**Introduction:** Solar radiation is the primary energy source for the Earth and other terrestrial planets in the solar system. This energy establishes the thermal structure of Earth’s extended environment and initiates chemical and dynamical processes that couple adjacent domains in space and time (Figure 1).

![Figure 1. The coupled Sun-Earth System.](image)

The Sun’s spectrum at visible and near infrared wavelengths is typical of a black body at 5770 K, with peak emission near 500 nm [1]. This radiation heats Earth’s surface, which then radiates thermally to space; the balance between incoming and outgoing energy establishes the planet’s surface temperature. Solar radiation at ultraviolet and extreme ultraviolet wavelengths exceeds that of a black body by orders of magnitude; this energy heats the Earth’s middle and upper atmosphere, which absorb it completely. Solar UV dissociation of molecular oxygen produces the protective ozone layer and EUV photoionization of oxygen and nitrogen produces the ionosphere.

Earth’s elliptical orbit around the Sun, tilted at 23.4° to the ecliptic plane, modulates solar radiation reaching Earth; this modulation drives the dominant variability modes observed in the Earth’s environment from surface to space [2]. There is an annual cycle in solar radiation received at Earth (of magnitude ±3.4%) because the Earth is closer to the Sun in January than in July. As well, the distribution of (daily averaged) received solar radiation is hemispherically symmetric at the equinoxes but asymmetrical at the solstices, producing additional annual and semiannual oscillations throughout Earth’s extended environment (Figure 2).

Solar radiant energy also varies intrinsically as a result of fluctuations in the Sun’s magnetic activity which has dominant cycles at 11, 80-90, 200-210 and 2,500 years. Bright faculae and dark sunspots occur more frequently and with larger areas during times of higher solar activity. These features alter the background (quiet) radiation from the Sun’s surface and throughout its atmosphere, thereby altering solar radiant energy at all wavelengths of the electromagnetic spectrum. Variations in solar irradiance at ultraviolet wavelengths (a few percent) and extreme ultraviolet wavelengths (tens of percent) are larger than at visible and near infrared wavelengths (tenths of percent). Solar irradiance variability drives changes in the Earth’s environment at 11 years and also 27-days, which is the period of the Sun’s rotation on its axis. The 11-year cycle determines the amount and area of facular and sunspot features on the Sun and solar rotation alters their distributions on the hemisphere of the solar disk projected to the Earth. At the Earth’s surface the magnitude of the solar activity-related cycles is orders of magnitude smaller than the orbital-driven seasonal variability, but in the upper atmosphere it is more than twice as large. This reflects, in part, the much smaller solar cycle variation in visible solar radiation (~0.1%) that heats the Earth’s surface than in EUV radiation absorbed in the upper atmosphere (>50%), relative to the 7% orbital change.

![Figure 2. Annual and semiannual oscillations driven by changing Sun-Earth geometry pervade the Earth’s environment. Seasonal fluctuations manifest in the global surface temperature (bottom), the total ozone concentration of the middle atmosphere (~30 km, middle) and the total number of electrons in the ionosphere (~250 km, upper). Solar activity further modulates the solar radiation at earth, imposing an additional 11-year cycle on terrestrial temperature and composition. This is most evident in the ionosphere and upper atmosphere, where the magnitudes of the annual and semiannual cycles are larger during times of high solar activity (e.g., 2000-2002) than during solar minima (e.g., 2008-2010).](image)
The solar-driven climatology of Earth’s environment thus manifests as a combination of orbitally-driven fluctuations in received solar radiation and solar-activity-driven fluctuations in solar irradiance. The typical approach for determining climatological variations at the Earth’s surface, in the lower and middle atmosphere and for the ozone layer, is to first deseasonalize the observations by removing the (orbital-driven) seasonal cycle, taken to be constant and determined as the average of monthly variations observed over many years. This approach assumes the absence of variability in seasonality, i.e., that drivers of Earth’s climatology, whether from natural or anthropogenic influences, do not modulate seasonality itself. This assumption is not valid for observations in the upper atmosphere where the solar activity cycle significantly modulates seasonality [3]. For example, the amplitude of the annual oscillation in total electron content is 3× larger, and the SAO amplitude 5× larger, at solar activity maxima than minima.

Following deseasonalization, time series of terrestrial variables such as global surface temperature and total ozone (Figure 3) are analyzed to detect and identify the multiple causes of their climatology. At the surface and in the middle atmosphere, solar and anthropogenic forcings are the primary influences on decadal time scales, with the strength of the solar component increasing relative to the anthropogenic component at higher altitudes. Volcanic activity and internal variability, such as that associated with the El Niño Southern Oscillation (ENSO) and the quasi biennial oscillation (QBO), produce variability on times scales of months to years, and must be properly quantified in order to extract the longer-term solar and anthropogenic components [4].

The increase in solar radiative energy during high solar activity drives dynamical response in the terrestrial atmosphere. More of the increased energy is deposited at low latitudes. This alters the tropospheric circulation that transports excess energy at low latitudes to higher latitudes (Figure 4, from [1]). It further alters the meridional flow in the stratosphere from the summer to winter hemisphere, which overlies, and interacts with, the tropospheric circulation. Zonal inhomogeneities in the meridional flow manifest primarily at the interfaces of the tropospheric circulation cells and alter the longitudinal character of, for example, the circumpolar vortex (polar jet) and intertropical convergence zone. Consequently the terrestrial response pattern to solar irradiance variability has significant regional inhomogeneities that differ notably from the distribution of the forcing itself.

**References:**


**Additional Information:** The Chief of Naval Research and NASA funded this work.