

OBSERVED INTERDECADAL CHANGES IN CLOUDINESS: REAL OR SPURIOUS?

J. R. NORRIS

*Scripps Institution of Oceanography
University of California, San Diego
9500 Gilman Drive 0224
La Jolla, California 92093-0224
jnorris@ucsd.edu*

This study documents multidecadal variations in low-level, upper-level, and total cloud cover over land and ocean independently obtained from surface synoptic observations and from satellite data produced by the International Satellite Cloud Climatology Project. Substantial agreement exists between global mean time series of surface- and satellite-observed upper-level cloud cover, indicating that the reported variations in this cloud type are likely to be real. Upper-level cloud cover has decreased over almost all land regions since 1971 and has decreased over most ocean regions since 1952. Global mean time series of surface- and satellite-observed low-level and total cloud cover exhibit very large discrepancies, however, implying that artifacts exist in one or both datasets. The global mean satellite total cloud cover time series appears spurious because the spatial pattern of correlations between grid box time series and the global mean time series closely resembles the fields of view of geostationary satellites rather than geophysical phenomena. The surface-observed low-level cloud cover time series averaged over the global ocean appears suspicious because it reports a very large 5 %-sky-cover increase between 1952 and 1997. Unless low-level cloud albedo substantially decreased during this time period, the reduced solar absorption caused by the reported enhancement of cloud cover would have resulted in cooling of the climate system that is inconsistent with the observed temperature record.

1. Introduction

Clouds have a large impact on Earth's radiation budget due to their reflection of solar or shortwave (SW) radiation back to space and their restriction of the emission of thermal or longwave (LW) radiation to space. The difference between actual radiation flux and what it would be were clouds absent is called cloud radiative forcing (CRF). Clouds at upper levels in the troposphere make the largest contribution to LW CRF because they are cold and thus emit less radiation than the surface under clear skies, and clouds that are optically thick make the largest contribution to SW CRF because they have greater albedo than the surface under clear skies. In the global annual average, the magnitude of top-of-atmosphere (TOA) SW CRF is greater than the magnitude of TOA LW CRF, corresponding to a loss of energy and consequently an overall cloud cooling effect in the present climate state.

Despite the greater sensitivity of Earth's radiation budget to variations in cloudiness than to equivalent percentage variations in CO₂ concentration (Slingo 1990), we currently do not know whether clouds are changing so as to mitigate or exacerbate anthropogenic greenhouse warming (Moore et al. 2001). One leading reason for this uncertainty is that global climate models (GCMs) do not correctly or consistently represent clouds and their radiative effects (e.g., Bony et al. 2006). The severe deficiencies in GCM simulations of cloudiness motivate the investigation of how observed clouds have changed over the past several decades, a period of rapidly rising global temperature.

The present study documents changes in low-level, upper-level, and total cloud cover since 1971 over land and since 1952 over ocean. Global mean time series averaged from gridded surface and satellite observations are compared during their period of overlap to assess how well the two independent datasets agree. Substantial similarity indicates which cloud type variations are reliable whereas disagreement implies the existence of artifacts in one or both datasets. The particular regions of the world that contribute most to the global mean time series are discerned by creating maps of correlation values between grid box time series and global mean time series. Maps of linear trends at each grid box are created for upper-level cloud cover, and a concluding section describes our current knowledge of the likely impact of cloud trends on Earth's radiation budget.

2. Data

Individual surface synoptic cloud reports were obtained from the Extended Edited Cloud Report Archive (Hahn and Warren 1999) globally over land during 1971-1996 and globally over ocean during 1952-1997. The land cloud reports came from stations assigned official numbers by the World Meteorological Organization (WMO), and the ocean cloud reports, primarily made by Volunteer Observing Ships, came from the Comprehensive Ocean-Atmosphere Data Set (Woodruff et al. 1987). A synoptic cloud report includes the fractions of sky dome covered by all clouds and by the lowest cloud layer, as seen by a human observer at the surface (WMO 1987). Upper-level cloud cover, defined in this study as the coverage by midlevel and high-level clouds, was inferred by assuming random overlap with obscuring lower-level clouds using the method described in Norris (2005a). Surface-observed low-level cloud cover values were also adjusted in some cases to represent the "satellite view" by assuming random overlap and removing the portion of low-level cloud cover overlapped by higher clouds (Norris 2005a).

Cumulonimbus clouds were included in the low-level category even though they have high tops because that is the usual practice for surface observations. This choice has little impact on the results of this analysis since sky-dome coverage by cumulonimbus (Warren et al. 1988) is usually less than one third of sky-dome coverage by upper-level clouds (Norris 2005b). Moreover, horizontal coverage of cumulonimbus clouds is actually smaller than that reported by surface observers, who include cloud sides as part of cloud cover.

Only daytime observations are used to avoid observer biases resulting from poor nighttime illumination (Hahn et al. 1995). Individual synoptic reports were averaged to monthly $5^\circ \times 5^\circ$ values using a special procedure that minimized geographical and temporal sampling biases (Norris 2005a). Subtraction of long-term monthly means from each grid box yielded $5^\circ \times 5^\circ$ monthly anomalies. Although the surface cloud data lack complete global sampling due to the scarcity of stations and ships in remote land and ocean regions, the occurrence of missing data has little impact on global mean values.

Monthly mean cloud fraction as seen by geostationary and polar-orbiting weather satellites was obtained from the International Satellite Cloud Climatology Project (ISCCP) at $2.5^\circ \times 2.5^\circ$ grid spacing for July 1983 onwards (Rossow et al. 1996, Rossow and Schiffer 1999). Pixels are classified as cloudy if they are brighter in the visible channel (VIS) and/or colder in the infrared window channel (IR) than clear-sky pixels beyond a specified threshold. ISCCP high clouds have tops above the 440 hPa level; ISCCP midlevel clouds have tops between 680 hPa and 440 hPa; and ISCCP low-level clouds have tops below the 680 hPa level. For this study, ISCCP high-level and mid-level clouds were combined to provide upper-level cloud fraction. Note that ISCCP low-level cloud fraction takes into account only those low clouds that are not obscured by higher clouds. Only ISCCP daytime (VIS+IR) data were examined since ISCCP may have trouble correctly detecting transmissive cirrus or low-level clouds using IR alone (Rossow and Schiffer 1999). As done for the surface data, the seasonal cycle was removed by subtracting long-term monthly means from each grid box.

3. Results

Global mean anomalies of surface- and satellite-observed upper-level, low-level, and total cloud cover for land only, ocean only, and land+ocean were created by averaging monthly anomalies over all grid boxes with weighting by grid box area and land/ocean fraction. A 13-point Lanczos 1-year low-pass filter was applied to the resulting time series, displayed in Figure 1, in order to improve readability and emphasize low-frequency variability. The surface and satellite observations exhibit agreement only for upper-level cloud cover, and linear correlations between the upper-level cloud cover time series are 0.58, 0.65, and 0.68 for land only, ocean only, and land+ocean, respectively. Assuming ten degrees of freedom (from 12 years of overlapping data), the coefficients are significant at the 95% level. The similarity of these two independent datasets strongly suggests that the reported upper-level cloud variations are real during their period of overlap and furthermore likely to be reliable before and after that interval. One exception to this conclusion, however, is the June 1991-1993 time period when the presence of Mt. Pinatubo volcanic aerosol caused some upper-level clouds to be misdiagnosed as low-level clouds in the satellite data over the ocean but not over land (Luo et al. 2002). Another exception is the period of October 2001 onwards when there appears to be a large discontinuity in the satellite time series.

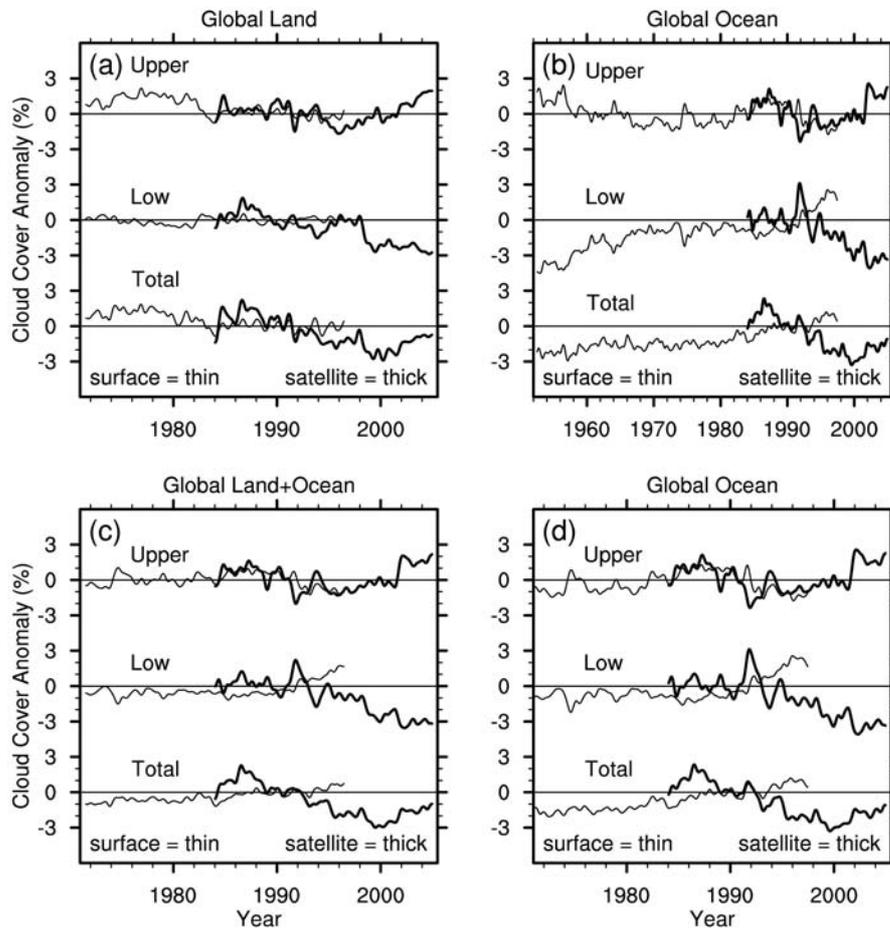


Figure 1. Monthly anomalies of surface-observed (thin) and satellite-observed (thick) upper-level (top), low-level (middle), and total cloud cover (bottom) globally averaged over: (a) land during 1971-2005, (b) ocean during 1952-2005, (c) land and ocean during 1971-2005, and (d) ocean during 1971-2005). Surface-observed low-level cloud cover was adjusted for overlapping higher clouds to correspond to the satellite view, and the time series were smoothed with a 13-point 1-year low-pass filter.

A very large discrepancy occurs between the low-level cloud cover time series; the surface data exhibit a generally increasing trend over ocean whereas the satellite data exhibit a generally decreasing trend over land and ocean (Figure 1). This leads to a corresponding disagreement between the total cloud cover time series since total cloud cover is the sum of upper-level cloud cover and low-level cloud cover as seen from a satellite. Although perfect correspondence should not be expected due to the differing measurement methods, the disparity between the time series is so great that

it is very likely that one or both of the datasets is contaminated by spurious variability.

The time series of ocean-only surface-observed low-level cloud cover appears suspicious because a least-squares linear fit reveals that marine low-level cloudiness strongly increased by about 5 %-sky-cover between 1952 and 1997. Such a change would enhance the amount of SW radiation reflected back to space with little change in outgoing LW radiation due to the low altitude of the clouds, thus acting to cool the Earth. An examination of Earth Radiation Budget Experiment data (Barkstrom et al. 1989) indicates that the ratio of net CRF divided by low-level cloud cover is on the order of 1 W m^{-2} per 1 %-sky-cover in regions with few upper-level clouds (e.g., Klein and Hartmann 1993). Assuming that this value applies to low-level clouds over all ocean regions and that all other cloud properties remain constant, this implies that the reported increase in low-level cloud cover caused an approximate 5 W m^{-2} decline in energy absorbed by ocean areas between 1952 and 1997. This estimated change in TOA radiation flux does not match the record reported by the Earth Radiation Budget Satellite during 1985-1997 (Wielicki et al. 2002, Norris 2006a). Moreover, considering that the increase in anthropogenic greenhouse radiative forcing since pre-industrial times (1750) is only about 2.5 W m^{-2} (Ramaswamy et al. 2001) and that global temperature increased between 1952 and 1997, it seems that the large low-level cloud cover increase reported by ship observers must either be spurious or accompanied by a compensating substantial decrease in cloud albedo. Unfortunately, synoptic cloud reports do not provide quantitative information on cloud optical properties that could be used to examine whether cloud albedo has experienced a long-term decline.

The nature of global mean cloud variability was explored by calculating correlation coefficients between the global mean time series and the time series at each grid box. High positive correlation values identified those regions that contributed most to the global mean cloud changes and thus to the apparent artifacts. The top plot of Figure 2 presents the correlation map for satellite-observed total cloud cover, which was analyzed instead of low-level cloud cover to avoid ambiguities related to overlap by higher cloud layers. As previously noted in Norris (2000a), the spatial correlation pattern of satellite total cloud cover consists of circular regions filled with positive values that closely correspond to the fields of view of the geostationary satellites contributing to ISCCP. These obviously artificial features strongly suggest that low-frequency variations in global mean satellite total cloud cover are not real. Positive correlations are also highest near the east/west boundaries of the fields of view, which Campbell et al. (2004) attribute to biases related to systematic decreases in satellite view angle over time. The correlation map for satellite-observed upper-level cloud cover does not exhibit the pattern seen in top plot of Figure 2 (not shown).

The bottom plot of Figure 2 presents the correlation map for ocean-only surface-observed low-level cloud cover without any adjustment to “satellite view”. Values are not plotted for the high latitude oceans where sampling is sparse. Almost all of the remaining grid boxes are positively correlated with the global ocean mean time series, a feature that is consistent with the finding of Norris (1999) that low-level

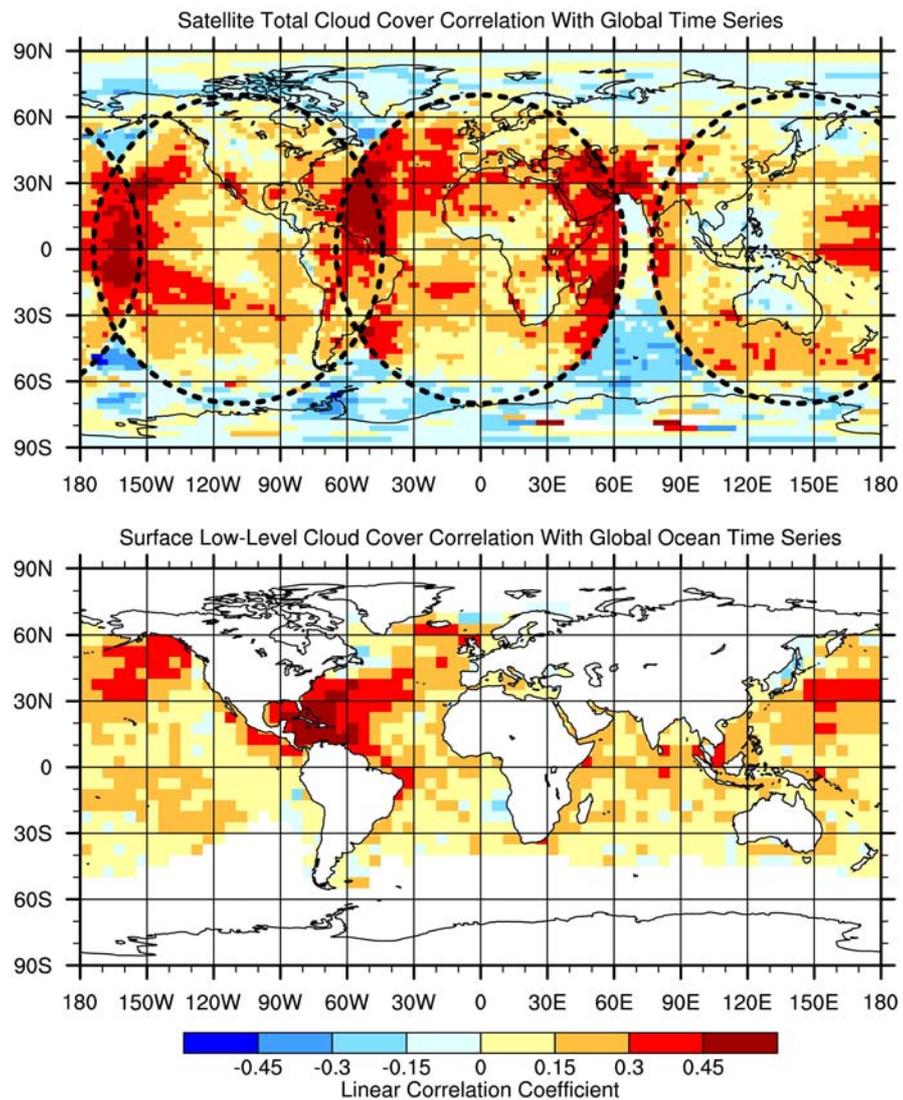


Figure 2. Map of correlation values between grid box anomaly time series and 1-year low-pass global mean anomaly time series for: (top) satellite-observed total cloud cover and (bottom) surface-observed low-level cloud cover not adjusted to “satellite view”. Grid boxes with data missing more than half the time are not plotted. Dashed circles in the top plot show the approximate fields of view of the U.S., European, and Japanese geostationary satellites.

cloud cover reported by ships increased from 1952 to 1995 not only in the global mean but also in every latitude band. Since individual ships travel on many different routes, it is possible that some unidentified artifact would thereby be spread around

the global ocean. Low-level cloud trends should therefore be deemed reliable only when they are corroborated by physically consistent trends in related meteorological parameters, as is the case for the midlatitude North Atlantic and North Pacific (e.g., Norris and Leovy 1994, Norris 2000b). The origin of high positive correlations in the western subtropical Atlantic has not yet been identified. Land grid boxes do not exhibit a large number of positive correlations with the global mean time series of low-level cloud cover (not shown).

Only 12% of the coefficients in the correlation map for ocean-only surface-observed upper-level cloud cover are greater than 0.15 (not shown), unlike 47% for low-level cloud cover. This suggests the absence of a globally coherent artifact in surface-observed upper-level cloud cover over the ocean. It is currently not known how a potential artifact could be absent from upper-level clouds yet presumably present in low-level clouds that are directly seen by surface observers.

Least-squares linear trends in upper-level cloud cover were calculated between 1952 and September 2001 over ocean and between 1971 and September 2001 over land. Surface and satellite cloud anomaly records were concatenated in order to have the longest time period possible with averaging of the two datasets during the interval in common (1984-1996). Furthermore, the anomalies were calculated with respect to the 1984-1996 period in both datasets so as to avoid discontinuities with the pre-1984 surface-only period and post-1996 satellite-only period. Satellite observations over ocean during June 1991-1993 were not used to avoid the volcanic aerosol problem. Assuming that each year is independent, the median value for 95% statistical significance is 0.2 %-sky-cover per decade over ocean and 0.4 %-sky-cover per decade over land.

The top plot of Figure 3 shows that upper-level cloud cover has decreased over most of the North Pacific, the western tropical Pacific, the subtropical regions of the Atlantic Ocean and the South Pacific, and the equatorial Indian Ocean. The only areas that have experienced widespread increases in upper-level cloud cover are the equatorial South Pacific, the tropical Atlantic Ocean, and the midlatitude North Atlantic. The study of Norris (2005b) demonstrated that the positive and negative cloud trends over the tropical Indo-Pacific region were physically consistent with shifts in surface wind convergence and precipitation. Moreover, the long-term changes in upper-level cloud cover resembled the spatial pattern of the interannual cloud response to El Niño, although the cloud trends were larger than would be expected from a linear relationship to the trend in El Niño SST anomalies. The distribution of positive and negative cloud trends over the North Atlantic is similar to the interannual upper-level cloud response to the North Atlantic Oscillation (not shown), and the directions of the long-term cloud changes are consistent with the previously reported trend in the North Atlantic Oscillation between the 1960s and 1990s (e.g., Hurrell and Van Loon 1997). The origin of the large increase in upper-level cloud cover off the coast of southwest Africa is currently unknown.

The bottom plot of Figure 3 shows reductions in upper-level cloud cover over almost all land regions since 1971. Although the causes of these trends have not yet been identified, the trends appear to be real since surface and satellite cloud variations exhibit close agreement in several different regions (not shown).

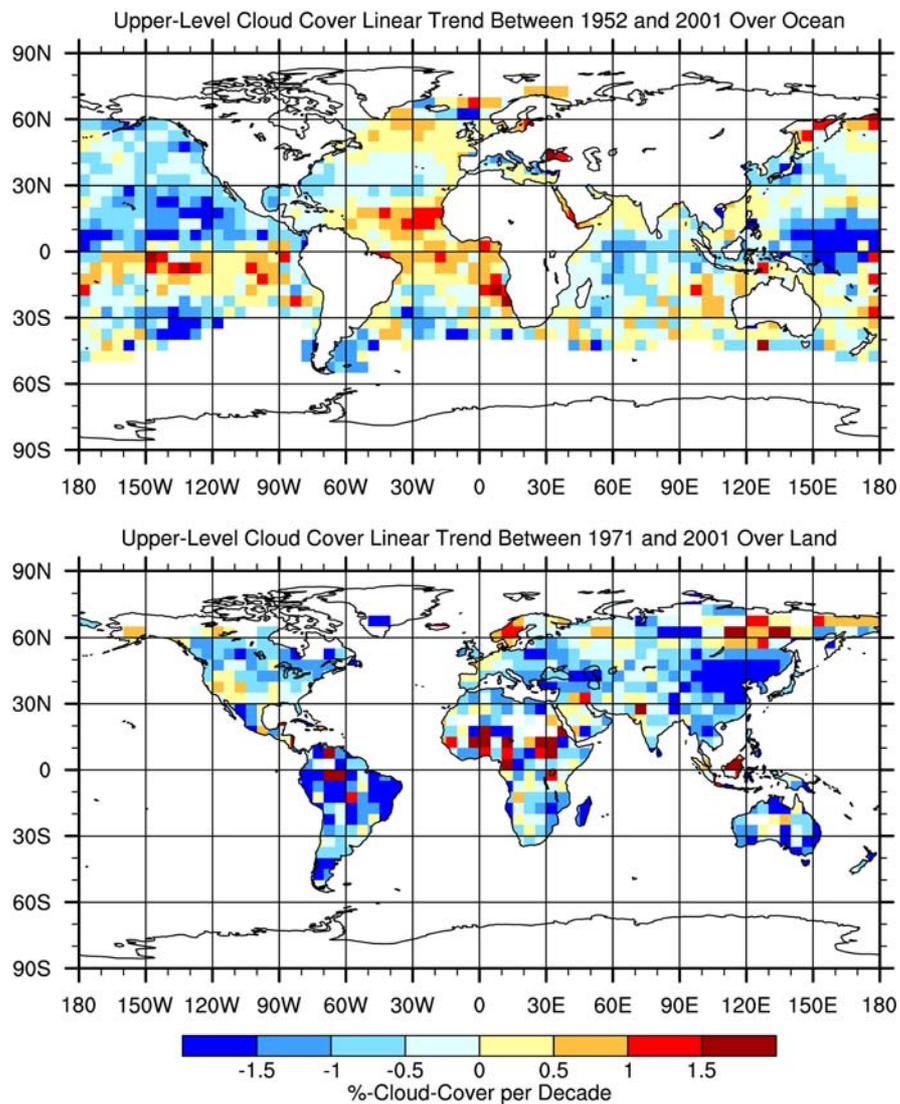


Figure 3. Map of linear trends in combined surface- and satellite-observed upper-level cloud cover at each grid box over: (top) ocean between 1952 and September 2001 and (bottom) land between 1971 and September 2001. Grid boxes with data missing more than half the time are not plotted, and ocean satellite data during June 1991-1993 were not included. Assuming that each year is independent, the median value for 95% statistical significance is 0.2 %-sky-cover per decade over ocean and 0.4 %-sky-cover per decade over land.

4. Conclusions

Multidecadal cloud cover variability over land and ocean was examined using surface and satellite observations. Global mean time series of low-level and total cloud cover obtained from surface and satellite data substantially disagree, implying that low-frequency variability in one or both datasets is spurious. Further evidence of an artifact in satellite total cloud cover is the pattern of correlations between grid box time series and the global mean time series that closely resembles the fields of view of geostationary satellites rather than meteorological features. Contrastingly, global mean time series of surface- and satellite-observed upper-level cloud cover are similar, providing confidence that the reported cloud variations are real. Based on the calculation of least-squares linear trends at each grid box, upper-level cloud cover decreased over most ocean regions between 1952 and 2001 and decreased over almost all land regions between 1971 and 2001.

The reduction of upper-level cloud cover during the past several decades will have allowed more LW radiation to escape to space (all else held constant), thus keeping the Earth cooler than it otherwise would have been. Diminished upper-level cloud cover will also have reflected less SW radiation back to space, thus acting to warm the Earth at the same time, but the entire cloud impact on net radiation unfortunately cannot be determined without reliable knowledge of trends in low-level cloud cover. Surface observers report that low-level cloud cover has increased by about 5 %-sky-cover between 1952 and 1997 over the ocean, corresponding to an approximate 5 W m^{-2} decrease in energy absorbed by the climate system if cloud albedo remained constant during that time period. Such a large change in net CRF is physically implausible and indicates that there has either been a substantial decline in cloud albedo or that the surface-observed low-level cloud cover trend is spurious. Consequently, it is currently not possible to ascertain whether recent multidecadal variations in clouds have mitigated or exacerbated anthropogenic global warming. More research needs to be done to identify and remove apparent artifacts from the satellite and surface cloud datasets.

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