GEOPHYSICAL RESEARCH LETTERS, VOL. 27, NO. 14, PAGES 2137-2140, JULY 15, 2000

# Causes of global temperature changes during the 19th and 20th centuries

Natalia G. Andronova and Michael E. Schlesinger

Climate Research Group, Department of Atmospheric Sciences, University of Illinois at Urbana-Champaign

**Abstract.** During the past two decades there has been considerable discussion about the relative contribution of different factors to the temperature changes observed now over the past 142 years. Among these factors are the "external" factors of human (anthropogenic) activity, volcanoes and putative variations in the irradiance of the sun, and the "internal" factor of natural variability. Here, by using a simple climate/ocean model to simulate the observed temperature changes for different state-of-the-art radiative-forcing models, we present strong evidence that while the anthropogenic effect has steadily increased in size during the entire 20th century such that it presently is the dominant external forcing of the climate system, there is a residual factor at work within the climate system, whether a natural oscillation or something else as yet unknown. This has an important implication for our expectation of future temperature changes.

## Introduction

Recently *Tett et al.* [1999] found the increase in global-mean near-surface temperature during the first half of the twentieth century may be due to variations in the sun's irradiance. This supports the earlier findings of *Kelly and Wigley* [1992] and *Schlesinger and Ramankutty* [1992]; further support is provided by *Marcus et al.* [1999], *Drijfhout et al.* [1999] and *Beer et al.* [2000]. However, previously an oscillation in the near-surface temperature over the North Atlantic Ocean and its surrounding continental margins with a period of about 65-70 years was found in the instrumental temperature record by *Schlesinger and Ramankutty* [1994] that appears to explain the observed global warming during the first half of the twentieth century and its subsequent reversal until the mid-1970s. This finding has been given support by analyses of paleoclimate data (tree rings, ice cores, ice melt, lake varves, coral, historical data) [*Mahasenan et al.*, 1997; *Mann et al.*, 1995, 1999] and by simulation studies with coupled atmosphere-ocean models [*Delworth et al.*, 1993, 1997; *Delworth and Knutson,* 2000].

The influence of the external factors on the global near-surface temperature can be analyzed by expressing them in the form of radiative forcing. Comparison of the observed geographical temperature distribution with the geographical temperature distributions simulated by a general-circulation-climate model for different radiative-forcing factors can be used to estimate which of these factors have influenced the temperature, as done in the fingerprint detection studies of *Barnett and Schlesinger* [1987], *Santer et al.* [ 1995], *North* [1995a,b] and *Tett et al.* [1999]. As such studies are not yet conclusive, we examine six state-of-the-art radiative-forcing models described below – anthropogenic alone (anthro), anthropogenic plus *Hoyt and Schatten* [1993] solar forcing (anthro+HS), anthropogenic plus *Lean et al.* [1995] solar forcing (anthro+LN), anthropogenic plus volcanic forcing (anthro+volc), anthro+volc+HS and anthro+volc+LN.



Paper number 2000GL006109.
0094-8276/00/2000GL006109$05.00

## Radiative forcing models

The anthropogenic radiative forcing consists of greenhouse-gas (GHG) forcing beginning in 1765 [*Harvey et al.,* 1997] due to the increasing concentrations of $CO_2$, methane, $N_2O$, chlorofluorocarbons and tropospheric ozone [*Stevenson et al.,* 1998], and the direct (clear air) plus indirect (cloudy air) radiative forcing by tropospheric sulfate aerosols beginning in 1857 [*Harvey et al.,* 1997] (Fig. 1A). Stratospheric-ozone forcing due to ozone depletion is ignored here as it is small [*Forster,* 1999].

Volcanic radiative forcing estimated by *Andronova et al.* [1999] (Fig. 1B) is predominantly due to the scattering of incident solar radiation back to space by stratospheric sulfate aerosols created from $SO_2$ gas injected into the stratosphere by major volcanic eruptions, for which we have optical-depth data beginning in 1850 [*Sato et al.,* 1993].

Solar radiative forcing larger than the 0.1% variation of the solar irradiance observed by satellites since 1978 over two 11-year sunspot cycles is hypothesized to have occurred before 1978 based on the observed variations of other characteristics of the sun and sun-like stars. Two models of solar forcing are examined here. One was constructed by *Lean et al.* [1995] for the period 1610-1994 based on sunspot areas and locations, He 1083 nm emission, group sunspot numbers, and Ca emissions from the sun and sunlike stars. This model was updated through 1998 by *Fröhlich and Lean* [1998]. The other model was constructed by *Hoyt and Schatten* [1993] for 1700-1992 based on the fraction of sunspot area occupied by the penumbra, solar-cycle length, equatorial rotation rate, decay rate of the solar cycle, and the mean level of solar activity. We shifted the irradiances of the HS solar model by 4 $W/m^2$ such that they matched the 1978 solar irradiance observed by satellite [*Fröhlich and Lean,* 1998], and we extended the irradiances of the HS solar model from 1992 through 1998 using the data from *Fröhlich and Lean* [1998] (Fig. 1C).

## Method

As in the studies by *Schlesinger and Ramankutty* [1992, 1994], we simulate the near-surface (and ocean) temperature change from 1765 to 1997 using our simple climate/ocean model [*Schlesinger et al.,* 1997] with prescribed climate

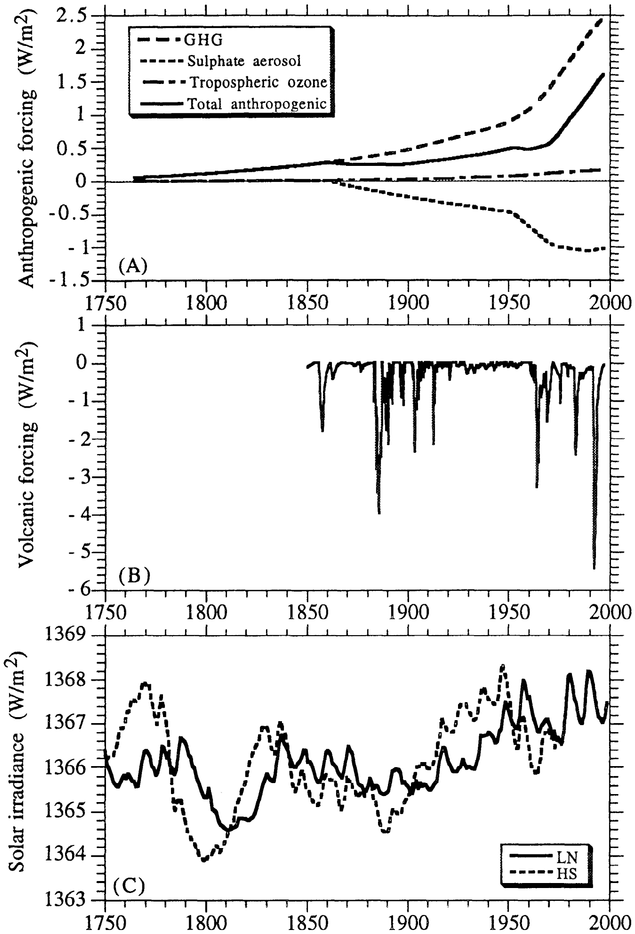


**Figure 1.** Radiative-forcing factors as a function of time. (A) anthropogenic forcing, (B) volcanic forcing, and (C) solar irradiance forcing for the models by *Lean and colleagues* [*Lean et al.,* 1995; *Fröhlich and Lean,* 1998] (LN) and by *Hoyt and Schatten* [1993] (HS).

sensitivity, $\Delta T_{2x}$ – the change in global-mean near-surface temperature for the radiative forcing equivalent to a doubling of the pre-industrial $CO_2$ concentration – and prescribed direct radiative forcing by anthropogenic sulfate aerosols ($SO_4$) in 1990, $\Delta F^{D}_{SO4}(1990)$. The ratio of the indirect and direct $SO_4$ radiative forcings was set equal to 2.7 [*Harvey et al.,* 1997] after tests showed that the total $SO_4$ radiative forcing in 1990, $\Delta F_{SO4}(1990)$, was insensitive within 2% percent to values of this ratio from 0 to 10. An optimum pair of $\Delta T_{2x}$ and $\Delta F_{SO4}(1990)$ was obtained for each radiative-forcing model by minimizing over the period of temperature observations [*Jones et al.,* 1999], 1856-1997, the root-mean-square-differences respectively between the simulated and observed global-mean temperature (rmsc), and between the simulated and observed interhemispheric temperature difference (rmsd).

## Results

Figure 2 presents the optimum simulated global-mean near-surface temperature changes for the six radiative-forcing models in comparison with the observed global-mean near-surface temperature changes, together with the corresponding values of $\Delta T_{2x}$, $\Delta F_{SO4}(1990)$, rmsc and rmsd. The estimated optimum value of $\Delta F_{SO4}(1990)$ is $-1.08\pm0.01$ $Wm^{-2}$ (mean ± standard error), indicating its virtual independence of radiative-forcing model. The estimated optimum value of $\Delta T_{2x}$ ranges from 2.0°C to 5.0°C and depends strongly upon whether solar forcing is included, and weakly upon whether volcano forcing is included. The $\Delta T_{2x}$ estimates of 5.0°C and 4.5°C for the radiative-forcing models without solar-irradiance variations (Figs. 2A, B) are respectively above and at the maximum of the IPCC range, 1.5°C-4.5°C [*Kattenberg et al.,* 1996]. The inclusion of solar forcing reduces $\Delta T_{2x}$ by about 53% for HS (Figs. 2C, D) and 44% for LN (Figs. 2E, F), both to within the IPCC range. Clearly it is important in terms of climate impacts and policy to determine whether or not the sun's irradiance varied as constructed by HS and LN. The inclusion of volcanic forcing also reduces $\Delta T_{2x}$, but only by 6-18% (Figs. 2B, D and F). Better agreement between the simulated and observed temperatures (smaller rmsc and rmsd) is obtained with the volcanic forcing excluded. However, unlike solar-irradiance variations that may or may not have occurred, volcanic eruptions did occur during the time period studied. The large differences between the simulated and observed temperature changes following the Krakatoa (1883) and Pinatubo (1991) eruptions indicate that either their estimated radiative forcings are too large or factors other than volcanos, such as El Niño, contributed warming to the observed temperatures near the times of these volcanic eruptions.

We now determine the individual contributions by the anthropogenic, volcanic and solar radiative forcings to the simulated temperature changes for four time periods: (1) 1856-1990, from the year of the first minimum of the observed temperature to the year of its last maximum before the Pinatubo eruption; (2) 1904-1944, the first period of observed global warming; (3) 1944-1976, a period of observed global cooling; and (4) 1976-1990, the most recent period of observed global warming. The contribution by each radiative-forcing factor is taken as the difference across the time period of its contribution to the simulated temperature change. The difference between the observed temperature change across the time period and the total temperature change simulated across the time period by all the forcing factors in a radiative-forcing model is identified as the residual or unexplained observed temperature change.

Figure 3 shows the individual contributions due to the anthropogenic, solar and volcanic radiative forcing for each radiative-forcing model, together with the corresponding residual contribution. For the longest time period, 1856-1990 (Fig. 3A), the temperature change simulated for the anthropogenic forcing is 54-84% of the observed temperature change, with the minimum contribution being for the anthro+volc+HS radiative-forcing model and the maximum contribution for the anthro+volc radiative-forcing model. The contribution by the volcanic radiative forcing, for the radiative-forcing models that include it, is negative and thus is of opposite sign to the observed temperature change. The contribution by the solar radiative forcing, for the radiative-forcing models that include it, is positive and 22-27% of the observed temperature change. The contribution by the residual, that is the part of the observed temperature change different from the total simulated temperature change, is positive and ranges from 16% for the anthro forcing model to 37% for the anthro+volc model. According to these results

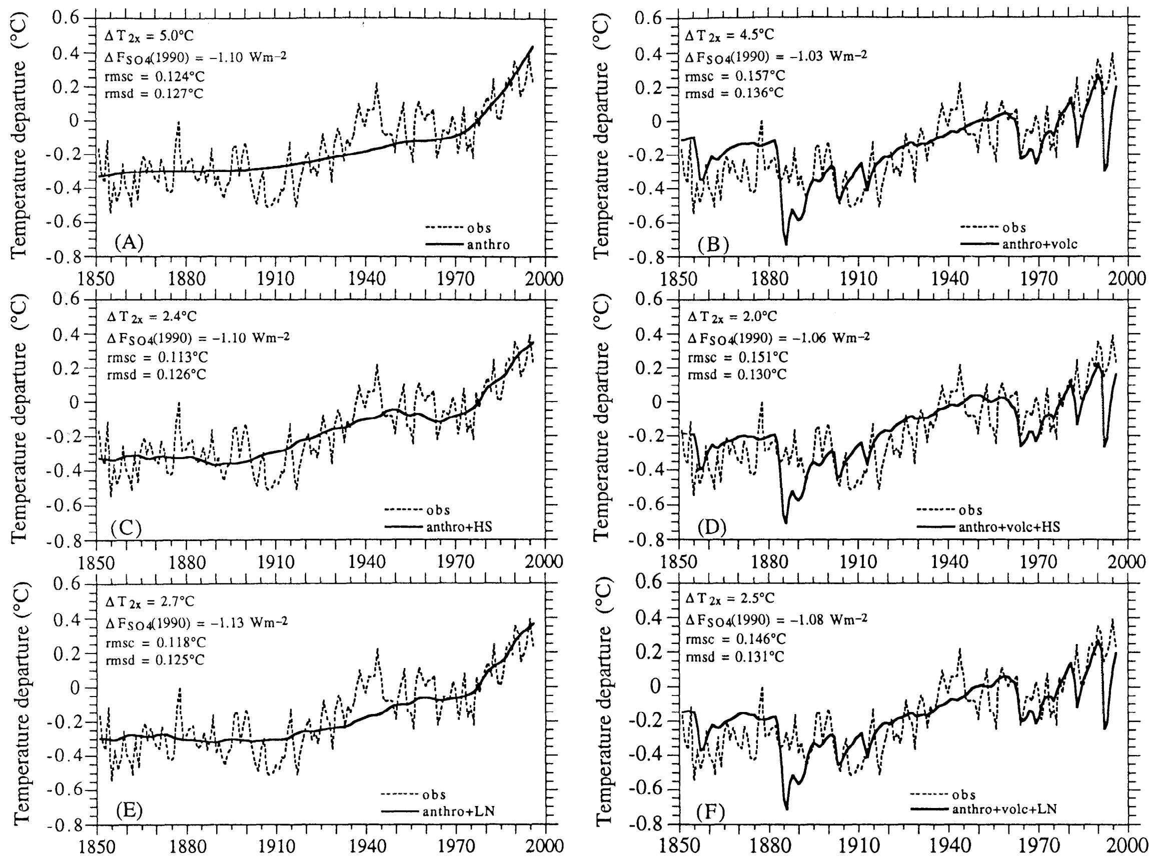


**Figure 2.** Optimum global-mean near-surface temperature simulated by the simple climate/ocean model for each of six radiative-forcing models (solid line) in comparison with the observed global-mean near-surface temperatures [*Jones et al.,* 1999] (dashed line). For each radiative-forcing model are shown the climate sensitivity, $\Delta T_{2x}$, the total $SO_4$ radiative forcing in 1990, $\Delta F_{SO4}(1990)$, and the root-mean-square-differences between the simulated and observed global-mean temperatures, rmsc, and between the simulated and observed interhemispheric temperature difference, rmsd.

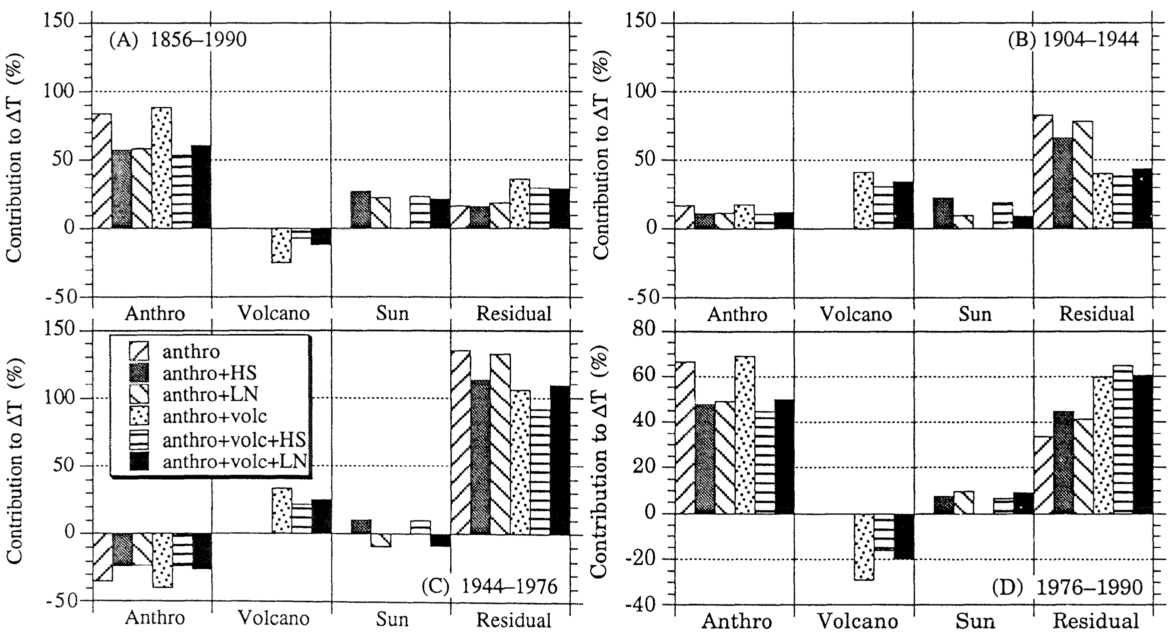


**Figure 3.** Percentage contribution to the observed temperature change over 1856-1990 (A), 1904-1940 (B), 1944-1976 (C) and 1976-1990 (D), for each radiative-forcing model, by the temperature change simulated individually for the anthropogenic (Anthro), volcanic (Volcano), and solar (Sun) radiative-forcing factors, together with the percentage contribution not explained by the simulated total temperature change (Residual).

the observed warming over 1856-1990 was predominantly due to anthropogenic radiative forcing plus an unexplained residual warming, with the sun contributing a warming less than half that contributed by the anthropogenic factor – if indeed the solar irradiance varied as constructed, and with volcanoes contributing a small cooling.

In the light of this finding it is of interest to determine whether the warmings observed during 1904-1944 and 1976-1990 were similarly predominantly due to anthropogenic radiative forcing. Figure 3B indicates that this is not the case, with the 1904-1944 warming being predominantly due to the residual factor and volcanic forcing, the latter as a result of the decrease in volcanic eruptions during 1904-1944 relative to the late 19th century (Fig. 1B). The role of the residual factor is even more dominant during 1944-1976 (Fig. 3C) when the anthropogenically induced warming was in opposition to the observed cooling (Fig. 2). During both 1904-1944 and 1944-1976, the sun, if it varied as constructed, played only a minor role in the observed temperature change. The warming observed during 1976-1990 (Fig. 3D) is about equally due to anthropogenic radiative forcing and the residual factor, with volcanoes contributing a cooling, and the sun at most a small warming.

## Conclusions

According to our results, the anthropogenic effect, while present during the entire 20th century, has steadily increased in size (Fig. 2A) such that it presently is the dominant external forcing of the climate system. Nonetheless, the residual factor is at work within the climate system. What is the residual factor responsible for the observed 1904-1944 warming and subsequent 1944-1976 cooling? A possible explanation for this was given by *Schlesinger and Ramankutty* [1994] as being the result of a temperature oscillation over the North Atlantic Ocean and its adjacent land areas with a period of 65-70 years. Another possible explanation is a missing climate forcing [*Hansen et al.*, 1997]. Accordingly, it is prudent not to expect continued year-after-year warming in the near future and, in so doing, diminish concern about global warming should global cooling instead manifest itself again.

**Acknowledgments:** We thank David Parker and Briony Horton of the United Kingdom Meteorological Office for providing us the near-surface temperature data. This study was supported by the National Science Foundation under grant ATM-9522681.

## References

Andronova, N. G., *et al.*, Radiative forcing by volcanic aerosols from 1850 through 1994, *J. Geophys. Res.*, *104* (D14), 16,807-16,826, 1999.

Barnett, T. P., and M. E. Schlesinger, Detecting changes in global climate induced by greenhouse gases, *J. Geophys. Res.*, *92*, 14,772-14,780, 1987.

Beer, J., *et al.*, The role of the sun in climate forcing, *Quaternary Science Reviews*, *19* (1-5), 403-415, 2000.

Delworth, T. L., and T. R. Knutson, Simulation of early 20th century global warming, *Science*, *287* (5461), 2246-2250, 2000.

Delworth, T., *et al.*, Interdecadal variations of the thermohaline circulation in a coupled ocean-atmosphere model, *J. Climate*, *6* (11), 1993-2011, 1993.

Delworth, T. L., *et al.*, Multidecadal climate variability in the Greenland Sea and surrounding regions: a coupled model simulation, *Geophys. Res. Lettr.*, *24* (3), 257-260, 1997.

Drijfhout, S. S., *et al.*, Solar-induced versus internal variability in a coupled climate model, *Geophys. Res. Lettr.*, *26* (2), 205-208, 1999.

Forster, P. T. D., Radiative forcing due to stratospheric ozone changes 1979-1997, using updated trend estimates, *J. Geophys. Res.*, *104* (D20), 24,395-24,399, 1999.

Fröhlich, C., and J. Lean, The Sun's total irradiance: Cycles, trends and related climate change uncertainties since 1976, *Geophys. Res. Lettr.*, *25* (23), 4377-4380, 1998.

Hansen, J., *et al.*, The missing climate forcing, *Phil. Trans. Roy. Soc. London B*, *352*, 231-240, 1997.

Harvey, L. D. D., *et al.*, An introduction to simple climate models used in the IPCC Second Assessment Report, pp. 50, Intergovernmental Panel on Climate Change, Bracknell, U.K., 1997.

Hoyt, D. V., and K. H. Schatten, A discussion of plausible solar irradiance variations, 1700-1992, *J. Geophys. Res.*, *98*, 18,895-18,906, 1993.

Jones, P., *et al.*, Surface air temperature and its changes over the past 150 years, *Rev. Geophys.*, *37* (2), 173-199, 1999.

Kattenberg, *et al.*, Climate models – Projections of future climate, in *Climate Change 1995: The Science of Climate Change*, edited by J.T. Houghton, L.G. Meira Filho, B.A. Callander, N. Harris, A. Kattenberg, and K. Maskell, pp. 285-358, Cambridge University Press, Cambridge, U.K., 1996.

Kelly, P. M., and T. M. L. Wigley, Solar cycle length, greenhouse forcing and global climate, *Nature*, *360*, 328-330, 1992.

Lean, J., *et al.*, Reconstruction of solar irradiance since 1610: Implications for climate change, *Geophys. Res. Lettr.*, *22* (23), 3195-3198, 1995.

Mahasenan, N., *et al.*, Low-frequency oscillations in temperature-proxy records and implications for recent climate change, *Geophys. Res. Lettr.*, *24*, 563-566, 1997.

Mann, M. E., *et al.*, Global interdecadal and century-scale climate oscillations during the past five centuries, *Nature*, *378*, 266-270, 1995.

Mann, M. E., *et al.*, Northern hemisphere temperatures during the past millennium: Inferences, uncertainties, and limitations, *Geophys. Res. Lettr.*, *26* (6), 759-762, 1999.

Marcus, S. L., *et al.*, Models of solar irradiance variability and the instrumental temperature record, *Geophys. Res. Lettr.*, *26* (10), 1449-1452, 1999.

North, G. R., Detection of forced climate signals. Part I: Filter theory, *J. Climate*, *8*, 401-408, 1995a.

North, G. R., Detection of forced climate signals. Part II: Simulation results, *J. Climate*, *8*, 409-416, 1995b.

Santer, B. D., *et al.*, Towards the detection and attribution of an anthropogenic effect on climate, *Climate Dynamics*, *12*, 77-100, 1995.

Sato, M., *et al.*, Stratospheric aerosol optical depths, 1850-1990, *J. Geophys. Res.*, *98* (D12), 22,987-22,994, 1993.

Schlesinger, M. E., and N. Ramankutty, Implications for global warming of intercycle solar-irradiance variations, *Nature*, *360*, 330-333, 1992.

Schlesinger, M. E., and N. Ramankutty, An oscillation in the global climate system of period 65-70 years, *Nature*, *367*, 723-726, 1994.

Schlesinger, M. E., *et al.*, Modeling and simulation of climate and climate change, in *Past and Present Variability of the Solar-Terrestrial System: Measurement, Data Analysis and Theoretical Models. Proceedings of the International School of Physics "Enrico Fermi" CXXXIII*, edited by G. Cini Castagnoli, and A. Provenzale, pp. 389-429, IOS Press, Amsterdam, 1997.

Stevenson, D. S., *et al.*, Evolution of tropospheric ozone radiative forcing, *Geophys. Res. Lettr.*, *25* (20), 3819-3822, 1998.

Tett, S. F. B., *et al.*, Causes of Earth's near-surface temperature change in the twentieth century, *Nature*, *399*, 569-572, 1999.

N. G. Andronova and M. E. Schlesinger, Climate Research Group, Department of Atmospheric Sciences, University of Illinois at Urbana-Champaign (e-mail: natasha or schlesin@atmos.uiuc.edu)

(Received 1/14/00;
accepted 5/19/00)