A staircase signal in the warming of the mid-20th century

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Abstract

The residual dynamics left after adjusting global surface temperature anomalies (1950-2014) for short-term variability from El Niño Southern Oscillation (ENSO) and volcanic eruptions have a staircase pattern. Linear trends for three quasi-stable periods 1950-1987, 1988-1997 and 1998-2014 are near zero with nearly all warming occurring during two step-like shifts in the years 1987/1988 and 1997/1998. We analysed several global datasets: HadCRUT v4.5 – land and sea surface temperature (SST) anomalies; ICOADS v2.5 – SST anomalies measured from ships; NCEP OI v2 – SST measured by satellite instruments; UAH MSU v5.6 and RSS MSU v3.3 – two satellite datasets measuring temperature of the lower troposphere (TLT). The ENSO signal was removed by EOF analysis, and gave comparable results for all datasets. A similar staircase behavior was found in global NCEP/NCAR reanalyses of 300mb meridional wind and outgoing longwave radiation (OLR) in northern and southern midlatitudes. These many different sources confirm the reality of the regime-shift staircase structure of recent warming, which is masked by short-term ENSO variability and the effects of volcanic eruptions.

Keywords: climate; global warming; regime shift; ENSO variability; time series analysis; decadal change

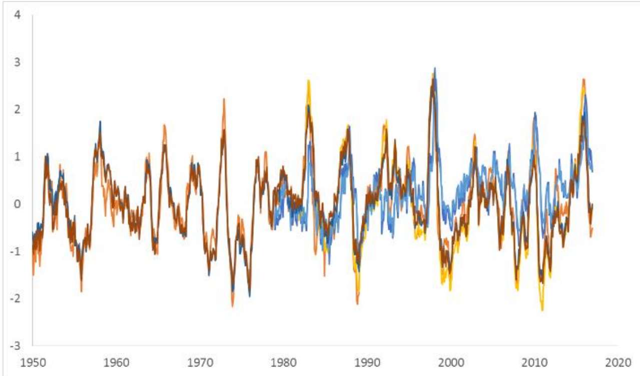
1. Introduction

Regime-shift like structures in decadal climate change have been detected in many studies of temperature and related climatic variables (Yasunaka and Hanawa 2002; Chavez *et al*. 2003; Lo and Hsu 2010; Reid and Beaugrand, 2012; Jones, 2012; Reid *et al*., 2016; Jones and Ricketts, 2017). Much attention has been given to a pause in warming (hiatus) during 1998-2014 (Tollefson 2014). We recently suggested and applied a simple method to adjust HadCRUT4 surface temperature anomalies for ENSO effects (Belolipetsky *et al*. 2015). After this adjustment for major ENSO and volcanic effects, the hiatus is even more pronounced. Moreover, we observed similar quasi-stable periods during 1950-1987 and 1988-1997 and almost all the warming occurred during the ~1987 and ~1997 shifts. It should be mentioned that a similar shift has likely occurred in 2015-2016, but this issue is outside the scope of this short paper. Here we want to demonstrate the reality of the staircase pattern using different measurements and climate parameters. It is well known that most short term global temperature variability is due to the well-defined ENSO natural oscillation (see: Wang and Fiedler, 2006). During strong El Niño events global average temperature rises by a few tenths Kelvin and reverts back subsequently. If spatial patterns are considered however, it is seen that global average temperature is most influenced by changes in the eastern tropical Pacific (Wang and Fiedler, 2006). Our 2015 study (Belolipetsky *et al*. 2015) takes into account variability in the spatial pattern of ENSO. Here we have applied the same method that uses a simple linear regression model to a broader set of parameters to reveal a clear staircase pattern in warming global temperature in the middle of the 20th century.

2. Methods

We analysed several global datasets: HadCRUT4.5 – land and sea surface temperature (SST) anomalies from the UK MetOffice; ICOADS – SST anomalies measured from ships; NCEP OIv2 – SST measured by satellites instruments; UAH MSU v5.6 and RSS MSU v3.3 – two satellite datasets measuring the TLT. Then we removed the ENSO signal from each dataset using EOF analysis. This method is a powerful tool for extracting major modes of variability in climate fields (Deser *et al*. 2010). The resulting orthogonal functions and corresponding principal component time-series (PCs) may not necessarily represent real physical modes. For example, this statistical analysis may have difficulty separating different processes and as a result mixes several modes. In this study, however, the first PC clearly reproduces the influence of ENSO on corresponding fields (Fig. 1a). For this result we only applied the method to sea temperature data in HadCRUT4.5; otherwise the high variability of northern latitude land temperature anomalies hides the ENSO signal. Linear detrending of ICOADS and HadCRUT4.5 SST was also performed before application of EOF analysis because in other cases the first PC occurs as the sum of ENSO and global warming signals. In contrast the analysis of satellite-based datasets did not require any detrending because the natural modes and the warming signal are distinguished without it. The analyses were restricted to the 30S-30N latitudinal belt for the TLT datasets because the tropospheric surface temperate anomalies (like land) exhibit large variability at high latitudes. We do not describe the details of the EOF analysis here as it is widely used in climate research (see: Deser *et al*. 2010). In general, it is used to find the modes of variability represented by spatial functions (EOFs) and time-series (PCs), which describe the maximum variance. There are many software tools that implement this method (e.g. Matlab). All the data, methods and plots for this paper were obtained using Climate Explorer (climexp.knmi.nl). In each dataset the first principal component (PC) represents the ENSO signal, and all of them are similar (Fig. 1a). Spatial projections for corresponding fields in contrast show marked differences, representing varying responses to ENSO, for example, in sea surface and troposphere temperatures (Fig. 1b, c, d). In order to adjust for the largest ENSO effects the linear influence of the first PC on each grid cell of the corresponding field was subtracted.It may be impossible to fully remove the influence of ENSO from the temperature anomaly datasets. So our aim was to adjust for the largest variations produced by ENSO and to minimise the risk of introducing biases. Subtracting the linear influence of the first PC from each grid cell of the corresponding field is likely to be the simplest and most unbiased method. By this procedure regions with high and low ENSO responses are not mixed in contrast to consideration of global averages. An explanation and full description of the method is given in Belolipetsky (2014) and Belolipetsky *et al*. (2015). Some ENSO residuals will remain after adjustment, but the greater part of short term ENSO effects will be removed.

3.



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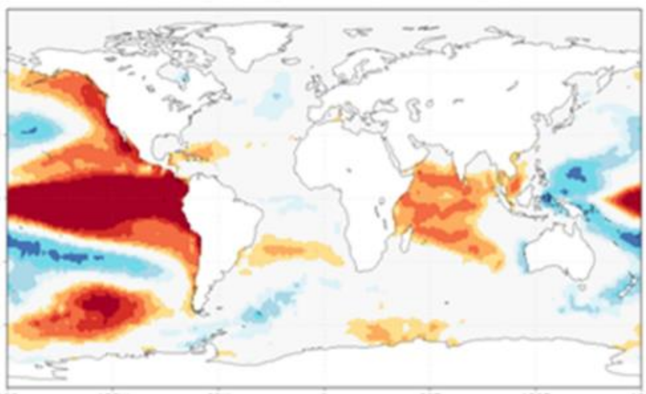

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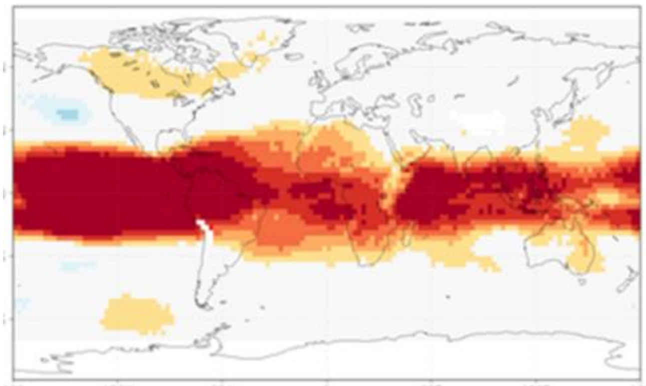

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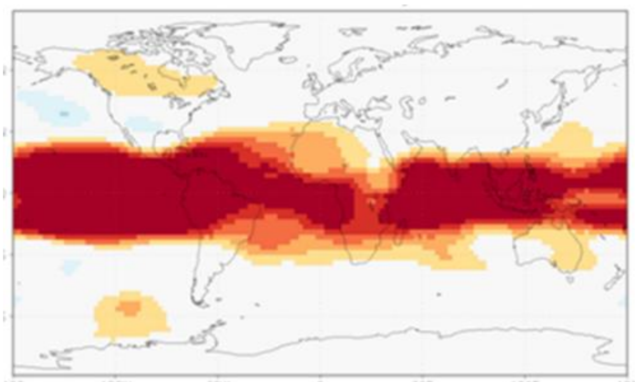


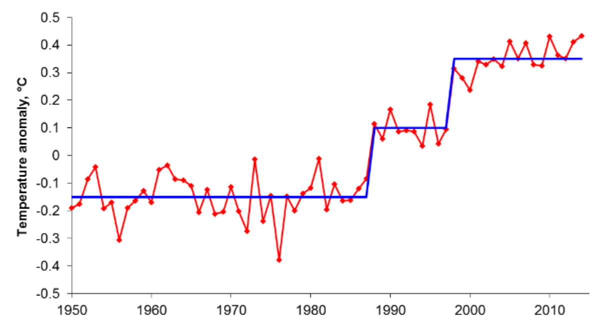
(d)

Figure 1. (a) Comparison of the Nino3.4 ENSO index and the first principal components (PC) of all the considered datasets. Projections of the first PC on the corresponding geographical fields: (b) NCEP OI satellite SST; (c) RSS MSU and (d) UAH MSU lower troposphere temperatures. The colours on the maps show the coefficient of correlation.

5. Results

The warming amplitude of the analysed datasets has not changed significantly after the adjustment, but the shape changed considerably. Adjusted for ENSO temperature dynamics the considered datasets have a striking staircase form: linear trends for three quasi-stable periods 1950-1987, 1988-1997 and 1998-2014 are near zero and nearly all warming occurred during the two shifts of 1987/1988 and 1997/1998 (Fig. 2a, b, c and d). The staircase behavior in the dynamics of temperature anomalies without adjustment is hidden because this shape is masked by ENSO variations. It is reasonable to suppose that some parameters may not be influenced by ENSO but are affected by the staircase signal. NCEP/NCAR reanalysis 300mb meridional wind (Fig. 2e) and outgoing longwave radiation (OLR) for the northern and southern mid-latitudes (Fig. 2f) are shown as possible examples. These different sources confirm the reality of the regime-shift staircase structure of recent warming, which is masked by short-term ENSO variability and the effects of volcanic eruptions.The periods between shifts are not exactly constant. It should be taken into account however, that at short timescales regional properties of climate may be affected by local oscillation modes and/or random weather variation. It is therefore, not surprising that the adjusted observations do not fall directly on a straight line. However, these divergences have no structure, look random and have a small amplitude compared to the shifts in 1987/1988 and 1997/1998.A notable consequence of the staircase dynamics of recent warming is that observed temperature anomalies (HadCRUT4.5) from 1950 till 2014 could be almost reproduced as the linear sum of only two factors(!) : ENSO variability and the staircase function (Fig. 3). Here we used the Nino3.4 index to describe ENSO variability. Our simple linear regression model accounts for 78% of the monthly mean and 87% of the yearly mean global temperature anomalies.

a



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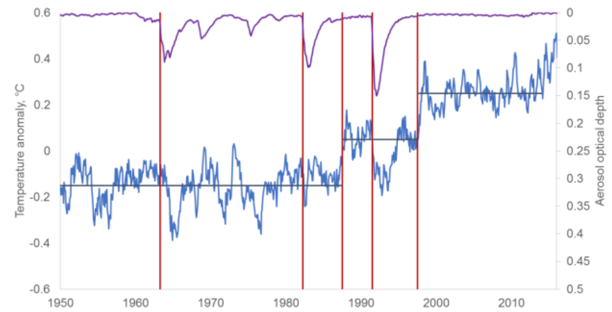

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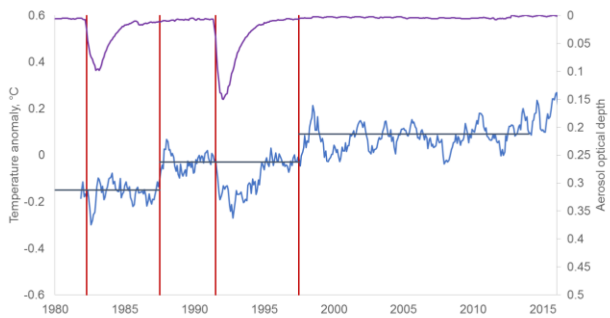

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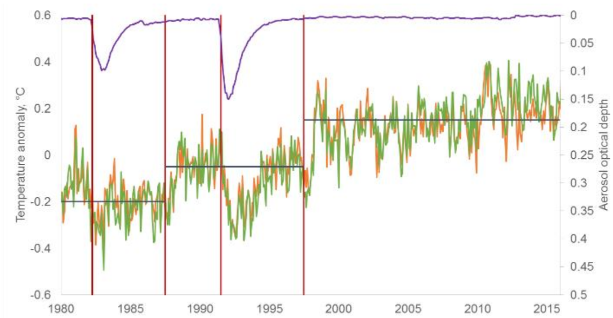

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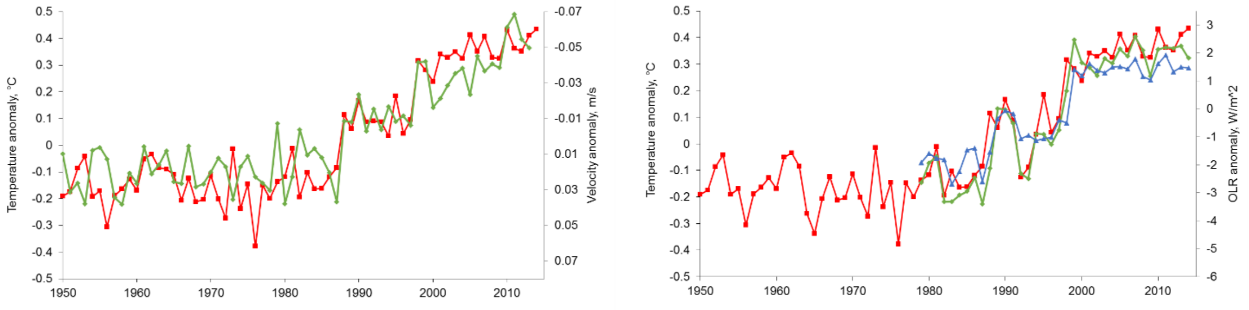

Figure 2. Staircase consisting of regimes and shifts in various climate parameters: (a) adjusted for ENSO and volcanoes: yearly global surface temperature anomalies (HadCRUT4), 1950-2014 years; (b) adjusted for ENSO monthly SST anomalies (ICOADS), 1950-2016 years and aerosol optical depth (reflecting the influence of major volcanic eruptions); (c) The same as ‘b’ for satellite based SST measurements (NCEP OI v2), 1983-2016 years; (d) The same as 'b’ for databases of satellite measurements of lower troposphere temperature (UAH MSU v6.0 and RSS MSU v3.3), 1980-2016 years; (e) Comparison of global meridional wind at 300mb height of NCEP/NCAR reanalysis (green line) and adjusted surface temperatures (red line), 1950-2014 years; (f) Comparison of satellite measurements of outgoing longwave radiation (UMD/NCEI) at 30N-70N (green line), at 30S-70S (blue line) and adjusted surface temperatures (red line), 1950-2014 years.

a) b)

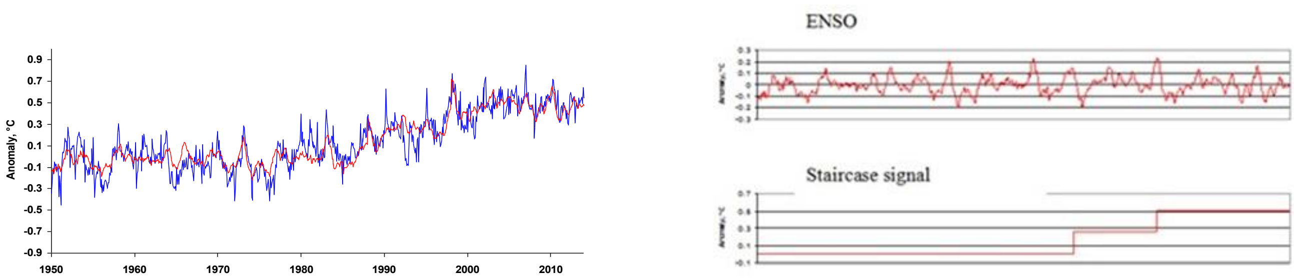

Figure 3. (a) Blue line - global temperature anomalies (HadCRUT4), red line - linear regression on the Nino3.4 ENSO index and the staircase signal, 1950-2014 years. (b) The ENSO influence on global temperature anomalies, 1950-2014 years. (c) The staircase signal influence on global temperature anomalies, 1950-2014 years.

6. Discussion and conclusion

Yasunaka and Hanawa (2002) define a regime shift as an "abrupt transition from one quasi-steady climatic state to another, and this transition period is much shorter than the length of the individual epochs of each climatic state". Subtracting the ENSO signals from global temperature time series is not the only technique that has been used to detect 1987/1988 and 1997/1998 shifts. Shifts with the same timing have been detected by other methods and for many other parameters (Reid *et al*. 2016; Lo and Hsu 2010; Li *et al* 2010; Hare and Mantua 2000). Reid *et al*. (2016) for example analysed 72 different biological and physical time series from different regions over the period 1946 to 2012. They detected 165 statistically significant step changes, 40% of which were close to 1987 and 25% close to 1997. The identification of the shifts in so many different parameters provides further support for the reality of the 1987 and 1997 global temperature shifts revealed here. Thus a very simple model almost totally reproduces global surface temperature dynamics from 1950 to 2014 – a linear sum of ENSO and the staircase signal with two shifts.

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