A comparative study on cloud radiative forcing over Sri Lanka and Indian monsoon region

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ABSTRACT

Total and high clouds are comparatively less over Sri Lanka compared to Bay of Bengal. Though the clouds over Sri Lanka and Bay of Bengal are of similar height, the cloud optical thickness is less over Sri Lanka when compared to Bay of Bengal. The subsidence appears to suppress the cloud growth over Sri Lanka. During summer monsoon season only middle and high clouds are present over Sri Lanka, possibly advected from faraway places by tropical easterly jet. The magnitudes of shortwave CRF (Cloud Radiative Forcing) and longwave CRF are less when compared to Bay of Bengal but equal in magnitude. Hence near cancellation of shortwave CRF and longwave CRF is found over Sri Lanka. The CRF components show a strong seasonal cycle over Bay of Bengal but such seasonality is absent over Sri Lanka. Among the middle and high clouds, altocumulus, cirrus and cirrostratus are predominantly over Sri Lanka. It is found that cirrus and cirrostratus clouds influence the NCRF (Net CRF) over Sri Lanka but the influences are opposite in nature. Present study suggests that as the cirrus cloud cover increases, the NCRF is tending to be positive. But in case of cirrostratus, increase in cloud cover leads to higher cooling. Complex interaction between these two clouds with radiation may be the cause for the observed near cancellation of shortwave CRF and longwave CRF over Sri Lanka.

1. Introduction

Clouds exert a large influence on the radiation budget of the earth-atmosphere system. They reflect a fraction of the incoming solar radiation and thereby cool the system and trap a fraction of the outgoing longwave radiation and thereby warm the system. Clouds of different types, cloud top heights, cloud fraction and micro-physical properties influence the radiance balance differently. For example, net cloud radiative forcing is negative over the sub-tropical low cloud regions, positive over regions covered by cirrus clouds, near zero over the tropical deep convective clouds and negative over the Indian summer monsoon region *(Kiehl and Ramanathan, 1990; Kiehl 1994; Rajeevan and Srinivasan, 2000; sathiyamoorthy et al, 2004).*

By affecting micro and macro-physical properties of the clouds, prevailing atmospheric circulation over a region is found to influence the radiation budget (e.g. *Sohn and Smith, 1992; Bony et al, 1997)*. Earlier studies pointed out that the unusual subsidence motion occurred during 1998 El Nino reduced the cloud top height and thereby influenced the net cloud radiative forcing (NCRF) over the Western Pacific warm pool region. *Sathiyamoorthy et al (2004)* suggested that the horizontal spreading of Asian summer monsoon cloud tops by the strong wind shear associated with the upper tropospheric tropical easterly jet stream increases the cloud cover amount which helps to reflect the solar radiation more effectively. Increased reflection leads to an unusual cooling by clouds over the Asian Monsoon Region (AMR). By this way, the tropical easterly jet has a profound influence on the radiation budget over the Asian monsoon region. *Bony et al (1997)* showed that the changes in large scale vertical motion accompanying sea surface temperature (SST) changes is the reason behind the strong dependence of shortwave cloud radiative forcing (SWCRF) and longwave cloud radiative forcing (LWCRF) to SST.

Several observational and modeling studies were made to understand the climate sensitivity feedback process of the clouds. Some of them pointed out that there is a large spread of cloud feedback among the climate models that may be a major source of uncertainty for climate sensitivity estimates *(Cess et al, 1990; Colman, 2003; Stephens, 2005).* Hence the understanding the cloud-radiation interaction is very much essential to have a more meaningful understanding of our climate and climate projections from climate model simulations.

Top of the atmosphere cloud raditive forcing refers to the difference in earth radiation budget components between clear-sky and all-sky conditions. The cloud radiative forcing terms shortwave cloud radiative forcing (SWCRF), longwave cloud radiative forcing (LWCRF) and net cloud radiative forcing (NCRF) at top of atmosphere are defined as follows:

SWCRF = S (α_{clr} - α)

Where, S is the monthly mean incoming solar flux at the top of the atmosphere and α and α_{clr} are all-sky and clear-sky albedo respectively of the earth-atmosphere system. The SWCRF is generally a negative quantity because clear-sky reflected shortwave flux is less than all-sky reflected shortwave flux. LWCRF =

F_{clr} – F

Where, F and F_{clr} are all-sky and clear-sky longwave fluxes at the top of atmosphere. The LWCRF is generally a positive quantity because clear-sky emitted longwave flux is more than all-sky emitted longwave flux.

NCRF=SWCRF+LWCRF

The NCRF is either a positive or a negative quantity depending upon the magnitudes of SWCRF and LWCRF.

2 Cloud radiative forcing over the Globe

The global average LWCRF in July is around 30Wm^{-2} and it is the greenhouse effect of the clouds. It is larger than that resulting from the doubling of CO_2 by a factor of 7. The CO_2 concentration in the atmosphere has to be increased by more than two orders of magnitude to produce a greenhouse effect comparable to that of the clouds. The SWCRF for July is -46 Wm^{-2}. The NCRF, which is the sum of longwave and shortwave cloud forcing, is -16 Wm^{-2}. A negative cloud forcing of similar magnitude was also obtained for other months. Thus, the clouds have a net cooling effect on the globe.

2.1 Cloud radiative forcing in the tropical region

In the tropics, SWCRF and LWCRF of deep convective clouds are nearly equal in magnitude but opposite in sign. It is well known that the cooling and the warming effect of the clouds nearly cancel out each other (Fig. 2.1) in the deep convective regions of the tropics (*Kiehl,1994; Kiehl and Ramanathen, 1990 and Hartmann et al., 2001*). Fig 2.1 clearly shows the observed near cancellation of LWCRF and SWCRF over the Western Pacific with a lot of deep convective activity in April.

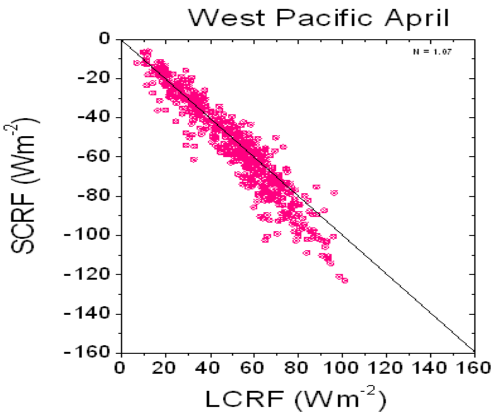

Fig. 2.1 Variation of LWCRF (Wm^{-2}) and SWCRF (Wm^{-2})during 1985-1989 in the Equatorial Western Pacific with deep convective clouds During April (Sathiyamoorthy et al, 2004, Journal of Climate

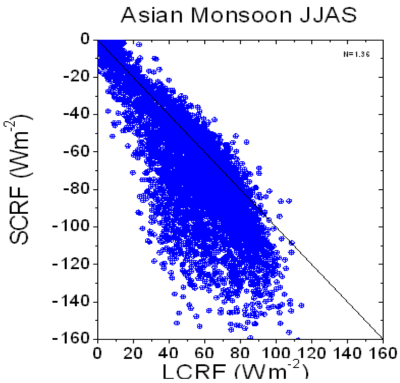

Fig. 2.2 Variation of LWCRF (Wm^2) and SWCRF (Wm^2) during 1985-1989 in the AMR during June – September (Sathiyamoorthy et al, 2004, Journal of Climate)

2.2 Cloud radiative forcing in the Asian monsoon region (AMR)

The NCRF at the top of the atmosphere is negative and near cancellation is found to be invalid (*Rajeevan and Srinivasan, 2000*) over the AMR (Fig 2.2) during the summer monsoon season (June-September), though it is situated inside the tropical latitudes. The value of NCRF is < -30Wm^2 over a considerable large area (typically **25%**) during the June-September period.

This cooling behavior of the Asian summer monsoon region was mainly attributed to the persistence of large amount of high altitude clouds with high cloud optical depth, which is unique feature of this region (*Rajeevan and Srinivasan, 2000*). Due to strong upper-tropospheric Easterly wind Tropical Easterly Jet (TEJ) in the AMR cool this region by spreading the cloud tops and increase the high-cloud amount (Fig. 2.3) during the summer monsoon season (*Sathiyamoorthy et al, 2004*). They suggest that apart from TEJ, other meteorological (e.g., shift in the position of convective clouds between excess and deficient monsoon years) and cloud microphysical properties such as cloud water amount, ice particle size, shape etc may also affect the CRF in the AMR.

3. Data

The ERBE S-4 data archive (*Barkstrom, 1984*) consists of monthly mean all-sky and clear-sky radiative fluxes (longwave and shortwave) at the top of atmosphere at 2.5^0×2.5^0 latitude-longitude resolution. Errors in individual clear and overcast sky measurements in ERBE data are estimated to be less than 2% and much lower when time and space averages are performed (*Harrison et al., 1990*). The uncertainty limit of ERBE data is ± 10 Wm^{-2} (*kiehl, 1994*). Monthly averages of various cloud parameters are provided by ISCCP-D2 dataset on 2.5^0 latitude × 2.5^0 longitude grids.

A brief discussion about reliability of ISCCP data over the Indian region, can be found at *Bony et al.,(2000)*, but the inadequate diurnal coverage of the polar orbiting satellites caused several discontinuities in the data.

The NCEP/NCAR 40 years reanalysis should be a research-quality data set suitable for many uses, including weather and short-term climate research. The data are available in 2.5^0 latitude × 2.5^0 longitude grid resolutions.

Two multispectral precipitation products, the 3-hourly and monthly TRMM Multi-satellite Precipitation Analysis (TMPA) products (3B42 and 3B43) are the most popular because of their high spatial and temporal resolutions. For this study 3B42 and 3B43 data sets are used.

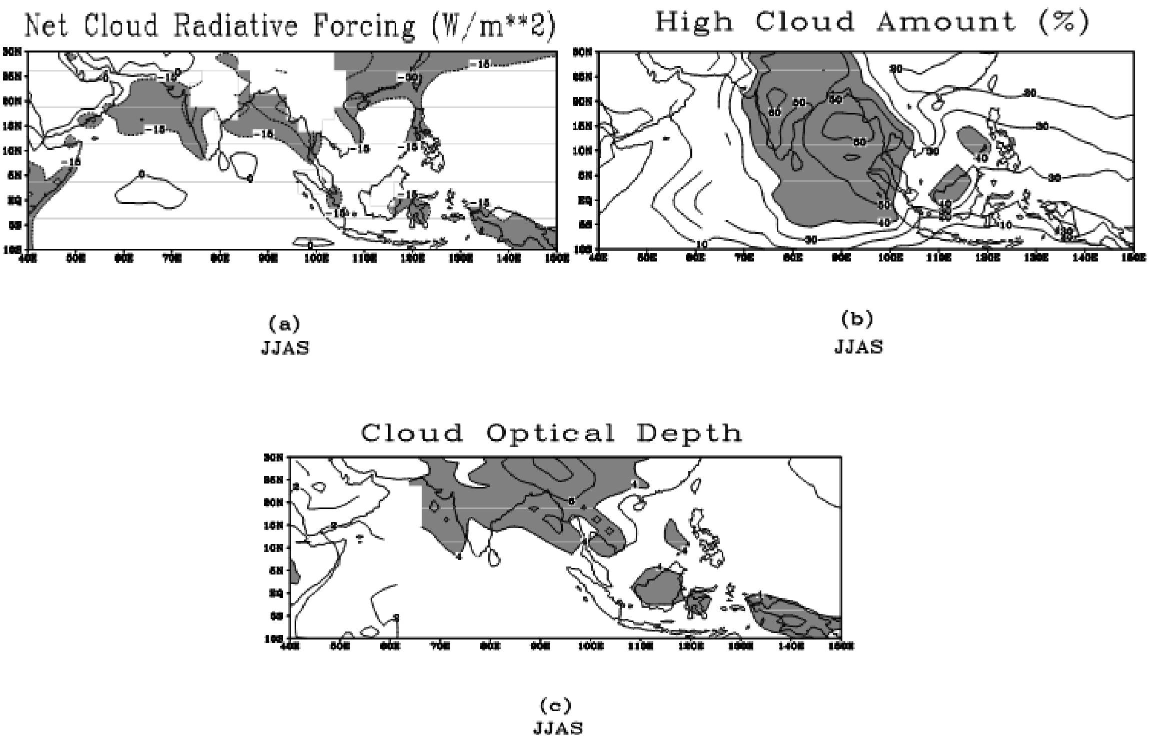

Fig. 2.3 The 5 year (1985-1989) mean (a) NCRF (Wm^{-2}) (b) high-cloud amount (%) (c) cloud optical depth over the Asian monsoon region for June to September months. (Sathiyamoorthy et al, 2004, Journal of Climate)

4. Methodology

For the present study, rainfall, cloud physical and radiative properties over Sri Lanka are compared with those over the Indian monsoon region. Since Indian monsoon region is bigger than Sri Lanka, two equal 10^0 longitude × 7^0 latitude boxes one situated over Sri Lanka (5^0N -12^0 N; 78^0E -88^0 E) and another representing IMR over head Bay of Bengal (15^0N -22^0 N; 85^0N -95^0 N) are selected (Fig. 4.1). The differences and similarities and the causes behind the observed cloud radiation interaction between Sri Lanka and Bay of Bengal regions are analyzed in this study by examine over the two boxes.

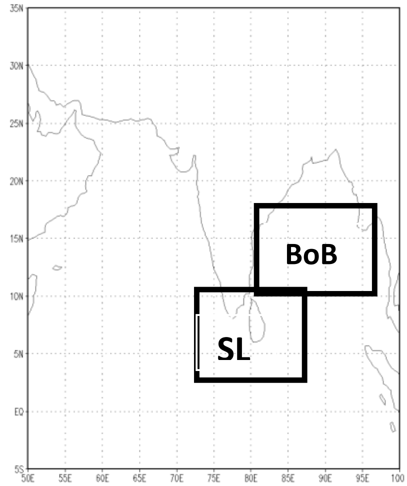

Fig. 4.1 Map of the study region showing Sri Lanka (SL) and North Bay of Bengal (BoB) boxes considered for the comparison study.

5 Result and discussion

5.1 Comparison of Cloud Physical properties between Sri Lanka and India.

In this study, cloud physical and radiative properties over Sri Lanka and India are studied during the summer monsoon season. Fig 5.1 shows 8-year average (2000-07) total and high cloud cover over Indian monsoon region during the peak monsoon months of July and August.

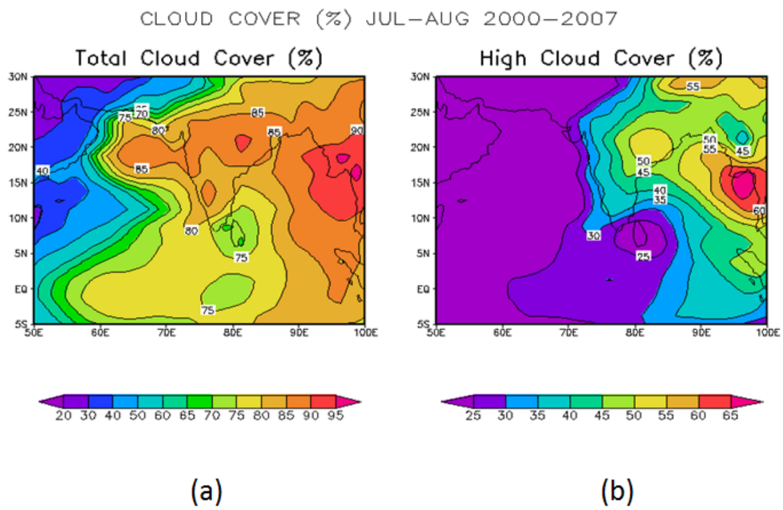

Fig. 5.1 (a-b) The 8–year (2000-07) average (left) total cloud cover amount (%) and (right) high cloud cover amount (%) over Indian monsoon region during July-August months.

Fig 5.1 sugge*sts* that though the total cloud cover over Sri Lanka is more (about 75%) it is slightly less than that over the central parts of India and northeast Bay of Bengal. The high cloud cover suggests that there is considerable decrease in high cloud cover over South Indian Peninsula and Sri Lanka where subsidence prevails. The high cloud cover is about 25% over the Sri Lanka whereas it is more than 60% over northeast Bay of Bengal. Other important cloud physical parameters that help to understand the characteristics of clouds are cloud optical depth (COD) and cloud top pressure (CTP). Fig. 5.2 shows distribution of 8-year average (2000-07) CTP and COD over IMR during peak monsoon season.

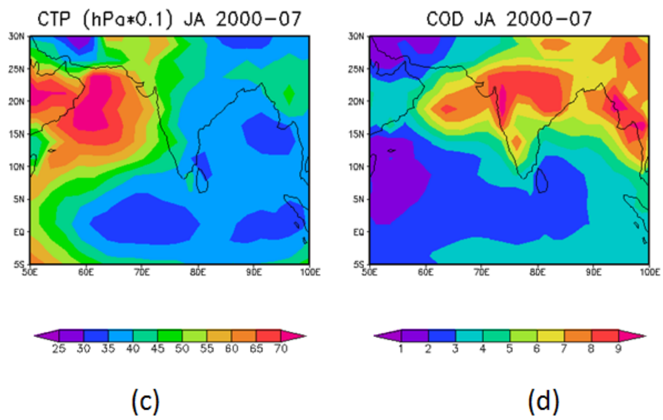

Fig. 5.2 The 8–year (2000-07) average (a) cloud top pressure (b) cloud optical depth over Indian monsoon region (5°S- 30°N and 50°E - 100°E) using ISCCP data.

Over Bay of Bengal and South Indian Ocean including Sri Lanka, CTP is almost comparable and it varies between 300 hPa - 400 hPa. It clearly signifies that tall clouds are present over this region during Indian monsoon season. i.e., clouds over Sri Lanka are of similar height to that of Bay of Bengal. Fig. 5.2-(b) shows COD over IMR. It is interesting to note that COD is very much different between Sri Lanka and central India Bay of Bengal region. The COD is more than 5 and reaching up to 10 over Central India and northeast Bay of Bengal where as it is 3 or less over Sri Lanka. Hence it is clear that though the cloud tops over Sri Lanka are comparable to that of Indian monsoon and Bay of Bengal regions, Clouds over Sri Lanka are optically thin. The large differences in COD may play an important role in modulating cloud-radiation interaction over these two regions.

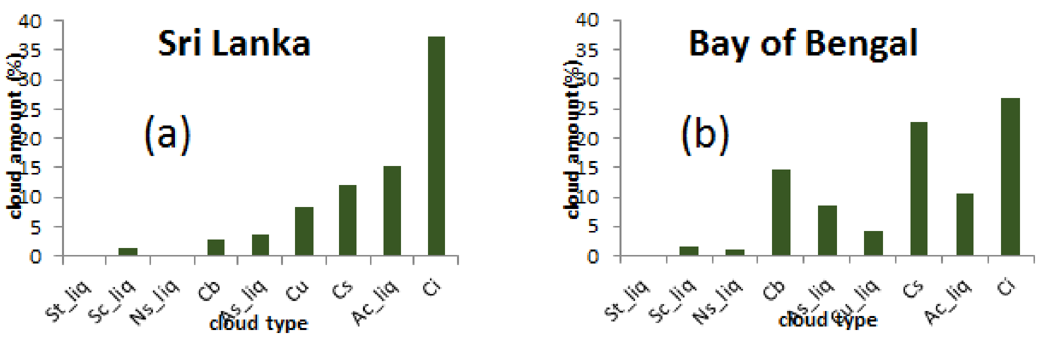

Fig. 5.3 The 5–yr (1985-89) average cloud amount over (a) Sri Lanka (5°N- 12°N and 78°E - 88°E) (b) Bay of Bengal (15°N- 22°N and 85°E - 95°E) during July and August using ISCCP data.

Fig 5.3 shows the 5-year (1985-89) average distribution of different ISCCP cloud types over Sri Lanka and Bay of Bengal during peak monsoon months of July and August for comparison. Over Bay of Bengal low (stratus, stratocumulus and cumulus), middle (nimbostratus, altostratus and altocumulus) and high clouds (cirrus, cirrostratus) are found during the monsoon season whereas only middle and high clouds found over Sri Lanka. This figure also confirms that Sri Lankan region is generally free of low and middle clouds possibly due to the subsidence prevailing over this region. It is likely that the subsidence is unfavourable for local cloud growth. Considerable amount of high cloud present over this region may possibly be due to the advection of cloud tops by tropical easterly jet similar to that observed over the Indian monsoon region. A recent study by *Rajeev et al.,(2011),* suggests that Sri Lankan region is generally free from low and mid-level clouds during monsoon season but loaded with a large amount of high clouds. They also suggested that large amount of high cloud cover over Sri Lanka may possibly be coming from the horizontal spreading of tall monsoon clouds found over northern and northeastern parts of Bay of Bengal by upper tropospheric tropical easterly jet stream as demonstrated by *Sathiyamoorthy et al (2004).* In contrast, low, middle and high clouds are all seen over Bay of Bengal. These differences in distribution of different cloud types may lead to differences in cloud radiative forcing over Sri Lanka when compared to Indian monsoon region.

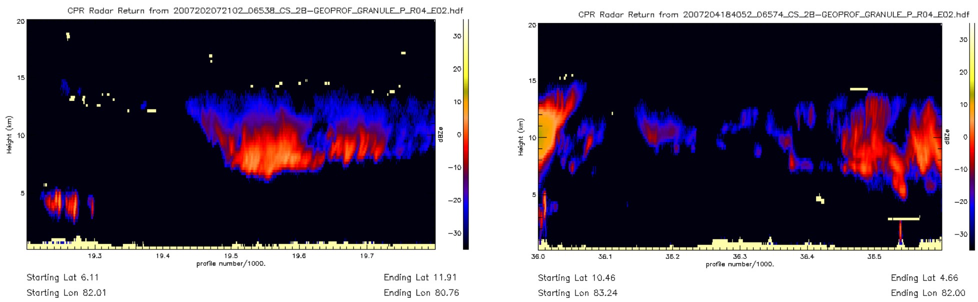

Fig 5.4 *Cloud Profiling Radar (onboard Cloudsat) returns over Sri Lankan region during July 2007. (Left) 22 July 2007 [starting positing of the satellite track 6.11 °N,82.01 °E and ending position 11.91 °N, 80.76 °E] (Right) 23 July 2007 [starting position 10.46 °N, 83.24 °E and ending position 4.66 °N, 82.0 °E]*

In Fig.5.4, Cloud Profiling Radar (CPR) returns from Cloudsat returns over Sri Lanka during 22 and 23 July 2013 (typical peak monsoon days) are shown. Both the image confirms that only middle and high clouds are present and low clouds are absent over Sri Lanka. These types of middle/high clouds alone can present over a regions when distant clouds are advected over the regions by strong upper tropospheric winds.

5.2 Comparison of CRF over Sri Lanka and India

In this section, the spatial distribution of CRF components namely SWCRF, LWCRF and NCRF during the summer monsoon season is studied. Fig. 5.5 shows 8-year average (2000-07) LWCRF, SWCRF and NCRF over IMR during peak summer monsoon months of July-August. Over Sri Lanka and Southern tip of India, LWCRF varies between 45 Wm^{-2} and 60 Wm^{-2} (Fig.5.5-a) whereas SWCRF varies between -30 Wm^{-2} and -60 Wm^{-2} (Fig.5.5-b). In Fig. 5.5-c the NCRF is shown and it varies from -5 Wm^{-2} to 5 Wm^{-2} over Sri Lanka and adjoining peninsular India. But over Central Indian and north Bay of Bengal, magnitudes of LWCRF and SWCRF are comparatively more. For e.g., over North Bay of Bengal, LWCRF is more than 70Wm^{-2} and magnitude of SWCRF is more than 100 Wm^{-2}. As a result, the NCRF is highly negative (< -50Wm^{-2}) over the North Bay of Bengal.

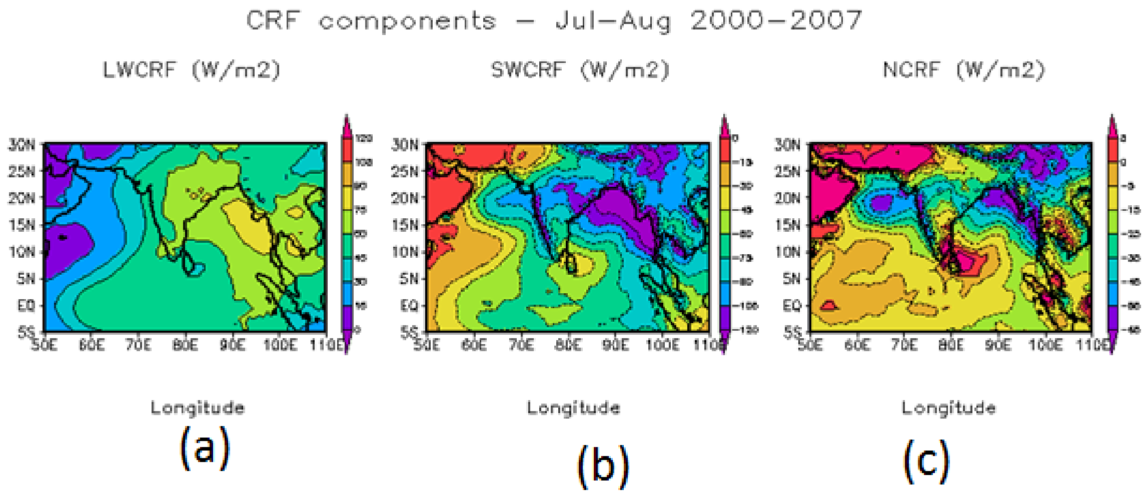

Fig. 5.5 8-year (2000-07) average (a) LWCRF (Wm^{-2}), (b) SWCRF (Wm^{-2}) and (c) NCRF (Wm^{-2}) during the peak summer monsoon months of July and August computed using CERES data.

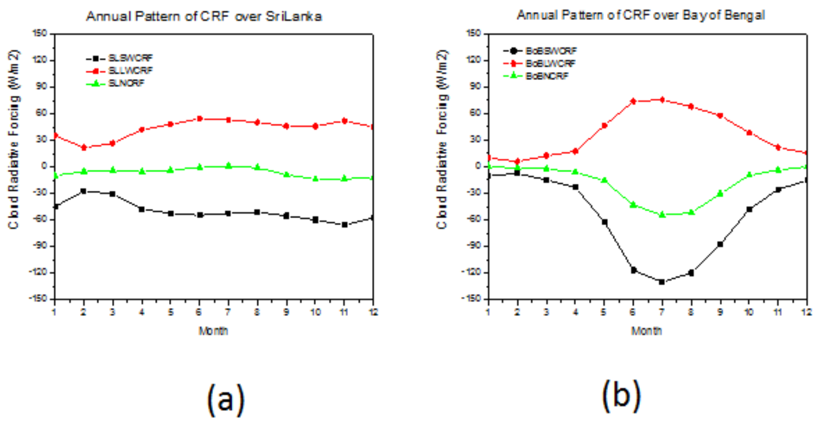

Fig. 5.6 Average annual evolution of CRF components over Sri Lanka and Bay of Bengal.

In Fig. 5.6, comparison between annual evolution of CRF components (SWCRF, LWCRF and NCRF) over Sri Lanka and Bay of Bengal are shown. Over Bay of Bengal, strong seasonality is seen in CRF components similar to the seasonality in cloudiness. The magnitudes of CRF components are high during monsoon months and close to zero in the winter/spring season. But such a strong seasonality is missing over Sri Lanka. CRF components are almost constant throughout the year.

In Fig. 5.7 variation of LWCRF and SWCRF over Bay of Bengal (Fig. 5.7-b) and Sri Lanka (Fig. 5.7-a) during peak monsoon season are presented for comparison in the form of scatter plots. Over Bay of Bengal, the magnitude of LWCRF is more than the SWCRF (cooling dominates warming) and hence a strong imbalance is found between them which leads to a net cooling over this region. Over Sri Lanka, a near cancellation between SWCRF and LWCRF appears to be existing. But the magnitudes of LWCRF and SWCRF over Sri Lanka are comparatively less. The ratio 'N' (defined as –SWCRF/LWCRF) averaged for

Bay of Bengal is 1.7, indicating a strong cooling by clouds whereas the N is 1.0, indicating the balance between SWCRF and LWCRF. But it is interesting to note that such a balance is generally found over deep convective regions of the tropics. The results of the previous analysis suggests that Sri Lanka is void of deep convective clouds (expect during break monsoon conditions of Indian monsoon) due to the presence of subsidence over this region. Hence it is interesting to study about the perfect balance between SWCRF and LWCRF over Sri Lanka. To understand the possible causes behind the perfect balance between SWCRF and LWCRF, further analysis has been carried out.

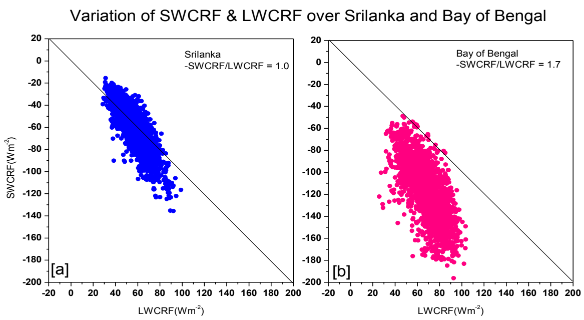

Fig. 5.7 Variation of LWCRF (Wm^{-2}) and SWCRF (Wm^{-2}) over (a) Sri Lanka and (b) Bay of Bengal during peak summer monsoon months of July and August year (2000-07).

5.3 Possible causes for the observed CRF over *Sri Lanka*

To understand the possible causes behind the observed near-cancellation between SWCRF and LWCRF over Sri Lanka, the association between ISCCP high cloud cover and CRF components have been studied using scatter diagrams and statistical correlations. It does not provide any useful information. Hence, association between prominently seen high and middle cloud types and CRF components over Sri Lanka has been explored. In Fig 5.8, the spatial distribution of four major cloud types found over Sri Lankan region is shown for the summer monsoon months of July-August. This figure also clearly suggests that cirrus and cirrostratus are the dominant clouds prevail over Sri Lanka during summer monsoon season though cumulus and altocumuls are also seen to small extent. Hence the association between cirrus and cirrostratus clouds and CRF over Sri Lanka will be explored.

In Fig. 5.9 scatter plots between the two important clouds namely cirrus and cirrostratus cloud cover and NCRF during the peak summer monsoon months of July-August is shown for the Sri Lankan and adjoining regions. It is interesting to note that both these clouds have statisticall*y* significant association with the NCRF over Sri Lanka. But the association is opposite in nature for these two cloud types. Whenever the cirrus cloud cover increases (due to the spreading of tropical easterly jet, etc), NCRF is tending to be positive. On the other hand, whenever cirrostratus cloud cover increases, NCRF is tending to be negative. In other words, increase in cirrus cloud cover leads to net warming and increase in cirrostratus cloud cover leads to net cooling over the Sri Lankan region during summer monsoon season. It is well known that cirrus clouds allow incoming solar radiation but effectively block the outgoing earth emitted longwave radiation due to their cold temperatures. So cirrus clouds exert a net warming effect. Increase iv cirrus cloud cover over Sri Lanka there for lead to net warming. But cirrostratus clouds are good in blocking incoming solar radiation. So increase in cirrostratus cloud cover leads to increased cooling. The correlation between cirrus and NCRF is

0.52 and cirrostratus and NCRF is -0.56 both are statistically significant at 99% confidence level. Over Sri Lanka, two high level clouds namely cirrus and cirrostratus having opposite effect on NCRF are present significantly when compared to other cloud types. The NCRF over Sri Lanka is a net result of cloud-radiation interaction of these two clouds and small contributions from other cloud types with marginal coverage.

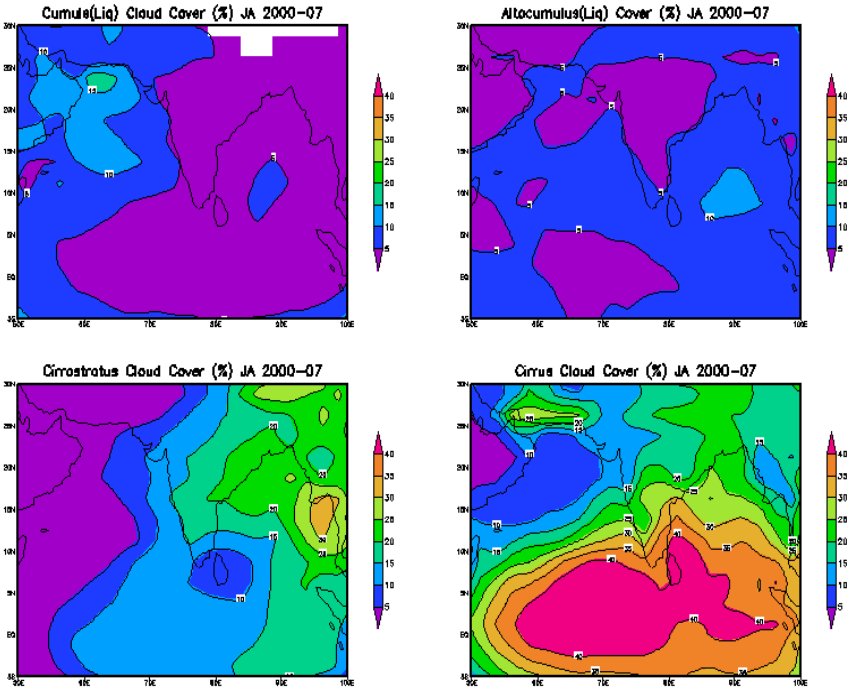

Fig. 5.8 8-year average cloud cover (%) for Cumulus(liquid), Altocumulus(liquid), Cirrostratus and Cirrus clouds during peak summer monsoon months of July-August.

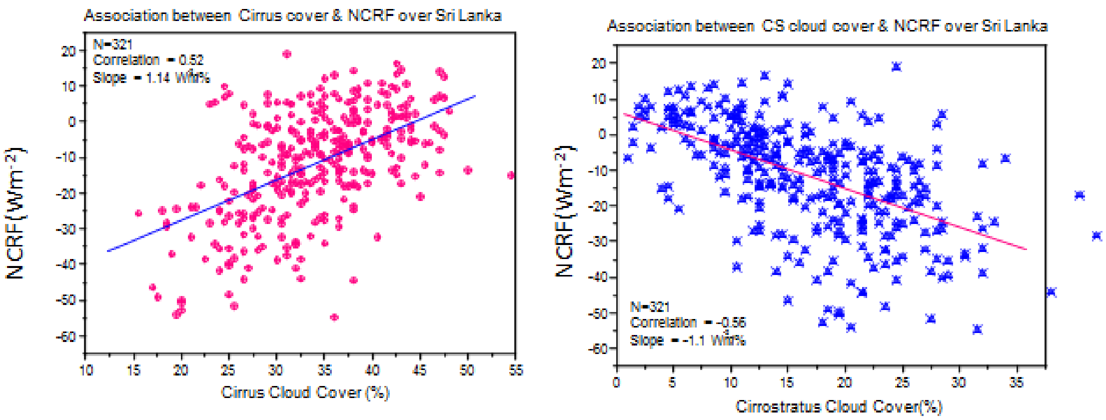

Fig 5.9. Scatter plot between cirrus and cirrostratus cloud cover (%) versus NCRF (Wm^{-2}) during peak monsoon months of July-August over Sri Lanka and its surrounding.

Conclusion

Sri Lanka is situated in subsidence region and as a result cloud development is less during Indian summer monsoon season. Over Sri Lanka low and middle cloud amounts during Indian summer monsoon season are less than 15%. But according to the ISCCP data it shows unusual large high cloud amount (more than 35%) with CTP around 300 hPa over Sri Lanka and adjoining Southern tip of India. Due to ISCCP cloud type analysis it proved present of Ci clouds and when consider its low COD and CTP around 300 hPa, it certify that they are optically thin tall clouds. Cirrostratus is the other important cloud type which affect to NCRF over Sri Lanka. Influence of these two dominant cloud types to NCRF is completely opposite. Increase in cirrus cloud cover leads to net warming and increase in cirrostratus cloud cover leads to net cooling over the Sri Lankan region during summer monsoon season.

Due to the positive correlation at about 0.405, between Ci cloud amount and TEJ (300 hPa) it concludes that the high clouds are swept by TEJ from nearest Bay of Bengal areas to Sri Lanka and Southern tip of India. Incoming short-wave radiation penetrates through these thin Cirrus clouds and these clouds are trapped outgoing long-wave radiation. As a result LWCRF is greater than or almost same to SWCRF and it causes marginally positive close to zero NCRF over Sri Lanka and Southern tip of India. Apart of that cloud microphysical properties and Meteorological parameters also can be effect to the marginally positive CRF with compared to surrounding areas of IMR.

Very small area over South-west of Sri Lanka and adjoining sea area it shows negative NCRF. Over this area convergence of low level winds take place and as a result cloud development is little higher than the other Sri Lankan area. On the other hand this particular area is situated in windward side of the central hills of Sri Lanka (peak around 2500 m) and because of that orographic effect also can be help to this cloud development. So, in the above area SWCRF is higher than LWCRF and show negative NCRF.

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