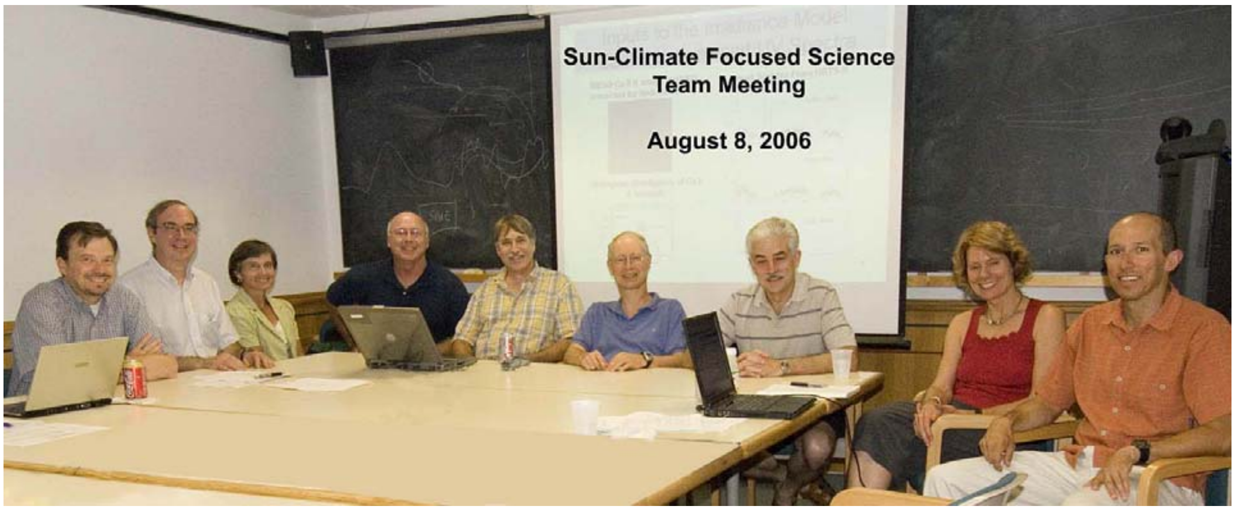
Sun-Climate Focused Science Team

Sensitivity of Regional and Global Climate to Solar Forcing

Summary of Accomplishments – Year 2
July, 2006 - July, 2007

Submitted 9 August 2007



Sun-Climate Focused Science Team Meeting at the National Center for Atmospheric Research, August 8, 2006. From left to right: Don McMullin, Linton Floyd, Cora Randall, Terrence Nathan, Jeff Morrill, Charles Jackman, Rolando Garcia, Judith Lean, Eugene Cordero.

TEAM MEMBERSHIP

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SUMMARY

The Sun-Climate Focused Science Team's (FST's) activities and accomplishments for year-2 (2006-2007) and the plans for the third and final year are described in the main body of this document. The highlights are:

- A Sun-Climate FST web site was developed in order to share the team's news, publications and newly developed resources with the broader climate community.
  Link: http://sun-climate.lawr.ucdavis.edu
- Team members T. Nathan, E. Cordero L. Hood, and C. Jackman will co-convene a special session of the Fall 2007 AGU Meeting titled, "*Solar variability effects on Terrestrial Climate*." This session will provide a forum for the team to share and highlight its findings with the climate community.
- A pathway for communicating and amplifying the solar-modulated ozone signal has been identified and examined using a newly derived ozone-modified refractive index for planetary waves.
- Acquisition and analyses of high resolution SUSIM spectra (0.15 nm) have produced an estimate of a pure quiet sun irradiance spectrum at 0.15 nm resolution and an estimate of the wavelength dependent correlation between spectral irradiance and total solar activity visible on the disk in the ~200-400 nm range.
- Analysis of three independent satellite data sets has supported previous conclusions that the observed stratospheric ozone response to the solar cycle differs in vertical structure from that simulated by most models, especially in the tropics. Experiments using a two-dimensional model have shown that part of this unexpected structure could be caused by a solar cycle modulation of the QBO combined with decadal changes in tropical upwelling rates.
- Solar proton events (SPEs) have been incorporated into the NCAR Whole Atmosphere Community Climate Model (WACCM). The model simulations show that the SPEs produce an increase in stratospheric NO_x that is in agreement with measurements obtained by the Halogen Occultation Experiment (HALOE).
- Sun-Climate FST meetings were held at the Fall 2006 AGU Meeting in San Francisco and in August 2006 at NCAR.
- A dedicated Sun-Climate FST meeting is planned for 14 September 2007 at NCAR. The meeting will focus on the current status of the team and the progress it's making in meeting the "deliverables" mapped out in the FST's original three-year plan.

During the next year the Sun-Climate FST anticipates bringing to fruition the vast majority of its most important tasks, including:

- A more complete characterization of the long-term - solar cycle (SC) and perhaps beyond - behavior of the solar UV spectral irradiance and the effects of SPE-induced changes on the circulation of the middle atmosphere.
- An assessment of how SC-modulated wave-ozone interactions affect wave transience and wave dissipation, processes that are vital to driving the zonal-mean circulation.
- A better understanding of the pathways that operate to amplify the SC signal and communicate it throughout the climate system.
- A more complete assessment of how the 11-year SC affects Earth's atmosphere, from the troposphere to the lower thermosphere.

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I. EVOLUTION OF THE FOCUSED SCIENCE TEAM (FST): YEAR-2

Genesis. During 2004 the Living with a Star (LWS) Targeted Research and Technology Program at NASA issued a call for proposals to address problems related to the effects of solar variability on terrestrial climate change. In response to that call NASA-LWS chose a select number of proposals to fund. The principle investigators on those proposals were then combined into a Sun-Climate Focused Science Team (FST). The original Sun-Climate FST was established in August 2005, with funding for most team members beginning Fall 2005. The original FST consisted of six members: Terry Nathan (team leader), Eugene Cordero, Linton Floyd, Rolando Garcia, Charlie Jackman, and Jeff Morrill. After the first team meeting in San Francisco in December 2005 and prior to the second team meeting at NCAR in August 2006, it became clear that other NASA-LWS funded investigators shared similar interests and goals as the team. Therefore, in early 2006, the team expanded to include several additional scientists whose expertise adds to the team's ability to meet the scientific challenges surrounding the effects of solar variability on terrestrial climate change. The additional team members are: Lon Hood, Judith Lean, John McCormack, and Cora Randall, David Rind (see cover page).

Current status. Several team members have coalesced to form sub-groups whose collaborative efforts are producing results that are central to the team's overall goals. The results from these collaborative efforts are described in Section III below.

Expectations. During the third and final year of the team effort we expect that the various sub-groups of the team will merge to form a more complete picture of the sun-climate connection. At the conclusion of the team effort in 2008, the anticipated state of the FST is one in which new directions for research have been identified and new observational data and modeling tools developed for evaluating the relative importance of variable solar forcing versus anthropogenic forcing on climate. These broad measures of success will aid the scientific community's efforts to improve its assessment and prediction of the global atmospheric response to perturbations in Earth's climate system.

II. RESEARCH PLAN - OVERVIEW

There are several **scientific challenges** surrounding the effects of the 11-year solar cycle (SC) on climate. Among these challenges are identifying pathways by which a small decadal change in solar irradiance (<0.1%) can be amplified beyond what current models imply to produce a significant response in the climate system, and distinguishing the SC signal from other climate signals that arise from human activities (e.g., enhanced greenhouse gases) and natural causes (e.g., volcanic activity). Adding to the challenges is the fact that these climate forcing mechanisms are subtle, nonlinearly interacting, and modulated by internal atmospheric variability. Moreover, drawing definitive conclusions from a paucity of SC data - only about four SCs of meteorological data are currently available for statistical analysis – poses additional challenges. Nevertheless, the record of observations and output from long-term model simulations continue to grow and support a connection between the SC and several atmospheric circulation features (e.g. Labitzke et al. 2002 and references therein).

The Sun-Climate Focused Science Team (FST) and its broad-based expertise will meet the above challenges by a combination of basic research, numerical modeling and observational validation. This work flow will allow us to address our main **objective**, which is to provide improved understanding of sun-climate feedback mechanisms and to provide more accurate climate simulations involving the SC.

The FST's **conceptual framework** for addressing the team's objective is shown schematically in Fig. 1. The framework hinges on examining how changes in SC irradiance and solar proton events (SPEs) alter the communication at and between "phenomenological interfaces." These interfaces include: (a) solar irradiance-middle atmosphere chemistry; (b) middle atmosphere chemistry-atmospheric dynamics; (c) QBO-planetary waves; (d) tropical upwelling-planetary waves; (e) mesosphere-lower thermosphere; (f) and troposphere-stratosphere.

A unique aspect of the FST's research plan is its holistic approach to synthesizing these various phenomenological interfaces. In most previous sun-climate research studies these interfaces have been considered in isolation and aligned along four broad avenues. The first avenue is based on observational data that suggests a portion of the SC signal is communicated globally via the modulation of the equatorial QBO (e.g., Labitzke et al., 2004). The second avenue is based on observational data that shows a strong connection between variations in solar irradiance and stratospheric ozone (e.g., Hood, 2004). The third avenue is based on global modeling that suggests stratospheric ozone feedbacks can amplify the effects of the SC, leading to changes in the index of refraction of planetary waves and thus in the global circulation (e.g., Shindell et al, 1999). And the fourth avenue is based on modeling studies that show that wave-induced ozone heating can have an important effect on large-scale wave motions (e.g., Cordero and Nathan, 2005). The FST research plan will merge these avenues by reconstructing the most up-to-date record of solar UV changes over the past 100-years and use this record in a suite of models, ranging from mechanistic tropical and extratropical models to NCAR's Whole Atmosphere Community Climate Model, version 3 (WACCM3).

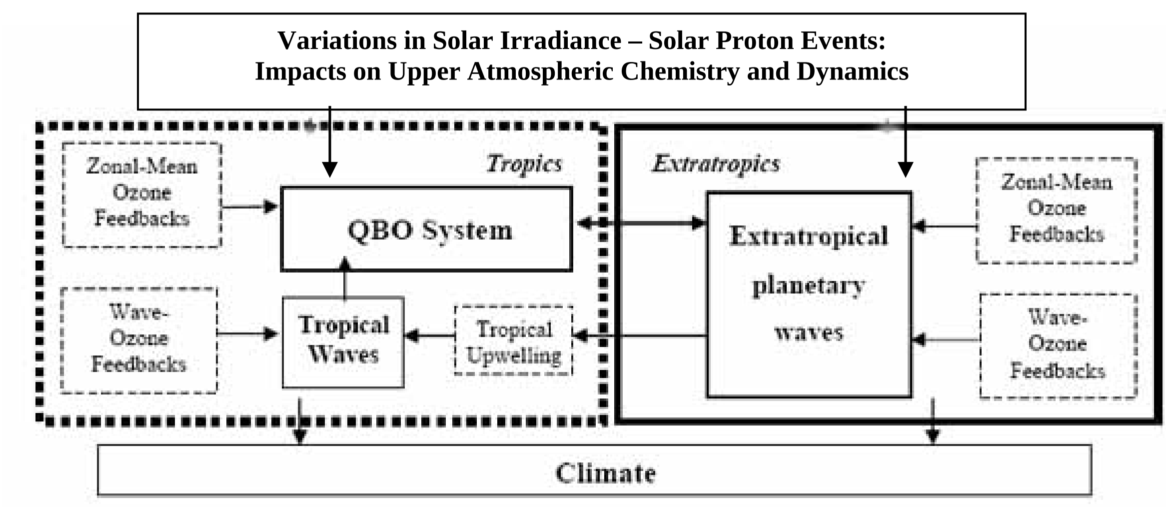


Figure 1. Schematic of the sun-climate system that is being examined by the FST.

III. COLLABORATIONS

This section summarizes the *current and projected* collaborations among FST members.

T. Nathan, E. Cordero, R. Garcia, J. McCormack. One of the challenges in sun-climate research is identifying a pathway (or pathways) where relatively small variations in solar spectral irradiance can be amplified and communicated throughout the climate system. In this collaborative effort we have identified one such pathway. The pathway hinges on wave-induced ozone heating, wherein wave-like perturbations in the wind and temperature fields produce wave-like perturbations in the ozone field. The phasing and structure of these three wave fields, which are coupled to each other as well as to the background distributions of wind, temperature and ozone, directly affect wave transience and wave dissipation, processes vital to the driving of the zonal-mean circulation. Thus any perturbation to the wave-induced ozone heating, solar cycle induced or otherwise, will be imparted to the zonal-mean field. Indeed, as our numerical and analytical results have shown (e.g., Nathan and Cordero, 2007), solar cycle induced changes in the zonal-mean ozone field can affect the wave-induced ozone heating, which in turn affects the zonal-mean wind and residual circulation. The pathway associated with wave-induced ozone heating is shown schematically in Fig. 2.

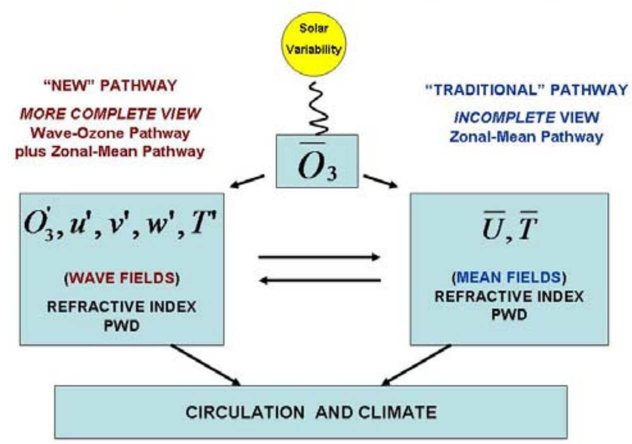


Figure 2. A more complete pathway for communicating changes in solar spectral irradiance to the atmospheric circulation. This more complete pathway includes the effects of wave-induced ozone heating.

The role of the Nathan-Cordero mechanism in communicating solar cycle modulated changes in stratospheric ozone to the troposphere is currently being investigated using an analysis of the residual circulation, which serves as a proxy for the Brewer-Dobson circulation. In the *time-mean*, the residual circulation can exert "downward control," whereby the body force exerted by the planetary wave drag (PWD) causes a mean meridional circulation and a simultaneous mass adjustment that is reflected in the surface pressure (Haynes et al., 1991). Using a mechanistic model of the extratropical atmosphere, an explicit expression that relates the PWD to the solar-modulated stratospheric ozone shows that in the absence of a stratospheric reflecting surface, changes in the residual vertical velocity due to wave-induced ozone heating are local; this is due to the one-dimensional model framework which confines the waves to propagate solely in the vertical. In the presence of a stratospheric reflecting surface, solar-modulated changes in stratospheric ozone can produce a signal in the troposphere. During the next year the Nathan-Cordero mechanism will be investigated further using more sophisticated global models [e.g., CHEM2D model (J. McCormack) and NCAR Whole Earth Community Climate Model (WACCM; R. Garcia)].

C. Randall, C. Jackman, R. Garcia, L. Hood. This collaborative effort has focused in part on incorporating solar proton events (SPEs) into the NCAR WACCM. The model simulations show that the SPEs produce an increase in stratospheric NO_x that is in agreement with measurements obtained by the Halogen Occultation Experiment (HALOE). For example, as shown in Fig. 3, there is generally good agreement between the HALOE NO_x profiles (1991-2000) inside the late winter/spring southern hemisphere vortex and the NO_x profiles simulated by a version of WACCM that includes SPEs. The generally good agreement between the HALOE 2000 and WACCM profiles of NO_x confirms a hypothesis put forth by Randall et al. (2001), who had speculated that the large excess NO_x in 2000 was the result of the strong SPE on 14 July 2000. The results of this collaboration are reported in a paper titled, "Short- and Medium-term Atmospheric Effects of Very Large Solar Proton Events," by C. H. Jackman et al., which was submitted in June 2007 to *Atmospheric Chemistry and Physics Discussions*.

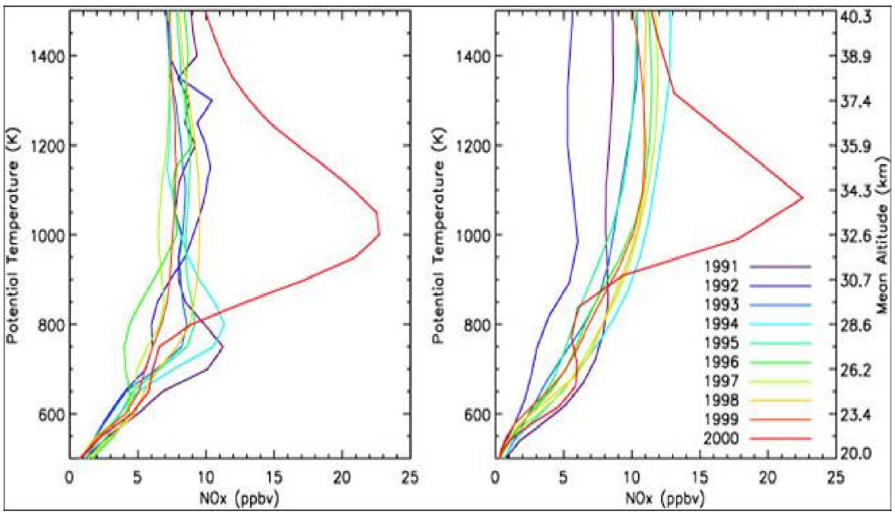
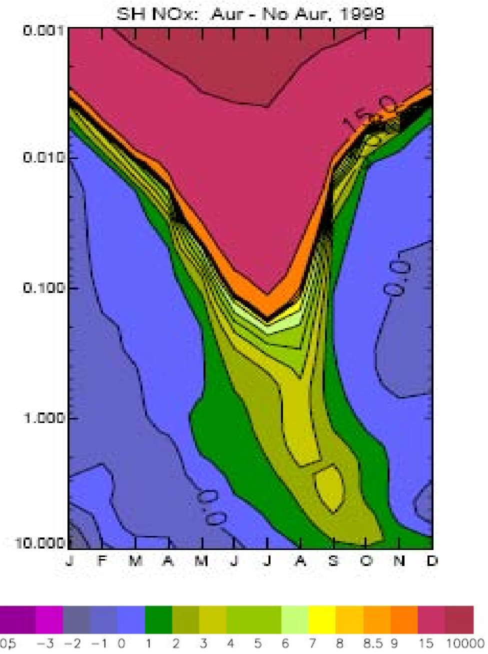


Figure 3. Comparison of HALOE NO_x (left panel) inside the late winter/spring southern hemisphere vortex and the NO_x profiles simulated by a version of WACCM (right panel) that includes SPEs. The HALOE profiles are for the period 1991-2000.

The WACCM model has also been augmented to include medium energy electrons. This allows for investigation of the atmospheric effects of precipitating electrons of all energies. Figure 4 shows the difference in NO_x between a WACCM simulation that included significant auroral electron precipitation and a simulation where precipitation was minimized. This plot pertains to the southern hemisphere in an arbitrary year. Note the tongue of high NO_x descending into the stratosphere. This is very similar to the signatures of enhanced NO_x after energetic particle precipitation observed by numerous instruments. In collaboration with Rolando Garcia, investigations into the climatology of these simulated NO_x enhancements as well as related effects such as ozone depletion and dynamical perturbations are continuing.

Figure 4. Difference in NO_x between a WACCM simulation that included significant auroral electron precipitation and a simulation where precipitation was minimized. This plot pertains to the southern hemisphere for an arbitrary year. Contours are in ppbv.



Additional work is also underway to quantify solar cycle variability in energetic particle induced changes in stratospheric NO_x. Hood and Soukharev (*Geophys. Res. Lett.*, Nov. 2006) performed a linear multiple regression analysis on all HALOE NO_x measurements and found a positive correlation in the polar regions with both the solar cycle (Mg II index) and Ap index. They concluded that these correlations resulted from NO_x created by energetic particles in the upper atmosphere that subsequently descended into the stratosphere (EPP-NO_x). Using HALOE data, Randall et al. (2007) have independently quantified the EPP-NO_x entering the southern hemisphere stratosphere and found an excellent correlation with the Ap index, but a poor correlation with the solar f10.7 index. Work that is currently in preparation shows that northern hemisphere EPP-NO_x entering the stratosphere does not correlate well with either solar indices or the Ap index. A joint effort is underway with Lon Hood to understand the discrepancies between the correlations obtained from the different investigations.

J. McCormack, L. Hood. The main goal of this collaboration is to investigate the solar cycle modulation of the quasi-biennial oscillation (QBO) in stratospheric zonal winds and its impact on stratospheric ozone using an updated version of the zonally-averaged CHEM2D middle atmosphere model (McCormack et al. 2006). The modeled solar cycle ozone response, which was determined via multiple linear regression, was compared with observational estimates from the combined Solar Backscatter Ultraviolet (SBUV/2) data set for the period 1979-2003. The model simulations show that combining imposed Ultraviolet (UV) variations, the zonal wind QBO, and an imposed 11-year variation in planetary wave 1 amplitude produces a lower stratospheric ozone response of ~2.5% between 0^0-20^0S, and an upper stratospheric ozone response of ~1% between 45-55 km, in good agreement with the SBUV-derived ozone response (see Fig. 5 and Table 1 below). However, a substantial disagreement between the model simulation and the SBUV observational estimates remains in the middle and upper stratosphere. An analysis of three independent satellite data sets by Soukharev and Hood (2006) has further supported the validity of the observationally derived vertical structure. This analysis also showed that a similar vertical structure in the tropics is obtained for separate time intervals with a statistically insignificant response invariably near 10 hPa. Such a consistent vertical structure is difficult to explain by random interference from the QBO and volcanic eruptions in the statistical analysis (e.g., Lee and Smith, 2003). Possible explanations for the lack of a statistically significant signal near 10 hPa in the tropics continue to center on a solar cycle modulation of the QBO that is not completely accounted for in the present CHEM2Dsimulations, such as the Nathan-Cordero mechanism cited earlier (Cordero and Nathan, 2005; Nathan and Cordero, 2007).

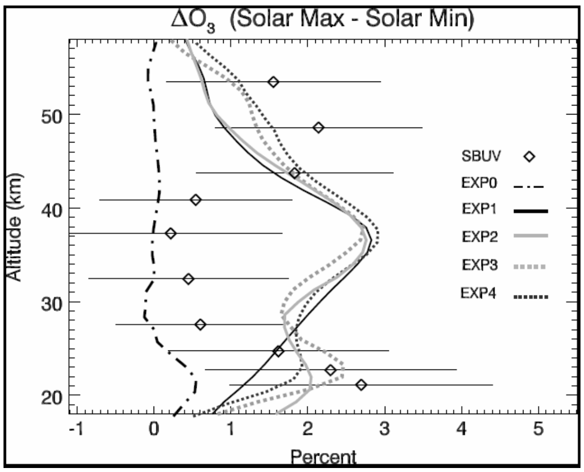


Table 1. Description of experiments

Experiment	Description
EXP0	Fixed solar UV with zonal wind QBO
EXP1	Varying solar UV without zonal wind QBO
EXP1RF	Same as EXP1 using McCormack [2003] Rayleigh friction profile
EXP2	Varying solar UV with zonal wind QBO
EXP3	Varying solar UV with zonal wind QBO and planetary wave forcing
EXP4	Varying solar UV with planetary wave forcing and without QBO

Figure 5. Annual mean regression coefficients from model experiments 0-4 (see table 1) averaged between 0^0-20^0S, and corresponding regression coefficients (diamonds) derived from the 1979-2003 SBUV/2 record with ±σ uncertainty estimates (Soukharev and Hood, 2006).

L. Floyd and J. Morrill. The broad goal of this collaborative effort is to model the solar UV spectral irradiance going back to the start of the 20th century. An archive of solar images is used as a basis for the model. Because these images do not provide an absolutely calibrated measure of the solar UV irradiance, they need to be supplemented with coincident direct measurements of the solar UV spectral radiance over at least a portion of the solar image time period. Comparisons of model UV irradiance variations and those of coincident solar UV irradiance measurements allow for the calibration of the model. Using those calibrations, the model can then be used to estimate the solar UV irradiance for earlier time periods.

The work being conducted in this collaborative effort covers two main areas: (1) acquisition of high resolution SUSIM spectra (0.15 nm) and associated analysis; (2) comparison of spectral irradiance time series produced from the SUSIM observations. The main results from (1) are an estimate of a pure quiet sun irradiance spectrum at 0.15 nm resolution and the wavelength dependent correlation between spectral irradiance and total solar activity visible on the disk in the ~200-400 nm range. The first result should provide information on the solar spectrum during periods of little or no solar activity during present times as well as during historical periods such as the Maunder Minimum. The second result will be utilized as one of a number of means to estimate the solar spectrum based on Ca II K images during the past century.

IV. SUN-CLIMATE FOCUSED SCIENCE TEAM: YEAR-3

The plans for the Sun-Climate FST for the third and final year of its effort include:

- A dedicated Sun-Climate FST meeting is planned for 14 September 2007 at NCAR. The meeting will focus on the current status of the team and the progress it's making in meeting the "deliverables" mapped out in the FST's original three-year plan.
- Team members T. Nathan, E. Cordero L. Hood, and C. Jackman will co-convene a special session of the Fall 2007 AGU Meeting titled, "*Solar variability effects on Terrestrial Climate*." This session will enable the team to share and highlight its findings with the broader scientific community.

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VI. PUBLICATIONS

Publications Related to FST Research Plan and Supported by NASA-LWS
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