

SOLAR VARIABILITY, WEATHER AND CLIMATE

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ABSTRACT

A vast literature attests to much research and lively interest in solar influences on weather and climate. Yet very little has been firmly established, perhaps with exception of modulation of climate by the earth's orbital elements. Other suspected relations have either been refuted or are not yet confirmed. Among the latter are the possible effect of ionizing solar emissions on thunderstorms, the injection of stratospheric air into the troposphere, and - on a longer time scale - the coupling of the U.S. drought rhythm west of the Mississippi River with the solar Hale cycle. Presently no solar-terrestrial links applicable to forecasting are known.

1. INTRODUCTION

Probably no subfield of meteorology has had as much effort devoted to it as the effects of solar variability on weather and climate. And none has had as little to show for the research labor. The magnitude can best be seen by the large bibliographies and review papers that have been devoted to the topic. About a quarter century ago Meteorological Abstracts and Bibliography compiled a literature survey which up to that time listed 1278 titles (2). More recently a particularly carefully written review paper by Pittcock (3) added about 150 more references written in the 1960s and 1970s. Recent symposia have been partially or totally devoted to this topic (4, 5).

How did it all start? Although the existence of sunspots was known in classical antiquity, scientific observations of these solar phenomena began with the invention of the telescope by Galileo. In 1611 four early astronomers, including Galileo, announced their discovery almost simultaneously. The astronomer F. W. Herschel in 1801 indicated the variability of solar emissions. The approximate periodicity of solar activity was not published until 1844 and the first relation to meteorology was claimed by Köppen in 1873 who cautiously suggested a negative correlation between sunspot number and temperature. That set the ball rolling and it hasn't stopped since.

2. LONG-TERM CHANGES

Geological work in the middle of the 19th century established the occurrence of continental glaciations in the recent geological past. Geological work also estab-

lished an alternation of ice ages and interglacials. This started attempts to explain the apparent regularity of occurrence in the Quaternary period. In 1875 the astronomer James Croll, who had discovered the periodic changes of the eccentricity of the earth's orbit around the sun, published a book "Climate and Time" (6). In it he tried to explain that the varied position of the earth with respect to the incoming solar radiation, including the then well-known precession cycle could be the cause for the ice ages. As with any new hypothesis a long-lasting controversy ensued. Another orbital element, the varying inclination of the ecliptic had to be included. Finally the whole so-called astronomical theory was reworked by Milankovich for whom this model is now named. Aside from elaborating the complex geometry and interaction of the three main cycles, he calculated the changes in radiation received by the high latitudes of the earth (7). Improved astronomical observations since have fixed the main cycle of orbital eccentricity at 100,000 years, the cycle of obliquity of the ecliptic at 41,000 years, the main cycle of precession at 22,400 years. Further calculations of the climatic implications have been made by Vernekar (8). But the clinching argument has been furnished by deep-sea cores. The layers in these were dated by radioactive isotopes and the sea-surface temperatures at the time of deposition of these layers were determined both by isotope ratios ( $O^{16}/O^{18}$ ) and by temperature sensitive plankton species (9). The coincidence of low temperatures with timing of diminished radiation for the past approximately 1/2 million years establishes the path elements of the earth as prime contenders for the various Pleistocene glaciations. This is now widely accepted by astronomers, geologists, and climatologists (10, 11, 12).

3. SOLAR FLUCTUATIONS

Since the middle of the last century, with the discovery of rhythmical sunspot variations, it had become clear that solar-terrestrial interactions of similar rhythmicity take place. This was obvious for the external parts of the earth's magnetic field. In the atmosphere the polar aurora frequency was similarly affected. Attempts began early to establish the total energy received from the sun at the mean distance of the earth from the sun. The distance is generally designated as one astronomical unit (1 AU). This quantity was given the label "solar constant", an

undesirable term because it isn't constant. It has, in recent years, fortunately been gradually replaced by the term "solar irradiance".

From about 1905 onward the Smithsonian Institution made pyrheliometric measurements on high mountains in the clearest accessible areas of the world. By extrapolation to the boundary of the atmosphere to allow for ozone absorption aerosol and molecular extinction, estimates of the total solar energy received were made. In a succession of papers C. G. Abbot documented these observations (13). He made early analyses of quasi-periodic fluctuations on weather, especially precipitation (14).

Regrettably the calculated values of the irradiance were afflicted by considerable uncertainties. The correlations to weather were equally shaky. The observations are, however, far from being useless because they give valuable information on atmospheric turbidity caused by suspensions in the high atmosphere. Using the Smithsonian information, Hoyt (15) was able to show that transmission is principally affected by volcanic debris. Up to 1957 there was no evidence of any anthropogenic component. This still seems to be the case up to 1980 from observations at Davos, Switzerland, where a long, homogeneous series of pyrheliometer observations since the beginning of the century exists (16).

The beginning of space exploration finally made it possible to measure solar irradiance extra-atmospherically. At first, this was based on sporadic information with uncertain instrumental errors. Robinson (17) gave the following values from the literature:

Author	Year	Irradiance Value ( $\text{Wm}^{-2}$ )
M. Nicolet	1951	1380
F. S. Johnson	1954	1394
M. A. Thekaekara & A. J. Drummond	1971	1353

Note:  $\text{Wm}^{-2}$  is Watts/meter<sup>2</sup>; replaces Calories/meter<sup>2</sup>.

A range of estimates from 1338 to 1368  $\text{Wm}^{-2}$  has been given by other authors (18).

Finally, since 1978 there are two sets of satellite measurements available, one from Nimbus 7 (19), the other from NASA's Solar Maximum Mission (20, 21). These show rather clearly that there are small day-to-day variations which seem to be related to the flux from active areas on the sun. The Nimbus 7 values, from November 1978 to May 1979, show an irradiance of 1376  $\text{Wm}^{-2}$ , with a root mean square devi-

ation of the daily values of  $\pm 0.05$  per cent. The Solar Maximum Mission observations, from March through December 1980 yield 1368  $\text{Wm}^{-2}$  with an uncertainty of less than  $\pm 0.05$  per cent. It is as yet unclear if the difference of 0.006 per cent is of any significance. Fröhlich and Brusa (22) have reevaluated all data for the 15-year interval 1965 to 1980 and concluded that the solar irradiance, within the uncertainties of measurement, has not changed.

#### 4. EFFECTS OF SOLAR VARIATION ON CLIMATE

What are we then to make of a century of claims of effects of solar variations on climate? Nearly all of these have been based on the fluctuations of the sun spots. The relative sun spot number is an arbitrary index based on the number of spots on the visible disk of the sun and the number of spot groups and a reduction coefficient. This number, available with reasonable comparability since about 1700, shows the well-known changes from year to year. One can hardly call these cycles. Although the interval between maxima of sunspots is about 11 years, the range has been between 7 and 17 years. For minima the average is 11 years too, but the range is from 9 to 14 years. The magnetic polarity of sunspots also shows a quasi-periodic variation of twice the length of the basic sunspot rhythm. This double sunspot rhythm, often referred to as the "Hale cycle", has an average length of 22 years. There has been another suspected rhythm, variously placed at values between 90 and 100 years, the "Gleissberg cycle".

The search for these solar periodicities in time series of meteorological elements, mainly temperature and humidity, has been the target for scores of studies. Most of them have been disappointing. Although power spectrum analyses have shown in some of these series statistically significant periodicities in the solar rhythm bands, their contribution to the total variance is usually less than 10 per cent. The longest temperature series available is that of Manley (23) for Central England. Only about 6 per cent of its variance could be explained by the basic sunspot rhythm. The power spectrum of a reconstruction of northern hemisphere temperatures since 1579, about 400 years, fails to show any significant power for the shorter sunspot rhythms. However, a significant peak shows up for a 99-year cycle. This may be the Gleissberg cycle but with a series only four times as long, it would be bold to make any claims for its reality (24).

The question has been rightly raised if the relative sunspot number is a suitable index to indicate solar energy output. Hoyt (25) has suggested that the ratio of



umbral to penumbral areas of sunspot, an indication of solar convection, would be a better index. This author calculated annual umbral/penumbral ratios between 1874 and 1970. These were compared with northern hemisphere temperature values for that interval by Borzenkova et al. (26). The correlation between that solar activity index and the temperature is 0.57. Although this is a statistically highly significant value, only a moderate 32 per cent of the variance is explained.

The method of Hoyt suggests that an active sun has lower energy emissions than when it is inactive. This agrees with the views of Agee (27, 28) who attributes the slight hemispheric cooling since 1940 to a waxing phase of the Gleissberg cycle. Papers by Eddy (29, 30) had postulated the opposite, namely that an active sun radiated more energy than a quiet sun. He based this in part on his impressions of effects of the so-called "Maunder Minimum" of sunspots and its alleged cooling effects on the earth. This minimum of sunspots, placed in the interval of 1645-1715, while apparently low in solar activity, was not as minimal as represented. Many sunspot (and associated auroral) observations, not in standard compilations, were overlooked. Material found in various diaries, dissertations, and other publications clearly imply that the solar rhythm was maintained and that the lull in solar activity was definitively over in 1704 (31, 32). Also the contention that the Maunder interval was particularly cold cannot be maintained. Actually decades just before that period and toward the end of the 18th century and in the beginning of the 19th century were definitely colder in the northern hemisphere (24).

As far as temperature is concerned the contemporary solar activity rhythms seem to have only small influence. A better case can be made for precipitation. The power spectra for long precipitation series tend to show a notable coherence with the sunspot numbers, especially in tropical and monsoonal areas. But even in this case the total amount of variance explained remains small, usually below 10 per cent (33, 34, 35). Droughts in the U.S. west of the Mississippi River have also been linked to the solar rhythm. Mitchell et al. (36) have demonstrated that the area of moisture stress in the western U.S. show a concentration of variance at periods near 22 years. They based this conclusion on power spectra of the annual relative area showing symptoms of drought in tree rings at various levels of severity. This information can be established for over 300 years. It has, however, been suggested that there is interference with the solar rhythm by an 18.6 year lunar cycle (37). As the solar rhythm is irregular and in itself only partially

predictable, one is left with a rather general conclusion that droughts in the West will probably recur at about 20 year intervals with uncertainty of 2 or 3 years in the timing.

## 5. EFFECTS ON WEATHER

There was a flurry of excitement in the early 1970s when several papers seemed to link a solar magnetic index with atmospheric pressure patterns. Roberts and Olsen (38) claimed that about 2 to 4 days after magnetic storms 300 millibar troughs in the northeast Pacific deepened during the cold season. Further work led to elaboration of an index of areas of high vorticity in the northern hemisphere and its relation to passages of sector boundaries of the solar magnetic field (39). All this was based on a variety of statistical tests and the usual debate over applicability and validity of these tests ensued. But ultimately only very substantial doubt about the reality of the relation remained (40, 41).

Russian workers have followed similar lines of investigation. They related invasions of solar protons near the magnetic poles to subsequent pressure patterns in the area during winter. In the north polar region lowered pressure followed these invasions after about 3 days. In the south polar region the lag was about 6 days (42). The number of cases, especially for the south polar regions, is small so that the significance of these observations remains an open question.

The link of solar particulate invasions into the high atmosphere to the lower atmosphere has been further explored by Reiter (43). He measured isotopes produced by cosmic rays in the high atmosphere, such as Beryllium 7 on a mountain station 3 km high. Increased concentrations were considered indicative of transport of stratospheric air into the troposphere. These transports increased by about 50 per cent after  $H_{\alpha}$  flares near the central meridian on the sun, with a lag around 4 days. Such stratospheric air invasions into the troposphere following notable changes in the solar wind have not yet been confirmed by other methods of analysis nor has a full physical explanation been given.

A final tie claimed between solar events and the weather needs some scrutiny. Herman and Goldberg (44) based on alleged correlations between solar activity and thunderstorm frequency, advanced the hypothesis that solar proton invasions could change the electric field above clouds and thus enhance electrical storm formation in extra-tropical regions. This is also the basis of a somewhat more elaborate model of Markson (45) who argues that the in-



