Explosive temperatures

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Abstract

This paper finds that global temperature anomalies are characterised by (temporary) explosiveness, a statistical feature typically found in financial and commodity market data during episodes of extreme price increases. This finding dramatically illustrates the extent temperature changes have already reached. This paper also finds that there are differences across hemispheres: while Northern hemispheric temperature anomalies are clearly found to be explosive, evidence is much weaker in Southern hemispheric data. This finding is attributable to the phenomenon of Arctic amplification. This paper complements recent studies in both climate econometrics and science which find that climate models seem to underestimate this phenomenon.

Keywords: Global temperature anomalies, Hemispheric temperature anomalies, Explosiveness, Climate change

JEL-Classification: C12, C22, Q54

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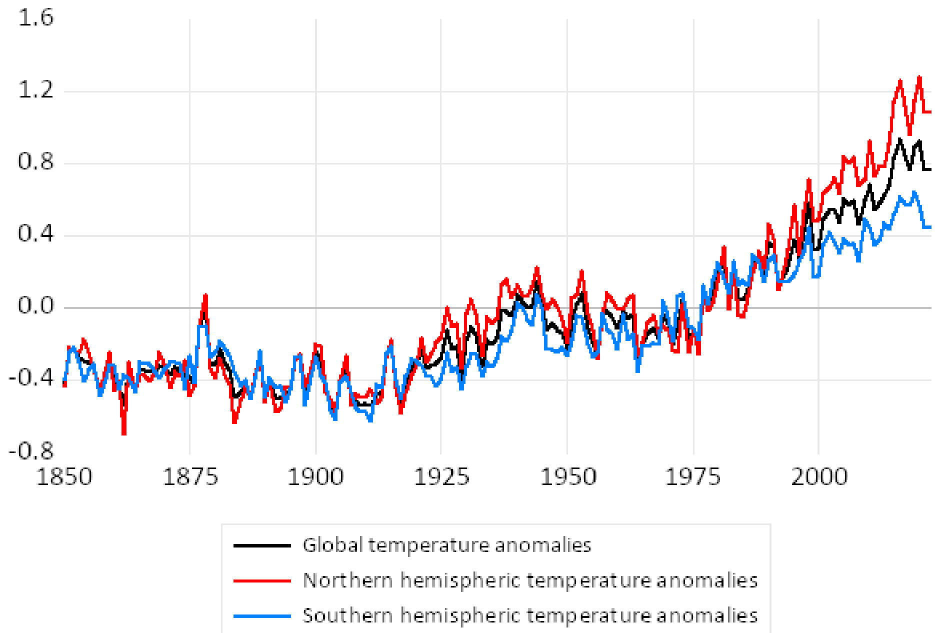
1 Introduction

Climate change, for a long time, has been a rather abstract phenomenon; something that will happen in the distant future. Its consequences, however, already became apparent in the form of rising temperatures, changes in weather patterns and an increase in extreme weather events. All of those, in turn, already became economic problems: Kotz et al. (2022) analyse the effect of rainfall changes on economic production, Felbermayr et al. (2022) the economic impact of weather anomalies, and Somanathan et al. (2021) deal with the impact of temperatures in productivity and labour supply.

The objective of this paper is to demonstrate how fast temperature increases have been. It uses an empirical approach which is commonly used to capture extreme price increases in financial markets: the test for (temporary) explosiveness pioneered by Phillips et al. (2011, 2015). Their seminal paper analyses Nasdaq prices which reached their historical high early in Year 2000. Extreme price episodes also occur in other markets: crude oil prices peaked in Summer 2008, and Bitcoin prices hit a record high end of 2017. These two markets have been analysed by Gronwald (2016) and Gronwald (2021), respectively. Worth highlighting is that price increases during the episodes mentioned above happened over longer periods of time: the Nasdaq index began to increase in the early 1990s, crude oil prices around year 2003, Bitcoin prices in early 2017.[1]

[1] In other words, the price movements under consideration here are not sudden, extreme movements such as those typically captured using jump models as in Gronwald (2012).

Figure 1: Global and hemispheric temperature anomalies.



According to the Intergovernmental Panel on Climate Change (IPCC), "human activities are estimated to have caused approximately 1.0 degree C of global warming above pre-industrial levels in 2017".[2] A graphical representation of this statement can be found in Figure 1 which displays global temperature anomalies from 1850-2022.[3] It is evident that temperatures indeed increased, but a steeper upward movement only began around 1975. An increase that began 50 years ago can certainly be categorised as one

[2]See IPCC (2018).

[3]Data is taken from the HadCRUT5 data set provided by the Met Office Hadley Centre; see Morice et al. (2021). The data frequency is annual, and the period of observation is 1850-2022. Note that the anomalies in this data set are calculated relative to the temperatures in the period 1961-1990.

that is happening very gradually, over an extended period of time. At the same time, those 50 years are short in the sense that the benchmark are pre-industrial levels, and for the first 120 years of the sample, temperatures did not increase systematically. Figure 1 also reveals that there is heterogeneity in the extent to which temperatures increase in the Northern and Southern hemispheres. During the largely horizontal movement witnessed from 1850 to 1975, Northern as well as Southern hemispheric temperature anomalies did not deviate systematically from the global average. This continues to be the case after the begin of the steep increase in 1975. However, a very different picture emerges after the Year 2000: the increase in Northern hemispheric temperatures is clearly larger than the one observed for the Southern hemisphere.

The analysis of the temperature anomalies presented in Figure 1 is the subject of this paper; the applied methods are tests for explosiveness proposed by Phillips et al. (2011, 2015). The objective is to improve the understanding of time series behavior of temperature anomalies. The literature this analysis contributes to finds its origin in the debate whether temperatures are characterised by deterministic (Estrada et al., 2013) or stochastic (Kaufmann et al., 2013) trends. A direct motivation for this paper are recent contributions such as Chang et al. (2020) and Holt and Teräsvirta (2020). While the former propose a refined testing procedure that allows one to distinguish between functional unit roots on the one hand and functional deterministic trends or explosive behavior on the other, the latter focus on co-shifting between hemispheric temperature series. Worth highlighting is that both papers point to differences in the time series behaviour in the Northern and Southern hemispheres. Chang et al. (2020) find evidence of two stochastic trends in Northern hemispheric data, but only one in the Southern Hemisphere; Holt and Teräsvirta (2020) find that shifts in the mean of the Northern series can be adequately characterised by three logistic function components, two are sufficient for the case of the Southern one.

The key finding of this paper is that global temperature anomalies are characterised by (temporary) explosiveness. This finding indicates that temperatures, given the extended period without systematic change, increase fast and the witnessed increase is large. What is more, clear evidence of explosiveness is only found in Northern hemispheric data; in the South, this is considerably less pronounced. What this paper finds is also relevant for the analysis of the relationship between carbon emissions and warming. Among the questions addressed in that literature is whether or not temperatures and radiative forcings from greenhouse gases share the same common trend; in other words, if a cointegration relationship exists. Of particular interest in this context is if that relationship is stable. Papers such as Agliardi et al. (2019) as well as Eroglu et al. (2021) epitomise these research efforts. Despite the above-mentioned dispute about the behaviour of the individual series, the conventional view is that there is a stable linear cointegration relationship. This view is based on climate science studies such as Matthews et al. (2009). The findings of this paper challenge this notion. In addition, this paper shares concerns expressed in Rantanen et al. (2022) about an underestimation of temperature increases in the Arctic by climate models.

The remainder of this paper is organised as follows: Section 2 outlines the empirical approach; Section 3 presents the results. Following a discussion of the results in Section 4, Section 5 concludes this paper.

2 Empirical approach

Phillips et al.'s (2011) as well as Phillips et al.'s (2015) testing procedures consist of the recursive application of an augmented Dickey-Fuller unit root test. The main difference to the standard unit root test is the way the alternative hypothesis is formulated: Rather than testing the null of a unit root against a stationary alternative, the alternative in this case is an explosive root. The procedure is based on estimating the following equation:

$$\Delta y_t = \hat{\alpha}_{r_1,r_2} + \hat{\beta}_{r_1,r_2} y_{t-1} + \sum_{i=1}^{k} \psi^i_{r_1,r_2} \Delta y_{t-i} + \hat{\epsilon}_t. \tag{1}$$

where k is the transient lag order. $T_w = \lfloor T r_w \rfloor$ is the number of observations in the regression.[4] The resulting ADF statistic is denoted as $ADF_{r_1}^{r_2}$.

Phillips et al. (2011) propose to estimate Equation 1 in a forward recursive manner: Initially, a subset of the sample, denoted r_w, is used. The size of that sample expands from r_0 to 1. The starting point of each subsample, r_1, is fixed at 0; thus the endpoint of each sample, r_2, equals r_w and changes

[4] $\lfloor . \rfloor$ denotes the floor function which gives the integer part of the argument.

from r_0 to 1. In other words, in each subsequent regression, this subset is supplemented by successive observations. This procedure yields a sequence of t-statistics, where $ADF_0^{r_2}$ denotes the statistic for a sample that runs from 0 to r_2. Phillips et al. (2011) propose to use simply the sup statistic, referred to as SADF, in order to test for explosiveness of the time series:

$$SADF(r_0) = \sup_{r_2 \in [r_0, 1]} ADF_0^{r_2} \tag{2}$$

This test is also referred to as SADF test. Phillips et al.'s (2015) so-called Generalized SADF (GSADF) test builds upon this procedure. The key idea of using subsamples of data in a recursive manner remains unchanged, but now the subsamples used are more extensively: this procedure not only varies the endpoint of the regression, r_2, but also the starting point, r_1.[5] Phillips et al. (2015) then define the GSADF statistic as the largest ADF statistic in this double recursion:

$$GSADF(r_0) = \sup_{r_1 \in [0, r_2 - r_0], r_2 \in [r_0, 1]} ADF_{r_1}^{r_2} \tag{3}$$

Phillips et al. (2015) show that this revised procedure is better at dealing with multiple explosive periods than the original SADF test. As this type of method is commonly applied to analyse financial markets this concern is justified. This paper, however, analyses temperature time series; it is less likely that multiple explosive periods occurred. Nevertheless, this paper

[5]It is ensured that r_1 is from within a feasible range, from 0 to $r_2 - r_0$.

applies both these methods.[6]

In the context of financial markets it is not only of interest whether or not a particular time series exhibits explosive behaviour; it is also an important question to date explosive periods.[7] To be specific, in order to assess whether a specific observation τ belongs to an explosive period, Phillips et al. (2011) initially proposed to apply the procedure outlined above using data from the beginning of the sample up to the observation in question. As also this procure insufficiently takes into account the possibility of multiple explosive periods, Phillips et al. (2015) propose the so-called backward sup ADF test; a double recursive test procedure. The key idea of this test is to apply a sup ADF test on a backward expanding sample sequence. The endpoint of each sample is fixed at r_2; the start point varies from 0 to $r_2 - r_0$. This procedure yields an ADF statistic sequence $\left\{ADF_{r_1}^{r_2}\right\}_{r_1 \in [0, r_2 - r_0]}$, and the backward SADF statistic is defined as the sup value of that sequence. Note that Phillips et al.'s (2011) original procedure is a special case of this backward sup ADF test with $r_1 = 0$; the corresponding test statistic is denoted ADF_{r_2}. These sequences are used to identify origination $\hat{r}_e$ and end dates $\hat{r}_f$ of explosive behaviour in the data by comparing the individual elements of the sequences with the appropriate critical value.This procedure is also referred to as date stamping.

[6]For a complete methodological discussion, see the original papers.

[7]Note that periods of explosiveness in financial markets can be interpreted as bubble periods in case the underlying fundamental value of the asset is not showing explosive behaviour as well.

3 Results

This section presents the empirical results, beginning with the results of the SADF and GSADF test procedures in Table 1.[8] The key finding that emerges from this analysis is that global temperature anomalies are found to be explosive: the null of a unit root is rejected for two of the three lag length selection approaches employed in this paper.[9] Thus, the number of lags included in the estimation has a certain influence; the evidence of explosiveness is nevertheless sufficiently strong. Table 1, furthermore, presents the results of the analysis of hemispheric data. It is evident that Northern hemispheric temperature anomalies are also found to be explosive; however this does not apply to those in the Southern hemisphere. Thus, there are indeed differences in time series behaviour of temperature anomalies in the two hemispheres. This finding is in line with Chang et al. (2020) as well as Holt and Teräsvirta (2020).

Applying Phillips et al.'s (2011) as well as Phillips et al.'s (2015) date stamping procedures yields some additional detailed insights. As highlighted above, the temperature anomaly series used in this paper exhibit some peculiar behaviour: both global and hemispheric temperature anomalies began to increase around 1975, but only from 2000 onwards temperatures in Northern and Southern Hemisphere began to deviate from each other. Figures 2 to 4

[8] The critical values are simulated using the Monte Carlo technique; see Phillips et al. (2011). This paper uses Caspi's (2017) implementation of the empirical procedure.

[9] Only when the more conservative SIC is applied, the null of a unit root can no longer be rejected.

Table 1: SADF and GSADF

	Global temperature anomalies					
Lag length	SADF			GSADF		
selection	fix	AIC	SIC	fix	AIC	SIC
Test statistic	1.5949 (0.027)	1.5949 (0.027)	1.0326 (0.134)	1.6768 (0.053)	1.6768 (0.053)	1.07767 (0.234)
	Northern hemispheric temperature anomalies					
Test statistic	1.619 (0.026)	1.1221 (0.114)	1.1221 (0.114)	1.7443 (0.045)	1.6395 (0.059)	1.1847 (0.187)
	Southern hemispheric temperature anomalies					
Test statistic	0.7700 (0.198)	0.4492 (0.329)	0.4492 (0.329)	0.7932 (0.347)	0.5021 (0.494)	0.5021 (0.494)

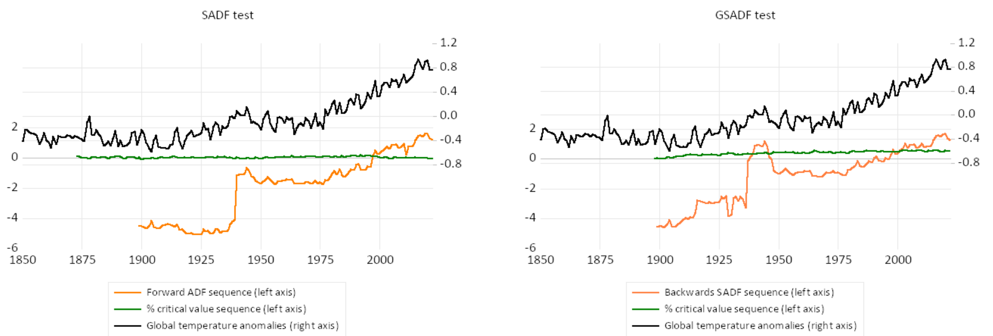
Note: Three different approaches have been used to select the number of lags when estimating Equation 1: a fixed number of 5 lags as well as automated lag length selection using both AIC and SIC with a maximum number of 5 lags. The initial subsample consists of 50 observations.

present the results. In each case, the respective ADF sequence, the sequence of critical values as well as the temperature series are displayed.[10] An observation is considered part of an explosive period when the ADF statistic exceeds the critical value - in other words, when the orange line crosses the green from below.

According to Figure 2, the explosive period of global temperature anomalies began in the late 1990s, using the 95% confidence level. The two date stamping procedures agree in this regard; however the backward sup ADF test also identifies an explosive period during the 1940s. As highlighted above, the purpose of the introduction of this test was to identify multiple explosive periods; thus, this test seems to be more sensitive. The finding

[10]The lag length has been selected automatically using AIC with a maximum number of 5 lags. The initial subsample consists of 50 observations.

Figure 2: Testing for explosiveness: Global temperature anomalies

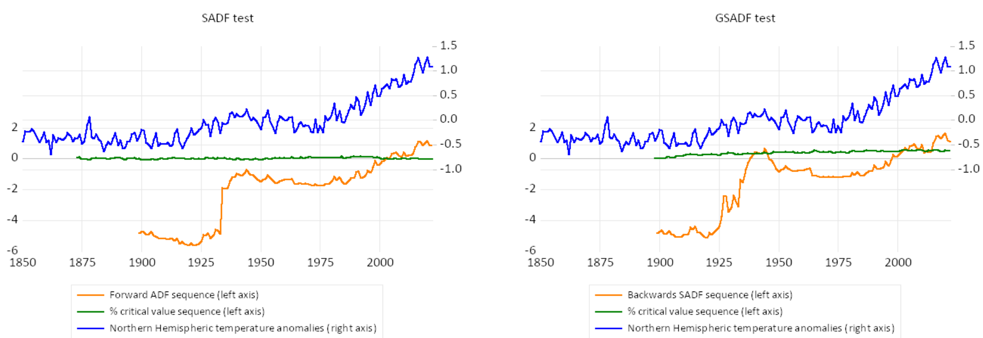


(a) SADF

(b) GSADF

that the identified start date of explosive period is only in the late 1990s even though the temperature increase began around 1975 can be explained as follows: the change in a time series needs to be sufficiently large before the applied testing procedure classifies this change as explosive. To express this differently, the finding of explosiveness in temperature data is attributable to the steep increase witnessed after 1975 rather than the increase overall. This implies that comparisons of temperature increases to the pre-industrial averages are somewhat misleading as this masks this dramatic change in time series behaviour. This finding alone makes an important contribution to the literature. As Figures 3 and 4 show, this pattern in the results also emerges at the hemispheric level, only that the explosive period in the Northern hemisphere is found to begin only in the early 2000s. The backward sup procedure also in this case identifies an explosive period in the 1940s; however evidence is weaker. It is worth highlighting that this test also picks up the so-called climate change hiatus during which temperatures no longer classified as explosive. Except for a short explosive period identified by the forward ADF test starting in 2010, Southern hemispheric temperature anomalies are again found to be not explosive.

Figure 3: Testing for explosiveness: Northern hemispheric temperature anomalies

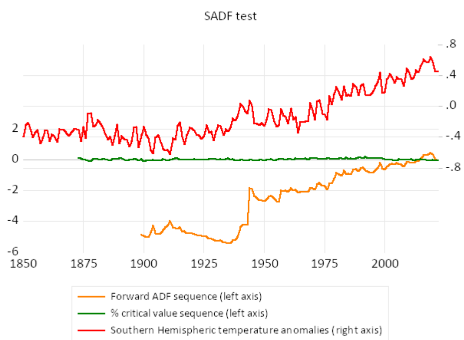


(a) SADF (b) GSADF

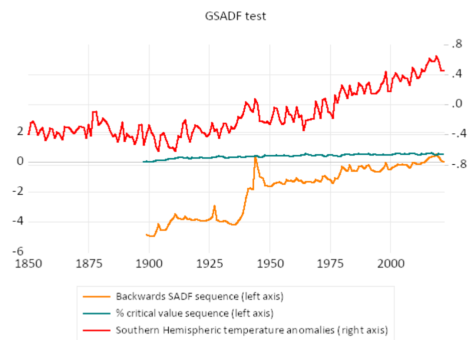
To summarize, this paper finds that temperature anomaly time series have different properties across hemispheres., a finding in line with Chang et al. (2020) and Holt and Teräsvirta (2020). These papers, however, do not attempt to provide an explanation for the observed patterns, but it is likely that this finding reflects the so-called Arctic amplification phenomenon (Serreze and Barry, 2011; Rantanen et al., 2022).[11] The following section discusses this in more detail.

[11]For a discussion of the general phenomenon of polar amplification; see IPCC (2013).

Figure 4: Testing for explosiveness: Southern hemispheric temperature anomalies



(a) SADF



(b) GSADF

4 Discussion

Concerted research efforts by climate scientists have been and are still undertaken in order to enhance the understanding of the relationship between carbon emissions and warming. That literature is vast. Contributions to this discussion also come from the perspective of climate econometrics. This literature predominantly deals with the following two questions: first, the analysis of time series properties of global and hemispheric temperature anomalies and, second, modelling the relationship between those temperatures and radiative forcing from greenhouse gases. As the latter is often done using cointegration models, it is obvious that the former is not merely a statistical exercise. Cointegration between two (or more) time series implies that the series share the same common trend and, thus, this trend has to be described appropriately in the first place. The conventional view is that there is a cointegration relationship between temperature anomalies and greenhouse gas emissions which is linear and not characterised by structural breaks; see Agliardi et al. (2019) and Eroglu et al. (2021)

The notion of a linear or proportional relationship between these variables is based on climate science studies such as Matthews et al. (2009), Ricke and Caldeira (2014), and Gillett et al. (2013). This research is highly relevant in the context of so-called climate-carbon response and the calculation of cumulative emissions that are compatible with certain warming targets. However, Eroglu et al. (2021), emphasise that Chang et al.'s (2020) finding of a second stochastic trend in Northern hemispheric data might imply that the cointegration relationship is no longer stable. One way to interpret the findings obtained in this paper are that temperatures in the Northern hemisphere not simply increase to a larger extent than those in the South; they are also governed by a different data generating process.

The climate science literature refers to the phenomenon of faster-increasing temperatures in the Northern hemisphere compared to the South as Arctic amplification; see Serreze and Barry (2011) as well as Rantanen et al. (2022). This phenomenon, however, is also relevant from an economic policy perspective: Brock and Xepapadeas (2017) argue that ignoring Arctic amplification in climate economic modelling can result in suboptimal climate policies. Recent contributions to the climate economic literature such as Dietz et al. (2021), which are also motivated by Matthews et al. (2009) as well as Ricke and Caldeira (2014), however, do not explicitly consider the phenomenon of polar amplification. This potentially implies that the climate policy recommendations they derive are suboptimal as well. Tol (2021) summarises in general terms: "Economic models of climate change are the basis for climate policy design. However, incorrect representation of physical dynamics in these models could lead to biased advice." However, recently concerns emerged about climate science models itself. Rantanen et al. (2022), find that "the Arctic has warmed nearly four times faster than the globe since 1979". The authors conclude that this is "either an extremely unlikely event or that climate models systematically tend to underestimate the amplification". Diebold and Rudebusch's (2021) climate econometric study express similar concerns. These authors empirically analyse Arctic sea ice coverage and show that this coverage is declining at an increasing rate. Based on this model, they predict that there is a 60 percent chance of witnessing an ice-free Arctic ocean as early as at some point in the 2030s. This is much earlier than what global climate models on average predict. This paper in hand is a useful complement to Diebold and Rudebusch (2021). To summarise, climate econometric studies not only help evaluate climate economic models in specific, but even perhaps climate science in general.

5 Conclusions

This paper analyses time series properties of global as well as hemispheric temperature anomalies using a frequently applied empirical approach to test for (temporary) explosiveness. The paper finds, first, that global temperatures are explosive. Second, the paper also finds clear evidence of temporary explosiveness in Northern hemispheric data while in the Southern hemisphere respective evidence is much weaker. In other words, temperatures in the two hemispheres seem to be governed by different data generating processes.

The literature this paper directly contributes to is dominated by the discussion whether stochastic or deterministic trends are present in temperature time series; see Chang et al. (2020) for a recent contribution. In addition, these insights are relevant for the literature that deals with the relationship between temperatures and radiative forcings from greenhouse gases using cointegration methods. Studies such as Agliardi et al. (2019) and Eroglu et al. (2021) epitomise those research efforts. This paper's findings should be viewed as evidence against a stable, linear cointegration relationship of these variables. There is, however, a more general message that emerges from this paper. The empirical pattern described here is attributable to so-called Arctic amplification, a phenomenon widely discussed in the climate science literature. There is an ongoing debate about the correct representation of climate dynamics in climate economic models; see Tol (2021) as well as Dietz et al. (2021). While the concerns expressed in those papers are of more general nature, Brock and Xepapadeas (2017) specifically argue that insufficiently taking Arctic amplification into account can lead to sub-optimal climate policies. However, both climate studies such as Rantanen et al. (2022) and climate econometric studies such as Diebold and Rudebusch (2021) express concerns about climate science models as well: they seem to underestimate Arctic amplification.

This paper's finding of explosiveness in temperature anomalies is noteworthy as this empirical feature is commonly found in financial as well as commodity markets data during extreme episodes such as the so-called "Nasdaq exuberance" or when crude oil prices peaked in 2008. To put this differently, that an empirical technique which is commonly used to capture extreme price movements also appropriately describes changes in temperatures illustrates the extent these changes already reached. Thus, views expressed in Rantanen et al. (2022) are shared here. Finally, this paper illustrates how climate econometric studies support the evaluation of these economic and climate models alike.

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