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Patterns in 100 years of global warming (1910-2009)

António R. Tomé[1], Pedro M. A. Miranda[2]

Abstract — The world's surface is clustered according to the centennial evolution of near surface temperature, using a continuous piecewise trend methodology applied to the GISS surface temperature data for the last 100 years. A spatial distribution of the timing of onset of local warming, alongside with the local decadal trends are presented and discussed. Time series of temperature, obtained by averaging only regions with the same temperature low frequency behaviour, are also presented and discussed. The world's globe surface is divided into 5 clusters defined by the surface trend temperature behaviour: (1) first and last period of warming having an cooling period in between (59% of the Earth surface), (2) later warming after a continuous cooling period (11% of the Earth surface), (3) later cooling after an initial warming period (9% of the Earth surface), (4) continuous warming (7.5% of the Earth surface) and (5) first and last periods of cooling having an warming period in between (5.4% of the Earth surface).

Keywords — Global warming, non linear fitting, temperature clustering, trends.

1 INTRODUCTION

Several studies have looked at the mean global near-surface temperature, searching for significant changes in the global warming trends in historical data. Karl et al. [1] identified 1910, 1945 and 1975 as years of change in the sign of the global temperature trend. That result has inspired some authors (e.g. Jones et al [2], work fully reproduced in the 2001 IPCC report [3]) into performing linear unconstrained trends for the nodes of a global surface grid for the partial periods 1910-1945, 1945-1975 and 1975-2000. This however doesn't take into account that those grid nodes may have dissimilar low-frequency behaviour from the mean temperature, and thus the chosen period limits may be meaningless for many grid points.

Instead of imposing limits obtained for the global averaged temperature time series, Tomé and Miranda ([4],[5]) developed an objective method that automatically fits a broken line to each time series. By applying such technique to the dataset produced by NASA's Goddard Institute of Space Studies (GISS) for the period 1951-2004, Miranda and Tomé [6] produced a global analysis of the spatial heterogeneity of climate trends in the second half of the twentieth century, which emphasizes the anomalous behaviour of the North Atlantic region in recent warming. A similar methodology is applied, here, to an extended GISS dataset, covering 100 years from 1910 to 2009. The increased duration of the dataset required the ability to deal with more complex time evolutions: whereas in the period 1951-2004 the method only allowed one breakpoint, in the extended period an extra breakpoint may be needed. This change and the inclusion of the recent years (2005-2009), may help in characterizing the spatial structure of global warming, including the relevance of the North-Atlantic behaviour.

2 DATA AND PROCEDURE

This study uses GISS gridded monthly mean temperature data, a dataset that has been specially produced for climate change studies (Hansen et al. [7], [8]). The data results from the analysis of observed air temperature at meteorological stations, and sea surface temperature in the ocean, corrected for homogenization and removal of urbanization effects. To have a larger spatial coverage we only use data after 1910, getting exactly 100 years of data (1910-2009), and have accepted grid points with a few missing values. Thus, we accept as valid data grid points with at least 9 months of data per year, and with less than 15 missing years from 1910 to 1940, 10 missing years from 1941 to 1980 and less than five missing years after 1981. In spite of these conditions the valid GISS grid points still cover 92% of the world surface.

The methodology proposed by Tomé and Miranda [5], is applied to locate breakpoints in each valid data grid point with the following constraints: (a) there are at most two breakpoints; (b) at breakpoints there is a minimum trend change of 0.1°C/da (degrees/decade); (c) trends are only computed for periods with at least 15 years. There is some arbitrariness in these options: their choice results

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[1] *António R. Tomé, is with the Universidade da Beira Interior, Rua Mateus D'Ávila e Bolama 6200 Covilhã, Portugal and with the Instituto Dom Luiz (IDL) of Universidade de Lisboa. E-mail: artome@ gmail.com*

[2] *Pedro MA Miranda is with the Universidade de Lisboa, Campo Grande, Portugal and with the Instituto Dom Luiz (IDL) of Universidade de Lisboa.E-mail: pmmiranda@ fc.ul.pt.*

from (1) the averaged surface temperature presents only two breakpoints in the period 1910-2010 and (2) the minimum 0.1°C/da of trend change (1°C/century), is of the same order as the mean centennial warming rate, assuring some relevance to the breakpoints found. Tomé and Miranda [5] discuss the statistical significance of the general methodology used here, using an empirical approach based on the inversion of synthetic data.

3 RESULTS

3.1 Clustering of spatial temperature trends

With up to 2 breakpoints allowed, there are many possible temperature histories (e.g. continuous warming without breakpoints, continuous warming but with varying trends, warming then cooling then warming, and so on). If one aggregates those histories, according only to the sign of individual trends, the result obtained is shown in Fig. 1, where the gray areas represent near 8% of the Globe surface with insufficient GISS data.

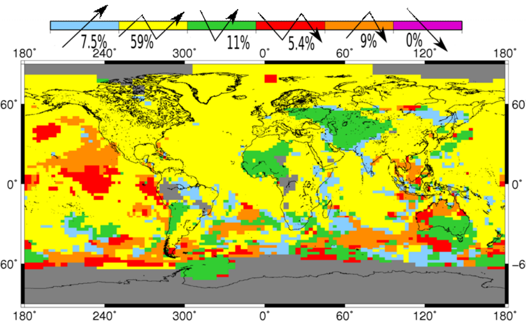

Fig. 1. Classification of the evolution of local temperature (1910-2009): The "two" breakpoints regions (green and orange) aggregate areas where two continuous segments have the same sign in the trend. The no-breakpoint classifications (cyan and magenta) aggregate areas with the same sign in the trend of all segments.

Fig 1 shows a lot of coherency in the evolution of annual mean temperature, with about 59% of the area (yellow) evolving as the world mean (warming-cooling-warming).

However, Fig. 1 also shows that near 15% of the world's area is experiencing recent cooling, mostly in SH ocean areas, but with a large area in the North Pacific bordering North America. This result is consistent with the literature [9] and it is directly related with the SST negative trend observed in the western North Pacific. It is also interesting to notice that 5.4% of the global surface has a trend behaviour that in a way mirrors the average history: it experienced first a cooling period followed by a warming period and a then cooling again. This happened in scattered areas in the Antarctic Ocean, but also in a relevant area of the Equatorial Pacific. There is also a relevant portion of surface (near 28%) that didn't experience a three line sign changing trend behaviour. Instead, 7.5% of the global area has experienced continuous warming (0.5% continuous linear warming, 7% with two or three line fit all with positive trends), 11% experienced only a sign changing trend year having experienced first a cooling period and then a warming trend, with a relevant fraction of this area is on a narrow corridor above Poland and enlarges south and eastwards reaching Kazakhstan. Another 9% of the area mirrors the latter behaviour, experiencing first a warming trend and then a cooling trend period. In summary, of the 6 possible composite histories, the one absent corresponds to continuous cooling.

3.2 Breakpoint years and trend intensities

The analysis one can do just by looking at Fig. 1 is necessarily incomplete as it does not provide the years of the breakpoints. Thus two regions that in the Fig 1 seem to be "in phase" in terms of the temperature trends, can in fact have a very dissimilar behaviour if the breakpoint years occurred in years that are far apart. Fig 2 (a) and (b) show the first and second breakpoint years.

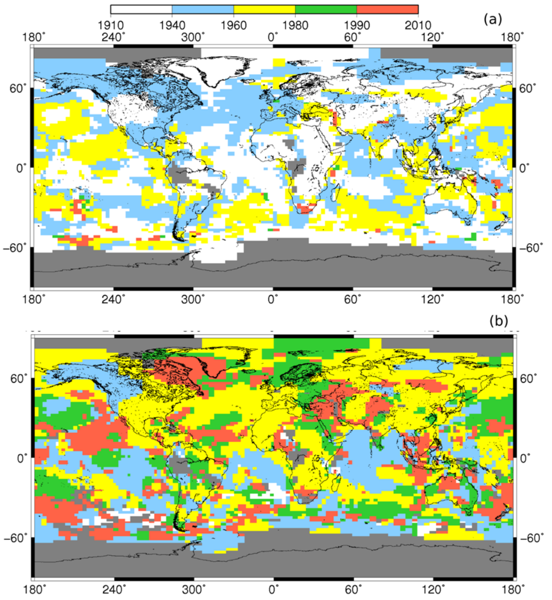

Fig. 2. (a) First breakpoint year; (b)second breakpoint year. In cases of only one breakpoint, this is shown in (b) and the corresponding location in (a) is white. White areas in (b) represent regions without a breakpoint (continuous warming).

From Fig 2, it becomes obvious that in spite of Fig. 1 representing near 60% of the globe area as following the same history as that of the mean global temperature (warming-cooling-warming, yellow area), the details are very different, as a much smaller area presents trend changing years in the 40's and in the 70's, as found for global temperature [1].

The picture becomes complete with Fig. 3(a-c), showing the rates of warming (or cooling) in each of the 3 time periods defined by the two breakpoints. Note that, in this case, two subsequent periods may experience trends with the same sign (both warming or both cooling), so they would be identified in the 1 or no breakpoint histories in Fig. 1.

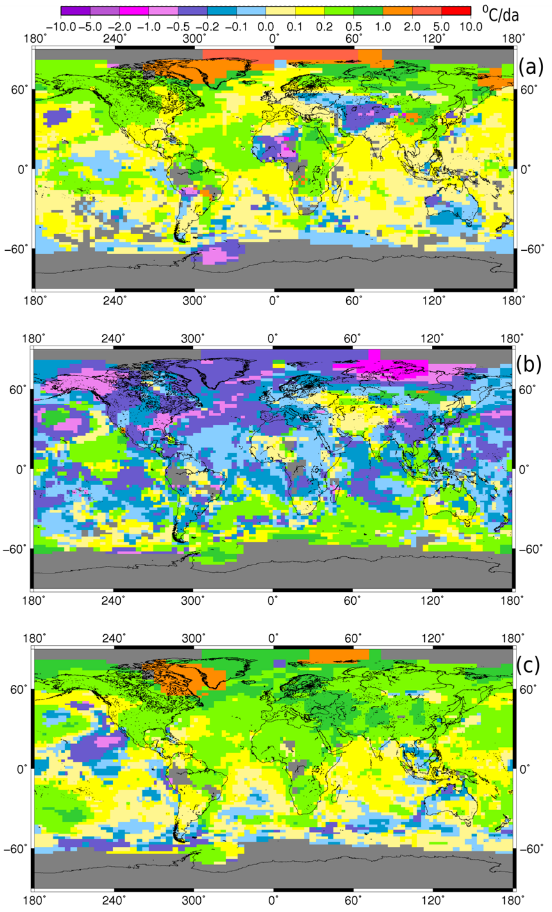

Fig. 3. (a)Temperature trends before the first breakpoint; (b) trends between the first and second breakpoint year, (c) trends after the second breakpoints. In cases of only one breakpoint the (a) chart region is gray and in cases of no breakpoint at all the (a) and (b) map are gray. Trend values in (°C/da).

The (b) panel of the Fig. 3 is especially interesting as it is commonly argued that the cooling period observed on the global averaged temperature is somewhat ill defined as it presents a very low value. However Fig 3 (b) shows that there are several large regions, special in Northern Hemisphere (e.g., North America and the Arctic), that present significant cooling trends during the cooling period.

3.3 Trends by spatial aggregation

Using the classification presented on Fig. 1, one may compute 5 time series of the mean temperature in areas with similar temperature histories. The result is shown in Fig 4, where for reasons of completeness the global averaged time series is also presented.

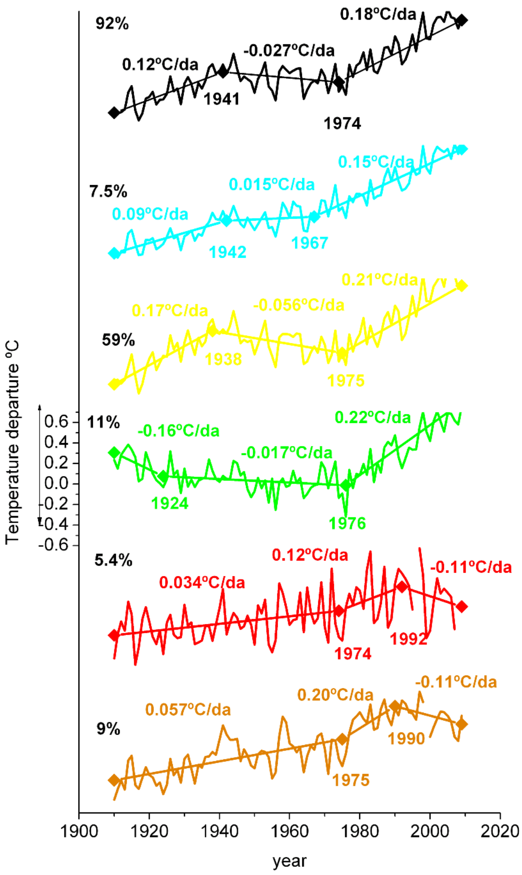

Fig. 4, Evolution of the area weighted mean temperature anomaly in different regions of the world in the GISS dataset, grouped in 5 classes plus the global averaged mean: from top to bottom: full dataset (92% of the world area);always warming (7.5%); warming + cooling + warming (59%); later warming after an initial cooling regardless of any changes in the initial cooling rate (11%); cooling + warming +cooling (5.4%); later cooling after an initial warming regardless of changes in the warming rate (9%). All the lines share the same vertical scale. Colors correspond to shading in Fig. 1.

While Fig. 5 may help to visualize different “histories” of global warming, it does not solve the problem of smoothing fast local changes, as the same histories (Fig. 1) may have had different timings of their breakpoints.

3.4 Last warming period length and intensity

In terms of the Global warming discussion it is important not only to analyse the averaged trend values but also the timing of the last warming evolution, and its geographical distribution.

Fig 5. shows the starting year of the warming period for regions that are experiencing recent warming: the blue, yellow and green regions of Fig. 1. They represent near 78% of the globe area.

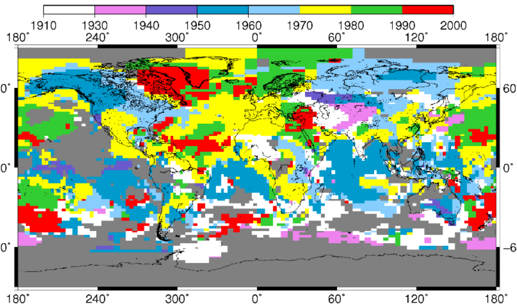

Fig 5. Decade of onset of recent warming. This corresponds to the year of the last breakpoint or of the first one if the second breakpoint only changed the warming rate. It is 1910 if there is a linear warming trend since 1910.Regions of missing data or regions that are experiencing recent cooling are gray.

From Fig. 5 one can see there is not a single decade that can be pointed out as the starting year of the recent warming. The mid 1970's is generally referred because it is relevant for the mean global temperature (top black line in the Fig 4.). What Fig 5 shows us is that there are significant parts of the globe surface that started the warming process in the 1950's and 1960's, e.g. North America, Russia, Indian Ocean and South Tropical Pacific; others started only in the 1980's and 1990's, e.g., Baffin Bay, Greenland, European Nordic areas and the tropical Atlantic Ocean. There are also a few areas (7.5%) that presented continuous warming during the last 100 years.

One interesting point is to know if the regions that started the warming process at a later stage have warmed less than the others, or, by the contrary, have already been able to catch up the from late warming onset by following faster warming trends.

The mean warming trend values after the onset warming are presented in the panel (a) of Fig 6. In cases where warming started early in the series, the value shown is the weighted mean value of the later warming periods. Otherwise it is just the recent warming trends. The panel (b) of the Fig 6 provides the geographical distribution of the surface temperature increase, in °C, after the warming onset year.

One sees that some regions that were experiencing cooling until the 1990's have started to warm up at a very fast pace and that the integrated temperature rise they have experienced in the last twenty years is larger than the integrated temperature increase of several regions that have started to warm up much earlier in the 1960's. This feature is specially striking in the Baffin Bay region, especially when compared with north American areas that started to warm up in 1960's. The recent warming around Baffin Bay, peaking above 2.5 °C, is larger than found in many areas that have been progressively warming from the 1960s. The anomalous behaviour of this area and its relation with North Atlantic circulation features are discussed in Miranda and Tomé [6].

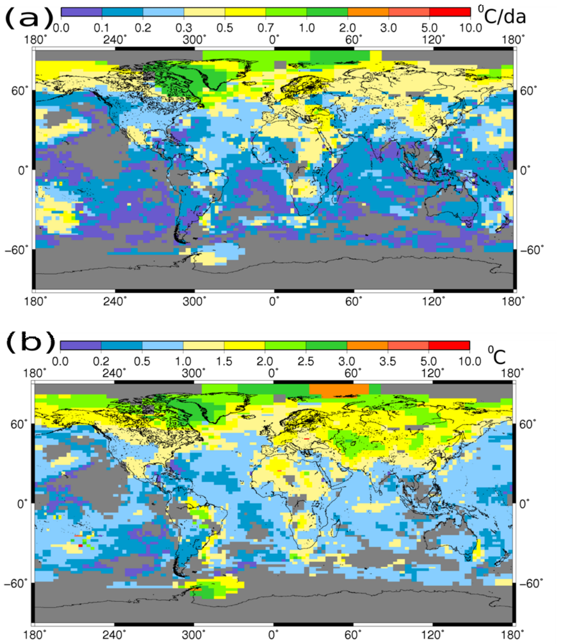

Fig .6 (a) Mean warming trend (°C/da) after the warming onset year (shown in Fig 5) (b) Warming in °C after the warming onset year. .

4 FINAL REMARKS

A simple linear trend methodology only provides trend values and the only spatial aggregation possible would be by the global warming cooling rates ignoring the spatial patterns of trend evolution. The non linear continuous trend fitting methodology used here allowed to identify relevant changes in the low frequency evolution of the near surface temperature time series. In this particular study we consider as an important result the geographical distribution of the year of onset of recent warming, obtained by an objective least-squares approach. Further studies are needed to correlate that distribution with atmospheric circulation variability. The recent evolution of the surface temperature field in the North Atlantic area and Baffin Bay stands out as the major anomalous feature in the temperature trend pattern that clearly is not well fitted by a simple linear trend, and where there is evidence of accelerating warming rates, a point already addressed by Miranda and Tomé [6].

The trends evaluation of spatial integrated fields usually smoothes the trend values, especially if one aggregates regions with completely different trend behaviour. We managed to go a little further by aggregating only regions with the same trend pattern. The cooling period in the global averaged series has only a small negative trend of -0.026 °C/da from 1945 till 1975, but it has twice that value when one considerers only the regions that, in fact, experiences this behaviour. Globally this period can be considered of less importance, but locally it has a large significance, as Fig 3 shows. In a recent study Kenyon [10] tried to explain the reason of this cooling in North Pacific area.

Climate trends can vary from place to place. The results shown here may help to clarify the observed large scale patterns of global warming, quantifying the recent and previous trends in different regions, and especially the timing of local trend change, a factor that is highly relevant in the studies of correlation with different climate processes.

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