An analysis of precipitation trend in Leh, Ladakh, Northern India

Grand Challenge Scholar Thesis

Submitted by

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Abstract

In the recent HinduKush Himalaya Assessment published by ICIMOD, a regional intergovernmental learning and knowledge sharing centre, the increased risk from natural hazards like floods, landslides, avalanches, droughts and earthquakes due to global climate change for Himalayan communities is highlighted. Such natural hazard is already occurring in Leh, a himalayan town in Ladakh, Northern India. Since the last two decades, Leh is experiencing an increase in hydrological disasters in the form of cloudburst and flash floods. The 2010 cloudburst and it’s subsequent flash flood received the most media attention however, it is one of many extreme precipitation events occurring in the region. Despite the growing importance, there’s a lack of scientific study that attempts to understand the region’s changing climate. Therefore this paper studies the changing precipitation pattern in the region using daily precipitation data from Integrated Multi-satatelliteE Retrievals for GPM (Global Precipitation Model). Using Mann Kendall trend test, an increasing trend in daily mean precipitation is observed in the region. However, no significant trend is observed for extreme precipitations happening in the region.

1. Introduction

Ladakh, a cold desert is nestled amongst Zanskar and Ladakh mountain ranges within the Trans-Himalayan region, between the Great Himalayas to the south and the Karakoram to the north (Ziegler et al., 2016). The region receives an annual precipitation of 115 mm on average (Thayyen et al., 2013) as it is situated in the rain shadow area of the Trans-Himalayan region. However, in the last two decades, noticeable change in the precipitation pattern has been observed in the form of cloud bursts, flash floods, debris flows and snowstorms in the region (Ziegler et al., 2016). One of the most devastating events experienced by the locals was a cloudburst in 2010 which was followed by flash flood in the town center of the region - Leh and its neighbouring areas. Some initial reports claimed that the rainfall intensity reached 100mm/h. The official record however lists rainfall depths of only 12.88mm on 5 August, and 21.4 mm on 6 August (Ziegler et al., 2016). The devastating event took 234 lives and 800 more people were reported missing according to an army hospital record (Gupta et al., 2012). The livelihood and living situation of the locals were severely affected as crops, roads, bridges and houses were either washed away or destroyed. A total of 71 villages were badly affected with >1450 houses completely or partially destroyed (Ziegler et al., 2016). Similar flooding events were experienced in other parts of Ladakh such as Achinathang, Phuktel, Gya, Kargil and UleyTokpo in the last two decades. The 2010 flood received a lot of media attention and was studied widely by the research community compared to other flooding events in the region.
In recent years, there’s a growing interest from both the physical and social science research community to understand the changing climate of the region. Most of the research studies are focused on studying the climate adaptation strategies of the communities. Of the few physical science based studies, a large portion of the studies (Bhan et al., 2015; Banerjee & Dimri, 2019; Thayyen et al., 2013) conducted in the region focused mainly on singular events such as cloudburst in 2010 instead of a broader climate analysis. *Climate change over Leh (Ladakh), India* published in 2016 is one of the few papers that studied the changing precipitation pattern of the region. The study included both temperature and precipitation data to analyse the trend over the region using polynomial trend lines and Mann Kendall test. With the use of different climate datasets, the study period from 1901 to 2013 was broadly divided into three different periods as a result of the analysis. The period from 1901 - 1979 saw a rise in temperature but the precipitation was found to be low. While the temperature lowered between 1979 and 1991, precipitation increased in the region until 1995. During the last time period from 1991 - 2013, there was a rapid increase in temperature and a decreasing trend in precipitation after 1995. Although there was an inverse relationship between temperature and precipitation as indicated above, an increasing trend in the overall trend of precipitation and temperature of the region was observed (Chevuturi et al., 2016). Additionally, Yangchan et al. (2019), a study conducted to understand climate change induced impact on water resources of Ladakh region reported that irregular rainfall patterns and water scarcity are major problems in Ladakh region.

Very few climate studies have been conducted in Ladakh region since Chevuturi et al. (2016) paper. There is a lack of climate study that challenges or agrees with the findings from Chevuturi et al. (2016). Therefore, this study proposes a detailed analysis of precipitation trends over Leh and discusses the trend observed in the specified region.

2. **Study Area**

The study is focused on Leh, one of the two districts of recently formed Union Territory of Ladakh, in the northern part of India. The district was part of the former Jammu and Kashmir state. Ladakh is popularly known as a cold desert as it lies in the rain shadow area of the Indian Himalayan region. Leh is the urban center of the region and Ladakh Autonomous Hill Council, the regional governing body is seated in the city. It lies in the foothills of Ladakh range and in the catchment of the Indus River. It has an elevation of 3500 m (Chevuturi et al., 2016) and is spatially located at 34.15°N latitude and 77.58°E longitude. Two major highways in the region namely Leh-Manali Highway, Srinagar-Leh Highway pass through the area.
Based on the article titled “Ladakh Floods: A Timeline of Disaster”, other areas in Ladakh such as Achinathang, Phuktel, Gya, Kargil and UleyTokpo have a history of flooding and cloudburst in the last two decades. These regions however, are not as populated as Leh hence the risk and vulnerability of these are relatively lower than Leh. Therefore, Leh is the only location that is examined in this study.

3. Data and Methodology

To study the changing climate of the region, precipitation is the main climate variable that is analysed for the site. Two major types of precipitation data are gridded satellite data and in-situ rain gauge observations. The gridded precipitation data is acquired from Integrated Multi-satellitE Retrievals for GPM (IMERG), a unified algorithm that provides the multi-satellite precipitation product for the U.S. GPM (Global Precipitation Model) team. The dataset is derived from a data called GPM Level 3 IMERG *Final* Daily 0.1 x 0.1 arc. It has a spatial resolution of 0.1 x 0.1 arc, equivalent to 11.132km and a temporal resolution of 24 hours. Other options for gridded satellite precipitation datasets include CMORPH AND GPCP. Compared with IMERG datasets which are available only from 2000, these datasets have greater time coverage as they are available from 1998 (CMORPH) and 1979 (GPCP). However, they have lower spatial resolution of 0.25 x 0.25 arc (CMORPH) and 2.5 x 2.5 arc (GPCP) (Chevuturi et al., 2016). Therefore, GPM IMERG dataset is preferred in this study amongst other dataset as it has the best spatial resolution, an attribute that is required to characterize the region's precipitation trends better. Moreover, the record of IMERG datasets from 2000 is the most important dataset as the paper focuses mainly on observing precipitation trends in the last two decades. In-situ observations of the precipitation data despite its importance, are not used in this study due to limited access to these datasets.
India Meteorological Department and Indian Airforce Station data used in Chevuturi et al. (2016) are unfortunately not freely available on the internet. Therefore, only gridded satellite datasets are analyzed in this study.

The analysis begins with the extraction of required data from a larger IMERG dataset using the geographic coordinates of the region and finding the nearest gridded dataset. The extracted data is then further processed using x-array to form annual time series and seasonal time series data. X-array, a python package is a useful tool implemented in this analysis to simplify data processing with regards to labeled multidimensional dataset such as climate data.

To analyse these extracted data sets further, different statistical tools are employed using Python. First, daily mean precipitation is calculated using the simple average method over the entire time series. The spread of the precipitation data is found by calculating the standard deviation over the entire dataset. Using x-array, the annual time series is derived and the daily mean precipitation, it’s standard deviation and the 95th and 99th percentile for each corresponding year are calculated and plotted for the dataset. Seasonal time series is formed for four different seasons namely DJF(December, January, February for winter), MAM(March, April, May for spring), JJA(June, July, August for summer) and SON(September, October, November for autumn) using x-array. For each seasonal dataset, daily mean precipitation, its standard deviations are calculated and plotted. Extreme precipitations are also analyzed by plotting the 95th and 99th percentile of seasonal dataset in a particular year in Figure 3, 4, 5 and 6. Finally, the annual precipitation during a particular season is also calculated with its standard deviation.

The main component of the study is to analyse the trend of increasing or decreasing precipitation over the years in the region. For that, Mann Kendall, a non parametric statistical test is used. It is a popular method employed to determine monotonic trends in series of hydrological and climate datas. The null hypothesis of the test is the absence of monotonic trend whereas the alternative hypothesis indicates that the data follow a trend which may be either positive or negative trends. The strength of the trend is said to depend on the magnitude, sample size and variations in a data set. Additionally, the trend observed is not significantly affected by the outliers in the data series since the MK test statistic depends on positive and negative signs (Gedefaw et al., 2018).

All of the tests are run in a Python Jupyter notebook using pymannkendall, a python package for Mann Kendall family of trend tests. Each test run outputs eight values, out of which five of them provide the most valuable information for this study. The first two variables ‘trend’ and ‘h’ describes the existence of a trend explicitly. ‘Trend’ variable describes the increasing, decreasing or no trend in a data series. Variable h outputs ‘true’ if trend is present and ‘false’ if trend is absent. ‘p’ variable determines the p-value of the significance for the null hypothesis. If the p-value is high, the null hypothesis is accepted and if the p-value is lower than 0.05, the alternative hypothesis of a trend availability is confirmed.
Kendall Tau and Mann-Kendall score provides the test statistics for the analysis which describes the increase against time versus the decrease in the overall possible time-differences. Positive test statistics indicates an increasing trend within the time series and negative test statistics indicates a decreasing trend for the dataset Gedefaw et al., 2018).

4. Results and Discussion

4.1 Annual Statistical Summary

The primary goal of the study is to examine the changing precipitation pattern in the region. According to the analysis of IMERG precipitation dataset, 66.77 mm of rain falls on the site annually, on an average. Compared with average annual rainfall in neighbouring cities like Delhi, it is one-twelfth of the annual precipitation in Delhi which is around 800 mm. This agrees with the fact that Ladakh is a cold desert region with sparse rainfall. The variation in precipitation over the region is determined by standard deviation which is around 0.96. The mean of daily precipitation for a year varies annually as plotted in figure 1. In the plot, it is clearly seen that the daily average precipitation in 2010 (0.31 mm/day) and 2015 (0.39 mm/day) are relatively higher than the rest of the data set. The annual precipitation for the year 2010 and 2015 are also higher with 113 mm and 142 mm respectively. This corroborates with the ground reality of heavy flood occurrence in 2010 and 2015 (Sharma, 2018). Extreme precipitation events for the region are analysed by calculating the 95th and 99th percentile for each precipitation data set. As assumed, in 2010 and 2015, they have the highest 95th percentile precipitation value of 1.44 mm/day and 1.61 mm/day respectively. As for the 99th percentile plot, three highest peaks were observed in 2006, 2015 and 2018. This shows that the extreme precipitation occurred in 2006 and 2018 although the average precipitation value doesn’t indicate so.

![Figure 2. The plot of daily mean precipitation over the years with its standard deviation, 95th percentile and 99th percentile.](image-url)
Figure 3. The plot of annual precipitation data over the years.

<table>
<thead>
<tr>
<th>Precipitation Values</th>
<th>Annual</th>
<th>DJF</th>
<th>MAM</th>
<th>JJA</th>
<th>SON</th>
</tr>
</thead>
<tbody>
<tr>
<td>Daily mean (mm/day)</td>
<td>0.189</td>
<td>0.212</td>
<td>0.125</td>
<td>0.284</td>
<td>0.0135</td>
</tr>
<tr>
<td>Daily mean standard deviation</td>
<td>0.962</td>
<td>0.663</td>
<td>0.663</td>
<td>0.663</td>
<td>0.663</td>
</tr>
<tr>
<td>Annual mean (mm/year)</td>
<td>66.76</td>
<td>17.75</td>
<td>11.54</td>
<td>26.17</td>
<td>11.87</td>
</tr>
<tr>
<td>Annual mean standard deviation</td>
<td>11.91</td>
<td>11.92</td>
<td>6.44</td>
<td>22.79</td>
<td>10.98</td>
</tr>
</tbody>
</table>

Table 1. A table containing the daily mean precipitation, it’s standard deviation, annual mean precipitation and it’s standard deviation on both annual and seasonal basis. DFJ stands for December, January, February as winter months; MAM stands for March, April and May as spring months; JJA stands for June, July, August as summer months and SON stands for September, November and December as winter months.

As for the monthly precipitation pattern, the month of July receives the highest rainfall followed by August and September. The precipitation is also relatively high in February due to snowfall. To account for seasonality, these months are divided into four different seasons: December, January, February (DJF) as winter months; March, April, May (MAM) as spring months; June, July, August (JJA) as summer months and September, October, November (SON) as autumn months. The highest rainfall occurs during summer months with 26.17mm annually on average. It is followed by winter months (DJF).
with 17.75 mm of annual average rainfall. During transition seasons i.e. autumn and spring season, the region receives an annual rainfall of 11.87mm and 11.54mm respectively.

**Figure 4.** The plot of mean of daily precipitation over the months in a year

**Figure 5.** The plot of daily mean precipitation during each season over the years

To delve more into the seasonal findings, daily mean precipitation during winter months have maintained a relatively stable trend throughout the years. From the 99th percentile plot, a case of heavy snowfall in 2005 can be deduced. Otherwise, the rest of the 99th percentile values have high and low snowfall alternatively. Precipitation during March, April and May is lower than the rest of the seasons. Even the plot of the 99th percentile of daily mean precipitation has a relatively lower value than the rest
of the seasonal plots. With regards to summer months, year 2010 and 2015 received the highest amount of rainfall. The magnitude of these precipitation were so high that it’s influence is noted in Figure 2 where daily mean precipitation on an annual basis is plotted. According to the data, the recorded precipitation in 2015 for the 99th percentile is higher than the value in 2010. This observation is found true in the local observations (Sharma, 2018). However, the impact of 2010’s cloud burst and flood is larger than the 2015 precipitation event, therefore the flood hazard in 2010 was covered by the media extensively. The order of the event also influenced the vulnerability of the community affected by the natural disaster. In the case of 2015, locals residing in the region were better protected due to the previous experience and the heightened safety measures post 2010 flooding. Finally during autumn months, the peak of the daily mean precipitation with 99th percentile was recorded in 2018 as specified in Figure 9. Unlike other seasons, a gradual increasing trend with alternate lows can be observed. However, the presence of the trend can only be deduced and confirmed using Mann Kendall method.

Figure 6. Plot of daily mean precipitation during winter months with its standard deviation, 50th percentile, 95th percentile and 99th percentile
Figure 7. Plot of daily mean precipitation during spring months with its standard deviation, 50th percentile, 95th percentile and 99th percentile values

Figure 8. Plot of daily mean precipitation during summer months with its standard deviation, 50th percentile, 95th percentile and 99th percentile values
Figure 9. Plot of daily mean precipitation during autumn months with its standard deviation, 50th percentile, 95th percentile and 99th percentile values

4.2 Trend Analysis

To detect a trend in both annual and seasonal datasets, Mann Kendall test is used. For the annual precipitation mean data set, an increasing trend in precipitation is observed with the p-value of 0.015. This is different from the finding made by Chevuturi et al. (2016) where a decreasing trend in annual precipitation was observed between 1996 and 2013 for two of the datasets (GPCP: Global Precipitation Climatology Project and IMDG: India Meteorological Department 0.5° gridded precipitation data). Most likely, the additional set of data points (from 2013 to 2019) used in the current analysis might have changed the outcome of the trend analysis. Positive trend is also detected for the standard deviation of the daily precipitation on an annual basis as detailed in Table 2. This shows that the standard deviation increased with time, suggesting an increased erratic behavior of the precipitation in the past few years. However, when the Mann Kendall test is applied for a 95th percentile daily precipitation dataset to analyze trends of extreme precipitation in the region, no trend is detected. The p-value of the M-K test is found to be 0.256 which is way larger than the required 0.05 to observe a trend in the scenario.

For seasonal data series, Mann Kendall (M-K) test is carried for each season with its daily mean precipitation data series. Although no particular trend is observed, the p-value for summer months (June, July and August) is the smallest compared to other p-values. The p-values of the daily mean precipitation of each season are 0.496 for DJF (Winter), 0.726 for MAM (Spring), 0.127 for JJA (Summer) and 0.67 for SON (Autumn). Likewise, no trend is observed all four seasons when the Mann Kendall test is applied to the standard deviation of the daily mean precipitation values for each season. When the M-K test is
carried out on a set of extreme precipitation dataset (95th and 99th percentile of daily mean precipitation dataset) for each season, no trend is detected. However, it is interesting to note that all the values i.e. Kendall score, P-values and Kendall Tau are positive regardless of the trend detection as observed in Table 2. This may imply that there’s an increasing trend but it can’t be validated except for a few values due to dissatisfaction of the p-value threshold of 0.05 needed to confirm the trend.

<table>
<thead>
<tr>
<th></th>
<th>Annual</th>
<th>DJF</th>
<th>MAM</th>
<th>JJA</th>
<th>SON</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>P-value</td>
<td>Kendall Tau</td>
<td>Kendall Score</td>
<td>Kendall Tau</td>
<td>Kendall Score</td>
</tr>
<tr>
<td>Daily Mean (mm/day)</td>
<td>0.015</td>
<td>0.4</td>
<td>76</td>
<td>0.496</td>
<td>0.116</td>
</tr>
<tr>
<td>Daily Mean Standard Deviation</td>
<td>0.03</td>
<td>0.358</td>
<td>68</td>
<td>0.496</td>
<td>0.116</td>
</tr>
<tr>
<td>95th percentile</td>
<td>0.256</td>
<td>0.189</td>
<td>36</td>
<td>0.673</td>
<td>0.074</td>
</tr>
<tr>
<td>99th percentile</td>
<td>0.074</td>
<td>0.295</td>
<td>56</td>
<td>0.496</td>
<td>0.116</td>
</tr>
</tbody>
</table>

Table 2. Mann Kendall test analysis showing P-value, Kendall’s tau factor and Kendall’s score for precipitation annually and seasonally (DJF, MAM, JJA and SON).

To put the current study in context, this finding accounts for less than 1% of the total area under Leh district jurisdiction which is roughly 45,110 km$^2$. The study area is centered in the Leh town where the urban center is located and is around 121 km$^2$. Although the GPM data helped in obtaining detailed analysis of the particular site, the study needs to cover larger areas in the future analysis to draw conclusions of trends observed on a wider scale. Additionally, these satellite data sets are indirectly calculated from other variables such as microwave i-r estimates unlike rain gauge datasets that are directly measured on the ground. The indirect method may lead to a set of uncertainties in the data hence the need to combine observational pointed dataset in the future. Satellite dataset also doesn’t account for heterogeneity in the landscape such as the mountainous region where the site is located. This may create further uncertainty in the dataset. Therefore combining both in-situ and satellite observation is the way
forward. Finally, to understand the climate of the region, similar analysis should be carried out using temperature data sets. The findings from Chevuturi et al. (2016) regarding temperature can be used as a baseline to see if it is still valid or not. That’s how the future study can be more robust and representative of the larger region.

5. Conclusions

To understand the precipitation pattern in Leh region of Ladakh, GPM IMERG datasets were downloaded and analysed to find basic statistical summary including mean, standard deviation and percentiles. The presence or absence of a precipitation trend in the region is shown by employing Mann-Kendall test on the data sets. After the analysis, the average annual rainfall in the region is found to be 66mm/year and the daily precipitation mean is 0.189 mm/day. The most interesting finding of this study is the presence of an increasing trend in daily mean precipitation in the last two decades. Similar increasing trend is also observed with the standard deviation of daily mean precipitation. These research findings disagree with the decreasing precipitation trend (1995 - 2013) observed in the Chevuturi et al. (2016) paper. One of the possible explanations for the different result could be the larger amount of datasets used in the study compared to the previous research. If such a phenomenon of increasing precipitation persists in the future, it may dramatically impact agricultural production and may lead to food insecurity in the region. The occurrence of floods and debris flow may increase and affect vulnerable groups of people. Therefore climate change adaptive measures should be put in place to protect them in the face of future climate disasters.

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