# The Role of Geomagnetic Induction Heating in Climate Change*

by

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# The Role of Geomagnetic Induction Heating in Climate Change

## Abstract

During the last 70 years the heat content anomalies of the global upper ocean layer have shown a strong, statistically significant correlation with observed geomagnetic field variations, which in turn are caused by the cooling and heating cycles of the Earth's ferromagnetic core. Climate change is largely controlled by the oceans' energy variations, which in turn are demonstrably influenced by the induction heating of the main ocean currents that traverse the Earth's variable geomagnetic field. The ferromagnetic core heating and cooling cycles, and therefore the geomagnetic field variations, are in turn likely driven by solar wind fluctuations, which can therefore be seen as a main cause of the Earth's decadal to centennial ocean energy variability, and therefore the ultimate precursor of climate change.

## Introduction

Much of the recent climate change attribution research by the Intergovernmental Panel on Climate Change (IPCC) has focused on the role of Anthropogenic Radiative Forcing due to GreenHouse Gasses (RFGHG) on the earth's Global Mean Surface Temperature (GMST). A major conclusion is that "*it is extremely likely that human influence has been the dominant cause of the observed warming since the mid-20th century*"[1], though they warn that their climate models show "*differences between simulated and observed trends over periods as short as 10 to 15 years*"[1]. These differences in simulated and observed trends – termed "internal variability" by the IPCC – constitute temporal and spatial variability observations that cannot be explained by the current climate models, and must therefore be related to unmodeled physical processes. This paper demonstrates that many of these anomalies can be attributed to the – currently unmodeled - process of geomagnetic induction heating of the main ocean currents as they traverse the Earth's variable geomagnetic field.

## A review of IPCC's Optimal Fingerprint Analysis methodology

The validation of numerical models simulating time-variant variables such as GMST is generally achieved by comparing simulation model output to observed time series data in a process commonly referred to as a history match. A type of history match, termed Optimal Fingerprint Analysis, is used by the IPCC to evaluate "*the relative contributions of multiple causal factors to a change or event with an assignment of statistical confidence*" [2]. The term "fingerprints" is used by IPCC to describe model-simulated responses – temporal trends – in the modeled forcing, which can then be compared to the historical record: attribution occurs when the simulated trends match the observed trends. The IPCC attribution studies compare output from the 9 distinct climate models that form the Coupled Model Intercomparison Projects (CMIP3/CMIP5), as well as a multi-model average model, to the time-series data of a number of variables, such as GMST and Global Upper Ocean Heat Content (GUOHC) anomalies. The IPCC reports[2]: "*Models may be very simple, just a set of statistical assumptions, or very complex, complete global climate models: it is not necessary, or* *possible, for them to be correct in all respects, but they must provide a physically consistent representation of processes and scales relevant to the attribution problem in question*."

Ideally, climate models simulate the physical processes (forcings) that determine the global and regional energy variations, and produce output that matches the observed data when using best-estimate input for key data parameters such as solar irradiation energy and atmospheric $CO_2$ concentrations. In practice, climate model output differs – sometimes significantly – from observations, due to an incomplete modeling of the physical processes. It is therefore common modeling practice to multiply model output with a scaling factor in order to obtain a better history match. If such scaling factors are close to 1 then it can be assumed that the physical processes have been fairly completely and correctly modeled, while scaling factors differing significantly from 1 imply improperly modeled physics, either due to omission of an important process or due to an incompletely or erroneously modeled process.

An underlying principle to the IPCC attribution studies is that the Earth's climate system can be viewed as a natural steady-state system, whereby the fairly constant solar energy supplied to the Earth is partially absorbed by its oceans, land surfaces and atmosphere, and partially lost via the atmosphere back to space, resulting in a fairly stable climate. Climate change is attributed to the variations in this steady-state, which is why data is often presented as "anomalies" relative to a selected multi-decadal average that is viewed as a proxy for the natural steady-state. Such an approach obviates the need to determine the steady-state, and allows the attribution studies to fully focus on the variability of key climate variables, whereby the "fingerprints" of these variables effecting climate change are recognized in the observed variability. The principal focus of the IPCC attribution study is therefore to determine the relative contributions of Natural vs Anthropogenic forcings to the GMST anomaly variability, with special attention dedicated to the observed warming of 0.6 C in the 1951-2010 period[2]. Two main Natural Forcings are recognized: Solar Irradiation Forcing, which actively heats the Earth, and Volcanic Forcing, that sporadically limits the solar irradiation that reaches the Earth's surface. The Anthropogenic Forcings include RFGHG, whose main effect is to allow the Earth to retain more energy, and Other Anthropogenic Forcings, a catchall that includes e.g. anthropogenic aerosols. The IPCC attribution studies demonstrate that the "Natural" null hypothesis – there is no relationship between observed data variability and the 2 Natural Forcings – cannot be rejected, i.e. numerous attribution studies fail to detect a natural forcing signal in the observed data. This is demonstrated for a large number of variables (GMST, GUOHC, etc.), leading to such main conclusions as: "*overall, we conclude that it is extremely unlikely that the contribution from solar forcing to the warming since 1950 was larger than that from GHGs*." Simply put: Natural Forcings remain relatively constant, GMST is increasing, therefore it must be RFGHG, the only forcing whose trends match the significant GMST increase in the 1950-present time frame. Note that the Anthropogenic null hypothesis - there is no relationship between observed data variability and Anthropogenic Forcings – is rejected by default, i.e. by comparing the relative contributions of the two main forcings and determining that if climate change is not due to Natural Forcing then it must be due to Anthropogenic Forcing.

The relative contributions of each forcing are determined using the Optimal Fingerprint methodology, whereby climate models initially simulate the response to each forcing separately (Fig.1). The individual responses are then individually scaled (Fig. 1, right), and then linearly combined – using new scaling factors – to calculate the overall model response. As can be seen in Fig. 1 (top axis), the determination of the Anthropogenic scaling factor is heavily weighted by the post-1960 data, due to the fact that its simulated response increases in step with the increasing GMST trend, while the Natural scaling factor is heavily weighted by the pre-1960 data, due to the fact that the simulated response remains relatively flat and therefore more in line with the relatively constant pre-1960 GMST. This guarantees that the post-1960 GMST data will match the Anthropogenic climate model trends well, as the scaling factor has been selected to ensure this. Which means the IPCC comment "*GHG attribution is based on the consistency of observed and modeled changes across the climate system*"[2] is somewhat disingenuous, as the model output has been conditioned by scaling factors modeled on the observed changes: models do not simulate the magnitude of Anthropogenic Forcing in a physically correct manner unless the Anthropogenic scaling factor is close to 1. In practice (Bindoff at al. [2], Fig. 10.4; note scaling factors limited to the -2 and 2 interval) the Anthropogenic and Natural scaling factors show a worrying range of [-2,2] or larger:

- A scaling factor of 2 implies the climate model only predicts half the magnitude of the observed change.
- A scaling factor of 0 implies that the climate model simulates a change in the variable that is not observed
- A scaling factor of -2 implies that the climate model is off in both magnitude and direction, e.g. a small increase was forecast, but a big decrease observed.

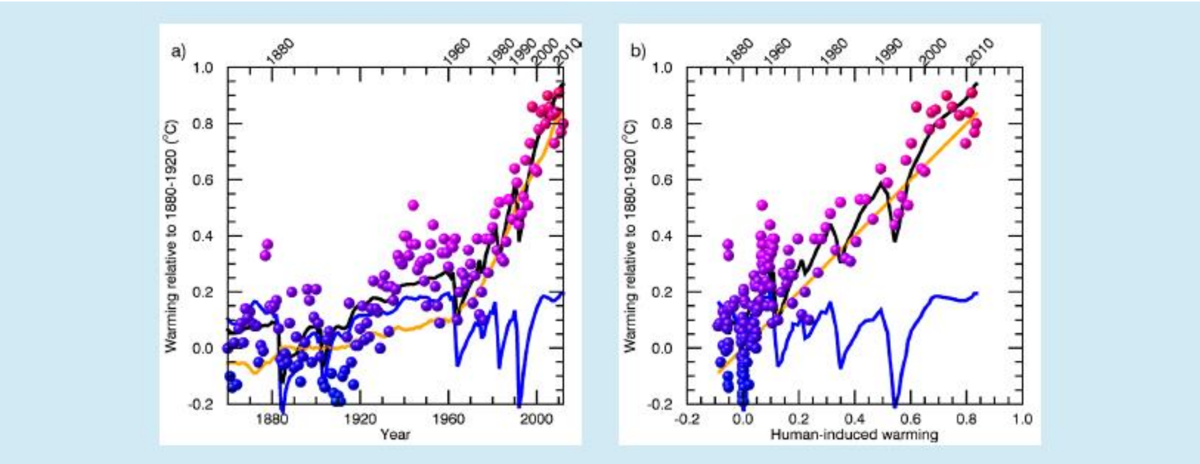


**Figure 1:** Example of a simplified Optimal Fingerprint Analysis. (a) Observed global annual mean temperatures relative to 1880–1920 (coloured dots) compared with CMIP3/CMIP5 ensemble-mean response to anthropogenic forcing (orange), natural forcing (blue) and best-fit linear combination (black). (b) As (a) but all data plotted against model-simulated anthropogenic warming in place of time. Selected years (increasing nonlinearly) shown on top axis. [From: Bindoff at al. [2], Box 10.1]

IPCC state that "*Attribution does not require, and nor does it imply, that every aspect of the response to the causal factor in question is simulated correctly*"[2]. This suggests, as mentioned above, that the climate models are either improperly modeling the physics of the Natural and Anthropogenic Forcings, or that the climate models have omitted (unrecognized) important physical processes. The former is deemed unlikely, the latter is admitted by the IPCC; these discrepancies are often (still) the subject of scientific investigation. For example, a warming period between 1900-1945 has been recognized in both the GMST data, as well as the upper 400 m ocean layer [2,3] Studies indicate that "*the observed 1918–1940 warming was significantly greater than that simulated by most of the CMIP3 models*." [2] Clearly unrecognized, and therefore unmodeled, physical processes are responsible for these regional and temporal discrepancies. These known unknowns are termed “internal variability” by the IPCC, and are often the subject of intense attribution debate. IPCC note[2] that “*the observed trend in GMST since the 1950s is very large compared to model estimates of internal variability*”, a further indication of unmodeled processes that should be taken into account in future attribution exercises.

## The Fingerprints of an important unmodeled process

This paper proposes that much of the IPCC-reported “internal variability” can be attributed to the geomagnetic induction heating of the main ocean currents that occurs when the currents traverse the Earth’s variable geomagnetic field, i.e. that a single unrecognized and unmodeled process, geomagnetic induction heating, is responsible for – and shows its fingerprints in - many of the observed GMST and GUOHC anomalies that cannot be simulated by the current climate models. This section is dedicated to highlighting these key “internal variability” features.

The IPCC use of the Optimal Fingerprint methodology for the GMST attribution exercise is questionable, as it relies on the linear combination of temperature data. The attribution also requires the modeling of very small temperature increases caused by physical processes operating on a large (global) scale. No such limitations exist for the GUOHC anomalies, the energy anomalies of the upper 700 m of the world’s oceans. As a bonus, the addition of a third dimension – ocean depth – to the analysis increases the scope for identifying more unmodeled anomalies. As the oceans’ energy increases account for 93% of the Earth’s total energy increase[3], the GUOHC, and its attribution, can be seen as a climate change elephant in the room. Although its high-quality time-series data spans a shorter time interval (1951-2020) than the GMST data (1880-2020), a crossplot of the two variables (Fig. 2) demonstrates a high degree of correlation, indicating the two attribution exercises are largely equivalent.

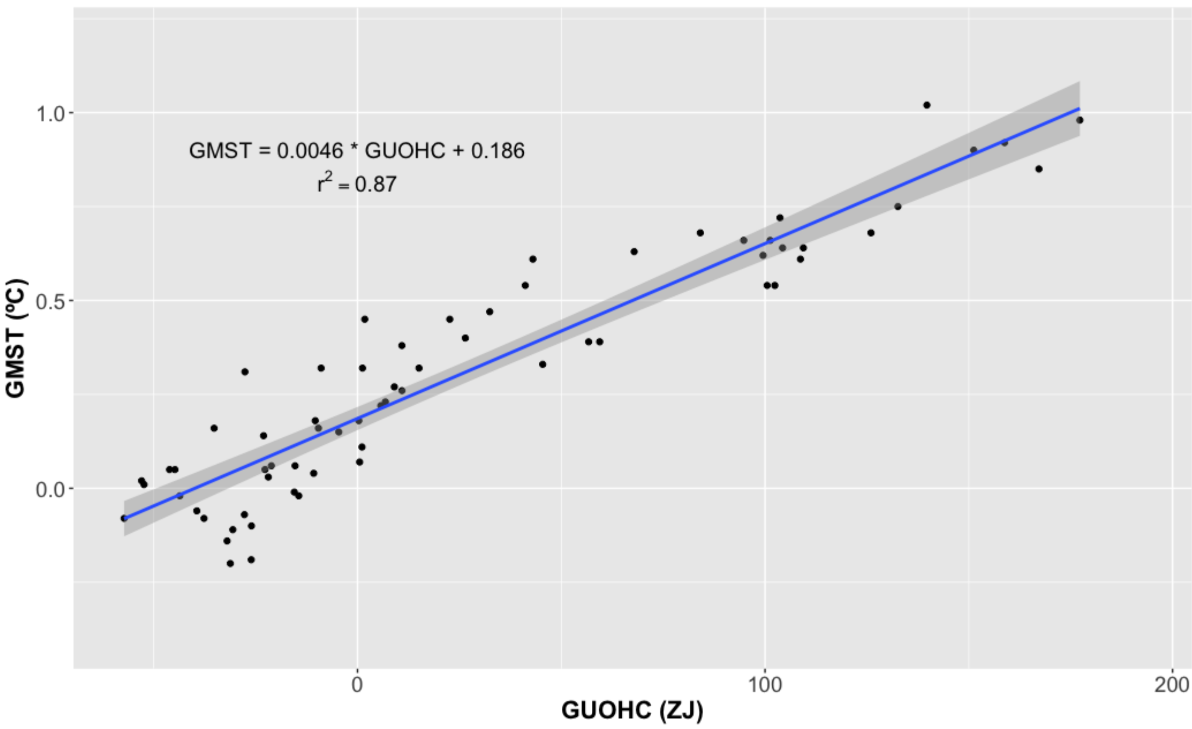


**Figure 2:** Crossplot of Global Mean Surface Temperature (GMST) anomalies relative to the 1951-1980 average (source: NASA, data.giss.nasa.gov) versus Global Upper Ocean Heat Content (GUOHC) anomalies relative to

the 1955-2006 average (source: NOAA, climate.gov); least-squares regression line (thick solid line) with 95% confidence interval (grey-shaded area), and regression equation.

This good correlation suggests that the pre-1955 GMST trends were likely in sync with GUOHC trends, a conclusion supported by the IPCC report[3] that the 1900-1945 GMST increase concurred with a 1900-1945 warming of the upper 400 m ocean layer.

The IPCC GUOHC attribution plot (Fig.3; note that GUOHC is plotted as "OHC", and that $10^{22}$ J = 10 ZJ) shows a poor-fair climate model match for the post-1980 period, and a generally poor model output match in the pre-1980 period. The post-1980 "nat+anthropogenic" model outputs roughly match the observed multi-decadal increase of over 90 ZJ, but poorly matches the multi-yearly variations. As mentioned above, the determination of the anthropogenic scaling factors during the Optimal Fingerprint analysis favor (bias) the multi-decadal match. The pre-1980 climate models poorly match the observed GUOHC energy fluctuations: between 1950 and 1970 the latest IPCC climate models show little variability and often either overpredict (1950-1954; 1968-1970), or underpredict (1956-1958; 1964-1966) the global upper ocean heat content by several ZJ. For example, the climate models did not simulate a large heat decrease that occurred between 1958-1968 – mainly between 1965-1968 - when globally the upper 700 m layer of the oceans apparently lost almost 42 ZJ. 1 ZJ is roughly double the annual global energy consumption (https://en.wikipedia.org/wiki/World_energy_consumption). These heat losses must be attributable to either a relative increase of GUOHC energy loss to space via the atmosphere, or the relative decrease in one of the GUOHC heating processes. The decrease in heating cannot be explained by natural forcings, whose simulated energy effects show a relatively flat line, while an increase of heat loss via the atmosphere is contradicted by a monotonously increasing RFGHG, which should have increasingly limited the energy loss to space. The conclusion must be that a significant, unmodeled heating process was supplying significantly less heat energy between 1965-1968. Similarly, the large energy increases during the mid-late 1950's and between 1968-1977, when 57 ZJ were regained by the global upper ocean layer, are hard to explain via either natural (fairly constant) or anthropogenic (increasing gradually) forcings, and should be attributed to a significant, unmodeled heating process that was acting as the swing energy source during these pre-1980 periods.

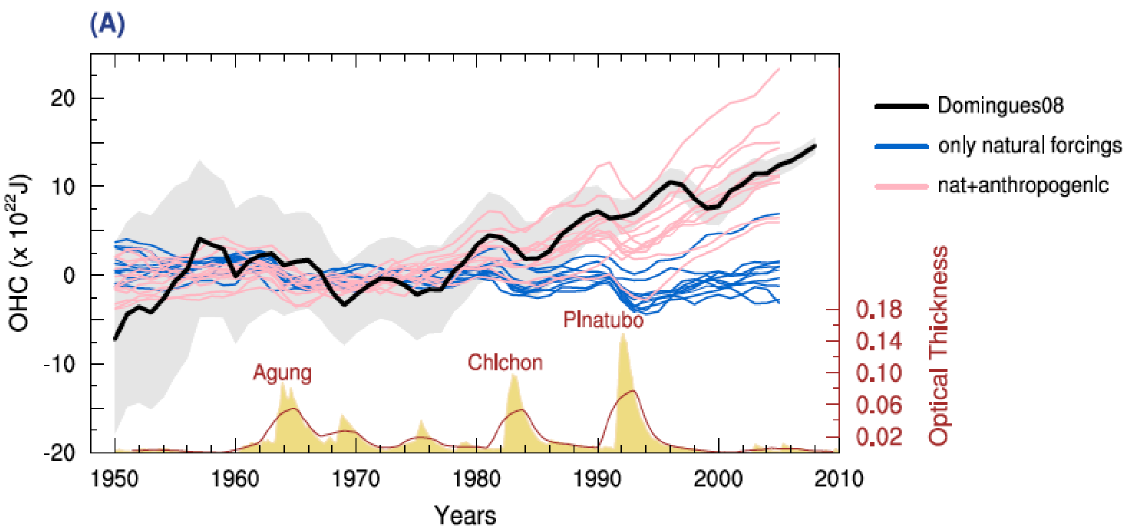


**Figure 3:** Comparison of observed global ocean heat content for the upper 700 m with simulations from ten CMIP5 models that included only natural forcings ('HistoricalNat' runs shown in blue lines) and simulations that included natural and anthropogenic forcings ('Historical' runs in pink lines). Grey shading shows observational uncertainty. The global mean stratospheric optical depth in beige at the bottom indicates the major

volcanic eruptions and the brown curve is a 3-year running average of these values. [From: Bindoff at al. [2], Fig. 10.14]

FP1): the mid-late 1950's GUOHC increase, the 1965-1968 GUOHC decrease, the 1969-1974 GUOHC increase, the 1900-1945 increase of GMST & GUOHC, the 1945-1970 decrease of GMST & GUOHC.

A striking feature of the Fig.3 attribution graph is the divergence of the Natural only vs Natural+ Anthropogenic model output lines around 1980. This despite only a slight increase in reported average global $CO_2$ concentrations ([data.giss.nasa.gov](data.giss.nasa.gov)) from 325.5 ppm (1970) to 338.9 ppm (1980) to 354.4 ppm (1990). There is no physical reason for RFGHG to significantly increase around 1980 without assuming some complex climate feedback loops that result in a $CO_2$ threshold value around 330 ppm.

FP2): An acceleration of ocean heating around 1980.

IPCC atmosphere attribution exercises (Bindoff at al.[2], Fig. 10.8) show that the climate models over-predict atmospheric warming: "*During the satellite era CMIP3 and CMIP5 models tend to warm faster than observations*"[2]. In particular, at the ocean-atmosphere boundary, the interface at which the heating of the ocean due to RFGHG is taking place, the IPCC report[2] the existence of "*factors other than observational uncertainties that contribute to inconsistencies between observed and simulated free troposphere warming*", i.e. significant, unmodeled processes.

FP3): Climate models over-predict atmospheric heating, and therefore the role of RFGHG in heating the oceans.

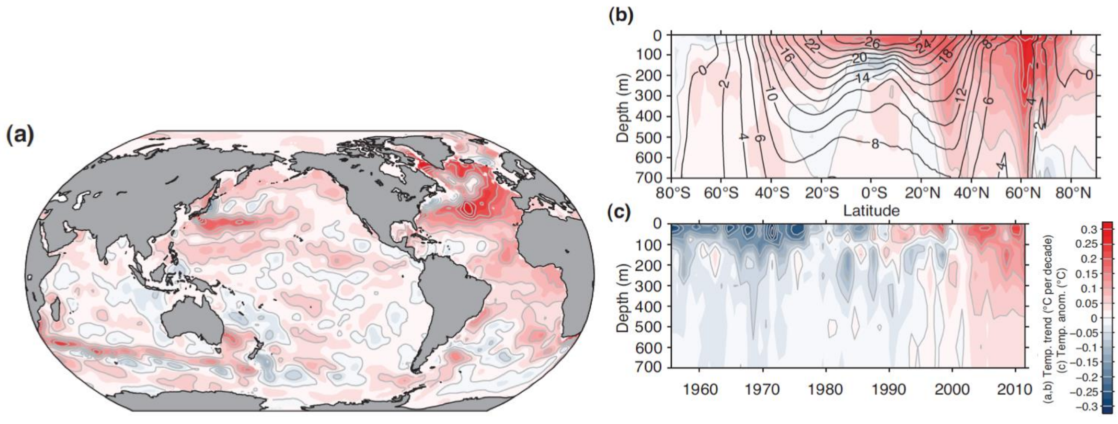


**Figure 4:** (a) Depth-averaged 0 to 700 m ocean temperature trend for 1971–2010; (b) Zonally averaged temperature trends for 1971–2010; (c) Globally averaged ocean temperature anomaly relative to the 1971–2010 mean; (d) Global upper [0-700 m] ocean heat content anomaly [Source: Rhein et al.[3], Fig. 3.1]

The observed GUOHC anomalies show "internal variability" (temporal and regional trends) that cannot be simulated by the existing climate models (Fig. 4). A global map of the temperature trends (Fig. 4a, b) for the 1971-2010 period clearly shows that the Northern hemisphere is warming more rapidly than the Southern, or as stated by the IPCC[2]: "*Over the period 1979–2010 most observed regions exhibited warming [...] but much of the eastern*

*Pacific and Southern Oceans cooled. These regions of cooling are not seen in the simulated trends over this period in response to anthropogenic and natural forcing*."

FP4): The Southern hemisphere is heating less than the Northern hemisphere

It is also visually apparent (Fig. 4a) that the Northern Atlantic is heating more than any other ocean. In addition, the IPCC report that the 1900-1945 warming period showed[2]: "*the most pronounced warming in the Arctic during the cold season, followed by North America during the warm season, the North Atlantic Ocean and the tropics.*"

FP5): The (Northern) Atlantic Ocean is heating more than the Pacific during the last two multi-decadal periods of global warming

RFGHG is a forcing that operates on a global scale, and therefore cannot directly explain regional variability such as the relatively large temperature anomaly of the Northern Atlantic, in general, or the spatial coincidence of heat anomalies with major ocean currents, such as the Gulf Stream (40º N), East Greenland and Labrador currents (60º N), or the offshore-Japan North Pacific current (40º N) (Fig. 4 a,b).

FP6): Regional GUOHC anomalies spatially coincide with major ocean currents

Similarly, differences in Natural Forcings cannot explain why the high-latitude offshore-Greenland seas – where solar irradiation forcing is relatively low due to its high angle of incidence – show a significantly higher temperature trend than e.g. the cooling seas to the west of equatorial Sumatra. In addition, these heat anomalies should in theory dissipate their heat to the cooler surrounding waters unless a "heat pump" is locally actively maintaining an energy gradient. Several secondary processes could in theory pump heat energy against the energy gradient to the Northern Atlantic – e.g. the Atlantic Multi-decadal Oscillation (AMO) was investigated - but IPCC climate model studies could not identify any process that reproduces the location or magnitude of the observed trends: e.g. "*studies that find a significant role for the AMO show that this does not project strongly onto 1951–2010 temperature trends*"[2]. This lack of heat dissipation and lack of a viable large-scale energy pump suggest that a significant, unmodeled process is warming the Northern Atlantic and offshore Japan currents in-situ.

FP7): Major ocean currents are being warmed in-situ

Finally, the role of the uppermost (75m) layer of the oceans requires investigation. It's temperature and energy properties are clearly distinct from the lower ocean layers (Fig. 4c), as is reflected by a significant difference in temperature trends over the 1971-2010 period: 0.11°C per decade for the uppermost layer, decreasing to 0.015°C per decade by 700 m[3]. Only this uppermost layer directly interacts energy-wise with the IPCC modeled natural and anthropogenic forcings. The mass of this 75m layer is roughly 8 times smaller than the mass the 625 m below it, while its temperature increase was roughly 7.5 times larger, leading to the conclusion that roughly half of the GUOHC energy anomalies are due to this upper layer. This in turn implies that the GMST attribution only examines the origins of half of the energy of the GUOHC attribution.

The temperature anomalies of the uppermost 75 m are significantly more variable than the underlying layers: a pre-1975 cooling period is separated from a post-1990 warming period by only a few years of “average” temperature trends. In contrast, the underlying 625m layer gradually transitions from slightly below-average cooling to slightly above average warming during the same period, though since the late ‘90’s the warming has been consistently high.

FP8) Sharp increase in GMST & GUOHC trends since 2000 not reflected in $CO_2$ concentrations

Another striking feature is that the surface heat anomalies that coincide with major ocean currents (Fig. 4a) apparently extend over the full depth of the ocean column (Fig. 4b). As only the uppermost ocean layer interacts with the IPCC modeled natural and anthropogenic forcings, either an unidentified, unmodeled energy pump redistributes energy from this uppermost layer, or a significant, unmodeled process is heating the ocean depths in-stu. The former would require a physical process with improbable properties:

- Constantly increasing supply of energy to the deeper oceans even during periods (e.g. 1998-2004) of relatively unchanging energy content
- Deeper ocean energy dissipation needs to be counteracted by a heat pump that transports heat energy against an energy gradient
- Heating of a huge volume of water by a volumetrically insignificant layer
- Redistribution of surface energy along the full water column

Such a hypothetical process is hard to imagine and has yet to be recognized.

FP9) Ocean layers deeper than 75 m are being heated in-situ.

## Geomagnetically induced heating

As mentioned above, the Earth’s energy balance can be seen as a steady-state, whereby disruptions of this balance due to variable forcings result in climate change. This paper investigates whether an additional forcing – geomagnetically induced heating of the oceans’ large currents - acts as a swing energy supply, causing the oceans to warm during its periods of high activity, and to cool when its lower activity fails to compensate the energy lost to space through the atmosphere.

Induction heating occurs when a volume of magnetically susceptible material is subjected to a varying magnetic field, whereby induced electrical energy is partially or fully converted to heat. The electromotive force, $\varepsilon$, induced by a varying magnetic field is given by the Lenz-Faraday law[4]:

$$\varepsilon = -\frac{\delta\Phi}{\delta t}$$

whereby $\Phi$ is the magnetic flux and t is time. Note that the negative sign denotes a direction: the generated current counterbalances the varying magnetic field. The sign is irrelevant for induction heating applications, as both increases and decreases in magnetic field strength produce an electromotive force and thus a heating effect.

Joule’s Law[4] states that the power transmitted via the electromotive force is proportional to $\varepsilon^2/\rho$, whereby ρ is the electrical resistivity of the material. This induced power is converted to heat energy. The 1971-2010 heat gain translates to roughly 0.55 $W/m^2$ across the global ocean surface area ($3.60 \times 10^{14}$ $m^2$) [3]. Assuming induction heating of the full ocean column, as the geomagnetic field does not change with ocean depth, and an average ocean depth of 3500 m would mean the 1971-2010 heat gain translates to 0.15 $mW/m^3$ of sea water. Assuming a sea water resistivity of 0.03 Ω.m indicates the induced electromagnetic force per cubic meter of sea water, supplied continuously over the oceans between 1971-2010, is on the order of 2.3 mV, a surprisingly small induction heating requirement.

## The case for geomagnetically induced heating of the oceans

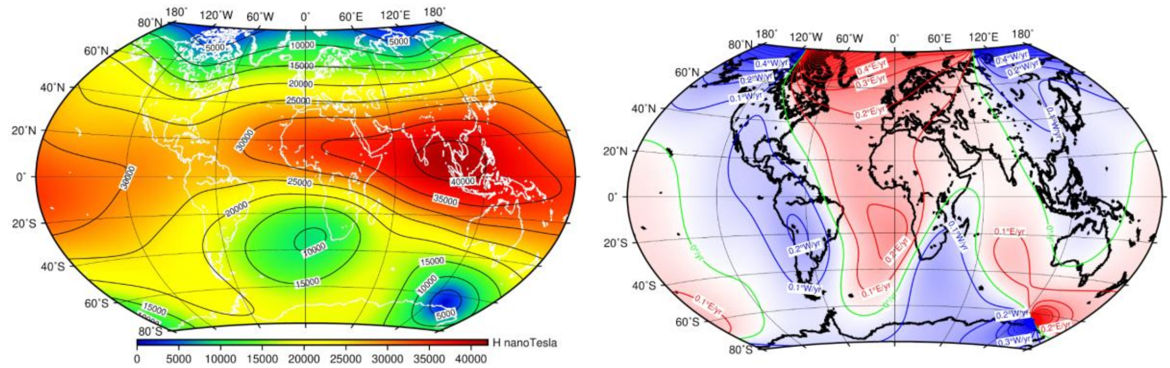


**Figure 5: Left**: Map of 2020 Geomagnetic Field Horizontal Intensity; **Right**: Map of predicted annual rate of change of declination (degrees/year East or West) for 2020.0-2025.0 [Source: http://www.geomag.bgs.ac.uk/education/earthmag.html]

A map of the Earth's geomagnetic field (Fig. 5, left) shows that its horizontal field strength varies considerably with surface position, so an ocean current that traverses the surface will undergo induction heating due the changing horizontal field strength. Given the diamagnetic nature of sea water – sea water is magnetically repelled by both positive and negative magnetic poles – it is even plausible that the geomagnetic field is partially responsible for the speed and direction of the main ocean currents, i.e. that ocean currents will preferentially follow magnetic gradients. For example, the Gulf Stream originates as the North Equatorial stream off the coast of West Africa (~30000 nT), crosses the Atlantic to offshore Florida (~25000 nT), then crosses the Atlantic again to offshore Western Europe (~20000 nT). According to the Lenz-Faraday and Joule laws the sea water, which is diamagnetic and electrically conductive, will be continuously heated as the current traverses this changing field. However, as the geomagnetic field is relatively stable in time, such induction heating should be deemed part of the steady-state, i.e. cannot account for any recent GMST or GUOHC increases. Any recent changes attributable to induction heating need to be ascribed to recent changes in the geomagnetic field.

A map of the Earth's predicted annual rate of declination change (Fig. 5; Right) shows some remarkable similarities with the depth-averaged global upper ocean temperature trend for 1971–2010 (Fig. 4a). Three of the main North Atlantic currents – the Gulf Stream, the East Greenland, and Labrador Currents – traverse areas where the annual rate of declination change is relatively large. According to the Lenz-Faraday and Joule laws these magnetic field variations will induce additional induction heating if any sea water, regardless of whether it is moving or not. The additional heating component will be greater in currents (more change) as well as during years when the geomagnetic field is rapidly changing, e.g. in 2020 (Fig. 5 right), when the declination is varying significantly in conjunction with a significant North Magnetic Pole movement.

The oceans will heat more during periods when the declination, i.e. the North Magnetic Pole position, varies more. To test this, the North Magnetic Pole locations since 1590 were downloaded from NOAA (https://www.ngdc.noaa.gov/geomag/data/poles/NP.xy), and converted to yearly NPDT (North Pole Distance Travelled) values using R's distm() function (distHaversine method). The NOAA data features 5-yearly, step-wise changes (Fig. 6) that are an artefact of the 5-yearly magnetic model updates, so a LOESS-smoothed (10% smoothing) data set was used for analysis purposes. The GUOHC data were downloaded from a NOAA data server (http://data.nodc.noaa.gov/) and averaged per year. Note that ocean heat data are only available for the 1955-2019 period, but that this period coincides with the main focus period of the IPCC investigations.

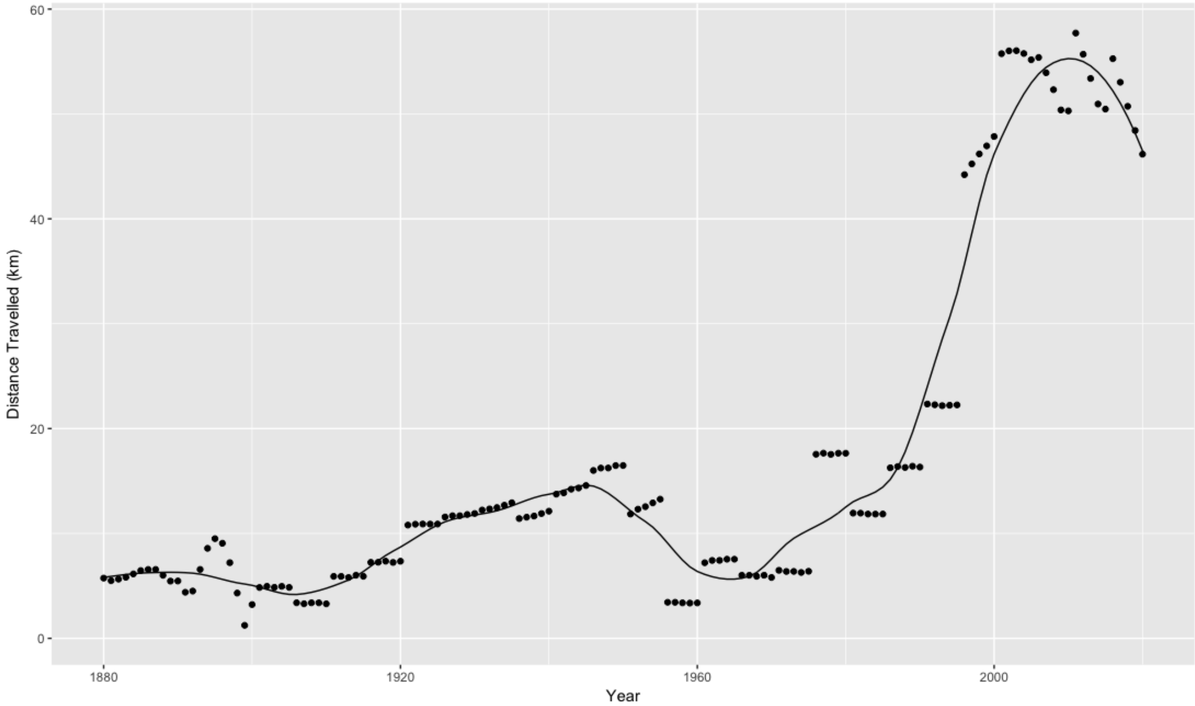


**Figure 6:** Yearly distance travelled by the Earth's Magnetic North Pole (points) and LOESS-smoothed regression (line)

The fingerprints of this curve are encouragingly similar to the observed GMST and GUOHC variations that are unexplained by current climate models: the 1900-1945 increase, the 1945-1970 decrease, the late '50s increase, the mid-60's decrease, the 1980 acceleration, the sharp increase around 2000. A crossplot (Fig. 7) reveals that a strong relationship exists between the two variables: all of the global upper ocean cooling years occurred when the NPDT was less than 18 km, and nearly all of the ocean heating occurred when the NPDT was greater than 18 km, indicating that geomagnetic induction heating of the ocean's currents due to a varying geomagnetic field is a viable swing energy producer.

A sigmoidal model can be used to predict GUOHC from DNMP.

$$GUOHC(ZJ) = 18.2 - \ln\left(\frac{53.9}{NPDT(km)} - 1\right) * 24.3$$

Note that Figure 4 has (unconventionally) been plotted with the dependent variable on the horizontal axis, in order to highlight the asymptotic plateaus of the sigmoid, and to model the equation. Also note that the equation is an empirical summary of the last 70 years, i.e. caution must be used when extrapolating beyond the 70-year interval, or when using unsmoothed data. The model is actually composed of 3 relationships:

- A positive, linear correlation between the two variables for the 1955-1968 and the 1974-2011 period.
- A "flat" relationship for the 1968-1974 period (low tail), during which little correlation exists: the GUOHC decreases despite a fairly constant NPDT of 5-7 km. Possible explanations for this feature could include:
  - Effects of other forcings are causing scatter
  - LOESS smoothing causes loss of signal detail
  - The preceding 1964-1967 period was exceptionally cold, so the Upper Ocean layer may have acted as a temporary negative heat sink during the 1968-1974 period: geomagnetic induction heating failed to compensate further energy losses to space.
- A slightly negative, linear correlation between 2011-2019 (high tail): GUOHC increases despite a slightly decreasing NPDT. Possible explanations could include:
  - The LOESS NPDT regression data were used for the analysis, so the decrease of NPDT may be an artefact of the smoothing. The data points (Fig. 6) show significant scatter, which is likely an artefact of the International Geomagnetic Reference Field model.
  - More retention of heat, e.g. due to RFGHG forcing, despite a relatively constant heat supply
  - The relationship has somehow entered a new phase since 2011, e.g. due to a shift of the area of intense declination covering the ocean currents
  - The heat is accumulating due to prolonged warming: a positive heat sink, geomagnetic induction heating overcompensates energy losses to space

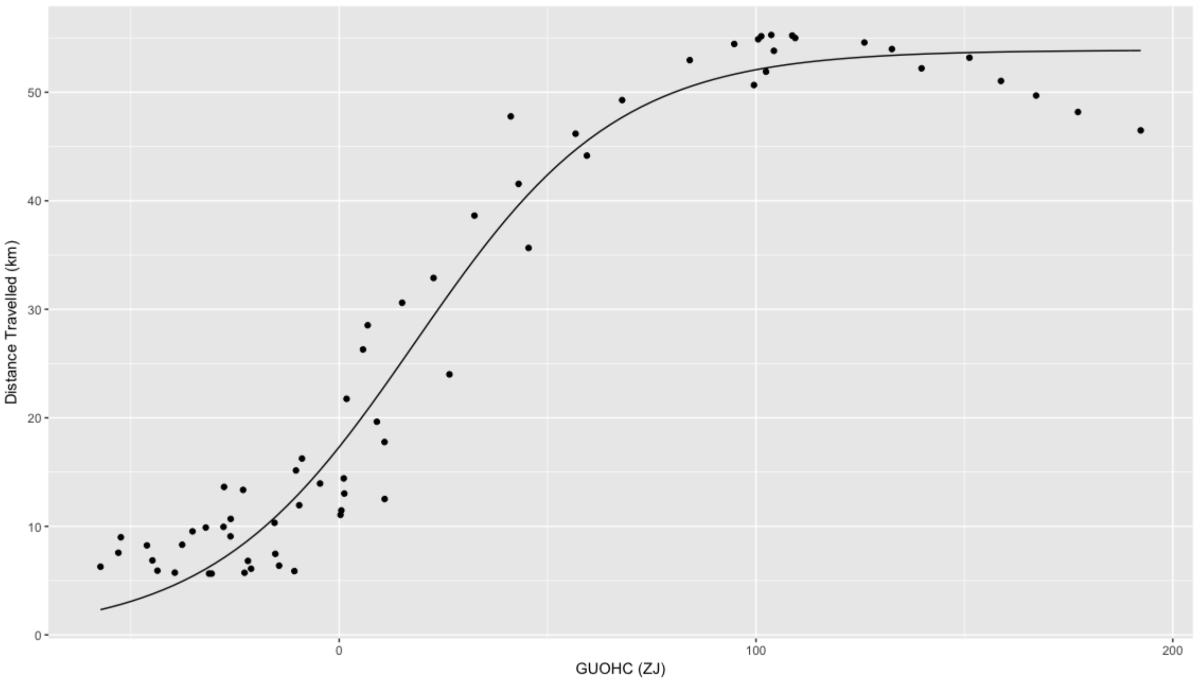


**Figure 7:** Yearly distance travelled by the Earth's Magnetic North Pole (in km) versus Global Upper Ocean Heat Content Anomaly (in ZJ), with Sigmoidal model (line) of the relationship.

Three elements are necessary for demonstrating an NPDT-GUOHC cause-effect relationship:

1) Temporal precedence of the cause (NPDT) to the effect (GUOHC)
2) Covariation of cause and effect
3) No plausible alternatives

The first can never be proven: the changes in both variables occur simultaneously for the yearly-averaged data. The second is is demonstrated by the strong covariation in Fig. 7. A statistical analysis reveals that the null hypothesis – no relationship between the two variables – can be rejected ($p<0.001$), so the relationship is statistically significant. This signifies that any attribution of ocean heat variability should take geomagnetic field variability into account. The only plausible explanation how an energy transfer from the geomagnetic field to ocean heat can happen is induction heating of the oceans' main currents:

- The ocean's heat anomalies coincide spatially with the main, strong Northern Hemisphere ocean currents (Fig. 4) that traverse varying geomagnetic fields
- The heating varies as a function of North Magnetic Pole movement, which was taken as a proxy for the intensity of the geomagnetic field variations, indicating that these variations play a role in the heating of the oceans. The reverse relationship – that heating of the oceans varies the geomagnetic field – seems implausible.

The energy fluctuations of the oceans' upper 700 m are therefore likely caused by the induction heating of main ocean currents that traverse the varying geomagnetic field. Though the induction heating of diamagnetic sea water only produces a weak induction effect, due to its fairly high electrical resistivity when compare to ferromagnetic materials, such small effects are multiplied by the magnitude of the geomagnetic field variations, the huge volume of sea water in the currents, the non-stop nature of the process, and the fact that at a given location the Earth's magnetic field (and other geomagnetic disturbances) do not substantially change with water depth, i.e. the energy transfer occurs over the full water column (Fig. 4 b&c).

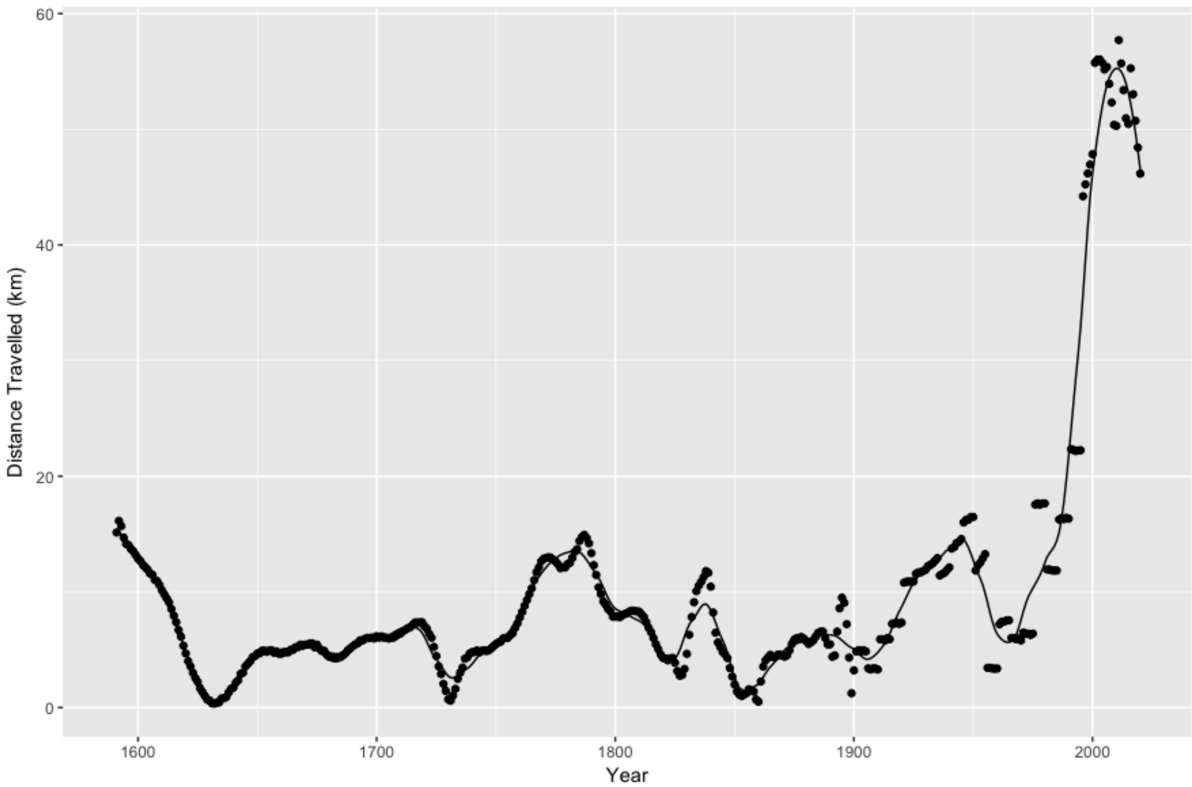


**Figure 8:** Yearly distance travelled by the Earth's Magnetic North Pole Distance (points) and LOESS-smoothed regression (line)

Note that the Southern Magnetic Pole shows much smaller movements (https://www.ngdc.noaa.gov/geomag/data/poles/SP.xy), so induction heating due to the declination variation caused by the Magnetic South Pole movement will be significantly less.

A look at the NPDT for the full NOAA 1590-2019 data set (Fig. 8) reveals that two of the three estimated dates of the "Little Ice Age" temperature minima (1650, 1770, 1850)[5] roughly correspond to the NPDT minima, and that NPDT was less than 18 km for the full 1600-1770 period, indicating that a similar process as the one described above may have been partly or fully responsible for cooler oceans and temperatures since the late-16$^{th}$ century. It also demonstrates how exceptional the NPDT and associated induction heating since the late-90's has been.

## Geomagnetic Induction Forcing

The GUOHC attribution via Optimal Fingerprint Analysis evaluates "*the relative contributions of multiple causal factors to a change or event with an assignment of statistical confidence*" [2]. The previous sections have demonstrated that the IPCC analyses using identified natural and anthropogenic forcings cannot fully explain observed data variability. The IPCC recognize such deficiencies and lump all unmatched variability under the category of "internal variability"[2]. Much of the observed "internal variability" can be explained by including an additional forcing - Geomagnetic Induction Forcing (GMIF) - in the climate models, as its "fingerprints" van be recognized in the unexplained variability, so its relative contribution to change must be on the same order or larger than the currently modeled forcings.

FP1): the late 1950's GUOHC increase, the 1965-1968 GUOHC decrease, the 1969-1974 GUOHC increase, the 1900-1945 increase of GMST & GUOHC, the 1945-1970 decrease of GMST & GUOHC & FP8) Sharp increase in GMST & GUOHC since 2000. The NPDT curve (Fig. 6) – a proxy for geomagnetic field variability – shows significant concurrence with these increases and decreases.

FP2): An acceleration of ocean heating around 1980. (Fig. 6)

FP3): Climate models over-predict atmospheric heating, and therefore the role of RFGHG in heating the oceans. This can possibly be explained as an over-reliance on RFGHG as a heating mechanism due to the non-recognition of GMIF.

FP4): The Southern hemisphere is heating less than the Northern hemisphere. The Northern Magnetic Pole moves significantly more than its Southern counterpart, so geomagnetic field variability – and its associated induction heating - is greater in the Northern hemisphere.

FP5): The (Northern) Atlantic Ocean is heating more than the Pacific during periods of global warming. The Northern Atlantic currents are far more affected by the changing geomagnetic field, e.g. the Labrador current is proximal to the North Magnetic Pole and is moving in an almost opposite direction, so will experience greater geomagnetic variability than its Pacific counterparts (Fig. 5, right)

FP6): Regional GUOHC anomalies spatially coincide with major ocean currents & FP7): Major ocean currents are being warmed in-situ & FP9) Ocean layers deeper than 75 m are being heated in-situ. GMIF does not vary significantly with ocean depth, so ocean currents moving through a variable geomagnetic field will heat in-situ at all depths.

## Causes of the Earth's Geomagnetic Field variations

The analysis above reveals a previously unrecognized Earth-internal energy flux: geomagnetic energy is being converted into ocean heat energy, which begs the question how this geomagnetic energy originates and is maintained, as such energy transfers cannot continue indefinitely without replenishment.

The Earth's magnetic field is produced by the Earth's ferromagnetic core via energy released during its cooling, i.e. strong field variations are produced by rapidly cooling cores[6]. Geomagnetic variability is caused by two types of internal core variations: slow convection movement, resulting in centennial-scale variations, and hydromagnetic waves, resulting in annual-scale variations[6]. Surface-observable variability includes Magnetic Pole movements and Geomagnetic Jerks. The term "jerk" is borrowed from the field of Electrodynamism and refers to a relatively quick change in the second derivative of the Earth's magnetic field with respect to time:

$$\frac{\delta\Phi}{\delta t^2} = -\frac{\delta\varepsilon}{\delta t}$$

The above equation demonstrates that changes in the second derivative are proportional to temporal variability of the acting electromagnetic forces. Recent computer simulation studies indicate Geomagnetic Jerks are caused by hydromagnetic waves created through cooling of the core[6]. Geomagnetic Jerks on average occur every 10 years, a number that is similar to the 10-11 solar cycles[7], suggesting a link between the two. Strong Geomagnetic Jerks were observed globally in 1901, 1913, 1925, 1969, 1978, 1991, and 1999[6].

## The case for geomagnetically induced heating of the ferromagnetic core

The heating and cooling episodes that drive the geomagnetic field variability indicate a variable energy source is acting as a swing energy supply that modifies the core heat content on decadal and centennial time scales; geomagnetically-induced heating of the Earth's ferromagnetic core due to the solar wind/solar storms, i.e. solar magnetic flux variations, is a likely candidate. In brief summary, this paper provides evidence for two different geomagnetically induced energy effects:

1) The non-stop heating of the diamagnetic sea water due to continuous movement of sea water across a varying geomagnetic field.

2) The heating of Earth's strongly ferromagnetic core due to relatively small (100's of nT) magnetic fluxes of the solar wind over short time intervals (hours to days).

This paper proposes the Earth acts as a giant battery that is charged by the solar wind-induced heating of its core, whereby stored heat energy is converted to geomagnetic energy during periods of lower solar wind activity leading to core cooling, i.e. increasing the Earth's magnetic field strength while cooling the core. Geomagnetic energy is subsequently lost to the induction heating of the Earth, whereby a significant part of the geomagnetic energy heats the oceans, the lowest resistivity large body of material near the Earth's surface.

Solar wind is generated by solar coronal mass ejections[7], and causes strong geomagnetically-induced currents in pipelines and electrical grids in the areas surrounding the North Atlantic[8] during more active periods ("storms"). These currents are induced by variations in the earth's magnetic field due to the interactions of solar storms with the Earth's magnetosphere, and cause highly-energetic disruptions on the Earth's surface: e.g. in 1989 a severe geomagnetic storm tripped the Hydro-Québec power grid, causing a severe power outage[8]. The Lenz-Faraday and Joule laws predict these storms induce similar highly energetic effects in the Earth's ferromagnetic core, whereby the induced electromotive power is converted to core heat.

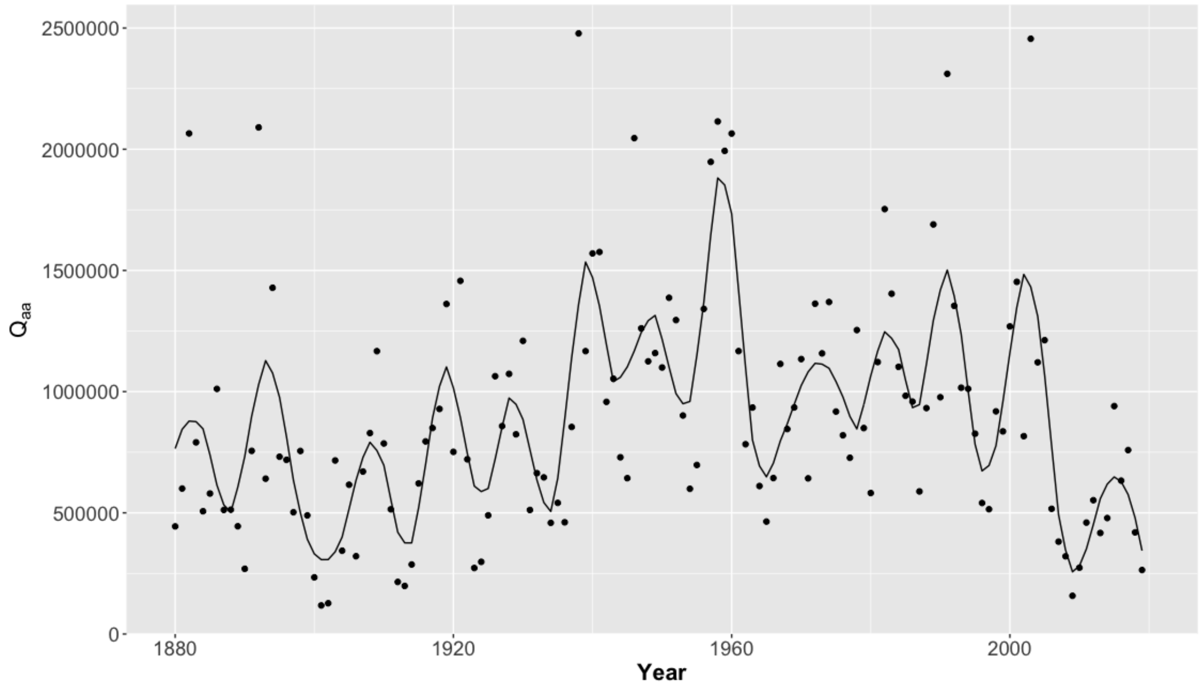


**Figure 9:** Yearly variation of $Q_{aa}$ between 1880-2020 and its LOESS-smoothed regression (line)

Geomagnetic observatories have measured near-Earth solar wind variations – the aa index - since 1868. For the following analysis the ISGI (http://isgi.unistra.fr/data_download.php) aaindex data was used. As mentioned above, it is the change in magnetic flux that creates an electromotive force. The ISGI data provides a 3-hourly measurement of the aaindex, so for analysis purposes a Δaa variable was calculated as the difference between two temporally adjacent aaindex measurements, i.e. the absolute value of the difference of the aaindex at a given time with the value measured 3 hours earlier. This aaindex change represents the magnetic flux change over the three-hour time interval, so is proportional to the induced electromagnetive force (Lenz_Faraday law). The squared difference is proportional to the induced Joule Heating power, so a variable, $Q_{aa}$, was calculated as the yearly sum of the squared three-hour differences. $Q_{aa}$ represents a measure of the induced power due to solar wind, so changes in $Q_{aa}$ are proportional to the overall induced energy heating the core. Low $Q_{aa}$ values represent periods of low induction heating, during which the core can cool by converting heat to geomagnetic energy, while increasing $Q_{aa}$ values represent induction heating of the core and increasing core temperatures. The resultant dataset (Fig. 9) shows an 11-year $Q_{aa}$ cyclicity, which – unsurprisingly – is very similar to the 10-11 solar cyclicity: geomagnetic storms are more prevalent during periods of high solar activity.

Figure 9 demonstrates that 5 (exceptions: 1969, 1991) of the 7 observed global Geomagnetic Jerks occur within 0-2 years of $Q_{aa}$ lows. This suggests the Geomagnetic Jerk cycle may consist of:

- Induction heating of the core during increasing $Q_{aa}$
- Cooling of the core when $Q_{aa}$ drops below a threshold value
- Conversion of core heat energy to magnetic energy during cooling periods resulting in increasing geomagnetic field strength during periods of low heating, i.e. low solar wind activity.
- Geomagnetic jerk when $Q_{aa}$ – and the associated induction heating - is at a minimum, when the core switches from cooling to heating.

The large drops in $Q_{aa}$ between 1991-1993 and 2003-2009 could possibly be the cause of a major cooling event in the core, resulting in a sudden increase in the geomagnetic field variability, which could have caused the North Magnetic Pole drift acceleration from the 1990's onwards.

The process above could explain why Europe experienced a temperature low during the Maunder Minimum (1645-1715)[9]: the extremely low sunspot activity – a proxy for solar wind activity[9] – during this period meant that the Earth's core was no longer being significantly heated through solar wind induction. This in turn meant lower $Q_{aa}$ variability, which in turn lowered the geomagnetic field variability, which in turn lowered the induction heating of the oceans' currents. This process could also explain why the strength of the Earth's magnetic field axial dipole component reached a maximum preceding this time: declining $Q_{aa}$ values preceding the lull in the solar wind activity at the Maunder Minimum caused a lack of magnetic core heating, resulting in an uninterrupted cooling of the Earth's core, resulting in a prolonged period of conversion of heat to geomagnetic energy, and strengthening of the geomagnetic field. This longer-scale interaction suggests that the core's slow convection movement may interact with centennial-scale solar cycles.

## Summary

The suggested process whereby the solar magnetic flux changes the Earth's climate during a global warming period can be summarized as:

- Increasing solar wind heats the Earth's magnetic core through magnetic induction
- The core cools during periods of lower solar wind, whereby the heat energy is converted into geomagnetic field energy
- Intense solar wind variations cause energetic core reactions that locally change the geomagnetic field orientations, i.e. increase geomagnetic field variability, including North Magnetic Pole drift speed
- Increased geomagnetic field variability results in greater geomagnetic induction heating of the oceans' currents
- The increased ocean heat content is redistributed via the Earth's climate systems.

The main evidence in support:

- It is the only plausible process explaining the spatial coincidence of the oceans' main heat anomalies with the main ocean currents.
- It is the only plausible explanation for the strong correlation between North Pole Distance Travelled and Global Upper Ocean Heat Content anomalies.
- It explains why these surface heat anomalies occur the deeper water columns.
- It offers a reasonable explanation for observed Geomagnetic Field perturbations, such as Geomagnetic Jerks and North Magnetic Pole drift.
- It offers a reasonable explanation for the temporal coincidence of the Little Ice Age, Maunder Minimum, and the geomagnetic axial dipole component maximum in the mid-17th century.

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