

## Evidence of surface cooling from absorbing aerosols

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[1] Anthropogenic emissions over the Asian region have grown rapidly with increase in population and industrialization. Air-pollutants from this region lead to a brownish haze over most of the North Indian Ocean and South Asia during winter and spring. The haze, with as much as 10–15% of black carbon (by mass), is known to reduce the surface solar insolation by about 10% ( $-15 \text{ W m}^{-2}$ ) and nearly double the lower atmospheric solar heating. Here we present an analysis of observed surface-temperature variations over the Indian subcontinent, which filters out effects of greenhouse gases and natural variability. The analysis reveals that the absorbing aerosols have led to a statistically significant cooling of about  $0.3^\circ\text{C}$  since the 1970s. The seasonally asymmetric cooling, which is consistent with the seasonality of the South Asian aerosol forcing, raises the new possibility that the surface cooling underneath the polluted regions, is balanced by warming elsewhere. **INDEX TERMS:** 0305 Atmospheric Composition and Structure: Aerosols and particles (0345, 4801); 1610 Global Change: Atmosphere (0315, 0325); 0345 Atmospheric Composition and Structure: Pollution—urban and regional (0305); 0368 Atmospheric Composition and Structure: Troposphere—constituent transport and chemistry

### 1. Introduction

[2] Each year, during the winter and spring months, anthropogenic haze spreads over most of North Indian Ocean, South and Southeast Asia [Ramanathan *et al.*, 2001a]. This is a unique region for studying the climate response to radiative forcing by absorbing aerosols. Firstly, the percentage contribution to global anthropogenic emissions from the South and East Asian countries has increased considerably over the last few decades [Smith Steven *et al.*, 2001]. Estimates of anthropogenic sulfur-dioxide ( $\text{SO}_2$ ) emissions from fossil fuels over the South Asian region reveal that emissions have more than doubled during the last twenty years (Figure 1). Aerosol measurements during the Indian Ocean Experiment (INDOEX) documented the presence of several inorganic (including Sulfate) and carbonaceous species (including black carbon) [Lelieveld *et al.*, 2001; Satheesh *et al.*, 1999]. These tropical aerosols were found to be largely of absorbing type (with mid-visible single-scattering albedo at ambient relative humidity in the range of 0.87–0.9) and anthropogenic sources contributed nearly 70% or more of the observed optical depth and the estimated radiative forcing [Ramanathan *et al.*, 2001a].

[3] The second major feature of the South Asian haze phenomenon is its distinct seasonal manifestation that provides a natural setting for testing the tropical aerosol impact on regional climate. The aerosol loading over South Asia builds up in the winter and pre-monsoon dry season in the presence of

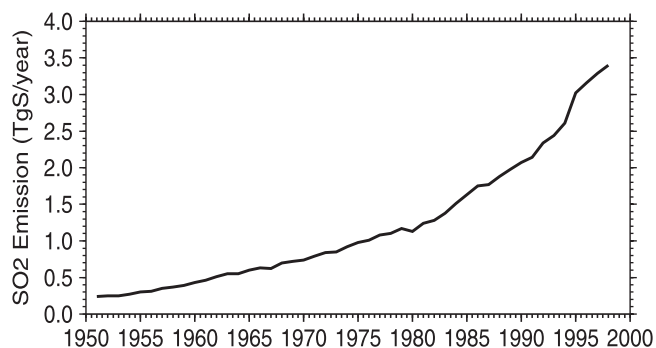
stable boundary layer inversion and the transport of pollutants by low-level northeasterly winds over the region [Ramanathan *et al.*, 2001a; Rajeev and Ramanathan, 2001; Krishnamurti *et al.*, 1998; Rajeev *et al.*, 2000]. The aerosol burden is small during the June–September months under the washout and scavenging influence of the summer monsoon precipitation. Rainfall persists over Southern India in the post-monsoon months of October–December. In association with such a marked seasonal cycle of the meteorological conditions, the aerosol loading over South Asia tends to be nearly two times higher during the winter season than that of the summer months [Smith Steven *et al.*, 2001].

[4] The INDOEX observations showed that the absorption and scattering of solar radiation by the aerosols resulted in a threefold decrease of daily mean clear-sky radiative heating at the surface as compared to the reduction at the top of the atmosphere (TOA) [Satheesh and Ramanathan, 2000]. The large difference between the surface and the TOA forcing is due to solar absorption in the atmosphere by black carbon, fly ash and dust. The seasonally and daily averaged reduction of solar radiation at the surface by the aerosols is in the range of  $-10$  to  $-30 \text{ W m}^{-2}$  between the equator and  $25^\circ\text{N}$  [Ramanathan *et al.*, 2001a] and a heating of the aerosol layer (0 to 3 km) of about 10 to  $30 \text{ W m}^{-2}$ . Given this atmospheric heating and surface-cooling pattern, it is not obvious whether the surface will cool or warm in response to the aerosol forcing. GCM simulations suggest a decrease in land surface temperature by about  $0.5$  to  $1^\circ\text{C}$  over South Asia [Chung *et al.*, 2001]. Such absorbing aerosols are also typical of other regions in the world [Hansen *et al.*, 1997].

### 2. Analysis of Surface Temperature Records

[5] Century-long observations of global surface temperature [Jones, 1994; Parker *et al.*, 1995] provide an excellent opportunity to examine the effect of absorbing aerosols over South Asia. In addition to global surface temperature records, long-period observations of both the maximum and minimum temperatures are available from a dense network of Indian stations [Rupa Kumar *et al.*, 1994]. Figure 2 shows that the annual mean temperatures both for the globe and the Indian subcontinent have similar positive trends during the last century. The overall long-term increase of surface temperatures for the subcontinent is consistent with earlier results [Rupa Kumar *et al.*, 1994]. We now apply two different ways of analyzing the seasonal asymmetries in the warming trend. In the first method (thin green line in Figure 3a), we examine the difference in the temperature variations ( $\langle T^* \rangle$ ) between the dry season (Jan–May) and the rest of the year (Jun–Dec), for the Indian subcontinent. This approach allows us to take advantage of the seasonal behaviour of the South Asian aerosol forcing. The implicit assumption is that the temperature trends due to the greenhouse forcing (and other forcing terms) are not seasonally dependent and as a result, differencing the temperatures for the two seasons factors out the greenhouse forcing. The second method (thick blue line in Figure 3a) extracts a similar signal from the temperature record by utilizing instead, the difference [ $T'$ ] between the temperature variations over the Indian subcontinent and the global mean temperatures for the dry season (Jan–May). By so

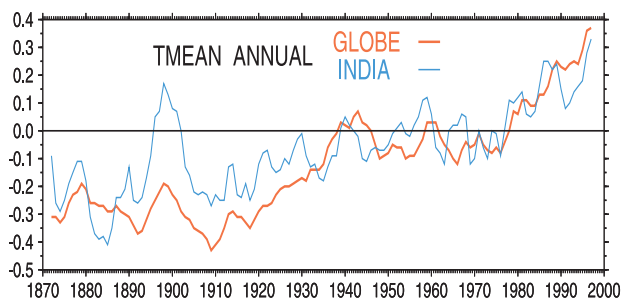
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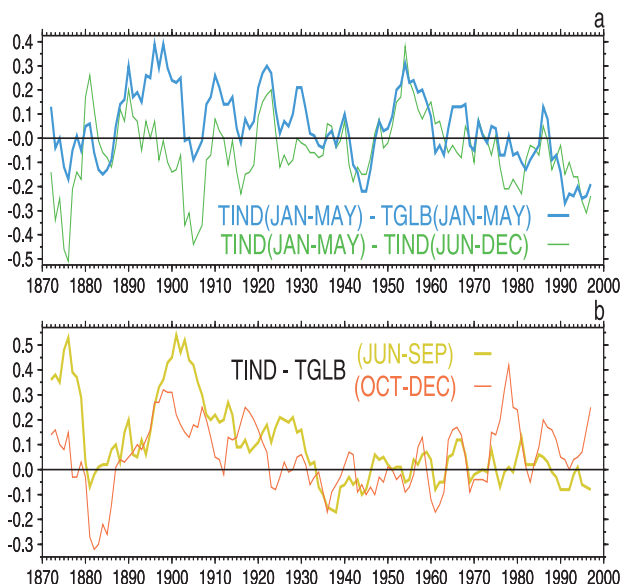
**Figure 1.** SO<sub>2</sub> emissions (TgS/year) over South Asia during (1951–98) [Smith Steven *et al.*, 2001]. The back projection uses emission inventories and information on the regional consumption of fossil fuels to scale the emission components (coal, oil and gas) back in time. Long-period data of black carbon emissions over South Asia is not available and so the fossil SO<sub>2</sub> time-series is a surrogate for anthropogenic emissions. The burning of bio-fuels, such as wood, dung and agricultural waste is a major source of pollutants notably over rural areas of India, whereas in the urban areas the fossil fuel emissions are higher because of the increasing energy demand for industry and transport [Lelieveld *et al.*, 2001].

doing, we are effectively filtering out much of the global-warming trend and large-scale natural variabilities which otherwise tend to mask the regional temperature records.

[6] It can be seen from Figure 3a that both the methods reveal a significant decreasing trend during the post-1950s implying a surface temperature cooling in the dry season over South Asia as compared to other months. Both the  $\langle T^* \rangle$  and  $[T']$  time-series show high inverse correlations of  $-0.71$  and  $-0.80$  with the regional fossil SO<sub>2</sub> emission curve (Figure 1) for the period (1951–97). Much of the emission increase over South Asia occurred after the mid-1960s. This motivated us to evaluate the linear trends during the recent three decades (1968–97). The negative trends for  $\langle T^* \rangle$  and  $[T']$ , estimated from linear least-square fit method [Sachs, 1985], are found to be  $-0.062^\circ\text{C}$  per decade and  $-0.092^\circ\text{C}$  per decade respectively, both of which exceed the 95% level of statistical significance. One also notices in Figure 3a that the  $[T']$  time-series shows a decrease between 1895–1940. However, this decrease of  $[T']$  during the early half of the twentieth century seems to be unrelated to the aerosol effect for the following reasons.

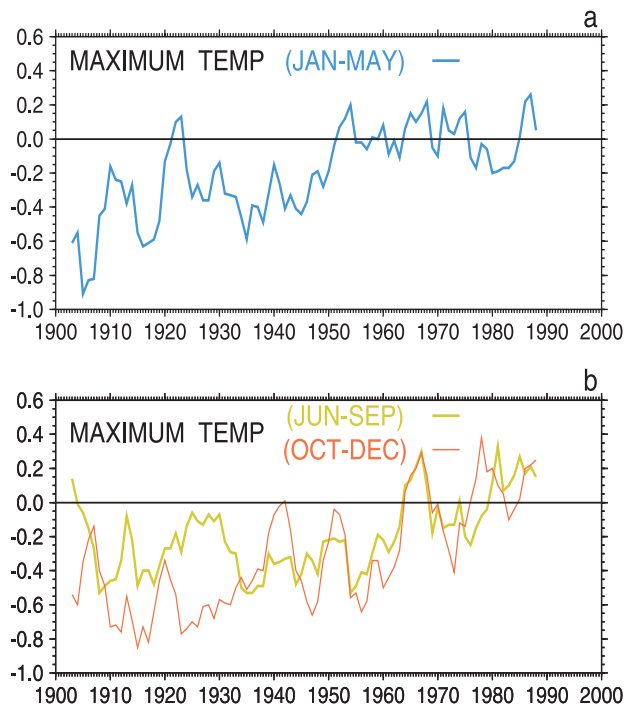


**Figure 2.** Time series of the observed annual mean surface temperature ( $^\circ\text{C}$ ) during (1872–1997) based on dataset of [Jones, 1994; Parker *et al.*, 1995]. The thick red curve is the global mean and the thin blue curve is the temperature averaged over the Indian subcontinent ( $75-95^\circ\text{E}$ ;  $10-30^\circ\text{N}$ ). The anomalies are constructed relative to 30-year (1961–90) climatological normals. A 5-year running mean has been applied to the (1899–1999) time-series; the first two and last two points of the smoothed time-series are ignored.



**Figure 3.** (a) The thin green curve  $\langle T^* \rangle$  is the time-series difference of temperature variations ( $^\circ\text{C}$ ) between the dry season (Jan–May) and the rest of the year (Jun–Dec) over Indian subcontinent. The thick blue curve  $[T']$  is the difference between the variations of temperature ( $^\circ\text{C}$ ) over India and the global mean for the (Jan–May) season. (b) The thick yellow curve is  $[T']$  for the Summer Monsoon (Jun–Sep) season; the thin red curve is  $[T']$  for the Post-Monsoon (Oct–Dec) season.

Firstly, the time-series of  $\langle T^* \rangle$  in Figure 3a, does not show a decrease during the early period 1895–1940. This is in contrast to the post-1950 period for which both  $\langle T^* \rangle$  and  $[T']$  clearly show declining trends. Secondly, the decrease of  $[T']$  during 1895–1940 is apparent in all the seasons, as evident from Figure 3b. However, during the post-1950 period, the  $[T']$  time-series does not reveal any discernible cooling trend for the (Jun–Sep) monsoon and (Oct–Dec) post-monsoon seasons (Figure 3b). This seasonally asymmetric temperature change in the more recent decades explicitly corroborates with the seasonal cycle of anthropogenic aerosol forcing over South Asia. The third supporting evidence for the aerosol effect in recent decades comes from the maximum (day-time) temperature record over India. Signatures of the direct effect of aerosols on the surface solar radiation should manifest in the maximum temperatures ( $T_{max}$ ). Figure 4a reveals that  $T_{max}$  over India for the dry season steadily increased from the 1900s up to the mid-1950s in association with the global warming trend. However the upward trend of  $T_{max}$  curve decelerated following the mid-1950s (Figure 4a) which is consistent with the increasing importance of aerosol forcing after the 1950s. On the other hand, the time-series of  $T_{max}$  for the monsoon and post-monsoon seasons (Figure 4b) considerably differ from that of the dry season and in fact show that the positive trend accelerated beyond the 1950s. Clearly the above seasonal character of the  $T_{max}$  variations over the subcontinent provides additional support for the aerosol cooling effect. It is realized that the dry season trends  $\langle T^* \rangle$  and  $[T']$  noted in Figure 3a are likely to be influenced by natural variability as well. For instance, the high temperature variations during the early decades (around 1875 and 1900) appear to be partly in association with large amplitude interannual fluctuations of the monsoon rainfall. Rainfall records indicate the occurrence of severe monsoon droughts around 1875 and 1900 [Parthasarathy *et al.*, 1995], which can also be confirmed from the large positive peaks of  $[T']$  for the (Jun–Sep) monsoon season (Figure 3b). Similarly, the positive peak seen after 1985 in Figure 3a, coincides with an increase of surface temperature due to precipitation decrease



**Figure 4.** Time-series of  $T_{max}$  ( $^{\circ}\text{C}$ ) over India. (a) Dry season (Jan–May) (b) Thick yellow curve is for (Jun–Sep) season and the thin red curve is for (Oct–Dec). The All-India temperatures based on an average of 121 (fixed) uniformly distributed stations covering the whole of India [Rupa Kumar *et al.*, 1994] is available for the period (1901–90).

associated with three major consecutive droughts (1985–87) over India. Modeling experiments will be needed to evaluate the relative roles of naturally and externally forced variabilities due to anthropogenic effects.

### 3. Discussions

[7] The observed surface cooling (Figures 3 to 4), when juxtaposed with the aerosol radiative forcing (positive in the atmosphere and negative at surface) raises an important and fundamental question (concerning the climate effects of absorbing aerosols), which is taken up next. The radiative forcing of the South Asian haze during the dry season, averaged for the period between 1996 to 1999, is about  $-14 \text{ Wm}^{-2}$  at the surface and  $+14 \text{ Wm}^{-2}$  within the atmosphere (mostly confined to the first 4 kilometres), with a net forcing of  $0 (\pm 2) \text{ Wm}^{-2}$  at the TOA [Ramanathan *et al.*, 2001a, 2001b]. These estimates are derived from INDOEX measurements for 1999, with the assumption that the pre-industrial concentration of anthropogenic aerosols was zero. Roughly 50% of the estimated uncertainty ( $\pm 2 \text{ Wm}^{-2}$ ) in the cloudy sky direct forcing is due to uncertainty in cloud fraction, about 25% is due to the uncertainty in the vertical profile of aerosols and the balance of 25% is due to the uncertainty in clear sky forcing [Ramanathan *et al.*, 2001a]. For comparison, the greenhouse forcing for this region is  $+1 \text{ Wm}^{-2}$  at the surface and  $+1.6 \text{ Wm}^{-2}$  within the atmosphere, and the sum of  $2.6 \text{ Wm}^{-2}$  is the traditionally quoted TOA forcing [Ramanathan *et al.*, 2001b].<sup>1</sup> If the region underneath the haze layer (the Indian subcontinent in the present analysis) cools (as shown by Figures 3 and 4), what happens to the  $+14 \text{ Wm}^{-2}$  heating due to the atmospheric aerosol absorption? The answer to this question is critical for understanding how absorbing aerosols (most anthropogenic aerosols around the globe are absorbing type) influence climate. Before we consider this

question, we should note that aerosols also influence the radiative forcing through their influence on cloud properties. On the one hand, they lead to a cooling effect by increasing the number of cloud drops and their life times which is estimated to be about  $-5 \text{ Wm}^{-2}$  for the South Asian haze [Ramanathan *et al.*, 2001a]. This is the so-called indirect effect. On the other hand, the soot heating of the boundary layer is estimated (by a cloud model) to reduce cloud cover [Ackerman *et al.*, 2000] and lead to a net positive forcing that is of similar magnitude (but opposite in sign) to the indirect effect. A recent study by Norris [2001] indicates an increase in low-level cloudiness over the Indian Ocean during recent decades. However, the 50 year increase in cloud fraction over the Northern Indian Ocean noted by Norris [2001] is about 2%. The decrease in solar radiation from this small increase is about  $-2 \text{ Wm}^{-2}$  which is quite small as compared to  $-14 \text{ Wm}^{-2}$  average decrease due to haze. Further, we understand (through a personal communication from J. Norris) that the change in cloud fraction for the winter season is nearly same as the summer season and therefore should not have impact on the winter minus summer temperature difference. The net cloud effect is still uncertain, but its magnitude should be significantly smaller than the  $+14 \text{ Wm}^{-2}$  atmospheric heating. The climate system could respond by transporting the absorbed solar radiation ( $+14 \text{ Wm}^{-2}$ ) to regions outside the haze layer and thus warming the surface there. In other words, the region that contributes to the haze will be subject to cooling whereas the regions outside could be warming, thus contributing to global warming. In addition, some fraction of the solar absorption will be balanced by a decrease in convective flux of latent and sensible heat from the surface, thus directly perturbing the hydrological cycle [Ramanathan *et al.*, 2001b]. The present findings take on added significance in view of the following.

[8] Nearly half of the world's population is concentrated over South and East Asia, and hence the potential for growing pollutant emissions is large [Lelieveld *et al.*, 2001]. If indeed the anthropogenic solar absorption over the Asian region contributes to warming outside this region and reduces the tropical precipitation, the global role of Asian aerosols warrant careful consideration. While the absorbing haze phenomenon over South Asia is prevalent during the winter and spring seasons, the cooling effect of the mainly reflecting aerosol over Europe, North America and northern mid-latitudes is more apparent during summer [Kiehl and Briegleb, 1993; Schneider and Held, 2001]. Such seasonally asymmetric heating and cooling patterns have implications to the global circulation. Further observational and modeling studies will be necessary in order to unravel the impacts of the degrading air quality on the hydrological cycle and the regional climates of the Northern Hemisphere.

### 4. Summary

[9] The rapid increase of anthropogenic emissions over the Asian region during recent decades is a matter of serious concern to the environment, mankind and the ecosystem at large. The INDOEX observations documented the role of absorbing aerosols like black carbon in increasing the atmospheric solar absorption and leading to a correspondingly large reduction in the solar radiation reaching the surface [Ramanathan *et al.*, 2001a]. This

<sup>1</sup> This includes contributions due to the well-mixed greenhouse gases ( $\text{CO}_2$ ,  $\text{CH}_4$ ,  $\text{N}_2\text{O}$  and halocarbons). According to the recent IPCC report on Climate Change [Ramaswamy *et al.*, 2001], the change in the greenhouse radiative forcing from the pre-industrial (1750) to present time (1998) is estimated to be about  $+2.43 \text{ Wm}^{-2}$  [comprising  $\text{CO}_2$  ( $1.46 \text{ Wm}^{-2}$ ),  $\text{CH}_4$  ( $0.48 \text{ Wm}^{-2}$ ),  $\text{N}_2\text{O}$  ( $0.15 \text{ Wm}^{-2}$ ) and halocarbons ( $0.34 \text{ Wm}^{-2}$ )]. The forcing due to loss of stratospheric ozone ( $\text{O}_3$ ) between 1979 and 1997 is estimated to be  $-0.15 \text{ Wm}^{-2}$ . The global average radiative forcing due to increases in tropospheric  $\text{O}_3$  since pre-industrial times is estimated to be  $+0.35 \pm 0.15 \text{ Wm}^{-2}$ .

paper has presented an analysis of long-period historical surface temperature records over the Indian subcontinent and has for the first time provided observational evidence for surface cooling due to absorbing aerosols, in the dry season, by as much as  $0.3^{\circ}\text{C}$  during the last three decades. The seasonally asymmetric cooling which manifests during the dry months of (Jan–May) is consistent with the seasonal nature of aerosol forcing over South Asia. The findings raise the possibility that while the region underneath the haze layer experiences surface cooling; the unpolluted exterior regions could be subject to warming. Although we are clearly far from unravelling the climate effects of these dark particles, the present observational analysis is nevertheless a significant step in the right direction.

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## References

- Ackerman, A. S., et al., Reduction of tropical cloudiness by soot, *Science*, 288, 1042–1047, 2000.
- Chung, C. E., V. Ramanathan, and J. T. Kiehl, Impact of low-level anthropogenic absorbing aerosol on monsoon precipitation and air-sea heat exchange, *11th Conference on Interaction of the Sea and Atmosphere, San Diego, California*, 2001.
- Hansen, J., M. Sato, and P. Ruedy, Radiative forcing and climate response, *J. Geophys. Res.*, 102, 6831–6864, 1997.
- Jones, P. D., Hemispheric surface-air temperature variations. A reanalysis and an update to 1993, *J. Clim.*, 7, 1794–1802, 1994.
- Kiehl, J. T., and B. P. Briegleb, The relative roles of sulfate aerosols and green house gases in climate forcing, *Science*, 260, 311–314, 1993.
- Krishnamurti, T. N., B. Jha, J. M. Prospero, A. Jayaraman, and V. Ramanathan, Aerosol and pollutant transport and their impact on radiative forcing over the tropical Indian Ocean during the January-February, 1996 pre-INDOEX cruise, *Tellus B*, 50, 521–542, 1998.
- Lelieveld, J., et al., The Indian Ocean Experiment: Widespread air-pollution from South and Southeast Asia, *Science*, 291, 1031–1036, 2001.
- Norris, J. R., Has Northern Indian Ocean cloud cover changed due to increasing anthropogenic aerosol?, *Geophys. Res. Lett.*, 28, 3271–3274, 2001.
- Parker, D. E., C. K. Folland, and M. Jackson, Marine surface temperature: Observed variations and data requirements, *Climatic Change*, 31, 559–600, 1995.
- Parthasarathy, B., A. A. Munot, and D. R. Kothawale, Monthly and seasonal rainfall series for all-India homogeneous regions and meteorological subdivisions: 1871–1994, *Tech. Rep. RR-065, Indian Institute of Tropical Meteorology, Pune, India*, 1995.
- Rajeev, K., and V. Ramanathan, Direct observations of clear-sky aerosol radiative forcing from space during the Indian Ocean Experiment, *J. Geophys. Res.*, 106(D15), 17,221–17,235, 2001.
- Rajeev, K., V. Ramanathan, and M. Meywerk, Regional aerosol distribution and its long range transport over the Indian Ocean, *J. Geophys. Res.*, 105, 2029–2043, 2000.
- Ramanathan, V., et al., The Indian Ocean Experiment: An Integrated Analysis of the Climate Forcing and Effects of the Great Indo-Asian Haze, *J. Geophys. Res.*, 106(D22), 28,371–28,398, 2001a.
- Ramanathan, V., P. J. Crutzen, J. T. Kiehl, and D. Rosenfeld, Aerosols, Climate and the Hydrological Cycle, *Science*, 294, 2119–2124, 2001b.
- Ramaswamy, V., et al., Radiative forcing of climate change, *Climate Change, Third Assessment Report of the IPCC*, 349–416, 2001.
- Rupa Kumar, K., K. Krishna Kumar, and G. B. Pant, Diurnal asymmetry of surface temperature trends over India, *Geophys. Res. Lett.*, 21, 677–680, 1994.
- Sachs, L., Applied Statistics Handbook of Statistics, *Springer Verlag*, pp. 436–439, 1985.
- Satheesh, S. K., et al., A model for the natural and anthropogenic aerosols over the tropical Indian Ocean derived from Indian Ocean Experiment data, *J. Geophys. Res.*, 104, 27,421–27,440, 1999.
- Satheesh, S. K., and V. Ramanathan, Large differences in tropical aerosol forcing at the top of the atmosphere and Earth's surface, *Nature*, 405, 60–63, 2000.
- Schneider, T., and I. M. Held, Discriminants of twentieth-century changes in earth surface temperature, *J. Clim.*, 14, 249–254, 2001.
- Smith Steven, J., H. Pitcher, and T. M. L. Wigley, Global and regional anthropogenic sulfur dioxide emissions, *Global and Planetary Change*, 29, 99–119, 2001.

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