Response to Gleisner *et al* (2015): Recent global warming hiatus dominated by low latitude temperature trends in surface and troposphere data

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A new paper has been published in *Geophysical Research Letters* which investigates the geographical fingerprint of the recent slowdown in global warming. Gleisner *et al*. of the Danish Meteorological institute perform an analysis of a number of temperature datasets to investigate the latitudinal distribution of warming over the recent period (2002-2013). The paper contains results which are consistent with other studies of the oceanic and volcanic contributions to the slowdown in warming. Surprisingly, however, they fail to find a contribution from the rapidly warming Arctic, which is missing from some versions of the temperature record, in contrast to the temperature analysis presented by Cowtan and Way 2014 (henceforth CW14).

Gleisner *et al.* (henceforth G15) investigate the latitudinal distribution of warming in three satellite datasets: two are the familiar microwave sounding data from UAH and RSS. The third is a new Radio Occultation (RO) dataset, which derives information from the delay in radio signals due to the refractive index of the Earth's atmosphere. A fourth dataset is also considered - G15's own version of the HadCRUT4 surface temperature data (Morice *et al*., 2012), using a novel approach to address the coverage bias issue previously examined in C14.

Temperature trends are compared for two periods: Firstly a pre-hiatus period which G15 define as 1985 to 1997. Secondly a hiatus period which G15 define as the years 2002-2013, roughly consistent with the period of observed, unprecedented trade wind strength in the Pacific (England *et al*. 2014, Boisséson *et al*. 2014). The central result of the paper is Figure 4, replotted below, which compares the temperature trends for the pre-hiatus and hiatus periods at various latitudes. The left side of the plot represents temperature trends in a narrow band around the equator, with the width of the band increasing until at the right hand edge of the plot we have the temperature trend for the whole planet.

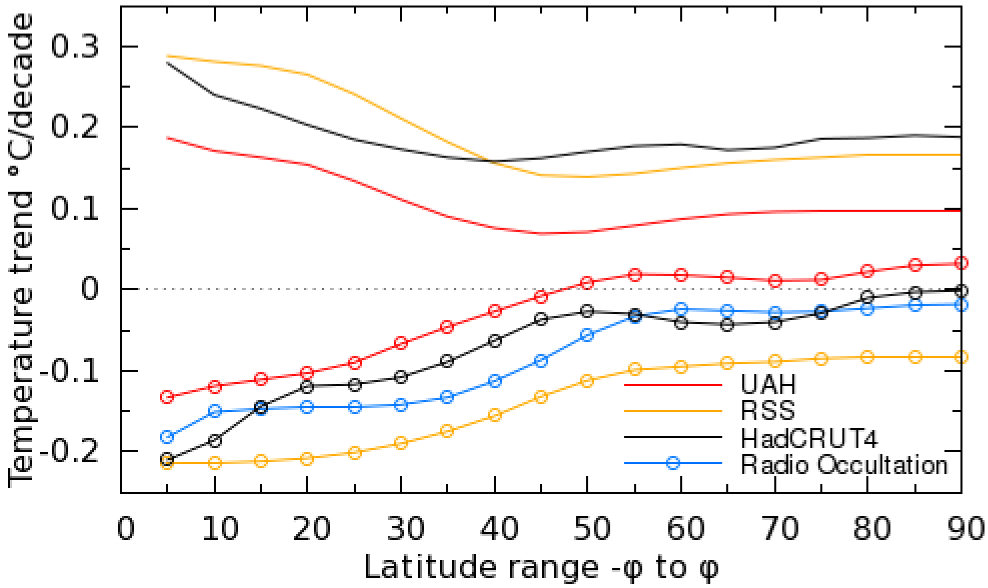

Figure 1: Temperature trend plotted against latitude range covered, with equatorial temperature trends on the left and global temperature trends on the right. The figure contrasts pre-hiatus trends (top lines) which hiatus trends (bottom lines). Replotted from G15 figure 4.

This figure agrees well with our present understanding of the drivers of temperature change during recent years. Observations and modeling have shown that natural variability in the tropical Pacific, related to the Interdecadal Pacific Oscillation, has played a large role in suppressing the rate of surface warming (Kosaka and Xie 2013, Trenberth and Fasullo 2013, England *et al*. 2014, Meehl *et al*. 2014)

Ground and satellite observations have also shown that moderate volcanic activity during this period has also contributed to the slowdown in the rate of surface warming (Ridley *et al*. 2014, Santer *et al.* 2014). The influence of oceanic variability is strongest at low latitudes, whereas volcanic activity is geographically variable.

The recent cooling of boreal winters (Cohen *et al.* 2012; Trenberth *et al.*, 2014) is also visible in the HadCRUT4 curve as a dip around 60N.

Contrary to prior analyses (CW14, Simmons and Poli, 2014), the hiatus trends show only a small increase at the high latitudes. In the case of the satellite datasets, this is not unexpected: rapid arctic warming is known to be a near surface phenomena, while free troposphere trends are more moderate (Simmons and Poli, 2014). For the G15 hiatus period on the region north of 70N ERA-interim shows a trend of 1.1°C/decade at 2m, dropping to -0.2°C/decade at 700mb.

Surface localisation of Arctic warming is also an expected fingerprint of sea-ice related feedbacks of Arctic amplification (Screen and Simmons, 2010, Serreze and Barry, 2011, Cohen *et al*., 2014). This may also explain why the CW14 UAH-hybrid reconstruction does not capture all of the Arctic warming demonstrated by some atmospheric reanalyses. But as a result the satellite datasets cannot be used to determine the impact of Arctic warming on the surface temperature record.

G15 also suggest that the *surface* temperature record does not show an increase when high latitude temperatures are included, interpreting this as evidence against a coverage bias contribution to the hiatus. There are two contributory factors to the discrepancy: The first concerns the temperature reconstruction method, and the second the choice of the start date of the hiatus period. These will be considered in turn in the next section.

Validation of temperature reconstruction methods

In order to ensure the robustness of its results, much of CW14 was devoted to validation of the temperature reconstruction method. While most of the validation tests involved evaluating the geographical distribution of temperature estimates, the skill in reconstructing global mean temperature was also tested, and the G15 reconstruction can be analysed the same way.

The test was adopted from the HadCRUT4 analysis (Morice *et al*. 2012). The starting point for the test is a set of globally complete surface temperature maps. These do not have to correspond to the historical temperature field, they merely need to be physically realistic. Temperature data from the MERRA atmospheric reanalysis product were used on the basis that of the modern reanalyses it shows the least Arctic warming, making it a conservative choice.

The validation is performed as follows:

1. The global mean temperature is determined from the globally complete reanalysis data for a given month.
2. Coverage of the reanalysis data is then reduced to match the actual observations. (For the CW14 kriging calculation the data are also separated into land and ocean maps.)
3. A temperature reconstruction is performed from the reduced data, using just the cells where there are observations (the HadCRUT4 approach), or averaging in latitude bands (the G15 approach), or by kriging the land and ocean data (the CW14 approach).
4. Finally the reconstructed temperatures are compared with the true global temperature from step 1. The difference between the estimate and true value is the error in the reconstruction. The calculation is repeated for each month, and the root-mean-squared average of the errors is determined for each method.

The G15 temperature reconstruction involves taking the average of all temperatures present in a given latitude band, and then taking the average across all latitude bands. The G15 method will be compared to the Cowtan and Way version 2 analysis, in which the unobserved region is infilled by separate kriging of the land and sea surface temperatures.

The errors in the reconstructions by month are shown in figure 2. The impact of coverage bias is detectable as a negative trend in the HadCRUT4 error around 2001, although it is obscured by month-on-month variability. This bias is somewhat mitigated in the G15 method, but with only a small reduction in month-on-month error. However, the errors are significantly reduced by kriging, consistent with the results of Dodd *et al*. (2014).

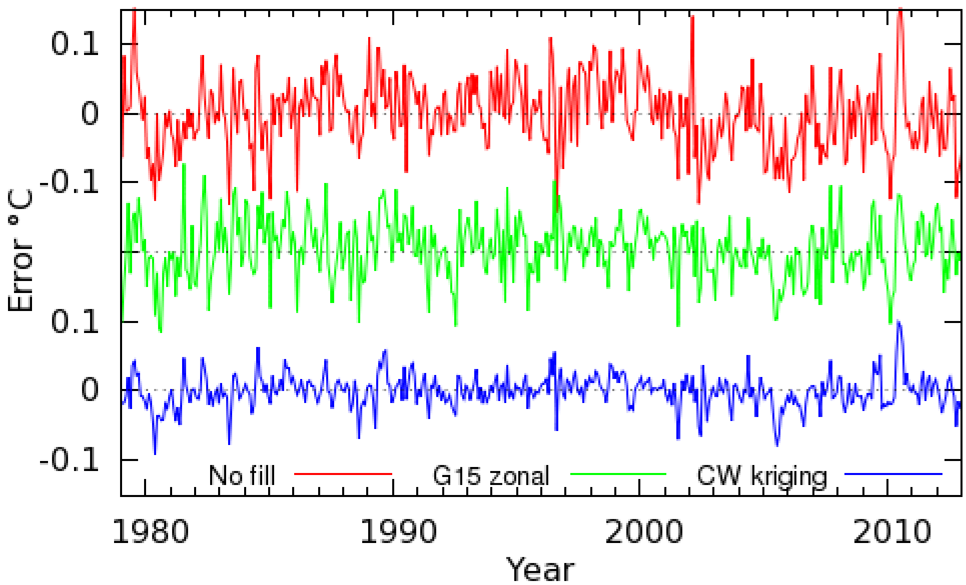

Figure 2: comparison of the errors in reconstructing the MERRA temperature field using no infilling, the G15 method, and two kriging approaches.

The root means squared errors are given in the following table..

Method	**RMS error**
HadCRUT4 (no coverage correction)	0.051
Gleisner *et al.* (zonal)	0.043
Cowtan and Way (kriging)	0.024

Despite its simplicity, the G15 method does offer a small improvement over the HadCRUT4 approach of ignoring missing cells. However kriging outperforms the G15 method, more than halving the RMS error relative to HadCRUT4.

The G15 approach appears to be limited by the decision to segregate by latitude. Although coverage is somewhat improved at high latitudes, at low latitudes missing cells can be determined in part from the temperature of cells on the opposite side of the planet.

Information from cells immediately to the north or south of the unobserved cell, which would likely be much more closely correlated, is discarded.

Having established that kriging outperforms the G15 approach in this validation test, the kriging reconstruction can be added to the trend comparison from G15, shown in figure 3. The effect of different choices of start date for the pre-hiatus period have also been examined - the G15 'pre-hiatus' period starts with a cold La Niña event and ends in the start of the extremely hot 1997/1998 El Niño, and so may show an unrepresentative trend.

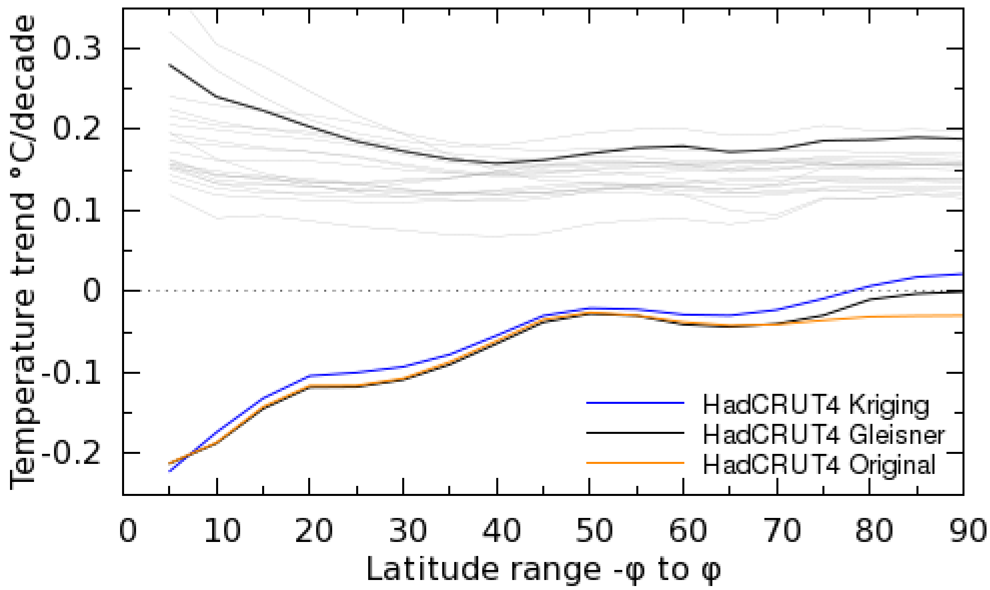

Figure 3: As Figure 1, but comparing three different reconstruction methods: The original HadCRUT4, the G15 approach and kriging (bottom lines). Pre-hiatus trends (top lines) are shown for the G15 hiatus start date (black line) and for start dates in the range 1968-1988 (thin grey lines).

When the temperature trends from G15 are compared with HadCRUT4, G15's reconstructed global trends are higher than for HadCRUT4, and the difference is at high latitudes. However the impact of coverage is certainly smaller than reported in CW14. The increase in hiatus trends is rather more substantial using the kriging calculation. The increase covers the whole latitude range, however it is greatest at high latitudes.

The G15 pre-hiatus trend is also the second highest possible for any start year. In addition the high equatorial warming rate (the uptick on the left hand side) is characteristic of certain start years only, particularly 1984, 1985 and 1988. These are all La Niña years. Coupled with the end date falling in an El Niño, the shape of the latitudinal trend curve appears to be determined by the El Niño state at the beginning and end of the trend period - the same may apply for the hiatus period as well.

The same comparison is performed over the original C14 study period (1997-2012) in figure 4. In this case infilling the unobserved region has a much larger effect on the trend.

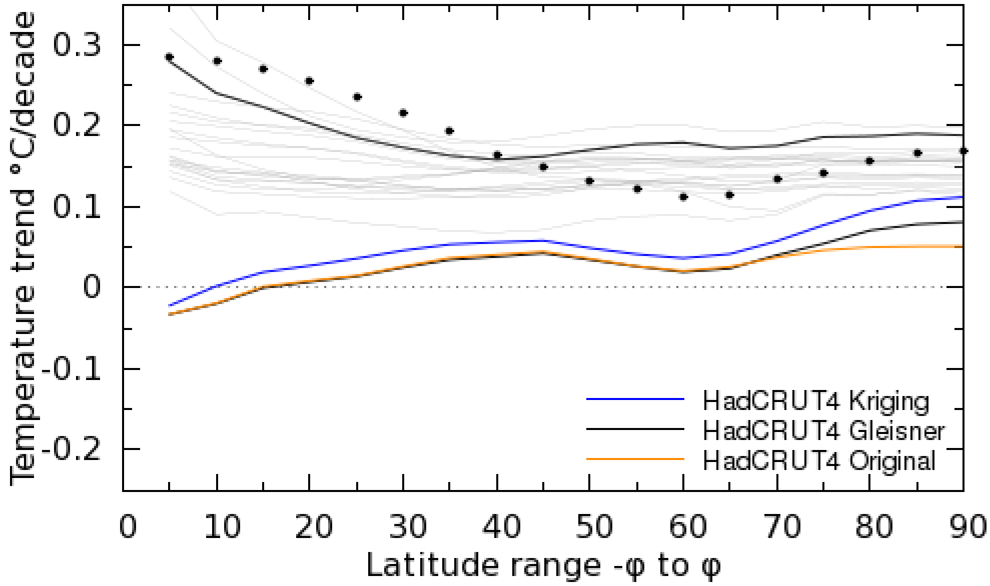

Figure 4: As Figure 3, but with the hiatus trends (bottom) covering the period since 1997-2012 (as CW14) rather than 2002-2013. The black points show the G15 method applied to the period 1999-2010 when the ENSO trend is inverted with respect to the period 1997-2012.

Coverage bias accounts for at least half of the difference between the pre-hiatus trend and the 1997-2012 trend (the study period of CW14) for all but two pre-hiatus start years. The ENSO effect on both the rate and latitudinal distribution of warming is tested by repeating the calculation for the period 1999-2010 (a subset of the CW14 study period). The results (solid circles) look more like the G15 pre-hiatus period with the exception of an uptick on the right due to rapid Arctic warming. This is also consistent with the slope of the curve being determined by the ENSO trend over the study period.

Discussion

G15 reinforces the conclusion that rapid Arctic warming is a surface phenomena. Further, the latitudinal distribution of the post-2002 trend divergence is informative, and it will be interesting to see where the sea surface temperatures of 2014 stand with respect to this trend. However there is evidence from both the pre-hiatus and hiatus periods that this is simply an indication of the phase of tropical Pacific variability over the study periods, arising due to ENSO and/or lower-frequency modes such as the IPO. This does raise the possibility of using zonal temperature gradients as an alternative index of ENSO state.

The comparison of our work with G15 raises an interesting question about the evolution of hiatus factors over time. Based on this work it appears that coverage bias increases to 2005 and then levels off, explaining the limited contribution or coverage bias over the G15 study period even after correction of the reconstruction method. This finding is in agreement with results from reanalyses (e.g. NCEP/NCAR in CW14 figure 2). The final results in CW14 figure 6 show a more gradual increase over the entire period, however this may be an artifact of smoothing or a difference between reconstruction versions (e.g. infilled vs. hybrid, version 1 vs. version 2).Together with C14, G15 and the present analysis suggest that what has been commonly believed to be the start of the hiatus period (1997/1998) is actually the product of coverage bias and cherry-picking the extreme El Niño. This "false", earlier-starting hiatus can be contrasted with what appears to be the shorter, genuine hiatus period of 2002-2013, during which internal variability and natural forcings have indeed temporarily reduced the underlying rate of surface warming (Huber and Knutti 2014). However coverage bias shows considerable year-on-year variability, so this may be an artifact of the choice of start date; this is an area for further work.

We agree with many of the points raised in G15. The authors state that "*omission of successively larger polar regions from the global-mean temperature calculations, in both tropospheric and surface data sets, clearly indicates that data gaps poleward of 60° latitude can not explain the observed differences between the hiatus and the pre-hiatus period*", and we agree. In our briefing document we state:

> To interpret the 16 year trend, it is necessary to take into account all of these factors, including volcanoes, the solar cycle, particulate emissions from the far East and changes in ocean circulation. The bias addressed by this paper is just one piece in that puzzle, although a largish one.

On the last point our only disagreement with G15 arises from the choice of research question. In seeking to explain temperature trends post-2002, coverage bias does play a more limited role in the temperature trends. However, we suggest that even over this period G15's conclusions arise from a combination of the use of tropospheric datasets which do not capture Arctic surface warming, and upon a surface temperature reconstruction which shows only limited skill in validation.

However in seeking to explain trends back to the late 1990s coverage bias is more significant. Further, if we wish to explain model-observational divergence, ignoring the role of coverage bias leaves an unexplained offset between the models and observations which is already largely in place by the start of the G15 study period. In our view, analyses that take into consideration the full range of observed and physically-valid contributions to the rate of warming (e.g. Schmidt et al. 2014; Huber and Knutti 2014) represent our best understanding of the the evolution of modeled and observed trends.

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