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downhill currents is quite general and not restricted only to DLCs. However, it is important to note that the existence of downhill currents is a necessary but not sufficient condition for achieving ultrasmoothness. Amorphicity is another important prerequisite. Indeed, a transition to nanocrystallinity at higher temperatures or at higher impact energies is accompanied by considerable surface roughening also in the case of DLC films (*8*, *9*, *17*).

In summary, the multiscale theory presented here explains the origin of the ultrasmoothness of DLC coatings. Atomistic impact-induced downhill currents are responsible for the rapid erosion of asperities. Our detailed theoretical predictions are in excellent agreement with experiments. Our model is not restricted to ta-Cs. It can also be applied to explain the smoothness of other amorphous coatings deposited at high ion energy, the ion polishing of smooth surfaces, the chemical vapor deposition of hydrogenated tetrahedral amorphous carbon films, and the surface evolution of DLC films overgrown on structured substrates.

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26. The impact of a series of atoms with random impact points $\mathbf{u} = (u_1, u_2)$ on the surface $h = x_1 \tan\alpha$ results in an average transport of

$$\delta = \int d^2u \int_{-\infty}^{0} dx_1 \int_{0}^{\infty} dx_1' \langle t(x_1 - u_1, x_1' - u_1) - t(x_1' - u_1, x_1 - u_1)\rangle = \left\langle \sum_l d_1^{(l)} \right\rangle$$

atoms per impact across the x_2 axis. Here, $\langle\ \rangle$ indicates the average over many impacts and $t(x_1, x_1') = \sum_{l=1}^{N} \delta(x_1^{(l)} - x_1)\delta(x_1^{(l)} + d_1^{(l)} - x_1')$ measures the number of atoms displaced from x_1 to x_1' upon the impact of an atom onto the origin $\mathbf{u} = 0$. The initial lateral coordinates of the atoms in the system are denoted by $\mathbf{x}^{(l)}$.
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The Effect of Diurnal Correction on Satellite-Derived Lower Tropospheric Temperature

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Satellite-based measurements of decadal-scale temperature change in the lower troposphere have indicated cooling relative to Earth's surface in the tropics. Such measurements need a diurnal correction to prevent drifts in the satellites' measurement time from causing spurious trends. We have derived a diurnal correction that, in the tropics, is of the opposite sign from that previously applied. When we use this correction in the calculation of lower tropospheric temperature from satellite microwave measurements, we find tropical warming consistent with that found at the surface and in our satellite-derived version of middle/upper tropospheric temperature.

Much of the surface warming of Earth observed over the past century is understood to be anthropogenic (*1*, *2*). In the upper air, the situation is less clear because of the relative paucity of data and short period of observation (*3*). In situ temperature measurements made by radiosondes have limited spatial coverage, particularly over large portions of the oceans, and are subject to a host of complications, including changing instrument types, configurations, and observation practices (*4*). For the past two decades, microwave radiometers flown on a series of National Oceanic and Atmospheric Administration (NOAA) polar orbiting weather satellites have provided a complementary source of observations, which have been used to calculate temperature here. Nine microwave sounding unit (MSU) instruments have been 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 that must be addressed if they are to be used for climate change studies. For MSU channel 2 (MSU2), the data and its associated biases have been analyzed by a number of groups, yielding warming trends over the 1979–2004 period ranging from 0.04 to 0.17 K per decade (*5*–*9*). Unfortunately, interpretation of the raw MSU2 measurements is complicated by the fact that 10 to 15% of the signal in MSU2 arises from the stratosphere, which is cooling more rapidly than either the surface or the troposphere is warming, thus canceling much of the warming signal. Recently, Fu *et al.* have used weighted combinations of different MSU channels to remove the stratospheric influence from MSU2 (*10*–*12*). 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 (*13*).

A more direct measurement of the lower troposphere can be obtained by using the MSU nadir-limb contrast to extrapolate the channel 2 brightness temperatures downward and remove nearly all of the stratospheric influence (*5*, *14*, *15*) [supporting online material (SOM) text and fig. S1]. 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 Earth, particularly in the tropics. This finding is at odds with theoretical considerations and the predictions of climate models (*16*–*18*), both of which predict that any warming at the surface would

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be amplified in the tropical troposphere. The surface/TLT disconnect is a problem only 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 (*19*, *20*).

We present results from a new TLT analysis that uses a different, model-based, method to remove spurious trends caused by the slow evolution of each satellite's local measurement time over the diurnal cycle in atmospheric temperature. Each satellite typically exhibits a slow change of the local equator-crossing time (LECT) (Fig. 1A) and a decay of orbital height over time due to drag by the upper atmosphere (*21*). The LECT is the time at which the satellite passes over the equator, moving in a northward or "ascending" direction. Changes in LECT indicate corresponding changes in local observation time for the entire orbit. If the temperature being measured changes with the time of day (e.g., the diurnal cycle of daytime heating and nighttime cooling), slow changes in observation time can cause spurious long-term trends, which must be removed from each satellite's data record before attempting to merge the data together into a single data set (*22*).

Christy *et al*. estimated the effect of the diurnal cycle by calculating the mean rate of diurnal warming and cooling by subtracting the temperature measurements on one side of the satellite measurement swath from the other (*15*). This provided an estimate of the temperature change due to the difference in local observation times from one side of the satellite swath to another, about 40 min at the equator (*23*). Unfortunately, this method is extremely sensitive to small changes in the satellite attitude, particularly the satellite roll angle, calling its accuracy into question (SOM text).

In our work on MSU2, we used a different approach to evaluate the diurnal cycle. We used 5 years of hourly output from a climate model as input to a microwave radiative transfer model to estimate the seasonally varying diurnal cycle in measured temperature for each satellite view angle at each point on the globe (*7*). For the middle/upper troposphere (MSU2) on a global scale, there are no important differences between the two methods, although there are significant latitude-dependent differences (SOM text). In this work, we extend our method to TLT. In Fig. 1, B and C, we show a color-coded time-latitude plot of the corrections applied to TLT. For most latitudes, the Christy *et al*. TLT correction is of opposite sign from our TLT correction and from the corrections applied by either group for the middle/upper troposphere (fig. S2).

We argue that the sign change exhibited by the Christy *et al*. correction is physically inconsistent with our understanding of the vertical structure of the diurnal cycle. For MSU2, the globally averaged diurnal cycle is dominated by the surface and near-surface diurnal cycle over land regions. This is supported by a number of findings: Maps of temperature differences between the ascending and descending MSU2 measurements show much larger differences over land than over ocean (*7*, *24*). When these ascending/descending differences are examined as a function of Earth incidence angle, the differences are much larger for near-nadir angles than for larger incidence angles over land, suggesting that the bulk of the signal arises at or near the surface (fig. S3 and SOM text), in general agreement with radiosonde measurements (*25*) and general circulation models, including the Community Climate Model 3 model we used to calculate our diurnal correction.

Surface and near-surface effects will be even more dominant for TLT, whose vertical weighting function peaks several kilometers closer to the surface and has a surface contribution roughly double that of MSU2. Thus, we expect the TLT diurnal cycle and diurnal correction to be similar in shape to the MSU2 diurnal cycle, but with larger amplitude. This is consistent with the diurnal correction we calculate from the climate model and is inconsistent with the Christy *et al*. correction.

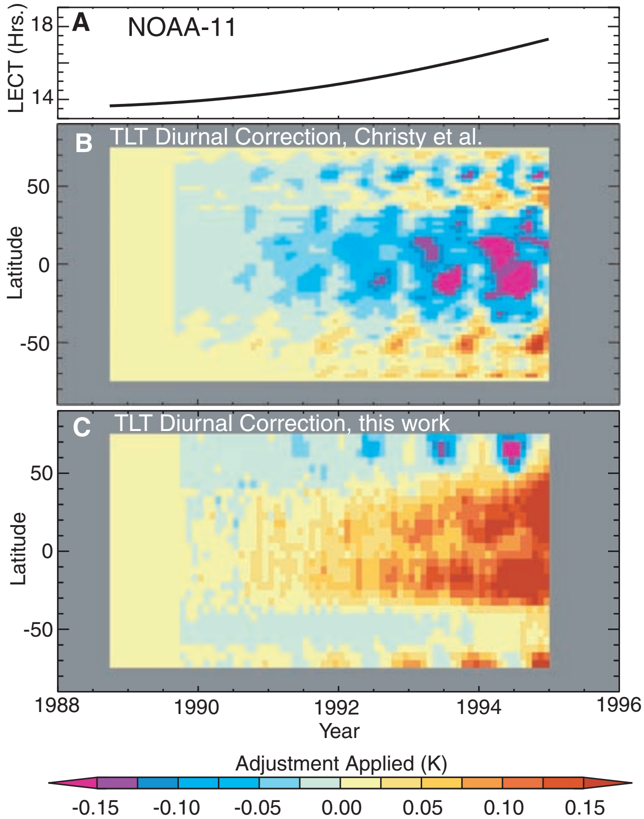

Fig. 1. Diurnal correction applied to MSU TLT for the NOAA-11 satellite. We use NOAA-11 as an example because it underwent a large drift in LECT of more than 6 hours before its ultimate failure in mid-1998. We show only the 1988–1993 period here because this is the only part of the NOAA-11 data used by Christy *et al*. NOAA-14 also underwent a similar drift, with its drift becoming more rapid after 1998, and by mid-2002, it had drifted by more than 4 hours. Most satellites in the MSU series drifted by at least 2 hours, with a few of the short-lived satellites drifting less than 1 hour. (**A**) LECT for the NOAA-11 satellite plotted as a function of time. (**B**) TLT correction applied by Christy *et al*. (**C**) TLT correction applied in this work.

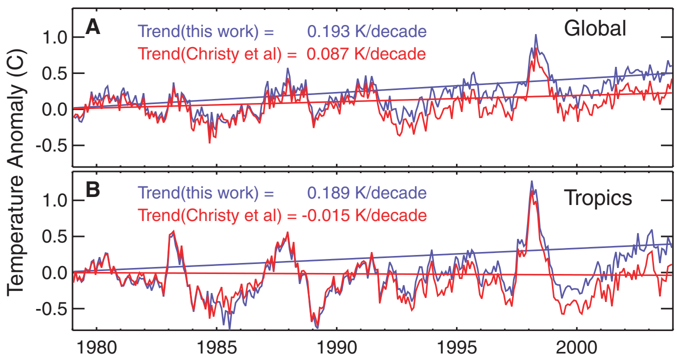

Fig. 2. TLT brightness temperature time series average over the globe (**A**), 70°S to 82.5°N, and the tropics (**B**), 20°S to 20°N, both for this work and for results from Christy *et al*. The straight lines are linear fits to the data. Our results indicate increased warming, particularly in the tropics, where the differences between the two diurnal corrections are the greatest. The differences between the time series become prominent after about 1991, when the drift in LECT for NOAA-11 begins to accelerate. A similar acceleration of drift in the NOAA-14 satellite occurs after 1998, with a corresponding increase in the difference between these time series.

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 on the 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 (*5*, *7*, *15*) (SOM 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 (*26*).

When we merge the data from the nine 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. 2, we show global and tropical average monthly anomaly time series for our analysis and for Christy *et al*. Our global (70°S to 82.5°N) trend of 0.193 K per decade (1979–2003) is about 0.1 K per decade warmer than the trend calculated over the same area from the Christy *et al.* data, whereas our trend in the tropics (20°S to 20°N) of 0.189 K per decade is about 0.2 K per decade warmer (*27*). We estimate the 2σ uncertainty in these trends to be 0.09 K per decade, including both internal and structural uncertainty (SOM text).

To estimate what portion of the trend difference between our respective results is caused by the difference in diurnal correction, we performed a set of numerical experiments, where we substituted the Christy *et al.* diurnal correction into our analysis, and/or where we fixed the values of the target factors to the values used by Christy *et al.*, allowing us to mimic different parts of the Christy *et al.* merging procedure separately and in combination. The results of these experiments (table S3) suggest that the difference in diurnal correction accounts for over 50% of the difference in trends for global averages and over 70% of the difference in trends for tropical averages.

In Fig. 3, we show global maps of TLT and surface trends (*28*) (1979–2003) and differences between these trends. The Christy *et al.* results indicate that the lower troposphere is cooling dramatically relative to the surface over almost all parts of the tropics, which is in sharp disagreement with both climate model output and theoretical arguments (*20*, *29*). Our results suggest that the tropical troposphere is warming slightly more than the surface in most regions, in accordance with expectations, although scenarios where the tropical troposphere is cooling relative to the surface are also possible within the range of uncertainty.

Our results are also in agreement with middle tropospheric results obtained for our data by removing the stratospheric contamination in our MSU2 data using MSU channel 4 (*10*, *11*), indicating a measure of vertical consistency in our results that is absent in the Christy *et al.* results (*12*). Also, the warming of the TLT in the tropics is in accordance with observed trends in total columnar water vapor from satellite observations made over the tropical oceans since 1988, which show an increase of more than 2% per decade (*19*, *30*). 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 data sets show less warming than our results (*31*–*33*) 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 (*32*). In the northern extratropics, there is excellent agreement between the Christy *et al.* results and a subsample of the radiosonde sites chosen to have consistent instrumentation type and thus thought to be relatively free of error (*15*). Presumably the agreement between these radiosondes and our data would be somewhat worse, although this has not been tested.

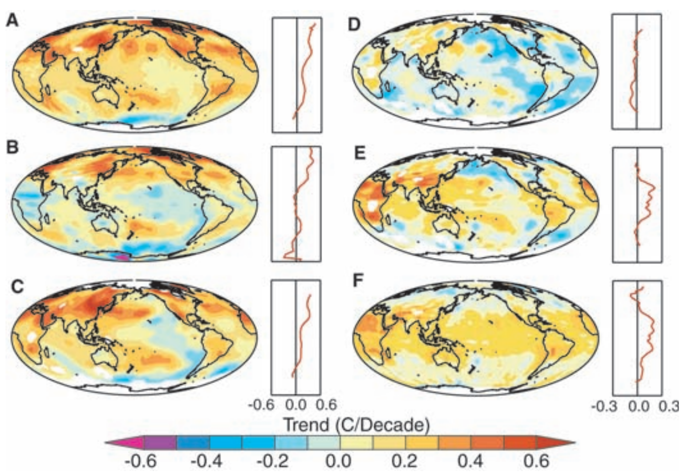

Fig. 3. Global maps and zonal averages of linear temperature trends (1979–2003). Missing data are shown as white areas. (**A**) TLT temperature trends from this work. (**B**) TLT temperature trends from Christy *et al.* (*5*). (**C**) Surface temperature trends from (*28*). Trend difference, surface minus TLT, (**D**) this work and (**E**) Christy *et al.* (**F**) TLT trend difference, this work minus Christy *et al.*

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21. The decay of orbital height also has an important effect on measurements of long-term temperature trends (*34*). This adjustment is done in the same way in the work reported here and in (*15*). Because it is not a cause of the current discrepancy, we do not discuss it further.
22. Both at Earth's surface and in the troposphere, the diurnal cycle in temperature is dominated by the first harmonic. At a given point on Earth, the ascending and descending passes of the NOAA satellites make measurements separated by approximately 12 hours, so that averaging together the data from ascending and descending orbits has the effect of removing most of the first harmonic of the diurnal cycle. This cancellation becomes less effective as one moves toward the polar regions, where the local measurement times become closer together. We define diurnal correction to be the removal of any residual effects remaining after averaging the ascending and descending parts of the orbit together.
23. The cross-scan time difference grows slowly to about an hour at 45°N or S and to more than 2 hours in the polar regions.
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26. We chose these values of the target factors to produce our final results because we have concluded that they are the most likely to be free of errors. They are calculated from oceanic observations to reduce errors from uncorrected diurnal variations, and we use unweighted MSU channel 2 data (T2 in SOM) to avoid additional noise due to the differencing procedure used to calculate TLT. The values of the intersatellite offsets needed to be recalculated to remove obvious intersatellite differences. In the supporting online material, we discuss the impact of using different data subsets to determine the target factors. This information is used to help determine the structural uncertainty.
27. We obtain this estimate of the tropical TLT trend when we recalculate the intersatellite offsets to optimize them for tropical data. If this reoptimization is not performed, as it is not in producing maps such as those shown in Fig. 3, we obtain a smaller trend value of 0.164 K per decade.
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Supporting Online Material
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Figs. S1 to S4
Tables S1 to S3
References and Notes

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Amplification of Surface Temperature Trends and Variability in the Tropical Atmosphere

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The month-to-month variability of tropical temperatures is larger in the troposphere than at Earth's surface. This amplification behavior is similar in a range of observations and climate model simulations and is consistent with basic theory. On multidecadal time scales, tropospheric amplification of surface warming is a robust feature of model simulations, but it occurs in only one observational data set. Other observations show weak, or even negative, amplification. These results suggest either that different physical mechanisms control amplification processes on monthly and decadal time scales, and models fail to capture such behavior; or (more plausibly) that residual errors in several observational data sets used here affect their representation of long-term trends.

Tropospheric warming is a robust feature of climate model simulations that include historical increases in greenhouse gases (*1–3*). Maximum warming is predicted to occur in the middle and upper tropical troposphere. Atmospheric temperature measurements from radiosondes also show warming of the tropical troposphere since the early 1960s (*4–7*), consistent with model results (*8*). The observed tropical warming is partly due to a step-like change in the late 1970s (*5*, *6*).

Considerable attention has focused on the shorter record of satellite-based atmospheric temperature measurements (1979 to present). In both models and observations, the tropical surface warms over this period. Simulated surface warming is amplified in the tropical troposphere, corresponding to a decrease in lapse rate (*2*, *3*, *9*). In contrast, a number of radiosonde and satellite data sets suggest that the tropical troposphere has warmed less than the surface, or even cooled, which would correspond to an increase in lapse rate (*4–12*).

This discrepancy may be an artifact of residual inhomogeneities in the observations (*13–19*). Creating homogeneous climate records requires the identification and removal of nonclimatic influences from data that were primarily collected for weather forecasting purposes. Different analysts have followed very different data-adjustment pathways (*4–7*, *12*, *14*, *17*). The resulting "structural uncertainties" in observed estimates of tropospheric temperature change (*20*) are as large as the model-predicted climate-change signal that should have occurred in response to combined human and natural forcings (*16*).

Alternately, there may be a real disparity between modeled and observed lapse-rate changes over the satellite era (*9–11*, *21*). This disparity would point toward the existence of fundamental deficiencies in current climate models (and/or in the forcings used in model experiments), thus diminishing our confidence in model predictions of climate change.

This scientific puzzle provides considerable motivation for revisiting comparisons of simulated and observed tropical lapse-rate changes (*10*, *13*, *21*, *22*) with more comprehensive estimates of observational uncertainty and a wide range of recently completed model simulations. The latter were performed in support of the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC), and involve 19 coupled atmosphere-ocean models developed in nine different countries. Unlike previous model intercomparison exercises involving idealized climate-change experiments (*23*), these new simulations incorporate estimated historical changes in a variety of natural and anthropogenic forcings (*24*, *25*).

Our focus is on the amplification of surface temperature variability and trends in the free troposphere. We study this amplification behavior in several different ways. The first is to compare atmospheric profiles of "scaling ratios" in the IPCC simulations and in two new radiosonde data sets: HadAT2 (Hadley Centre Atmospheric Temperatures, version 2) and RATPAC (Radiosonde Atmospheric Temperature Products for Assessing Climate). These were compiled (respectively) by the UK Met Office (UKMO) (*6*) and the National Oceanic and Atmospheric Administration (NOAA) (*7*). The scaling factor is simply the ratio between the temperature variability (or trend) at discrete atmospheric pressure levels and the same quantity at the surface (*26*). Observed trends and variability in tropical surface temperatures (T_S) were obtained from the NOAA (*27*) and HadCRUT2v data sets (*28*, *29*).

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