clouds appears to be related neither to the occurrence of CME as observed by SOHO/LASCO nor to solar activity cycle
2. The intensity of geomagnetic storms related to magnetic cloud is affected by both solar activity and the occurrence frequency of CMEs and
3. about 91% of magnetic clouds induced geomagnetic storms

ISCS HIGHLIGHTS AND ACHIEVEMENTS – continued

3. Solar Energetic Particle Variation by D. Lario and G. Simnett (2004)

The population of energetic particles in the heliosphere is modulated by the solar activity. At the solar minimum, the main sources of the energetic particles observed at 1 AU are:

1. The interstellar medium in the form of galactic cosmic rays observed at energies above 200 MeV for protons and above 3 MeV for electrons
2. The termination shock in the form of anomalous cosmic rays
3. The corotating interaction regions which accelerate electrons up to around 300 keV and ions up to a few MeV/nucleon; and
4. the Jovian magnetosphere that generates electrons observed at 1AU during quiet times in the range from a few hundreds keV to a few MeV.

ISCS HIGHLIGHTS AND ACHIEVEMENTS – continued

Solar Energetic Particle Variation

At the solar maximum, the Sun becomes the dominant source of energetic particles. These particles fill the heliosphere even up to the highest latitudes. The processes under which solar particles are accelerated and released into the helio spheric medium are related to flares and shocks.

The contribution of these processes in the production of large solar energetic events is still under debate. Measurements of the charge states of heavy ions in SEP events give important information on the source population and acceleration processes. Coronal shocks may accelerate near-relativistic electronic provided a suitable seed population is present.

ISCS HIGHLIGHTS AND ACHIEVEMENTS – continued

Solar Energetic Particle Variation

CMEs play an important role in accelerating the bulk of non-relativistic ions seen around 1 AU and such acceleration takes place as a CME-driven shock propagates both through the corona and then out into the interplanetary medium. Electron and ion acceleration is usually most effective at a few solar radii from the Sun, but interplanetary acceleration plays an important role in large gradual events.

ISCS HIGHLIGHTS AND ACHIEVEMENTS – continued

Solar Irradiance Variations – Measurements and Composites (by Judit Pap and Linton Floyd)

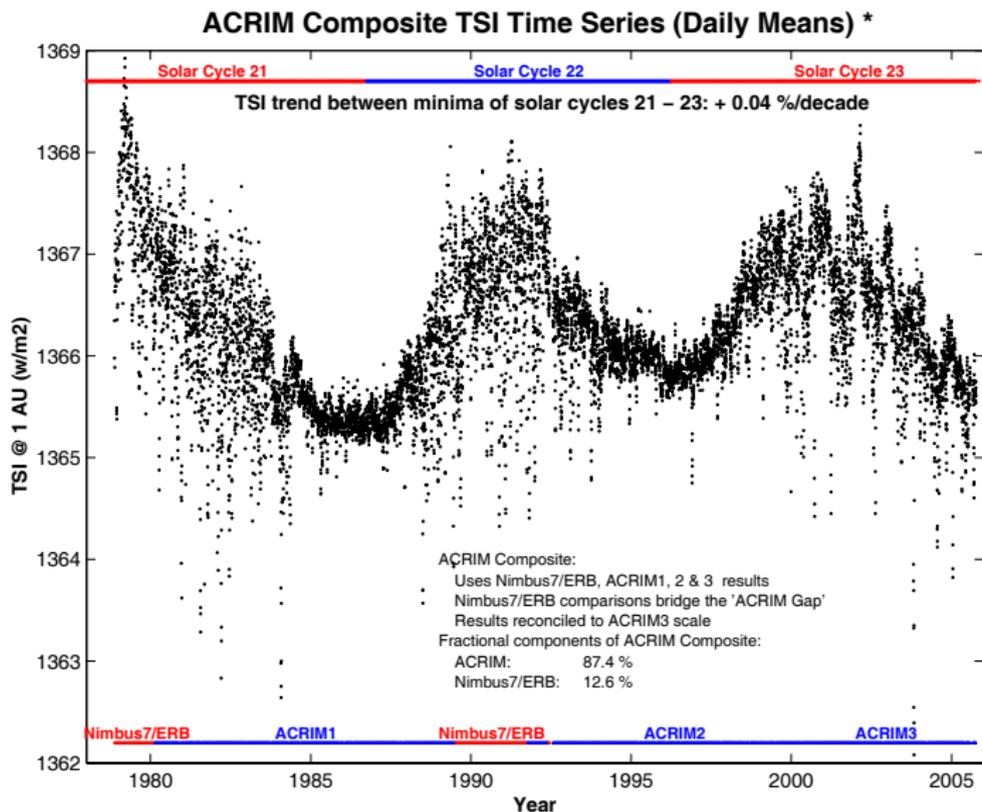
Space observations of total irradiance started in late 1978, from various platforms.

To study the long-term variations and possible climate effect of irradiance variations, two composites have been compiled:

- ▶ ACRIM
- ▶ PMOD (version d41-61-0510)

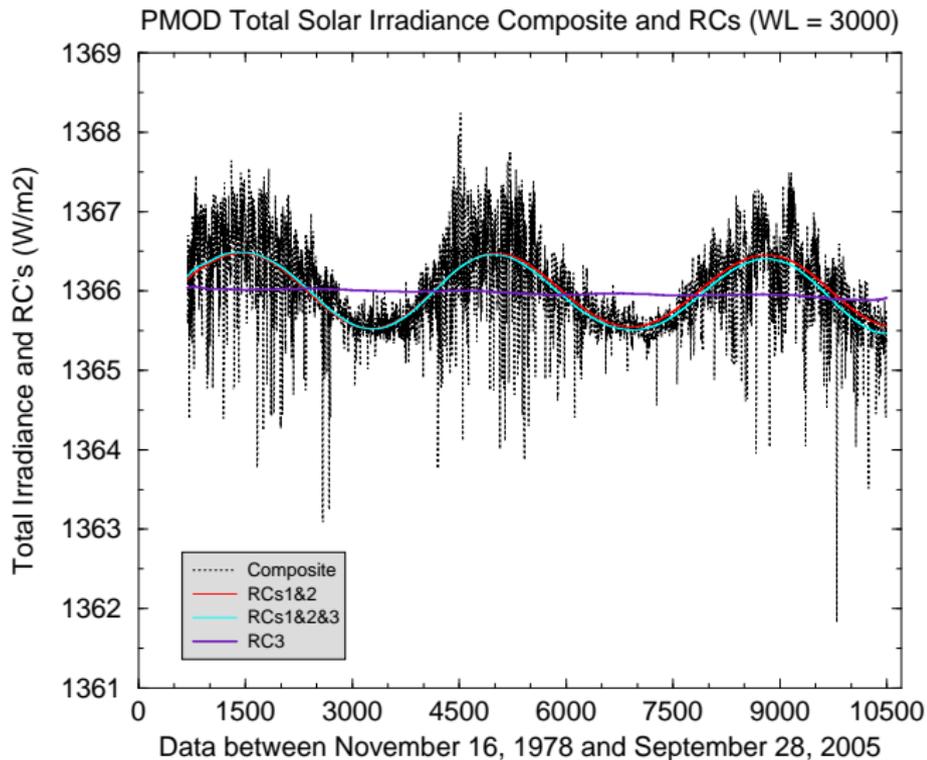
TOTAL SOLAR IRRADIANCE (TSI) – continued

PMOD Composite Time Series



TOTAL SOLAR IRRADIANCE (TSI) – continued

PMOD Composite Time Series



Both composites show the apparent solar-cycle-related variation. The difference between the two composites is that the PMOD composite shows a rather symmetrical variation over the last three cycles - with about the same maximum and minimum activity levels. In contrast, the ACRIM composite shows a secular trend having a higher minimum during cycle 22 than during cycle 21.

However, the similarity of the two composites is that both show a high maximum during the weak cycle 23. Further, both composites show that TSI has reached its minimum level relative to the former cycles during the declining portion of cycle 23, when almost all other solar indices do not yet reached solar minimum level.

A unique feature of cycle 23, is the occurrence of high activity periods when many large sunspots erupted during the declining phase of the cycle. The occurrence of large sunspots during this time lowers the TSI minimum level to the level of the last cycle.

EXAMINED SOLAR ACTIVITY INDICES

The Mg II h & k core-to wing ratio derived from the vicinity of 280 nm (as derived at NOAA/SEC, Rodney Viereck). This index is considered as a good proxy for faculae

The He-line equivalent width at 1083 nm (EWHe). Although observations at this line were developed to study coronal holes, EWHe has been found to correlate well with indices for faculae and plages

Ca II K-line observations are available from several observatories, providing a good indicator for chromospheric activity

EXAMINED SOLAR ACTIVITY INDICES – continued

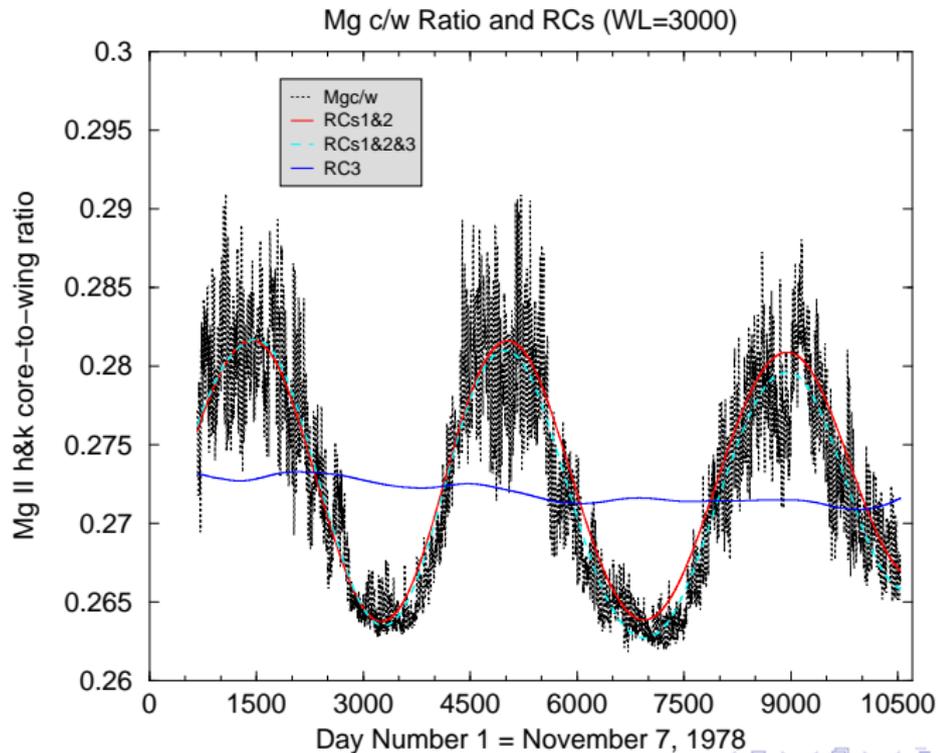
Full disk magnetic field strength data from the National Solar Observatory at Kitt Peak

The 10.7 cm radio data which are available since 1947 and considerable effort has been devoted to extend irradiance models using this index

The sunspot number (SSN), which is the longest solar time series available for solar modeling (other than the cosmogenic isotopes)

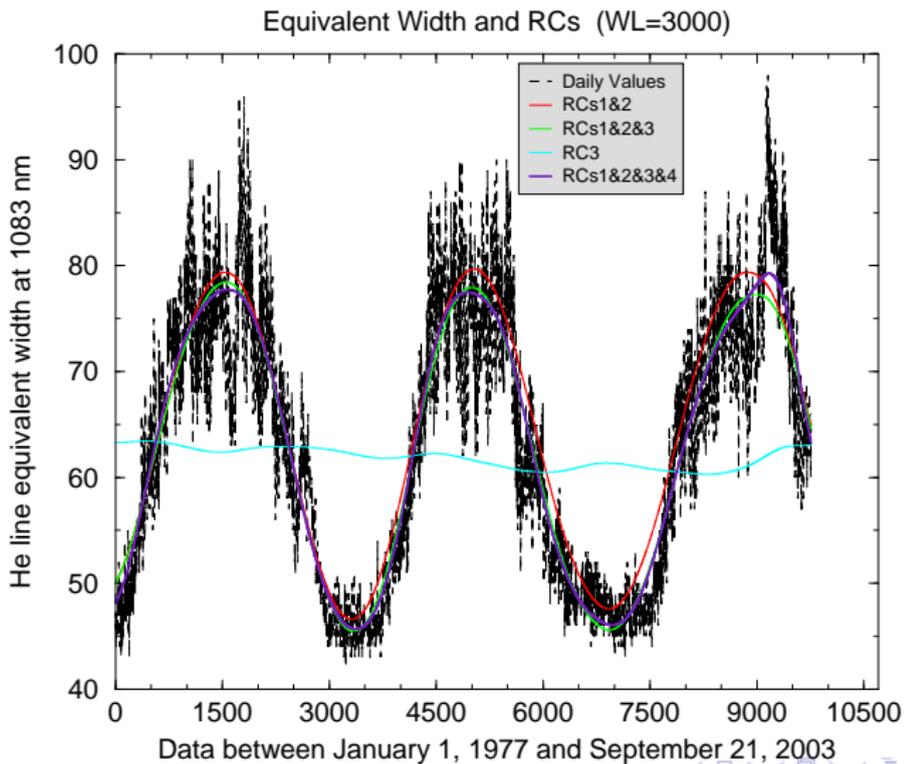
VARIATIONS IN THE CHROMOSPHERIC INDICES

Mg II Core-to-Wing Ratio (Mg c/w)



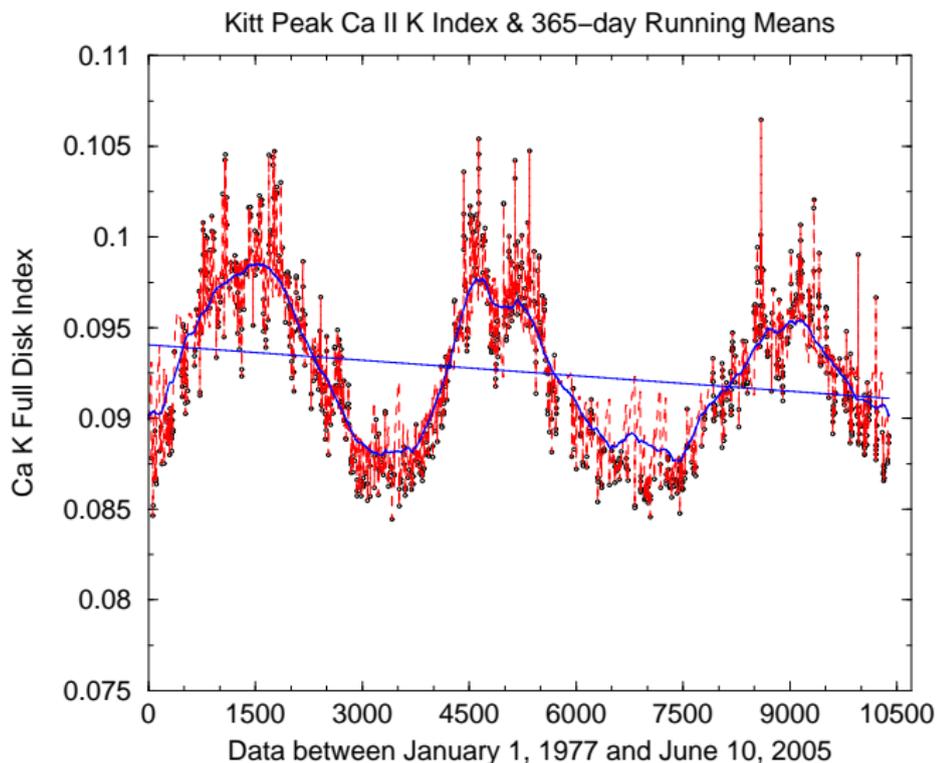
VARIATIONS IN THE cHROMOSPHERIC INDICES – continued

He-1083 nm Equivalent Width (EWHe)



VARIATIONS IN THE CHROMOSPHERIC INDICES – Continued

Ca K line



VARIATIONS IN THE CHROMOSPHERIC INDICES – Continued

Analyses based on the Mg c/w ratio, EWHe and the CaK index have led to the conclusion that the long term variations in total irradiance are mostly related to the bright surface magnetic activity features, such as faculae and the network.

However, significant differences exist between these indices. For example, the maximum level of EWHe is much higher at the maximum of cycle 23 than the maximum level of the Mg c/w ratio.

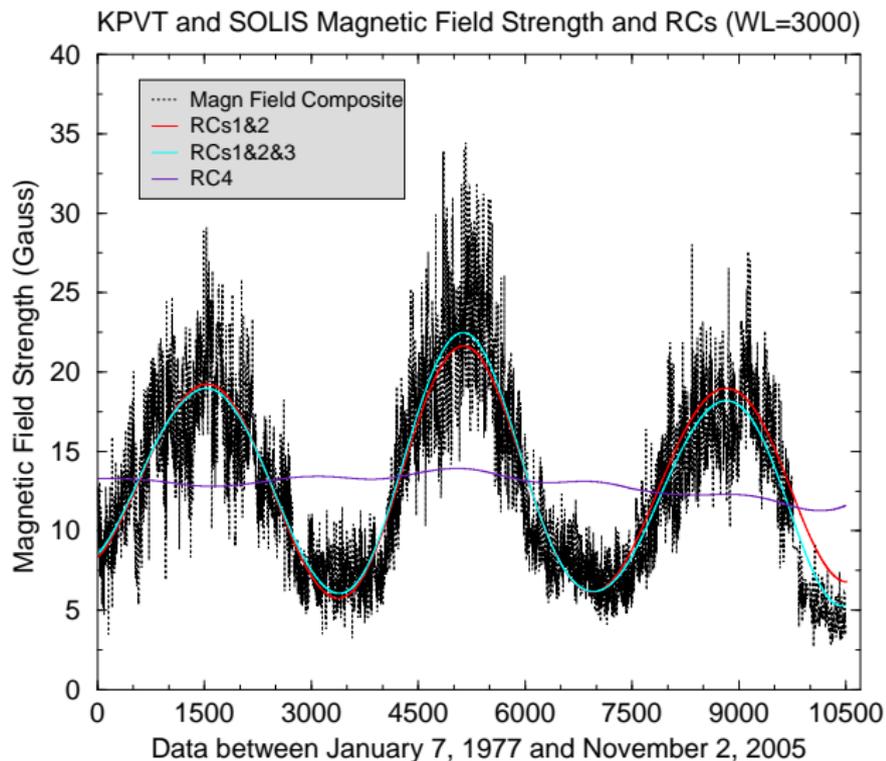
The CaK line shows a lower maximum, but by June 2005 it almost reached the same level as at the time of the last minimum.

SOLAR MAGNETIC INDICES

Since 1975 full disk magnetograms are taken to produce two numbers for each one: the average field strength (sum of all the individual measurements divided by the number of measurements) and the average absolute field strength (same but take absolute value of the measurements first). Major changes occurred in 1992 and 2003 when the instruments changed. Minor changes occurred at other times when software changed.

The KPVT observations were carried out in the 868.8 nm starting in 1977. For day numbers between 8146 and 8357, a different spectrum line (550.7 nm) has been used. After day number 8357 (11 30 03), the new SPMG was in use with the 868.8 nm line.

SOLAR MAGNETIC INDICES – continued



SOLAR MAGNETIC INDICES – continued

As estimated, the magnetic field values are all on the same scale (this is probably correct to of order 10%).

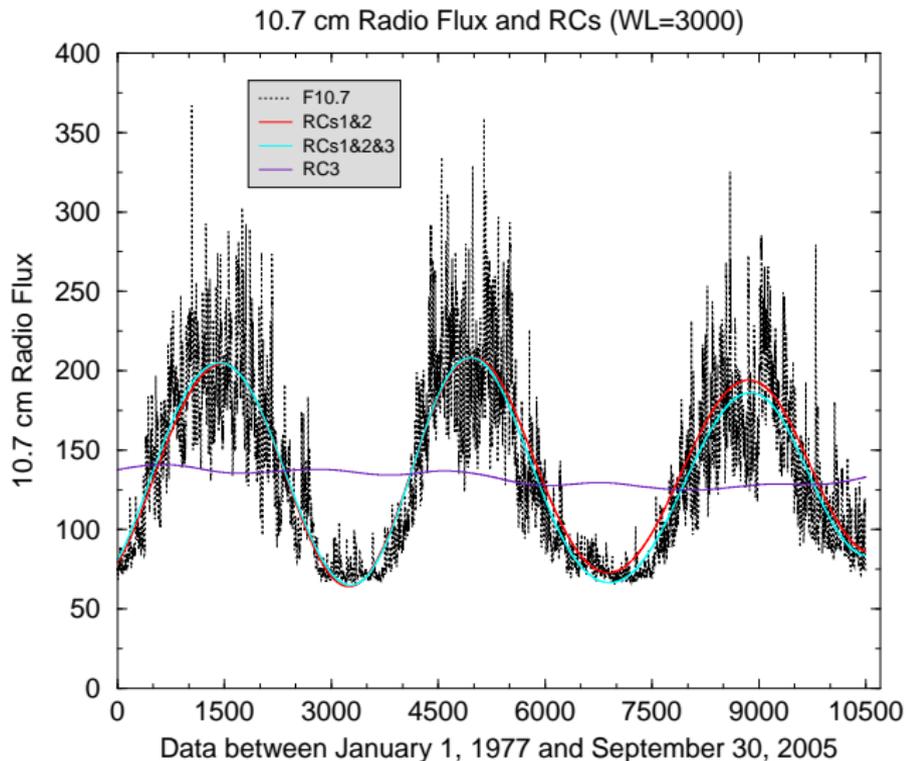
As we saw, the maximum of cycle 23 was far lower than the last cycle – despite the fact that solar irradiance was almost as high as during the last strong cycles.

By mid-2005, the KPVT data were close to minimum condition, and the SOLIS data indicate that we are already close to solar minimum conditions.

However, in the case of the absolute values of the measured field can be at error due to various effects (error in the zero point level, image resolution, instrumental noise, J. Harvey, private communication). Thus, further studies are required to confirm whether the low level of the absolute magnetic field strength during the declining portion of cycle 23 is entirely (or to what extent) due to the Sun.

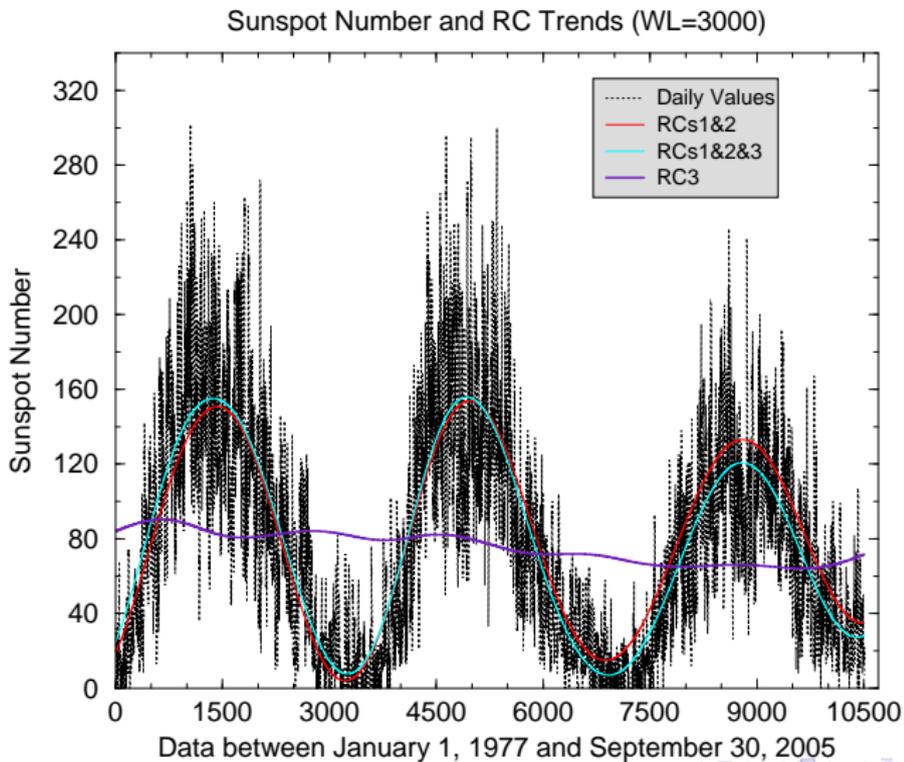
LONG TERM SOLAR ACTIVITY INDICES

F10.7 Time Series



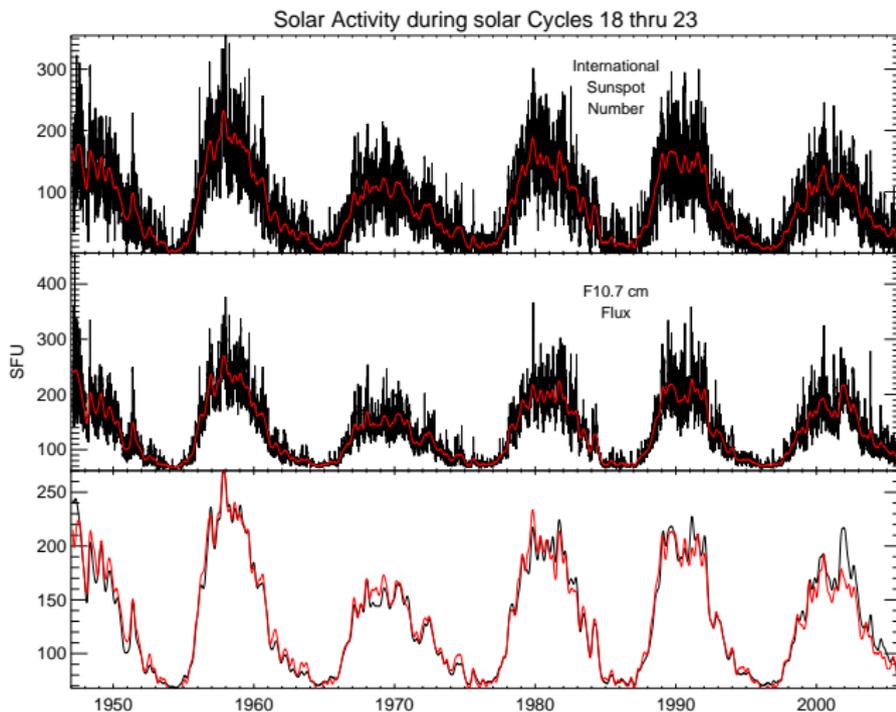
LONG TERM SOLAR ACTIVITY INDICES – continued

Sunspot Number Time Series



LONG TERM SOLAR ACTIVITY INDICES – continued

Sunspot Number (ISSN) and $F_{10.7}$ Flux

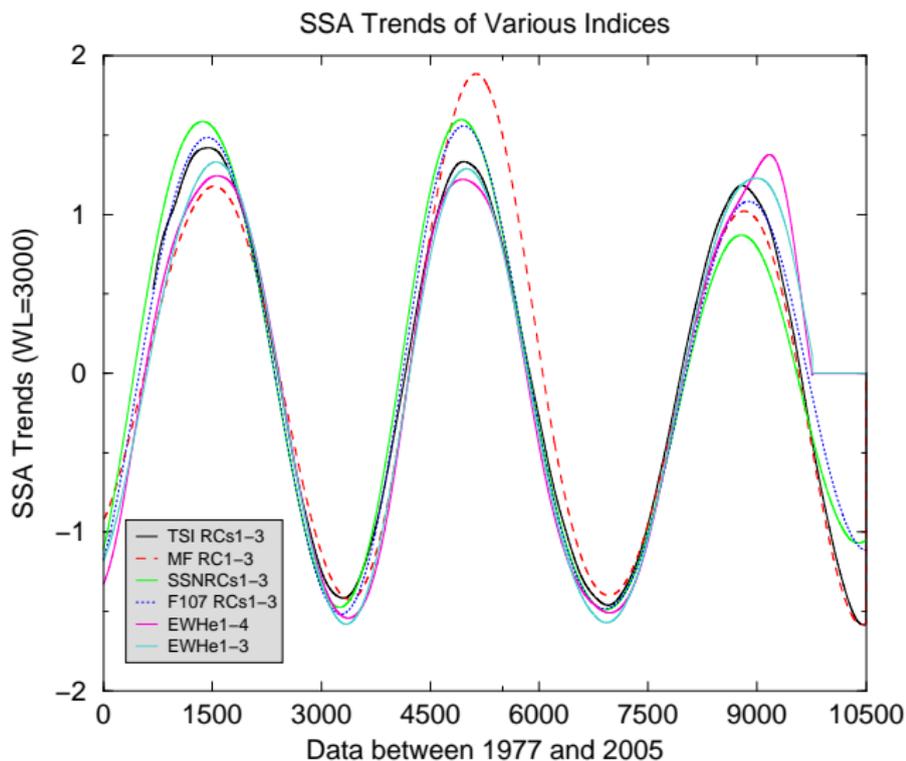


LONG TERM SOLAR ACTIVITY INDICES – continued

The overall shape of the two indices is similar, although the maximum amplitude of F10.7 is much higher at cycle 23 relative to the previous cycles than that of SSN.

As the long-term trend components show, while SSN does not yet show solar minimum, F10.7 - similar to TSI indicate that we are close to minimum.

LONG-TERM RECONSTRUCTED COMPONENTS OF VARIOUS INDICES



CLIMATE IMPLICATIONS OF SOLAR VARIABILITY

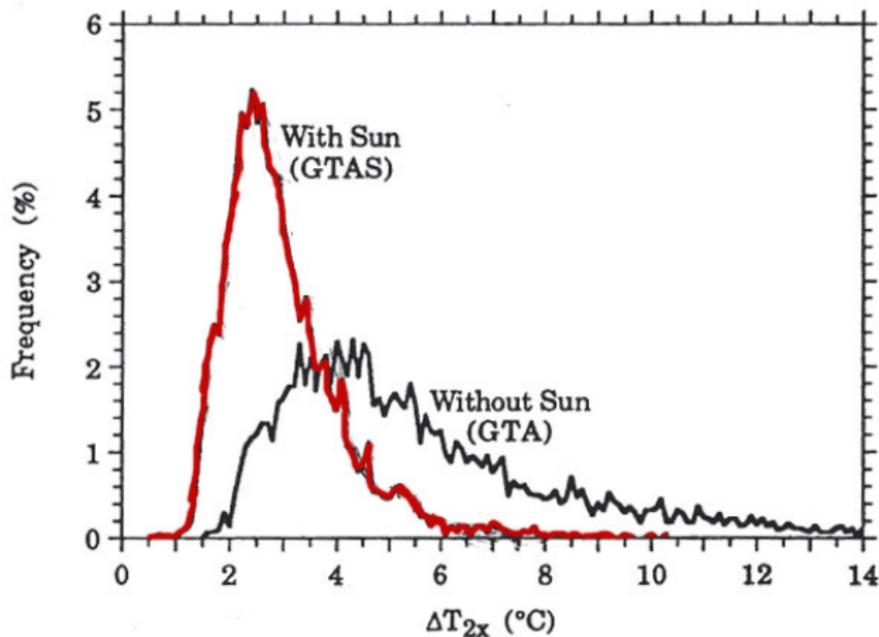
The role of solar variability in climate change has been debated for a long time. Now, the new results from various space experiments monitoring the radiative and particle emission from the Sun have opened a new era in solar-terrestrial physics.

The shown high-resolution spatial and temporal observations conducted from space and the ground demonstrate that the surface of the Sun and its outer atmosphere are highly variable on almost all time scales – and the variable solar output may affect the climate in many fundamental ways.

As shown, climate models predict a 4 to 5 degree increase in the Earth temperature without taking into account the Sun's influence. In contrast, taking into account the solar influence, the anticipated temperature increase will be smaller but will occur with a much higher probability.

CLIMATE IMPLICATIONS OF SOLAR VARIABILITY – continued

Frequency Distribution for ΔT_{2x}



Conclusions

There is a phase shift between total irradiance and the absolute value of the averaged magnetic field strength at the beginning of both solar cycles 22 and 23, total irradiance leading the magnetic field values.

While the sunspot number and magnetic field strength show that the maximum of solar cycle 23 is lower than the maxima of the two previous cycles, the maximum level of total irradiance, the Mg II h & k core-to-wing ratio, He 1083, and $F_{10.7}$ flux is higher during solar cycle 23 than the maximum of the magnetic indices.

Further discrepancies can be found between the level of total irradiance and various activity indices during the declining phase of cycle 23.

Conclusions – Continued

These results highlight that during solar cycle 23 the examined solar activity indices, which describe magnetic features, cannot properly account for solar variability, as measured by solar irradiance; thus these indices used in long-term irradiance models may not account for the longer term changes.

Improvements in long-term solar irradiance models will require long-term and better quality measurements, improvement of radiometry as well as improvement of irradiance models using high resolution images (HMI, PICARD) to better account for the weak field component which is excluded from the current empirical models.

Most importantly we need to understand the physics of all surrogates and thus the origin of irradiance variations to better predict their effect on past and future climate changes as well as solar effects on the Earth's space environment.