1.9 LARGE SCALE SPATIAL STRUCTURE OF OBSERVED TEMPERATURE TRENDS

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1. INTRODUCTION

In the last three decades we have been looking for unequivocal signs of global warming in series of global and local mean temperatures. Different datasets of world temperature have been produced in recent years (e.g. Jones et. al 1999, Hansen et al 1999), by careful analysis of scattered observations. Based on those data, the IPCC (2001) estimated a 20th century global warming of 0.6ºC. However, Karl et al. (2000) showed that the fitting of a single line to the global temperature series leads to an underestimation of the current rate of global warming, and concluded that observations at meteorological stations indicate that the average Earth surface temperature has increased between 1910 and 1945, followed by a slight decrease until 1975 and a significant increase thereafter. The mean warming rate observed in this last period, was estimated at 2ºC/century, about 3 times faster than estimates based on overall linear trends (Karl et al. 2000).

Tomé and Miranda (2004) proposed a more general objective method of analyzing the partial trends in climate series, by least-squares fitting of a set of continuous line segments, where the number and location of the trend changing points are simultaneously optimized, subject to chosen constraints. That method was found to lead to results very similar to those obtained by Karl et al. (2000) for the mean world temperature. However, it allows a further decomposition of climate data, based on the analysis of the slow behavior of the surface temperature of large contiguous regions, leading to a new insight into the large scale spatial structure of recent climate change.

The detailed analysis of the spatial structure of climate data requires the availability of good quality gridded data with global coverage. The obvious choice would be reanalysis data available from 1950 onwards (Kalnay et al. 1996), and obtained through the assimilation of meteorological observations by a state of the art numerical weather prediction model. However, the use of that dataset for climate change studies, as recently done by Kalnay and Cai (2003), has been strongly criticized (Basist and Chelliah 1997, Hurrell and Trenberth 1998, Santer et al. 1999, 2000, Stendel et al. 2000) due to the effects of time dependent biases in the[1] data that is used by reanalysis, namely in what concerns satellite data. Until unbiased reanalysis data is available one must work with datasets obtained from station data. These datasets have other problems, especially in what concerns spatial coverage, missing data and small scale effects, such as urbanization, but is generally considered a better choice for the detection of long term climate trends.

The Goddard Institute for Space Studies (GISS) dataset (Hansen et al. 1999, 2001) has been specifically produced for climate change studies. The data results from the analysis of observed air temperature at meteorological stations and sea surface temperature in the ocean, interpolated to a regularly spaced grid. To avoid biases in the trend analysis in the present study we will only considered grid boxes of that dataset without missing values, covering about 87.6% of the world surface area. Here, the GISS data is analyzed by the computation of the set of continuous linear segments that best fit the time series of mean temperature at each grid point, with the following constraints: only one breakpoint is allowed at most, each trend has a minimum duration of 10 years, the trends must change sign at the breakpoint. This last condition implies that if the best fit corresponds to two segments with the same trend signal (both warming or both cooling trends, although at different rates) the method discards the breakpoint. Details of the method may be found in Tomé and Miranda (2004).

2. RESULTS

Fig. 1 shows the spatial distribution of the year of change in temperature tendency – the breakpoint year – grouped by decade for easier visualization. In 12.4% of the world area, including most of the Antarctic region, central Africa and Australia no analysis was performed due to missing data (gray areas). In 12.1% of the world area, the method identified no breakpoints (blank areas), because continuous warming was observed. For most of Northern Asia, North America and the western tropical Pacific, the breakpoint occurred in the 1960s. In most of the North Atlantic, parts of Western Europe, southern Asia, eastern North America, and in other scattered areas, the breakpoint occurred in the 1970s. In most of China, Japan, Scandinavia, Southeast Europe and some scattered oceanic regions, the breakpoint happened in the 1980s. Finally the temperature breakpoint occurred in the early 1990s in most of eastern tropical Pacific (near the El Niño region), West South Pacific near Australia, Greenland and Eastern Canada.

While the breakpoint distribution is rather complex, it shows remarkable spatial coherency, with neighboring regions experiencing similar behavior. This is a signature of changes in the global heat transfer

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processes in the climate system and in some regional circulations.

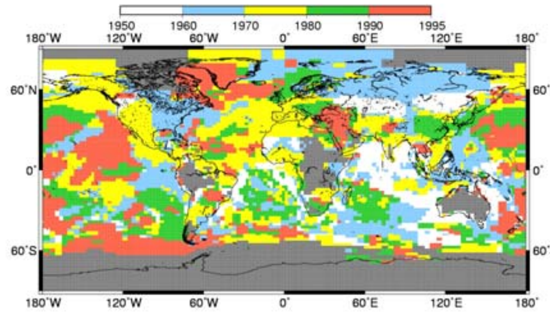

Fig. 1. Breakpoint year: year of change in sign of local temperature tendency. Blank in regions with no breakpoint and gray in regions of missing data.

Fig. 2 shows the spatial distribution of the temperature tendencies before and after the breakpoint. Places where no breakpoint was found are blank while regions with missing data are gray. Due to the imposed conditions, when a region cools in the first period its temperature must increase in the second period, and vice versa. Fig. 2 is remarkably coherent on the large scale, even more that the breakpoint map. It clearly shows that not all the world displays signs of recent warming. Mean temperature has been increasing in 67% of the world area, with 55% experiencing a period of cooling followed by warming and 12% showing continuous warming, but some 20% of the world area, including the eastern tropical and South Pacific, the South Atlantic and part of the Indian Ocean, have first warmed up and are recently experiencing cooling. In the period prior to the breakpoint, the fastest cooling was found in Eastern North America and nearby Atlantic Ocean, whereas the strongest warming rates were located in the eastern subtropical Pacific and large areas of the southern oceans. In the period after the breakpoint, faster warming is found in the Baffin Bay Region, between North America and Greenland and in Middle East, while cooling is observed in South Atlantic, South Pacific and Eastern subtropical Pacific.

Recent warming is observed in 67% of the world surface but the net temperature increase prevails in 75% of the world area for the 1951-2002 period. That means that in some regions where the surface has been cooling in recent years the decrease in temperature is not enough to offset the warming observed prior to the breakpoint. The same also happens in some regions of recent warming, especially in North America, where earlier cooling was not yet fully compensated by the recent warming.

Other studies have looked at the spatial distribution of surface temperature change, by the analysis of local trends (e.g. Hansen et al. 1999). However, those studies have been unable to detect the fast changes shown in Fig. 2b, due to the averaging between cooling and warming periods. For a similar reason the analysis of global temperature series tends to underestimate the current rates of climate change: in this case due to averaging not only between different periods but also between regions experiencing opposite behavior.

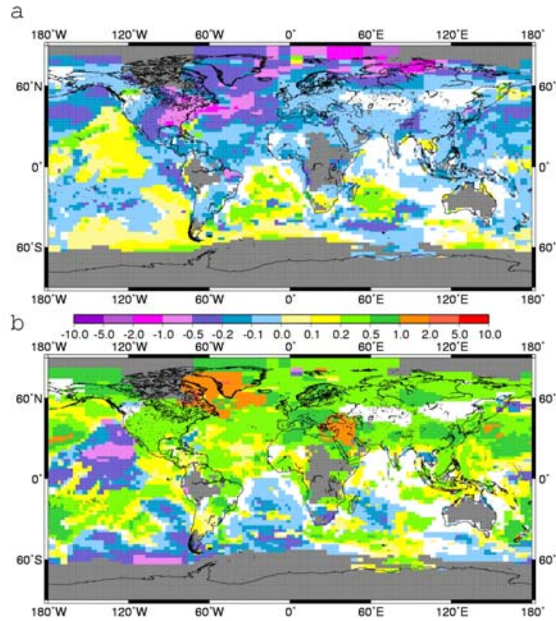

Fig. 2. Trends in mean surface temperature, in ºC/decade: (a) Before the breakpoint; (b) After the breakpoint. Blank in regions with no breakpoint and gray in regions of missing data.

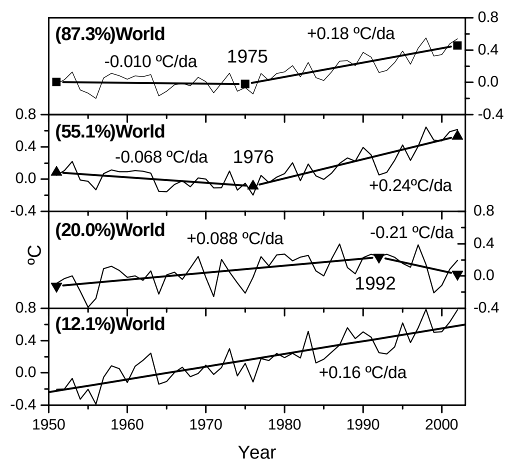

Figure 3. Evolution of the area weighted mean temperature anomaly in different regions of the world, from top to bottom: whole world without missing data, 55.1 % of the world area with warming after the temperature breakpoint, 20.0% of the world area with cooling after the temperature breakpoint, 12.1% of the world area with continuous warming.

The temperature tendency maps shown in Fig. 2 suggest a new way of looking into the evolution of the Earth's surface temperature, by separately averaging the surface temperature of regions that are experiencing similar warming/cooling behavior. An example of that kind of data compositing is shown in Fig. 3, which compares the evolution of the area averaged surface temperature in 4 large regions: the whole globe (87.6%

of the area, without missing data), areas which have first cooled and then warmed (55.4% of the world area), areas that evolved in the opposite direction (20.0%) and areas of continuous warming (12.1%). The computed partial tendencies capture the slow behavior of the average temperature in each region. The partial tendencies are significantly higher than mean tendencies that can be computed from each series. The breakpoint in the tendency of the average world temperature is located, for this dataset, in 1975, which coincides with the estimate of Karl et al. (2000), and the warming trend thereafter, around 0.18ºC/decade, is also very close to the one obtained by Karl et al. (2000). Some of the details shown in the Fig. 3 are quite interesting: the warmest year on record (1998) is clearly visible in the world average temperature and also in the average temperature of all areas with recent warming. However that year is not particularly warm in the areas of recent cooling. On the other hand, the El-Niña year 1999, which has been relatively cool in the context of the last decade, appears anomalously cool in the areas of recent cooling, which include a significant area in the Pacific.

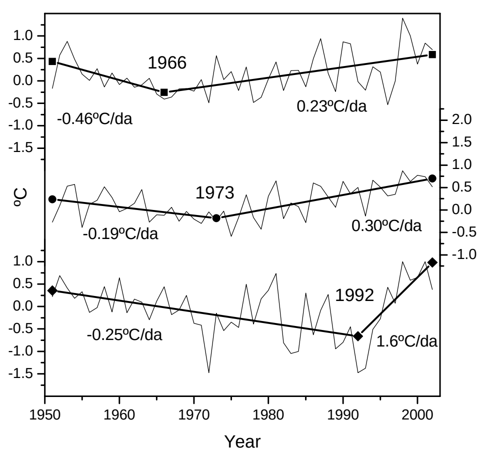

Fig. 4. Evolution of the area weighted mean temperature anomaly in different regions of North America, from top to bottom: North and East where recent warming is occurring from the 1960s onwards (blue in Fig. 1), regions warming from the 1970s onwards and Greenland, part of North America and nearby Atlantic ocean where recent warming only started in the 1990s.

Fig. 4 uses another area decomposition, showing the evolution of the area averaged temperature of 3 regions around North America, grouped according to the breakpoint decade. This is an important region because a simple linear trend applied to the North American temperature indicates a net cooling in the last half century (Hansen et al. 2001). However, all subregions presented in Fig. 4 reveal recent warming, and the warming rates are larger in regions where the breakpoint in the tendency occurred later. The Greenland region, covering Baffin Bay and parts of Northeast Canada, started to warm only in the early 1990s, but has been warming at an incredibly fast rate of 1.6ºC/decade. Overall, these results support the idea that America is indeed warming and suggest that warming rates are likely to increase in the near future.

3. DISCUSSION

The remarkable spatial coherency of the decadal evolution of surface temperature suggests that one may relate that evolution with changes in the large scale atmospheric and oceanic circulations. To understand the changes in the climate in the North Atlantic region one may look at the North Atlantic Oscillation index (Hurrell 1995). As shown by Tomé and Miranda (2004) the slow evolution of the NAO indicates an increasing trend between the 1960s and the early 1990s, followed by a decrease, in a good match with the temperature breakpoints in the two North America regions closest to the Atlantic, analyzed in Fig. 4. Fig. 5 shows the evolution of the two most prominent circulation indices: the NAO and the SO (Southern Oscillation). In both cases, the breakpoint analysis here proposed seems to capture important features of its slow evolution. In particular the recent opposite trends of both series seem well correlated with changes in surface temperature in large areas of the world, namely North America and the Pacific.

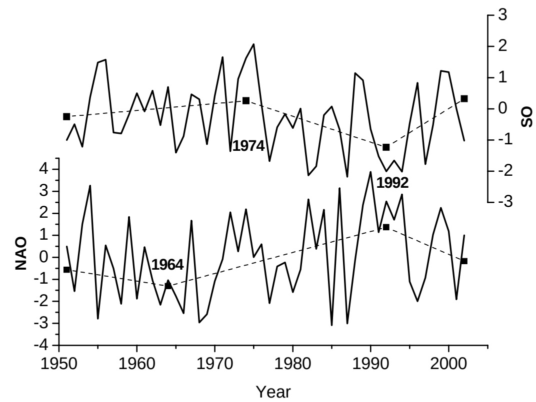

Fig. 5. Evolution of the annual mean North Atlantic Oscillation (NAO) and Southern Oscillation (SO) indices.

The sustained positive trend of the NAO index between the 1960s and the 1990s, previously analyzed by Ostermeier and Wallace (2003), is an important aspect of the anomalous climate in recent decades. In this context, the evolution of temperature in the Baffin Bay region may be interpreted in the light of changes in the position and intensity of the Icelandic pressure low (Hilmer and Jung 2000), with the delayed onset of warming in that region being caused by the anomalous behavior of the NAO leading to increased northerly winds in the region. On the other hand, the fact that most of the recent cooling is observed in the southern oceans suggests that it may be associated with a change in the oceanic circulation, as suggested by Broecker et al. (1985) and by Manabe and Stouffer (1995), although it may also be due to increases in low cloud cover and to other effects.

In spite of the great care that has been put in the preparation of GISS dataset the quality of data varies from point to point and it is likely that data over the oceans is less reliable. On the other hand, it is clear in the analysis of Fig. 3 that recent cooling tendencies in those oceanic areas are not well constrained by the data, since they are associated with large interanual oscillations of the mean temperature. An analysis using only gridpoints with available air temperature measurements, covering only about 40% of the Earth's surface and including most of the continental areas, leads to temperature tendencies significantly higher than those shown in Fig. 3, with a mean warming of +0.27 ºC/decade from 1972, and very limited areas of recent cooling.

The method described in this paper was also applied to the NCEP/NCAR reanalysis dataset (Kalnay et al. 1996) available for the same period. The results differ in many details, namely in the sizes of the partial tendencies. However, the large scale structure of the temperature change, which is the main target of this study, is rather similar, in particularly in what concerns the distribution of the main areas with recent cooling and warming and also in most of the analysis of the North American evolution of surface temperature. We believe that the coincidence gives extra support to the reported results.

The fitting of partial trends to climate data offers a new way to analyze the time and space patterns of climate variability and change. The method is far richer than simple linear trend analysis or spectral analysis, as it allows the evaluation of non-monotonic and non-periodic climate oscillations. It is also more direct, and easier to interpret, than other data decomposition techniques. Finally, it offers a simple and objective way of obtaining the slow evolution of climate data, subject to sensible constraints.

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