Solar Variability and the Effects on Earth's Atmosphere

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Introduction: It is known that the Earth's climate is dependent on the Sun as its primary source in radiative energy. It is also known that the Sun goes through minimum and maximum cycles, involving variability in the Sun's magnetic field, temperature, and sunspots. This variation has little effect on the sun as a whole, with as little as a tenth of a percent of the total solar irradiance experiencing change. However, the Earth maintains a fine balance of radiative energy, and how these cycles impact the Earth's climate is still a topic of research. For instance, as the atmosphere absorbs the Sun's radiation across the full spectrum, different layers of the atmosphere experience a change in temperature. Through the circulation of the Hadley, Mid-Latitude, and Polar cells, air is transported through different atmospheric layers, causing warmer air to be carried throughout the atmosphere. These thermodynamic processes could have an effect on both weather and, given enough time, climate. The goal for this study is to determine on what scale this solar variability affects the Earth's atmosphere, in order to lead to a greater understanding of Sun-Earth interaction and the climatological effects thereof. This study used two sets of data. The first was data gathered from the solar irradiance monitor (SIM) and total irradiance monitor (TIM) instruments on board the SORCE satellite. This data was taken from 16 May 2004 to 20 May 2009 using ten day averages due to solar differential rotation. Among these averages, a reference ten day average was chosen during solar minimum to represent the "quiet sun", which was taken to be five days prior to November 9, 2007, up to five days after November 9, 2007. The second set of data came from the models produced by MODTRAN 5, an atmospheric radiative transfer modeling program. Several different parameters were entered into the program such as time of year, the global location, and the irradiance gathered from the ten day averages.

Brightness Temperature: The Sun acts as a 'near' black body object. At certain temperatures, a perfect black body would have a maximum set wavelength. This is shown in Wein's Displacement Law: T * λmax = 2.898*106 nm K. Since the Sun acts as a 'near' black body, it follows a very similar trend to Wein's Displacement Law. When the Sun is viewed over all wavelengths, it is clear that that the two areas of maximum brightness temperatures are in the visible and infrared regions (See Fig. 1a). Infrared rays are good indicators of temperature. Visible and infrared wavelengths are mostly produced in the Sun's photosphere as shown in the graph (Fig 1a) of effective solar temperature of the Sun. Effective temperature is the temperature a black body would need to produce an irradiance of 1361 W m^{-2} as observed in TSI (i.e. by solving the Stefan-Boltzmann equation). Both the visible and the infrared wavelengths are above the effective solar temperature, meaning they brighten as solar activity lessens. However, the ultraviolet and near infrared are below the effective solar temperature, so these wavelengths experience a dimming effect as solar activity lessens. To emphasize this difference during the quiet and active Sun, both of their brightness temperatures have been graphed.

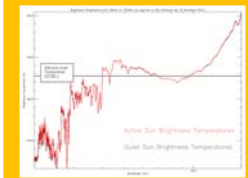

Fig. 1a

$$\sigma T_{eff}^4 \frac{\Omega_{sun}}{\pi} = 1361 \text{ W m}^{-2}$$

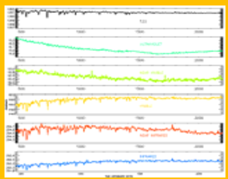
Fig. 1b

Data taken from Solar Irradiance Monitor (SIM) and Total Irradiance Monitor (TIM) instruments on the SORCE satellite

Dates: 16 May 2004, 20 May 2009

Solar Output Across Multiple Wavelengths as the Sun Enters Solar Minimum (See Fig. 1b): The total solar irradiance (T.S.I.) shows more variation when more active regions are present. In the absence of active regions, the T.S.I. shows little solar variability. Across the spectrum, the various bands of wavelengths respond differently to the waning solar variability. The SIM and TIM data show an approximate 0.8% decrease in irradiance in the ultraviolet and near visible wavelengths as solar variability weakens. This decrease is to be expected as the UV intensity decreases with the reduction in the number of active regions present on the solar disk. The visible and infrared wavelengths show the opposite effect during the solar cycle with a nearly compensating effect. The irradiance of the infrared wavelengths shows how the temperature of the "surface" of the sun has changed in this time. There is a direct correlation between the T.S.I. to the summed visible, near IR, and IR wavelengths with the passage of active regions.

Layers of Earth's Atmosphere: The atmosphere displays different temperature trends throughout its layers. Vertical temperature profiles from three different latitudes are shown to illustrate that closer to the equator, the trend is to experience a sharper temperature inversion (See Fig. 2a). However, the general inclination of profiles across the globe is very similar: cooling through the free troposphere, and heating in the stratosphere due to the production of ozone.

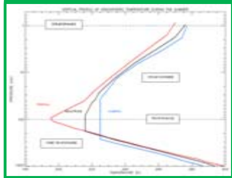
Fig. 2a

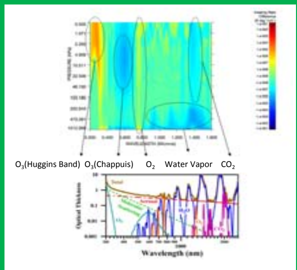

Fig. 2b

Changes in Absorption Bands: There is a clear difference from the active sun (2004/05/16, SORCE Day 478) to the near quiet sun (2007/12/19, SORCE Day 1790) when compared to a reference solar minimum case (2007/11/09, SORCE Day 2030) as shown by the changes in absorption bands in Figure 2c. The dominant solar cycle variations in the free troposphere are due to the different heating rates of water vapor and the UVB wavelengths, as seen at approximately 0.300 Microns. In the stratosphere, the dominant differences are stronger heating rates of the Huggins ozone band, the stronger negative heating rates of the Chappius ozone band, and the more negative CO2 absorption band. There is a clear difference between this active sun scenario and the near quiet sun case. The dominant difference in the free troposphere are the rise of the heating rates of water vapor, and the weakening of the UVB wavelength.

Integrated heating rates in the Different Atmospheric Layers as the Sun Enters Solar Minimum : The graph (Fig. 2d) reflects the impact of solar variability on the various layers of the atmosphere. The y-axes of the graphs measure the difference between the integrated heating rate of the respective atmospheric level on the respective averaged standard day from the integrated heating rate at the same respective atmospheric layer as on the averaged reference standard day of the quiet sun (9 November 2007).The surface and free troposphere are well below the average reference standard day's heating rate towards the beginning of the data. The increased solar activity produces less visible light, and, in turn, causes the temperature of the sun to slightly weaken. This then results in a decrease in infrared light emission, thus lowering the heating rate of the water vapor. However, this was reversed when the sun went into solar minimum and more visible light was available, thus increasing the heating rates of water vapor in the free troposphere to values close to that of the reference day. The tropopause, stratosphere, and stratopause all show heating rates well above that of the reference day's at the beginning of the data. The ozone present in the upper atmosphere absorbs the UV light emitted by active regions, keeping the heating rate higher than that of the averaged reference standard day's heating rate. However, when solar minimum was reached, the heating rate returned to values near the averaged reference standard day.

Absorption Bands and Heating Rates (See Fig 2b): The lower graph shows the absorption bands of several atmospheric gases. The higher graph displays the differential heating rate between of the quiet sun and another average ten day period when the sun was active. The ten day heating rate averages will be referred to by their median day for sake of saving space. This graph will also show the change in heating rates of different wavelengths at different heights. When the absorption bands from the lower graph are applied to the higher graph, different gases can be identified on the higher graph. Using this comparison, we are able to see the presence of water vapor and oxygen at surface levels and in the free troposphere. Oxygen, found throughout the entire troposphere and stratosphere, absorbs near infrared light, while the water vapor in the free troposphere and near the surface absorbs infrared light. In the upper stratosphere, the absorption bands show the presence of ozone and oxygen. The oxygen absorbed near infrared and infrared light. There are two bands of ozone that were very predominant in this graph: the Huggins, as seen in the ultraviolet, and the Chappius, as seen in the visible. By absorbing these different wavelengths, these gases created a heating rate. A heating rate is the radiatively induced rate of change of temperature due to the absorption or emission of radiation within the gas.

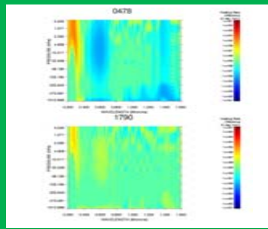

Fig. 2c

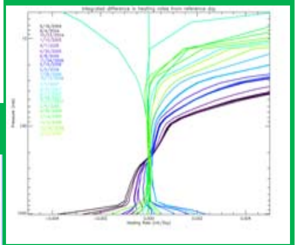
Fig. 2e

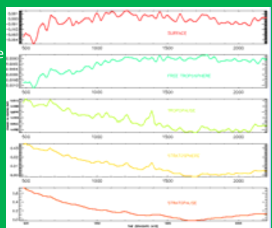
Fig. 2d

Integrated Difference in Heating Rates: Figure 2e is the representation of the integrated difference in heat rates. This was calculated so that all wavelengths can be included and the change in heating rates in the free troposphere and stratosphere can be emphasized. Each line represents a different averaged standard day. This was done to emphasize the change in heating rate as the sun entered solar minimum. The structure of the atmosphere can also be seen in the graph, as well. At the tropopause (100 mb), most of the heating rates begin to increase at a greater rate. The lower troposphere is characterized by a wide range of heating rates due to the presence of water vapor. As seen on the difference of heating rate graph, water vapor is the strongest absorption band near the surface. As the sun enters solar minimum, water vapor begins to absorb the increased amount of infrared wavelengths, which in turn raises the heating rate in the lower troposphere. However, after the reference day of quiet sun is reached, the sun slowly starts to leave solar minimum, decreasing the amount of infrared wavelengths produced by the sun. Therefore, the later dates on the graph show a return to a trend similar to that of active sun, but to a smaller degree.

Conclusion: Through the effort of this research, it has been determined that the variations on the sun play a direct role in the Earth's atmosphere; whether it be during solar minimum, when water vapor in the lower free troposphere has an increased heating rate due to the increased amounts of infrared produced by the sun, or during solar maximum, when ozone in the stratosphere has an increase in heating rate due to the increased amounts of ultraviolet light produced by active regions. However, this research raises questions pertaining to climate. To what effect will a prolonged solar minimum or maximum have on the Earth's climate? Will the change in heating rates of the atmosphere have an effect on the oceans ? Will the increased amounts of UVA and UVB during solar maximum threaten plant, animal, or human life? Though these questions cannot be answered through this study alone, the data gathered could be used in future research in an effort to find the answers.