What is the temperature of the earth?

The political aspects of global temperature estimates are obvious and don't require elaboration. Below I summarize the key points of a new *Climate Dynamics* (CD) paper that I think opens up new perspectives on understanding and estimating the relevant uncertainties. The main message is that the primary sources of error and bias are *not* those that have been the subject of the most attention - they are *not* human in origin. The community seems to have done such a good job of handling the "heat island", "cold park", and diverse human induced glitches that in the end these make only a minor contribution to the final uncertainty. The reason of course, is the huge amount of averaging that is done to obtain global temperature estimates, this averaging essentially averages out most of the human induced noise.

Two tough sources of uncertainty however remain: missing data and a poor definition of the space-time resolution; the latter leads to the key scale reduction factor.

The good news: In spite of these large low frequency uncertainties, at centennial scales, they are still only about 13% of the IPCC estimated anthropogenic increase (with 90% certainty).
The bad news: The IPCC estimates of the warming are essentially correct.

Key science aspects

1) The usual uncertainties have short-range Auto Regressive type correlations, so that when averaged over long enough periods, the differences between series will eventually be close to white noises. This is presumably the main type of error that we could expect if there were the usual human glitches caused by changing station locations, technologies and the like; the usual sources of human bias. The corresponding fluctuations fall off relatively rapidly with time interval Δt: as $\Delta t^{-1/2}$. This type of behaviour is never observed even at scales of a century (see figs. 1, 2; Haar fluctuations were used, see the note at the bottom). If this type of error were indeed dominant, then the centennial scale differences between the series would be about $\pm 0.005\ ^{o}C$, which is about ten times smaller than those observed.

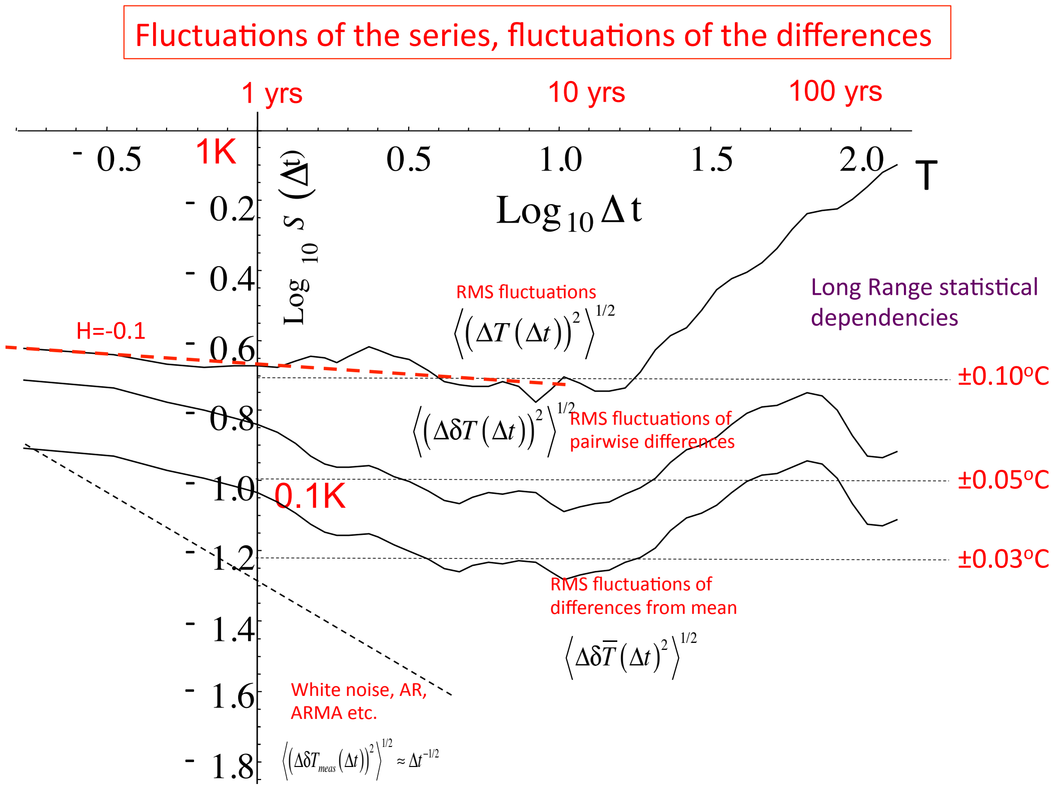

Fig. 1: The Root Mean Square (RMS) Haar fluctuations (structure functions $S(\Delta t)$) averaged over the six series (top), averaged over all the 15 pairs of differences (second from top), averaged over the differences of each with respect with the overall mean of the six series (third from top), and the standard deviation of the $S(\Delta t)$ curves evaluated for each of the series separately (bottom). Also shown for reference (dashed) is the line that data with independent Gaussian noise would follow. Adapted from fig. 2 of CD.

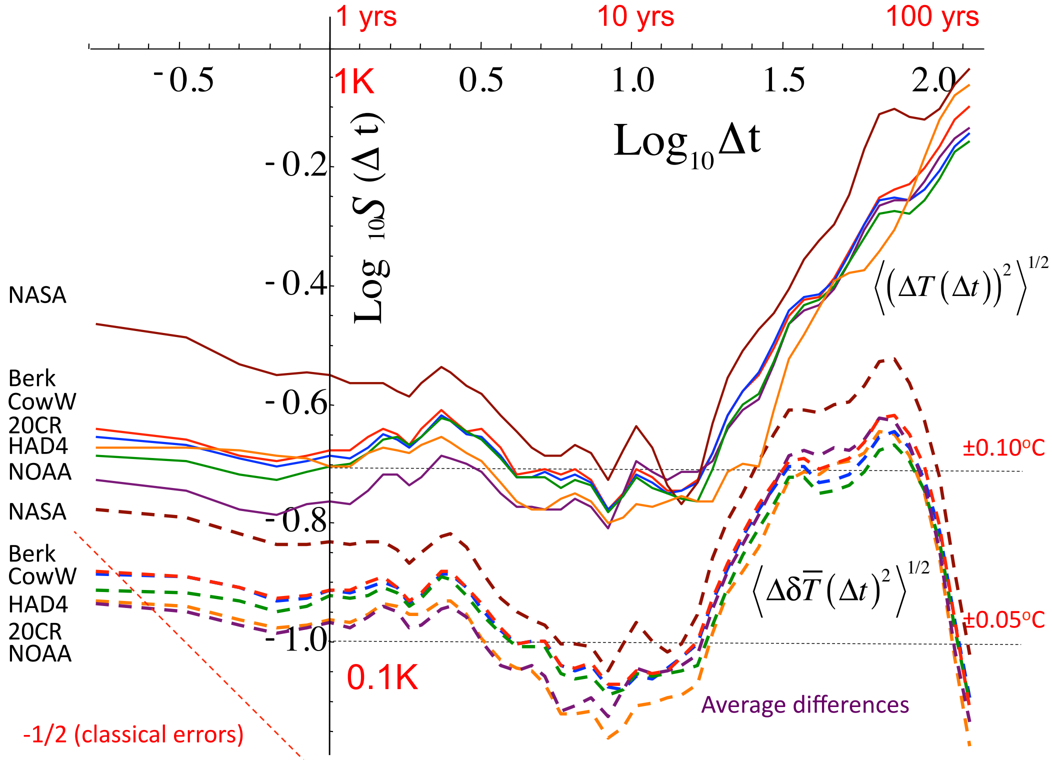

Fig. 2: The top set of curves (solid) are $S(\Delta t)$ for each of the different series, the bottom set (dashed) are the differences of each with respect to the mean of all the others: NOAA dark purple, NASA (brown), HAD4 (green), Cow (blue), 20CR (orange), Berk (red) (indicated at the left in the order of the curves). Adapted from fig. 3 of CD.

2) All the series seemed to be both statistically very similar to each other and each was pretty much equally distant from the mean of all the others (i.e. equally similar or dissimilar to each other, depending on your view). Significantly, this included the 20 Century Reanalysis (20CR) that didn't use any temperature station data whatsoever (fig. 2) and even turned out to be the closest (with NOAA) to the mean of all the others!
3) Up until a scale of about 10 years (the macroweather regime), the fluctuations in the series and in the differences between the series have different amplitudes (the ratio is between 2 and 3), but both are scaling with roughly the same fluctuation exponent $H \approx -0.1$ (fig. 1, 2). This implies strong long-range statistical dependencies (long range memories) in both the series themselves and in their differences. The obvious interpretation is that over this range of scales that each of the series are missing data (typically about 50% of pixels have no data), but each series misses somewhat different data.

4) For scales longer than about 10 years, the global temperature fluctuations begin to increase with time scale: the internal macroweather variability is increasingly dominated by low frequency changes due to anthropogenic warming: this is the beginning of the climate regime. At the same time, the fluctuations in the differences between the series stops following the fluctuations in the series themselves, leveling off at about ±0.05 ^oC (fairly independently of the time scale). This is a kind or irreducible uncertainty (figs. 1, 2).
5) It turns out that this irreducible uncertainty (the series differences at frequencies below about (10 yrs)$^{-1}$), can be easily explained as a problem of poorly defined space-time data resolutions. Fig. 3 shows that the more we average – in either space or in time – that the amplitude of the fluctuations systematically decreases with averaging scale according to somewhat different exponents in both space and in time.

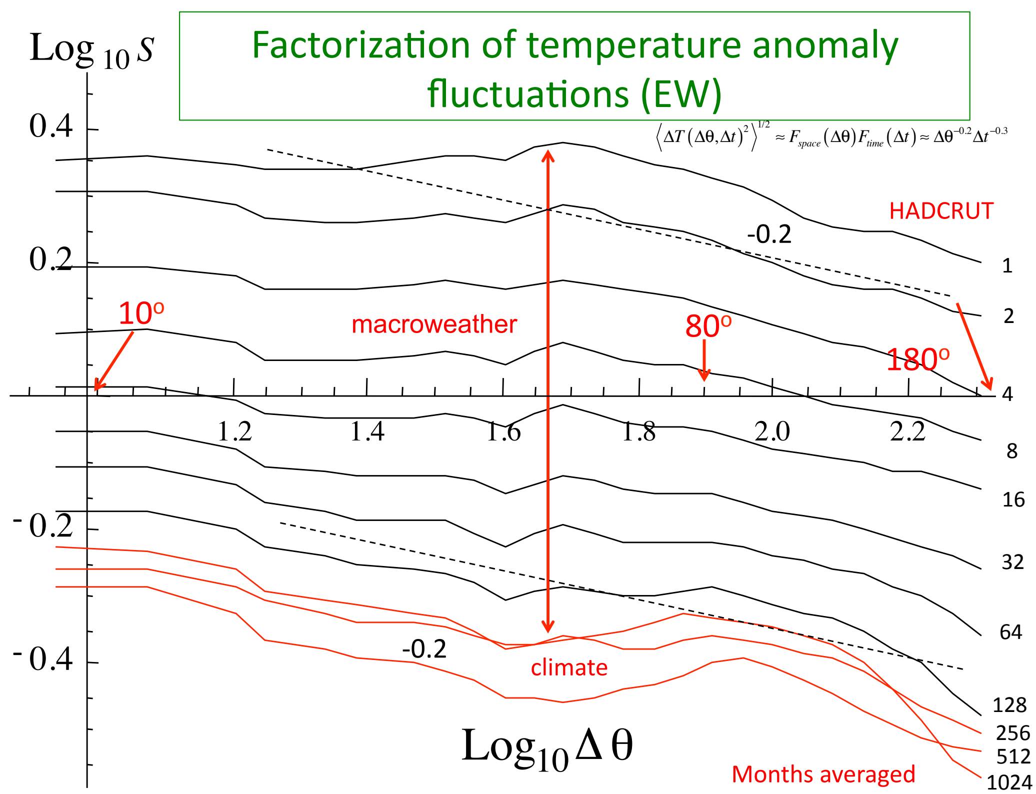

Fig. 3: The zonal spatial analysis of the HADCrut surface data (on a 5° x5° grid) as functions of temporal averaging (systematically doubling from one month to 1024 months ≈ 85 yrs, top to bottom). Although it is "noisy", roughly the effect of temporal averaging is the decrease the amplitude of the fluctuations at all spatial scales. This is as predicted by the macroweather space-time factorization property. The double headed arrow shows the predicted downward shift from one

to 128 months (red curves) with temporal exponent = -0.3. The reference line has slope = -0.2. Adapted from fig. 4 of CD.

Let's say that the basic data were gridded at 5^o resolution in space and at one month in time. In that case, there is a typical amplitude of 5^oX5^oX 1 month space-time temperature fluctuation, but since there are generally insufficient data in each 5^oX5^oX 1 month "space-time box" they are not perfectly estimated, there is not enough data to sufficiently average it over the nominal space-time scales. Because the fluctuation exponents in fig. 3 (in both and in time) are negative, this implies that the amplitudes of the fluctuations are spuriously large by a *multiplicative* factor that depends on the difference between the actual "effective" resolution and the nominal resolution (5^oX5^oX 1 month). This is the origin of the scale reduction factor and it has the particularity of being multiplicative: it affects all scales. This is the dominant source of error at scales beyond a decade. It gives the dominant contribution to errors in estimating anthropogenic warming.

6) In order to go beyond relative errors estimated via the series to series differences, to obtain the absolute errors, we constructed a simple stochastic model (fig. 4) of both the actual temperature and the three sources of error: the classical short range error, the missing data term and the scale reduction factor. Using statistical analysis of the fluctuations of the series to series differences, we estimated the statistics of the amplitudes from each contribution (fig. 5). The key results of the paper follow, notably:

-Up to 10 years, missing data was the main source of error: 15±10% of the temperature variance. The ±10% about the 15% refers to series to series variation in the amount of missing data (these are one standard deviation limits).

-After ten years, the scale reduction factor was dominant giving an error of 11%±8% error. This is the main source of centennial scale error.

-Overall, with 90% confidence it was found that the true temperature lies in the range -0.109 ^oC to 0.127 ^oC of the reported monthly values (90% confidence).

- Overall: the change since the 19th century can be estimated with nearly the same uncertainty as for the monthly value: ±0.108 ^oC (90% confidence).

-This uncertainty is much higher than conventional (AR type) approaches predict, (about ±0.005^oC).

-All of these numbers are much smaller than the roughly 1 ^oC of warming that has occurred since the 19th century, so that we can be quite confident of the magnitude of the warming.

Data simulation comparison

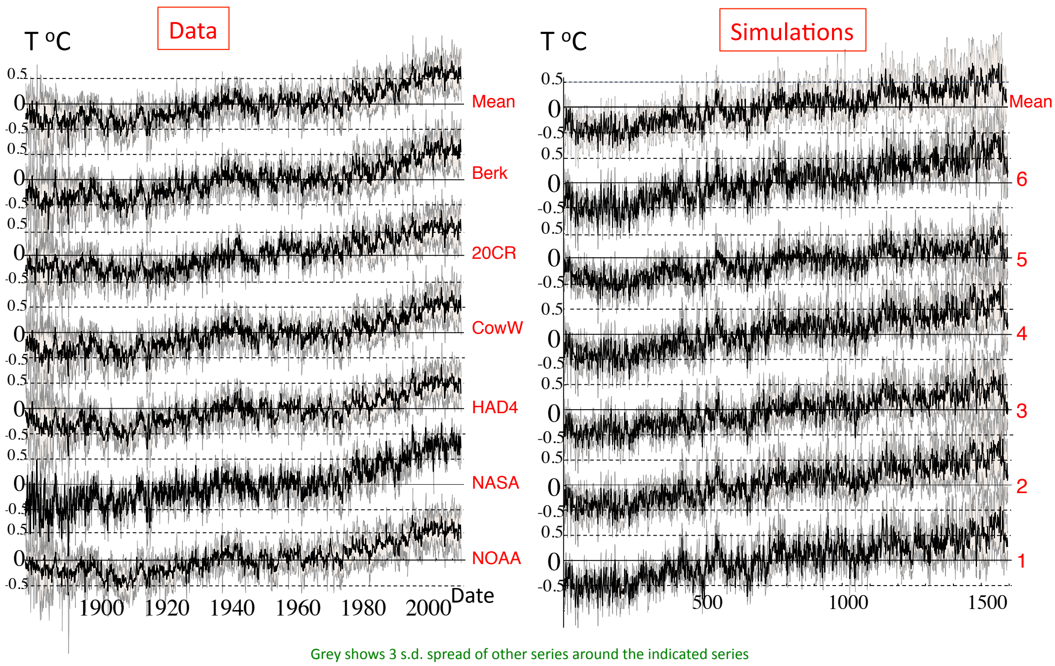

Fig. 4:
Left: The six monthly global surface temperature anomaly series from 1880 to 2012 (black) with 3 standard deviation uncertainties in grey with the mean of all six (top). From bottom to top: NOAA NCDC, NASA GISS, Hadcrutem4, Cowtan and Way, the 20 Century Reanalysis, the Berkeley series and the overall mean. Each series represents the anomaly with respect to the mean of the entire period, indicated by the black horizontal axes. For each of the bottom six series, the uncertainties are determined from the standard deviations of the other five.
Right: The six simulated earth temperature measurement series are shown using the same presentation as for the data on the left i.e. with the grey indicating the three standard deviation limits of the excluded series. The top is the mean of all and the three standard deviation spread is due to spread of all the others. The low frequency anthropogenic warming is approximated by a straight line, using a low frequency linear in CO_2 forcing is more accurate.

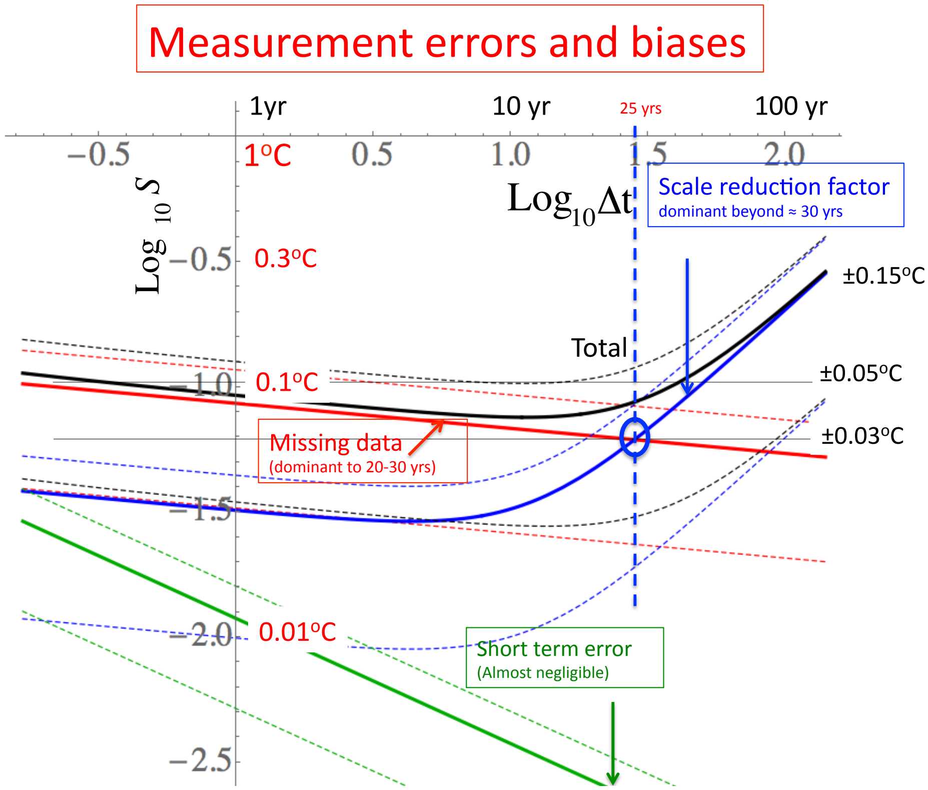

Fig. 5: The RMS fluctuations (structure functions, *S*) of the various measurement errors with one standard deviation limits shown as dashed lines (corresponding the variation from one measurement series to another). The blue curve is the contribution of the scale reduction factor, the red is from missing data (slope = H = -0.1) and the green is the short-range measurement error (slope -1/2). The black curve is the sum of all the contributions. Notice that most of the contributions to the errors are from the scaling parts. These Haar structure functions have been multiplied by a canonical factor of 2 so that the fluctuations will be closer to the anomalies (when decreasing) or differences (when increasing). Note that these show essentially the difference between the true earth temperature and the measurements; the difference between two different measured series will have double the variances, the difference structure function should thus be increased by a further factor $2^{1/2}$ before comparison with fig. 2, 3 or the figures below. Adapted from fig. 6 of CD.

7) The stochastic model was able to closely reproduce not only the temperature statistics but also the differences between series, and this at all scales from one month of > 100 yrs. This is a strong validation (see figs. 9, 10, 11 of CD).
8) The 20CR series is not based on anomalies but actuals, yet it was statistically just as close to the others as if it had been based on anomalies. We can therefore use it to determine the absolute temperature of the earth; the error estimates in the above paragraph will hold.

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Note on the use of Haar fluctuations: Haar fluctuations were used because they are the simplest that can do the job. A Haar fluctuation $\Delta T(\Delta t)$ of the temperature $T(t)$ over a time interval Δt is simply the average of $T(t)$ over the first half of the interval minus the average over the second half (i.e. the average from $T(t)$ to $T(t\text{-}\Delta t/2)$ minus the average from $T(t\text{-} \Delta t/2)$ to $T(t\text{-} \Delta t)$). That it! The interpretation is simple: when the mean (or RMS) of $\Delta T(\Delta t)$ is increasing with interval Δt, it is close to the mean difference in temperature, when decreasing, it is close to the mean anomaly (here defined as the average over an interval Δt of series with the long term mean removed).

References:

Lovejoy, S. (2017), How accurately do we know the temperature of the surface of the earth? , **Clim. Dyn.**, doi:10.1007/s00382-017-3561-9.

The slightly corrected proofs (not subject to copyright) can be found here:
http://www.physics.mcgill.ca/~gang/eprints/eprintLovejoy/neweprint/measurement.proofs.correction.pdf

There is a popular summary that was published in *The Huffington Post*:

http://www.huffingtonpost.ca/shaun-lovejoy/earth-temperature_b_15567152.html

A French language version may be found in *Le Huffington Post*:
http://quebec.huffingtonpost.ca/shaun-lovejoy/temperature-surface-terre-environnement_b_15567788.html