

Long-Term Trend of Cloud Fraction over the Indian Ocean in the Warming Era

Abstract

The long-term changes in clouds can lead to regional and global climate change. At present, the interaction of clouds with different earth system components is difficult to parametrise in the climate models. Hence, they are the major source of uncertainty in future climate projections. The key is to understand the long-term changes in cloud properties using observational datasets at a regional scale. Previous global and regional studies of clouds reported long-term trends in clouds up to 2009. However, the inadequacy of recent results and regional contrasts in results emphasise on the need to analyse the long-term trends in cloud properties at a regional scale and extend the analysis to the most recent years. Clouds over the Indian Ocean are vital for regional and global climate. Most cloud-related studies over the Indian Ocean are either of short study periods or focused on the cloud-aerosol-microphysical interaction, highlighting a need for studying long-term changes in clouds over the region. Among the micro- and macro-physical properties of clouds, cloud fraction (CF) stands out as a key parameter deriving the cloud-climate interaction. This study highlights the long-term changes and associated modulation of radiative feedback of CFs over the Indian Ocean.

Currently, all long-term CF datasets have limitations, ground-based and ship observation datasets suffer from limited temporal and spatial resolution and are not free from human bias. The satellite datasets often contain technical artefacts or are available for a short time duration, rendering them unsuitable for climate studies. European Centre for Medium-Range Weather Forecasts (ECMWF) fifth-generation reanalysis (ERA5) provides global three-dimensional CF data at $0.25^{\circ} \times 0.25^{\circ}$ spatial and hourly temporal resolution at 37 pressure levels for more than four decades, making it fit for climate studies. This study first evaluated the ERA5 CF against resolution-corrected Multi-angle Imaging Spectroradiometer (MISR), view-angle corrected Moderate Resolution Imaging Spectroradiometer (MODIS) and GCM-Oriented Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO) Cloud Product (CALIPSO-GOCCP) datasets.

The diurnal, seasonal, inter-annual and long-term variation of CF is evident over the Indian Ocean. During the period of the last four decades (1979-2018), the low-level CF (LCF) has

decreased by 0.04, the mid-level CF (MCF) has increased by 0.05, and the high-level CF (HCF) has increased by 0.05-0.12 over the Indian Ocean. The observed changes in the CF has caused a change in the LCF radiative feedback by $1.17 \times 10^{-3} \text{ Wm}^{-2}\text{K}^{-1}$ and a change in the MCF and HCF radiative feedback by $2.95 \times 10^{-3} \text{ Wm}^{-2}\text{K}^{-1}$ and $3.3 \times 10^{-3} \text{ Wm}^{-2}\text{K}^{-1}$ respectively. The temporal and spatial characteristics of all three types of clouds are well explained by sea surface temperature (SST). Additionally, a seasonally varying SST threshold between 28.5°C and 29°C for HCF is observed over the Indian Ocean, which has increased by 0.5°C in the last four decades. This study suggests that the overall warming and positive radiative feedback over the Indian Ocean is contributed by the long-term changes in the CF.

A novel ‘Diurnal Clock’ method has been used to scrutinise the seasonal and spatial patterns of the diurnal variations of CF in this study. The climatologically high values of LCF, MCF and HCF are observed to peak after midnight to morning hours, while the secondary values are observed to peak during afternoon to evening hours. The long-term changes in CF have altered the diurnal amplitude of clouds over the Indian Ocean. The diurnal amplitude of LCF has decreased, while the diurnal amplitudes of MCF and HCF have increased over the last four decades. The time of maximum CF (TCmax) over the Indian Ocean has also changed over the last four decades. The CF over the Indian Ocean shows an increase during midnight to morning hours and a decrease during the afternoon to evening hours. These results have important implications for the local energy budget and hydrological cycle.

All three types of clouds exhibited inter-annual variability from September to November (SON) period, with the highest inter-annual variability shown by HCF. This study asserts that inter-annual variability of CF over the Indian Ocean is predominantly governed by the direct and indirect consequences of mean-sea level pressure (MSLP) anomalies of the subtropical high. The CF increases over the western side during the positive phase of the Indian Ocean dipole (IOD) and El Niño. Conversely, the CF increases over the eastern side during the negative phase of IOD and La Niña. The inter-annual anomalies of CF over the eastern side of the Indian Ocean are governed by a mixed effect of SST and moisture convergence anomalies, while governed by moisture convergence anomalies over the western part of the Indian Ocean. During the positive phase of IOD and ENSO, the coastal upwelling and shallowing of

thermocline near the Indonesian Coast is triggered by the basin-scale spatial spread of MSLP anomalies. During the negative phase of IOD and ENSO, moisture over the eastern part of the basin is transported by the strong westerly wind anomalies near the equator.

In summary, the long-term changes of low-, mid-, and high-level CFs and the associated modulation of radiative feedback are highlighted in this study. The long-term changes in the diurnal amplitude of clouds are associated with long-term changes in the CF over the Indian Ocean. There has been a shift in the tendency of clouds to peak after midnight to morning hours as compared to afternoon to evening hours, and this transition suggests plausible changes in the diurnal temperature range, regional warming and changes in the precipitation patterns. Apart from the diurnal and long-term changes, clouds over the Indian Ocean are also affected by the IOD, ENSO and dynamics of subtropical high causing inter-annual variations in the spatial patterns of CF. The results of this study suggest the role of contrasting trends of CF in positive radiative feedback over the Indian Ocean.

Future research should expand the analysis by including a broader set of cloud-controlling variables to better understand the mechanism behind cloud formation and variability. Comparative modelling studies could be conducted to validate the cloud radiative feedback results obtained in this study. Additionally, the diurnal clock method could be applied to investigate the diurnal variation of clouds over other regions of the Indian Ocean, providing a more comprehensive view. Future work might also focus on identifying the underlying causes for the observed shift in the TCmax, particularly over the Bay of Bengal (BOB) region.