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Notes and Correspondence
On increasing global temperatures: 75 years after Callendar

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In 1938, Guy Stewart Callendar was the first to demonstrate that the Earth's land surface was warming. Callendar also suggested that the production of carbon dioxide by the combustion of fossil fuels was responsible for much of this modern change in climate. This short note marks the 75th anniversary of Callendar's landmark study and demonstrates that his global land temperature estimates agree remarkably well with more recent analyses.

Key Words: global temperatures; history; Guy Stewart Callendar

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1. Introduction

Discussion of the human influence on global temperatures has a long history. For instance, Fourier (1824) first discussed why the Earth was warmer than expected from solely considering solar radiation reaching the planet. Fourier ruled out geothermal effects, considered the temperature of outer space and pondered about heat being trapped in the atmosphere, but did not come to any firm conclusions. Tyndall (1861) suggested a solution to this conundrum by experimentally demonstrating that gases such as carbon dioxide can effectively absorb infrared radiation, i.e. the 'greenhouse effect'.

Later, Arrhenius (1896) used the results of Tyndall and others to produce the first estimate of the sensitivity of global temperatures to increases in carbon dioxide. Much of this research was aimed at understanding historical climatic variations such as ice ages rather than any modern changes (e.g. Ekholm, 1901). However, in the early 1900s the theory that increases in atmospheric carbon dioxide could change the climate was not widely accepted.

Separately, widespread temperature records were being used to estimate the variability in global land air temperatures during the late 1800s (e.g. Köppen, 1881), but no trend was evident. These activities eventually culminated in the work of Callendar (1938), who was the first to show that the Earth's land temperature had increased over the previous 50 years. Callendar also suggested that the production of carbon dioxide by the combustion of fossil fuels was responsible for a large part of this warming, which became known for a time as the 'Callendar Effect' (see Fleming (2007) and Weart (2008) for further discussion).

This short note marks the 75th anniversary of Callendar's landmark study, originally published in the *Quarterly Journal of the Royal Meteorological Society* in April 1938.

2. Comparing global temperature estimates

As highlighted by Le Treut *et al.* (2007), many studies have produced consistent estimates of the smoothed decadal variability in global temperatures in the instrumental period (since about 1850). Here we compare the interannual variability of three of these land-based records as consistently as possible.

Figure 1 compares the latest CRUTEM4 (Jones *et al.*, 2012) estimates for annual near-global land temperatures with those of Callendar (1938). The agreements in trends and variability are striking: the correlation between the two time series during their common period is $r = 0.81$. However, CRUTEM4 shows larger amplitude variability. Callendar had access to temperatures from just 147 land-based stations to reconstruct his global temperature time series, whereas CRUTEM4 includes more than 200 in 1880, increasing to more than 2000 by 1935. The differing amplitudes of variability are therefore perhaps surprising, as fewer stations might be expected to result in higher variance (e.g. Jones *et al.*, 1997), but this feature remains unexplained.*

The analysis is restricted to 60°S–60°N because Callendar did not include any Antarctic or Arctic stations in his record. However, he did note that the omitted Arctic stations had the largest variations and that the northern latitudes were warming faster than other regions. More recently, Wood *et al.* (2010) demonstrated that the high northern latitudes underwent a striking temperature rise during this period.

In addition, Callendar produced time series for different regions, including Western Europe and New York State, as well as different latitudinal bands. Sadly he did not publish the values for these, except for decadal averages of the Northern temperate

*The data in the original paper are tabulated as annual means, so we have assumed this to be correct. However, it is possible that Callendar temporally smoothed some of the data, resulting in a lower variance.

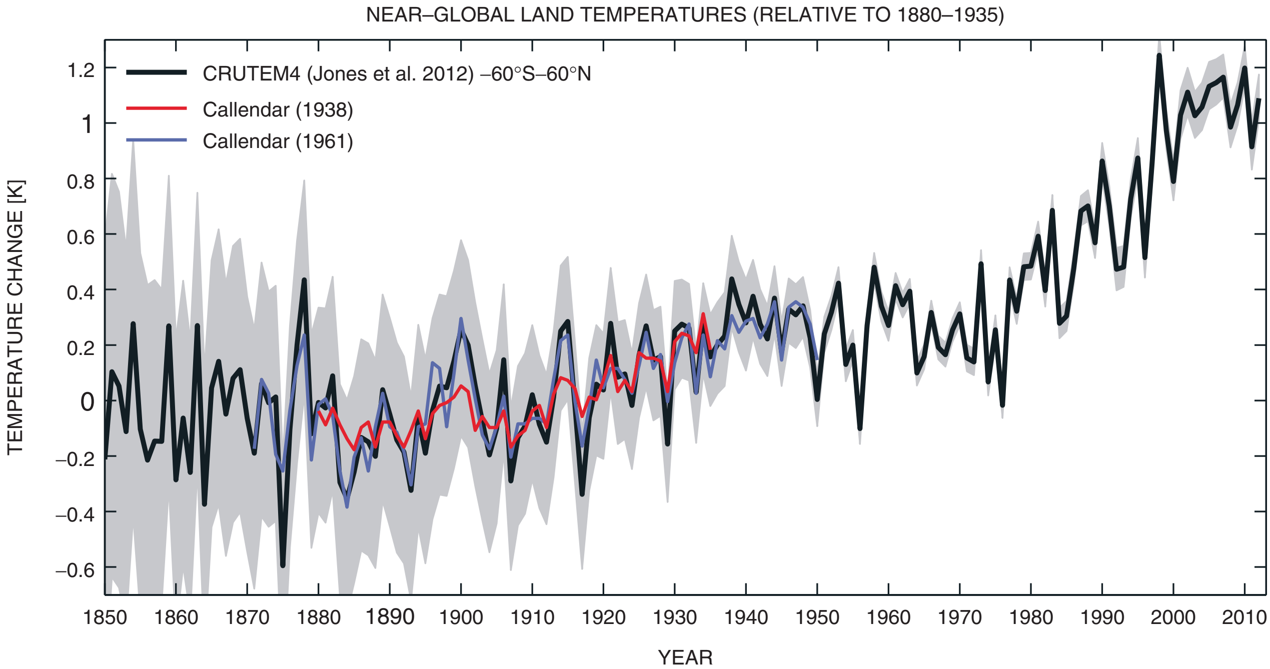

Figure 1. Comparison of historical reconstructions of near-global land temperatures using CRUTEM4 (black: Jones *et al.*, 2012) with results of Callendar (1938) (red) and Callendar (1961) (blue), using a reference period of 1880–1935. The CRUTEM4 estimates are for 60°S–60°N (to accord with Callendar's series), with grey shading representing 95% uncertainty.

zone. Callendar suggests that '*quite a moderate number of reliable temperature records may be used to give the period anomalies of very large areas*', a fact that has been discussed in a number of more recent articles (see e.g. Madden *et al.*, 1993; Jones *et al.*, 1997). The latter provide a quantification of the number of stations required to derive reliable large-scale averages in terms of the expected number of spatial degrees of freedom. The number depends on the time-scale of interest, but as few as 50 well-spaced locations should provide reliable estimates on the annual time-scale.

Callendar later expanded his estimates of global and regional land temperatures using a much larger number of station records and also published the data for zonal and seasonal averages (Callendar, 1961). A comparison of this extended near-global (60°S–60°N) annual mean dataset is also shown in Figure 1, which agrees even better with CRUTEM4 ($r = 0.92$) and has a similar amplitude of variability.

3. Reasons for the observed temperature increase

A large part of Callendar (1938) discusses the change in global temperatures that would have been expected given the observed increases in atmospheric carbon dioxide concentration. The calculations were somewhat hindered by the existing understanding of atmospheric radiative physics and by the limited available observations of the infrared absorption spectrum and carbon dioxide concentrations (Callendar also collated the available observations of atmospheric carbon dioxide concentrations himself). However, he considered the energy balance at the surface instead of at the top of the atmosphere. Nevertheless, Callendar estimated that global temperatures should have warmed by around 0.03 K decade^{-1} due to the increasing levels of carbon dioxide. The global temperature estimates exhibited a larger trend of 0.06 K decade^{-1}, leading to his conclusion that the combustion of fossil fuels was making a significant contribution to the observed warming. Perhaps Callendar was slightly fortunate that the observed rise in temperatures was larger than expected from purely anthropogenic effects, therefore making it easier to detect.

Callendar also considered other reasons for the temperature increase, notably the urban heat island (UHI) effect. He separated his sample into stations within cities and those in rural areas and found '*no secular increase of temperature due to city influence*', although his sample sizes were small. More recent estimates also suggest that the effect of the UHI and exposure of thermometers on global temperatures is small (Parker, 2010; Jones and Wigley, 2010).

4. Discussion

Callendar's conclusions were treated with a degree of scepticism. He even starts his introduction by saying that '*[f]ew of those familiar with the natural heat exchanges of the atmosphere, which go into the making of our climates and weather, would be prepared to admit that the activities of man could have any influence upon phenomena of so vast a scale*'. The peer-review discussion section that appears with Callendar (1938) expresses concern about the radiative physics calculations and the accuracy of the carbon dioxide measurements used. In fact, Callendar's findings on the role of carbon dioxide were largely dismissed by the scientific community until improved estimates of the infrared absorption spectrum were obtained and analysed (Callendar, 1941; Plass, 1956).

There was also debate about whether the observed temperature increase was in fact a natural fluctuation or caused by changes in atmospheric circulation, rather than an anthropogenic fingerprint. Indeed, there is still much discussion (e.g. Delworth and Knutson, 2000; Bronnimann, 2009) over the causes of this early twentieth century warming, which may have had considerable spatial and seasonal variations. However, it seems likely that there were multiple causes, including an internal climate fluctuation and recovery from the large volcanic forcing at the end of the 19th century as well as solar and anthropogenic influences.

We also note that additional weather observations are even now becoming available from many previously non-digitized historical records, including the period covered by Callendar. For example, the Old Weather project (http://www.oldweather.org) has recently completed the digitization of over 1.5 million new observations from British Royal Naval ship logbooks from the 1914–1923 period, using volunteers to transcribe the hand-written pages. Projects such as Old Weather and the 20th Century

Figure 2. A photograph of Guy Stewart Callendar (1898–1964), taken in 1934. Image from University of East Anglia archives (http://www.uea.ac.uk/is/archives/callendar). Additional photographs can be found in Fleming (2007).

Reanalysis (Compo *et al.*, 2011) continue to refine our estimates and understanding of historical climate variability.

In the 75 years since the work of Callendar (1938), great progress has been made in understanding the past changes in Earth's climate and whether continued warming is beneficial or not. In 1938, Callendar himself concluded that '*the combustion of fossil fuel [. . .] is likely to prove beneficial to mankind in several ways*', notably allowing cultivation at higher northern latitudes and because '*the return of the deadly glaciers should be delayed indefinitely*'.

Callendar's achievements are remarkable, especially as he was an amateur climatologist, doing much of his research in his spare time without access to a computer. He was meticulous in his approach and a large collection of his notebooks is currently archived at the University of East Anglia. For completeness, Callendar's tabulated global land temperatures are presented as Supplementary Information.

Finally, Fleming (2007) gives a comprehensive review of the life and times of Guy Stewart Callendar (Figure 2), whose efforts in attempting to estimate and understand the changing temperatures of the planet has, we hope, been suitably acknowledged.

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Supporting Information

The following supporting information is available as part of the online article:
Data S1. Callendar's tabulated global land temperatures: 1938 data.
Data S2. Callendar's tabulated global land temperatures: 1961 data.

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