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Contrasting impacts of net cloud radiative forcing on the surface temperature trends in India

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Abstract

The rise of spatial heterogeneity in surface temperature \((T_s)\) over India cannot be explained by only the direct effect of enhanced greenhouse gas forcing. Here we propose an analytical framework to estimate the impact of the net cloud radiative forcing (CRF) trend on the observed \(T_s\) trend for the duration of 2000–2019. The cloud sensitivity \((\Delta T_{1\sigma})\) estimated from the satellite observations vary in the range –0.180 to 0.241 K per W m\(^{-2}\) across the seven \(T_s\) homogeneous zones in India. Net average \((\pm1\sigma)\) CRFs over the Indian landmass during 2000–2019 in the shortwave and longwave are –15.5 \(\pm\) 11.3 and 12.4 \(\pm\) 7.4 W m\(^{-2}\), –28.1 \(\pm\) 22.4 and 24.6 \(\pm\) 9.8 W m\(^{-2}\), –75.1 \(\pm\) 20.4 and 55.0 \(\pm\) 13.8 W m\(^{-2}\) and –23.3 \(\pm\) 14.9 and 21.6 \(\pm\) 14.8 W m\(^{-2}\), respectively for the winter (Dec–Feb), pre-monsoon (Mar–May), monsoon (Jun–Sep) and post-monsoon (Oct–Nov) seasons. We find that in some of the \(T_s\) homogeneous regions, seasonal \(T_s\) trends are suppressed, whereas in some other \(T_s\) homogeneous regions, seasonal \(T_s\) trends are accelerated by the net CRF. Our framework can be useful in studying the role of clouds in observed surface warming trends.

1. Introduction

Clouds perturb the Earth’s radiation budget by inducing a cooling effect at the top-of-the-atmosphere (TOA) in shortwave (SW) and a warming effect in longwave (LW) depending on the type of cloud (high or low), liquid/ice content, etc. The net cloud radiative forcing (CRF) is governed by cloud macrophysical (i.e., cloud fraction, \(f_c\)) and cloud top temperature, \(T_{ctop}\) and microphysical (i.e., phase, effective radius and optical depth, \(\tau_c\)) properties that show large spatial and temporal variations in the Indian subcontinent (Rajeevan and Srinivasan 2000, Rajeevan et al 2012, Saud et al 2016, Ali et al 2019, Kant et al 2019). The impact of net CRF at TOA in modulating the surface temperature \((T_s)\) trend through cloud radiative feedback (Stephens 2005, Haugstad et al 2017) is poorly understood not only in the Indian subcontinent but also anywhere else in the world. This issue can be addressed using climate models, but they have large uncertainty (and discrepancy across models) in cloud radiative feedback estimates (Klein et al 2013, Yin and Porporato 2017). Net CRF variability is examined over the Indian subcontinent utilizing the ERBE (Earth Radiation Budget Experiment) data (Rajeevan and Srinivasan 2000, Patil and Yadav 2005, Sathiyanamoorthy et al 2011) for the period 1985–1989, focusing mainly on the monsoon season (June–September) and using CERES (Clouds and the Earth’s Radiant Energy System) data (Saud et al 2016, Kant et al 2019) for the recent decades. Observational data from the Indian Meteorological Department (IMD) network is employed to study surface temperature trends in India (Kothawale and Rupa Kumar 2005, Dash and Mamgain 2011, Srivastava et al 2017, Ross et al 2018, Nengzouzam et al 2019, Bhatla et al 2020).

The general finding from IMD data is that the Indian region is warming (Kothawale and Rupa Kumar 2005), and this can be attributed to human interference beyond any doubt (Dileepkumar et al 2018). However, the warming trends show regional variations across the seven \(T_s\) homogeneous zones (see supplementary figure S1(a) available online at stacks.iop.org/ERC/4/041005/mediata for the zonation)—Western Himalaya (WH), East Coast (EC), West Coast (WC), Northwest (NW), Northeast (NE), North Central (NC) and Interior.
Peninsula (IP). These $T_s$ homogeneous zones are demarcated based on geographical, topographical, and climatological features to identify the regional patterns of temperature variation within India (Kothawale and Rupa Kumar 2005). Figure S1(b) shows the linear trend (°C/10yr) in annual maximum and minimum temperatures for all-India and homogeneous regions using data available from Kothawale and Rupa Kumar (2005) for the period 1971–2003. Both for maximum and minimum temperature, positive trends suggest increasing temperature for all-India as well as seven homogeneous regions. Also, the day and nighttime $T_s$ trends are different in the winter, pre-monsoon, monsoon, and post-monsoon seasons. In general, over twice of the global land area, the daytime $T_s$ has been increasing at a lower rate than the nighttime $T_s$ (Cox et al 2020), thereby suppressing the diurnal temperature range (Kothawale and Rupa Kumar 2005). Recently, Sanjay et al (2020) have observed that annual mean, maximum and minimum temperatures averaged over India as a whole show significant warming trends of 0.15 °C, 0.15 °C, and 0.13 °C per decade, respectively, since 1986.

Padma Kumari et al (2007) examined the $T_s$ trend in India in terms of solar insolation flux and greenhouse gas (GHG) forcing. They showed that despite a drastic decrease in surface-reaching solar radiation (referred to as solar dimming), maximum and minimum $T_s$ over India are increasing. But the change in increase in maximum $T_s$ is only marginal from the decade (1981–1990) to decade (1991–2000) under the present scenario of increasing greenhouse gas emissions. This is likely as a result of natural climate variability that modulates (either suppress or enhance) greenhouse gas warming. On the contrary, the increase in minimum $T_s$ has doubled, indicating an increasing greenhouse gas forcing (Padma Kumari et al 2007). Ross et al (2018) studied the $T_s$ trend in India in connection with aerosols and explained the warming and cooling patterns in the decadal mean temperature based on the presence of a large region of brownish haze that is found over most of the North Indian Ocean and South Asia, particularly in the winter and spring months. Sea surface temperature (SST) and associated winds are examined to understand the possible mechanism behind the trends and variability of temperature over the west coast of India (Revadekar et al 2016). According to this study, SST variability alters the strength of winds to cause anomalies in temperature over the west coast. Kothawale et al (2016) has investigated temperature trends over various Indian cities and hill stations in view of urbanization and industrialization. Gautam and Singh (2018) studied the impact of urbanization on low-laying clouds near ground fog over Indo-Gangetic plains and they found suppressed fog fraction, amidst increased fog occurrence over the Indo-Gangetic Plains. This direct impact of urbanization on cloudiness has its effect on $T_s$ trend as well.

Various studies in the literature clearly indicate that the $T_s$ trend in the Indian region shows strong spatial heterogeneity across the seven $T_s$ homogeneous zones that cannot be explained in terms of only greenhouse gas forcing. The influence of clouds in the observed $T_s$ pattern is least understood in this regard. There exist very limited studies that examine the $T_s$ pattern in terms of net CRF at TOA for all $T_s$ homogeneous zones. This research gap forms the scope of the present study. Here we examine the role of net CRF on the observed $T_s$ trends in India using an analytical framework. We define a ‘cloud sensitivity’ ($\lambda_{cld}$) term that links the net CRF trend (expressed in the form of $\Delta CRF$) to $T_s$ trend attributed to clouds (hereafter represented as $\Delta T_{s,cld}$). We estimate the mean seasonal day and nighttime $\lambda_{cld}$ values and subsequently $\Delta T_{s,cld}$ for the homogeneous $T_s$ zones in India using satellite-based albedo and cloud products. In the next section, we first derive the conceptual framework, followed by the analysis, and subsequently, the results are discussed.

2. Methodology

2.1. Analytical framework

$T_s$ is influenced by various parameters, such as CRF, atmospheric circulation ($C_a$), GHGs ($G$), aerosols ($A$), and other factors ($O$). Mathematically it can be represented as

$$ T_s = T_s(CRF, C_a, G, A, O) $$

The total differential change in $T_s$ can be expressed as

$$ dT_s = \frac{\partial T_s}{\partial CRF} d(CRF) + \frac{\partial T_s}{\partial C_a} dC_a + \frac{\partial T_s}{\partial G} dG $$

$$ + \frac{\partial T_s}{\partial A} dA + \frac{\partial T_s}{\partial O} dO $$

(1)

Therefore, the total change in $T_s$ (over time) can be written as

$$ \Delta T_s = \frac{\partial T_s}{\partial CRF} \Delta CRF + \frac{\partial T_s}{\partial C_a} \Delta C_a + \frac{\partial T_s}{\partial G} \Delta G $$

$$ + \frac{\partial T_s}{\partial A} \Delta A + \frac{\partial T_s}{\partial O} \Delta O $$

(2)
The climate sensitivity term ($\lambda$) is defined as

$$\lambda = \frac{\partial T_s}{\partial \text{ CRF}},$$

where RF is anthropogenic radiative forcing at the TOA.

Analogous to this concept, we define the cloud sensitivity ($\lambda_{Cld}$) term as

$$\lambda_{Cld} = \frac{\partial T_s}{\partial \text{ CRF}}. \quad (3)$$

Finally, the total change in $T_s$ can be rewritten in terms of various sensitivity terms as,

$$\Delta T_s = \lambda_{Cld} \Delta \text{ CRF} + \lambda_{C} \Delta C_a + \lambda_{G} \Delta G + \lambda_{A} \Delta A + \lambda_{O} \Delta O \quad (4)$$

where, $\lambda_{Cld} = \frac{\partial T_s}{\partial \text{ CRF}}$, $\lambda_{C} = \frac{\partial T_s}{\partial C_a}$, $\lambda_{G} = \frac{\partial T_s}{\partial G}$, $\lambda_{A} = \frac{\partial T_s}{\partial A}$, $\lambda_{O} = \frac{\partial T_s}{\partial O}$

Furthermore, $\Delta T_s$ could be rewritten as,

$$\Delta T_s = \Delta T_{s}^{Cld} + \Delta T_{s}^{G} + \Delta T_{s}^{A} + \Delta T_{s}^{O} \quad (5)$$

where,

$$\Delta T_{s}^{Cld} = \lambda_{Cld} \times \Delta \text{ CRF}$$

$$\Delta T_{s}^{G} = \lambda_{G} \times \Delta G$$

$$\Delta T_{s}^{A} = \lambda_{A} \times \Delta A$$

$$\Delta T_{s}^{O} = \lambda_{O} \times \Delta O. \quad (6)$$

Evidently, equation (5) suggests that total change in surface temperature $\Delta T_s$ is driven by $\Delta T_{s}^{Cld}$ change in $T_s$ attributed to clouds), $\Delta T_{s}^{G}$ (change in $T_s$ attributed to atmospheric circulation), $\Delta T_{s}^{A}$ (change in $T_s$ attributed to GHGs), $\Delta T_{s}^{O}$ (change in $T_s$ attributed to aerosols), and $\Delta T_{s}^{G}$ (change in $T_s$ contributed by other factors). In this section, we develop a mathematical framework to quantify $\Delta T_{s}^{Cld}$, which is the change in surface temperature, $T_s$ due to clouds only.

We carry out our analysis by conceiving a simple cloud-modified radiative heat flux budget model. We assume a single layer cloud as a radiation shield, covering a fraction of the domain, $f_c$ with cloud macrophysical properties, such as cloud emissivity ($\varepsilon_c$) and cloud top temperature, $T_{clr}$. The entire cloud layer is assumed to be at a spatially homogeneous temperature, $T_{clr}$. Thereafter, the alteration of radiation budget due to the presence of this single layer cloud is investigated, and subsequently $\Delta T_{s}^{Cld}$ is mathematically derived in terms of $\lambda_{Cld}$ and $\Delta \text{ CRF}$.

It has already been shown in equation (6) that $\Delta T_{s}^{Cld}$ can be expressed as the product of $\lambda_{Cld}$ and $\Delta \text{ CRF}$, where $\lambda_{Cld}$ (K per Wm$^{-2}$) is interpreted as the $T_s$ trend attributable to the cloud radiative feedback per unit net CRF trend ($\Delta \text{ CRF}$). Positive (negative) $\lambda_{Cld}$ implies an increment (decrease) in $T_s$ in response to an increase in net CRF at TOA. We derive $\lambda_{Cld}$ using the conventional definition of net CRF (i.e., the sum of SW and LW CRF) at the TOA:

$$\text{CRF}_{Total} = \text{CRF}_{SW} + \text{CRF}_{LW} \quad (7)$$

Both CRF$_{SW}$ and CRF$_{LW}$ can be represented as:

$$\text{CRF} = \uparrow_{clr} - \uparrow_{all} \quad (8)$$

where $\uparrow$ denotes the outgoing flux at the TOA and the subscripts ‘Clr’ and ‘All’ represent ‘clear-sky’ and ‘all-sky’ conditions.

SW CRF can be expressed as

$$\text{CRF}_{SW} = \frac{S_0}{4} (\alpha_{Clr} - \alpha_{All}) = \frac{S_0}{4} \alpha_d \quad (9)$$

where $S_0$, $\alpha_{Clr}$ and $\alpha_{All}$ are TOA incoming solar flux, ‘clear-sky’ albedo, and ‘all-sky’ albedo, respectively. The term $\alpha_d$ is the difference between $\alpha_{Clr}$ and $\alpha_{All}$. In the LW regime,

$$\uparrow_{Clr} = \varepsilon_c \sigma T_s^4 + \varepsilon_a \sigma T_a^4 \quad (10)$$

where $\varepsilon_c$, $\varepsilon_a$ and $\sigma$ denote surface emissivity, atmospheric emissivity, and Stefan-Boltzmann constant, respectively. $\uparrow_{All}$ can be expressed as a sum of five terms:

$$\uparrow_{All} = \varepsilon_a (1 - f_c) \sigma T_s^4 + f_c \varepsilon_a (1 - \varepsilon_c) \sigma T_s^4 + f_c \varepsilon_c \sigma T_{clr}^4$$

$$+ f_c \varepsilon_a (1 - \varepsilon_c) \sigma T_{clr}^4 + \varepsilon_c (1 - f_c) \sigma T_{clr}^4 \quad (11)$$

where, $\varepsilon_c$ and $f_c$ represent cloud emissivity and cloud fraction, respectively. The first term of the RHS of equation (11) denotes atmospheric emission from the cloud-free area. The second and third terms quantify emission from the atmosphere below the cloud layer that transmits through clouds and emission from clouds, respectively. The fourth term represents surface-emission that transmits through clouds, and the last term denotes the surface-emission from the cloud-free area. For our study, we consider a first-order approximation,
where atmospheric temperature $T_s$ may be represented by $T_s$ using [Marshall and Plumb, 2008]:

\[ T_s^4 = T_s' / 2 \]  

Equation (12)

Putting equations (10), (11) in equation (8), we get

\[ CRF_{\text{SW}} = A_l T_s^4 + BT_s^3 + CT_{\text{cld}}^3 \]  

Equation (13)

where, $A = \varepsilon_c \varepsilon_s \sigma + \varepsilon_c \sigma (\varepsilon_s - 1)$, $B = \varepsilon_s \sigma (\varepsilon_s - 1)$ and $A = -\varepsilon_c \sigma$.

Now, the trends in CRF for SW and LW are calculated as

\[ \Delta CRF_{\text{SW}} = \frac{S_0}{4} \Delta \alpha_d + \frac{\alpha_d}{4} \Delta S_0 \]  

Equation (14)

\[ \Delta CRF_{\text{LW}} = (AT_s^4 + CT_{\text{cld}}^3) \Delta f_c + (4AT_s^3 f_c + 4BT_s^2) \Delta T_s \]  

Equation (15)

Therefore, the final expression for the net CRF trend can be written as

\[ CRF_{\text{Total}} = \frac{S_0}{4} \Delta \alpha_d + \frac{\alpha_d}{4} \Delta S_0 + (AT_s^4 + CT_{\text{cld}}^3) \Delta f_c + (4AT_s^3 f_c + 4BT_s^2) \Delta T_s + 4CT_{\text{cld}}^2 \Delta T_{\text{cld}} \]  

Equation (16)

Combining (3) and (16), we get:

\[ \lambda_{\text{cld}} = \frac{\partial T_s}{\partial CRF_{\text{Total}}} = \frac{\partial T_s}{\partial CRF_{\text{Total}}} \]  

Equation (17)

\[ \therefore \lambda_{\text{cld}} = \left( \frac{S_0}{4} \frac{\partial \alpha_d}{\partial T_s} + \frac{\alpha_d}{4} \frac{\partial S_0}{\partial T_s} + A_l \frac{\partial T_s}{\partial T_s} + B_l \frac{\partial T_{\text{cld}}}{\partial T_s} + C_l \frac{\partial T_{\text{cld}}}{\partial T_s} \right) \]  

Equation (18a)

\[ \therefore \Delta T_{\text{cld}} = \lambda_{\text{cld}} \times \Delta CRF \]  

Equation (18b)

where,

\[ A_l = AT_s^3 + CT_{\text{cld}}^3 \]  

Equation (19)

\[ B_l = 4CT_{\text{cld}}^3 f_c \]  

Equation (20)

\[ C_l = 4AT_s^3 f_c = 4BT_s^3 \]  

Equation (21)

In these three equations (19)–(21), $A_l$, $B_l$, $C_l$ are region-specific constants that have been estimated separately for each $T_s$ homogeneous zone of India.

\[ \lambda_{\text{cld}} \] depends on incoming solar radiation at the TOA ($S_0$), and trends of $T_s$, $T_{\text{cld}}$, $f_c$, and $\alpha_d$ (difference of ‘clear-sky’ and ‘all-sky’ albedo). Note that the expression of $\lambda_{\text{cld}}$ includes the ‘$T_s$ trend’ term (i.e. $\frac{\partial T_s}{\partial T_s}$) in the equation (18a), implying that radiative feedback is incorporated in estimating cloud-induced changes in $T_s$, because $\Delta T_{\text{cld}}$ is linked to $\Delta CRF$ through $\lambda_{\text{cld}}$. $\lambda_{\text{cld}}$ decreases in response to an increasing trend in $S_0$ and $\alpha_d$, but increases in response to an increasing trend in $T_{\text{cld}}$, while the response to $f_c$ trend can go either way depending on the zone and season.

2.2. Data and analysis

We analyze two different datasets to compute mean seasonal $\lambda_{\text{cld}}$ in the day and nighttime (table 1). Time series data of $f_c$ and $T_{\text{cld}}$ are obtained from Moderate Resolution Imaging Spectroradiometer (MODIS) onboard EOS-Terra satellite (Barnes et al 1998). $T_s$ trends are used from ground-based measurements of IMD with a grid resolution of $0.5^\circ \times 0.5^\circ$ for the period of 1971–2003 (Kothawale and Rupa Kumar 2005). The CRF is computed from the flux data obtained from Cloud and the Earth’s radiant energy system (CERES) onboard the same EOS-Terra satellite (Wielicki et al 1996). CERES products give double accuracy in the estimates of radiative fluxes due to improvements in the input fluxes, scene identification, and new models of the solar zenith angle dependence of albedo as a function of the new angular distribution model scene types (Loeb et al 2002). $S_0$, clear- and all-sky albedo time series are also taken from CERES.

We perform all the analysis at $1^\circ \times 1^\circ$ grid using daily level 3 MODIS and CERES data and present the statistics averaged over the seven $T_s$ homogeneous zones. All seasonal trends are calculated as linear regression for the period 2000–2019 (tables S1 and S2 in SI). Regarding equation (18b), $\Delta CRF$ is calculated from the linear trends of net CRF in each of the homogeneous zones separately for day and nighttime in each season. Finally,
mean seasonal $\Delta T_s^{Cld}$ is calculated for each $T_s$ homogeneous zone using the proposed analytical framework and compared against the total changes in $T_s$ during the study period (used from Kothawale and Rupa Kumar 2005).

3. Results

The mean seasonal daytime and nighttime net CRFs in the $T_s$ homogeneous zones in India are shown in figure 1. Three key features are noteworthy. LW CRF is positive in every season in every $T_s$ homogeneous zones because clouds partially absorb outgoing LW radiation causing net warming at the TOA. In the nighttime, cloud-radiation interaction is limited to only LW, and hence the net CRF is always positive in the nighttime (in the absence of any SW cooling). The magnitude, however, depends on $f_c$ and $T_{Cld}$ (mean seasonal values are given in S1 table S1 and S2). Higher cloud tops (i.e., lower $T_{Cld}$) and larger $f_c$ lead to larger LW CRF, which is evident in all homogeneous zones during the monsoon and in some of the $T_s$ zones in the other seasons that provide conducive conditions for cloud invigoration.

Secondly, in the daytime, clouds reflect solar radiation, causing cooling at the TOA, and hence the net CRF depends on the relative magnitudes of LW warming and SW cooling. In the monsoon, SW cooling is stronger than LW warming by the deep convective clouds (Saud et al 2016), and hence the net CRF is cooling in all the regions except EC. In other seasons, we observe a mixed signal. In the pre-monsoon season, most (five out of seven) of the $T_s$ regions have a net positive CRF in the daytime. In this season, SW cooling is at its minimum because of the low moisture content and low $f_c$ in most of the regions. In the NE region that is frequently affected by thunderstorms in this season, the SW cooling dominates over the LW warming. During the post-monsoon and winter season, SW cooling and LW warming are of almost similar magnitudes leading to near-zero net CRF. Thirdly, the diurnal variation in net CRF is the largest in the monsoon season because the SW cooling is the largest in this season due to the high frequency of convective clouds.

Next, we examine mean seasonal daytime and nighttime $\lambda_{Cld}$ for the seven $T_s$ zones (figure 2). Positive $\lambda_{Cld}$ values imply that $\Delta T_s^{Cld}$ would increase in response to an increase in net CRF and negative $\lambda_{Cld}$ values imply that $\Delta T_s^{Cld}$ would decrease in response to an increase in net CRF. In the winter, all $T_s$ zones show a positive $\lambda_{Cld}$ during daytime and a mixed sign during nighttime. In the regions (e.g., EC, NE, and NW) where the signs are opposite in the day and nighttime, either an increase or decrease in net CRF in both day and nighttime would enhance the diurnal temperature range (DTR). In the regions where $\lambda_{Cld}$ is either positive (e.g., IP, WC, and WH in the winter) or negative (e.g., NC, NE, and WC in the pre-monsoon), an increase (decrease) in net CRF would accelerate (retard) or retard (accelerate) surface warming. In the pre-monsoon and post-monsoon seasons, all the regions show a similar pattern in $\lambda_{Cld}$ during the daytime and nighttime. In the monsoon, all the regions except NC show the same sign for $\lambda_{Cld}$. Larger $\lambda_{Cld}$ values imply that the impact of net CRF would be larger in those regions (and seasons) due to even a smaller change in net CRF.

We now discuss the mean ($\pm$standard deviation) seasonal changes in $T_s$ due to the net CRF trends in the seven $T_s$ homogeneous zones of India (figure 3). This is explained by the variations in $\lambda_{Cld}$ in conjunction with the changes in net CRF (table 1). In the EC, negative $\Delta T_s^{Cld}$ during March-September implies that clouds have a net cooling effect on $T_s$ in both day and nighttime. However, this should not be interpreted in absolute terms.

| Dec–Feb | Mar–May | Jun–Sep | Oct–Nov |
|---------|---------|---------|---------|
| $\lambda_{Cld}$ | $\Delta CRF$ | $\lambda_{Cld}$ | $\Delta CRF$ | $\lambda_{Cld}$ | $\Delta CRF$ | $\lambda_{Cld}$ | $\Delta CRF$ |
| EC | +0.048 | −0.069 | +0.049 | −0.316 | +0.009 | −0.377 | −0.016 | −0.439 |
| IP | −0.042 | −0.383 | +0.035 | −0.290 | +0.018 | −0.343 | −0.039 | −0.845 |
| NC | +0.002 | −0.187 | −0.009 | −0.126 | −0.180 | −0.210 | +0.010 | +0.083 |
| NE | +0.035 | −0.013 | −0.094 | −0.197 | +0.058 | −0.452 | +0.027 | −0.162 |
| NW | +0.015 | +0.090 | −0.004 | −0.173 | −0.045 | +0.271 | −0.017 | +0.197 |
| WC | −0.071 | −0.217 | −0.062 | −0.262 | −0.119 | −0.238 | −0.026 | −0.538 |
| WH | −0.016 | −0.123 | +0.120 | −0.102 | +0.013 | −0.517 | +0.014 | −0.020 |
| | −0.123 | −0.034 | +0.183 | −0.101 | +0.006 | +0.025 | +0.015 | −0.014 |
| | +0.083 | −0.160 | −0.037 | −0.106 | +0.035 | −0.566 | +0.009 | −0.295 |
| | +0.182 | −0.138 | −0.036 | −0.310 | +0.028 | −0.498 | +0.014 | −0.366 |
| | +0.063 | −0.069 | +0.025 | −0.760 | +0.039 | −0.757 | +0.067 | −0.297 |
| | +0.200 | −0.023 | +0.034 | −0.199 | +0.074 | −0.133 | +0.138 | +0.010 |
Figure 1. Mean (±standard deviation, shown as error bars) seasonal daytime and nighttime net CRFs for the seven T_1 homogeneous zones of India.

Figure 2. Daytime and nighttime $\lambda_{CI,4}$ (unit: K per W m$^{-2}$) over the various $T_1$ homogeneous zones in India.
(as a decrease in $T_s$); rather it means that in the absence of clouds, the observed rate of increase in $T_s$ in this region would have been higher. A similar impact is observed in the winter during nighttime. During the daytime in the winter and day and nighttime in the post-monsoon, the impact is reversed (i.e., $T_s$ rising trend is accelerated due to cloud feedback).

Generally, $T_s$ increases at a faster rate during the nighttime than during the daytime (Davy et al 2017) due to global warming leading to a reduction in DTR. In the IP, throughout the year, clouds suppress the $T_s$ warming trend in both day and nighttime with a larger impact during nighttime in ON and DJF and daytime in the pre-monsoon and monsoon. These results imply that the DTR would increase in ON and DJF and decrease in the other two seasons due to cloud feedback if the current trends continue. A similar impact is observed in the WH except for the nighttime in the post-monsoon and the WC except in the pre-monsoon. In the NW, the cloud feedback is least as the region is dry and has the lowest $f_c$ (tables S1 in SI). In this and the other two (NC and NE) homogeneous zones, $\Delta T_s^{Cld}$ is opposite in day and nighttime except in the post-monsoon for NC, and the winter and pre-monsoon for NE. A positive $\Delta T_s^{Cld}$ value in the daytime and a negative $\Delta T_s^{Cld}$ in nighttime indicates that the DTR would not reduce, while the opposite (negative $\Delta T_s^{Cld}$ in the daytime and positive $\Delta T_s^{Cld}$ in the nighttime) would reduce the DTR if the current trends persist.

4. Discussions and conclusions

Our proposed analytical framework to estimate the impact of net CRF trend on $T_s$ trend utilizes observed data and therefore can be universally applicable. We note that the observed $T_s$ trends is a manifestation of all the driving factors (including clouds), but here we quantify the roles of clouds only. Similar frameworks can be developed to understand the roles of other driving factors on the observed $T_s$ trend following the same philosophy.

We discuss a few key issues that are important for the proper interpretation of the results. First, we note that the Terra spacecraft crosses the Indian region at 10:30 AM and 10:30 PM, and so the cloud and albedo measurements and $T_s$ measurements do not coincide temporally. We feel that the temporal difference would not alter our broad conclusions. Second, we assume that the impact within a $T_s$ homogenous zone is unperturbed by the changes in net CRF in the adjacent region. Third, the trends used in cloud properties used in our analytical framework may be impacted by the uncertainty in cloud retrieval. For example, MODIS $f_c$ may be
over-estimated in the cumulus-dominated regions (Dutta et al 2020, Zhao and Di Girolamo 2006) due to the resolution effect. Without any ‘true’ $f_c$ estimates, it is difficult to quantify such uncertainty. Fourth, $f_c$ responds to global warming through feedback processes as a function of cloud optical depth and $T_{	ext{cl}}$ (Zhou et al 2013). To estimate $\lambda_{\text{cl}}$ in our framework, we consider the rate of change of $f_c$ and $T_{\text{cl}}$ (equation 18a). Therefore, any changes in $f_c$ and $T_{\text{cl}}$ due to the feedback are already incorporated into the framework. Finally, we analyze 20-year data that may not be sufficient for detecting significant trends in all the parameters considered here. However, based on our analytical framework, the parameters without significant trends have a minimal impact on $\lambda_{\text{cl}}$.

Comparing the estimates of changes in $T_s$ attributed to cloud net CRF with the changes in $T_s$ in the last 20 years, we interpret that in the regions where $\Delta T_{\text{cl}}$ is negative, the $T_s$ would have increased at a higher rate had there been no influence of cloud radiative forcing. On the other hand, the regions where $\Delta T_{\text{cl}}$ is positive, it accelerates the observed warming trend. We identified these regions in India and discussed the patterns in this work. Our results can be compared with climate model simulations with and without cloud radiative feedback for robust interpretation of the impacts of net CRF on surface temperature trends over India. The framework relies on the observed data that are available globally, and hence the framework can be applied universally. Finally, we note that a similar analysis is required to separate the role of other key factors like GHG forcing, aerosols, urbanization and natural climatic variability, which also impact the surface temperature trends (as discussed at the beginning of the framework).

The key conclusions of this study are as follows:

1. In the nighttime, the net CRF is positive in every season in every $T_s$ homogeneous zone in India with the largest LW CRF observed during the monsoon due to higher cloud tops (i.e. lower $T_{\text{cl}}$) and larger $f_c$. In the daytime, net CRF shows a dual pattern depending on the relative strengths of SW cooling and LW warming.
2. The cloud sensitivity can be either a negative or a positive in India and varies in the range –0.180 K to +0.241 K per W m$^{-2}$ net CRF.
3. Clouds are found to have a dual impact on the surface warming trends by suppressing the trends in regions where the cloud sensitivity and net CRF show opposing trends and accelerating the trends in regions where the cloud sensitivity and net CRF show similar trends.

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Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

Competing financial interest

The authors declare no competing financial interests.

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References

Ali M A, Islam M M, Islam M N and Almazroui M 2019 Investigations of MODIS AOD and cloud properties with CERES sensor based net cloud radiative effect and a NOAA HYSPLIT Model over Bangladesh for the period 2001–2016 Atmos. Res. 215 268–83
Barnes W L, Pagano T S and Salomonson V V 1998 Prelaunch characteristics of the Moderate Resolution Imaging Spectroradiometer (MODIS) on EOS-AM1 IEEE Trans. Geosci. Remote Sens. 36 1088–100
Bhatla R, Verma S, Ghosh S and Gupta A 2020 Abrupt changes in mean temperature over India during 1901–2010 J. Earth Syst. Sci. 129 166
Cox D T C, Maclean I M D, Gardner A S and Gaston K J 2020 Global variation in diurnal asymmetry in temperature, cloud cover, specific humidity and precipitation and its association with leaf area index Global Change Biol. 26 7099–111
Dash S K and Mamgain A 2011 Changes in the frequency of different categories of temperature extremes in India J. Appl. Meteorol. Clim. 50 1842–58
Davy R, Esau I, Chernokulsky A, Outen S and Zilitinkevich S 2017 Diurnal asymmetry to the observed global warming Int. J. Climatol. 37 79–93
Dileepkumar R, AchutaRao K and Arulalan T 2018 Human influence on sub-regional surface air temperature change over India Sci Rep. 8 8967
Dutta S, Di Girolamo L, Dey S, Zhan Y, Moroney C M and Zhao G 2020 The Reduction in Near-Global Cloud Cover After Correcting for Biases Caused by Finite Resolution Measurements Geophys. Res. Lett. 47 1–9
Gautam R and Singh M K 2018 Urban heat island over Delhi punches holes in widespread fog in the Indo-Gangetic Plains Geophys. Res. Lett. 45 1114–21
Haugstad A D, Armour K C, Battisti D S and Rose B E J 2017 Relative roles of surface temperature and climate forcing patterns in the inconstancy of radiative feedbacks Geophys. Res. Lett. 44 7455–63
Kant S, Panda J and Gautam R 2019 A seasonal analysis of aerosol-cloud-radiation interaction over Indian region during 2000–2017 Atmos. Environ. 201 212–22
Klein S A, Zhang Y, Zelinka M D, Pincus R, Boyle J and Gleckler P J 2013 Are climate model simulations of clouds improving? An evaluation using the ISCCP simulator J. Geophys. Res. Atmos. 118 1329–42
Kothawale D R, Despande N R and Rupa Kumar K 2016 Long term temperature trends at major, medium, small cites and hill station in India during the period 1901–2015 J. Clim. Change. 5 383–98
Kothawale R and Rupa Kumar K 2005 On the recent changes in surface temperature trends over India Geophys. Res. Lett. 32 L18714
Loeb N G, Kato S and Wielicki B A 2002 Defining top-of-atmosphere flux reference level for earth radiation budget studies J. Clim. 15 3391–9
Marshall J and Plumb R A 2008 Atmosphere, Ocean, and Climate Dynamics: An Introductory Text (Amsterdam: Elsevier Academic Press)
Nengrouzam G, Hodam S, Bandypadhyay A and Bhadra A 2019 Spatial and temporal trends in high resolution gridded temperature data over India Asia-Pacific J. Atmos. Sci. 55 761–72
Patil S D and Yadav R K 2005 Large-scale changes in cloud radiative forcing over the India region Atmos. Environ. 39 4609–18
The year 2013 has been replaced with 2012 Rajeevan M, Rohini P, Niranjan Kumar K, Srinivasan J and Unnikrishnan C K 2012 A study of cloud feedbacks in the climate system: A critical review Bull. Am. Meteorol. Soc. 93 383–92
Ross R S, Krishnamurthy T N and Pattanaik S 2018 Decadal surface temperature trends in India based on a new high-resolution data set Sci. Rep. 8 7452
Sanjay J et al 2020 Temperature changes in India ed R Krishnan, J Sanjay, C Gnanaseelan, M Mujumdar, A Kulkarni and S Chakraborty Assessment of Climate Change over the Indian Region (Singapore: Springer)
Sathiyamoorthy V, Shukla B P and Pal P K 2011 A study on radiative properties of Indian summer monsoon clouds Meteorol. Atmos. Phys. 113 55–66
Saud T, Dey S, Das S and Dutta S 2016 A satellite-based 13-year climatology of net cloud radiative forcing over the Indian region Atmos. Res. 182 76–86
Srivastava A K, Kothawale D R and Rajeevan M N 2017 Variability and long-term changes in surface air temperatures over the indian subcontinent ed M Rajeevan and S Nayak Observed Climate Variability and Change over the Indian Region. Springer Geology. (Singapore: Springer)
Stephens G L 2005 Cloud feedbacks in the climate system: A critical review J. Clim. 18 237–73
Wielicki B A, Barkstrom B R, Harrison E F, Lee R B, Smith G L and Cooper J E 1996 Clouds and the Earth’s Radiant Energy System (CERES): An Earth observing system experiment Bull. Am. Meteorol. Soc. 77 853–68
Yin J and Porporato A 2017 Diurnal cloud cycle biases in climate models Nat. Commun. 8 2269
Zhao G and Di Girolamo L 2006 Cloud fraction errors for trade wind cumuli from EOS-Terra instruments Geophys. Res. Lett. 33 L20802
Zhou C, Zelinka M D, Dessler A E and Yang P 2013 An analysis of the short-term cloud feedback using MODIS data J. Clim. 26 4803–15