Climatology and Trend of Tropical Cloud Cover Using Gridded Satellite (GridSat) Data

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Research Article

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Abstract

Climatology and trend of different types of clouds over the tropics are studied using 22 year long (1998-2019) Gridded Satellite (GridSat) data. Brightness temperature in window and water vapor channel is used as the proxy for the cloud top altitude. Threshold and bispectral methods are used to classify clouds depending on their cloud top altitude. Clouds are classified into Low level clouds, Mid level clouds, Deep clouds, Very Deep clouds (VDC), and Semi Transparent Cirrus (STC) clouds. Climatology of the spatial distribution of each cloud type over the tropics is examined. Tropical mean of occurrence of different cloud types show a steady declining trend with a value of -0.18% /decade, -0.06% /decade, -2.12% /decade, -2.29% /decade for mid level clouds, deep clouds, STC, total clouds respectively. Low level cloud shows a steady increasing trend of 0.08% /decade. Interestingly, VDC shows a steady declining trend up to 2011, and thereafter it shows a significant increasing trend of 0.1% /decade. Though the spatial distribution of total cloud cover generally shows a negative trend, the Western equatorial Pacific Ocean, Indian subcontinent, Indian Ocean, and Saharan desert region show a positive trend. Though low level clouds show an increasing trend, the regions of abundant low clouds show a negative trend. VDC show a declining trend over the western Pacific region, whereas other prominent VDC regions show a positive trend.

1. Introduction

As an important component of the climate system, clouds significantly affect the hydrological cycle and energy budget of the earth-atmospheric system. They do exist on a wide range of time and space scales. Cloud cover and its temporal evolution predominantly drive the variability of atmospheric reflectivity that determines the amount of solar radiation reaching the Earth's surface (Danso et al., 2019). Through various dynamic and thermodynamic processes, clouds also have significant feedbacks on the atmospheric circulation and climate (Stephens, 2005; Bony et al., 2006; Huang et al, 2015). Because of the disagreement among climate models and observational datasets, perhaps, clouds are the largest uncertainty in our understanding of climate change (Dufresne and Bony, 2008). A large degree of uncertainty in global climate models (GCMs) due to the inaccuracy of cloud representation is the main reason for the uncertainty in climate sensitivity estimates and climate change predictions (Collins et al. 2013; Bony et al. 2015). To reduce this uncertainty, long-term and high-resolution cloud observations from both surface and satellite-based remote sensing are highly essential. These observations could be used to formulate a better cloud parametrization and thereby improve existing models or develop a better climate model with higher spatiotemporal resolution (Huang et al, 2015).

Long term observations and climate models revealed that the cloud properties like cloud amount, height, thickness, geographical distribution, and morphology are being changed in the warming climate. Warren et al., (2007) by using surface observations for a period of 1971–1996 and Dim et al. (2011) by using satellite observations during 1982–2006, reported that the global cloud cover over land is declining. Mao et al., (2019) studied global mean cloud cover by using Moderate Resolution Imaging Spectroradiometer (MODIS) data from 2003 to 2012 and reported that cloud cover over land areas (especially North America,
Antarctica, and Europe) decreased, whereas cloud cover over ocean areas (especially the Indian and Pacific Oceans) increased. Also, Warren et al., (2007) reported a declining trend of cirrus cloud cover over all continents. Eastman and Warren (2013) reported a declining trend in total cloud cover of the order of 0.4% /decade and this is due to the declining trend of middle latitude’s high and middle level clouds. Hong et al., (2008) examined the occurrence of mean tropical deep convective clouds and found a slightly decreasing trend with − 0.016% /decade in 1999–2005 while the mean convective overshooting has a distinct decreasing trend with − 0.142% /decade. Using surface observation of upper-level clouds from 1952 to 1997, Norris (2005) found an overall decline of cloud cover over the tropical ocean in general and the Indo-Pacific region in particular. However, Dai et al (2006) reported an increasing trend of total cloudiness over US by using surface and satellite observation from 1976 to 2004. Kaiser (1998; 2000) studied the trends in Chinese total cloud amount for the period 1951–1994 by using a database of 6-hourly weather observations and found that a decreasing trend in both midday and midnight cloud amount over much of China with a statistically significant decreases of 1–3% sky cover per decade.

The availability of long-term and homogeneous global observations of clouds is one of the main difficulties to examine the climatology of the global cloud cover. Even though surface observations of cloudiness may enable the study of climatology and trends, these are available only at selected meteorological stations and their time series are often inhomogeneous (Karl and Steurer, 1990). However, the present day uses a long time series of observations by different satellite sensors to examine the climatology of global cloud cover and properties. The International Satellite Cloud Climatology Project (ISCCP; Schiffer and Rossow 1983; Rossow and Schiffer 1999) leading the satellite based study of the climatology of cloud cover and cloud properties globally since 1983. The ISCCP uses the spectral channels common to the operational weather satellites—the 0.5-µm visible channel, the 6.7-µm infrared water vapor channel, and the 11-µm longwave infrared window channel. The IR channel senses Earth’s surface under clear-sky conditions, cloud-top temperatures of thick clouds, and a combination of cloud and surface for optically thin clouds or broken clouds within a pixel, and the visible channel also provides information on clouds and the surface. The water vapor channel is sensitive to humidity in the upper troposphere. Cloud information is also available from reanalysis products, though it tends to underestimate the cloud cover (Bedacht et al. 2007; Griggs and Bamber 2008; Naud and Booth 2014). Model simulations of cloud cover and their comparison with observations are also available in the literature(eg. Klein et al. 2013; Enriquez-Alonso et al. 2016)

The present study attempted to examine the climatology and the recent trend in the occurrence of different cloud types over the tropics by using a 22-year long brightness temperature data obtained from Gridsat for a period of 1998 to 2019. Section 2 describes the data and method of analysis which followed by results and discussions in Sect. 3. Section 4 summarizes the present study.

2. Data And Methodology

This study is uses 22 years of Gridded Satellite (GridSat) data (Knapp et al., 2011) from 1998 to 2019 to examine the climatology and the trend of different cloud types over the tropics. GridSat data are derived
from the ISCCP B1 data (Knapp, 2008b) having similar spatial, temporal, and spectral features to the Hurricane Satellite (HURSAT) dataset (Knapp and Kossin 2007), but at a global scale. The spatial resolution of the GridSat data is at an equal area grid of 0.07° latitude (~8 km at the equator) and spans the globe in longitude and ranges from 70°S to 70°N in latitude. The spatial and temporal coverage of the satellites contributing to ISCCP B1 is provided in Fig. 1 of Knapp et al., (2011). The data derive from full-disk images of these satellites whose scans are closest to the synoptic times 0000, 0300,. . ., 2100 UTC. GridSat data provide observations of the infrared window and visible channels at 11 and 0.6 µm, respectively during the entire period of records. Whereas, the infrared water vapor channel near 6.7 µm is available since 1998, on a global basis. Since both the infrared window and water vapor channel data is available from 1998, the data period of this study is started from 1998 onwards. Data are calibrated and stored in GridSat files as brightness temperature (T_b) for longwave channels and reflectance for the visible channel. GridSat data attempted to reduce intersatellite differences by intersatellite normalization and also performs temporal normalization via calibration against High-Resolution Infrared Radiation Sounder (HIRS) during the GridSat period of record. GridSat IR calibration uncertainty is less than 0.5 K for any satellite with a very stable temporal uncertainty that is less than 0.1 K decade^{-1} (Knapp et al., 2011).

In this study, the brightness temperature (T_b) data in the water vapor (WVIR) and thermal window (TIR) channel obtained from GridSat used as the proxy for cloud top altitude (Roca et al., 2002; Rajeev et al., 2008) to classify the different types of clouds in terms of its altitude of occurrence. The clouds are classified using the threshold criteria followed by Muhsin et al., (2019) and Roca et al., (2002). Table 1 summarizes the thresholds used in this study. The cloud top altitudes identified using these T_b thresholds are validated by Meenu et al. (2010) with those obtained from CALIPSO observations and showed a fairly good agreement between the two. The clouds are classified into Low level, Middle level, Deep, Very deep, and Semi Transparent Cirrus (STC) clouds. STCs and low level clouds are obtained by using bispectral methods (Roca et al., 2002) and other clouds are classified using threshold methods (Muhsin et al., 2018). All the cloud types except STC are optically thick and T_b from the window channel is sufficient to determine the cloud top altitude. Whereas, in the case of STC, the radiance observed in the window channel does not correspond only to the cloud top, but weighted by the radiation emitted from the altitudes below. This causes the T_b observed in the window channel through a thin cloud to be larger than the actual T_b of the cloud top, leading to erroneous identification of such cirrus as warm clouds. T_b from the water vapor channel is highly sensitive to the clouds and humidity content in the upper troposphere (Soden and Bretherton, 1993), and hence a combination of T_b observed in the window and water vapor channel can be used to detect STC (Desbois et al., 1982). The occurrence of each cloud type is calculated for each file (every three hours) from 1998 to 2019 over the tropics. These cloud occurrences are later used to obtain the climatology as well as the trend of each cloud type over the entire tropics.
Table 1

| Cloud type                   | TIR threshold | WVIR threshold | Cloud top altitude |
|------------------------------|---------------|----------------|-------------------|
| Low level cloud              | 280 > TIR > 270 | WVIR > 246     | < 2km             |
| Mid level cloud              | 270 > TIR > 246 | --             | < 8km             |
| Deep cloud                   | 246 > TIR > 210 | --             | < 14km            |
| Very Deep cloud              | TIR < 210     | --             | > 14km            |
| Semi Transparent Cirrus cloud| TIR > 270     | WVIR < 246     |                   |

3. Result And Discussion

Figure 1 shows the mean and standard deviation of 22 yearlong brightness temperature (T_b) in the window (~ 10.5 µm) and the water vapor (~ 6.7 µm) channel over the tropics. It should be noted that there are discontinuities that can be seen in the data at the borders between areas covered by different satellites and this is more clear in the water vapor channel. Since T_b is the proxy for the clouds, this figure depicts the climatology of clouds over this region. The larger value of T_b in the window channel corresponds to clear sky or low level clouds and the smaller values represent the presence of clouds with higher cloud top altitude. Mean T_b in the window channel varies from 255 K to 295 K and the spatial pattern shows the typical cloud climatology over the tropics with smaller values of T_b at ascending limbs of walker circulation and in the regions of Inter Tropical Convergent Zone (ITCZ) indicating the presence of deeper clouds. The higher values of T_b are shown at the subtropical high pressure zones over the oceans and the subtropical deserts over land. This indicates that these regions are either cloud free region or there exist low level clouds. The outlines of the Andes Mountains, Himalayas, and Tibetan Plateau are also seen in the mean window channel T_b plot and these are likely the surface emissions caused by high-altitude mountains. Mean T_b from water vapor channel is also shows a similar spatial pattern as that of T_b in window channel with values varies from 230 K to 255 K. Generally, T_b in the Water vapor channel is taken as a proxy of concentration of water vapor in the upper troposphere. A low value of the T_b implies a higher concentration of water vapor in the upper troposphere. The standard deviation of both T_b shows that the regions of larger deviation of T_b observed are the regions having smaller mean T_b values and the regions of smaller deviation of T_b are the regions of larger values of mean T_b exist. This indicates that the regions where large values of mean T_b are observed always exist either cloud free conditions or only low level clouds. Similarly, the regions with smaller mean T_b values (large deviation in T_b) indicate that the cloud occurrence varies significantly. This may be due to seasonal or inter annual or decadal variations of cloud occurrence.

Figure 2 shows the climatology of the spatial distribution of occurrence of different types of clouds derived from T_b by employing the threshold conditions and bispectral method, detailed in the previous
The occurrence of a particular cloud type means the relative percentage of occurrence of that cloud type with respect to total observations including clear sky condition. The spatial distribution of the total cloud is obtained by summing up all clouds derived from the $T_b$. Clouds are present nearly all the time over the ascending limb of the walker circulation, namely the western Pacific and Indonesian region, Central Africa, and Northern South America. Nearly 80% of the time clouds are present along the ITCZ regions and the southwestern Pacific Ocean. The cloud occurrence at the northern hemispheric subtropics is comparatively less (50–60 %) and the regions of southern hemispheric eastern Pacific and the Atlantic Ocean exhibit very less cloud occurrence (~ 20%). Comparatively large occurrence (~ 20%) of low level clouds are observed near the coast of Chile and moderate occurrence (~ 10%) of low level clouds are observed near the Atlantic coast of southern Africa, Southern Indian Ocean, Australia, and eastern China. Northern hemispheric desert region and Pacific coast of Mexico are showing a lesser (~ 5%) occurrence of low level clouds. The occurrence of Mid level clouds, Deep clouds, and very deep clouds show a similar spatial pattern with different occurrence values with large values for mid level clouds and least values for very deep clouds. The spatial occurrence of STC also shows an almost similar pattern as that of mid level clouds with a wider area of occurrence.

Figure 3 shows the 22-year variation of the monthly mean occurrence of different clouds over the entire tropics (30° S – 30° N). The red and blue lines are the best fit lines determined using the linear regression model and these are above 95% significant level. The occurrence value of each cloud type is with respect to the total observations including clear sky conditions. The occurrence of tropical low level clouds is 1–4% with maximum and minimum occurrence during June-July and February-March months respectively. It shows a positive trend of occurrence with a value of 0.08% /decade. Whereas, Mid level clouds show a declining trend of occurrence with a value of -0.18% /decade. It shows a clear seasonal pattern with maximum occurrence up to 12% during the winter season. The deep cloud occurrence is 5.5–7 % with a maximum occurrence during the winter season. This cloud type also shows a decreasing trend of -0.06% /decade. Very deep clouds (cloud top altitude above 14 km, including overshooting clouds) occur 0.6 to 0.8 % of the time and do not show a clear seasonal pattern. Unlike other cloud types, VDC shows a peculiar trend of occurrence. It shows a decreasing trend up to 2011 and suddenly the trend becomes positive with a value of 0.1% /decade. This is a significant trend value when compared to its total occurrence and it means that VDC occurrence is increasing 1.3% every year. STC took a major contribution towards the total cloudiness of the tropics with an occurrence frequency of 36–48 %. This cloud also has a negative trend line with a value of -2.12% /decade. Over the tropics, the occurrence of the total cloud is 54–66% and it has a steady decreasing trend with a value of -2.29% /decade. This large value of the decreasing trend is majorly contributed by the STC trend. The decreasing trend of total cloud cover and STC is already reported by Warren et al. (2007) and Dim et al. (2011).

In order to examine how these mean tropical trends of different clouds are spatially distributed, the trend at each pixel of satellite observation is calculated and presented in Fig. 4. As mentioned in Fig. 1, the discontinuities at the borders between areas covered by different satellites are clearer, especially in the subplots of total clouds and STC. Though total cloud cover generally shows a negative trend, the western
equatorial Pacific Ocean, Indian subcontinent, Indian Ocean, and Saharan desert region show a positive trend. Southern hemispheric Pacific Ocean loses its cloud cover at the rate of \( \sim 0.1\% / \text{decade} \). Low level clouds generally show an increasing trend. Whereas, subtropics of the Indian Ocean region and the Pacific coast of the Mexico shows a negative trend of low cloud cover. Interestingly, these are the pockets of abundant low level clouds. Mid level and deep clouds show an almost similar pattern of cloud cover trend with the positive trend at western and northeastern Pacific Ocean, North Africa, and the Indian region. STC shows a similar spatial pattern as that of the total cloud. Though STC shows a declining trend in general, it shows an increasing trend across the longitude region of the Indian subcontinent. Pandit et al. (2015) also reported an increasing trend of the sub-visible cirrus clouds over the Indian region by using 16 years of lidar observations. VDC shows a decreasing trend over the western Pacific region, whereas the other prominent VDC regions show a positive trend. Interestingly, the western equatorial Indian Ocean shows a positive trend though it is not a prominent VDC occurring region.

Eastman and Warren (2013) reported a declining trend of global total cloud cover of the order of 0.4% /decade and this is due to the declining trend of high and middle level clouds in the midlatitude. Also, they reported that the declining trend of zonal cloud cover indicates the poleward shifts of the jet streams in both hemispheres. The present study also shows a declining trend of total cloud cover over the tropics but for a larger magnitude. Hong et al. (2008) studied the trend of tropical deep convective and overshooting clouds during 1999–2005 and found that both are in the decreasing trend. Though the present analysis also in consistent with this result during the period, it shows an increasing trend from 2011. Wylie et al. (2005) reported a small but statistically significant increase of high clouds (cloud top altitude \(< 440 \text{ mb} \)) over the tropics and the northern hemisphere by using NOAA High Resolution Infrared Radiometer Sounder (HIRS) polar-orbiting satellite data from 1979 to 2001. Norris (2005) studied the spatial pattern of linear trends in upper level cloud cover using surface observations over the tropical Indo-Pacific Ocean during 1952–1997. They reported that upper-level cloud cover increased by about 4% over the central equatorial South Pacific and decreased by about 4–6% over the adjacent subtropics, the western Pacific, and the equatorial Indian Ocean. The present study also observed a similar trend over the western Pacific and the equatorial Indian Ocean. However, the other two regions show an exactly opposite trend in high cloud cover. Norris (2005) also mentioned that the calculated trend is a linear trend and the trend direction may change in the future. Norris et al. (2016) reported that cloud amount is increased over the northwest and southwest tropical Pacific Ocean, the northwest Indian Ocean, and north of the Equator in the Pacific and Atlantic oceans. The present study also showing a very similar cloud cover trend at all the above mentioned regions except for the southwest tropical Pacific Ocean which shows a decreasing trend in this study.

4. Summary

22 year long (1998–2019) brightness temperature \( (T_b) \) data in window and water vapor channel from Gridded Satellite (GridSat) data is used to examine the climatology and trend of different types of cloud cover over the tropics. \( T_b \) is used as the proxy for the cloud top altitude and classified different types of
clouds depending on its cloud top altitude by employing the threshold and bispectral methods. Mean $T_b$ in the window channel varies from 255 K to 295 K and that for the water vapor channel is 230 K to 255 K. The spatial distribution of mean values shows a typical tropical cloud climatology with smaller values at the ascending limb of Walker circulation and larger values at the descending limb. The variability of $T_b$ values is larger in the regions of small mean values of $T_b$ and vice versa. Climatological spatial distribution of total cloud cover reveals that most of the times (~ 80%) clouds are present along the ITCZ regions and the western Pacific Ocean and whereas the regions of southern hemispheric eastern Pacific and the Atlantic Ocean exhibit very less cloud occurrence (~ 20%). Low level clouds are abundant over the coast of Chile, the Atlantic coast of southern Africa, the Southern Indian Ocean, Australia, and eastern China. Mid level clouds, Deep clouds, and very deep cloud cover show a similar spatial pattern with different occurrence values. STC is also showing an almost similar pattern but with a wider area of occurrence. Different cloud types show a steady decreasing trend with a value of -0.18% /decade, -0.06% /decade, -2.12% /decade, -2.29% /decade for mid level clouds, deep clouds, STC, and total clouds respectively. Low level cloud shows a steady increasing trend of 0.08% /decade. Interestingly, VDC shows a steady decreasing trend up to 2011, and thereafter it shows a significant increasing trend with a value of 0.1% /decade. Though the spatial distribution of total cloud cover generally shows a negative trend, the western equatorial Pacific Ocean, Indian subcontinent, Indian Ocean, and Saharan desert region show a positive trend. Though low level clouds show an increasing trend, the regions of abundant low level clouds show a negative trend. VDC shows a decreasing trend over the western Pacific region and other prominent VDC regions show a positive trend.

Declarations

Acknowledgment

GridSat data is downloaded from https://www.ncei.noaa.gov/data/geostationary-ir-channel-brightness-temperature-gridsat-b1/access/. This work is done during the period of the National Postdoctoral Fellowship grant PDF/2018/ 001128 from the Science & Engineering Research Board of the Department of Science and Technology (DST- SERB), India.

Conflict of interest

The author declares that he has no conflicts of interest.

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Availability of data and material

GridSat Data is publically available from www.ncei.noaa.gov website.

Code availability
GridSat data analysis code is available from the public domain. The author is ready to provide the analysis code on request.

**Author Contribution**

Muhsin - Study concept and design, Data Collection, Analysis, Interpretation, Manuscript preparation

**Ethics approval**

NA

**Consent to participate**

NA

**Consent for publication**

NA

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Figures
**Figure 1**

Climatological mean and standard deviation of brightness temperature in the window (TIR) and Water vapor (WVIR) channel obtained from GridSat data during 1998-2019. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

**Figure 2**
Climatology of the spatial distribution of different types of tropical cloud cover derived from GridSat data from 1998 to 2019. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

**Figure 3**

Variation of monthly mean cloud cover over the entire tropics (30° S – 30° N) from 1998 to 2019 obtained from GridSat data. Red and blue lines are the best fit lines obtained from the linear regression model and these are above 95% significant level.

**Figure 4**

Spatial distribution of trend of different clouds over the tropics obtained from the linear regression model. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.