Climate Change and Solar Variability

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I. Studying the Sun

As Earth's most important source of energy and gravitational center of orbit, the Sun is vital to life on our planet and fuels the climate system (Beer et. al., 2006). Every second, the Sun loses ~4 million tons of weight that is irradiated into space, mainly in the form of visible light (Beer, 2005). It is obvious why a proposed link between the Sun and climate exists, especially with growing concerns of unprecedented warmth, along with pure curiosity. Known changes in solar radiation at various latitudes are responsible for different climatic regimes, thus people seek a connection between the Sun and changes in climate (Geophysics Research Board, 1982). It is important to note that when examining the effect of solar forcing, we are discounting the effects from Milankovitch cycles and orbital forcing from the discussion. While these cycles do account for varying insolation that causes seasonal changes, these fluctuations occur regularly and may change on extremely large time scales, which is not terribly relevant to the issue of modern climate change (Ruddiman, 2013). For our purposes, we are concerned with the variance in output of energy from the Sun and the potential of small solar variations to have a large impact on the climate system (Kopp & Lean, 2011). Current models indicate that a change of ~0.1% in the strength of solar insolation has the potential to alter global mean temperature by as much as 0.2 degrees Celsius if it persisted for many decades (Ruddiman, 2013).

Our climate system is highly dynamic, which has been apparent recently with fossil fuel emissions, the greenhouse effect, and late Holocene warmth. It is also notable that the Sun is dynamic, since we know that the accepted solar constant of 1360 W/m^2 is not actually constant (Beer, 2005). The "faint young sun paradox" refers to the fact that the Sun was weaker by at least 30% about 4.5 billion years ago when the solar system was created, and that solar output has steadily increased since then, and it will continue to do so for another 4 billion years or so (Beer, 2005). This concept provides evidence that the Sun varies in intensity. Researchers are revealing more and more about solar processes every year; an understanding of which is vital to this topic. A dynamic climate which is known to have a lagging response to forcing factors and a dynamic sun lead to a field of study that is constantly being molded by new debates, understandings, findings, and questions (Hansen et. al., 2005).

II. Understanding the solar forcing

The Sun, as previously mentioned, is now highly studied. Lack of understanding of the solar forcing in the past has fueled an increased motivation for more concrete research in the past few decades. Arguably most important to understanding solar processes is the concept of total solar irradiance (TSI), or the amount of energy from the Sun (in W/m^2) that reaches the Earth's upper atmosphere (Beer et. al., 2006). TSI and solar activity are proven to be so positively correlated (Figure 1) that we can practically use the terms interchangeably (Beer et. al., 2006). TSI is highly periodic and provides further evidence that the Sun is a variable star (Roth & Joos, 2013).

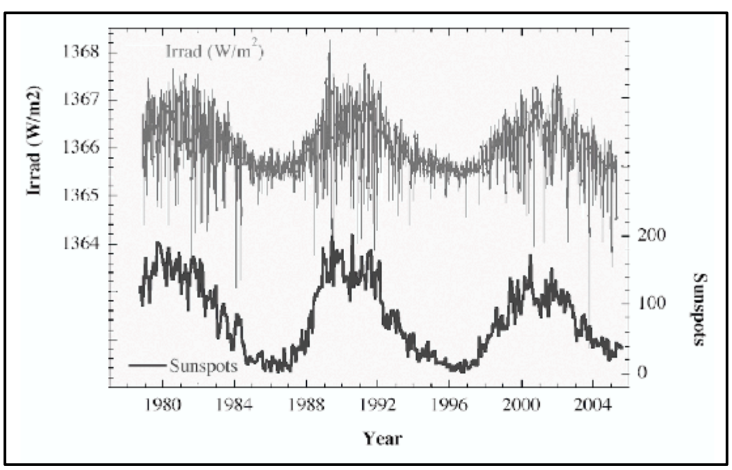

Fig. 1: Solar irradiance compared to sunspots (Beer, 2005).

Another distinction that is crucial to understanding solar activity is the relative abundance of sunspots, typically referred to as the "sunspot number", and what it implies about energy balance (Ruddiman, 2013). Sunspots are marked by their dark appearance and are characterized by their round shape, dark color, and relatively lower temperature; however, they are correlated with higher solar activity, since their presence often indicates a higher amount of solar flares and more active, bright faculae (Ruddiman, 2013). Most of the radiation emitted by the Sun comes from its faculae, which are rings that often surround sunspots (Ruddiman, 2013), shown in Figure 4. Some argue that the sunspot number is the best indicator of solar activity (Raisbeck & Yiou, 1980); however, this claim is quite outdated and is currently under much speculation and scrutiny by present-day researchers (Pedro et. al., 2011).

Regular fluctuations of relatively low and high solar activity are referred to as grand minima and grand maxima, respectively (Kopp & Lean, 2011). During grand minima, it is not unusual to recognize sunspot minimums: periods in which there are very low numbers of observed sunspots, and subsequently lower solar activity, shown in Figure 2. The most recent sunspot minimum, and arguably the most notable, is known as the Maunder Minimum (Figure 3), during which there were close to no sunspots for decades, lasting from about 1645 AD until 1715 AD (Beer et. al., 2006). TSI during this time period was reported to be 0.85 ± 0.16 W/m^2 lower than the typical average of 1365.9 W/m^2 (Roth & Joos, 2013). This difference, while seemingly small, could have had significant implications, and further proves that the solar "constant" does, in fact, fluctuate (Beer, 2005). More sunspots have been observed during the last few decades than during any time in the Holocene (Figure 3), further explaining why some have proposed a solar role in late Holocene warmth (Versteegh, 2005). It is well known that solar activity typically oscillates on what is known as the “11-year cycle” (Space Studies Board, 2012). This encompasses both the presence of sunspots and levels of solar activity, which is inevitable given the highly correlational relationship between the two (Figure 1).

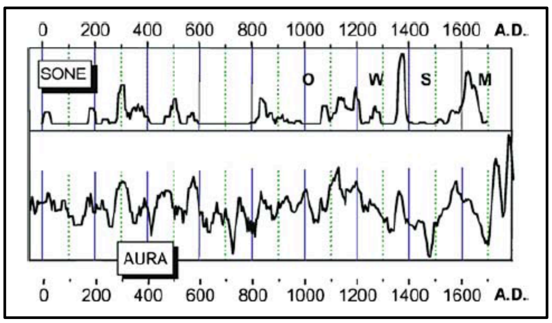

Fig. 2: Notable sunspot minima: O=Oort, W=Wolf, S=Sporer, M=Maunder, and aurorae (Versteegh, 2005).

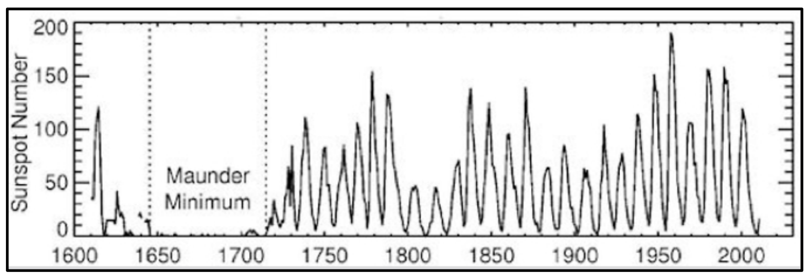

Fig. 3: Maunder sunspot minimum in more recent history (Space Studies Board, 2012).

Lastly, an important factor relating to radiative energy in the atmosphere and at Earth’s surface is, quite generally, geomagnetism. Along with the output of mass in the form of energy by radiation and solar flares, the Sun dispenses a charged cloud of particles: ionized gas that is referred to as "solar wind" which is deflected by Earth's geomagnetic shield (Ruddiman, 2013). Geomagnetic variation and changes in solar deflection have the potential to alter how much energy penetrates the shield and reaches Earth's atmosphere (Ruddiman, 2013). The intensity of cosmic rays that reach the Earth is modulated by the shielding of the field as well as the modulation controlled by the particles in the solar wind itself (Roth & Joos, 2013). In simpler terms, the solar wind has the potential to deflect cosmic rays from reaching the Earth's upper atmosphere. This "modulation process" entails a loss of energy from galactic cosmic ray (GCR) protons due to the "increased intensity of the magnetic field carried by the solar wind" (Beer et. al., 2006).

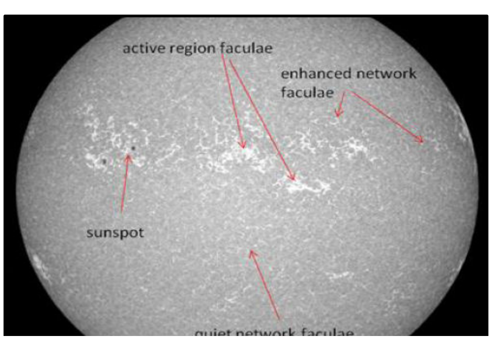

Fig. 4: Notable features of the Sun (Space Studies Board, 2012).

III. Methods and research tools

While it may seem primitive, some of the earliest direct observations of solar activity on a decadal to centennial scale date back to ~400 years ago in the early seventeenth century (Beer et. al., 2006). These observations included historical records of sunspots using early telescopes as well as sightings of aurorae (Ruddiman, 2013). Observers in the 1850s noticed an association between the sunspot cycle and aurora borealis, which led to the convincing correlation with disturbances in Earth's geomagnetic field and evidence of real, terrestrial, solar effects (Geophysics Research Board, 1982). Direct observations evolved to include aa-index, which is used to measure geomagnetism and is understood to correlate with how much irradiance reaches Earth's surface (Cliver et. al., 1998). Measurements of TSI at the upper atmosphere extend ~30 years back (Beer et. al., 2006); however, these calculations have been extended farther into the past due to advancements in modeling using global circulation models and proxy studies, which are also used to examine critical shifts in the climate system (Kopp & Lean, 2011).

Looking to palaeoclimatic proxies has allowed researchers to piece together solar history on a broader and earlier scale. Long-term reconstructions of solar activity and TSI have been made possible by two particular cosmogenic radionuclide isotopes, Beryllium-10 (^{10}Be) and Carbon-14 (^{14}C) (Roth & Joos, 2013), both of which are formed by collision of cosmic rays with atmospheric particles (Ruddiman, 2013). ^{10}Be and ^{14}C are conveniently the most abundant radionuclides, as well as the two that reach farthest back in time (Raisbeck & Yiou, 1980). ^{10}Be records are able to reconstruct to ~10 ka, and ^{14}C reaches ~7 to 10 ka (Ruddiman, 2013). Both are used equally to assist in long-term reconstruction and are relevant to climate change and solar variability due to their varying isotope ratios from fluctuating contact with cosmic rays (Lockwood & Frohlich, 2007). Their relation to solar activity is clear due to their vastly different transportational and depositional processes, leaving the incident cosmic ray flux as the common link between the two (Lockwood & Frohlich, 2007). This connection is helpful in reducing the chance of covariance due to non-solar forcing (Versteegh, 2005) and the correlation between the two can be viewed in detail in Figure 5. It is important to note that both ^{10}Be and ^{14}C are "anti-correlated" with solar activity, meaning that less solar activity leads to higher levels of radionuclides, or faster rates of production (Raisbeck & Yiou, 1980). When there is more solar activity, there is a higher amount of deflection by solar wind particles (Ruddiman, 2013). Therefore, less cosmic rays reach the geomagnetic field to contact atmospheric particles, and subsequently less radionuclides are produced, or they are produced more slowly (Yiou et. al, 1997).

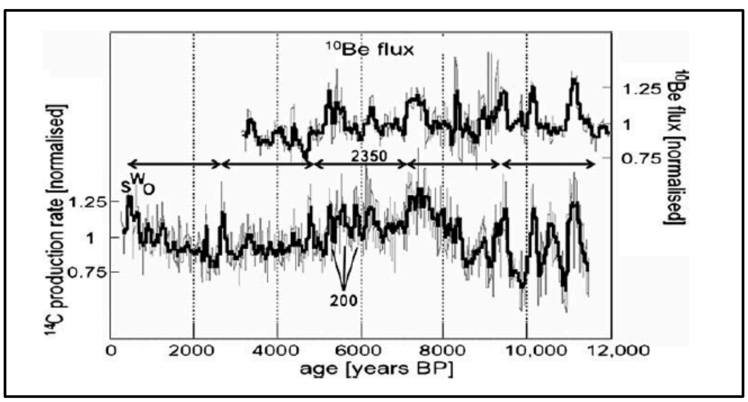

Fig. 5: Comparison of Beryllium-10 (^{10}Be) and Carbon-14 (^{14}C) (Versteegh, 2005).

While this relationship was proposed quite some time ago, it has since been confirmed that high solar activity leads to a stronger magnetic shielding of galactic cosmic rays (GCR), thus lowering the production rate of cosmogenic radionuclides (Roth & Joos, 2013). It has been theorized that three major parameters control the production of radionuclides: primary cosmic ray intensity, solar modulation, and geomagnetic modulation (Yiou et. al., 1997). We are mainly interested in the first forcing, yet it is important to acknowledge how the other factors can significantly alter rates of production and potentially affect results of studies that are purely interested in TSI. Since the radionuclide production can depend on modulation and shielding effects that are separate from intensity of solar output, it can be difficult to attribute varying isotope levels to changes in TSI or cosmic ray intensity alone (Beer et. al., 2006).

^{14}C is produced by interaction of GCRs with nitrogen in the Earth's atmosphere (Lockwood & Frohlich, 2007). Most of the relevant studies use ^{14}C records from tree rings (Roth & Joos, 2013), and it is often associated with a slower response to climatic forcing factors due to the relatively lengthy process of carbon moving through large reservoirs in the carbon cycle (Lockwood & Frohlich, 2007). Another disadvantage to using ^{14}C as a proxy is that, in recent times, its levels may be affected by the "Suess Effect" and not truly due to variations in solar energy output (Raisbeck & Yiou, 1980). The "Suess Effect" refers to the idea that recent emissions due to burning of fossil fuels have coupled with the greenhouse effect to potentially alter the ratio of carbon isotopes in the atmosphere, which could potentially attribute varying ^{14}C levels to a different forcing than solar (Raisbeck & Yiou, 1980). Observed ^{14}C variations in tree ring data during the Holocene have also been criticized due to the probable cause of geomagnetic field variation or general climatic causes rather than solar variability (Yiou et. al., 1997).

^{10}Be, while also formed by interacting GCRs, involves oxygen, nitrogen, and argon from the atmosphere (Lockwood & Frohlich, 2007). ^{10}Be attaches the aerosols in the atmosphere and typically reaches the Earth's surface via precipitation or "wet deposition" within 1-2 years of attachment (Versteegh, 2005). Because of this, ice cores are the most frequently used research tool for measuring past ^{10}Be levels (Roth & Joos, 2013), but ocean sediment cores are also notable geophysical reservoirs (Lockwood & Frohlich, 2007). Notable studies of ice cores include Summit, Greenland, (GRIP) and Law Dome, Antarctica (Yiou et. al, 1997). Both have been linked on a verified time scale by the well-known ^{10}Be peak at ~41 ka (Raisbeck et. al., 2016). Centennial variations found in ^{10}Be core profiles are believed to result from solar variability (Raisbeck et. al., 2016); however, there is still much discussion regarding attribution of different forcing factors.

Due to its sensitivity to shifts in Earth's climate system, specifically currents, winds, and temperatures associated with thermohaline circulation (THC), ice-rafted debris (IRD) is sometimes used as a palaeoclimatic proxy as well. IRD refers to particles that are picked up by glaciers and deposited into ocean sediments when the glacier melts (Beer et. al., 2006). It is also found to be highly correlated with both ^{10}Be and ^{14}C cosmogenic isotopes (Lockwood & Frohlich, 2007). Some studies have found it to correlate with solar activity, but with a few anomalies (Figure 6). Cold periods with more ice-rafted debris are typically linked to periods of low solar activity and high ^{10}Be concentration (Beer, 2005).

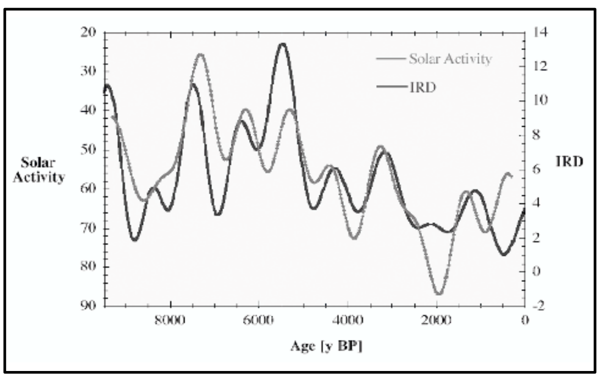

Fig. 6: Comparison of ice-rafted debris (IRD) and solar activity (Beer, 2005).

IV. Predicaments in studies

As much as technological advances and emerging information has progressed research in this particular field, studying the Sun is not without its shortcomings. Past researchers encountered the dilemma of a fundamental lack of physical understanding of solar processes, along with the lack of resources to further tighten their grasp on the topic (Geophysics Research Board, 1982). Basic solar functioning is much less controversial and more widely understood today, while its implications still remain a topic of discussion. Even though knowledge about physical processes has largely increased, the solar forcing is still the least understood of any radiative forcing that may be of relevance to modern climate change (IPCC, 2013). A pertinent modern issue is, in general, that a factor of uncertainty is already introduced without high-resolution age assessments, leading to a possible misinterpretation of spatial and temporal relationships (Versteegh, 2005). This is further complicated due to the often non-linear response of the climate system, making patterns even more difficult to identify (Beer, 2005).

The validity of records also introduces a level of ambiguity. Historical records of both the climate and direct solar observations are heavily biased to focus on larger, potentially catastrophic, or more unusual events, which can leave researchers with a degree of discontinuity (Versteegh, 2005). Natural records are not without their flaws, especially regarding quantification and interpretation of the information stored by nature (Beer, 2005). The need for a long-term solar record calls for the introduction of proxy studies, since direct records of TSI do not extend back into the last glaciation (Ruddiman, 2013). It is argued that the use of proxies ushers in more uncertainty due to the potential for attribution errors, as well as the difficulty of translating proxy records with a "transfer function" into quantitative climatic parameters (Versteegh, 2005). It can, at times, be difficult to attribute seemingly clear proxy results to solar forcing alone, which leads us to the issue of separating all of our known climate forcing factors, shown in Figures 7 and 8. The most ideal, favorable geophysical reservoir would have good resolution, reliable chronology, a continuous record, and minimal interference from other effects that may alter production of cosmogenic proxies (Raisbeck & Yiou, 1980); however, this is nearly impossible to find without compromising at least one aspect of the study.

Accurately measuring TSI can be extremely difficult, and it is also important to be cognizant of attribution errors due to instrumental drift (Kopp & Lean, 2011). Accurate and stable TSI timelines are necessary for attributing past changes to the solar forcing (Kopp & Lean, 2011), and the future of solar variability has proven to be difficult to construct and predict as well (Lockwood & Frohlich, 2007). Some observed changes have also been attributed to internal variability within the climate system (Mann et. al., 2009). Lastly, it is vital to have an accurate climate record with which we can compare reconstructed solar records. Most climate records are also proxy-based, and there are occasional disagreements on definitive climatic patterns (Versteegh, 2005). All of these predicaments lead to difficulty in studying the solar forcing and concluding concrete, practical information from various studies. Studying solar processes at too large of a scale may cause the effects to be underestimated or overlooked, while only studying smaller scales may cause the effects of the forcing to be lost in local peculiarities (Versteegh, 2005).

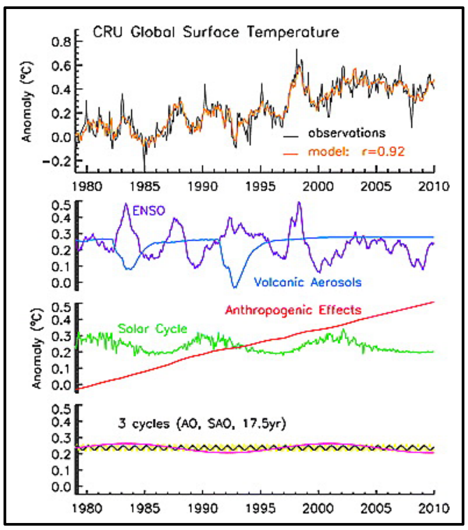

Fig. 7: Global surface temperature since 1980 AD compared to various forcing factors (Kopp & Lean, 2011).

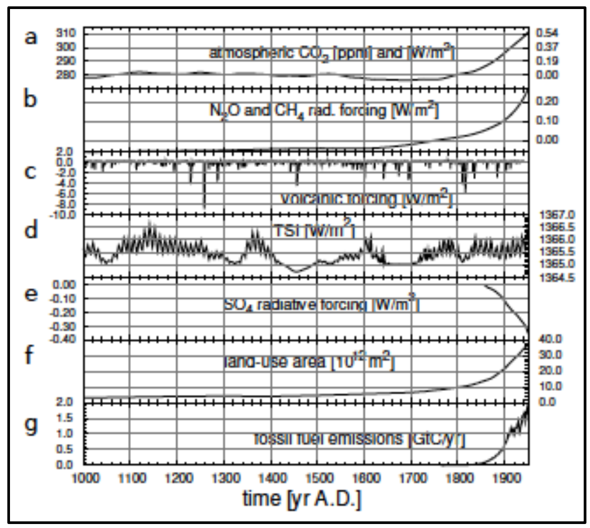

Fig. 8: Comparison of various climatic measurements since 1000 AD (Roth & Joos, 2013).

V. Theorized sun-climate links

There is no shortage of theories about the link between solar activity and the climate system, some more outlandish than others. The potential of the Sun to largely affect the entire balance of our planet has led to ideas about just how much it can affect us, and there is often much evidence offered in rebuttal to these grand conclusions. One of the very first proposed theories was that there was a link between the 22-year observed drought cycle in the United States, since it resembled a cycle double that of the 11-year sun cycle and coincided with the 22-year magnetic cycle of the Sun (Geophysics Research Board, 1982). However, this theory was proposed before there was extensive knowledge about solar processes and relationships, and was later disproven with evidence that there was no temperature signal response found for the 11-year cycle at any point in observable history (Ruddiman, 2013).

The issue of attribution recurs throughout the process of disproving of various theories in that it is difficult to attribute some changes to the solar forcing alone. One such example of this is the proposed link between ^{10}Be and $\delta^{18}O$, a well-known indicator of temperature, as evidence of a solar role on temperature in the last millennium (Ruddiman, 2013), shown in Figure 9. Researchers have also looked at solar variability as the cause of variable global ice around 41 ka (Ruddiman, 2013) due to the observed ^{10}Be peak found in polar ice cores (Figure 10). However, with both of these cases, it has been deduced that ^{10}Be can largely be affected by snow accumulation and ice sheet growth or retreat. This phenomenon in which snow may have an effect on results from polar ice cores has been referred to as the "Dilution Effect" (Yiou et. al., 1997). This begs the question: can we really attribute ^{10}Be changes to solar activity causing a climatic fluctuation, or is this simply just indicative of a climatic shift with questionable cause? Older studies suggest that variations in ^{10}Be flux are caused by a combination of cosmic ray variations and solar and geomagnetic modulation (Yiou et. al., 1997), but most evidence is not concrete to prove that the solar forcing has caused immediate surface temperature changes observed by δ^{18}O and ice sheet variability. No millennial-scale correlation between these two proxies has been observed before the Holocene (Ruddiman, 2013). Another notable explanation for the ^{10}Be peak ~41 ka proposed that solar variability combined with low geomagnetic intensity, since ~41 ka was the well-known Laschamp geomagnetic excursion (Raisbeck et. al., 2016). This is plausible, given the potential of geomagnetism to affect the effects of cosmic rays.

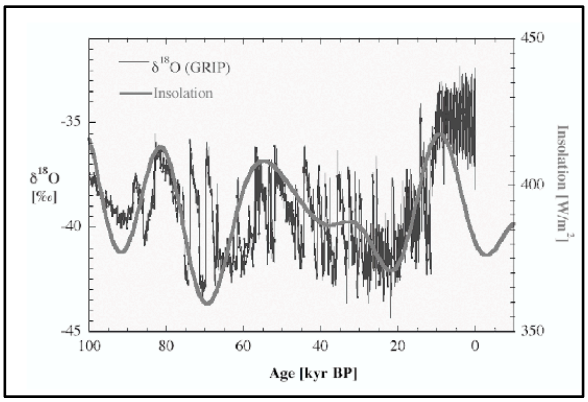

Fig. 9: Solar irradiance compared to $\delta^{18}O$ from ice core records (Beer, 2005).

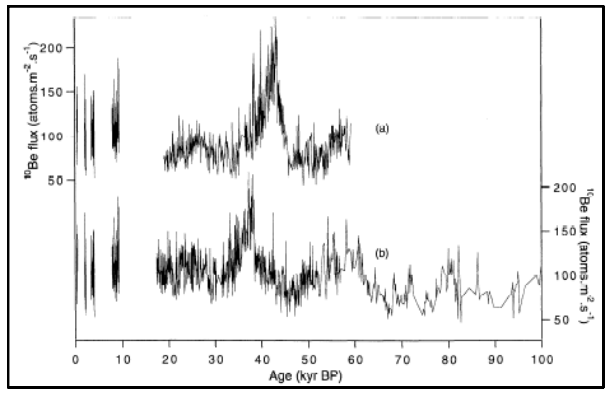

Fig. 10: Agreement between Beryllium-10 ice core samples from Antarctica and Greenland (Yiou et. al., 1997)

The ice cores taken at Law Dome, Antarctica, have effectively disproved previously believed correlations between ^{10}Be and δ^{18}O (Pedro et. al., 2011). This study found short-term peaks in ^{10}Be concentrations to be potentially altered by input of stratospheric air, which is typically rich in ^{10}Be, into the polar troposphere. However, the study mainly focuses on the unreliability of the ^{10}Be and δ^{18}O correlation due to the tendency of ^{10}Be deposition at Law Dome to be "dominated by precipitation-related processes" (Pedro et. al., 2011). Aside from true solar variability, the authors have also entertained the possibility that ^{10}Be production is altered by other processes such as variations in the solar magnetic field (Beer et. al., 2006). Estimates from this study conclude that up to 40% of the variance in ^{10}Be concentrations from this particular ice core may be explained by solar modulation of atmospheric production rates of radionuclides; however, the rest is open for speculation (Pedro et. al., 2011). Many researchers are in agreement that snow accumulation plays a large role in ^{10}Be production, and some even reaching as far as to claim that both ^{10}Be and ^{14}C production are solely responses to internal climatic functions, such as atmospheric and oceanic circulation (Ruddiman, 2013). It is well accepted that more dilution of the ^{10}Be signal, or interference due to precipitation, is present in cores from Antarctica than those from the GRIP project in Greenland (Raisbeck et. al., 2016).

Century-long changes in solar variability have also been proposed as a reason for cooling during the Little Ice Age (LIA), a period from about 1300 to 1870 AD during which Europe and North America experienced much colder winters, along with surface temperatures about 1 degree Celsius cooler than during the 20th century, due to its temporal correlation with the Maunder sunspot minimum (Geophysics Research Board, 1982). Before the industrial era, the effect of anthropogenic forcing on the climate was virtually negligible, leaving natural forcing factors to explain the low temperatures of the LIA (Beer, 2005). It has also been theorized that temperature change during this time was not entirely caused by solar variability, but also coupled with the volcanic forcing to create a joint amplified cooling effect (Mann et. al., 2009). However, it has been noted by many researchers that volcanic activity during this period is a strong argument alone for LIA cooling (Space Studies Board, 2012). Likewise, small changes in solar insolation during the past 1.5 ka most likely require additional forcing, particularly explosive volcanism, to have played a role in observed late Holocene cooling (Cabedo-Sanz et. al., 2016). An increased amount of SO_2 is emitted during an eruption, which reacts with water in the atmosphere to form sulfuric acid (Versteegh, 2005). These aerosols transported into the atmosphere from volcanic ash have the possibility to largely effect temperature since they block sunlight and increase atmospheric reflectivity, and can even have a long-term effect on the climate if the ash reaches the stratosphere (Ruddiman, 2013).

Various other claims have attempted to link solar variability to other known climatic shifts, such as recent Holocene warming. However, recent theories have placed this as implausible. Evidence lies in the Maunder Minimum, which previously mentioned, was marked by the nearly complete absence of sunspots (Beer, 2005). Researchers theorized that if these conditions would have persisted for much longer than they did, the climate would have had adequate time to produce an equilibrium response (Ruddiman, 2013). From this, we can conclude that changes that occur for this amount of time do not have a large effect on the climate system as a whole. Therefore, small amounts of solar variability would not be able to cause a climatic response as quickly as recent warming has occurred. Even studies that have applied amplification from various other mechanisms to the solar forcing still conclude that solar variability alone is not considerable enough to have entirely caused the rise in global mean temperatures after 1985 (Lockwood & Frohlich, 2007).

Through ice-rafted debris (IRD), researchers have proposed a link between solar variability and climate change on a millennial time scale. The evidence for this lies mainly in the Holocene (Ruddiman, 2013). However, this claim is not substantial due to the fact that there are no similar millennial-scale correlations found before the Holocene (Ruddiman, 2013). If there were a millennial-scale connection, it would have likely persisted farther back in climatic history. Other evidence against this theory is that various other sun-like stars were examined and none of them detected any millennial-scale change (Ruddiman, 2013).

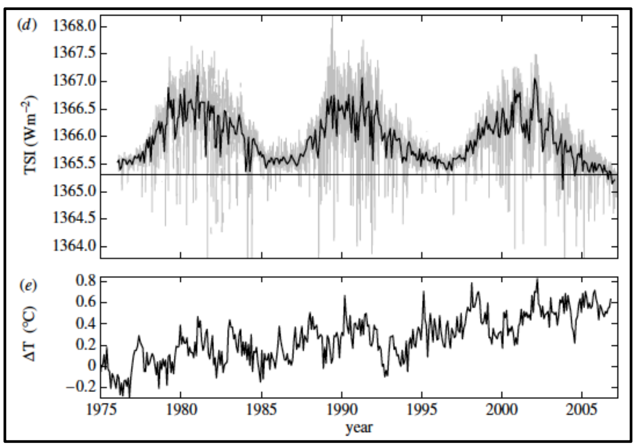

Fig. 11: Change in surface temperature compared to TSI (Lockwood & Frohlich, 1997).

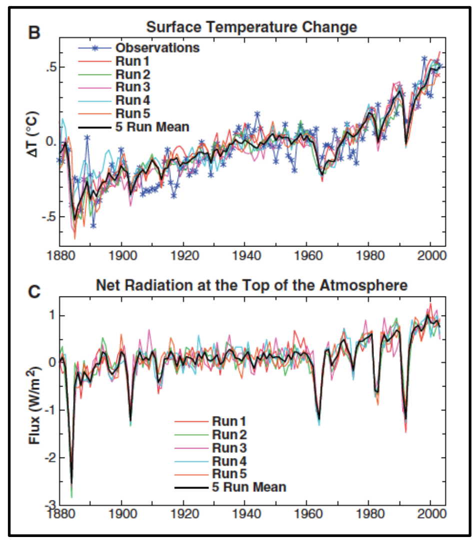

Fig. 12: Change in surface temperature compared to radiation reaching the atmosphere (Hansen et. al., 2005).

The last theory in discussion comes from an opposing claim that solar variability affects extremely short-lived climatic patterns, namely tropospheric weather (IPCC, 2013). Several theories suggest that the stratosphere plays a key role in putting the solar forcing of tropospheric climate into effect (Versteegh, 2005). In contrast to TSI, changes in the UV output from the Sun are theorized to play a role in the ozone content in the stratosphere (Beer, 2005), which in turn is believed to affect cloud cover and circulatory weather patterns in the lower atmosphere (IPCC, 2013). It has also been proposed that the formation of ozone can be altered by solar wind, also resulting in change in climate at Earth's surface (Ruddiman, 2013). This theory is not widely accepted, but it is also not yet widely studied nor completely understood. It is important to note that surface temperature does not respond to the 11-year cycle and changes in the lower atmosphere are separate from this fluctuation (Lockwood & Frohlich, 2007).

This launches us into the ongoing discussion of whether the sun-climate link is a “top-down” or “bottom-up” process (Space Studies Board, 2012). "Top-down" refers to the notion that the solar rays affect the atmosphere, and the effects continues downward towards the surface and further affects processes at the surface. In contrast, "bottom-up" is the opposite idea that solar rays would affect surface processes, such as ocean circulation, directly, and then the consequences move upward to affect the atmosphere and large-scale temperature dynamics (Space Studies Board, 2012). Figures 11 and 12 show surface temperature changes and several measures of solar radiation, showing minimal evidence that is immediately compelling with the exception of a few dips in temperature and radiation in Figure 13. One particular study examined global mean surface air temperature (SAT) due to TSI changes only through reconstructions and estimates (Figure 13), which yielded a value less than 0.15 degrees Celsius at any time during the Holocene, and extremely small moments of higher SAT were not consistent throughout the time period. (Roth & Joos, 2013).

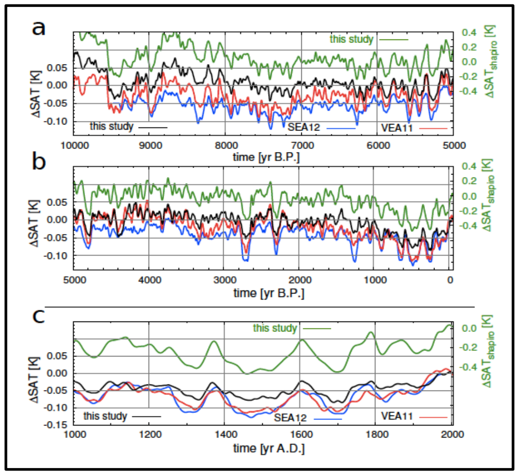

Fig. 13: Time vs. change in temperature due to TSI (Roth & Joos, 2013).

VI. Conclusion

In general, it is fair to conclude that the solar forcing remains a player in the climate system, but is not a major player (Ruddiman, 2013). Past estimates placed temperature changes due to solar forcing since the late 1800s at ~0.4 of the 0.8 degree Celsius change, or almost half of the warming; however, recent estimates place the correctly attributed warming in the range of 0.07-0.1 degrees Celsius, or, at most, ~12.5% of the total warming (Ruddiman, 2013). There is significant evidence of the effect of a variable solar "constant" on decadal and centennial scales, but it appears to be widely unaccepted that there is any correlation on a long-term, millennial scale, as well as a lack of climatically relevant results from these small deviations (Beer et. al., 2006). Millennial oscillations of climate are still largely believed to result from random behavior in the climate system, but their direct cause in the present interglacial are still under examination (Ruddiman, 2013). There is no temperature signal apparent for the 11-year cycle, since it is probable that these fluctuations are too small and too short-term to evoke an equilibrium response from Earth's climate system (Ruddiman, 2013). However, the relationship between solar variability and short-term climate should not be entirely dismissed. While the idea is still emerging and is not yet entirely proven, the proposed link between TSI and tropospheric weather patterns is hard to ignore. Sun-climate links through both the stratosphere and troposphere remain possibilities, but are largely speculative at this time (Ruddiman, 2013).

Studying the Sun is also relevant to cloud cover and a phenomenon known as "global dimming". While this refers more to the amount of solar radiation reaching the Earth's surface and less with the variable amount of output from the Sun, it is vital when examining reasons for recent climate change. During the 1950s through the 1980s, the heightened amount of fossil fuels being burned has added more aerosols to the atmosphere and even formed brown clouds in some regions (Ruddiman, 2013). Because of this, less radiation reaches the surface due to the blockage of the Sun's rays, or the reflection of radiation back into space. Satellites observed significantly less surface brightness of the Earth. It is theorized that this blocking of sun was strong enough to cancel greenhouse gas warming from these emissions from around 1940 to 1970 AD (Ruddiman, 2013). Since the 1980s, a drop in emissions from India and China has reduced this effect, causing more solar radiation to reach the surface; however, other countries have increased their industry and consumption, particularly in Southeast Asia where dimming is still experienced, causing uneven results across the globe (Ruddiman, 2013). In general, gaining more knowledge about natural forcing factors during the industrial era will lead to better quantification of anthropogenic effects, which will ideally lead to better predictions and solutions in the future (Beer, 2005). Since 1985, solar activity has been declining after the presence of a grand maximum, and it is predicted to do so over the next century. This could possibly reduce the solar forcing of climate, but it is quite questionable as to whether it will counteract anthropogenic causes of greenhouse warming (Lockwood & Frohlich, 2007).

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