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Research Article

Statistical Study of Cloud Vertical Structure in Troposphere Derived from High Resolution Radiosonde Measurements Over Addis Ababa - Ethiopia (9.010 N, 38.760E)

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Abstract

Clouds are mixtures of water droplets or ice crystals suspended at a certain height in the atmosphere, and formed when water vapor in the atmosphere reaches saturation. They are significant in the global radiation budget, atmospheric circulation, and hydrological cycle. However, knowledge regarding the observed climatology of the cloud vertical structure (CVS) over Ethiopia is still poor. Based on four years high-resolution radiosonde observations in Addis Ababa, Ethiopia (9.010 N, 38.760E), the CVS climatology, including the frequency distribution and seasonal variations, are investigated. Overall, the occurrence frequency of clear sky cases in Addis Ababa is slightly higher than that of cloudy sky cases, and cloud occurrence of frequency is highest in kiremt and lowest in bega. This is related to the accumulation of moisture in the atmosphere due to the effect of Inter Tropical Convergence Zone in the summer (kiremt) season. The occurrence of midlevel cloud is more frequent than that of high level cloud in all years demonstrating that mid-level cloud is dominant over Addis Ababa. The average cloud top height (CTH), cloud base height (CBH), and cloud thickness for mid-level clouds are 5 km, 2.4 km, and 2.6 km respectively. In case of high level clouds, CBH is 5.2 km having a CTH of 9.8 km, with cloud thickness of 4.6 km.

Keywords: Radiosonde; Cloud Vertical Structure; Relative Humidity; Dew Point Depression

Introduction

Clouds are mixture of water droplets or ice crystals suspended at a certain height in the atmosphere and formed when water vapor in the atmosphere reaches saturation, so the cloud vertical structure (CVS) can be obtained by identifying the saturated levels in the atmosphere. Clouds play a significant role in modulating the energy budget, atmospheric circulation, and hydrologic cycle of the Earth [1]. There are large uncertainties in the net impact of clouds on the energy radiation budget due to two opposite effects depending on cloud thickness i.e high clouds tend to warm the surface by absorbing long wave radiation, while low clouds tend to cool the surface by reflecting solar radiation [2]. Aerosols can directly influence the energy balance of the earth-atmosphere system by scattering and absorbing solar radiation [3]. Aerosol particles can also alter cloud microphysical processes and affect precipitation by acting as cloud condensation nuclei [4]. The impacts of cloud on the radiation balance of the Earth–atmosphere system depend not only on the vertical structure and distribution of the cloud but also on its base and top heights and optical properties [5]. Cloud vertical structure affects, and is affected by atmospheric dynamics, thermodynamics, and the hydrological cycle, as well as the radiation budget at the surface and within the atmosphere. Clouds have been recognized as a primary source of uncertainties in global weather and climate studies [6]. Ground based active sensors, such as cloud radars, lidars, and ceilometers, can provide cloud measurements with high accuracy and with continuous temporal coverage. However, these instruments are deployed at few locations around the world. The advent of space borne cloud radar and lidar now allows us to see through clouds and to develop cloud vertical structure on a global scale [7,8]. Radiosondes can also penetrate cloud layers to provide in situ cloud data. The vertical distributions of temperature, relative humidity and pressure measured by radiosondes are fundamental to the study of atmospheric thermodynamic and dynamic processes and provide information about the cloud vertical structure by identifying saturated levels in the atmosphere [9]. [10] estimated the cloud base and cloud top using temperature dependent dew point depression threshold derived from radiosonde by calculating the dew point depression at every height level in northern hemisphere. [11] (WR95 method) also determine cloud vertical structure by using radiosonde data with a slight modification of the PWR95 [10] method by computing RH with respect to ice instead of liquid water, for temperatures lower than 0^0C. [12] presented the trends in time series of cloud bases and tops from 795 radiosonde stations from 1964 to 1998 by utilizing the Comprehensive Aerological Reference Data Set (CARDS) and the method of second derivatives of temperature and humidity. [13] comprehensively analyzed the frequency distribution and seasonal variation of the cloud vertical structure over a tropical station in India during the period from 2006 to 2017, based on high-resolution radiosonde measurements. Based on 20-year global daily radiosonde profiles, [14] investigated the geographical distribution and seasonal variation of the cloud vertical structure by applying a relative humidity threshold method. Regarding our study area Ethiopia, till date insufficient studies had been reported on cloud vertical structure using radiosonde data, hence we are motivated to conduct preliminary work on cloud vertical structure using radiosonde data over Addis Ababa- Ethiopia. Accurate observations of CVS are crucial to improve the understanding of cloud-related processes and further to increase the predictive capabilities of large-scale models. The present work reports the first time determination of cloud vertical structure and seasonal variations using atmospheric thermodynamic profiles using long-term high vertical-resolution radiosonde observations over Addis Ababa, Ethiopia.

Material and Methods

Radiosondes are battery-powered telemetry instrument packages that are carried into the atmosphere typically by a weather balloon; they measure altitude, pressure, temperature, relative humidity and wind (both speed and direction) at high altitudes and transmit them by radio to a ground receiver. Radiosonde observations have been carried out daily at the Addis Ababa synoptic meteorological station since 1969. The radiosonde data from Addis Ababa synoptic meteorological station has undergone quality checks by Global Radiosonde Archive (IGRA) through scrutinizing presence of physically implausible values, climatological outliers, and temporal and vertical inconsistencies in temperature [15]. In this study, we use high-resolution sounding data at Addis Ababa station **(**9.01^0N, 38.76^0E**)** covering the period from 2017–2020 to validate cloud vertical structure at this site. Addis Ababa radiosonde station is the only available radiosonde station in Ethiopia.

Methodology

In this study, 4 years of high vertical-resolution radiosonde data are used to analyze CVS over Addis Ababa, Ethiopia. There are several methods proposed by different authors [9-12] (to determine cloud vertical structures from radiosonde profiles, among them we adopted the methodology proposed by [10,16] in our study. First we check the presence of cloud at a given atmospheric level.

$$\Delta T_d < 1.7^0c \text{ at } T > 0^oc, RH > 91.5\% \text{ at } T > 0^oc$$
$$\Delta T_d < 3.4^0c \text{ at } 0 > T > -20^oc, RH > 83\% \text{ at } 0 > T > -20^oc$$
$$\Delta T_d < 5.2^0c \text{ at } T < -20^oc, RH > 74\% \text{ at } T < -20^oc$$

Then relative humidity is converted to RH of ice for temperatures less than 0 ^{o}c.

Where ΔT_d is dew point depression ΔT_d= T- T_{dew}

Further we can determine cloud layers according to method developed by [16]. First, dew point depression must be calculated at every height level. Then, three pressure-dependent dew point depression thresholds are applied to find cloud layers:

$$\Delta T_d < 1.5^oc \text{ at } 1000hpa > P > 800hpa, RH > 92.5\% \text{ at } 1000hpa > P > 800hap$$
$$\Delta T_d < 2.5^oc \text{ at } 800ha > P > 550hpa, RH > 87.5\% \text{ at } 800hpa > P > 550hpa$$
$$\Delta T_d < 5^oc \text{ at } 550hpa > P > 300hpa, RH > 75\% \text{ at } 550hpa > P > 300hpa$$

Results and Discussion

In this section we analyzed four years radiosonde measurements of temperature, relative humidity, dew point temperature and dew point depression of vertical profiles starting from 2.2 km to 15 km. Our instrument measures data from 2.2 km onwards, henceforth we do not have chance to analyze and identified low level clouds which presumed to be persisted below 2 km with their lower bases [5,13]. A sample profile of temperature, relative humidity, dew point temperature and dew point depression is depicted in figure 1 (Jul_26_2020). We clearly identified mid-level and high level clouds between 2.4 km to 9.8 km. Mid-level clouds appeared with CBH and CTH around 2.4 km and 5 km respectively with cloud thickness of 2.6 km (Figure 1). Whereas high level clouds appeared with CBH and CTH are 5.2 km and 9.8 km respectively with thickness of 4.6 km. These results are in agreement with [13] which states that mid-level cloud bases ranging from 2-5km and high level clouds from 5 km onwards.

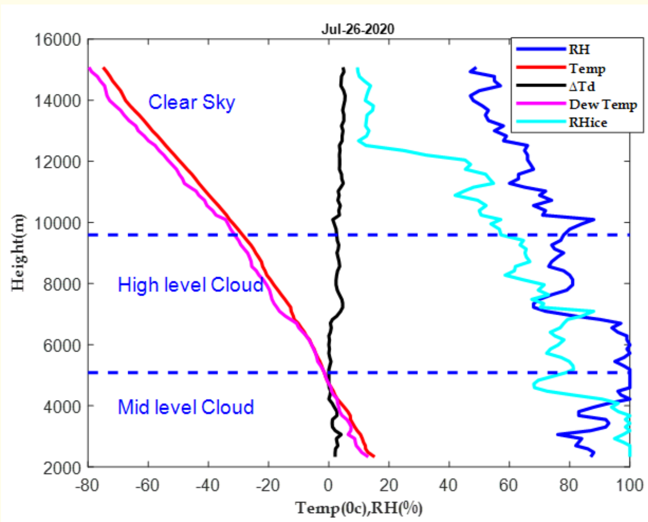

Figure 1: Cloud vertical structure derived from radiosonde measurements on July 26_2020.

Monthly variation of frequency of cloudy sky and clear sky

In this section we explore monthly variations of frequency of occurrence of cloudy skies and clear skies. The occurrence of frequency of cloudy profile or clear sky profile is defined as the ratio of the number of cases identified as cloudy or clear sky to all the valid radiosonde launches respectively. Frequency occurrence of monthly variations of cloudy skies for the individual period of 2017-2020 is shown in figure 2 (a, b, c, d) and for clear skies in figure 3 (a, b, c, d). It is evident from both figures, cloud cover increase starting from Jun to August and then decrease starting from September in all years. In 2017 the maximum occurrence of frequency of cloud cover is observed during September (25%) while in 2018 it shows maximum in Jun and November (21%). For the years 2019 and 2020, maximum occurrence of frequency exists in July and August (23% and 33%). The cause behind the maximum cloud cover during kiremt season (Jun, July and August sometimes September) are related to warm and moist air prevailing during this season, high amount of aerosol loading and the existence of much amount of moisture in the atmosphere. When there is warm air, there will be more vapor either from water bodies, plants or other sources that leads to form high amount aerosol in the atmosphere and these aerosols contributes for the formation of cloud that act as cloud condensation nuclei [3].

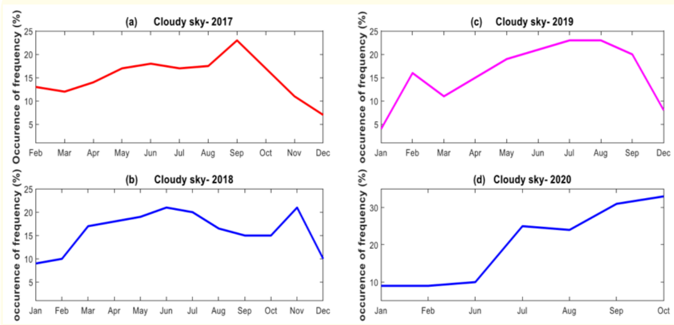

Figure 2: Monthly occurrence of frequency of cloudy sky from 2017-2020.

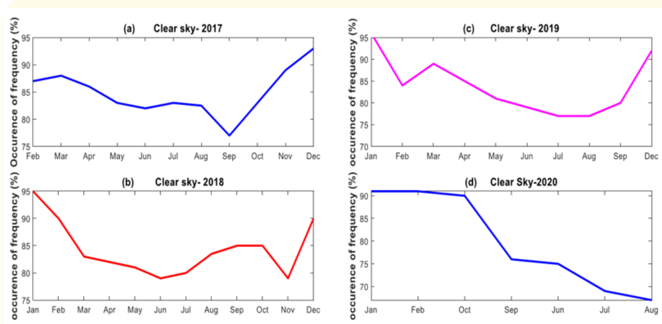

Figure 3: Monthly occurrence of frequency of clear sky from 2017-2020.

In addition to this local moisture source, there also oceanic moisture transport from different sources aided by a considerable moisture uptake along routes across the African continent. The Indian Ocean, the Congo Basin and the Red Sea were found to be important moisture source regions in Jun-August and the moisture flow from the Gulf of Guinea; flow from the Indian Ocean; flow from the Mediterranean region across the Red Sea and the Arabian

Peninsula identified as main transportation of moisture [17]. In contrary bega and belg months (January, February, March…) clear skies are occasionally observed. This is due to the existence of cold temperature that leads to decrease evaporation rate from the surface and results small amount of moisture in the atmosphere, small loading of aerosol contributes for the very small or no cloud formation over Ethiopia [3].

Seasonal variation of occurrence of cloud

In this section we separated clear sky from cloudy sky occasions based on the raw profiles of radiosonde observations using the method described in section 2. Further we analyzed the frequency of occurrence of clear and cloudy skies at different seasons in each individual years 2017-2020. Ethiopian seasons are classified as; summer (Kiremt) (June - August); autumn (Meher) (September-November); winter (Bega) (December – February) and spring (Belg) (March– May). Occurrence of frequency is defined as the ratio of the number of cases identified as mid or high level cloud to all the valid radiosonde launches respectively. In order to segregate frequency of occurrence of cloudy and clear skies at different seasons for the year 2017, the total number of raw profiles for Kiremt is1998, Meher is 1891, Bega is 343 and Belg is 904, among them the number of cloudy skies are 150, 147, 16, and 54 which accounts for 7.5%, 7.7%, 4.6% and 6% occurrence frequency.

Similarly for 2018, total number of raw profiles taken during Kiremt, Meher, Bega, and Belg are 2066, 1409, 580 and 1898, respectively. The numbers of cloudy profiles in these seasons are 180, 124, 25 and 162, and frequency accounts for 8.7%, 8.8%, 4.3 and 8.5%. During 2019, total number of profiles taken in Kiremt (1024), Meher (244), Bega (3574), Belg (996), and number of cloudy profiles in these seasons are 288, 33, 105, 72 accounts for occurrence of frequency of cloudy profiles 22.2%, 11.9%, 2.9 and 7.2% respectively. Maximum frequency of cloud exists in kiremt (~22.2%) and reaches a minimum in bega (~2.9%). In case of 2020, total number of profiles taken during Kiremt are (4399), Meher (3420), and Bega (1137) among those, the number of cloudy profiles in these seasons are 1208, 575, and 99, respectively. Cloudy profiles account for 27.5%, 16.8%, and 8.7%. Hence, the occurrence of frequency of clouds peaks in kiremt (~27.5%) and reaches a minimum in bega (~8.7%). Finally it is observed that the occurrence of frequency of cloudy sky is highest in kiremt and lowest in bega season in all

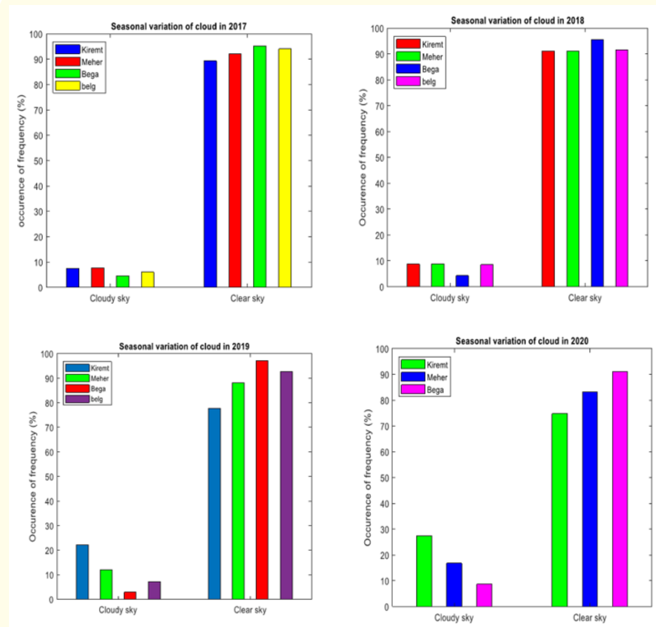

Figure 4: Occurrence of frequency of cloud in each season from 2017-2020.

years (2017, 2018, 2019 and 2020). It indicates that clouds occur more frequently in kiremt which is mainly related to warm and moist atmospheric conditions. Warm air can hold more water vapor than cold air and this water vapor condense to form moisture in the atmosphere which is responsible for the formation of cloud. During summer season evaporation rate also high and these forms aerosols in the atmosphere that can serve as cloud condensation nuclei (CCN) upon which cloud droplets and ice crystals forms [3]. In addition, moisture transport from different sources like Indian Ocean and Mediterranean ocean also contribute for the formation of clouds in Ethiopian continent [17]. Our results are in consistent with previous studies [18] stating that the frequency of occurrence of single-layer and multilayer cloud is highest in summer and lowest in winter in northern China based on cloud observing satellites CloudSat and Cloud Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO). [9] found that the occurrence of multilayer clouds is higher during summer than autumn over Shouxian. Hence, we conclude that clear sky appears more frequently during bega season of all years, which could be related to cold and dry atmospheric condition prevails in this station.

Average seasonal occurrence of frequency of mid-level and high level cloud

Occurrence of frequency of mid-level and high level clouds during different seasons is depicted in figure 5. High level clouds are more frequent in kiremt season during 2018 and 2020 (9.9% and 14.3%) respectively, but it is frequent in meher season during 2017 and 2019 (8.6% and 13.3%). In the case of mid-level cloud, it is more frequent in Meher season during 2017 and 2018 (8.3% and 8.5%) respectively, but frequent in kiremt during 2019 and 2020 (8.9% and 10.1%). Bega and belg season appears almost similar in case of mid-level clouds but it is very different in high level clouds during 2017. Meher and Belg season appears more frequently in both cases. The occurrence of midlevel cloud is more frequent than that of high level cloud in all years demonstrating that mid-level cloud occurrence is more dominant in Ethiopia.

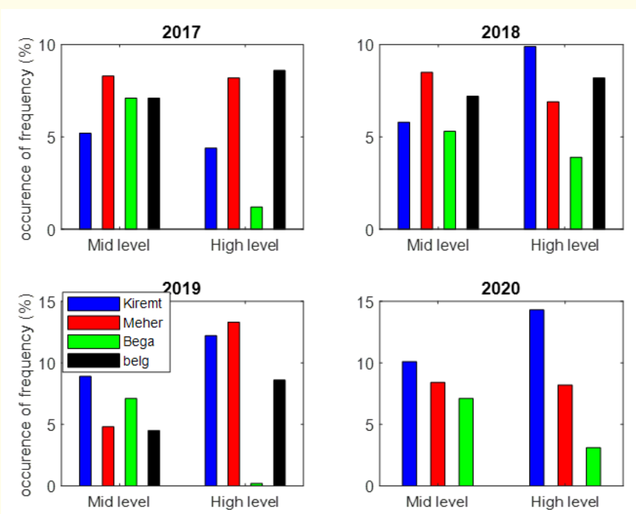

Figure 5: Average seasonal occurrence of frequency of mid-level cloud and high level cloud from 2017 to 2020.

Conclusion

In this article we explored, the cloud vertical structure, classification of cloud types and monthly and seasonal occurrence of frequency of clouds over Addis Ababa-Ethiopia based on four years (from 2017 - 2020) of radiosonde data. Our statistical analysis reveals that mid-level clouds exist in () height of the atmospheric region and high level cloud persists with cloud base height greater than 5km. Occurrence of frequency of cloudy cases (5-30%) over Addis Ababa is less than that of clear sky cases (75-95%). The occurrence of midlevel cloud is more frequent than that of high level cloud in all years demonstrating that mid-level cloud is dominant over Addis Ababa Ethiopia. Occurrence frequency of cloudy sky is highest in kiremt and lowest in bega season in all years. During kiremt season prevailing of warm and moist atmospheric conditions, high amount of aerosol loading in the atmosphere and the effect of inter tropical convergence zone (as warm, humid air rises in the ITZC, it cools, forming clouds) and moisture transport from different oceanic sources like Indian Ocean and Mediterranean ocean contribute for the formation of clouds in Ethiopian continent.

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Conflict of Interest

The authors declare that there is not any conflict of interests regarding the publication of this manuscript. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, and redundancy has been completely observed by the authors.

Life Science Reporting

No life science threat was practiced in this research.

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