Tropopause Height

Becomes Another Climate-Change "Fingerprint"

Computer models and observations show that emissions from human activities are raising the layer between the troposphere and stratosphere.

THE scientific puzzle of the nature and causes of climate change is highly complex. Now, an international team of scientists, led by researchers from Lawrence Livermore, has added another piece to this puzzle. The research team has discovered that emissions from human activities are largely responsible for a significant increase in the height of the tropopause—the boundary between the turbulent troposphere, which is the atmosphere's lowest layer, and the more stable stratosphere that lies above it.

The team's results show that human-induced (anthropogenic) changes in well-mixed greenhouse gases, which are fairly evenly distributed in the atmosphere, and ozone, a greenhouse gas that is found in higher concentrations in the stratosphere, are the primary causes of the approximately 200-meter rise in the tropopause that has occurred since 1979. In their research, team members used advanced computer models of the climate system to estimate changes in the tropopause height that likely result from anthropogenic effects. They then searched for, and positively identified, the model-predicted "fingerprints" in observations of tropopause height change.

The research team reported these findings in the July 25, 2003, issue of *Science*. The team included Livermore scientists Benjamin Santer, Karl Taylor, and James Boyle as well as researchers from Lawrence Berkeley National Laboratory, the National Center for Atmospheric Research (NCAR), the Institut für Physik der Atmosphäre in Germany, and the University of Birmingham in the United Kingdom. The Department of Energy's (DOE's)

Environmental Sciences Division funded the U.S. participation in the two-year study.

The tropopause height research is part of Livermore's long-standing effort to study and model global climate change. (See *S&TR* July/August 2002, pp. 4–12.) Santer, who leads the research team, is a member of Livermore's Program for Climate Model Diagnosis and Intercomparison (PCMDI). PCMDI develops methods and tools for diagnosing, validating, and comparing the global climate models used for predicting climate change. Such predictions are computationally demanding calculations that could not have been performed without the recent advances in supercomputing technology.

"Years ago, we were fortunate to get one calculation of a climate-change prediction," says Michael Wehner, an atmospheric scientist at Lawrence Berkeley National Laboratory and a member of the research team. "Today, we are able to perform these ensemble calculations because of the progress coming from DOE's Climate Change Prediction Program. DOE made a substantial investment in this program, both in model development at NCAR and in unclassified computer centers such as the National Energy Research Scientific Computing Center at Berkeley. That investment has paid off."

Sensitive to Temperature

The tropopause lies about 18 kilometers above the Earth's surface at the equator in the summer and 8 kilometers above the poles in winter. Tropopause height is sensitive to temperature changes in the troposphere and stratosphere. Warming the troposphere or cooling the stratosphere tends to increase tropopause height. Conversely, cooling the troposphere or warming the stratosphere lowers tropopause height. (See the box below.)

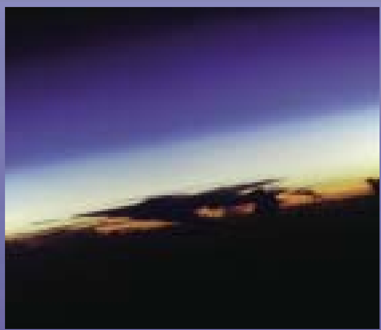
Climate is influenced by many natural and anthropogenic factors. These "forcings" of the climate system can have different effects on tropospheric and stratospheric temperatures and hence on tropopause height. For example, well-mixed greenhouse gases, such as the

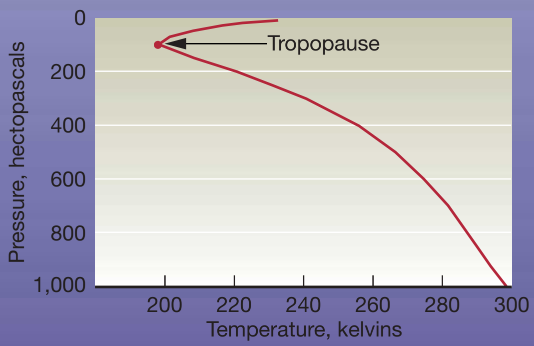
Earth's Atmosphere: A Short Primer

The Earth's atmosphere can be divided into several distinct layers. The lowest layer of the atmosphere is called the troposphere, which begins at ground level and extends to 8 kilometers at the poles and to 18 kilometers near the equator. The troposphere contains up to 75 percent of the mass of the atmosphere and almost all the atmospheric water vapor. Often turbulent, it is the home to such weather systems as hurricanes, tornadoes, and thunderstorms. The troposphere is characterized by temperatures that generally decrease with increasing height.

Above the troposphere lies the stratosphere, a relatively stable layer of the atmosphere. The stratosphere extends to about 50 kilometers in altitude. An important feature of the stratosphere is the ozone layer, which protects the Earth by absorbing much of the ultraviolet radiation from the Sun. There is considerable evidence that industrial chlorofluorocarbon compounds are depleting the ozone layer, so these chemicals are being phased out under the terms of an international treaty. The stratosphere is characterized by an overall increase of temperature with increasing height.

The tropopause, which is situated at the upper boundary of the troposphere and the lower boundary of the stratosphere, marks the limit of most weather systems. Its height is sensitive to the changes in atmospheric temperature caused by both natural and human factors. Previous studies of weather balloon data have shown that the tropopause has risen about 200 meters since 1979. The Livermore-led research is a first attempt to understand the possible causes of this height increase.





The troposphere is characterized by temperatures that generally decrease as altitude increases and atmospheric pressure decreases. Situated at the upper boundary of the troposphere and the lower boundary of the stratosphere, the tropopause marks the limit of most weather systems. Anvil-shaped thunderstorm clouds (left) are pushed up against the tropopause. (Photograph courtesy of the National Aeronautics and Space Administration.)

Climate is changed by both natural and human mechanisms. Natural mechanisms include (a, b) changes in solar irradiance and (c) the amount of volcanic dust in the atmosphere. Human mechanisms include changes in (d) aerosol particles from burning fossil fuels and biomass. (Photographs courtesy of the [a–c] National Aeronautics and Space Administration and [d] National Oceanic and Atmospheric Administration.)

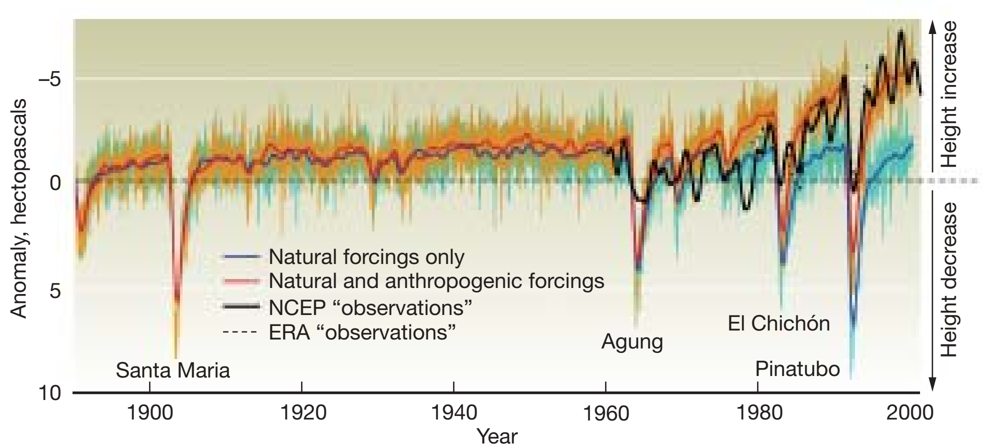
carbon dioxide produced from burning fossil fuels, simultaneously warm the troposphere and cool the stratosphere. Both effects increase tropopause height. The depletion of stratospheric ozone by chlorofluorocarbons cools the stratosphere, which tends to raise the tropopause. The sulfate aerosols produced by burning fossil fuels lower the tropopause by cooling the troposphere. Volcanic aerosols injected into the stratosphere during massive eruptions also lower the tropopause because they absorb incoming solar radiation, thus warming the stratosphere and cooling the troposphere.

According to Santer, direct observations from weather balloons and reanalyses—optimal combinations of weather observations and numerical weather forecasts—show that the tropopause has risen about 200 meters since 1979. "Previous work had documented an overall increase in tropopause height," he says, "but ours is the first detailed study of the possible causes for this increase." The innovative aspect of the Livermore-led research was its use of climate models to estimate the individual contributions of different forcing mechanisms to overall tropopause height changes.

The tropopause can be defined in different ways based on changes in the thermal, chemical, or dynamic properties of the atmosphere with increasing altitude. The team used a standard thermal definition of the tropopause to track changes in its height. In practical terms, this standard defines the tropopause to be close to the level where atmospheric temperature stops decreasing with altitude, a characteristic of the troposphere, and starts increasing with altitude, a characteristic of the stratosphere.

Parallel Supercomputers Required

The team used the DOE Parallel Climate Model (PCM), a three-dimensional (3D) global climate model designed for parallel supercomputers (machines using many processors in tandem). PCM was developed jointly by NCAR and Los Alamos National Laboratory, and it incorporates the latest



Simulations with the Parallel Climate Model show that human-caused changes in tropopause height are greater than those from natural effects alone. Major volcanic eruptions tend to decrease tropopause height while human activity tends to increase it. The modeling results are consistent with observational data from the National Center for Atmospheric Research and the National Center for Environmental Prediction (NCEP) and from the European Centre for Medium-Range Weather Forecasts (ERA). Maximum and minimum values for (light orange) natural and anthropogenic forcings from four realizations and (light blue) natural forcings only, also from four realizations.

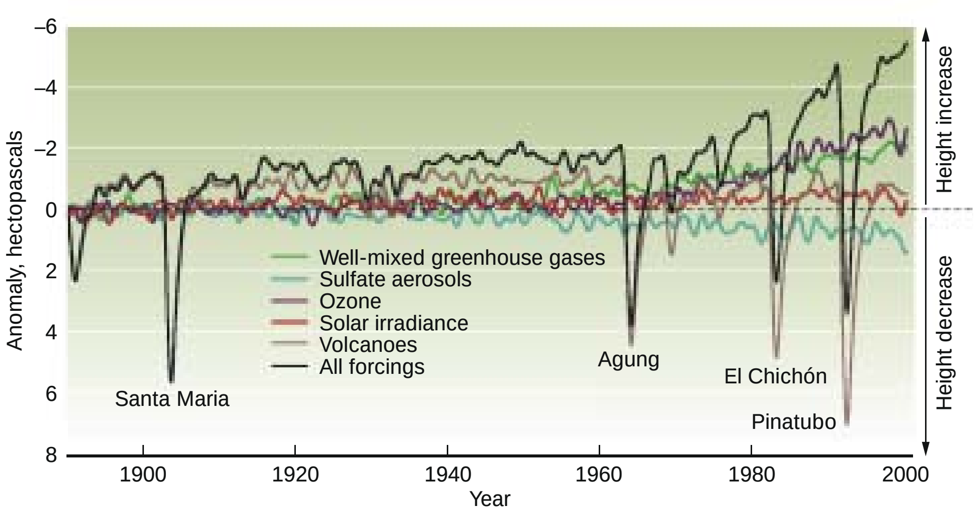
scientific understanding of the physical process at work in the Earth's atmosphere, oceans, and surface. The PCM calculations were performed at NCAR, Lawrence Berkeley's National Energy Research Scientific Computing Center (NERSC), and Oak Ridge National Laboratory.

The researchers looked at five different forcings—two natural and three human-related—that influence tropopause height. The anthropogenic forcings were changes in well-mixed greenhouse gases, the direct scattering effects of sulfate aerosols (see *S&TR*, September 2002, pp. 4–12), and ozone. The two natural forcings were changes in solar radiation and volcanic aerosols.

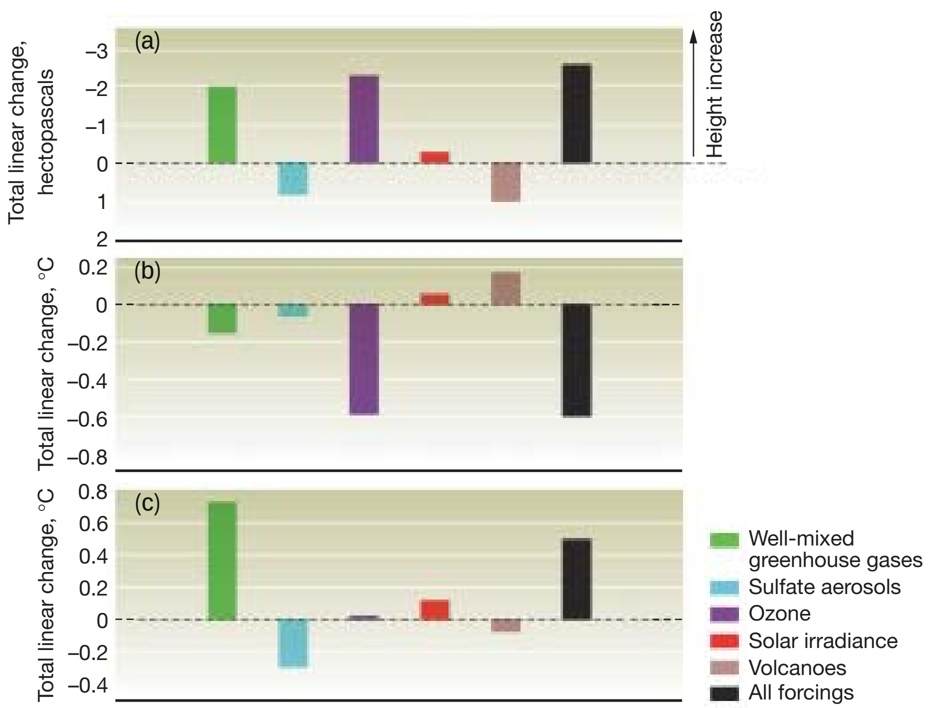
To isolate the key factors causing the height increase, the researchers analyzed the individual effects of these five factors. For each set of PCM calculations, they changed the levels of one forcing and held the others constant. For example, in one set, concentrations of well-mixed greenhouse gases were varied according to best estimates of their historical changes, while the other four forcings were held at preindustrial levels. In addition to these individual forcing experiments, various combinations were run, such as simultaneous variation of all five factors and variation of only the natural factors. All of the simulations covered the period 1890 to 1999.

"Because the PCM group performed such a comprehensive, structured array of experiments," says Santer, "we can isolate and quantify the effects of different forcings, and ask whether the climate response to these forcings is linear." He points out that it's rare for researchers to be able to study how individual factors affect global climate change—such a large array of simulations requires thousands of hours of supercomputer time.

To improve estimates of the true climate response to each forcing, the team performed four realizations of each climate-change experiment and started



Simulations reveal the relative contributions of different forcings to changes in tropopause height. Well-mixed greenhouse gases and ozone are the most important factors in raising the height of the tropopause.



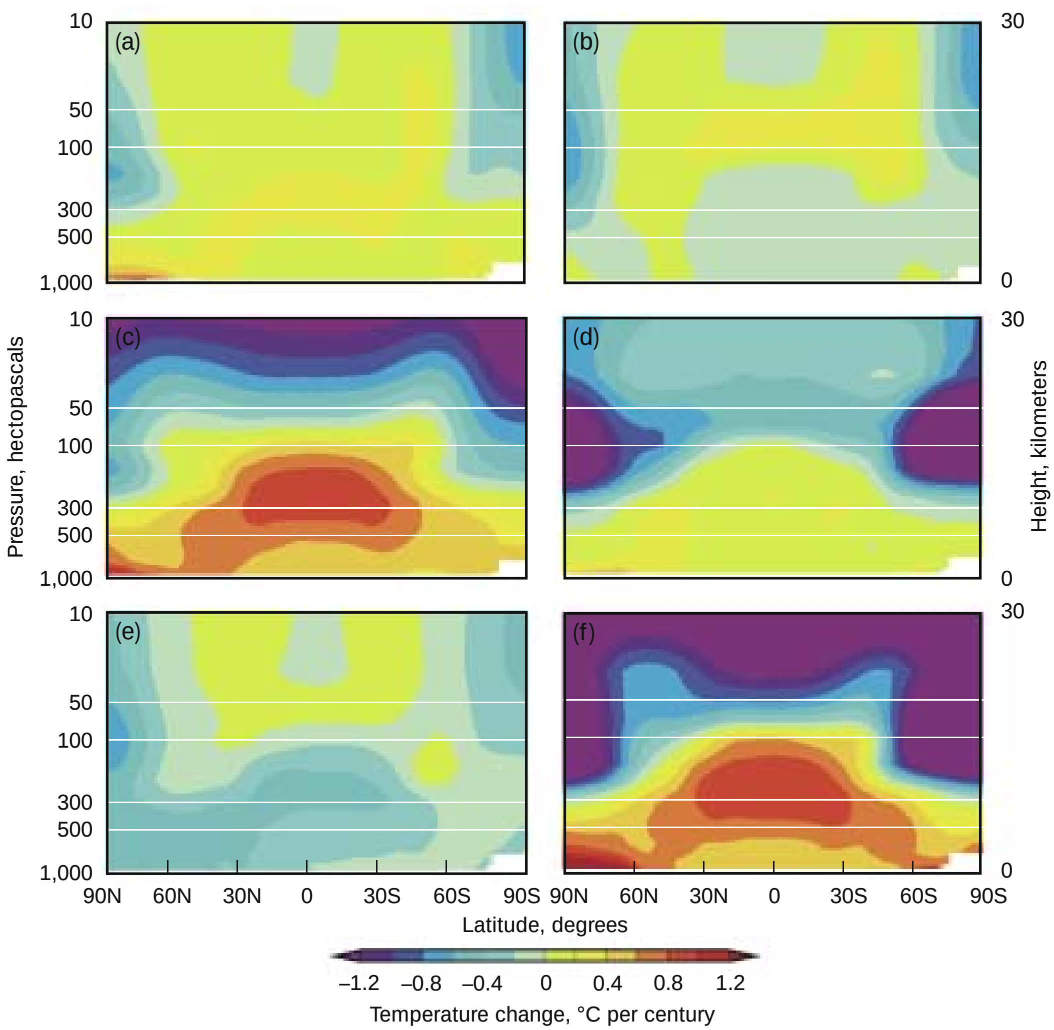
Relative contributions of different forcings to changes in (a) tropopause height and the temperature of (b) the stratosphere and (c) the troposphere. Human-induced changes in well-mixed greenhouse gases and ozone account for most of the height increase. Ozone acts by decreasing the stratospheric temperature, while well-mixed greenhouse gases influence tropopause height by raising tropospheric temperature. Both cooling the stratosphere and warming the troposphere tend to push up the tropopause.

each realization with slightly different initial conditions of the atmosphere and oceans. In addition, a 300-year control run was performed, in which all five forcings were fixed at preindustrial values. This control run provided information about the internal variability that naturally occurs in the climate system—that is, the fluctuations displayed by the system when all of the forcing changes are absent.

Nature Not a Major Culprit

Two of the simulations—the one incorporating all natural and anthropogenic forcings and the other involving only the two natural forcings—show only a small overall increase in tropopause height from 1890 to about 1965. However, from 1965 to 1999, the tropopause height increases markedly when all five factors are varied in the simulation, but not when only natural factors are varied. (See the bottom right figure on p. 14.) "These simulations clearly showed that in the 'PCM world,' the increase in tropopause height over the last two decades of the 20th century could not be caused by the Sun and volcanoes alone," says Santer.

Instead, the simulations with individual forcings indicate that human-induced changes in ozone and well-mixed greenhouse gases are responsible for about 80 percent of the tropopause height changes over the 20th century. (See the figures on p. 15.) Says Santer, "Our best understanding is that the recent tropopause height increase is due to two factors: warming of the troposphere, which is primarily caused by increasing concentrations of well-mixed greenhouse gases, and cooling of the stratosphere, which is caused mainly by depletion of stratospheric ozone."



Results from the Parallel Climate Model show fingerprints of the estimated temperature change from 1890 to 1999 for five natural and anthropogenic forcings, given as a function of latitude and altitude: (a) solar irradiance, (b) volcanoes, (c) well-mixed greenhouse gases, (d) ozone depletion, (e) sulfate aerosols, and (f) all five individual forcings varied in concert. The fingerprints are distinctly different. For example, the fingerprint for ozone depletion shows maximum cooling of the stratosphere in the Southern Hemisphere, where most ozone depletion has occurred. The sulfate aerosol fingerprint indicates that tropospheric cooling is greater in the Northern Hemisphere, where industrial production of sulfate aerosols is greater, than in the Southern Hemisphere.

Comparing Models to Observations

The concept of fingerprinting is a key aspect of studies seeking to unravel the multiple causes of climate change. Fingerprinting is an effective tool because each climate forcing mechanism has its own distinctive signature in climate records. Just as no two individuals have thumbprints with identical patterns of whorls and ridges, so no two climate forcings have identical 3D patterns of temperature change, as shown in the figure on p. 16.

Climate models such as PCM estimate the full geographic and altitudinal structure of the fingerprints that arise from different forcings. For example, when all five forcings are varied, the PCM simulation produces a fingerprint of tropopause height change with pronounced geographic structure. In this simulation, the largest height increases occur at high latitudes in the Southern Hemisphere, where ozone depletion is most pronounced.

To validate the simulation, the team then searched for this fingerprint in reanalysis data. Reanalyses are useful because they combine data from numerical weather forecasts with direct weather observations from balloons, ships, satellites, aircraft, and ground stations. "We don't have enough tropopause height data from direct observations to piece together a globally complete picture of tropopause height change," explains Santer. "We use weather forecast models to fill in the gaps." The reanalyses, the product of considerable scientific effort, give a spatially complete picture of the changes in global climate over the past two decades.

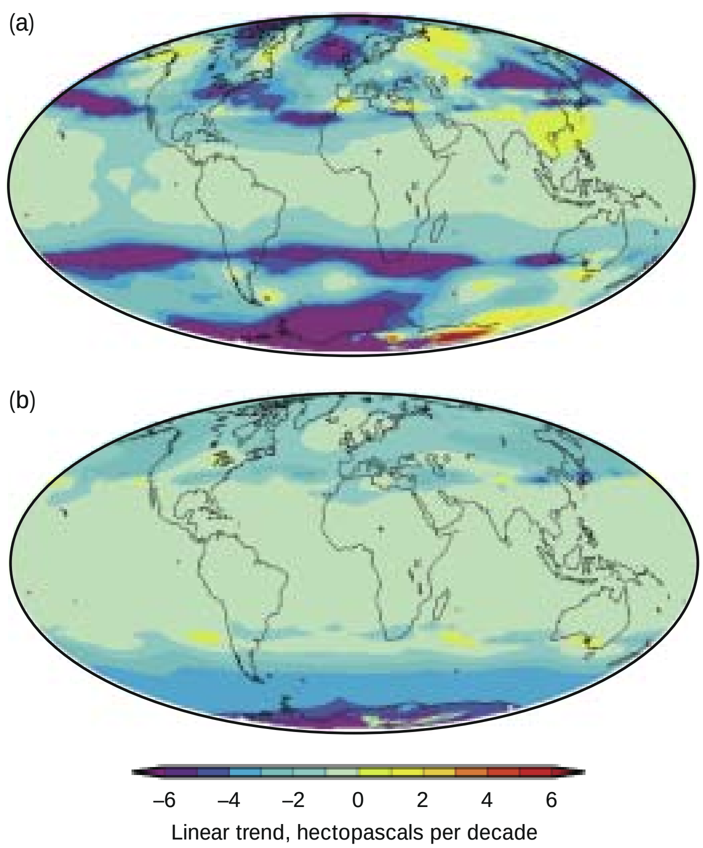
The team used two sets of reanalysis data to determine whether choosing a particular set of observations would affect the results. The first reanalysis was produced jointly by NCAR and the U.S. National Center for Environmental Prediction (NCEP). The second was from the European Centre for Medium-Range Weather Forecasts (ERA). The atmospheric temperature profiles in these data sets were used to calculate tropopause height. The start date chosen for monitoring height changes was 1979, the beginning of the ERA data and what the team considered the more reliable portion of the NCEP reanalysis.

Using a standard signal-detection method, the team was able to identify the PCM tropopause height fingerprint in both the NCEP and ERA reanalyses. Tropopause height increased markedly in both reanalyses, as it had in the PCM calculations that varied all five forcings. In the reanalyses, the smallest changes occurred in the tropics, and the largest increases were near the poles, particularly in the Southern Hemisphere.

This fingerprint is first apparent in the reanalysis data in 1988, just 10 years after the assumed start of monitoring, and becomes more apparent over time. Its early detection reflects the large atmospheric changes that have occurred over the past two decades. "By detecting this fingerprint in the reanalyses," says Santer, "we have considerable confidence in our ability to attribute tropopause height changes to the combined effects of anthropogenic and natural forcings."

Another Fingerprint

The height of the tropopause provides another fingerprint of human effects on climate, and Santer says it deserves further scientific attention. Previous fingerprints of Earth's changing climate have been evident in surface temperatures, ocean heat



(a) Patterns of tropopause height change (from 1979 to 1999) found in the reanalysis data from the National Center for Atmospheric Research and the National Center for Environmental Prediction resemble (b) those for the same period in the Parallel Climate Model simulation in which five climate forcings were varied simultaneously. Both the simulation and the reanalysis data showed increases in tropopause height, with the smallest changes occurring in the tropics and the largest increases toward the poles, particularly in the Southern Hemisphere.

content, polar ice cover, and atmospheric pressure patterns. "What we're now seeing with the rising tropopause and warming troposphere is that many different aspects of the climate system are telling us a consistent story—human activities are altering the Earth's climate. All of these changes are consistent with our scientific understanding of how the climate system *should* be responding to anthropogenic forcings. They are not consistent with the changes we would expect to occur from natural forcings alone."

Santer acknowledges that both reanalyses and computer climate models will always have deficiencies, so there will always be uncertainties in model-predicted tropopause height fingerprints, in observed estimates of tropopause height changes, and in scientists' understanding of the relative contributions of natural and anthropogenic factors to such changes. To lessen these uncertainties, the Livermore researchers are repeating their study—this time using data from more recent second-generation reanalyses, combined with improved weather forecast models and more sophisticated data assimilation systems. Climate scientists are also excited about the high-quality data on atmospheric temperature profiles that can now be obtained with Global Positioning System (GPS) technology. GPS data can provide an independent source of information on observed tropopause height changes.

The Livermore researchers now want to test the robustness of their findings, and they have several research options. One is to examine whether their results are sensitive to the number of atmospheric levels used in the calculations of tropopause height changes. The climate models and reanalyses the team originally used archived temperatures from 17 to 19 atmospheric levels, and the resolution of the temperature data near the tropopause was fairly coarse. "One concern we have," says Santer, "is that the calculations might produce different estimates of tropopause height changes if the vertical temperature gradients used in our models and reanalysis data were more detailed." Preliminary results indicate that the sensitivity to vertical resolution is relatively small, but this result must be verified with extended high-resolution climate model simulations. The computational resources available at Livermore and at NERSC provide excellent resources for performing such calculations.

Clearly, the change in the tropopause is another piece to help solve the complex climate-change puzzle.

—Arnie Heller

Key Words: Department of Energy's Parallel Climate Model (PCM), global warming, National Center for Atmospheric Research (NCAR), Program for Climate Model Diagnosis and Intercomparison (PCMDI), stratosphere, tropopause, troposphere.

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The article in* Science *can be found at: www.sciencemag.org/cgi/content/full/301/5632/479.

Output from these and other related climate models is available at: www.nersc.gov/projects/gcm_data.