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SEA LEVELS IN A CHANGING CLIMATE

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ABSTRACT: The rise of sea levels could have devastating consequences for coastal settlements, and it can easily be one of the most critical effects of climate change. Thus, all factors affecting sea levels need to be considered. One of the factors discussed in this paper is the natural variability of sea levels, which originates from the oscillation of the planets and solar activity. The effect of the Sun's activity on Earth's climate has been identified since the 1800s. However, there are still many unknowns regarding the mechanisms connecting the Earth's climate to the variation in solar irradiance. Climate modelling that implements the solar sciences is a novel approach that accounts for the considerable effect that natural factors have on the climate, especially at regional level. This paper discusses the noticeable effect that planet oscillations have on the Sun's activity, which gives a very good correlation with the observed patterns in global surface temperatures, rainfall records and sea levels. In agreement with many studies that have identified a 60-year cycle in the variation of Earth's temperature, it is expected that surface temperatures will reach a trough of the cycle around 2030-2040. Furthermore, considering the influence of the Solar Inertial Motion, a solar slowdown is predicted for Solar Cycles 24 and 25, which will create a weak grand minimum. It is anticipated that this weak grand minimum will be reflected in a dampening effect of global temperatures, and a subsequent moderation in the rate of sea level rise.

Keywords: Solar Activity, Sea Level Rise, Planetary Oscillations, 60-years Cycle

1. INTRODUCTION

There is abundant evidence of large changes in sea levels during Earth's history. For example, about 120,000 years ago during the warm period, the average global temperature was about 2 degrees Celsius higher than today, and the sea level was 5 m above present levels [1]. Then, 22,000 years ago during the Ice Age, the sea level was 120 m lower than today [1].

Paleoclimate reconstructions based on climate proxies such as ice cores, tree rings and lake sediments, show an association between these warm and cool periods on Earth and the Sun's activity. Most reconstructions of the solar activity are based on the sunspot number, the solar cycle's length or frequency. Eddy [2] noted a correlation between periods of significant change in the number of sunspots in the past millennium and large changes in the climate of the Earth. Hence, many studies have reported that lower than average European temperatures were recorded during periods of low solar activity [3]–[7]. Such periods of low solar activity are the Maunder minimum (1645-1715), Dalton minimum (1800-1820), 1900 minimum (1880-1900), and a slight decrease between 1940 and 1970. In addition, a sharp rise in global temperatures around 1830 relates to high solar activity. Superimposed on these long-term trends of minima and maxima are short-term fluctuations caused by the Schwabe cycle [8], [9]. Furthermore, other studies suggest that the climate and atmospheric oscillations, such as the Pacific Decadal Oscillation (PDO), the Atlantic Multidecadal Oscillation (AMO) and El Niño Southern Oscillation (ENSO), are synchronized to the natural oscillations of the Solar System, which are driven by the movements of the planets around the Sun and lunar gravitational tides [7], [10]–[12]. In addition, Chambers *et al.* [13] identified multi-decadal oscillations of about 60 years in most of the ocean tide gauges examined, which are believed to be related to wind forcing and current variations [14]. As such, they are not spatially uniform and are directly associated with atmospheric oscillations such as the PDO, AMO and ENSO, and they influence sea surface temperatures, pressure levels and surface winds [15]. Moreover, Reid [16] compared the long-term trend of Sea Surface Temperature (SST) with the corresponding trend of solar activity and found a significant correlation, especially during the minima periods.

Numerous studies have reported that the Sun's activity is moderated by the oscillations of the planets in our Solar system, modifying so the relative location of the Barycenter to the Sun's center of mass [10], [17], [18]. These studies also noted that the oscillations of the planets have a close link with the variations of Earth's global average temperatures, sea temperatures and sea levels.

Zhang and Church [19] suggested that coastal regions are mainly impacted by the combined effect of long-term sea level rises and natural variability. The fact that sea level rises are not uniform across the oceans of the world makes it difficult to separate natural variability from the signal of climate change at a regional scale. In agreement with the Intergovernmental Panel for Climate Change (IPCC) physics-based projections models, it was predicted that sea level changes are likely to observed on over 80% of the world's oceans by 2030 [20]. However, another study [21] suggested that, in the next 20 years, at a regional scale, the signature of natural variability is likely to exceed the effect of the anthropogenic climate change on sea levels for many areas of the globe.

Despite the general agreement that Solar activity affects the Earth's climate, which is supported by the broad data and re-emerging theories, the solar effects on climate are not yet well-defined. Jones *et al.* [22] used a simple climate model to assess the potential implications for future climate projections for a range of solar radiance scenarios, and predicted that the influence of future solar activity will be much smaller than the range of forecasted changes of the modelled anthropogenic effects. However, this study was based on Total Solar Irradiance (TSI) variations and concluded that the use of TSI may not capture the net effect of solar variability, as it fails to incorporate ultra-violet (UV) variability and 'top-down' influences through stratospheric changes. Another important aspect to consider is that, even though the solar influence shows small effects on global temperatures compared with the modelled anthropogenic effects, the regional and seasonal variations around the globe are more closely linked to solar activity. Hence, regional climate modelling needs to consider a larger forcing due to solar and natural variability [4], [23]. Subsequently, it is expected that regional sea level changes will be closely related to natural variability and solar forcing.

Van Loon and Meehl [7] noticed that when the sunspots peak and the North Atlantic Oscillation (NAO) are in phase, there is an intensified positive NAO with negative Sea Level Pressures (SLP) anomalies in the North Atlantic greater than 6 hPa and positive anomalies of about 3 hPa in the subtropical North Atlantic. This is likely to have a considerable effect in the ocean basins, given that under a positive NAO index (NAO+), the 'inverse barometer effect' is observed on a regional basis, where the reduction in atmospheric pressure creates a regional rise in sea levels. This effect is important for both the interpretation of historic sea level records and predictions of future sea level trends, as mean pressure fluctuations of the order of few hector-Pascals can lead to sea level fluctuations of the order of centimeters [24].

There are various factors that contribute to sea level rises, although the thermal expansion of water in the oceans is the most influential factor, and it accounts for about 35% of the predicted sea level rises [25]. Thermal expansion of the oceans is complex and depends on the water temperature, the global surface temperature, and the ocean's thermal inertia. Therefore, observing the trends and oscillations of global temperatures can serve as a guide to the shifts in the levels of world's oceans.

Some studies [10], [26], reported that the average global temperature records are characterized by decadal and bi-decadal oscillations. In general, these oscillations are in good correlation with the 11-years Schwabe and the 22-years Hale Solar cycles, with higher global temperatures related to higher solar activity. Current predictions on Solar activity show that we are in a low sunspot cycle, which is similar to that of the 1900 Minimum, and subsequent cycles are predicted to have even lower Solar activity, and therefore a drop in global temperatures is expected [27]–[29]. Based on this last statement, and considering that the thermal expansion of the oceans is a very influential factor, it is predicted that sea levels will follow the global temperature oscillations (with a lag due to thermal inertia), resulting in a subsequent moderation in the rate of sea level rise, as happened in 2010-2011 due to an exceptionally strong La Niña event [30].

2. SEA LEVELS

There are two main data sources for global sea levels, namely satellite altimeters and tide gauges. Figure 1 presents the Global Mean Sea Level (GMSL) monitored between 1993 and 2015 by the TOPEX/Poseidon, Jason-1, and Jason-2 satellites [31]. It should be observed that the trend is linear, with an increase rate of 3.4±0.4 mm/yr.

It is important to note that there are many methods used to review sea level rises, and they employ different approaches and assumptions. At times, the outcomes of these analysis lead to contradictory acceleration and deceleration inferences. Visser *et al.* [32] examined in detail around 30 of the methodologies used to review sea levels. Multiple analysis methods and additional information, such as the SOI or PDO, were used to provide a better description of sea level trends.

Watson [33] developed a methodology to provide a consistent and transparent appraisal of the acceleration in mean sea level records using the Singular Spectrum Analysis (SSA). This technique readily separates the trend of sea levels from the 60 years dynamic ocean oscillations and noise.

It should be noted that the Satellite data (Fig. 1) has some limitations, as it spans only over 20 years, and hence cannot encapsulate and describe larger multi-decadal scale natural oscillations. In contrast, tide gauges offer a long-term view of the changes in mean sea level. However, the tide gauges are mainly located in the Northern Hemisphere (Europe, Japan, the United States), which results in poor sampling [34].

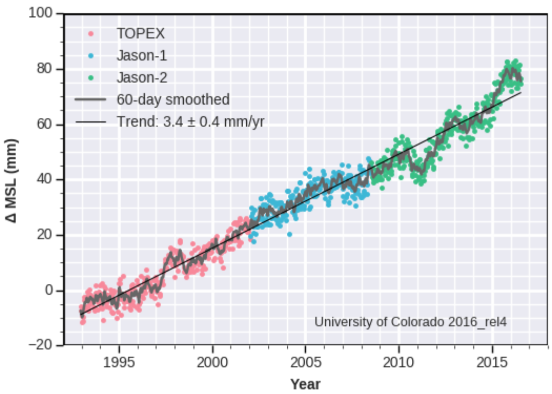

Fig. 1 Satellite altimetry time series 1993-2016 [31]

Additionally, tide gauge records do not cover the same time period [34]. Therefore, it is useful to define sea level variations on a regional base, and to consider a wide range of local processes to eliminate misleading estimates that global ocean level averages could introduce. Furthermore, the effects of natural variability are likely to influence ocean levels without adding to the volume of water.

3. FUNDAMENTAL DRIVERS FOR NATURAL CLIMATE CHANGE VARIABILITY

Fluctuations in oceans levels are common, and this paper investigates their relationship to natural variability and oscillations. These natural oscillations have drivers, such as solar variations, planetary forces, and Earth's orbital changes. It is suggested that these three natural drivers for climate variability have a noticeable influence on surface temperature patterns, and consequently sea level rises [35]. Other natural drivers, such as volcanic eruptions and regular, repeatable lunar motions, are excluded from this paper [36].

3.1 Solar Variation

In 1843, astronomer Henrich Schwabe was the first to demonstrate the 11-year cycle of sunspots. English astronomer Walter Maunder reported that sunspots had been generally absent from 1645 to 1715. Such a period with a minimum number of sunspots is now known as the Maunder Minimum (Fig. 2), and was accompanied, in Europe and other regions, by the most severe temperature dip for several millennia [37].

Eddy [2] noted a correlation between periods of significant change in the number of sunspots in the past millennium and large changes in Earth's climate. Figure 3 illustrates the correlation between the sunspots' activity and the drops of temperature registered in history. It should be observed that the periods of minimum temperature (Maunder, Dalton and 1900 Minimum in Figure 2), occurred when the number of sunspots was considerably lower than for other periods.

The solar activity alternates between active and quiet phases with a frequency of 11 years, which is known as the Schwabe cycle. Figure 3 presents the 11-year cycles of solar activity. It shows a maximum of 150 sunspots for Cycle 24, contrasting with 81.9 sunspots reported by NOAA in April 2014. This is the cycle with the lowest maximum of sunspots since Cycle 14, which had a maximum of 64.2 sunspots recorded in February, 1906. Cycle 14 coincides with the 1900 Minimum [29].

The variations in the sunspot number reflects the solar activity, and therefore they are related to the changes in Total Solar Irradiance (TSI). The monitored values of TSI since the beginning of the 1990s show a decline, and the last value measured for Cycle 24 was 1361.53 W/m^2.

Research by [29], predicts that the Solar Cycle 25, which will peak around 2022, will be the weakest one in centuries. In addition, it is anticipated that the

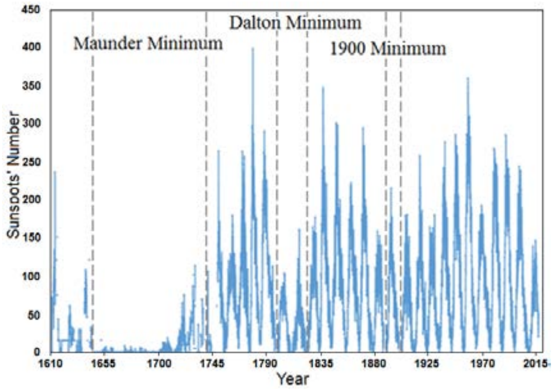

Fig. 2 Sunspots numbers and the periods of reduced Solar activity (after [8], [37])

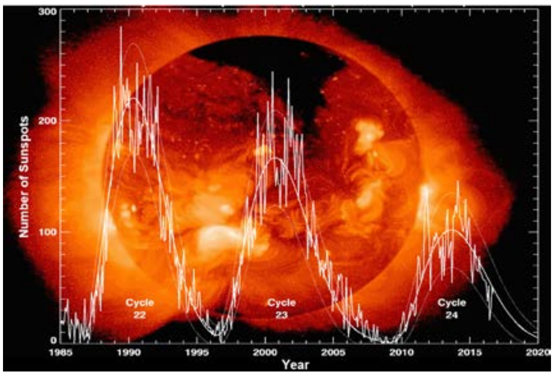

Fig. 3 Projected and observed sunspots (after [37])

reduction in the Sun's activity will result in a drop in temperature, due to the reduced solar energy received.

These changes in TSI would be counterweighed by the thermal inertia of the ocean. However, a low TSI for two or more consecutive cycles will cause temperatures to drop, and cause a delayed sea level decline, due to the thermal inertia of the ocean. It is worth noting that the variation of the TSI might be increased by feedback mechanisms that amplify the solar variations, generating large weather effects. It is believed that some of these mechanisms are radiative forcing, cosmic rays, the stratospheric solar vortex, cloud cover and albedo, cosmic rays related to changes of the ozone layer, etc. [38], [39]. However, these mechanisms are outside the scope of this paper.

3.2 Planet Forces

In addition to the findings reported earlier, many studies [28], [40]–[42] concluded that the Sun's activity is moderated by the Solar System planets' oscillations, which shift the location of the Solar System Center of Mass (SSCM) or the Solar System Barycenter (SSB). Furthermore, there is a close link between planetary oscillations and Earth's global average temperature variations, and thus with sea temperatures and sea levels.

Charvátová [43] reviewed work by Paul Jose, who was one of the first researcher to link solar modulation with planetary movements. Jose observed that the Sun oscillates around the center of mass of the Solar System (Barycenter), to balance the variation in the positions of the planets. Hence, the center of gravity remains at rest. The Solar Inertial Motion (SIM) and Solar variability studies found that the planets returned to roughly the same position every 178.8 years, or 172 years as suggested by others. It was observed that the sunspots activity has a similar frequency as the periodicity of the planets' movements [43].

The extent of the Sun's oscillation around the Solar System Barycenter is affected by the relative mass of the planets, as displayed in Fig. 4. Figure 4(a) shows the positon of the center of gravity of the Solar System. Figure 4(b) simulates the significant shift in the position of the Barycenter when Jupiter is removed from the Solar System. Figure 4(c) shows the change in the location of the center of gravity if both Jupiter and Saturn are removed. Once Neptune is removed, the effect of the remaining planets is barely noticeable. Hence, Jupiter has the highest effect on SIM, due to its largest mass [10], [28].

The gravitational forces between the planets and the Sun affect the dynamics of the Solar System, and cause harmonic resonances that also modify magnetic and electrical forces. Sharp [28] concluded that these harmonic drivers can be separated into three levels.

Level 1 includes the Ice Age Cycles, due to orbital changes as stated by Sharp, reporting on work by Milankovitch [28]. These cycles are very long and affect long-term climate variations, such as glacial and interglacial periods.

Level 2 comprises the Solar Grand Minimum andSolar Modulation Cycles. This level is governed by the SIM theory, which states that the Sun follows a kaleidoscope-like pattern orbit around the SSB [45], as shown in Fig. 4. The wobble of the Sun generates changes in its Angular Momentum (AM), velocity, acceleration and torque. Several studies have found a connection between the Grand Minima and the variations of the position of the Sun relative to the Barycenter [28], [41], [42], [46], [47]. Sharp [28] noted that this level is modulated by the 172-year conjunction of Neptune and Uranus, and suggested a spacing of 172-179 years between Grand Minima. Based on the influence of the Solar Inertial Motion, a solar slowdown is expected for Solar Cycles 24 and 25 that will create a weak grand minimum, which is expected to trough around 2030 [28]. The implications of this predicted weak grand minimum can be expected to be observed by a decline in global temperatures, and a subsequent moderation in the rate of sea level rise.

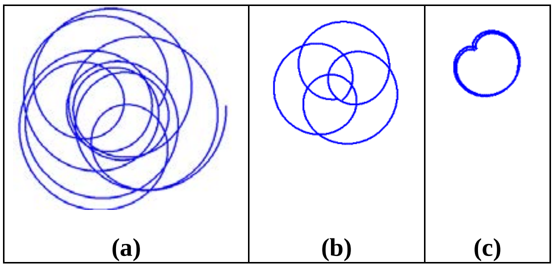

Fig. 4 Sun's path around the Barycenter (not to scale) when: (a) including all planets; (b) removing Jupiter; (c) removing Jupiter and Saturn (after [44])

Level 3 refers to the well-known, 60-year cycle in the Earth's temperature record that seems to align with the PDO/ENSO records. There is significant evidence that shows a coincidence between the global temperature record and the two Solar System harmonic patterns, namely the Solar velocity 60-year cycle and the Jupiter/Saturn synodic harmonic cycle, along with Lunar harmonics [10], [11], [18].

4. THE 60-YEARS OSCILLATION AND SEA LEVEL

Evaluating a substantial tide gauges database, researchers [13] identified a significant oscillation of about 60 years in the majority of the tide gauges they examined. Using the average of tide gauges in five ocean regions, [13] found similar phases and amplitudes for the North Atlantic, Western North Pacific and Indian Oceans, while there was a 10-year lag in the monitored tide gauges for the Western South Pacific Ocean. However, the mean sea level measured in the Central/Eastern North Pacific region did not show a 60-year fluctuation. As mentioned earlier, it was suggested by [13] that these fluctuations are related to wind forcing and current variations, which are not spatially uniform. However, Baldwin and Dunkerton [15] found a direct correlation between these atmospheric factors and the atmospheric oscillations (PDO, AMO, ENSO), which have a significant effect on sea surface temperatures, pressure levels and surface winds.

Merrifield *et al.* [48] reviewed several studies and found that, on decadal to multi-decadal time scales, variations of up to 1 cm in the level of the Pacific Ocean are believed to be caused by the Pacific trade winds. In addition, the reduced wind stress is associated with a minimal sea level rise in the Western Pacific Ocean, when this is compared with the Global Mean Sea Level [48]. There is an agreement between the sea level fluctuations in the Western Pacific Ocean and the PDO index, which is a finding based on tide gauge observations that provide a 60-year record [48]. Furthermore, it was suggested that the wind forcing in the Western Pacific led to a thickening of the upper ocean layer, which results in increased rates of sea level rise [48]. Assuming that the volume of the upper layer of the world oceans is conserved, the thickening in the upper layer of the Western Pacific Ocean is compensated by the thinning in the upper layer of the North East Pacific Ocean, leading to a reduced rate of sea level change in this region. Furthermore, Van Loon and Meehl [7] identified that the decadal time scale climate variability in the Pacific region was due to external forcing from variations in the solar irradiance and from the internal climate variability associated with the PDO. Therefore, Chambers [14] suggested that this regional variability and the strong effects of wind stresses in the Pacific Ocean could be the reason why his analysis did not show a 60-year oscillation for the Central/Eastern North Pacific regions. Chambers *et al.* [13] also points out that the 60-year oscillation in the mean sea level does not change the overall conclusion that sea levels have been rising over the last 110 years by, on average, 1.7mm/yr. This simply shows a natural oscillation that permeates into sea level measurements [13]. Therefore, this natural oscillation should be considered when estimating future sea level rises, as it has been shown to be directly related to the planetary orbits and solar activity, which, in time, modulates atmospheric variables, such as PDO, AMO, ENSO, etc.

The findings from Chambers *et al.* [13] are presented in Fig.5, which shows a 60-year cycle in the sea level data, which is smoothed with a 5-year running mean. The North Atlantic variation has an optimal period of 64 years (Fig. 5.a). However, this 64-year oscillation is not evident in the Central Eastern Pacific gauges (Fig. 5.b). The Western North Pacific and Indian Ocean levels seem to be in phase, whilst the North Atlantic gauges are slightly delayed. The minimum level is around 1915–25, with a peak around 1950–60, and another minimum around 1980–90. The phase of the South Pacific gauges around Australia/New Zealand lags by about 10 years (Fig. 5.b).

Chambers *et al.* [13] expressed concerns in using sea level records shorter than two cycles of 60 years, as it is not fully understood if there is a 60-year oscillation present in the GMSL. High hesitation was expressed by some researchers [13] to interpret the acceleration in GMSL based on only a 20-year record from satellite altimetry.

Chambers and his team's research, particularly, the findings presented in Fig. 5, supports the theory of natural variability underlining the changes in sea levels. On the other hand, assuming that thermal expansion may be a key factor contributing to sea level rises, and based on the effects of solar activity, it is logical to predict that a reduction in global average temperatures might manifest in a consequent slowing of the rate of sea level rise.

5. CONCLUSION

The oscillations of the planets have a noticeable effect on the Sun's activity, and show a good correlation with the observed patterns in global surface temperatures and sea levels.

A clear 60-year cycle has been identified in many studies, and in accordance with this, it is expected that temperatures will reach a trough of the cycle around 2030-2040. This is in agreement with the forecasted low sunspot activity that is usually linked to lower temperatures.

This dampening effect is expected to be more noticeable when assessing climate variability on a regional scale for decadal and multi-decadal projections. The implications of this weak grand minimum can be expected to be reflected in a dampening effect of global temperatures, and a subsequent slowing in the rate of sea level rise. This dampening effect is expected to be more noticeable when assessing climate variability on a regional scale

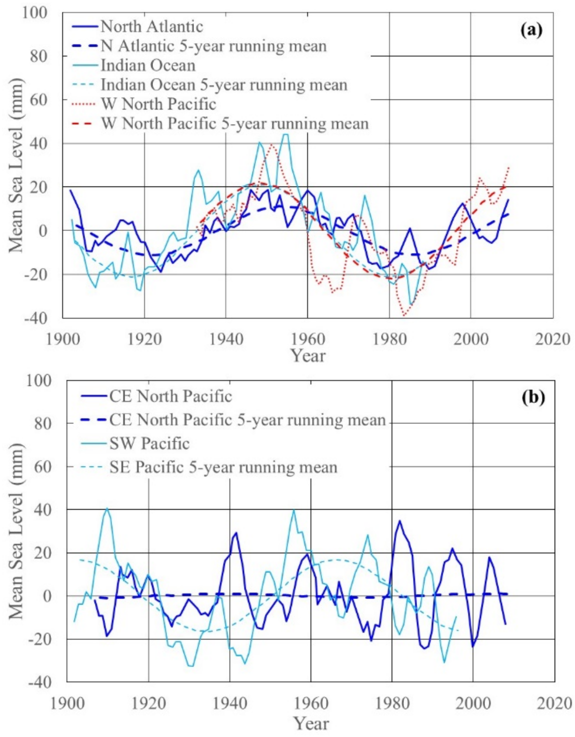

Fig.5 Sixty-year cycle in Mean Sea Level for world's oceans (after [13])

for decadal and multi-decadal projections.

The combination of natural forces and anthropogenic effects is paramount when analyzing our climate, as the natural variability has a larger effect at a regional scale. Therefore, the inclusion of solar and planetary influences in regional models is recommended.

The Earth's climate is a complex system that is affected by many factors that influence each other. This make the understanding of Earth's climate change more difficult, and there is still much work to be done to clearly identify the level of influence that each factor has on the variation of sea levels.

6. ACKNOWLEDGEMENTS

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