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A satellite-based 13-year climatology of net cloud radiative forcing over the Indian monsoon region

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ABSTRACT

We present a satellite-based 13-year (Mar. 2000–Feb. 2013) climatology of net cloud radiative forcing (CRF) over the Indian monsoon region (0–40°N, 60–100°E) using the Clouds and Earth's Radiant Energy System (CERES) radiation data and explained the net CRF variability in terms of cloud properties retrieved by Moderate Resolution Imaging Spectroradiometer (MODIS). Mean ($\pm 1\sigma$) seasonal shortwave (SW) CRF values averaged over the region are -82.7 ± 24.5, -32.1 ± 12.1, -17.2 ± 5.3 and -30.2 ± 16.2 W m^{-2} respectively for the monsoon (JJAS), post-monsoon (ON), winter (DJF) and pre-monsoon (MAM) seasons; while the corresponding longwave (LW) CRF values are 53.7 ± 14.2, 27.9 ± 10.0, 15.8 ± 7.0 and 25.2 ± 9.1 W m^{-2}. Regional analysis reveals the largest (least) negative net CRF over the northeast (northwest) rainfall homogeneous zone throughout the year due to the dominance of optically thick high clouds (low cloud fraction, f_c). Mean JJAS f_c is found to increase (by >0.01 per year) over large parts of the Arabian Sea, Bay of Bengal and the northwest region. Mean annual net CRF values for cumulus, stratocumulus and stratus (low level), altocumulus, altostratus and nimbostratus (mid-level clouds) and cirrus, cirrostratus and deep-convective (high level) clouds over the Indian monsoon region are estimated to be -0.8, -4.7, -6.9, $+3.3$, -6.3, -23.3, $+5.4$, -23.3 and -42.1 W m^{-2} respectively. Across a wide range of cloud optical depth (COD) and $f_c < 0.6$, near cancellation of SW cooling by LW warming, is observed for low clouds. Net CRF drops below -15 W m^{-2} for clouds evolving above 400 hPa, mainly in the monsoon season. Our results demonstrate that net CRF variability in the Indian monsoon region can be explained by variability in Cloud Top Pressure (CTP), COD and f_c. The study highlights the need for resolving a multi-layer cloud field in the future.

1. Introduction

Clouds can be considered as one of the major factors influencing the Earth's climate as they exert a cooling effect by reflecting the incoming solar radiation and a warming effect by absorbing the terrestrial longwave radiation (Altaratz et al., 2014; Wacker et al., 2011; Galli et al., 2004). Clouds play a fundamental role in the attenuation of solar radiation reaching the earth's surface, and may attenuate as much as 80% of the cloudless sky radiation depending on features such as cloud type, COD, and its distribution in the sky (Salgueiro et al., 2016; Serrano et al., 2015; Pyrina et al., 2015). The net effect of clouds on the radiation budget at the top-of-the-atmosphere (TOA), referred to as the cloud-radiative forcing (CRF) (Ramanathan et al., 1989) is highly uncertain at regional scale (Charlock and Ramanathan, 1985; Ramanathan, 1987; Cess and Potter, 1987; IPCC, 2013). Any uncertainty in estimated net CRF would therefore lead to an error in estimated climate forcing (Stephens, 2005). The spatio-temporal variation of net CRF depends on the macrophysical (f_c and cloud top temperature that in turn depend on CTP) and optical properties of clouds (such as COD, droplet size and phase) and other variables such as solar zenith angle and surface albedo (Pyrina et al., 2015; Liu et al., 2011; Dop and Wilson, 2006). In order to assess the fidelity of models in simulating cloud feedbacks, it is important to understand the variability of net CRF at regional scale in terms of the cloud properties.

CRF was first estimated globally from the space-borne Earth Radiation Budget Experiment (ERBE) satellite launched in 1984. One of the key observations was the high degree of cancellation of the LWCRF and SWCRF in the tropical convective regions (Ramanathan et al., 1989; Harrison et al., 1990). Near zero net CRF has been assumed to be the characteristics of all tropical convective regions, over both land and ocean due to the occurrence of cloud tops close to the tropical tropopause and the albedo of optically thick ice clouds (Kiehl, 1994). Analysis of ERBE data revealed a large cooling effect over the mid- and high-latitude oceans, with values reaching around -100 W m^{-2} and monthly average LWCRF reaching their maximum values of 50–100 W m^{-2} in the convectively disturbed regions of the tropics. Using ERBE data, Rajeevan and Srinivasan (2000) pointed out that

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the net CRF at the TOA over the Asian monsoon region during 1985–1988 is largely negative during the monsoon season because of a large amount of high clouds which are optically thick. A considerable fraction of deep convective clouds occurs within the tropical tropopause layer over the Bay of Bengal (BoB) during the June–August period (Meenu et al., 2010). The frequency of occurrence of deep convective clouds exceeds ~25% over the BoB during July and over the equatorial Indian Ocean during January (Roca and Ramanathan, 2000). Only a limited number of investigations targeting clouds and radiation budget over the Indian subcontinent and the surrounding oceanic regions exist (Grossman and Garcia, 1990; Gambheer and Bhat, 2000; Rajeevan and Srinivasan, 2000; Roca et al., 2002; Sathiyamoorthy et al., 2004; Thampi and Roca, 2014; Ravi Kiran et al., 2015) relative to a large number of publications on aerosol radiative forcing in global scale. In recent times, radiative properties of clouds over the Indian subcontinent and nearby oceanic regions during the Asian summer monsoon season (June–September) are investigated using the Clouds and Earth's Radiant Energy System (CERES) TOA flux data by Thampi and Roca (2014). Subrahmanyam and Kumar (2013) showed that the deep convective clouds frequently occur over northeast of the BoB, cirrus clouds over a wide region of south BoB–Indian peninsula–equatorial Indian Ocean, and stratocumulus clouds over the north Arabian Sea. Altocumulus clouds are observed preferentially over land, and a large amount of Altostratus clouds are found over the BoB. During January–April, a maxima in the occurrence of low clouds is seen at subtropical latitudes over the Arabian Sea (AS) and the BoB. These oceanic regions are dominated by cumulus clouds (Bony et al., 1999). The vertical distribution of clouds during the active and break spells of the Indian summer monsoon were examined recently by Rajeevan et al. (2012) by analyzing CloudSat data. Das et al. (2013) also carried out a similar analysis to characterize the monsoon clouds using the active remote sensing data. Ravi Kiran et al. (2015) also suggested that the vertical distribution of cloud microphysics has an important role in the variance of CRF over the BoB. However, they utilized only five years of data.

These recent efforts highlighted the need to understand the regional pattern of net CRF over India in recent times in view of the seasonal cycle of cloud characteristics. In this study, we analyze and present a 13-year seasonal climatology of net CRF in the Indian monsoon region (Fig. 1) for the period of Mar. 2000–Feb. 2013 using radiative fluxes from the CERES and cloud properties derived from MODIS measurements. CERES products include both solar-reflected and Earth-emitted radiation from the TOA to the Earth's surface. Cloud properties are determined using simultaneous measurements by other Earth Observation Satellite (EOS) instruments such as MODIS and the Visible and Infrared Sounder (VIRS). CRF estimation from the measurement of flux is similar to the earlier studies (described in detail in the next section). The major contribution of our study is the analysis of 13 years of data covering all the four seasons in recent years, while the previous studies (as discussed above) either focused on only the monsoon season or earlier decades. The spatial and seasonal variability of net CRF are reported. The results are discussed in view of the existing study and a comparative note with the results from ERBE era is presented.

2. Satellite data and analysis

2.1. CERES data

The CERES SYN1deg product (version 3A) gridded globally at $1^\circ \times 1^\circ$ spatial resolution has been used for this study. The dataset include TOA all-sky and clear-sky outgoing SW and LW flux, solar irradiance and albedo. More details are available online (http://ceres-tool.larc.nasa.gov/ord-tool/jsp/SYN1degSelection.jsp). The CERES instrument is a three-channel (SW in 0.3–5 μm, TIR in 8–12 μm and total 0.3–200 μm) broadband scanning radiometer with a spatial resolution of 20 km at nadir (Kim and Ramanathan, 2008). These measured radiances at a given Sun–Earth–satellite geometry are converted to outgoing reflected solar and emitted thermal TOA radiative fluxes. The products are

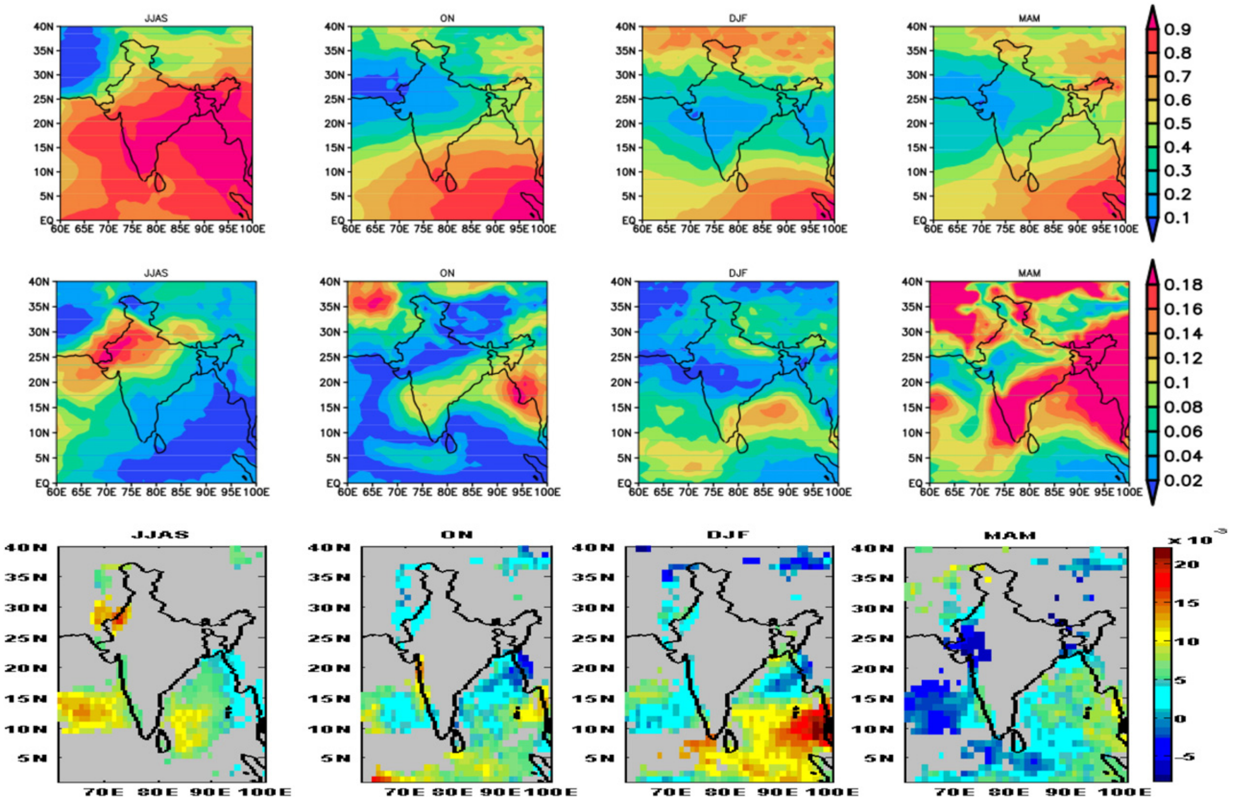

Fig. 1. Spatial variations of mean (upper panel) seasonal f_c, 1σ of f_c (middle panel) and trend (f_c per year) during the study period over the Indian monsoon region for the period Mar. 2000–Feb. 2013. Only the trends significant at 95% CI are shown in the bottom panel.