Arctic Sea Ice's Amplification as a Complement to Anthropogenic Global Warming

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Arctic Sea Ice's Amplification as a Complement to Anthropogenic Global Warming

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Abstract

Climate Change is a widely debated scientific subject and Anthropogenic Global Warming is its main cause. Nevertheless, several authors have indicated solar activity and Atlantic Multi-decadal Oscillation variations may also influence Climate Change. This article considers the amplification of solar radiation's and Atlantic Multi-decadal Oscillation's variations, via sea ice cover albedo feedbacks in the Arctic regions, providing a conceptual advance in the application of Arctic Amplification for modelling historical climate change. A 1-dimensional physical model, using sunspot number count and Atlantic Multi-decadal Oscillation index as inputs, can simulate the average global temperature's anomaly and the Arctic Sea Ice Extension for the past eight centuries. This model represents an innovative progress in understanding how existing studies on Arctic sea ice's albedo feedbacks can help complementing the Anthropogenic Global Warming models, thus helping to define more precise models for future climate change.

Introduction

Evidences from several scientific studies based on different proxies show the global average temperature has been far from constant in the pre-industrial era¹. In addition, several sources correlate the solar activity variation to historical climate change^{2, 3}.

If a new grand solar minimum is coming^{4, 5}, it is important to understand whether the supposed future solar activity reduction could be a forcing to climate change, additional to Anthropogenic Global Warming (AGW). Indeed, being the AGW the major cause to climate change⁶, additional forcing could complement it, but the single variation of solar forcing is too limited to cause the climate change recorded in the last millennium; global temperature's reduction during the last grand solar minimum (Maunder Minimum) could be mainly due to volcanic activity and causes other than solar activity⁶. The oceans are Earth's heat storage body, and variations of Earth's global average temperature shall be accompanied by equivalent changes of oceans' heat content (Nuccitelli⁷, NASA⁸ and NOAA⁹), but the variation in the Oceans Heat Content (OHC), due to changes in solar energy radiation, are insufficient to justify the observed and reconstructed temperature anomalies⁶. Nevertheless, positive feedback mechanisms, as the Arctic Amplification (AA), may amplify the sun-led activity led OHC changes. The AA increases the sun activity variations' forcing on the oceans temperatures, via changes of the Arctic sea ice extension (SIE). Increase or decrease of ice smelting changes consequently the Arctic regions' albedo, and albedo variations impact on the reflection of sun radiation, with large impacts on the Earth's overall energy balance.

According to Laubereau and Iglev¹⁰, the retreat of Arctic SIE is accompanied by enhanced solar input in the Arctic region, i.e. by a decrease of the terrestrial albedo. They studied this effect for the past six decades and estimated the corresponding global warming in the Northern Hemisphere. Their results indicate that the external forcing directly caused a temperature rise of only 0.2 K from 1955 to 2015, while a notably larger effect of 0.7 ± 0.2 K is found for the loss of Arctic sea ice in the same period. According to them, these numbers comprise most of the reported mean temperature rise of 1.2 ± 0.2 K of the Northern Hemisphere¹⁰.

In addition, Pistone, Eisenman and Ramanathan¹¹ state that the Arctic's albedo decrease amplifies the warming effect, revealing a striking relationship between planetary albedo and SIE, as inferred from two independent satellite instruments. They reconstructed the average global radiative forcing (RF) increase due to ice albedo effect of the Arctic ice cover from 1979 to 2011.

Other studies indicate that the Atlantic Multi-decadal Oscillation (AMO) variations may cause changes of the Arctic Atlantic sector ice cover (AASIC). The AMO index accounts for the thermal modes' variation of the North Atlantic Ocean¹². The AMO is the main oceanic variation with direct impacts on the Arctic Ocean, because the Arctic Ocean is opened only to the Atlantic Ocean and is closed to other ones (it is opened only via the Bering strait to the Pacific Ocean).

A positive AMO index (AMO+) implies a local increase of temperature in the Atlantic sector of the Arctic ocean, corresponding to a cooling in its equatorial sector and vice versa a negative one (AMO-). According to Li et al.¹³, over the 1979–1995 (1996–2016), years with AMO- (AMO+) correspond to above-normal (below-normal) December AASIC. This suggests that the AMO may be a second cause of the earth's albedo variation, due to its influence on AASIC (concurring with solar activity to the overall Arctic sea ice's albedo).

The AMO variations, differently from sun-led OHC changes, do not represent a net variation of Earth's heat balance, but a displacement of heat from the Southern sector (AMO-) to the Northern sector (AMO+) of the Atlantic Ocean.

The present article provides a conceptual advance in application of AA mechanisms for modelling the historical climate change of the last millennium: the proposed 1-dimensional physical model simulates the historical global average temperature anomaly and the SIE, using as physical inputs the Sunspot Number (SSN) count, used to estimate the Total Solar Irradiation (TSI), and the AMO index historical databases.

Other articles correlate the average global temperature anomaly to SSN count or oceanic indexes, but with different, mostly mathematical approaches³. Here, we investigate the causal effect of solar activity and AMO on the average global temperature anomaly and the SIE, via AA mechanisms. This model represents an innovative progress in applying existing AA studies to quantitatively model Earth's climate change. The AA effects described in this article are complementary to the AGW effects and the proposed model could help refining the existing climate change forecasts to better adapting to climate change in the next century.

Results

A 1-dimensional physical model is used to simulate the average global temperature anomaly and SIE along nine centuries' (1200 – 2100). Two independent causal mechanisms are proposed: the solar activity variation, measured by the total sunspot number (SSN), and the Atlantic Multidecadal Oscillation (AMO). They are described as two independent components of forcing and their effects are summed.

Determination of the first component: SIE_partial and T1

The first component considers the effect of solar activity's variation via AA on the global average temperature anomaly. SSN count from year 1200 to 2100 from various sources ^{4, 5, 14, 15, 16} is used. The actual count is available only from 1700 to 2019¹⁴, but several estimations exist for the previous periods and some forecast have been published for the next decades.

A set of data for the TSI from year 1610 to 2019 is used¹⁷ and correlated with SSN count for the same period. SSN values correspond to a coefficient of correlation of 0.87 to TSI values in the period from 1610 to 2019. Indeed, SSN count quantifies the solar activity, and a higher SSN count relates to stronger sun activity. During stronger solar activity's periods, the TSI is slightly increased, because of the balance between increased ultraviolet radiation and reduced visible radiation¹⁸.

The results of the correlation are extended, based on the SSN counts, to obtain a series of TSI data for the entire simulation period (1200 - 2100). TSI data (W/m² of area perpendicular to the sun rays) are converted to Radiative Forcing (RF), in W/m² of Earth's surface area.

RF variations have a cumulative impact on the OHC (OHC_sun). It is assumed that the RF's variations above or below its average shall lead to an increase or decrease of the OHC_sun with respect to its average value. In Figure 1, Σ represents the year-by-year summation of RF anomalies' annual contributions to variation of OHC_sun, assuming negligible black-body emission from oceans due to their temperature change (83% of outgoing radiation of the Earth's system is from clouds and atmosphere and oceans account for about 12%, according to NASA¹⁹);

OHC_sun variations cause a corresponding variation of temperature of oceans' active layer (from surface to about 1,000 metres depth) and an equivalent variation of Earth's surface average global temperature anomaly. T_sun is the component of the average global temperature anomaly due only to OHC_sun variation, not the total temperature anomaly, which is determined adding the feedback.

The validation of the obtained T_sun values can be made via benchmark comparison with IPCC⁶: the model's result for the period 1880 to 2010 is about 0.10°C, which is well matching the upper side of the range estimated by IPCC (0.1 W/m² x 0.8 °C/(W/m²) = 0.08°C).

The AA feedback is applied to T_sun to obtain the first component of the Arctic SIE variation (delta SIE_partial) and of the average global temperature's anomaly (T1).

Studies by Laubereau and Iglev¹⁰ and Pistone et al.¹¹ are based on a multi-decadal timeframe and consider positive feedback loops between SIE and temperature; therefore, the amplification effects estimated on temperature and SIE are not subject to further amplification effects and shall be considered as "short-term" linear amplifications in the considered multi-century timeframe of the model.

According to Laubereau and Iglev¹⁰, the average historical Arctic SIE is estimated as:

- 1955 13,400,000 km²;
- 1979 12,500,000 km²;
- 2011 / 2012 11,500,000 km²;
- 2015 11,000,000 km².

The difference between 1955 and 2015 is of 2.4 million km². Always according to the same reference, the external forcing directly caused a temperature rise of 17% from 1955 to 2015, out of the total of the reported mean temperature rise in the Northern Hemisphere. In addition, 58.3% is due to SIE feedback amplification, and 25% due to other feedbacks. Applied to HadCRUT4 Northern Hemisphere figures²⁰ of 0.70°C of total temperature anomaly for the same period (roughly equal to global temperature anomaly), it reverts to 0.12°C (external

forcing), 0.41°C (SIE feedback amplification) and 0.18°C (other feedbacks). Therefore, the SIE sensitivity is estimated as $-4.86 \times 10^{-8} \text{ }^{\circ}\text{C} (\text{T}_{\text{sun}})$ per km^2 SIE, or -20.57 million km^2 SIE per $^{\circ}\text{C} (\text{T}_{\text{sun}})$ from 1955 to 2015. According to Pistone et al.¹¹, the SIE feedback is equal to $-2.1\text{E-}07 \text{ W/km}^2$ from 1979 to 2012. Considering a λ_{ice} of $0.80^{\circ}\text{C}/(\text{W/m}^2)$, according to IPCC, and a variation of temperature of 0.29°C for the same time interval (Tokyo Climate Centre²¹), the total delta RF is 0.36 W/m^2 , of which the arctic feedback represents 57.93% of the total. This result is well in line with the data from Lauenbrau and Iglev¹⁰, which report a 58.33% ($0.41^{\circ}\text{C} / 0.70^{\circ}\text{C}$) of the temperature variation. It is therefore confirmed that the two references provide a consistent set of data on Arctic Amplification feedback. Results' robustness is further confirmed by the temperature sensitivity on RF (λ_{ice}) of $0.81^{\circ}\text{C}/(\text{W/m}^2)$; it correlates the two independent references used and coincides with IPCC-estimated value of $0.80^{\circ}\text{C}/(\text{W/m}^2)$. Figures obtained by correlating the data from the abovementioned sources can be summarised as illustrated in Table 1 (please refer to Methods for the correlation's full procedure):

Table 1: AA Correlation Factors

Factor	Sun	Ice	Other Feedback	Total Feedback	Total
RF / SIE ($\text{Wm}^{-2} / \text{km}^2$)		-2.10E-07			
T / SIE ($^{\circ}\text{C}/\text{km}^2$)	-4.86E-08	-1.70E-07	-7.29E-08	-2.43E-07	-2.92E-07
λ (T / RF) ($^{\circ}\text{C}/\text{Wm}^{-2}$)		0.81			

The amplification factor is $6^{\circ}\text{C} (\text{T}_{\text{total}}) / ^{\circ}\text{C} (\text{T}_{\text{sun}})$, as it can be inferred from the above table ($-2.92\text{E-}07$ divided by $-4.86\text{E-}08$ ($^{\circ}\text{C}/\text{km}^2$)).

In addition, it is possible to confirm the value of $-2.10\text{E-}07$ for Ice RF_feedback / SIE correlation ($\text{Wm}^{-2} / \text{km}^2$ SIE). Considering the reduction of SIE from 1979 to 2012 of about 1 million km^2 , it provides a net change of $0.21 \text{ W} / \text{m}^2$. Considering a TSI of $1,360.83 \text{ W/m}^2$, the midday solar irradiation at 75° latitude (where the majority of sea ice smelting is located) is estimated as 352.21 W/m^2 . Considering the nights and the average angle of the sun rays during the day, the average value is 124.52 W/m^2 . Neglecting cloudiness, the RF on ice-free sea can be calculated as 115.81 W/m^2 (albedo of 7%), and RF on ice as 18.68 W/m^2 (albedo of 85%); consequently the delta RF on 1 million km^2 is estimated as 97.13 W/m^2 . Reported to Earth's surface area, it provides an average global delta RF of 0.19 W/m^2 , which is in line with the used value ($0.21 \text{ W} / \text{m}^2$). This also provides insight concerning the causes of arctic temperature's stronger anomalies with respect to the average global temperature anomaly registered in the recent decades: the heating cause is located within the boundaries of the Arctic regions, therefore having higher impact than in the other world's regions .

Determination of the second component: AASIC and T2

The second component considers the effects of the AMO on the AASIC as concurring with solar activity to the overall Arctic albedo feedback effects. According to Li et al.¹³, the AMO variation is a further cause of the variation of Arctic albedo, due to its impacts on AASIC.

The Arctic Sea is extended for $15.06 \times 10^6 \text{ km}^2$, of which the Atlantic sector (72° – 85°N , 20°W – 90°E , excluding 15% of land areas) represents about the 20%. The overall surface of Arctic Sea is composed by:

- (1) Beaufort Sea: $0.92 \times 10^6 \text{ km}^2$
- (2) Chukchi Sea: $1.25 \times 10^6 \text{ km}^2$
- (3) Canada Basin: $0.71 \times 10^6 \text{ km}^2$
- (4) Central Arctic: $0.45 \times 10^6 \text{ km}^2$
- (5) Laptev Sea: $1.52 \times 10^6 \text{ km}^2$
- (6) North Pole: $1.40 \times 10^6 \text{ km}^2$
- (7) Nansen Basin: $0.53 \times 10^6 \text{ km}^2$
- (8) Barents and Kara seas: $2.11 \times 10^6 \text{ km}^2$
- (9) GIN Sea: $2.17 \times 10^6 \text{ km}^2$
- (10) Bering sea: $2.27 \times 10^6 \text{ km}^2$
- (11) Labrador Sea: $0.84 \times 10^6 \text{ km}^2$
- (12) Baffin Bay: $0.69 \times 10^6 \text{ km}^2$

AMO index data from year 1585 to 2019 were selected^{22, 23}. For the years in the interval from 1200 to 1584 and from 2019 to 2100, no data extension is possible, due to lack of literature sources; therefore, in these intervals, the AMO value is set at its average during 1585 - 2019.

AMO+ implies a local increase of temperature of the Atlantic sector of the Arctic ocean, corresponding to a cooling of the equatorial sector of the Atlantic Ocean. AMO- implies the opposite.

According to Li et al.¹³, the variation of AMO index from 1975 to 2012 (increased of 0.417) is associated to a decrease of December AASIC of about 1.271 million km^2 , from a maximum ice extension in 1975 of 2.40 million

km² to a minimum ice extension in 2012 of 1.13 million km². The data indicate a correlation factor of -3.05 million km² / delta AMO index and consequently of 0.74°C/delta AMO index (applying the factor of -2.43×10^{-7} °C_total feedback / km² SIE described in the previous section). Applying this factor to AMO provides the second component of the total anomaly of the average global Temperature (T2) and the AASIC variations.

Results summary and comparison with literature benchmarks

The two components are not alternative, but additional, and their independent effects on both global average temperature's and SIE / AASIC's anomaly are summed. After offsetting their zero value, the result of global average temperature and SIE are compared with historical data.

For the period 1200 – 2100, the overall average global temperature (T) reconstruction is reported in Figure 1. Several benchmarks have been used to compare the model results. Data from 1250 to 1859 are from Spencer²⁴ (data shifted of +0.08°C to set the zero at year 1880) and from Lockwood²⁵ (data shifted of +0.20°C to set the zero at year 1880); data from 1860 to 1900 are from the Hadley Centre²⁶ (data shifted of +0.40°C intercept Tokyo Climate Centre in 1905) and since 1900 are from Tokyo Climate Centre²¹ (data shifted of +0.75°C to set the zero at year 1880).

Figure 1. Author's modelled temperature anomaly vs. historical data of global average temperature anomaly for the entire data series from year 1250 to 2100. On x-axis the date in years and on y-axis the average global temperature in °C

Figure 2 details the same data of Figure 1 on the overall average global temperature (T) reconstruction but focussed to the period 1855 – 2019.

Figure 2. Author's modelled temperature anomaly vs. historical data of global average temperature anomaly for the data series from year 1855 to 2019. On x-axis the date in years and on y-axis the average temperature anomaly in °C

The total SIE value on the entire data series from 1200 to 2100 is shown in Figure 3.

Figure 3. Dataset on SIE. On x-axis the date in years and on y-axis the SIE

Figure 4 illustrates the result for the SIE overall reconstruction for the period 1950 – 2010 and compares it with historical data from year 1950 to 2010. March SIE data are from ACSYS, AARI sea ice data²⁷, September SIE data are from Alekseev²⁸.

Figure 4. Author's modelled SIE vs. historical data from year 1950 to 2010. On x-axis the date in years and on y-axis the average SIE in km^2

The results show an interesting match of the model with the historical data from literature. This suggests the model could help forecasting future climate change scenarios and identifying effective paths for climate change adaptation and for increasing human climate resilience for the next decades.

Discussion

For purpose of simplicity, Anthropogenic Global Warming effects have not been included in the model, to keep it focussed on forcing due to solar activity and AMO changes. A next step should be to integrate the model in the wider framework of Anthropogenic Global Warming models and understand the combined effect of the entire forcing on climate change. This integration will be object of further studies by the author.

It can be observed from Figure 2 that the model is well simulating the historically metered or reconstructed average temperature anomaly data since 1200.

As major exceptions, we can indicate a peak in 1575 - 1600, which finds no correspondence in the benchmark data. In addition, the Maunder Minimum appears in the model to further deepen in the period 1700 – 1725, contrary to historical evidence. Consequently, Dalton Minimum (1800 – 1830), is lower than historical data in absolute value, but its temperature relative decrease is well in line with historical benchmarks.

In addition, the 2016 – 2020 temperature peak is not explained by the model: instead, the Anthropogenic Global Warming well explains the peak, and this confirms that a combined model based on AGW and AA should be developed in order to account all the types of forcing on climate change.

Data from 1200 to 1250 are not shown, because the Model takes about 50 years from its first running year (1200) to get up to speed.

The AA overall effect is considered by Laubereau and Iglev¹⁰ in the period from 1955 to 2015, which covers a full cycle of the AMO (from maximum to minimum to new maximum, with a total zero effect); therefore, the model considers the two effects to be completely independent and sums them as two linear independent components of the forcing.

It is important to highlight that the AA effects on OHC_{sun} shall cause a further variation of the OHC itself; nevertheless, Laubereau and Iglev¹⁰ and Pistone et al.¹¹ studies are based on a multi-decadal timeframe and are already considering the cumulative impacts (feedback of feedback) on temperature and SIE. Therefore, the AA factor is applied to the variation of temperature due only to sun-lead oceans' heating (T_{sun}), linearising the problem.

Impacts of oceans' heating on the Antarctic ice extension are not considered in the model. This is because literature data on "Antarctic Amplification" are scarcely available, and the Antarctic region is expected to be less influenced than the Arctic one by OHC's changes, the Antarctic being a continent surrounded by sea and not an ocean surrounded by land.

It is important to note that reliable forecast data for SSN and AMO are not available for post 2020. This suggests the model should be updated in the future.

Methods

The physical model considers the SSN count and AMO index as input and the average temperature anomaly and SIE reconstruction as output. The 1-dimensional model is satisfactory in the sense of a Taylor expansion of the (unknown) functions $\Delta T(y)$ and $\Delta SIE(y)$ depending on a variety of local and geographical parameters, where second and higher order terms are neglected. Retaining only the first order terms of the expansion, the problem is linearised.

Step1: From SSN to TSI

Input Data

The observed data of SSN from 1700 to 2019 are obtained from the Royal Observatory of Belgium¹⁴.

Reconstructed data from 1200 to 1610 are obtained from Solanki¹⁵, where the data are adapted from Beryllium 10 data.

Data from 1610 to 1699 are obtained from Eddy¹⁶, where the data are reconstructed mainly from reported observations of the time.

Data from 2020 to 2040 and from 2041 to 2100 are respectively from estimations by Shepherd⁵ and Abdussamatov⁴.

Concerning Total Solar Irradiation (TSI), data are from SORCE¹⁷ for years from 1610 to 2019.

Model Description

SSN count is representative of the solar activity (of both quantitative TSI and its spectral characterisation), but the correlation is not linear. The model finds the correlation equation between SSN count and TSI for the overlapping period (1610 – 2019). Since TSI is strongly influenced by prolonged periods of solar grand minima, two different equations have been used in function of the 11-year SSN moving average. Period of grand solar minima have been characterised by SSN counts below 40 per month for prolonged periods, as well as periods of solar maxima by SSN counts above 40 per month for prolonged periods.

$$\text{if (11 years moving average SSN} < 40\text{): } TSI(y) = 0.0041 \times SSN(y) + 1360.28 \quad (1)$$

$$\text{if (11 years moving average SSN} > 40\text{): } TSI(y) = 0.0055 \times SSN(y) + 1360.70 \quad (2)$$

Where:

- TSI (y)= TSI (W/m²) in the year y
- SSN (y)= SSN monthly count in the year y
- y= Considered year

The overall R² on the period 1610 – 2019 is 0.75, coefficient of correlation (R) is 0.87.

Model Output

The TSI data on the entire data series from 1200 to 2100 are obtained. Unabridged data from SORCE have been used for this time interval, while the equations (1) and (2) have been used for the remaining years.

Step 2: From TSI to RF_sun

Input Data

Input data are the modelled TSI data.

Model Description

The following equation is used:

$$RF(y) = \frac{0.7 \times TSI(y)}{4} \quad (3)$$

Where:

- $RF(y)$ = sun Radiative Forcing in the year y
- $TSI(y)$ = TSI (W/m²) in the year y
- 0.7 = $1 - 0.3$ (where 0.3 is the average Earth albedo)
- y = Considered year
- 4 = sphere geometrical factor

Model Output

TSI is referred to orthogonal metered sun radiation. The average value for the unit of Earth's surface area (RF) shall be obtained. The solar RF data on the entire data series from 1200 to 2100 are obtained.

Step 3: From RF_sun to delta OHC_sun

Input Data

Input data are the modelled RF_sun data.

Model Description

The difference between RF_sun (y) and its average is considered to cause of the increase / decrease of the Ocean Heat Content (OHC_sun). The rationale is that when the RF is above its average value, OHC_sun is increasing, when it is lower, OHC_sun is decreasing. Since the last 800 years have been characterised by longer high solar activity periods than low solar activity ones, the mathematical average is not considered as a proper indicator. Therefore, the average value considered for RF_sun is the average of its mean value for periods with SSN < 40 (solar minima) and its mean value for periods of SSN > 40 (solar maxima).

The RF_sun value differential to its average is multiplied by the total Earth surface to obtain the differential absolute value of received energy. Yearly energy gains / losses are summed year by year, according to below equation.

$$OHC_sun(y) = \sum_{n=1200}^y \left(\frac{\Delta RF_sun(y) \times \text{Earth surface} \times 8760 \times 3.6}{10^{19}} \right) \quad (4)$$

Where:

- $OHC_sun(y)$ = cumulative OHC (10²² Joule) in the year y
- $\Delta RF_sun(y)$ = differential sun RF (W/m²) in the year y
- y = Considered year
- 8760 = Hours per year
- Earth surface = 5.101×10^{14} m²

Model Output

The results are reported in Figure 5.

Figure 5. Dataset on Solar induced OHC_sun Variations. On x-axis the date in years and on y-axis the OHC_sun

Step 4: From delta OHC_sun to delta T_sun

Input Data

Input data are the modelled OHC_sun.

Model Description

Considering the active layer of the oceans and the oceans' surface, the variation in oceans' temperature is obtained considering the sea water specific heat.

$$T_{sun}(y) = \frac{OHC_{sun}(y) \times 10^{22}}{3.85 \times \text{Ocean surface} \times \text{active layer} \times 10^6} \quad (5)$$

Where:

- $T_{sun}(y)$ = sun-induced temperature anomaly (°C) in the year y
- $OHC_{sun}(y)$ = cumulated OHC (10²² Joule) in the year y
- y = Considered year
- 3.85 = Sea water specific heat (Joule/(gram °C))
- ocean surface = $3.6 \times 10^{14} \text{ m}^2$
- ocean active layer = about 1,000 m

Given the overwhelmingly higher thermal inertia of the oceans with respect to the land, it is assumed to correspond to the average global temperature anomaly component caused by sun activity variations.

Model Output

The solar-induced component of global average temperature on the entire data series from 1200 to 2100 is shown in Figure 6.

Figure 6. Dataset on Sun-Induced Global Average Temperature Anomaly Component. On x-axis the date in years and on y-axis the sun-induced temperature anomaly T_{sun} ($^{\circ}\text{C}$)

It can be noted that the variation due to only sun effects from 1880 to 2010 is about 0.10°C , which is well in line with the upper side of the range estimated by IPCC ($0.1 \text{ W/m}^2 \times 0.8 \text{ }^{\circ}\text{C}/(\text{W/m}^2) = 0.08^{\circ}\text{C}$).

Step 5: From T_{sun} to Arctic Amplification (delta SIE and delta T1)

Input Data

Input data is the modelled data series T_{sun} .

Model Description

The coefficients of correlation between T_{sun} and Arctic Amplification (delta SIE and delta T1) are determined based on the input data reported in Table 2.

Table 2: Obtained AA Correlation Factors

Year	SIE (km^2)	RF sun (Wm^{-2})	RF ice (Wm^{-2})	RF other (Wm^{-2})	RF grand total (Wm^{-2})
Maunder Minimum	15,060,000	0.00			
1955	13,400,000				
1979	12,500,000	0.14	0.00	0.00	0.00
2011 / 2012	11,500,000	0.19	0.21	-0.04	0.36
2015	11,000,000				
Year	$T_{\text{sun}} \text{ NH}$ ($^{\circ}\text{C}$)	$T_{\text{ice}} \text{ NH}$ ($^{\circ}\text{C}$)	$T_{\text{other}} \text{ NH}$ ($^{\circ}\text{C}$)	$T_{\text{total feedb.}} \text{ NH}$ ($^{\circ}\text{C}$)	$T_{\text{grand total}} \text{ NH}$ ($^{\circ}\text{C}$)
Maunder Minimum					
1955	0.00	0.00	0.00	0.00	0.00
1979					
2011 / 2012					
2015	0.12	0.41	0.18	0.58	0.70

Coefficient	Sun	Ice	Other feedback	Total feedback	Grand total
RF / SIE (Wm ⁻² / km ²)		-2.10E-07			
T / SIE (°C/km ²)	-4.86E-08	-1.70E-07	-7.29E-08	-2.43E-07	-2.92E-07
λ (T / RF) (°C/Wm ⁻²)		0.81			
SIE sensitivity (10 ⁶ km ² / °C T _{sun})	- 20,571,429				
T Amplification (°C total / °C sun _{forced})	6.00				

Table 2 sources (top part):

- SIE extensions are from Laubereau and Iglev¹⁰, with the exception of the value for the Maunder Minimum, where it is assumed the SIE corresponded to the entire Arctic Sea area;
- RF_{sun} values are obtained from the model (Step 2);
- RF_{ice} are obtained for 1979 and 2011 /2012 from Pistone et al.¹¹;
- RF grand total is obtained from Temperature (Tokyo Climate Centre²¹) and λ = 0.8 (IPCC);
- FR other feedbacks is obtained as difference.

In Table 2 (Centre Part), Temperature anomaly components for the Northern Hemisphere (NH) are obtained applying the percentage of the different types of forcing from Laubereau and Iglev¹⁰ to the HadCRUT4²⁰ data for the same reference years (1955 and 2015). No figure has been derived from the model, and all values are from external references.

Table 2 (bottom part) reports the correlation factors as obtained from the two previous tables. The factors can be easily obtained dividing the numerator and denominator data difference for the same couple of years. Only factors of interest for the model are reported.

Model Output

The delta SIE_{partial} variation obtained multiplying the above constant by the T_{sun} values on the entire data series from 1200 to 2100 is obtained.

The global average temperature anomaly T1 is obtained multiplying the above constants by the T_{sun} values on the entire data series from 1200 to 2100.

Step 6: From AMO to delta AASIC and delta T2

Input Data

Data on the yearly AMO index are from the National Ocean and Atmosphere Administration²² for the years 1856 - 2019.

Data from 1585 to 1855 are reconstructed by Knudsen et al.²³.

Data from 1200 to 1584 and from 2020 to 2100 are assumed as the average value of the time interval 1585 – 2019, lacking any literature reference to extend further the data.

Model Description

According to Li et al.¹³, the variation of AMO index from 1975 to 2012 (increased of 0.417) is associated with a decrease of December AASIC of about 1.271 million km², from a maximum ice extension in 1975 of 2.40 million km² to a minimum ice extension in 2012 of 1.13 million km². The data indicate a correlation factor of -3.05 million km² / delta AMO index and consequently of 0.74°C/delta AMO index (applying the same T_{NH} & global correlation of -2.43 x 10⁻⁷ °C / km² SIE).

For the correlation, the 11-year average of the AMO Index is multiplied by the above-determined factors to obtain the AASIC and T2 variations.

Model Output

The delta AASIC variation on the entire data series since 1200 to 2100 is obtained.

The total average temperature anomaly induced by AMO (T2) on the entire data series from 1200 to 2100 is obtained.

Step 7: Obtaining the global average T and SIE anomaly

Input Data

Input data are modelled T1, T2, delta SIE_partial and delta AASIC.

Model Description

The results of the model are obtained through the two following equations.

$$T(y) = T1(y) + T2(y) + K1 \quad (6)$$

$$SIE(y) = \Delta SIE_{partial}(y) + \Delta AASIC(y) + K2 \quad (7)$$

Where:

- T(y)= average global temperature anomaly (°C) in the year y
- T1(y)= average global temperature anomaly (°C) due to Arctic Amplification in the year y
- T2(y)= average global temperature anomaly (°C) due to AMO in the year y
- SIE(y)= Total SIE (10⁶ km²) in the year y
- ΔSIE_partial(y)= SIE (10⁶ km²) anomaly in the year y (due to Arctic Amplification)
- ΔAASIC_partial(y)= AASIC (10⁶ km²) anomaly in the year y (due to AMO)
- y= Considered year
- K1= temperature offset of -0.25°C (arbitrarily set)
- K2= SIE offset of 13.7 x 10⁶ km² (arbitrarily set)

Model Output

The total average global temperature anomaly T on the entire data series from 1200 to 2100 is obtained.

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Additional Information

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Availability of materials and data

Materials, data and associated protocols are available to readers without undue qualifications in material transfer agreements. No restrictions on the availability of materials or information is given. All images are available for reproduction or adaptation without asking Author's permission.

Author contributions

Marco Morando provided the only contribution to this article.

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