3.5 A NEW LOWER TROPOSPHERIC TEMPERATURE DATASET USING MICROWAVE SOUNDING UNIT MEASUREMENTS

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1. INTRODUCTION

There is abundant evidence that the temperature of Earth's surface has been warming in most locations over the past half century. Simple physical arguments and the results of climate models both suggest that similar or greater warming should also occur in the troposphere, the layer of the atmosphere closest to the Earth. Whether or not tropospheric warming actually occurred has been the subject of a lengthy scientific exchange.

Since 1979, the Microwave Sounding Units or NOAA polar orbiting satellites have been measuring the temperature of thick layers in the atmosphere using microwave emission from thermally excited oxygen molecules. The MSU instruments are cross-track scanning radiometers, which measure upwelling microwave radiation from the earth at a number of view angles spaced by 9.47° (-47.35°, -37.88°, 28.41°,…,0.0,… 47.35°), and at several different microwave frequencies on the lower shoulder of a complex of oxygen absorption lines near 57GHz. These view angles correspond to a range of Earth incidence angles from -56.2° to 56.2°, after taking into account the height of the satellite above the curved surface of the earth. The "MSU2" dataset is an average of MSU channel 2 data over the 5 near-nadir views, which measures radiation from a thick layer of the atmosphere from the surface to the lower stratosphere.

For MSU channel 2 (MSU2), the data and its associated biases have be analyzed by a number of groups yielding warming trends over the 1979-2004 period ranging from 0.04 to 0.17 K/decade (Prabhakara et al. 2000; Christy et al. 2003; Mears et al. 2003; Vinnikov and Grody 2003; Grody et al. 2004). Unfortunately, the raw MSU2 measurements are limited by the fact that 10%-15% of the signal in MSU2 arises from the stratosphere, which is cooling more rapidly than either the surface or the troposphere are warming, thus canceling much of the warming signal. Recently weighted combinations of different MSU channels have been used to remove the stratospheric influence from MSU2 (Fu and Johanson 2004; Fu et al. 2004; Fu and Johanson 2005). However this method is a statistical inference that depends, in part, on the vertical coherence of stratospheric trends, rather than a direct measurement of the troposphere (Tett and Thorne 2004).

Because of the longer path of the radiation for the views with larger incidence angles, the effective weighting function for these views peaks higher in the atmosphere than for the near nadir views. By calculating the weighted difference between the near limb views and views closer to nadir, an effective brightness temperature (Temperature Lower Troposphere, or TLT) can be retrieved with an effective weighting function that peaks several kilometers lower in the troposphere than MSU2 with much reduced stratospheric influence (Spencer and Christy 1992). The reduction on stratospheric influence is coupled with a modest increase in the contribution of surface emission. The weights used to construct the datasets are made explicit in the equations below.

$$
\begin{aligned}
MSU2 &= 0.2\left(T_4 + T_5 + T_6 + T_7 + T_8\right) \\
TLT &= \frac{TLT_{left} + TLT_{right}}{2} \\
TLT_{left} &= 2\left(T_3 + T_4\right) - 1.5\left(T_1 + T_2\right) \\
TLT_{right} &= 2\left(T_8 + T_9\right) - 1.5\left(T_{10} + T_{11}\right)
\end{aligned}
\quad (1),
$$

where T_i is the brightness temperature measured for the ith view, with T_6 begin the nadir view. As originally constructed by Christy et al., this nadir-limb product (TLT or "Temperature Lower Troposphere") showed cooling relative to the surface in many regions of the earth, particularly in the tropics. This finding is at odds with theoretical considerations and the predictions of climate models (Santer et al. 2000; Wallace et al. 2000; Santer et al. 2003), both which predict that any warming at the surface would be amplified in the tropical troposphere. The surface/TLT disconnect is only a problem on decadal time scales; on shorter time scales the ratio of the temporal variability in the Christy et al TLT to the temporal variability of the surface temperature agrees well with expectations (Wentz and Schabel 2000; Santer et al. 2005).

Nine MSU instruments were flown, with high quality data extending from late 1978 to mid 2004. The MSU data suffer from a number of calibration issues and time-varying biases which must be addressed if they are to be used for climate change studies. The construction of a climate quality dataset is especially difficult for TLT, because the differencing procedure used to extrapolate the weighting function downward has the effect of amplifying noise in the data relative to the signal, making it more difficult to diagnose the methods used.

We have performed an analysis of the methods used by Christy et al to construct version 5.1 of their dataset. (Since we began this work, they have constructed version 5.2. We do not yet know enough about their new method to perform a detailed analysis of their new methods, but we will present comparisons of these new results to ours in Section 3) We find substantial evidence that the method they used to correct for drifts in local measurement time contain important errors, and we have applied a second method, based on hourly output from the CCM3 climate model (Kiehl et al. 1996), to independently makes estimates for the diurnal correction (Mears et al. 2002; Mears, Schabel et al. 2003).

2. CORRECTING FOR DIURNAL DRIFT

The NOAA satellites that fly the MSU instruments are flown in sun-synchronous polar orbits. The local equator crossing time for these orbits drifts slowly over the lifetime of the satellite, leading to slow changes of the local measurement time that if uncorrected, would alias the diurnal cycle into the long-term data record. This effect can be removed if sufficient details about the diurnal cycle as measured by the MSU channel in question can be obtained.

The Christy et al method for correcting for drifting measurement time was first presented in Christy et al 2000, and then refined further in Christy et al 2003. This method uses the mean difference between measurements made to the right of the satellite sub-track and those made to the left to deduce the slope of the diurnal cycle for the channel in question. This is in principle possible because the views to the right of the subtrack make measurements at later local time than those to the left for the ascending part of the orbit -- the opposite is true for the descending part. We find two problems that limit the accuracy of this method.

First, it is very sensitive to small errors in satellite attitude. In order for the method to produce meaningful results, any systematic errors in satellite roll angle must be more than an order of magnitude smaller than specified -- this problem is discussed in more detail in (Mears and Wentz 2005). This sensitivity may account for the odd results Christy et al. obtain using this method for correcting the raw MSU channel 2 measurements. The correction they deduce for NOAA-11 is shown in Fig. 1B. There are several features of their diurnal correction the lead us to question its validity. First, they find a large diurnal correction, and thus diurnal cycle for latitudes between 60S and 45S, where the Earth is mostly ocean. We would expect a very small diurnal cycle in the region due to the large thermal mass of the oceans and the mixing of the oceanic surface waters by the strong winds at these latitudes. In contrast, our CCM3-based correction shows a small diurnal correction in the region (Fig. 1C). A second feature is the large seasonal cycle in the Christy et al diurnal correction in the tropics, where

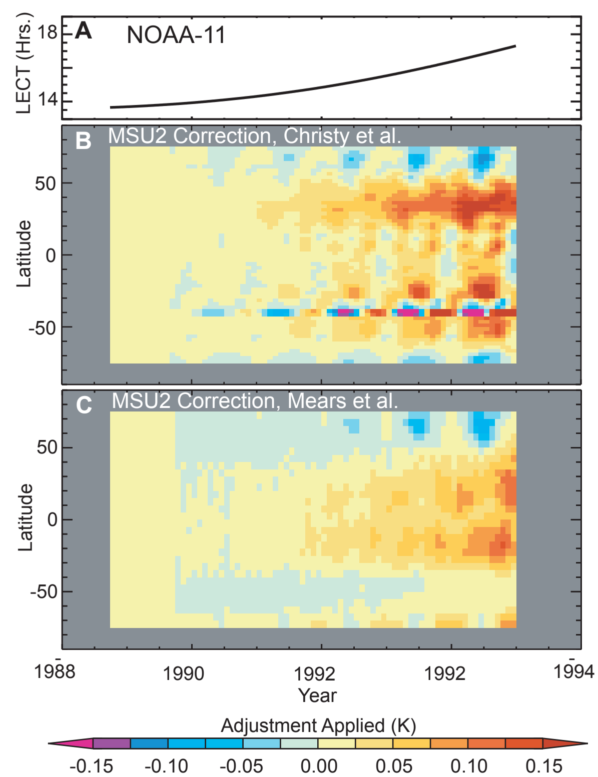

Fig 1. Diurnal correction applied to MSU2 for the NOAA-11 satellite. (A) LECT for the NOAA-11 satellite. (B) MSU2 correction applied by Christy et al. (C) CCM3-based MSU correction applied in this work.

Table 1

FOV	DT_i(minutes)
1	-35.4
2	-25.4
3	-17.2
4	-10.7
5	-5.2
6	0.0
7	5.2
8	10.7
9	17.2
10	25.4
11	35.4

we would expect the seasonal changes in the diurnal cycle to be relatively small compared to those for the northern mid-latitudes.

The second problem is specific to the TLT correction and is concerned with the interpretation of the expression Christy et al use to estimate the diurnal cycle in TLT. They use the difference between TLT_{right} and TLT_{left} (from Eq.1), divided by the average local time difference to estimate the slope dT_{TLT}/dt. The problem is that the single side estimates of TLT, e,g, TLT_{left}, already have some effects of the diurnal cycle included in them. This can be seen by examining Table 1, which shows the difference between the local measurement time for each view and the local measurement time at nadir. Nearly 25 minutes separate the different components of TLT_{left} from each other, more than the average time separation between TLT_{left} and nadir. The exact amount of error that this problem causes varies with the vertical profile of the diurnal cycle understudy, but in no case is the error small.

As an illustrative example, we consider a simple model where the temperatures of the surface and the atmosphere at all levels in increasing linearly in time at the rate of 1.0K/hour. In this case, the brightness temperature of each view is increasing at this same rate. Likewise, the retrieved TLT temperature should also increase at the rate of 1.0K/hour. Substituting this into the expressions for TLT_{left} and TLT_{right} for the ascending part of the orbit, we find that the change in TLT_{left} due to the diurnal cycle is +0.61 K, despite the fact that TLT_{left} is to the west of nadir, and therefore measured about 20 minutes before nadir. Thus the real change in TLT should be about -0.33 K, about half as large and of opposite sign. We also evaluated a second simple case, where we assume that the change due to the diurnal cycle occurs only at the surface. In this

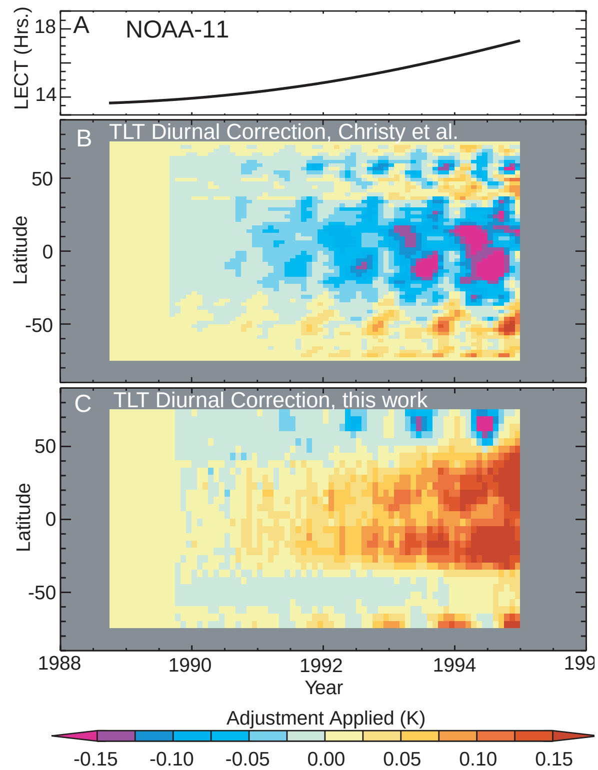

Fig 2. Diurnal correction applied to MSU TLT for the NOAA-11 satellite. (A) LECT for the NOAA-11 satellite. (B) MSU2 correction applied by Christy et al. (C) CCM3-based MSU correction applied in this work.

case the Christy et al procedure underestimated the effects of the diurnal cycle by about a factor of 3 without any sign change. These two cases roughly bracket the vertical profiles of the diurnal cycle that occur a most locations on the earth. In both cases, the Christy et al method results in large errors.

In Fig 2B, we show the diurnal correction applied to NOAA-11 TLT data by Christy et al. The correction applied in the tropics is of opposite sign of that applied by either group in this region for MSU2. Since much of the diurnal cycle originates near the surface. we argue that this reversal of sign is physically inconsistent, and perhaps is due to the problems with the TLT diurnal effect calculation discussed above. In Fig. 2C, we show the diurnal correction derived from the CCM3 model. In this case the correction is similar to, but larger than the correction applied to MSU2, which is consistent with the diurnal cycle being concentrated at the surface.

3. A NEW LOWER TROPOSPHERIC DATASET

The long-term behavior of a time series constructed from TLT is also dependent on the procedure used to merge the nine MSU satellites together into a single time series, in particular values of the parameters ("target factors") used to empirically remove the spurious dependence of the instrument calibration on the temperature of the hot calibration target (Christy et al. 2000; Christy, Spencer et al. 2003; Mears, Schabel et al. 2003) (see supporting online text). For the results presented below, we used exactly the same merging procedure and target factors (but different offsets) as we used when producing our results for MSU2.

When we merge the data from the 9 MSU satellites together using both our diurnal correction and target factors, we obtain a long-term time series that shows substantially more warming than the Christy et al. result, particularly in the tropics. In Fig. 3, we show global and tropical average monthly anomaly time series for our analysis and for Christy et al. Our global (70S to 82.5N) trend of 0.193K/decade (1979-2003) is about 0.1K/decade warmer than the trend calculated over the same area from the Christy et al. data, while our trend in the tropics (20S to 20N) of 0.153K/decade is about 0.15 K/decade warmer We obtain this estimate of the tropical TLT trend when we recalculate the intersatellite offsets to optimize them for tropical data. If this re-optimization is not performed, as it isn't in producing maps such as those shown in Fig. 3, we obtain a smaller trend value of 0.164 K/decade. We estimate the 2-σ uncertainty in these trends to be 0.09 K/decade, including both internal and structural uncertainty (Mears and Wentz, 2005). As mentioned above, Christy et al have released a new version of their data with any

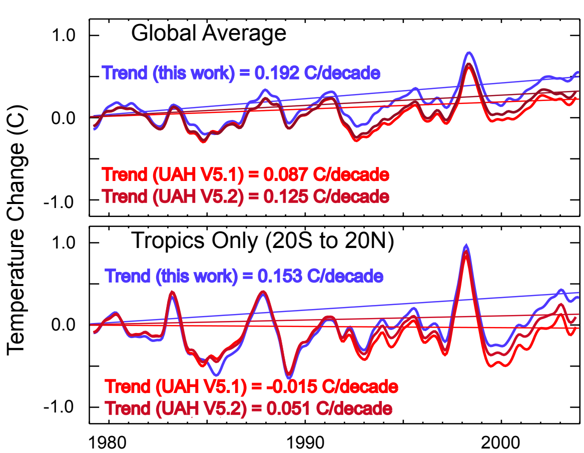

Fig. 3 MSU TLT anomaly time series.

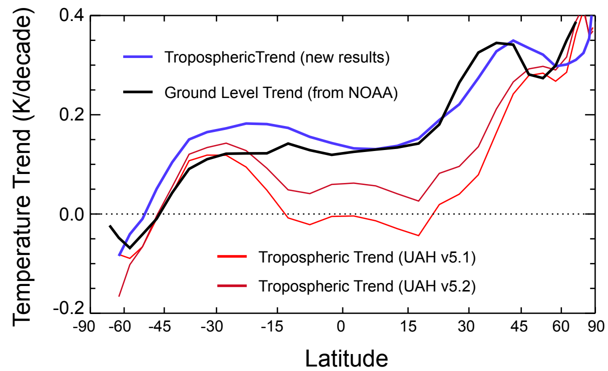

Fig. 4. MSU TLT and surface temperature trends plotted as a function of latitude.

updated diurnal correction. We also include time series from this new version in this plot. The new, V5.2 data is warmer both in the tropics and for the entire globe when compared to V5.1. This change is largest in the tropics, the region where the diurnal cycle used for V5.1 was most suspect.

In Figure 4, we show MSU TLT trends as a function of latitude for the 3 MSU datasets, as well as the GHCN-ERSST surface trends provided by NOAA (Smith and Reynolds 2005). (Over this time period, other surface datasets, such as those provided by NASA-GISS and the Hadley center are very similar.) Both the UAH trends are substantially below the reported surface trends. Our new data shows trends that are in closer agreement with the surface trends, while the Chirsty et al trends are in closer agreement with homogenized radiosonde data.

4. DISCUSSION

Our results are also in agreement with middle tropospheric results obtained for our data by removing the stratospheric contamination in our MSU2 using MSU channel 4 (Fu and Johanson 2004; Fu, Johanson et al. 2004), indicating a measure of vertical consistency in our results that is absent in the Christy et al. V5.1results (Fu and Johanson 2005). Also, the warming of the TLT in the tropics is in accordance with observed trends in total columnar water vapor from satellite observation made over the tropical oceans since 1988, which show more than a 2%/decade increase (Wentz and Schabel 2000; Trenberth et al. 2005). Although the correlation of total water vapor and temperature is often limited to the boundary layer, it would be difficult to explain a moistening of the tropical atmosphere without some warming within the layer measured by TLT.

In contrast, trends from temporally homogenized radiosonde datasets show less warming than our results (Lanzante et al. 2003; Lanzante et al. 2003; Thorne et al. 2005) and are in better agreement with the Christy et al. results. However, the radiosonde record is fraught with difficulties related to changes in instrument type, observing practices, data correction and station location. In the tropics, where they are the largest, these problems have been shown to be more likely to lead to spurious cooling trends than spurious warming trends in the unadjusted data, suggesting the possibility that any problems that were not detected during homogenization may result in a cooling bias in the homogenized radiosonde record (Lanzante, Klein et al. 2003; Randel and Wu 2005; Sherwood et al. 2005). In the Northern extratropics, there is excellent agreement between the Christy et al. results and a sub sample of the radiosonde sites chosen to have consistent instrumentation type and thus thought to be relatively free of error (Christy, Spencer et al. 2000). Presumably the agreement between these radiosondes and our data would be somewhat worse, though this has not been tested here.

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