# 1 INTRODUCTION

A COMPREHENSION OF HOW THE SUN AFFECTS THE Earth is a fundamental requirement for understanding how climate has varied in the past and how it might change in the future. This is particularly important in the context of determining the cause(s) of climate change: we need to understand natural factors to be able to attribute to human activity any past or potential future influence on a range of timescales.

The extent to which the Sun drives changes in the Earth's climate has been the subject of speculation, scientific investigation, and, often, controversy over many centuries. Solar energy maintains the equitable global temperature, while the distribution of insolation across the globe results in night and day, and geographic variations in weather and climate as well as their seasonal modulation. The fundamental role of the Sun in climate is therefore undeniable. The question that arises is whether and how solar activity varies over time and how possible variations might be affecting our environment.

Naked-eye observations of sunspots have been made since ancient times. Babylonian and Chinese astronomers in the seventh century BC recorded dark spots on the face of the Sun, and court astrologers in ancient China believed sunspots foretold important events. In

Greece in the fourth century BC Theophrastus, in his book on weather forecasting, suggested that black marks on the Sun predicted rain. Intermittent sunspot sightings were recorded during subsequent centuries, but it was not until the telescope was invented around 1600 that routine observations were made. The common interpretation then was that these spots were planets transiting the face of the Sun, but it was Galileo who noted that the varying shape and speed of each spot belied that possibility and indicated that they were in fact blemishes on the solar surface. Galileo made a number of sketches from his observations of sunspots, an example of which is shown in Figure 1.1 alongside a recent image of the Sun. Galileo's picture shows the dark centers of the spots (the umbra) and the lighter surrounding regions (penumbra).

Later observers, including William Herschel in London at the end of the seventeenth century, noted that the number of sunspots was not constant but varied between none and many, and it was he who carried out what was probably the first scientific study of the relationship between sunspot number and weather. His publication of 1801 identified five periods of a few years each in the interval 1650–1717 during which sunspot numbers (as compiled by French astronomers) were low. Herschel then examined records of the price of wheat during that span and argued that high prices corresponded to product scarcity, which must have reflected poor growing conditions. He acknowledged that this was a somewhat indirect measure of temperature but reasoned,

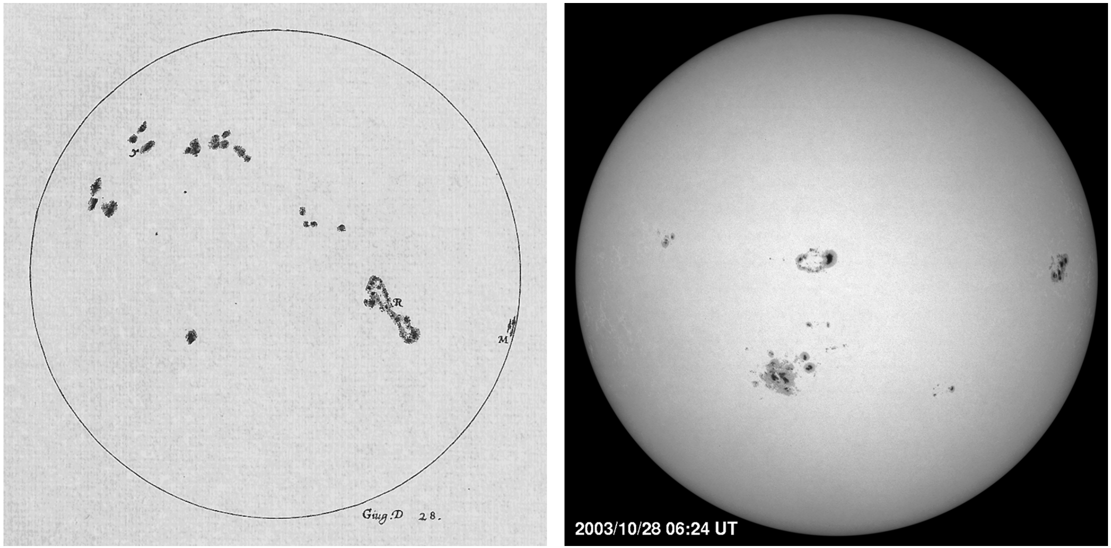


Figure 1.1 Left: An example from June 28, 1613, of Galileo's drawings of sunspots. (Used with the kind permission of Owen Gingerich.) Right: An image of the Sun in visible light acquired on October 28, 2003, by the MDI instrument on the SOHO spacecraft. (From http://sohowww.nascom.nasa.gov/)

pragmatically, "for want of proper thermometric observations, no other method is left for our choice." He concluded, "It seems probable that some temporary scarcity or defect of vegetation has generally taken place, when the sun has been without those appearances which we surmise to be symptoms of a copious emission of light and heat," that is, poor growing conditions when the Sun was less active. The statistical robustness of Herschel's work does not bear much scrutiny, but it set the scene for much that followed.

In the mid-nineteenth century the existence of the *sunspot cycle*, a semiperiodic waxing and waning in the observed number of sunspots, was discovered by a German apothecary and amateur astronomer, Heinrich Schwabe. Inspired by this finding, Rudolph Wolf, a Swiss schoolteacher, started to collate sunspot data and designed a system for intercalibrating observations, which is now called the *Wolf number*. He showed that the period of Schwabe's cycle varied between 8 and 17 years but averaged 11.1 years; records of the Wolf sunspot number now extend from the seventeenth century until the present day (see, e.g., Fig. 1.2). At about the same time as Wolf was doing his work on the sunspot cycle, several scientists noted that the Earth's magnetic field—measurements of which had been initiated by Carl Friedrich Gauss in 1835 and carried out at a number of observatories—varied almost in tandem. Studies had already been done on the relationship between geomagnetic storms and observations of auroras (northern lights), and the discovery of the sunspot cycle led to a

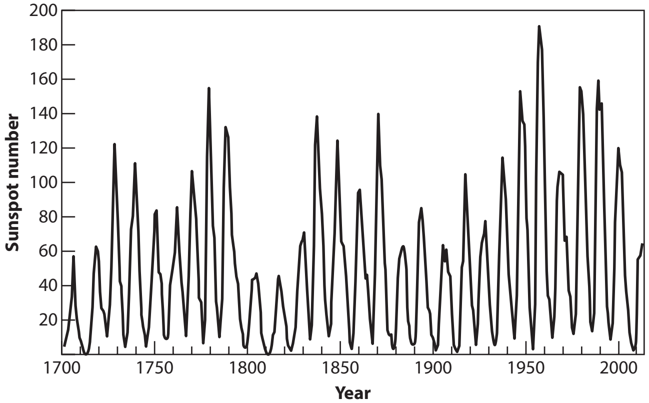


Figure 1.2 Yearly sunspot number for the years 1700–2013. (Data from WDC- SILSO, Royal Observatory of Belgium, Brussels, http://sidc.oma.be/silso/)

search for periodicities in auroral observations. It was understood that auroras were high in the atmosphere, but it was thought that they presaged fine weather near the Earth's surface, so the logical next step was to look for relationships between solar activity and weather.

A large number of studies ensued, whose major focus was on surface temperature, but other meteorological parameters of interest were precipitation (including evaporation, floods, droughts, river flows, and lake levels); atmospheric pressure; cloud cover; the position of storm tracks; the intensity and frequency of tropical storms and monsoons; temperature and winds at different levels in the atmosphere; as well as indirect measures such as the frequency of forest fires and shipping losses.

Notable among the studies were papers by Charles Meldrum, a Scottish meteorologist and government observer in Mauritius, who analyzed data from 144 stations across the globe over seven solar cycles in the mid-nineteenth century and found a solar cycle signal in rainfall; he also claimed "a strict relation" between sunspot number and the frequency of cyclones in the Indian Ocean. Another Scot, Charles Piazzi Smyth, Astronomer Royal for Scotland, counted meteorology among his many interests. He analyzed data acquired in the period 1837–1869 from four thermometers buried at different depths (to remove transient/diurnal signals) into the rock of Calton Hill in Edinburgh and has been widely quoted as finding significant correlation of temperature with sunspot number. That was a correct observation, but, interestingly, Smyth also noted "several numerical circumstances which show that the sunspots cannot be the actual cause of the observed waves of terrestrial temperature," demonstrating the skepticism which is unfortunately lacking in many works on apparent solar–climate links.

During that time the Indian subcontinent became part of the British Empire, and the government felt a concomitant responsibility to nurture agricultural productivity in that region. The severe impacts of Indian famines led to a focus on meteorology involving studies by, among others, Norman Lockyer (solar physicist, discoverer of helium, and founder of the journal *Nature*). Initially having traveled to India to observe a solar eclipse, Lockyer became interested in solar–climate links and compiled a list of all correlations established by researchers between sunspots, geomagnetism, temperature, and rainfall, focusing on cyclones and their effect on shipping.

Despite the large number of reports of Sun–weather links, by the end of 1870s there was a rise in criticism of the work. For example, a leading Indian government meteorologist stated in an official report to the famine commissioners that he could find no simple correlation. Concerns raised were based largely on some rather poor statistical relationships but also on the lack of any robust physical mechanisms that could account for the supposed association. The most plausible explanation would be a relationship between sunspot activity and solar energetic output. William Herschel believed that higher numbers of sunspots were associated with greater solar emissions of heat and light, but there was no evidence to support this hypothesis. Indeed, some believed that a preponderance of dark areas on the solar surface would result in reduced energy output.

Measurements of the Sun's radiant energy became the life work of Charles Greeley Abbott, director of the Smithsonian Observatory and secretary of the Smithsonian Institution in Washington, DC, during much of the first half of the twentieth century. He held a firm belief that solar irradiance varied and thus influenced weather, despite the claim by many climatologists that total solar irradiance (TSI) or "the solar constant" was just that. He set up carefully calibrated radiometers on mountains across the United States and in other countries, including Argentina, Chile, Egypt, and South Africa, and made measurements over nearly 40 years. At the same time many other scientists around the world were making similar measurements, and they produced a wide range of estimates of TSI: values published between 1900 and 1950 ranged from 1322 to 1465 W $m^{-2}$. No one was able to establish a repeatable link between sunspot number and irradiance, and instruments on balloons and rockets did not prove helpful. Finally, the launch of radiometers on Earth-orbiting satellites in the late 1970s made it possible to remove the effects of the intervening atmosphere and to show that TSI does vary, by a small fraction, in phase with sunspot number.

Despite some decline in enthusiasm for establishing solar–climate links at the end of the nineteenth century, work continued on a number of fronts, and papers continued to be published on statistical correlations. Over the next half century a confusing picture emerged with claims of in-phase and out-of-phase relationships, some of which switched behavior between periods. In 1957 the American Meteorological Society expressed its frustration with the statement that "[s]ome few results have been obtained that are highly suggestive. But none of these studies have produced any conclusive evidence that relationships do indeed exist."

While changes in irradiance provide the most likely candidate for any solar effect on climate, the lack of reliable measurements prior to the satellite era means that "proxies" such as sunspot number or geomagnetic indexes are still needed as indicators of past solar activity. Useful proxies can be found in isotopes such as carbon-14 ($^{14}C$) and beryllium-10 ($^{10}Be$) in ocean sediments and other geologic strata, ice cores, and tree rings. These isotopes are produced by reactions with galactic cosmic rays, whose flux into the Earth's magnetosphere is modulated by the strength and extent of the solar magnetic field. Thus the concentration of cosmogenic nuclides is inversely related to solar activity and can provide records for hundreds of thousands of years, although dating becomes problematic for the oldest samples.

The Schwabe cycle had been the focus of many studies, but longer-term variations in solar activity were also noted. Around 1887 the German astronomer Gustav Spörer identified a period circa 1645–1715 during which very few sunspots were observed, and this finding was confirmed in England shortly afterward by Edward Maunder, after whom the period was named the Maunder Minimum. Around eighty years later this topic was reinvestigated by U.S. solar physicist Jack Eddy, who used $^{14}C$ measurements to extend the solar activity record back to the eleventh century, identifying a Spörer Minimum in activity around 1500, another grand minimum around 1350, and a Medieval Maximum during the twelfth and thirteenth centuries. Eddy further claimed that the $^{14}C$ record provided an (inverse) measure of solar irradiance; thus low isotope levels would indicate a warmer Earth, and vice versa. He noted that the coldest excursions of the Little Ice Age coincided approximately with the Maunder and Spörer Minima, and the Medieval Climate Optimum with the solar Medieval Maximum.

Significant effort in contemporary climate science is invested in the attribution of causes to the general increase in global average temperature over the past one and a half centuries. It is very difficult to make a robust scientific case for anything other than a rise in the concentration of anthropogenic greenhouse gases as the major source of the warming; however, it is important to establish the roles of other factors—both those resulting from human activity (such as industrial particulates) and, importantly, those for which humanity cannot be held responsible (such as solar activity and volcanic eruptions). For this reason the evidence for Eddy's relationship has been the subject of much further investigation. Consideration of the Little Ice Age and Medieval Climate Optimum as global phenomena, rather than signals pertaining to northwestern Europe, has been challenged, and one interesting avenue of study is the influence of the Sun on regional, rather than global, climate.

The availability of high-performance computers, advances in climate modeling, and construction of comprehensive and robust records of meteorological variables are all helping in the quest to identify the extent to which the climate responds to changes in the Sun and to understand the physical mechanisms underlying these signals.

In this book we present some of the background to these endeavors. We start with an overview of the Earth's climate system—its composition, structure, and circulation—and some of the ways in which these vary naturally with time. We then look at key features of the structure of the Sun, its magnetic field, and atmosphere, and its emission of radiation and particles. In the next chapter we focus on solar radiation and its interaction with the terrestrial atmosphere in the context of the Earth's radiation budget and radiative forcing of climate, as well as its direct impact on atmospheric composition and temperature. We follow this discussion with a review of the temporal variation of several measures of solar activity. In the next section of the book we cover the evidence for an influence of solar variability on the atmosphere, oceans, and climate on timescales ranging from minutes (space weather) to thousands of years. We also consider the processes that might be responsible for the observed changes.

The subject of this volume is wide-ranging and sometimes controversial, and given space limitations, we cannot hope to provide a comprehensive coverage. Nevertheless, we hope the reader will take away a flavor of the science behind this complex and fascinating topic and of the challenges remaining to be addressed.