leading to new, more effective insect traps and repellents.

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COMMUNICATIONS ARISING

Climatology

Rural land-use change and climate

Kalnay and Cai[1] claim that urbanization and land-use change have a major effect on the climate in the United States. They used surface temperatures obtained from NCEP/NCAR 50-year reanalyses (NNR) and their difference compared with observed station surface temperatures as the basis for their conclusions, on the grounds that the NNR did not include these anthropogenic effects. However, we note that the NNR also overlooked other factors, such as known changes in clouds and in surface moisture, which are more likely to explain Kalnay and Cai's findings. Although urban heat-island effects are real in cities, direct estimates of the effects of rural land-use change indicate a cooling rather than a warming influence that is due to a greater reflection of sunlight.

The NNR use upper-air observations to produce analyses of atmospheric fields every 6 hours by using four-dimensional data assimilation that capitalizes on available multivariate data. As a consequence of the procedures used, the NNR do not directly include local surface influences or observations. Therefore, land-use and urbanization effects may contribute to differences detected with high-quality, measured station surface temperatures.

In addition, the reanalyses do not include effects of the changing atmospheric composition on radiation, despite carbon dioxide concentrations in the atmosphere increasing from 318 p.p.m.v. in 1960 to more than 370 p.p.m.v. — an increase of about 17% — over this time. Neither do the reanalyses deal with changes in surface wetness. Increases in cloudiness and rainfall over the Mississippi River Basin have increased evaporation but decreased potential evapotranspiration[2]. These trends have an important influence on the surface-heat balance.

The NNR did not include cloud information, and the depiction of clouds in the NNR is poor and the surface-heat budget has serious errors[3]. Detailed studies of the surface-heat budget and of why minimum temperatures are increasing at a faster rate than maximum temperatures reveal that the decreasing diurnal temperature range (DTR) is linked to a worldwide increase in cloud cover[4]. Clouds reduce DTR by sharply decreasing surface solar radiation and reducing radiative heat losses at night.

Processes involved in DTR, including radiation, surface fluxes of sensible and latent heat, and soil-moisture effects, have been investigated by using comprehensive measurements from the First ISLSCP (International Satellite Land Surface Climatology Project) Field Experiment (FIFE) in Kansas[4]. Changes in clouds, especially low clouds, largely determine the patterns of change of DTR. Soil moisture also decreases DTR by increasing cooling through daytime surface evaporation. Empirical relationships[4] using 3-hourly weather observations extend the results globally to show that DTR varies inversely with cloud cover and precipitation on several timescales, particularly over the United States. The reported decreases[1] in DTR are therefore consistent with the observed increases in cloud cover.

Across the southern two-thirds of the eastern United States, the DTR peaks in spring and autumn, with minima in winter and mid- to late summer[5]. Changes in DTR are traceable to the lengthening growing season, especially on sunny days, indicating that the increases in vegetation and associated evapotranspiration are important.

However, a direct assessment of the effects of changes in land use and vegetation[6,7] show that conversion of forests to crop land generally causes an increase in reflected sunlight that is greatest after the harvest in the autumn. The increased reflection results in a relative cooling, estimated to be in excess of 1 °C in autumn[6], which is due to changes in land use rather than to warming[1]. After the 1960s, the greatest land-use changes have been in the increase in crop land area in the midwestern United States and in reforestation in the northeast[6]. By contrast, urban heat-island effects are localized in cities, whose stations are not used in compilations of climate change. Also, changing snow cover contributes to the decrease in DTR during winter in the United States[8].

Changes in cloudiness and surface moisture are probably the main source of the discrepancies in trends found by Kalnay and Cai[1]. The NNR omit these influences in computing the surface-heat budget, although they are critical for getting surface-air temperatures right. Influences by processes not in the NNR model (including urbanization and land-use change) will be included in variables whose observations are analysed, but not in those variables calculated from the model (including surface-air temperature).

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Climate

Impact of land-use change on climate

Urbanization and other changes in land use have an impact on surface-air temperatures. Kalnay and Cai[1] report that the observed surface-temperature trend in part of the United States exceeds the trend in the NCEP/NCAR 50-year reanalysis (NNR) and conclude that changes in land use account for the difference (0.035 °C per decade according to their corrected values). Although land-use change may explain some of this discrepancy, the authors do not quantify the impact of the many changes in observational practice that occurred during the analysis period. Our findings indicate that these 'non-climatic' changes have a systematic effect that overwhelms the reported difference in trends and therefore calls Kalnay and Cai's central conclusion into question.

Historical archives kept at the National Climatic Data Center document many non-climatic changes in the area's observation stations. For example, from 1950 to 1999, over 25% of the stations switched from afternoon to morning observation schedules, imparting a gradual and systematic bias towards cooling to the area's temperature record[2]. More than 75% of all stations experienced some change in instrumentation, and many were also relocated on one or more occasions.

The Baltimore Customs House, whose record is shown in Kalnay and Cai's Fig. 1, is a station that has undergone several such changes (including instrumentation replacements in 1985, 1993 and 1998). Kalnay and Cai use raw data in their analysis but indicate that data adjustments for these non-climatic changes should result in a larger estimate of the impact of urbanization and other changes in land use.

To determine the effect of non-urban data adjustments, we performed an analysis identical to that of Kalnay and Cai, except that we used data from the US Historical Climatology Network (HCN) database[3]. The HCN is well suited for this purpose because it contains corrections that account for changes in observation time, instrumentation and location (adjustments for urbanization are also available, but were not used here because most HCN stations are in rural settings). We applied Kalnay and Cai's station-selection criteria to HCN, which yielded a set of 834 stations that are well distributed in their study area. We then used the authors' method to calculate the trend for the corrected HCN data for the period 1960–1999.

The resulting mean temperature trend in HCN (+0.224 °C per decade) exceeds Kalnay and Cai's observed temperature trend (+0.112 °C per decade). By the authors' reasoning, the difference between the HCN trend (+0.224 °C per decade) and the NNR trend (+0.077 °C per decade) is due to changes in land use. This trend difference (0.147 °C per decade) far exceeds their land-use value (0.035 °C per decade) and is ten times the size of the largest published urban estimate for the United States (0.015 °C per decade[4]). It also indicates that land-use change accounts for two-thirds of the warming over the past four decades. (The effect would have been even larger had a more urban network been used.)

In addition, this trend difference is decreasing over time. According to our calculations, the discrepancy between the corrected HCN trend and the NNR trend during the first two decades (0.202 °C per decade) is more than twice as large as during the past two decades (0.089 °C per decade).

These estimates seem improbable and indicate to us that the NNR trends are not accurate. We infer this in part because there is extensive evidence to support corrected HCN trends; they are spatially consistent with surface trends across international borders, with sea-surface temperature trends in adjacent oceans (which had no change in land use), and with tropospheric temperature trends derived from satellites and radiosondes[5].

We are not aware of any evidence demonstrating the reliability of the NNR surface-temperature trends. Neither can we think of a reason why the land-use effect should have decreased by more than 50% during the study period. The decrease in the NNR land-use estimate is particularly striking given the dramatic increase in temperature during the past two decades[6] (+0.343 °C per decade in HCN).

Our results indicate that the NNR alone is not sufficient to identify a land-use impact, casting doubt on Kalnay and Cai's conclusions. However, their work does draw attention to an important issue that requires further investigation.

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Cai and Kalnay reply — We do not deny the obvious importance of global warming and decrease in diurnal temperature range (DTR) due to greenhouse effects, which are present in both surface-station observations and the NCEP/NCAR 50-year reanalysis (NNR). Moreover, the NNR shows the largest warming trend over the past two decades, as reported in the surface-station data, suggesting that the NNR captures the dominant greenhouse-warming effect.

Our study[1] attributes the differences between the two data sets largely to land-use changes because the NNR is not subject to local surface influences. We deliberately used raw (unadjusted) surface observations and pointed out that the multiple non-climatic adjustments are uniformly positive, so our estimate should be considered as the lower bound of the effect of land-use changes. As we pointed out and Vose *et al.* confirm, adding these non-climatic adjustments to our lower-bound estimate does not alter the sign of the estimated land-use change effect but increases its magnitude.

Trenberth's comment that the reanalyses do not include the effects of the changing atmospheric composition seems to be based on the common misunderstanding that if the model used as a first guess does not have a carbon dioxide trend, for example, then the reanalysis may at best include only a 'watered-down' greenhouse-warming trend.

We showed by using an analytical study that the reanalysis can capture essentially the full strength of climate trends caused by the increase in greenhouse gases, even if this forcing is absent from the model used in the data assimilation (our unpublished data). This is because the reanalysis assimilates atmospheric temperatures and other observations that are affected by greenhouse gases and other changes. We point out that, even though the model has no volcanic aerosols, a reanalysis can capture the atmospheric heating resulting from volcanic eruptions[2].

The fact that both station observations and the NNR exhibits a decrease in DTR reflects the impact of an increase in low-level clouds[3]. However, the surface observations show an even larger decrease in DTR, and we attribute the difference largely to land-use changes. This agrees with previous studies showing that urban effects also have a substantial impact on the decrease of DTR[4].

The non-climatic adjustments can be added *a posteriori* to our estimate, leading to an upper-bound estimate of the impact of land-use changes. According to the calculations made by Vose *et al.*, the non-climatic adjustments to these raw station observations yield an averaged increase of 0.112 °C per decade. In other words, half of the averaged increase between 1960–1979 and 1980–1999 derived from the HCN data set (0.224 °C per decade) is the result of the non-climatic adjustments to the raw station observations.

Adding these non-climatic adjustments to our lower-bound estimate of the impact of land-use changes (0.035 °C per decade) yields 0.147 °C per decade. This upper-bound estimate is comparable to another study that also used the HCN data (0.12 °C per decade[5]). Therefore, the upper-bound estimate is not ten times the size of the largest published urban estimates for the United States.

We found that a decrease in the effect of total land-use change in 1960s–1970s to 1980s–1990s took place, primarily, over the rural stations. Reforestation, saturation of urban heat-island effects, and more regulated land-use changes could be leading factors resulting in such a decrease in land-use change. This decrease is independent of, and in no way contradicts, the "dramatic increase in temperature during the past two decades" because the NNR estimate also registers a larger increase in the daily mean surface temperature equal to 0.254 °C per decade over the past two decades, which is comparable with the estimate (0.343 °C per decade) derived from the HCN data set.

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