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Abstract

This paper uses fractional integration methods to obtain new evidence on polar amplification. The adopted modelling framework is very general since it allows the differencing parameter to take any real value, including fractional ones, and provides useful information on both the short and the long run. The analysis is carried out using monthly temperature anomaly data for both the Arctic and the Antarctic, as well as the Northern and Southern Hemisphere, which have been obtained from the NOAA (National Center for Environmental Information) archive. The main findings can be summarised as follows. There is evidence of Arctic amplification, since the upward trend in the Arctic data is more pronounced compared to that in the Northern hemisphere series, but not of Antarctic amplification, where the opposite holds. Also, the effects of shocks are more long-lived in the Arctic/Northern hemisphere than in the other pole/hemisphere. These results are robust to whether or not seasonality is explicitly modelled. In addition, temperature changes in the poles have bigger effects on those in the corresponding hemisphere if they occur in the Antarctic rather than in the Arctic.

JEL-Codes: C220, Q530, Q540.

Keywords: polar amplification, Arctic and Antarctic, Northern and Southern hemispheres, temperature anomalies, persistence, fractional integration.

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1. Introduction

The average temperature increase on the planet has been 1ºC since 1880 (IPCC 2021), but it has been three times higher in the Arctic region (AMAP 2021); in fact in some areas, such as the Barents Sea, warming has been seven times faster (Isaksen et al., 2022). This phenomenon, known as polar amplification, is much more pronounced in the Arctic (Pithan et al., 2014; Yamanouchi et al., 2020; Walsh, 2021; Chylek et al., 2022, 2023) than in the Antarctic (Salzmann 2017, Intergovernmental Panel on Climate Change, 2001). The reason is that the Arctic is an ocean covered by sea ice with a combination of feedback mechanisms that make it particularly vulnerable (Serreze et al., 2007; Miller et al., 2010), while the Antarctic is a high continent covered by ice and snow, and the ocean water comes from great depths and from such distant sources that it takes centuries before the water reaching the surface warms up (Cox et al., 2024).

The warming of the Arctic has various effects, such as the decrease in sea ice, which has reached historically low levels in recent years (Kinnard et al., 2011; United Nations Environment Programme, 2019), and in its thickness (Lindsay et al., 2015), which causes greater transmission of solar radiation to the ocean, accelerates the migration of ice and favours the formation of cyclones, among other climatic phenomena. The fact that there has also been an increase in the frequency of extreme weather events in mid-latitudes has led researchers to search for a causal relationship with Arctic amplification (Cohen et al., 2020). The AMAP 2021 report concludes that warming in the Arctic, between 1971 and 2019, has been three times faster than in the rest of the planet which is affecting global climate change.

The present paper provides new evidence on the role of polar amplification by analysing the stochastic behaviour of temperature anomaly series for the two poles as well as for the two hemispheres, and then the linkages between developments in the Arctic (Antarctic) and the

Northern (Southern) hemisphere as a whole. For this purpose, we use techniques based on fractional integration which shed light on the long memory feature observed in most climatological series and their long-run relationships (Gil-Alana et al., 2022; Yuan et al., 2022; etc.). The rest of the paper is structured as follows: Section 2 provides a short literature review; Section 3 outlines the methodology; Section 4 describes the data and discusses the empirical results; Section 5 offers some concluding remarks.

2. Literature Review

Rantanen et al. (2022) showed that in recent decades warming is accelerating in the Arctic more than in other parts of the world. For their research they analysed temperature data since 1979 and found that the Arctic has warmed on average 0.75°C per decade, i.e. four times faster than the rest of the planet.

Several papers have discussed trends in SAT (Arctic surface air temperature variability) over the past decades, reaching different conclusions regarding their magnitude and interpretation (Kuzmina et al., 2008; Bekryaev et al., 2010). Blackport (2020) advocated using an extended sample of observations to obtain more robust estimates, since in fact Arctic amplification is detectable well before 1990, despite some studies claiming that it only started at that stage (Cohen et. al., 2014; Xue et al., 2017)

Cai et al. (2011) analysed trends between 1850 and 2017 in summer sea ice area variations in six Arctic regions and suggested that their accelerating decrease reflected a combination of global warming and internal climate system variability rather than a single factor. England et al. (2021) showed that Arctic amplification is only a recent phenomenon: during much of the 20th century the Arctic cooled as global mean temperature increased and amplification would not have occurred without historical changes in greenhouse gases or aerosols. Johannessen et al. (2016) studied variability and trends in SAT between 1900 and 2014 for the entire Arctic and its different regions using an Arctic Amplification Index (AAI) that relates absolute values of Arctic and Northern Hemisphere (NH) trends calculated over successive 30-year periods, the index being calculated only for years in which both the NH and Arctic trends are significant at the 95 % confidence level. They conclude that the amplification is stronger during the early 20th century warming than during the recent years analysed.

Chylek et al. (2022) carried out simulations using 39 climate models and found that CMIP6 (Coupled Model Intercomparison Project 6) models do not reproduce the observed Arctic amplification behaviour, as they only capture the first increase in Arctic amplification around 1986, but not the second one around 1999. They argue that the former might have been due to external forces (greenhouse gases), while the latter might reflect internal climate variability.

While there are numerous studies confirming the Arctic amplification phenomenon, there is much less evidence concerning Antarctic amplification. Salzmann (2017) wondered why Arctic warming differs from Antarctic warming and found that the difference in altitude between the two poles explains this divergence. He used simulation methods to establish how climate would react if the atmospheric concentration of carbon dioxide (CO_2) were doubled and performed the same experiment in a scenario where the Antarctic had a similar height to the surface in the Arctic. His results suggest that if the Antarctic's land height were reduced, temperatures would respond more strongly to an increase in the concentration of greenhouse gases on the continent, thereby contributing to an increase in Antarctic warming and a smaller difference in polar amplification between the Arctic and the Antarctic.

Wang et al (2021) calculated the annual and seasonal mean surface air temperature (SAT) trend during 1979-2019 for the Antarctic and the mean trend of different southern sectors of Antarctic subregions. The observed temperature anomalies indicate that the smallest fluctuations occur in the austral summer and the largest ones in winter and spring, which implies that the mechanism of Antarctic amplification is unclear and suggests the need for future research on this issue. Zhu et al. (2023) noted that the largest amplification occurs in East Antarctic, followed by West Antarctic, whilst Antarctic amplification is absent in the Antarctic Peninsula. Xie et al. (2023) found a positive correlation between temperature changes in East and West Antarctic, but a negative one between Antarctic Peninsula temperatures and those in the Southern Hemisphere (SH). It appears therefore that Antarctic amplification is weaker than the Arctic one, which is related to a weaker surface albedo feedback and higher ocean heat uptake in the Southern Ocean (Smith et al., 2019; Zhu et al., 2023).

Other studies focus on the decrease of sea ice in the Antarctic caused by the warming of this region (Turner et al., 2022; Yadav et al., 2022; Purich et al., 2023). However, there is still a lack of consensus regarding the processes and mechanisms that determine historical sea ice trends (Schroeter et al., 2023).

Both the Arctic and the Antarctic have been shown to influence the climate of the entire planet (Overland et al., 2011; Screen, 2013; Tang et al., 2013; Pistone et al., 2019); therefore, the study of polar amplification is necessary to estimate the global average temperature change in the future (Miller et al., 2010): better knowledge of the climate system of the poles also improves the accuracy of global temperature prediction since what happens in these regions affects future developments in the rest of the planet (United Nations Environment Programme 2019; García, 2021).

The literature on climate change is extensive (Brunetti et al. 2001; Gil-Alana 2019, 2022; Caporale, et al. 2023; etc.) but there is no common modelling approach. In the present study we use a fractional integration framework where the differencing parameter d can be any real number (including fractional values); this method provides more accurate information on both the short and the long run (Huang et al., 2022) than others based on the dichotomy between I(0) (Bloomfield, and Nychka,1992; Woodward and Gray 1993; etc.) and non-stationary I(1) series (Woodward and Gray, 1995), or against trendless fluctuation models (Kantelhardt et al., 2001), or standard linear regressions (Vogelsang and Franses, 2005; Fatichi et al., 2009).

The long memory approach will allow us to detect the presence of long-run trends and to analyse the degree of persistence of the Arctic, Antarctic, Northern Hemisphere and Southern Hemisphere temperature anomaly series, and thus to obtain information on whether or not the series are mean-reverting, i.e. whether the shocks have permanent or transitory effects. Also, analysing the linkages between temperatures in the poles and the corresponding hemispheres will provide evidence about polar amplification and be useful to develop early warning indicators of climate change. This will result in a deeper understanding of how the climate is evolving and of its impact on the sea level, which is essential to design more effective environmental policies.

3. Empirical Methodology

The methods used for the empirical analysis are based on the concept of fractional integration and shed light on both the short- and long-memory properties of the series under investigation and their linkages. Below we provide some key definitions.

3.1 Short and Long Memory

A covariance stationary process $\{x(t), t = 0, \pm 1, \ldots\}$ with mean $E(x(t)) = \mu$ is said to exhibit short memory if the infinite sum of the autocovariances, defined as $\gamma(u) = E[(x(t) - \mu)(x(t+u) - \mu)]$, is finite, that is:

$$\sum_{j=-\infty}^{\infty} |\gamma(u)| < \infty. \tag{1}$$

Alternatively, one can define short memory in the frequency domain in terms of the spectral density function, $f(\lambda)$, that is the Fourier transformation of the autocovariances:

$$f(\lambda) = \sum_{j=-\infty}^{\infty} \gamma(u) e^{i\lambda u} = \sum_{j=-\infty}^{\infty} \gamma(u) \cos(\lambda u). \tag{2}$$

In this case, x(t) is said to be characterised by short memory if the spectral density function is positive and bounded at all frequencies, i.e.:

$$0 < f(\lambda) < \infty. \qquad \text{for all } \lambda \in [0, \pi). \tag{3}$$

This category includes the white noise model but also the stationary and invertible AutoRegressive Moving Average (ARMA) class of models in the presence of a time (weak) dependence structure. Short memory processes are sometimes called integrated of order 0 or I(0) processes.

On the other hand, a process is said to exhibit long memory if the infinite sum of autocorrelations becomes unbounded, i.e.:

$$\sum_{j=-\infty}^{\infty} |\gamma(u)| = \infty, \tag{4}$$

or, alternative, using the frequency domain definition, if the spectral density function goes to infinity at least at one point in the frequency $[0, \pi)$:

$$f(\lambda) \to \infty, \quad \text{for some } \lambda \in [0, \pi). \tag{5}$$

There are many processes that satisfy the above two properties ((4) and (5)), for example, the Fractional Gaussian noise introduced by Mandelbrot and van Ness (1968). The one based on the concept of fractional integration or integration of order d, or I(d) is most commonly used by time series analysts.

3.2 Fractional Integration

A process x(t) is said to be I(d) if it can be expressed as:

$$(1 - L)^{d} \; x(t) \; = u(t) \quad t = 0, \pm 1, ... \tag{6}$$

where L is the lag operator, i.e., Lx(t) = x(t-1) and u(t) is I(0). Then, as long as d is positive, x(t) in (6) will exhibit long memory in the sense that the infinite sum of the autocovariances becomes infinite. Alternatively, in the frequency domain, its spectral density function will be:

$$f(\lambda) = \frac{\sigma^2}{2\pi} \left| \frac{1}{1 - e^{i\lambda}} \right|^{\mathrm{d}}, \tag{7}$$

and it will tend to infinity as $\lambda \to 0^+$ with $d > 0$.

Using a binomial expansion, the polynomial in L in (6) can be expressed as:

$$(1 - L)^{d} = \sum_{j=0}^{\infty} \binom{d}{j} (-1)^{j} L^{j} = 1 - d\,L + \frac{d\,(d-1)}{2} L^{2}, \tag{8}$$

and equation (6) can be re-written as

$$x_t = d\,x_{t-1} - \frac{d\,(d-1)}{2} x_{t-2} + \frac{d\,(d-1)(d-2)}{6} x_{t-3} - .... + u_t,$$

and thus the differencing parameter d can be interpreted as a measure of the degree of persistence of the series: the higher the value of d is, the greater is persistence, namely the higher is the association between observations, even if they are far apart in time.

By allowing d to take fractional values, one can consider a wide range of processes including:

i) anti-persistence (if d < 0),

ii) short memory (if $d = 0$),

iii) stationary long memory (if $0 < d < 0.5$),

iv) nonstationary with mean reversion (if $0.5 \leq d < 1$),

v) unit roots (if $d = 1$),

vi) explosive patterns (if $d > 1$).

Reversion to the mean (which implies that shocks only have transitory effects) will occur as long as d is smaller than 1. On the contrary, if d is equal to or higher than 1, the series will not revert to its mean following a shock, namely the effects of the latter will be permanent.

4. Data Description and Empirical Results

We analyse temperature anomaly data for both the Arctic and Antarctic, as well as the Northern and Southern hemispheres. These provide information about departures from long-term averages, with positive (negative) values indicating warmer (cooler) temperatures than the reference values. The data source, as in several other global climate studies, is the NOAA (National Center for Environmental Information) archive. The series are monthly and span the periods from 1880 to 2022; they are the combined global land and ocean temperature anomalies, i.e., deviations from the 1901-2000 mean for each of the two hemispheres and from the 1910-2000 one for the Arctic and Antarctic.[1]

The estimated model is the following:

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[1] Please note that there exist other sources for Arctic temperatures such as GISS (Lenssen et al., 2019), HadCRUT5.0 (Morice, 2021) and HadCRUT4/CW (Cowtan et al., 2014); however, despite some slight differences between them, they all imply very similar arctic amplification periods (Chylek et al., 2022).

$$y(t) = \alpha + \beta t + x(t), \quad (1-L)^d x(t) = u(t), \qquad u(t) = \rho\, u(t-12) + \varepsilon(t) \quad (9)$$

where α and β are unknown parameters to be estimated, t is a time trend, L stands for the backshift operator, and d is the required differencing to make x_t a stationary I(0) process, where x_t are the integrated regression errors of order d or I(d); this implies that the d-differenced process, u_t, is short memory or I(0). Given the monthly frequency of the series we assume a monthly seasonal AR process for the error term u(t), , where ρ is the seasonal parameter and ε_t is a white noise process.

Table 1 displays the estimated coefficients from the model given by Equation (9). It can be seen that the time trend is statistically significantly and positive for all the four series examined (Arctic, Antarctic, Northern and Southern hemispheres), the highest coefficient being estimated in the case of the Arctic (0.00107) and being much higher than those of the Antarctic (0.00017) or of the two hemispheres (0.00063 and 0.00033 respectively). These results suggest that amplification occurs in the case of the Arctic (0.00107 versus 0.00063) but not of the Antarctic (0.00017 versus 0.00033). Concerning the degree of persistence, measured by d, the evidence implies that it is much higher in the two hemispheres than in the corresponding poles: the estimates of d are 0.50 and 0.60 respectively for the Northern and Southern hemispheres, and 0.32 and 0.17 for the Arctic and the Antarctic. This implies that the effects of shocks disappear at a faster rate in the poles than in the hemispheres. Since the seasonal coefficient appears to be close to 0 and insignificant for all four series, we consider next a model where the error term u(t) displays non-seasonal weak dependence. In particular, we use the exponential spectral model of Bloomfield (1973), which is a non-parametric approach that approximates well AR structures with very few parameters. This set of results are reported in Table 2.

INSERT TABLES 1 AND 2 ABOUT HERE

As can be seen, the evidence concerning the time trends is very similar to the previous case: the estimated coefficients are 0.00107 and 0.00017 for the Arctic and Antarctic, and 0.00064 and 0.00034 for the Northern and Southern hemispheres respectively. The estimates of d are also very close to the previous ones: 0.31 and 0.20 for the Arctic and Antarctic, and 0.52 and 0.62 for the Northern and Southern hemispheres respectively. These findings confirm that polar amplification occurs in the Arctic but not in the Antarctic, and also that there is a higher degree of persistence in the Northern than in the Southern hemisphere.

Next we analyse the relationship between temperatures in the two poles and the corresponding hemispheres. Table 3 reports the correlation matrix among the four series, which shows a higher correlation between the Arctic and Northern hemisphere than between the Antarctic and the Southern hemisphere.

INSERT TABLES 3 AND 4 ABOUT HERE

Table 4 shows the results of standard OLS regressions for each of the two hemispheres against that of the corresponding pole, first under the assumption of I(0) errors (see the right-hand side panels), and then estimating their order of integration (see the left-hand side panels). In the former set of regressions, the slope coefficient is positive and similar in the Northern/Arctic and Southern/Antarctic regressions (0.33559 and 0.37299 respectively). When estimating the order of integration, this is found to be significantly positive (0.55 and 0.65 in the Northern/Arctic and Southern/Antarctic regressions respectively), and the slope coefficient is very different, being much higher in the Southern/Antarctic relationship compared to the Northern/Arctic one (0.012413 vis-à-vis 0.14253). In other words, temperature anomalies in the Antarctic appear to have a greater impact on those in the corresponding hemisphere than in the case of the Arctic.

5. Conclusions

This paper uses fractional integration methods to obtain new evidence on polar amplification, namely the phenomenon that changes in the net radiation balance typically produce larger changes in temperature near the poles than in the corresponding hemisphere or the planet as a whole. The adopted modelling framework is very general since it allows the differencing parameter to take any real value, including fractional ones, and thus it does not impose any restrictions on the stochastic behaviour of the series of interest and provides useful information on both their short- and long-run properties.

The analysis is carried out using monthly temperature anomaly data for both the Arctic and the Antarctic, as well as the Northern and Southern Hemisphere, which have been obtained from the NOAA (National Center for Environmental Information) archive. The main findings can be summarised as follows. There is evidence of Arctic amplification, since the upward trend in the Arctic data is more pronounced compared to that in the Northern hemisphere series, but not of Antarctic amplification, where the opposite holds. This confirms previous results (see, e.g., Smith et al., 2008; Zhu et al., 2023) and might reflect a difference in altitude (Salzmann, 2017). Also, the effects of shocks are more long-lived in the case of the Arctic/Northern hemisphere than in the other pole/hemisphere. These results are robust to whether or not seasonality is explicitly modelled. On the other hand, the effects of shocks disappear faster in the poles than in the hemispheres, which implies that the former have a relatively greater ability to recover from sudden environmental perturbations compared to the latter; consequently, environmental policies should give priority to the protection of the poles given their greater resilience.

In addition, temperature changes in the poles have bigger effects on those in the corresponding hemisphere if they occur in the Antarctic rather than in the Arctic; as a result, Antarctic temperature anomalies may have a more significant impact in the Southern Hemisphere owing to a combination of geographic, climatic, and ecological factors. This could enhance Antarctic amplification, which in turn could have significant consequences for global climate as already found in previous studies (Wang, et al. 2021; Zhu et. Al 2023). However, the Antarctic amplification mechanism is a complex process that does not manifest itself uniformly across the Antarctic region due to differences between regions and seasonal variations.

Other important issues in this context are the possible presence of structural breaks and nonlinearities. It is well known that both are strongly related to long memory and fractional integration (e.g., Granger and Hyung, 2004), and thus not taking them into account might produce biases in the estimation results. Future research will focus on such issues to obtain additional empirical evidence and gain an even deeper understanding of polar amplification.

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Table 1 : Estimated coefficients in the model given by Equation (1). Seasonal MA errors

Series	d (95% band)	Intercept (tv)	Time trend (tv)	Seasonality
ARTIC	0.32 (0.29, 0.36)	-0.87633 (-4.33)	0.00107 (6.42)	0.0417
Northern Hem.	0.50 (0.47, 0.53)	-0.40316 (-4.30)	0.00063 (5.98)	0.0501
ANTARCTIC	0.17 (0.14, 0.20)	-0.15033 (-3.45)	0.00017 (5.08)	0.0073
Southern Hem.	0.60 (0.57, 0.63)	-0.11706 (-1.91)	0.00033 (3.30)	-0.0200

Note : The values in column 2 are the estimates of the differencing parameter d along with their 95% confidence bands ; those in columns 3 and 4 are the estimates of the constant and the linear trend with their associated t-values; those in the last column are the seasonal coefficients.

Table 2 : Estimated coefficients in the model given by Equation (1). Bloomfield errors

Series	d (95% band)	Intercept (tv)	Time trend (tv)
ARTIC	0.31 (0.28, 0.35)	-0.88490 (-4.56)	0.00107 (6.74)
ANTARCTIC	0.20 (0.16, 0.26)	-0.14666 (-2.82)	0.00017 (4.23)
Southern Hem.	0.62 (0.57, 0.69)	-0.11275 (-1.77)	0.00034 (3.30)

Note : The values in column 2 are the estimates of the differencing parameter d along with their 95% confidence bands; those in columns 3 and 4 are the estimates of the constant and the linear trend with their associated t-values.

Table 3: Correlation cofficients among the variables

	ARTIC	NORTHERN H	ANTARCTIC	SOUTHERN H
ARTIC	-----	-----	-----	-----
NORTHERN H	**0.7906**	-----	-----	-----
ANTARCTIC	0.1836	0.2846	-----	-----
SOUTHERN H	0.5658	0.8421	**0.4897**	-----

Note : The values in bold are the correlation coefficient between each poles and the corresponding hemisphere.

Table 4: Estimated coefficients in a regression model with I(d) errors

<table>
<tr><td colspan="5">$\text{NORTHERN H}(t) = \alpha + \beta\ \text{ARTIC}(t) + X(t); \quad (1 - L)^d x(t) = u(t) \sim \text{Bloomfield}$</td></tr>
<tr><td colspan="3">d estimated</td><td colspan="2">d = 0</td></tr>
<tr><td>d (95% band)</td><td>Intercept (tv)</td><td>Time trend (tv)</td><td>Intercept (tv)</td><td>Time trend (tv)</td></tr>
<tr><td>0.55
(0.51, 0.60)</td><td>-0.18085
(-2.18)</td><td>0.012413
(32.66)</td><td>0.03720
(7.41)</td><td>0.33559
(72.60)</td></tr>
<tr><td colspan="5">$\text{SOUTHERN H}(t) = \alpha + \beta\ \text{ANTARCTIC}(t) + X(t); \quad (1 - L)^d x(t) = u(t) \sim \text{Bloomfield}$</td></tr>
<tr><td colspan="3">d estimated</td><td colspan="2">d = 0</td></tr>
<tr><td>d (95% band)</td><td>Intercept (tv)</td><td>Time trend (tv)</td><td>Intercept (tv)</td><td>Time trend (tv)</td></tr>
<tr><td>0.69
(0.63, 0.75)</td><td>-0.06868
(-2.42)</td><td>0.14253
(47.22)</td><td>0.03659
(10.76)</td><td>0.37299
(42.29)</td></tr>
</table>

Note : The values in column 1 are the integration orders (with their 95% confidence bands); Columns 2 and 4 display the estimated intercept (and t-values), while those in columns 3 and 5 are the estimated time trend coefficients (and t-values). The values in columns 2 and 3 refer to the model with the value of d estimated from the data ; in columns 4 and 5, d = 0 a priori.