GEOPHYSICAL RESEARCH LETTERS, VOL. 28, NO. 17, PAGES 3271-3274, SEPTEMBER 1, 2001

Has Northern Indian Ocean Cloud Cover Changed due to Increasing Anthropogenic Aerosol?

Joel R. Norris

Scripps Institution of Oceanography, La Jolla, California

Abstract. The recent Indian Ocean Experiment (INDOEX) observed high aerosol concentrations with a sizeable soot fraction over the northern Indian Ocean. This aerosol mix substantially absorbs solar radiation, and recent modeling studies have proposed that the resulting atmospheric heating reduces daytime cloud cover. The present study tests this hypothesis by investigating whether low-level cloud cover has decreased over the northern Indian Ocean between 1952 and 1996, a time period when south Asian anthropogenic emissions have greatly increased. The observed slight increase in cloud cover indicates that other processes must compensate soot solar heating. A similar increase in cloud cover observed over the relatively clean southern Indian Ocean suggests the increase over the northern Indian Ocean does not have a special regional anthropogenic aerosol origin.

Introduction

The recent Indian Ocean Experiment (INDOEX) observed high aerosol concentrations over much of the northern Indian Ocean resulting from transportation of polluted air from south and southeast Asia during the dry monsoon season [*Rajeev et al.*, 2000; *Lelieveld et al.*, 2001]. Soot was a sizeable fraction of the aerosol mix and caused substantial absorption of solar radiation. *Satheesh and Ramanathan* [2000] infer from satellite and surface measurements that aerosol heating in the lower atmosphere over the northern Indian Ocean at local noon is 1-3 K/day, an increase of 50-100% over aerosol-free solar heating. *Ackerman et al.* [2000] use large-eddy simulation of a trade cumulus boundary layer to investigate the impact of soot heating and enhanced droplet concentration on cloud cover and liquid water path. In their model solar absorption by anthropogenic soot aerosol decreases relative humidity in the cloud layer and reduces boundary-layer mixing, causing a 25-40% reduction in daytime cloud cover. Such a large impact suggests that low-level cloud cover over the northern Indian Ocean has significantly decreased over the past several decades as anthropogenic emissions from south Asia have greatly increased. The present study examines changes in observed cloudiness between 1952 and 1996 to determine if this indeed is the case.

Analysis and results

Individual surface synoptic cloud observations over the ocean were obtained from the Extended Edited Cloud Report Archive [*Hahn and Warren*, 1999]. These report total cloud cover (N) and low-level cloud cover (N_h) in oktas and cloud type at low (C_L), middle (C_M), and high (C_H) levels according to WMO code [*WMO*, 1974]. A slight code change concerning the reporting of N_h that occurred in 1982 was avoided using the method described in *Norris* [1999]. Typical observations times over the ocean are 00, 06, 12, and 18 UTC. These correspond to 05, 11, 17, and 23 local time at 75°E. This study classified those few observations made an hour before or after 00, 06, 12, and 18 UTC with those hours. Nighttime cloud identification errors were avoided by only using observations with good illumination according to the criterion of *Hahn et al.* [1995].

Figure 1 displays the diurnally averaged 1952-96 climatology of low-level cloud cover over the Indian Ocean for the months of January-April, the time of year when low-level flow over the northern Indian Ocean is from Asia and large-scale subsidence caps the boundary layer with frequent and strong inversions [*Bony et al.*, 2000]. Cloud changes were investigated in the region 10-20°N, 65-90°E (indicated in Fig. 1). The latitudinal boundaries were chosen to avoid negligible cloudiness north of 20°N and ITCZ-associated convective cloudiness south of 10°N. The longitudinal boundaries were chosen to exclude the relatively unpolluted atmosphere observed west of 65°E [*Rajeev et al.*, 2000] and poor cloud sampling east of 90°E. For comparison, cloud changes were also investigated in the relatively clean Southern Hemisphere region 20-30°S, 65-90°E (indicated in Fig. 1). The SH region is 10° farther poleward than the NH region to account for the SH location of the ITCZ center.

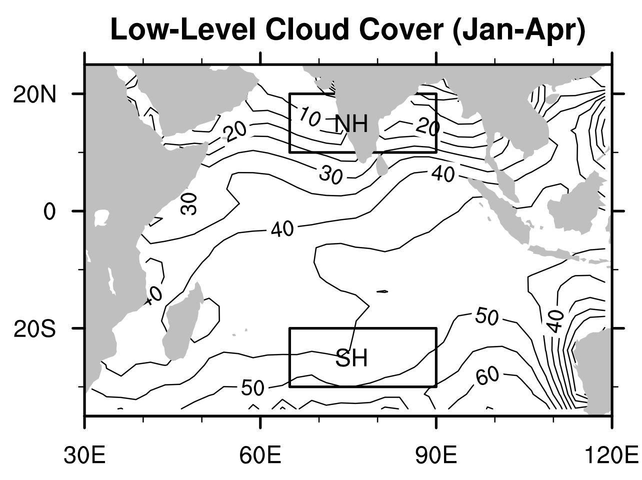

Figure 1. Climatological Jan-Apr low-level cloud cover. Contour interval is 5% sky-cover. Boxes mark NH and SH ocean regions where ocean cloud changes were investigated.

Paper number 2001GL013547.
0094-8276/01/2001GL013547$05.00

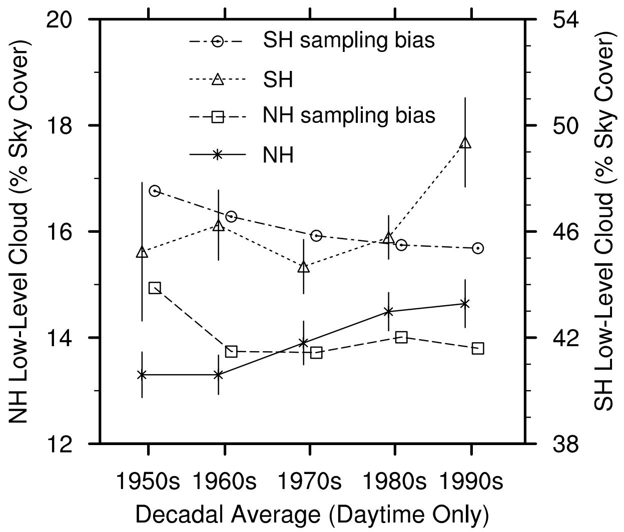

Figure 2. Full and partial decadal averages of low-level cloud cover during 1952-96: NH region (10-20°N, 65-90°E) (solid and ∗), SH region (20-30°S, 65-90°E) (dot and △). Also displayed are estimated biases resulting from sampling variations alone: NH region (dash and □), SH region (dot-dash and ⊙). Only daytime (11 and 17 local time at 75°E) observations were used. Vertical bars indicate 2 × standard errors of means. The points are slightly offset from the decade marks for readability.

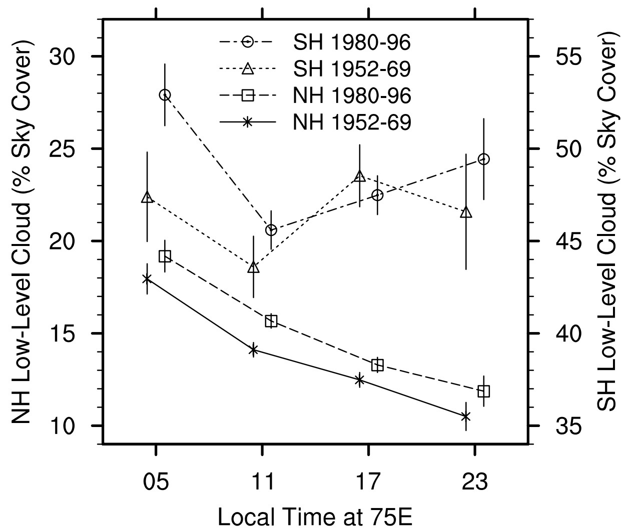

Figure 3. Mean low-level cloud cover for 05, 11, 17, 23 local time at 75°E averaged over: NH region (10-20°N, 65-90°E) during 1952-69 (solid and ∗), NH region during 1980-96 (dash and □), SH region (20-30°S, 65-90°E) during 1952-69 (dot and △), and SH region during 1980-96 (dot-dash and ⊙). Vertical bars indicate 2 × standard errors of means. The points are slightly offset from their hours for readability.

Both regions are dominated by cumulus cloudiness [*Norris*, 1998].

Statistical tests of *Warren et al.* [1986; 1988] indicate that the standard error of a cloud cover mean is well-approximated by the standard deviation divided by the square root of the number contributing. 2 × the standard error of the mean is approximately the 95% confidence interval. This is a lower limit to overall uncertainty since other unknown errors may also contribute. Fewer observations are available for the Indian Ocean than for the North Pacific and North Atlantic, and sampling uncertainties were minimized by averaging over larger geographical regions and multi-year time periods. One disadvantage of averaging over a large region is that non-uniform sampling in the presence of a strong climatological cloud cover gradient can produce biases. These sampling biases were estimated by calculating the spurious variation in cloud cover over time produced by the changing distribution of observations sampling the climatological distribution of cloud cover. Individual cloud cover reports were replaced by the climatological monthly values for the locations, and the time variation of the averages of these new values is the sampling bias.

Information about past change in soot aerosol is not available, but it has likely greatly increased with development and population growth in India. As a proxy, India fossil fuel SO_2 emissions are estimated to have increased from 0.25 to 3.16 TgS/yr between 1952 and 1996 (S. Smith, personal communication, 2001). Figure 2 shows that daytime low-level ocean cloud cover has increased over this time period in both NH and SH regions. The relatively larger increase in the SH region may simply reflect the greater cloud cover there. These observed increases in cloud cover are unlikely to result merely from changes in geographic sampling since estimated spurious variations in cloud cover due to sampling biases are flat or decreasing (Fig. 2).

Changes in low-level cloud cover over the diurnal cycle were explored by comparing averages over the 1952-69 and

Table 1. NH Region (10-20°N, 65-90°E) Information for 1952-69 and 1980-96

		Local Time at 75°E			
	Time Period	05	11	17	23
Number of Low-Type Observations	1952-69	3355	11435	10054	2818
	1980-96	3064	12904	9993	2533
Frequency of Cumulus (C_L 1, 2) (%)	1952-69	36.6	34.1	29.6	23.2
	1980-96	38.5	35.3	31.7	26.4
Frequency of Stratocumulus (C_L 4, 5, 8) (%)	1952-69	7.5	5.3	5.0	3.7
	1980-96	8.1	6.2	5.4	3.8
Frequency of Precipitation[a] when Low Cloud is Present (%)	1952-69		1.8	2.1	
	1980-96		1.5	1.6	

[a]Includes local, distant, and previous hour precipitation reported by present weather code.

Table 2. SH Region (20-30°S, 65-90°E) Information for 1952-69 and 1980-96

		Local Time at 75°E			
	Time Period	05	11	17	23
Number of Low-Type Observations	1952-69	666	1056	1051	327
	1980-96	1242	2806	2606	715
Frequency of Cumulus (C_L 1, 2) (%)	1952-69	41.2	54.4	52.4	53.8
	1980-96	40.6	53.4	52.6	44.1
Frequency of Stratocumulus (C_L 4, 5, 8) (%)	1952-69	29.1	23.9	23.7	20.2
	1980-96	31.4	21.1	24.2	27.6
Frequency of Precipitation[a] when Low Cloud is Present (%)	1952-69		14.9	18.9	
	1980-96		16.2	16.2	

[a]Includes local, distant, and previous hour precipitation reported by present weather code.

1980-96 time periods. Figure 3 displays these averages for 05, 11, 17, and 23 local time at 75°E for both NH and SH regions (numbers of observations contributing are listed in Table 1 and Table 2). Low-level cloud cover is observed to slightly increase from the earlier period to the later period at all hours of the day in the NH region and most hours of the day in the SH region. *Ackerman et al.* [2000] suggest soot solar heating acts to shorten stratocumulus anvil lifetimes, but the observed frequency of cumulus and stratocumulus both slightly increase over the northern Indian Ocean (Table 1).

Discussion

The observed all-hours increase in low-level cloud cover over the time period when soot aerosol has presumably greatly increased argues against a dominant effect of soot solar absorption contributing to cloud "burn-off". Other processes must be compensating. One possibility is greater anthropogenic CCN concentrations leading to more and smaller cloud droplets that inhibit precipitation and thus enhance cloud lifetime [*Albrecht et al.*, 1989]. The modeling study of *Lohmann and Feichter* [2001] finds that on global scales increased cloud lifetime due to greater CCN outweighs decreased cloud lifetime due to soot. INDOEX measurements indicate cloud droplet concentrations are greater over the polluted northern Indian Ocean than the relatively clean southern Indian Ocean [*Heymsfield and McFarquhar*, 2001]. However, there is no evidence for a precipitation decline over time. The very infrequent occurrence of precipitation in the NH region during the early period (Table 1) implies precipitation never was an important loss mechanism for northern Indian Ocean cloudiness and thus provides negligible opportunity for microphysical enhancement of cloud. Furthermore, the fact that increased low-level cloud cover is observed in both NH and SH regions despite dissimilar trends in aerosol conditions suggests a cause besides south Asian anthropogenic aerosol influence.

Several other possible mechanisms for the northern Indian Ocean cloud increase were investigated. Climatological cloud cover over the northern Indian Ocean is small due to strong subsidence and offshore flow of dry air from India. Analysis of NCEP Reanalysis 850 mb winds indicates that the strength of offshore flow has not decreased with time. This suggests that a change in atmospheric circulation is not responsible for the cloud increase. *Bajuk and Leovy* [1998] found that subtropical Indian Ocean cumulus frequency during Jan-May is greater during ENSO warm phases. However, the present study found negligible difference for the NH region between low-level cloud cover averaged over ENSO warm years and cloud cover averaged over ENSO cold years. This suggests that the greater number of ENSO warm events during the later part of the 1952-1996 time period is not responsible for the cloud increase. There is a strong increasing trend in sea surface temperature over the northern Indian Ocean during the 1952-96 time period, and increased surface buoyancy and evaporation generated by the warmer ocean would act to compensate the increased boundary-layer stratification and drying induced by soot solar absorption. Further investigation must be carried out to identify whether increased sea surface temperature or another unidentified process is responsible for the increased low-level cloud cover.

Acknowledgment. Preliminary work on this project was done while the author was a visiting scientist in the Princeton University Atmospheric and Oceanic Sciences Program. Comments from an anonymous reviewer were helpful.

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J. R. Norris, Scripps Institution of Oceanography, University of California, San Diego, 9500 Gilman Drive DEPT 0224, La Jolla, CA 92093-0224. (e-mail: jrnorris@ucsd.edu)

(Received May 29, 2001; revised June 21, 2001;
accepted June 25, 2001.)