Cooling Following Large Volcanic Eruptions Corrected for the Effect of Diffuse Radiation on Tree Rings

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Abstract

The lack of a larger cooling in proxy records of climate change following large volcanic eruptions such as those of Tambora in 1815 and Krakatau in 1883 has long been a puzzle for climatologists. These records, however, may have been biased by enhanced tree growth for several years following each eruption induced by additional diffuse radiation caused by the stratospheric volcanic aerosol clouds from the eruptions. By comparing proxy reconstructions of climate with and without tree ring data, this effect is demonstrated for the five largest eruptions for the period 1750-1980. When proxy records of Northern Hemisphere climate change are corrected for this proposed diffuse effect, there is no impact on climate change for time scales longer than 20 years. However, it now appears that there was a hemispheric cooling of about 0.6°C for a decade following the unknown volcanic eruption of 1809 and Tambora in 1815, and a cooling of 0.3°C for several years following the Krakatau eruption of 1883.

It is well known that volcanic eruptions produce stratospheric aerosol clouds that reflect a portion of the incoming sunlight, thus cooling the Earth's surface [*Robock*, 2000]. However, after some of the largest eruptions of the past several centuries, proxy records of surface air temperature did not indicate as much cooling would be expected. Now it seems that because of a new understanding of the effects of volcanic stratospheric aerosols on radiation and its effect on trees, enhanced tree growth following large eruptions may have masked some of the climate signal.

At the Mauna Loa observatory on the island of Hawaii (19°N), measurements of downward direct and diffuse radiation [*Dutton and Christy*, 1992; *Robock*, 2000; *Dutton and Bodhaine*, 2001] show that following the 1982 El Chichón and 1991 Pinatubo eruptions, the reduction in direct downward shortwave radiation was almost matched by an enhancement of downward diffuse flux, caused by enhanced forward scattering of incoming solar radiation caused by the volcanic aerosols (Fig. 1). The Mauna Loa observatory has also measured the CO_2 concentration since 1958 [Fig. 2, *Keeling and Whorf*, 2002], and this is a good representation of globally averaged surface CO_2 concentration since CO_2 has a sufficiently long atmospheric lifetime (~100 years), as shown by recent global observations [*Hofmann*, 2004]. However, since the Mauna Loa CO_2 record began the large upward trend (Fig. 2) has not been uniform (Fig. 3). Changes in emissions, land use changes, unusual atmospheric temperatures or precipitation (e.g., drought), and El Niño and La Niña episodes, through their effects on the land biosphere and oceans, explain part, but not all, of these interannual variations [*Jones et al.*, 2001; *Robock*, 2003; *Hofmann*, 2004].

The causes of interannual variations in CO_2 concentration are not completely understood, but the volcanic effect on diffuse and direct radiation, through its impact on plant growth, cannot

be ruled out as an important contribution. *Gu et al.* [1999, 2002, 2003], *Roderick et al.* [2001], and *Farquhar and Roderick* [2003] suggest that increased diffuse radiation allows plant canopies to photosynthesize more efficiently, increasing the CO_2 sink. In fact, *Gu et al.* [2003] actually measured this effect in trees following the 1991 Pinatubo eruption. On the other hand, *Cohan et al.* [2002] using a numerical model of plant growth showed that while adding aerosols to the atmosphere in a clear sky, producing an enhanced ratio of diffuse to direct radiation, increased the net primary productivity (NPP) and hence produced a positive carbon sink, under cloudy skies, assuming no indirect effects of aerosols on clouds, NPP decreased. Nevertheless, they find that their results support the idea that the 1991 Mt. Pinatubo eruption enhanced the carbon sink through the enhanced diffuse flux. *Jones and Cox* [2001] and *Lucht et al.* [2002], however, modeled the effect of temperature reduction following Pinatubo on tree growth and soils and explained the enhanced carbon sink as a larger reduction in soil and plant respiration than the temperature effect on reduced tree NPP. *Angert et al.* [2004] also modeled the change in carbon flux following Pinatubo and rejected the idea that change in diffuse radiation was responsible. However, they implemented diffuse radiation in their model incorrectly [cf., *Roderick et al.*, 2001] and used poor quality soil moisture simulations as if they were data [*Li et al.*, 2005]. The clear decrease in the rate of increase of CO_2 following each large volcanic eruption (Fig. 3) may be due to a combination of causes, and more work is needed to better understand this process.

Both the width [e.g., *Fritts*, 1976] and latewood density [e.g., *Briffa et al.*, 1998] of tree rings have been used as proxy evidence for the effect of volcanic eruptions on climate. Detailed analysis of all the volcanic effects on tree rings is beyond the scope of this paper, but there are important implications of changes in tree growth for interpretation of tree rings when used for proxy reconstruction of past climate change. While the direct effect of climatic cooling in the

summer reduces tree growth in boreal forests, where most tree rings are obtained [e.g., *Lucht et al.*, 2002] and is responsible for reduced ring width in trees following volcanic eruptions, enhanced growth because of the diffuse radiation effect would counteract some of the temperature effects on tree growth.

Mann et al. [1998] combined a large number of proxy data sets to produce a reconstruction of Northern Hemisphere climate change for the past six centuries. They produced reconstructions using only tree ring data (width and density), using only other data, and using all proxies together (Fig. 4). During the period from 1750 to 1980 (proxy reconstruction is problematic for the past 25 yr due to lack of proxy time series), there were three major volcanic eruptions, Unknown (1809), Tambora (1815), and Krakatau (1883), and two smaller ones, Santa María (1902) and Agung (1963) [*Robock*, 2000].

It can be seen in Fig. 4 that the *Mann et al.* [1998] reconstruction using tree ring data only shows much less cooling after the major eruptions of Tambora and Krakatau than do the ones without tree ring data. Because of the small sample, sophisticated statistical tests of this effect would not be appropriate. The conclusion that tree-ring-based reconstructions produce less cooling should be considered in light of the characteristics of the reconstructed time series. The tree-ring only reconstruction is biased toward the warm season, while that without tree rings tends to reflect the annual signal [*Rutherford et al.*, 2004]. As volcanic eruptions tend to produce strong cooling in the summer, but also winter warming which would cancel some of the cooling in annual reconstructions [*Robock*, 2000], the lack of tree-ring-based cooling is even more striking. The estimate without tree rings is based on a much smaller number of records, so should have a larger potential sampling error. While the climate field reconstruction technique used by *Mann et al.* [1998] may have a bias that limits the response to volcanic eruptions

[*Michael Mann*, pers. comm., 2004], it was applied to both the estimates with and without tree rings, so should not affect their relative response to volcanic eruptions.

Discussion

Climate model simulations of the effects of very large volcanic eruptions on surface temperatures tend to give more cooling than that in proxy reconstructions, when the models are driven by our best estimates of the radiative forcing from the eruptions. For example, *Free and Robock* [1999] find this result even for decadal averaged temperatures using an upwelling diffusion energy balance model, as do energy balance and general circulation model results shown in Fig. 8 of *Jones and Mann* [2004]. At the European Geophysical Union meeting in April, 2004, Phil Jones asked me why the climate response (as seen in proxy reconstructions based on tree rings) was so small after the 1259 volcanic eruption, the largest of the past 2000 years. The answer may be that the climate response was larger than we had previously thought. Detailed reanalyses comparing tree ring and non-tree ring proxy data, as well as biological models of tree growth that explicitly consider the effects of diffuse radiation along with temperature and soil moisture should in the future help to better understand this effect.

References

Angert, A., S. Biraud, C. Bonfils, W. Buermann, and I. Fung (2004), CO_2 seasonality indicates origins of post-Pinatubo sink, *Geophys. Res. Lett.*, *31*, L11103, doi:10.1029/2004GL019760.

Briffa, K. R., P. D. Jones, F. H. Schweingruber, and T. J. Osborn (1998), Influence of volcanic eruptions on Northern Hemisphere summer temperature over the past 600 years, *Nature*, *393*, 450-455.

Cohan, D. S., J. Xu, R. Greenwald, M. H. Bergin, and W. L. Chameides (2002), Impact of atmospheric aerosol light scattering and absorption on terrestrial net primary productivity, *Global Biogeochem. Cycles*, *16(4)*, 1090, doi:10.1029/2001GB001441.

Dutton, E. G., and J. R. Christy (1992), Solar radiative forcing at selected locations and evidence for global lower tropospheric cooling following the eruption of El Chichón and Pinatubo, *Geophys. Res. Lett.*, *19*, 2313-2316.

Dutton, E. G., and B. A. Bodhaine (2001), Solar irradiance anomalies caused by clear-sky transmission variations above Mauna Loa: 1958–99, *J. Climate*, *14*, 3255-3262.

Farquhar, G. D., and M. L. Roderick (2003), Pinatubo, diffuse light, and the carbon cycle, *Science*, *299*, 1997-1998.

Free, M., and A. Robock (1999), Global warming in the context of the Little Ice Age, *J. Geophys. Res.*, *104*, 19,057-19,070.

Fritts, H. C. (1976), *Tree Rings and Climate*, Acad. Press, London, 567 pp.

Gu, L., J. D. Fuentes, H. H. Shugart, R. M. Staebler, and T. A. Black, (1999), Responses of net ecosystem exchanges of carbon dioxide to changes in cloudiness: Results from two North American deciduous forests, *J. Geophys. Res.*, *104*, 31,421-31,434.

Gu, L., D. Baldocchi, S. B. Verma, T. A. Black, T. Vesala, E. M. Falge, and P. R. Dowty (2002), Advantages of diffuse radiation for terrestrial ecosystem productivity, *J. Geophys. Res.*, *107(D6)*, 10.1029/2001JD001242.

Gu, L., D. Baldocchi, S. C. Wofsy, J. W. Munger, J. J. Michalsky, S. P. Urbanski, and T. As. Boden (2003), Response of a deciduous forest to the Mount Pinatubo eruption: Enhanced photosynthesis, *Science*, *299*, 2035-2038.

Hofmann, D. J. (2004), Volcanic eruption influences on the rate of increase in major atmospheric greenhouse gases over the past 25 years, presentation at the IAVCEI General Assembly, Pucón, Chile, November 18, 2004.

Jones, C. D., and P. M. Cox (2001), Modeling the volcanic signal in the atmospheric CO_2 record, *Glob. Biogeochem. Cyc.*, *15*, No. 2, doi:10.1029/2000GB001281.

Jones, C. D., M. Collins, P. M. Cox, and S. A. Spall (2001), The carbon cycle response to ENSO: A coupled climate–carbon cycle model study, *J. Climate*, *14*, 4113-4129.

Jones, P. D., and M. E. Mann (2004), Climate over past millennia, *Rev. Geophys.*, *42*, RG2002, 10.1029/2003RG000143.

Keeling, C. D., and T. P. Whorf (2002), Atmospheric CO_2 records from sites in the SIO air sampling network. In *Trends: A Compendium of Data on Global Change* (Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, U.S. Department of Energy, Oak Ridge, Tenn., U.S.A.).

Li, H., A. Robock, S. Liu, X. Mo, and P. Viterbo (2005), Evaluation of reanalysis soil moisture simulations using updated Chinese soil moisture observations. *J. Hydrometeorol.*, in press.

Lucht, W., et al. (2002), Climatic control of the high-latitude vegetation greening trend and Pinatubo effect, *Science*, *296*, 1687-1689.

Mann, M. E., R. S. Bradley, and M. K. Hughes (1998), Global-scale temperature patterns and climate forcing over the past six centuries, *Nature*, *392*, 779-787.

Robock, A. (2000), Volcanic eruptions and climate, *Rev. Geophys.*, *38*, 191-219.

Robock, A. (2003), Introduction: Mount Pinatubo as a test of climate feedback mechanisms, in *Volcanism and the Earth's Atmosphere*, Alan Robock and Clive Oppenheimer, Eds., Geophysical Monograph 139, (American Geophysical Union, Washington, DC), 1-8.

Roderick, M. L., G. D. Farquhar, S. L. Berry, and I. R. Noble (2001), On the direct effect of clouds and atmospheric particles on the productivity and structure of vegetation, *Oecologia*, *129*, 21-30.

Rutherford, S., M. E. Mann, T. J. Osborn, R. S. Bradley, K. R. Briffa, M. K. Hughes, and P. D. Jones (2004), Proxy-based Northern Hemisphere surface temperature reconstructions: sensitivity to method, predictor network, target season, and target domain, Submitted to *J. Climate*.
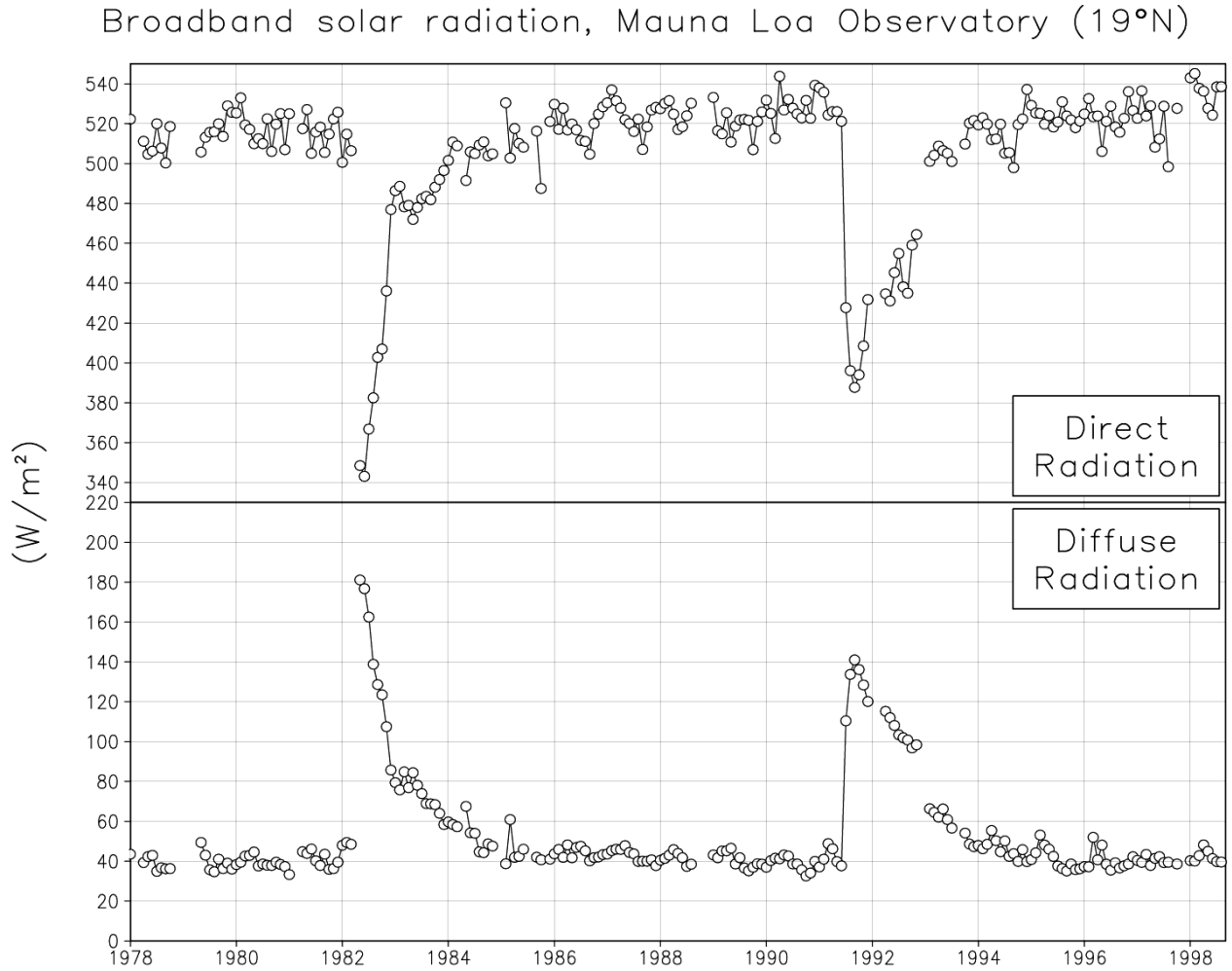
Figure 1. Direct and diffuse broadband radiation measurements from the Mauna Loa observatory, measured with a tracking pyrheliometer and shade disk pyranometer on mornings with clear skies at solar zenith angle of 60°, equivalent to 2 relative airmasses [*Dutton and Christy*, 1992]. The reduction of direct radiation and enhancement of diffuse radiation after the 1982 El Chichón and 1991 Pinatubo eruptions are clearly seen. Years on abscissa indicate January of that year. Data courtesy of E. Dutton. (Figure 4 from *Robock* [2000]. It is similar to Fig. 2 of *Dutton and Bodhaine* [2001].)
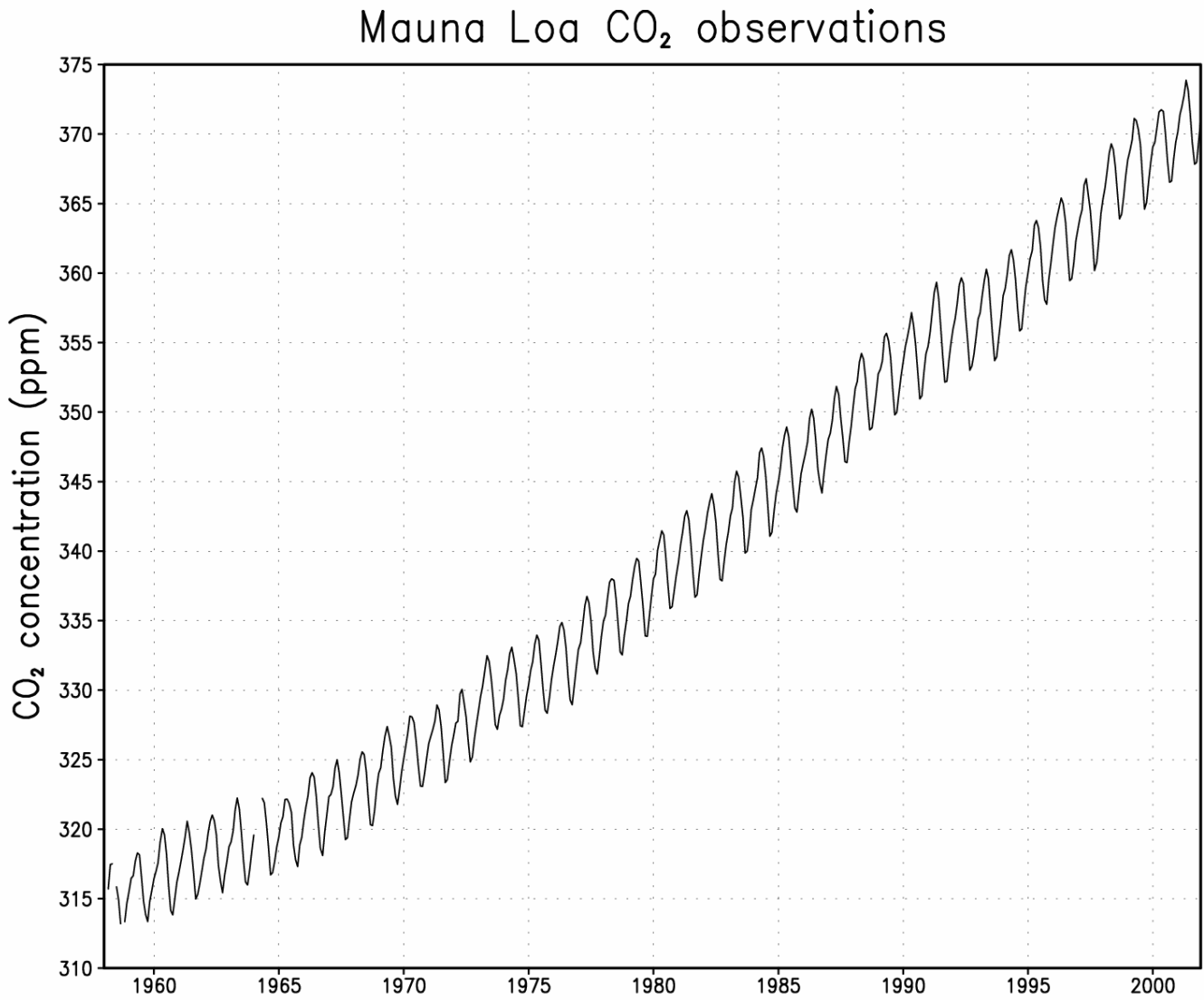
Figure 2. Record of CO_2 concentration at the Mauna Loa Observatory. Data are from *Keeling and Whorf* [2002]. (Figure 6 from *Robock* [2003].)
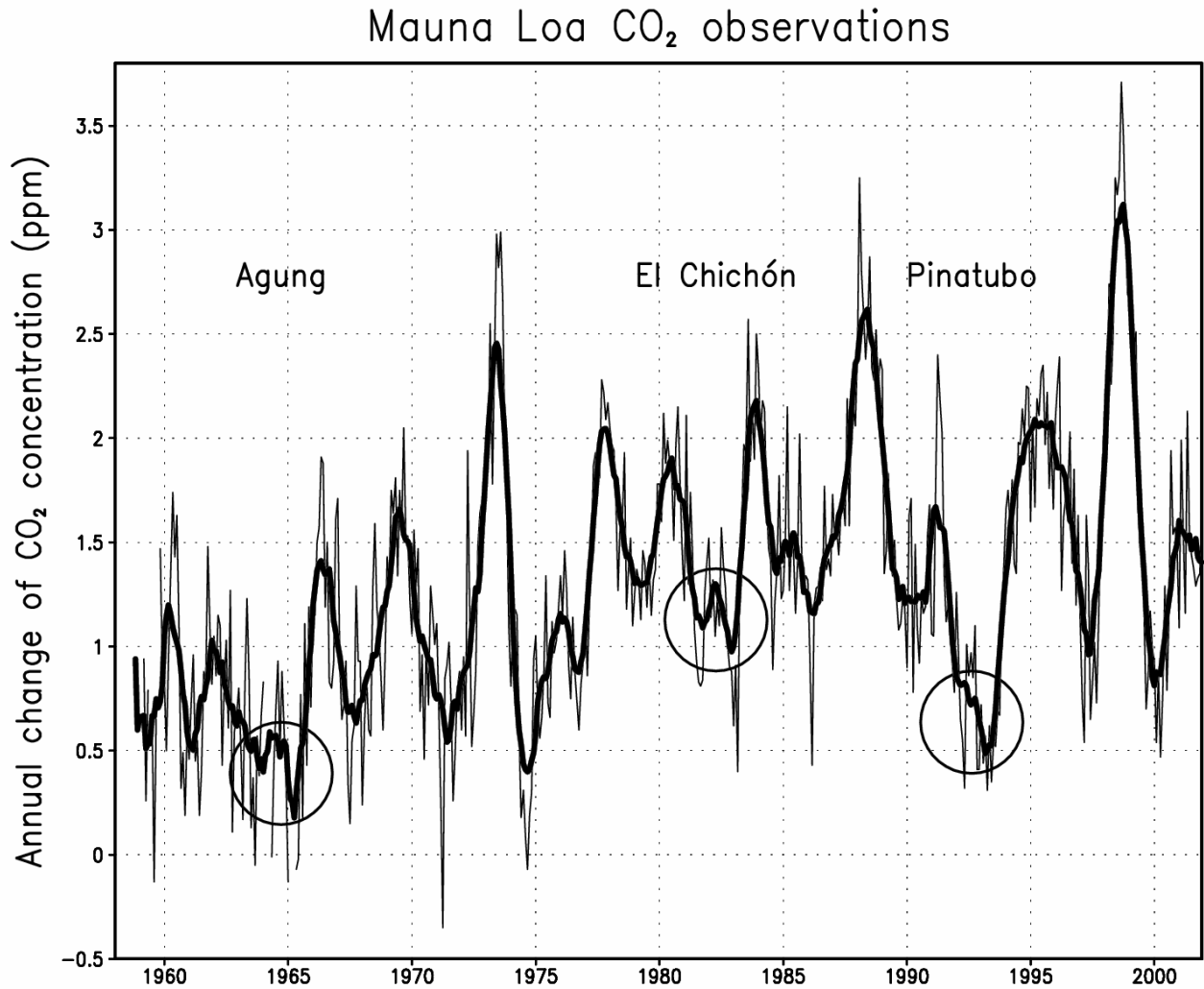
Figure 3. Annual rate of increase of CO_2 in the atmosphere. Data are from *Keeling and Whorf* [2002]. Thin line is monthly values and thick line is 9-month running mean. Minima following the largest volcanic eruptions of the period are indicated. Other interannual variations are partially due to biospheric responses to changing land climate, El Niños, and La Niñas. (Figure 7 from *Robock* [2003].)
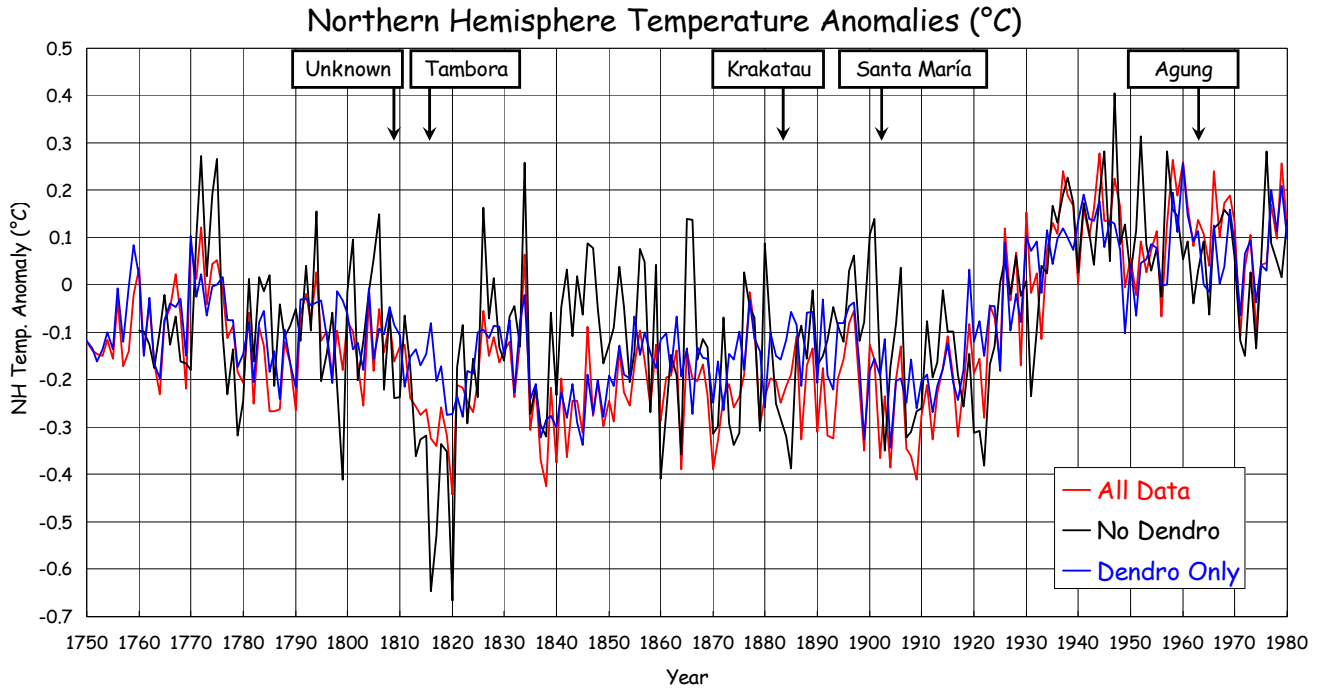
Figure 4. Multi-proxy reconstruction of Northern Hemisphere surface air temperatures from *Mann et al.* [1998] constructed from tree rings only (Dendro only), only non-tree-ring sources (No Dendro), and all sources. Data from http://www.ngdc.noaa.gov/paleo/ei/ei_data/globann-recon.dat . The much larger temperature decline in the No Dendro time series can be clearly seen after the major volcanic eruptions of Unknown (1809), Tambora (1815), and Krakatau (1883), and less clearly after the smaller Santa María (1902) and Agung (1963).