Responses to the reviewer comments of our manuscript (manuscript # acp-2018-201) titled "***Climatic and extreme weather variations over Mountainous Jammu and Kashmir, India: Physical explanations based on observations and modelling" by***

Sumira Nazir Zaz, Romshoo Shakil Ahmad, Ramkumar Thokuluwa Krishnamoorthy, and YesuBabu Viswanadhapalli submitted for possible publication in the journal, *Atmospheric Chemistry and Physics,* an open access European Geophysical Union publication.

General response:

We express our sincere thanks to the reviewer for his invaluable and insightful comments on our manuscript, which helps us to improve the quality of it immensely. Below we have provided our one to one responses to his all queries and we hope that the reviewer will be convinced of our responses and make positive recommendations to this revised manuscript, written by taking into account of his as well as the other reviewers' comments (Prof. Reyaz Dar and Dr. H. Varikoden, responses to their comments are pasted below, please find), for its possible publication in the journal, *Atmospheric Chemistry and Physics,* an open access European Geophysical Union publication. We have also enclosed the revised manuscript with changes tracked version. Our responses following each of the comments (in red color) are marked in blue color

One to one response to the reviewer comments:

L49-50: This sentence is weirdly structured, and at any rate probably not necessary

The sentence has been corrected

L58-60: These sentences need support from references: Dimri's 2015 review (doi:10.1002/2014RG000460) and Hunt et al 2018a (doi:10.1175/MWR-D-17-0258.1) would be good places to start.

These references are now incorporated.

L62: A reference to WD seasonality would be useful for the reader. Hunt 2018b (doi: C1 ACPD Interactive comment Printer-friendly version Discussion paper 10.1002/qj.3200) has such a climatology, as do many studies by e.g. Dimri

These references are now added

L67: You introduce the abbreviation PS here, but then don't use it again until the conclusion (where you reintroduce it anyway). I would remove it.

The abbreviation PS has been removed

L72: PV is not necessarily conserved on isobaric surfaces.

Potential vorticity on isobaric surfaces is considered as a conserved quantity in the case of Rossby waves generated due to large scale wind flows over topography. In this case, the waves are called barotrophic Rossby waves.

L77-92: This entire paragraph has no references. Consider e.g. Rasmussen and Houze 2012 (doi: 10.1175/BAMS-D-11-00236.1), Romatschke and Houze 2011 (doi: 10.1175/2010JHM1311.1), Houze and Rasmussen 2016 (https://atmos.washington.edu/MG/PDFs/Houze-etal_Uttarakhand-Flood.pdf), Martius et al 2012 (doi:10.1002/qj.2082) and references therein.

These references have been incorporated in the paragraph.

L98: Dee et al 2011, not 2001.

Corrected the reference

L186: Link incorrect.

It is now corrected.

Tables 1 and 2: This is not the correct way to perform statistical tests. You must decide on a null hypothesis, a sensible confidence value for significance testing, and then determine whether the evidence is sufficient to reject the null hypothesis at the selected confidence level. No doubt your results are significant, but you must not present them like this. If you feel the reader will benefit from these details, I will consider accepting a table of p-values, so long as the usage is clearly justified in the text.

The suggestion has been incorporated.

L223-238: Lots of spaces between words seem to be missing (true throughout the manuscript but especially bad here).

It is now corrected

Tables 4 and 5 are rather massive. I'm confident that you can substantially reduce them in size by omitting data of low relevance, or otherwise they should be demoted to supplementary.

The tables 4 and 5 omitted and the information in the table is now added in the tables 1 and 2. This is suggested also by other reviewer.

L273: 42 mm per what? Season?

42 mm per spring seasons during these 37 years, which is mentioned in the text now.

Fig 2: Text in subfigures is too small to read. Perhaps it would be clearer to present the orography in grayscale, and then have the cross colours related to the temperature changes. Text sixe fine in Fig 3, but the other point on clarity still applies.

The suggestion has been incorporated in Fig 2 and Fig3.

L291: You should state whether these correlation coefficients are significant.

The significance has been mentioned

L300-307: What does this paragraph (and associated figure) add to the discussion? If the purpose is to show that WRF well captures the climate features of the region, then you should state that and the implications. Personally, I think it could be removed.

It is stated now and the implications

L327: It is convention to refer to this as the 1997-98 El Nino

Now it is referred as 1997-98 El Nino

L350: Also Dimri and Dash 2012 (doi: 10.1007/s10584-011-0201-y)

Reference has been included.

L367: You say the rate of warming has been especially high in the last forty years and then have two references to twenty-year-old papers.

Some new references have been added now.

Fig 4: Why are some of the data smoothed and others not?

All the data have been smoothed

L406: And Lau and Kim 2012 (doi: 10.1175/JHM-D-11-016.1)

Added

The first and third paragraphs of Sec 4.5 (though you have it labelled as 4.3) might be better placed in the introduction, but I will leave this up to the authors

We fear that continuity of information will be lost if we put these two paragraphs in the introduction section

Fig 6: Difficult to tell the lines apart, could you use colour? At present, it is difficult to distil any useful information from this. This analysis could benefit from including discussion of western disturbance frequency, if possible

Now it is colored.

L466: “due to the effect of climate change” – how have you deduced this?

Modified these words to avoid ambiguities

Fig 13: 700 hPa is quite a low level to be looking at Rossby wave activity, what is the structure at higher levels?

Baroclinic Rossby waves are manifested simultaneously well in the lower and upper tropospheres. We afraid that number of figures will be increased further if we add information at higher levels as there are already 14 figures.

L446-532: I feel that the text in this section is overly explicit, and could be easily reduced for improved readability

Now it is improved for readability

Responses to the reviewer (Dr. H. Varikoden**,** hamza@tropmet.res.in) comments (interactive comment on Atmos. Chem. Phys. Discuss., https://doi.org/10.5194/acp-2018-201, 2018) of our manuscript (manuscript # acp-2018-201) titled "***Climatic and extreme weather variations over Mountainous Jammu and Kashmir, India: Physical explanations based on observations and modelling" by*** Sumira Nazir Zaz, Romshoo Shakil Ahmad, Ramkumar Thokuluwa Krishnamoorthy, and YesuBabu Viswanadhapalli submitted for possible publication in the journal, *Atmospheric Chemistry and Physics,* an open access European Geophysical Union publication.

General response:

We express our sincere thanks to the reviewer for his invaluable comments on our manuscript, which helps us to improve the quality of it immensely. Below we have provided our one to one responses to his all queries and we hope that the reviewer will be convinced of our responses and make positive recommendations to this revised manuscript, written by taking into account of his as well as the other reviewer's short comment (Prof. Reyaz Dar), for its possible publication in the journal, *Atmospheric Chemistry and Physics,* an open access European Geophysical Union publication. We have also enclosed the revised manuscript with changes tracked version. Our responses following each of the comments are marked as **bold faceted words.**

One to one response to the reviewer comments:

1. First, I am not in favour of the current title of the manuscript because the variations of extreme weather events are not addressed properly.

   Now the title is modified as
   Climate and the September 2014 flood event over Mountainous Jammu and Kashmir, India: Physical explanations based on observations and modelling

2. Throughout the manuscript, the authors highlight the data period of 37 years from 1980 to 2016. However, in the analysis they incorporated only from 1980 to 2010 (31 years). I suggest updating the figures and tables with updated results (1980-2016) and thus, the significance levels too. The WRF simulations are also to be updated accordingly. The NAO index is also available to date for your analyses.

   In the revised manuscript, all the results (including WRF simulations and NAO index data), figures and tables have been updated to 36 years up to 2016 and we have not found any significant changes in trends.

3. Figure 1 can be updated with an inset figure of Jammu and Kashmir to properly identify the study region

   Figure 1 has been updated.

4. The geographical settings can be summarized in a table and delete the corresponding explanations. The table should include station name, coordinates, amsl, and remarks about the stations.

Corrections as suggested by the reviewer have been incorporated.

5. How the seasons are defined? The cited article did not mention anything about the seasons. Please do the classification of seasons promptly with the standard classification followed by India meteorological department or by any other classical monographs. In addition, the authors classified winter as Dec-Feb. However, in many places they considered the winter from Dec to March. This discrepancy must be corrected throughout the article. Remember, if you select the seasons differently, your interpretations and conclusions will also be affected.

The reviewer can get clarified that with respect to NAO (Fig. 4) only it is considered December-March as winter months and in all other parts of the manuscript, December-February is considered as winter season as per the IMD definition. This is because, for the NAO index, normally December-March is considered as northern winter and we adopted the same definition here (Archer and Fowler, 2004; Iqbal and Kashif,2013). Since the result of linkage between winter NAO index and Kashmir precipitation does not affect other results of this manuscript, we don't need to do any corrections for other places. This explanation is provided in the revised manuscript while discussing the Fig. 4 as well as in the section 2.

6. The temporal resolution of ERA-I is missing.
The temporal resolution of ERA-I is monthly averaged, which is now mentioned in the revised manuscript.

7. The unit of pressure may be replaced with hPa instead of mb
mb is now replaced by hPa.

8. The coordinates of second domain with 9 km resolution is not mentioned. Please update.

It is now updated.

The dimensions of the WRF model domains are listed below

Domain -1 (18-km) extends from Longitude from 24.8516 E to 115.148E and Latitudes from 22.1127S to 46.7629 N

Domain -2 (6-km) extends from Longitude from 56.3838E to 98.5722E and Latitude from 3.86047 S to 38.2874 N

9. Tables 1 and 2 are not necessary, as the same information can be found in Tables 4 and 5.

This suggestion is well taken and has been incorporated

10. Table 3 can be rearranged in ascending order of elevation and one more column with changes in rainfall can also be added.

The table is arranged in descending order to show stations with higher increase in temperature. One more column of topography has been incorporated.

11. I suggest to overly the values of changes at the respective station positions in Figures 2 and 3. The significance levels may be given in the form of a superscript star (or any other appropriate symbol) and can be indicated in the figure captions.

We are sorry that it is difficult now to do and we will surely attempt to do as suggested by the reviewer during the final phase of publication if it is recommended for.

12. In many places, the authors quantified the changes by providing "less than" symbols. It is better to give exact values of the changes and discuss.

Exact values at corresponding confidence levels are already provided in closed brackets. The reviewer may kindly look for it in the manuscript. The following italicised sentences are there already in the starting portion of the section 4.

"S in S=99%" indicates statistically significant. It is to be noted that hereafter it will not be mentioned explicitly about the period 1980-2016 and the statistical significance of derived values. All the results are subjected to statistical tests with confidence level of statistical significance at S=99% unless otherwise mentioned explicitly. Further, values denoting "less than" refer to S=99% and the confidence levels corresponding to given values are provided within closed brackets.

13. First statement in section 4.3 can be rephrased to avoid confusion.
The statement has been now rephrased

14. Figure4e and f show a prediction line and are in good agreement with the observed line too. Please give the corresponding regression equation for the predicted line of temperature and rainfall.

The following algorithm from Microsoft Excel defines the forecast method applied here and this is now included in the revised manuscript.
The forecast algorithm calculates or predicts a future value by using existing values. The predicted value is a y-value for a given x-value. The known values are existing x-values and y-values, and the new value is predicted by using linear regression.

The syntax is as follows

FORECAST(x, known_y's, known_x's)

X is the data point for which we want to predict a value.

Known_y's is the dependent array or range of data.
Known_x's is the independent array or range of data.

The equation for FORECAST is a+bx, where:

$a = \bar{y} - b\bar{x}$ **and** $b = \frac{\sum (x-\bar{x})(y-\bar{y})}{\sum (x-\bar{x})^2}$

and where x and y are the sample means AVERAGE(known_x's) and AVERAGE(known y's

Figure 4 labelling is also not correct.
It is now corrected

15. You already discussed the skills of WRF temperature simulations in Figure 5 (please provide the station names in individual panels).

The reference simulations of WRF model is for the Kokarnag station which is now mentioned in the revised manuscript.

16. In addition, the precipitation simulations can also be compared with observation to assess the performance of WRF, to complete the study.

It is now compared the WRF precipitation data also (Fig. 6 now) and the results are discussed.

17. The change point of temperature and rainfall is given as 1995. What is the criterion for this turning point selection? This has to be stated and substantiated with valid reasons.

The turning point in temperature and precipitation as already mentioned in the manuscript is calculated using the Cumulative Deviation (parametric test for step jump in mean), however to validate the results distribution-Free CUSUM (non-parametric test for step jump in mean) has also been used in this study. We followed this reference in this regard.

Ahmad Reza Ghasemi,Changes and trends in maximum, minimum and mean temperature series in Iran, **DOI: 10.1002/asl2.569 ,** ***Atmos. Sci. Let.*** **16: 366–372 (2015).**

Responses to the reviewer (Dr. Reyaz Dar**,** reyazsopore@gmail.com) short comments (Interactive comment on Atmos. Chem. Phys. Discuss., https://doi.org/10.5194/acp-2018-201) of our manuscript (manuscript # acp-2018-201) titled "***Climatic and extreme weather variations over Mountainous Jammu and Kashmir, India: Physical explanations based on observations and modelling" by*** Sumira Nazir Zaz, Romshoo Shakil Ahmad, Ramkumar Thokuluwa Krishnamoorthy, and YesuBabu Viswanadhapalli submitted for possible publication in the journal, *Atmospheric Chemistry and Physics,* an open access European Geophysical Union publication

General response:

We express our sincere thanks to the reviewer for his interesting comments on our manuscript, which helps us to understand the importance of extending the data analyses up to 2018.

Specific response.

Author's query: The study has been undertaken in a well defined pattern where first local temperature and precipitation has been understood and then validated and predicted with the downscaled WRF model and then finding its linkages with the local topography and global phenomena. My suggestion in this regard would be to run the WRF model at least up to 2018 so that further insight into the phenomena will be understood.

As suggested by the reviewer, in the revised manuscript, all the results (including WRF simulations and NAO index data), figures and tables have been updated to 36 years up to December 2016 and we have not found any significant changes in trends. Because of the availability of both the observed and WRF data, at present we could update only to 2016. In the near future, we will try to update it as suggested by the reviewer

Climate and the September 2014 flood event over Mountainous Jammu and Kashmir, India: Physical explanations based on observations and modelling

~~Climatic and extreme weather variations over Mountainous Jammu and Kashmir, India: Physical explanations based on observations and modelling~~

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Abstract

The Himalaya is very sensitive to climatic variations because of its fragile environmental and climatic settings. There are clear and strong indicators of climate change reportedfor the Himalaya, particularly the Jammu and Kashmir region in the western Himalayas. In this study, the detailed characteristics of long and short term as well as localized variations of temperature and precipitation are analysed for six meteorological stations (Gulmarg, Pahalgam, Kokarnag, Q~~u~~azigund, Kupwara and Srinagar) over Jammu and Kashmir, India for a period of 37 years during 1980-2016 by making use of observed stations data, WRF model downscaled monthly-averaged surface temperature and precipitation and ERA-interim (ERA-I) reanalysis data. . The annual and seasonal temperature and precipitation changes were analysed by carrying outthe Student's t-test, Mann-Kendall, Linear Regression and Cumulative deviationstatistical tests. The results show an increase of 0.8°C in average annual temperatureover thirty seven years during 1980-2016 with higher increase in maximum temperature (0.97°C) compared to minimum temperature (0.76°C). Analyses of annual mean temperature at all the stations reveal higher rise at high-altitude stations of Pahalgam (1.13°C) and Gulmarg (1.04°C) at theconfidence level of S=(0.01)~~99%~~. Precipitation patterns in the valley showslightdecrease in the annual precipitation at Gulmarg and Pahalgam stations at theconfidence level ofS=(0.1 to 0.05)~~90%~~.Seasonal analyses show increase in the winter and spring temperature at all stations at the confidence level of S=(0.01 to 0.05)~~95%~~with prominent decrease in spring precipitation at S=(0.01 to 0.05)~~99%~~. The present study reveals that variation in temperature and precipitation during ~~northern~~ winter (December - March) has close association with the North Atlantic Oscillation (NAO). Further, the observed temperature data (monthly averaged data for 1980-2016) at all the stations shows good correlation of 0.86 with the results of WRF and therefore the model downscaled simulations can be considered as a valid scientific toolfor climatic changestudies in

this region.Though the correlation between WRF model and observed precipitation is significantly strong, the WRF model underestimates significantly the rainfall amount. Using ERA-I potential vorticities in the upper troposphere over the Jammu and Kashmir region, it is found that the extreme weather event of September 2014occurred due to the breaking of intense Rossby wave activity over Kashmir. As the wave could drag lots of water vapour from both the Bay of Bengal and Arabian Sea and dump them over the Kashmir~~in the~~ region through wave breaking, it is speculated to be resulted~~ing~~ in the historical devastating flooding of the whole Kashmir valley in the first week of September 2014, which was accompanied by ~~the~~ extreme rainfall events measuring more than 620 mm in some parts of the PirPanjal range in the South Kashmir.

1. Introduction

Climate change is a real Earth's atmospheric and surface phenomenon and the influences of which on all the spheres of life are considered significant everywhere in the world at least in the past few decades. Extreme weather events like anomalously large floods and unusual drought conditions associated with climate change play havoc withlivelihoods of even established civilizations particularly in coastal and high-mountainous areas~~.~~. Jammu and Kashmir, India, located in the Western Himalayan region, is one such cataclysmic mountainous regionwhere the significant influence of climate changeon local weather has beenobservedfor the last few decades;(1) shrinking and reducing glaciers,(2) devastating floods, (3) decreasingwinter duration and rainfall, (4) increasing summer duration and temperature etc.(Solomon et al., 2007; Kohler and Maselli 2009; Immerzeel et al., 2010;Romshoo et al., 2015; Romshoo et al., 2017). Western disturbances (WD) is considered as one of the main source~~s~~ of winter precipitation~~(in the form of rainfall/snowfall)~~for the Jammu and Kashmir region, which brings water vapour mainly from the tropical Atlantic Ocean, Mediterranean Sea, Caspian Sea and Black sea.~~The Indian south-westand north-east monsoons are other important sources during Northern summer and winter seasons respectively~~. Though WD is perennial, but it is most intense during northern winter (December-~~March~~~~February~~February)~~.~~(Demri et al 2015). Planetary-scale atmospheric Rossby-waves have potential to significantly alter the distribution and movement of WD according to their intensity and duration (few to tens of days). Since WD is controlled by planetary-scale Rossby waves in the whole troposphere of the subtropical latitude region, diagnosing different kinds of precipitation characteristics is easier with the help of potential vorticity(PV) at 350K potential temperature (PT) and 200 hPa~~mb~~ level pressure surface~~(PS)~~ as they are considered asproxies for Rossby wave activities (Ertel, 1942; Bartels et al., 1998; Demri et al., 2015 and Hunt et al 2018a).For example, (Postel and Hitchman~~(~~1999; Hunt 2018b) studied the characteristics of Rossby wave breaking (RWB) events occurring at 350K PT surface transecting the subtropical westerly jets. Similarly, Waugh and Polvani (2000) studied RWB characteristics at 350K PT surface in the Pacific region during northern fall–spring with emphasis on their influence on westerly ducts and their intrusion into the tropics.SincePVis a conserved quantityon isentropic and isobaric surfaces (ISOES & ISOBS), it is widely used for investigating large-scale dynamical processes associated with frictionless and adiabatic flows. Moreover, all other

dynamical parameters, under a given suitable balanced-atmospheric-background condition, can be derived from PV and boundary conditions [Hoskins et al., 1985].

Divergence of the atmospheric air flows near the upper troposphere is larger during precipitation, leading to increase in the strength of PV. Because of which generally there will be a good positive correlation between variations in the strength of PV in the upper troposphere and precipitationover the ground provided that the precipitation is mainly due to the passage of large-scale atmospheric weather systems like western disturbances, monsoons etc. Wind flows over topography can significantly affect the height distribution of water vapour and precipitation characteristics~~.~~. Because of this, one can expect that the positive correlationbetween variations in PV and precipitation be modified significantly depending upon both the topography and wind flow strength. These facts needto be taken into account while finding long-term climatic variations of precipitation nearmountainous regions like the western Himalaya.The interplay between the flow of western disturbances and topography of the western Himalaya ~~can~~ further complicate the identification of source mechanisms of extreme weather events (~~-~~Das et al., 2002; Shekhar et al., 2010) like the ones that occurred in the western Himalayan region; 2014 Kashmir floods, 2010 Leh floods, in the Jammu and Kashmir region and 2013 in the Uttrakhand region~~.~~ Kumar et al. (2015) also noted that the major flood events in the Himalayas are related to the changing precipitation intensity in the region.This necessitates making use of the proper surrogate parameters like PV and distinguishing between different source mechanisms ofextreme weather events associated with both the long-term climatic impacts of remote origin and short-term localized ones like organized convection~~.~~ (Romatschke and Houze 2011; Rasmussen and Houze 2012 ; Houze and Rasmussen 2016;Martius et al 2012~~-~~)

The main aim of the present study is to investigate the climatic variation of surface temperature and precipitation over the Jammu and Kashmir, India region of the western Himalayas in terms of atmospheric Rossby wave activity in the upper troposphere. Since PV is considered asa measure of Rossby wave activity, the present work analyses in detail, for a period of 37 years during 1980-2016, monthly variation of PV (ERA-interim reanalysis data, Dee et al., 2001~~1~~) in the upper troposphere (at 350 K potential temperature and 200 hPa~~mb~~ pressuresurfaces) and compares it with observed surface temperature and rainfall (India Meteorological Department, IMD) at six widely separated mountainouslocations with variable orographic features (Srinagar, Gulmarg, Pahalgam, Qazigund, Kokarnag and Kupwara). There exist several reports onclimatological variation of hydro-meteorological parametersin various parts of the Himalayas. For example,Kumar and Jain(2009) and Bhutiyani et al. (2010)found anincrease in the temperaturein the north-western Himalayas with significant variations in precipitation patterns.Archer and Fowler (2004) examined temperature data of seven stations in the Karakoram and Hindu Kush Mountains of the Upper Indus River Basin (UIRB) in search of seasonal and annual trends using statistical test like regression analysis.Their results revealed that meanwinter maximum-temperature has increased significantly while meansummer minimum-temperaturedeclined consistently. On the contrary,Lui et al (2009) examined long-term trendsin minimum and maximum temperatures over the Tibetan mountain range during1961-2003 and found thatminimum temperature increases faster than maximum temperature in all the months.Romshoo et al.

(2015)observed changes in snow precipitation and snow-melt-runoff in the Kashmir valley andattributed the observed depletion of streamflow to the changing climate in the region. Bolch et al. (2012) reported that the glacier extent in the Korakaram range is increasing.

These contrasting findings of long term variations in hydro-meteorological parameters in the Himalayas need to be verified by analyzing more historic climatic data available in the region.However, the sparse and scanty availability of regional climatedata poses challengesin understanding the complex microclimate in this region.Therefore, studying therelationshipofrecorded regional (Jammu and Kashmir) climatic variations in weather parameters with remote and large-scale weather phenomena such as the North Atlantic Oscillation (NAO), and El Niño Southern Oscillation (ENSO)become-necessity for understanding the physical processesthat control thelocally observed variations(Ghashmi, 2015).Archer and Fowler(2004) andIqbal and Kashif (2013) found that large-scale atmospheric circulation likeNAOinfluencessignificantly the climatic condition of Himalayas. However, detailed information aboutvariation intemperature and precipitation and its teleconnectionwith observed variations of NAO is inadequately available for this part of the Himalayan region (Kashmir Valley).

2. Geographical setting of Kashmir

The intermountainous valley of Kashmir has unique geographical setting and it is located between the Greater Himalayas in the northand PirPanjal rangesin the south, roughly within the latitude and longitude ranges of 33^0 55´ to 34° 50´ and 74^o30´ to 75° 35´ respectively (Fig.1). The heights of these mountains range from about 3,000 to 5,000 m and the mountains strongly influence the weather and climate of the region. Generally the topographic setting of the six stations, though variable, could be broadly categorized into two; (1) stations located on plains (Srinagar, Kokarnag, Qazigund and even Kupwara) and (2) those located in the mountain setting (Gulmarg, Pahalgam). Physiographically, the valley of Kashmir is divided into three regions; Jhelum valley floor, Greater Himalayas and Pir Panjal. In order to represent all the regions of the valley, six meteorological stations located widely with different mean sea levels (msl), namely, Gulmarg (2740m), Pahalgam (2600m), Kokarnag (2000m), Srinagar (1600m), Kupwara (1670m) and Qazigund (1650m)were selected for analyses of observed weather parameters. ~~The topographical nature of the surroundings of these six stations (Fig. 1~~2) ~~is given below.~~

1

. ~~Kupwara: Located on plane surface bounded on three sides by mountains.~~

~~2. Pahalgam: Located on mountain top~~

~~3. Kokarnag: Located onplane surface.~~

~~4. Srinagar: Located on plane surface in an urbanized area~~

~~5.Gulmarg: Located on mountain top~~

~~6. Qazigund: Located on plane surface.~~

The Kashmir valley is one of the important watersheds of the upper Indus basin harbouring more than 105glaciers and itexperiences the Mediterranean type of climate with marked seasonality(Romshoo and Rashid, 2014). Broadly, four seasons (Khattak et al 2011; Rashid et al., 2015)~~)~~are defined for the Kashmir valley; winter (December to February), spring (March to May), summer (June to August), and autumn (September to November). ~~It is to be clarified that with respect to NAO (Fig. 4) only, it is considered December-March as winter months and in all other parts of the manuscript, December-February is considered as winter season as per the IMD definition. This is because, for the NAO index, normally December-March is considered as northern winter and we adopted the same definition here(Archer and Fowler, 2004;Iqbal and Kashif,2013). The result of linkage between winter NAO index and Kashmir precipitation does not affect other results of the present work.~~ It is to be clarified that with respect to NAO (Fig. 4) only, it is considered December-March as winter months and in all other parts of the manuscript, December-February is considered as winter season as per the IMD definition. This is because, for the NAO index, normally December-March is considered as northern winter and we adopted the same definition here(Archer and Fowler, 2004;Iqbal and Kashif,2013). The result of linkage between winter NAO index and Kashmir precipitation does not affect other results of the present work. The annual temperature in the valley varies from about -10°C to 35°C. The rainfall pattern in the valley is dominated by winter time precipitation associated with western disturbances (Dar et al., 2014) while the snow precipitation is received mainly in winter and early spring season (Kaul and Qadri, 1979).

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3. Data and Methodology

India Meteorological Department (IMD) provided 37 years (1980-2016) of data of daily precipitation, maximum temperature and minimum temperaturefor all these six stations. Monthly averaged data were further analysed to find long term variations of the weather parameters. Statistical tests including Mann-Kendall, Spearman Rho, Cumulative deviation, Student's t-test were performed to determine long term trends and turning point of weather parameters with statistical significances. Similar analyses and tests were performed also for the Weather and Research Forecasting (WRF) model simulated and ERA-Interim reanalyses data (0.75° by 0.75° spatial resolution in the horizontal plane, monthly averaged time resolution) of same weather parameters and for the NAO index. Brief information about these datasets is provided below.

3.1.Observational and model datasets used in this study

The obtained observational data were carefully analysed for homogeneity and missing values. Analyses of ratios of temperature from the neighbouring stations with the Srinagar station were conducted using relative homogeneity test (WMO, 1970). It is found that there is no significant inhomogeneity and data gap for any station. Few missing data points were linearly interpolated and enough care was taken not to make any meaningful interpretation during such short periods of data gap in the observations.Annual and seasonal means of temperature and precipitation were calculated for all the stations and years. To compute seasonal means, the data were divided into the following seasons: winter (December to February), spring (March to May), summer (June to August) and autumn (September to November).Trends in the annual and seasonal means of temperature and precipitationwere determined usingMann–Kendall (non-parametric test) and linear regression tests (parametric test)at the confidence

levelsof S=99% or (0.01), S=95% or 0.05 and S=90% or 0.1. These tests have been extensively used in hydrometeorological data analysesas theyare less sensitive to heterogeneity of data distribution and least affected by extreme values or outliers in data series.Various methods have been applied to determine change points of a time series (Radziejewski et al., 2000; Chen and Gupta, 2012). In this study, change point in time series of temperature and precipitationwas identified using cumulative deviation test and student's t test (Pettitt, 1979). This method detects the time of significant change in the mean of a time series when the exact time of the change is unknown (Gao et al., 2011).

The data of winter NAO index during 1980–2010from Climatic Research Unitwereobtained for analyses from the web link https// www.cru.uea.ac.uk/data~~htpp://cru@uea.ac.uk~~. The winter (December - March) NAO index is based on the difference of normalized sea level pressure (SLP) between Lisbon, Portugal and Iceland, which is available from 1964 onwards. Positive NAO index isassociated with stronger-than-average westerlies over the middle latitudes (Hurrell,1997). Correlation between climatic variations of mean (December-March) temperature, precipitationand NAO index was determined using Pearson correlation coefficient method.To test whether the observed trends in winter temperature and precipitation are enforced by NAO, linear regression analysis (forecast) was performed (Fig. 4e and f).The following algorithm from Microsoft Excel defines the forecast method applied here. The forecast algorithm calculates or predicts a future value by using existing values. The predicted value is a y-value for a given x-value. The known values are existing x-values and y-values, and the new value is predicted by using linear regression.

The syntax is as follows

FORECAST(x, known_y's, known_x's)

X is the data point for which we want to predict a value.
Known_y's is the dependent array or range of data (rainfall or temperature).
Known_x's is the independent array or range of data (time).

The equation for FORECAST is a+bx, where:

$a = \bar{y} - b\bar{x}$ and $b = \frac{\sum (x-\bar{x})(y-\bar{y})}{\sum (x-\bar{x})^2}$

and where x and y are the sample means AVERAGE(known_x's) and AVERAGE(known y's).

3.2. WRF Model configuration

The Advanced Research WRF version 3.9.1 model simulation wasused in this study to downscale theERA-Interim (European Centre for Medium Range Weather Forecasting ReAnalysis) data over the Indian Monsoon region. The model is configured with 2two-way nested domains(18 km and 9-km horizontal resolutions), 51 vertical levels and model top at 10 hPa level.~~The first domain of the model extends over the whole Indian monsoon region (28°E to~~

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~~112ºE and 20ºS to 45ºN) with 18-km horizontal grid resolution while the second domain (9-km resolution)covers the Indian sub-continent region.~~

Domain -1 (18-km) extends from Longitude from 24.8516 E to 115.148E and Latitudes from 22.1127S to 46.7629 N

Domain -2 (6-km) extends from Longitude from 56.3838E to 98.5722E and Latitude from 3.86047 S to 38.2874 N

The initial and boundary conditionssupplied to WRF model are obtained from ERA-Interim 6-hourly data. Model physics used in the study for boundary layer processes is Yonsei University's non-local diffusion scheme (Hong et al., 2006), the Kain-Fritsch scheme for cumulus convection (Kain and Fritsch, 1993), Thomson scheme for microphysical processes, the Noah land surface scheme (Chen and Dudhia, 2001) for surface processes, Rapid Radiation Transfer Model (RRTM) for long-wave radiation (Mlawer et al., 1997), and the Dudhia (1989) scheme for short-wave radiation. The physics options configured in this study are adopted based on the previous studies of heavy rainfall and Monsoon studies over Indian region (Srinivas et al., 2013, Madala et al., 2016, PriyankaGhosh et al, 2016; Srinivas et al., 2018).

For the present study, the WRF model is initialized on daily basis at 12 UTC using ECMWF ERA interim data and integrated for a ~~complete~~ 36-hour period using the continuous re-initialization method (Lo et al., 2008; Langodan, et al., 2016; and Viswanadhapalli et al., 2017). Keeping the first 12-hours as model spin-up time, the remaining 24-hour daily simulations of the model aremerged to get the climate data during 1980-2016.To find out the skill of the model, the downscaled simulations of WRF model are validated at six IMD surface meteorological stations. The statistical skill scores such as bias, mean error (ME) and root mean square error (RMS)were computed for ~~both~~ the simulated temperature ~~and~~against the observed temperaturedata of IMD.

4. Results and Discussion:

4.1. Trend in annual and seasonal temperature

~~FromTable 1, it is evident that t~~Tables 1& 2 show the results of statistical tests (Mann-Kendall and linear regression, cumulative deviation and Student's t) carried out on the temperature and precipitation data respectively. All the parametric and nonparametric test carried out for the trend analysis and abrupt changes in the trend showed almost similar results.~~From~~ Table 1, therefore shows the results of the representative tests where ~~Higher~~higher values of statistical significance between ~~(~~Mann-Kendall~~-~~/~~and~~ linear regression test~~)~~ and ~~(~~Cumulative deviation/ student's t test ~~results~~are ~~is~~ considered ~~here.~~ It is evident that t~~T~~here is an increasing trend at different confidence levels in annual and seasonal temperatures of all the six stations (Pahalgam, Gulmarg, Kokarnag, Srinagar, Kupwara

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and Qazigund), located in different topographical settings (is shown in Table 3).Higher value of statistical significance between Mann-Kendall and linear regression test results is considered here.In Table 4, shows the these result of statistical tests(Mann-Kendall and linear regressionStudent's t)results are provided in detail along with Student's t test results for comparison. ,s It is to be noted here that the latter test is not recommended in general for trend analyses as it could not identify properly odd data points. During 1980-20160, Pahalgam and Gulmarg, located at higher elevations of about2500m amsl (above mean sea level), registered an increase in average annual temperature by 1.13°C and 1.04°C respectively at the confidence level of S=99%(0.01)(Fig. 2a). "S in S=99% or 0.01" indicates statistically verysignificant. It is to be noted that hereafter it will not be mentioned explicitly about the period 1980-20160 and the statistical significance of derived values. All the results are subjected to statistical tests with confidence level of statistical significance at S=99% unless otherwise mentioned explicitly. Further, values denoting "less than" refer to S=99% and the confidence levels corresponding to given values are provided within closed brackets. Kokarnag and Kupwara,located at the heights of about 1800-2000m amsl, showedan increase of 0.9°C and 1°C respectively at S=99% or 0.01 (Fig. 2a). However, Srinagar and Qazigund, located at the heights of about 1700m-1600m amsl, exhibitedan increase of 0.65°C and 0.44°Cat S=0.05 and 0.1 respectively at S=(Fig. 2a).

The analysis of maximum and minimum temperatures (Table 1 and Fig. 2b) for these six stations reveals higher increase in maximum temperature. At S=99%0.01, Pahalgam and Kupwara recorded the highest rise of ~1.3°C followed by Kokarnag (1.2°C) and, Srinagar (1.1°C) The exception is that Gulmarg and Qazigund(being a hilly station) shows less than 0.6°C in maximum temperature (0.6°C at S=0.190%).. The minimum temperature shows lowest increase of 0.3°Cat Srinagar and highest increase at Gulmarg station of 1.2°C at S=0.01.(Fig. 2c). Analyses of seasonal mean minimum and maximum temperatures in the valley reveal higher increase in maximum temperature in winter and spring seasons.Among four stations (Gulmarg, Pahalgam, Kokarnag and Kupwara), the mean winter temperature of Gulmarg indicates an increase of less than 1°C (1°C at S=0.1=95%)while Pahalgam, Kokarnag and Kupwara shows an increase of 0.9°C and less than 0.9°C (0.9°C at S=0.01) respectively(Table 1and Fig. 2d).On the contrary, Qazigund and Srinagar showed a slight increase of less than 0.4°C and 0.5°C (S=0.05) respectively. Mean spring temperature shows higher rise comparing to other seasons for all the stations. WhileGulmarg shows an increase of less than 1.4°C (S=0.05),Pahalgam, Kupwara and Kokarnag showed increase of 1.3°C at S=0.01 . Qazigund and Srinagar revealed0.6°C (S=0.05) and 1°C increaseat S=0.1reveals an increase of 1.3°C.andSrinagar and Qazigund display an increase of less than 1°C and0.6°C (S=95%)respectively as shown in Table 1and Fig. 2e. In summer, the temperature rise for Pahalgam is about less than 0.6°C (S=0.190%) and for Gulmarg and Qazigund , it is 0.4°C and 0.2°Cat(insignificant level (NS), Table 1).Kupwara, Kokarnagand Srinagar reveal an increase of less than 0.3°C, 0.2°C,0.4°C and 0.1°C at(S=0.190%) respectively (Fig, 2f). In Autumn, Gulmarg shows an increase of 0.9°C and whilePahalgam shows less than 0.6°C (S=0.0595%). On the contrary, and Qazigund shows less than 0.4°C at (S=0.1) but Srinagar shows no significant increase (Fig. 2g and Table 1).and Table 1).

4.2. Trend in annual and seasonal precipitation

The annual precipitation pattern of the valley is comparable to that of temperature with higher decrease observed at the upper elevation stations of Gulmarg and Pahalgam. These two stations show~~an~~ average decrease in annual precipitation at S=0.05~~95%~~ and S=0.190% respectively (Fig. 3a and Table 2). Similar to temperature, Table 2~~5~~provides in detail the test results of Mann-Kendall, linear regression and Student's t. Kokarnag and Kupwara show decrease at S=0.19~~0~~%. The lower elevated stations,Qazigund and Srinagar,exhibit decrease at NS(Fig.3a).The analysis of winter precipitation reveals maximum decrease at Gulmarg and Kokarnag followed by Kupwara and Pahalgam at S=90%. On the other hand, Srinagarand Qazigund display an average insignificant (NS) decrease (Table 2 and Fig. 3b) while the spring season precipitation exhibits decreasing trend at S=0.05~~95~~% at Qazigund and Gulmarg and Srinagar ~~Pahalgam~~(Fig. 3c). Kupwara, Kokarnag and ~~Srinagar, Gulmarg~~and Kokarnag show decrease at S=0.01 respectively. The lowest decreas~~eing trend~~ of 42mm precipitation during spring season was~~1980-2016~~0was observed at Kupwara at S=0.01~~99~~%.(Table 2).

During the summer months, precipitation follows the same decreasing trend but not at significant level (NS) forGulmarg, Kupwara, Kokarnag, Pahalgam and Srinagar (Fig. 3d, and Table 2). In addition, Qazigundshows no trendin summer precipitation. The autumn precipitation at Pahalgam,Kupwara, Kokarnag, Srinagar, Gulmarg and Qazigund shows~~an average~~ decrease at insignificant level (NS) (Fig. 3e and Table 2).Cumulative test was used to determine the change point oftrend in the annual and seasonal variations oftemperature and precipitation. The results reveal that the year 1995 is identified as the year of abrupt increase (change point) in temperature of the valley (Fig. 4a) and the sameis identified as the year of abrupt decrease for precipitation (Fig. 4b).

4.3. North Atlantic Oscillation (NAO) index and winter climatic fluctuations

~~Along with the trend analyses of temperature and precipitation, t~~The present study also investigated the teleconnection between theactivity of~~NAO~~(NAO index) with ~~and~~and temperature and precipitation over the Kashmir valley, particularly~~ the~~ during~~ northern~~the northern winter season (December - March). The results indicate~~d~~ that NAO hassignificant (S=0.05) negativecorrelation~~s~~(-0.54) with ~~the~~ winter precipitation~~suggest negative~~ while the ~~and~~winter temperature showssignificant (0.01) positive correlation~~s~~~~of -0.54 and~~ ~~of~~ (0.68) ~~between~~ with~~the~~ NAO ~~and the winter temperature,and precipitation respectively~~ (Fig. 4c). This ~~correlation study~~ suggests that winter precipitation and temperature has some association with the winter NAO index.~~Where H~~higher precipitation over Kashmiris associated with ~~the~~positive phase of NAO.~~This would indicate that positive phase of NAO is associated~~

~~with more precipitation~~.Further the abrupt change in ~~Interestingly, similar to the observed~~ temperature and precipitation from ~~infrom~~ 1995~~changes in Kashmir in mid-nineties,~~has clear ~~shows~~ association with abrupt variation in the NAO index~~ from the same year~~.~~is also identified in1995.~~ To test whether the trends in temperatures and precipitation are forced by theNAO, regression analysis was performed for temperatures and precipitation data during winter(December- March) which is depicted in the Figs. 4e and f. From the results it is clear that the observed trends in winter and spring temperature and precipitation would have been influenced by NAO.

The observed annual and seasonal variation of temperature at all the six stations (Gulmarg, Pahalgam, Kokarnag, Kupwara, Qazigund and Srinagar) iscorrelated with WRF downscaledsimulations. Thesimulationsshow a good correlation of 0.66, 0.67, 0.72, 0.62, 0.79 and 0.47forSrinagar, Gulmarg, Kokarnag, Kupwara, Pahalgam and Qazigund respectively. The annual mean simulated temperature shows very good correlation (0.85) with the observations.Figure5 shows the annual and seasonal correlation of temperature trends ~~between~~with the WRF model(location of Kokarnag is considered for WRF data) and observations.~~(Fig.5)~~.~~Gulmarg, Kokarnag and Pahalgam show higher correlation with the simulation comparing to Qazigund, Kupwara and Srinagar~~. However, the root mean square error(RMSE)analysis shows that model simulations do slightly underestimate the observed values with an average value of -0.43°C. Similar to Figure 5, Figure 6 shows the comparison between the WRF model and observed precipitation. Even though the trend is similar, WRF model severely underestimates rainfall amount. This issue needs to be addressed in our near future research studies.

4.4. Discussion

The Himalayan mountain system is quite sensitive to global climatic variations as the hydrology of the region is mainly dominated by snow and glaciers, making it one of the ideal sites for early detection of global warming (Solomon et al., 2007; Kohler and Maselli 2009). Various reports claim that in the Himalayas significant warming had occurred in the last century~~.~~(Fowler and Archer, 2006; Bhutiyani et al., 2007).Shrestha et al. (1999) analysed surface temperature at 49 stations located across the Nepal Himalayas and the results indicatewarming trends in the range of 0.06 to 0.12°C per year. The observations of the present study are in agreement with the studies carried out by Shrestha et al.(1999), Archer and Fowler (2004) and Butiyani (2007). In the present study, it is observed that the rise in temperature is larger at higher altitude stations of Pahalgam (1.13°C) and Gulmarg (1.04°C) whereas Kokarnag, Kupwara, Srinagar and Qazigund recorded a rise of 0.9°C, 0.99°C, 0.04°C, and 0.10°C respectively with an average rise of 0.8°C during1980-2016~~0~~. Liu et al. (2009) and Liu and Chen (2000) also reported higher warming trends at higher altitudes in the Himalayan regions. Wiltshire (2013) warned,using a climate change model, that the impacts of climate change in the future will be intense at higher elevations and in regions with complex topography.

The noteworthy observation in the present study is that drastic and significant increase in the temperature (change point) has from~~started in~~ 1995. The El Nino of 1998 has been recorded in the history of the earth as one of the strongest El-N~~n~~ino's that brought worldwide increase in temperature (Epstein et al., 1998). In contrast, during the 1992~~Elnino period~~, the decrease in temperature throughout the northern hemisphere is ascribed to the natural phenomena of volcanic eruption occurred on the Mt Pinatabu (Swanson et al., 2009; IPCC, 2013). This event interrupted the direct sunlight to reach on the surface of the earth for about two months.

Studies of trends in seasonal mean temperature in many regions across the Himalayas indicate higher warming trends in winter and spring months (Shrestha et al., 1999; Archer and Fowler, 2004; Butiyani, 2009).The seasonal difference found in the present study is consistent with other studies carried out for the Himalayas (Archer and Fowler, 2004; Sheikh et al., 2009 and Roe et al., 2003), Lancang Valley, China (Yunling and Yiping, 2005), Tibet (Liu and Chen, 2000) and the Swiss Alps (Beniston et al., 2010), where almost all stations recorded higher increase in the winter and spring temperatures comparing to autumn and summer temperatures.Recent studies found that reducing snows and shrinking glaciers may also be one of the contributing factors for the observed higher warming, because reduction in snow and glacier can change the surface albedo of the region, which in turn can increase the surface air temperature (Kulkarni et al., 2002;Groisman et al., 1994). Romshoo et al. (2015) and Murtaza and Romshoo (2016)have reported that reduction of snow and glacier cover in the Kashmir regions of the Himalayas during the recent decades could be one of the reasons of occurrence of higher warming particularly on the higher elevated stations of Gulmarg and Pahalgam.

In the Himalayan mountain system, contrasting trends have been noted in precipitation over the recent decades.IPCC(2001),Borgaonkar et al. (2001), Shreshtha et al. (2000),and Archer and Fowler (2004) observed increasing precipitation patterns over the Himalayas while (Mooley and Parthasarathy~~(~~1983~~)~~,~~and~~ Kumar and Jain ~~(~~2009 and Demri and Dash 2012~~)~~, reported large-scale decadal variation with increasing and decreasing precipitation periods. The results of the present study indicate that decrease in annual precipitation is slightly insignificant at all the six stations except thespring season. Increasing trend intemperaturecan trigger large-scale energy exchanges that become more intricate ascomplextopographyalters the precipitation type and intensity in manyways.Climate model simulations(Zarenistana et al. 2014; Rashid et al. 2015) and empirical evidence (Vose et al. 2005; Romshoo et al., 2015) also confirmthat increasing temperature results in increased water vapour leading to more intense precipitation events even when the total annual precipitation reduces slightly. Increase in temperature therefore increases the risks of both floods and droughts. For example, the disaster flood event ofSeptember 2014 occurred in the Kashmir valley due to high frequency and high intense precipitation.

The North Atlantic Oscillation (NAO) is the strongest weather phenomena that occur in the Northern hemisphere due tothe difference of atmospheric pressure at sea level between the Iceland low and the Azores high. It controls the strength and direction of westerly winds across the northern hemisphere. Surface temperatures have increased in the Northern Hemisphere inthe past few decades (Mann et al., 1999; Jones et al., 2001Hijioka et al.,

2014), and the rate of warming has been especially high (~ 0.15°C decade^{-1}) in the past 40 years (Folland et al., 2001; Hansen et al., 2001Peters et al 2013; Knutti et al 2016). NAO causes substantial fluctuations in the climate of the Himalayas (Hurrell, 1997; Syed et al., 2006; Archer and Fowler, 2004).Several workers found a strong connection between the NAO and temperature and precipitation in the north-western Himalayas (Archer and Fowler, 2004; Bhutiyani et al., 2007; Bookhagen, 2010;Sharif et al., 2012;Iqbal and Kashif, 2013). A substantial fraction of the most recent warming is linked to the behaviour of the NAO (Hurrell, 1997; Thompson et al., 2003;Madhura et al. 2015). The climate of the Kashmir Himalayas is influenced by the western disturbances particularly in winter and spring seasons. Figs.4c and &dshow correlation between the winter NAO and winter temperature and precipitation over the Kashmir region. Negative correlation (-0.54) exists between winter temperature and winter NAO index and positive correlation (0.68) for the precipitation.Linear regression analysis was used to determine whether the variation in temperature and precipitation during the winter months (December-March)is forced by NAO. It is found thatconsiderable variation in winter precipitation/temperature may be forced by winter NAO.The weakening effect of NAO particularly after 1995 has decreased the winter precipitation and increased winter temperature in the valley. Similarly, Bhutiyani et al. (2009) and Dimri and Dash (2012) also detected a statistically substantial decreasing trend in the precipitation pattern and identified considerable decrease in winter precipitation which they related to weakening of NAO index. However, detailed mechanism involved in these variations requires thorough investigation.

The comparison of WRF with the observed stations data shows a significantly strong correlation of 0.85. It is also found that the higher elevated stations show higher correlation than the lower elevated stations of Srinagar and Kupwara; however,good correlation could result if more precise terrain information is incorporated in the WRF model. Various researchers (e.g., Kain and Fritsch, 1990, 1993; Kain, 2004)also found good correlation between observed and WRF simulated rainfall events.In conjunction with large-scale features such as the NAO andENSO, it can result in large scale variability in the climate of this region (Ogura and Yoshizaku, 1988). Further, incorporation of mesoscaleteleconnectionsand their associations in the WRF model can further help in understanding large-scale weather forecasting particularly in this region.

4.5~~3~~. Physical mechanisms of climate and weather of Jammu &Kashmir

Large-scale spatial and temporal variations in the meridional winds could be due to the passage of planetary-scale Rossby waves (RW) in the atmospheric winds.~~.~~WhenRWs break in the upper troposphere, it could lead to vertical transport of atmospheric air between the upper troposphere and lower stratosphere and an irreversible horizontal transport of air mass between the subtropics and extra tropics (McIntyre and Palmer, 1983).Rossby waves have the characteristic of remaining coherent over many days and propagating long distances of the ordersynoptic to planetary scales leading to tele-connection of remote atmospheres of global extent. It is clear

from the studies by Chang and Yu (1999)that during northern winter months of December–January–February, Rossby wave packets can be most coherent over a large distance of from the northern Africa to the Pacific through the southern Asia. There are reports on extreme weather events connected to Rossby waves of synoptic to planetary scales in the upper troposphere (Screen and Simmonds, 2014).In the northern parts of India, there is increasing trend in heavy rainfall events, particularly over the Himachal Pradesh, Uttrakhand and Jammu and Kashmir (Sinha Ray and Srivastava, 2000; Nibanupudi et al., 2015). Long-scale Rossby waves can lead to the generation of convergence and divergence in the upper troposphere that in turn can affect surface weather parameters like precipitation through generation of instabilities in the atmospheric air associated with convergence and divergence (Niranjankumar et al., 2016).

Using observations and MERRA (Modern-Era Retrospective Analysis for Research and Applications reanalysis data; http://gmao.gsfc.nasa.gov/research/merra/),Rienecker et al.(2011) showed a strong correlation between 6-10 day periodic oscillations in the upper tropospheric winds associated with Rossby waves and surface weather parameters like atmospheric pressure, winds, temperature, relative humidity and rainfall during a severe weather event observed at the Indian extratropical station, Nainital (29.45° N, 79.5° E), during November–December 2011. Further they noted that when the upper troposphere shows divergence, the lower troposphere shows convergence and as a result more moisture gets accumulated there leading to enhancement of relative humidity and hence precipitation. It was asserted that Rossby waves in the upper troposphere can lead to surface weather related events through the action of convergence or divergence in the atmospheric air. It is to be noted that a passing Rossby wave can cause fluctuations in divergence and convergence in the atmosphere at periodicities (typically 6-10 days, 12-20 days) corresponding to the Rossby waves at a particular site.

It was reported that Rossby waves account for more than 30% of monthly mean precipitation and more than 60% of surface temperature over many extra tropical regions and influence short term climatic extremes (Schubert et al., 2011). Planetary waves affecting weather events severely for long duration of the order of months have been reported by many researchers(Petoukhov et al., 2013; Screen and Simmonds, 2014; ~~and~~ Coumou et al., 2014).Screen and Simmonds (2014)found that in the mid latitude regions there is a strong association between enhanced Rossby wave activity, surface temperature and extreme precipitation eventsduring 1979–2012. Since slowly propagating Rossby waves can influence weather at a particular site for long periods lasting more than few weeks, one can see the imprint of climatic variations of Rossby waves in weather events from monthly mean atmospheric parameters.

To understand the present observation of different precipitation characteristics at all the six mentioned stations over the study area, we compared the monthly variation of PV in the upper troposphere with precipitations at all these stations.Potential vorticity at 350K potential temperature (PT) surface is identified as a valuable information for investigating the activity of Rossby waves as its breakage (can be identified through reversal of gradient in PV) at this level can lead to exchange of air at the boundary between the tropics and extra tropics

(Homeyer and Bowman, 2013). Similarly PV at 200 hPa~~mb~~ pressure surface (PS) is more appropriate for identifying Rossby wave breaking in the subtropical regions (Garfinkel and Waugh, 2014).

Since the Srinagar city,among the six stations, is onthe plain land with comparatively less topographical features located in the centre of the Kashmir valley, precipitation here associated with western disturbances is under the direct influence of planetary-scale Rossby waves. Accordingly, correlation between PV at the 350 K PT (located near the core of the subtropical jet, Homeyer and Bowman, 2013) and 200 hPa~~mb~~ pressure surfaces and precipitation isfound significant and the correlation becomes weaker for the other stations located at higher altitudes due to significant orographic influences. As a result, one can see that PV (ERA-Interim data, Dee et al., 2011) in the upper troposphere varies in accordance with precipitation, which is clearly depicted in Fig. 7~~6~~, during the entire years of 1984, 1987, 1988, 1990, 1993, 1994, 1995, 1996, 1999, 2006 and 2009. One can observe that sometimes PV at 350 K PT surface and at other times at 200 ~~mb~~hPapressure surface follows precipitation. This would be due to the influence of Rossby waves generated due to baroclinic and barotropic instabilities respectively. Particularly,the correlation between PV (sometimes either one or both) and precipitation is significantly positive during the Indian summer monsoon months of June-September of all the years from 1980 to 2009 except 1983, 1985, 1989, 2000-2005 and 2009. At present it is not known why this relation became weak during1999-2010.

For Kokarnag (Fig.~~7~~8), topography similar to Srinagar but located in the vicinity of high mountains, the relation between PV and precipitation particularly during the Indian summer-monsoon-period is almost similar to that of Srinagar during 1983, 1985, 1989, 1991, 1998, 1999, 2000-2005, but in 2009 it became poor. This deterioration of the link between PV and rainfall over Kokarnagparticularly during 1999-2010 is really due to the effect of climatechange, which is similar to what was observed for Srinagar. It is intriguing that why this relation became poor during the years of 1999-2010. In the northern Kashmir region of Kupwara (Fig. 9~~8~~), mslhigher by ~1 km than Srinagar, the relation between PV and precipitation is good in the years 1982-1983, 1985-1988, 1990-1994, 1995-1996, 1999, and 2006. Similar to Srinagar and Kokarnag, Kupwara also shows apoor link during 1999-2010. Particularly during the summer monsoon period, the relation is good in all the years except 1989, 1998, 2000-2005, and 2009. One interesting observation is that 1983, 1985 and 1991shows better correlation for Kupwara than Srinagar and Kokarnag. Since Kupwara is located near elevated Greater Himalayan mountain range, Rossby waves associated with topography would have contributed to the good correlation between PV and precipitation here, which is not the case for Srinagar and Kokarnag. In the case of Pahalgam, (Fig.~~9~~10), located near the Greater Himalayas, generally the link is good in almost all the years 1980-2016 but with a difference that sometimes both the PVs and on other times only either of them follow precipitation during some months. Particularly during summer monsoon months, similar to Kupwara, these years1989, 2000-2003, 2005 and 2009 show poor correlation. From the present observations, it can be easily ascertained that stations located near the Greater Himalayas show similar characteristics influencedby topography-associated Rossby waves.

For the hilly station of Qazigund (Fig. 110), located in the south Kashmir region (~3 km height)near the foothills of PirPanjal mountain range, the relationship is better than that observed over the northern station Kupwara. For example, in 1988, the relation is much better over Qazigund than Kupwara. However the opposite is true in 1987. Interestingly, in 1985, both Kupwara and Qazigund show similar variation in PV and precipitation. This may be due to the effect of the nature of equator ward propagation of Rossby waves from mid latitudes. In 1995, 1997 and 1998, PV and precipitation follow similar time variation for both Kupwara and Qazigund except for three months of January-March during which precipitation over Qazigund but not Kupwara follows PV. Interestingly, in the whole year of 1999, precipitation at both the stations,Kupwara and Quazigund, follows exceedingly well with PV; however in 1998, only Qazigund but not Kupwara shows good relation. In 2009, precipitation does not follow PV for both the stations. Interestingly in all the monthsof 2006, PV follows well with precipitation for both Kupwara and Qazigund. However in September,Kupwara but not Qazigund shows good relation. In 2004, only PV at constant potential temperature surface (350K) follows well with precipitation for both the stations. For the summer monsoon period of June-September, these years do not show good correlation, namely, 1983, 1985, 1989, 1990, 2000-2003, 2005, 2007-2009, which is almost similar to Srinagar and Kokarnag.

In the case of Gulmarg (Fig. 12~~1~~), PV and precipitation follow each other well in the years of 1988, 1993, 1994 and 1995. In 1996, during the Indian summer monsoon period of June-September, only PV at constant potential temperature surface follows precipitation. Overall, during the summer monsoon period, the relationship between PV and precipitation is appreciable for all the years except for 1983, 1989, 1990, 1999 and 2000-2009, which is almost similar to Kupwara and Pahalgam. It may be noted that these stations are located near comparatively elevated mountains and hence topographically induced Rossby waves could have contributed to this good relation. From the observations of these stations, one can come to the conclusion easily that high altitude mountains affect the precipitation characteristics through topography generated Rossby waves. The interesting finding here is that irrespective of the different heights of mountains, all the stations show that during 1999-2010 the correlation between upper tropospheric PV and rainfall became poor, indicating that some unknown new atmospheric dynamical concepts would have played significant role in disturbing the precipitation characteristics significantly over the western Himalayan region. This issue needs to be addressed in the near futureby invokingsuitable theoretical models so that predictability of extreme weather events can be improved in the mountainous Himalaya.

During 2011-2016 (Fig. 13~~2~~), it may be observed that for Gulmarg the linkage between potential vorticities and precipitation is in general good for all these years except around July 2012, July-December 2013 and 2015. It is interesting to note here that during the historical flood event of September 2014, the potential vorticities and precipitation follow each other but in the preceding and following years of 2013 and 2015 the linkage between PV and precipitation is rather poor as noted earlier. Similarly, all the other stations (Srinagar, Pahalgam, Kokarnag, Kupwara, and Qazigund) also show that the link between PV and precipitation is good around September 2014. This would indicate clearly that the extreme weather event during September 2014 over the areaoccurred because of the intense large-scale Rossby wave activity and not because of any localized adverse atmospheric

thermodynamicalconditions like enhanced local convection etc. In Srinagar, most of the times PV and precipitation follow each other very well as observed during January 2011-June 2012, January-July of 2013 & 2014, whole 2015 and 2016. In Qazigund, this relation is good only during January-July and September-October 2014, during the entire 2015 and 2016 (similar to Srinagar). For Kupwara, PV follows precipitation well during whole of 2011, January-July 2012, January-May 2013, January-November 2014, whole of 2015 and 2016. In the case of Kokarnag, good relation is observed during March-August 2012, January-June 2013 and 2014, around September 2014. In contrast, the relationship is very poor in the entire years of 2015 and 2016. Pahalgam interestingly shows good correlation between PV and precipitation during the whole years of 2011 and 2012. In 2013, 2014, 2015 and 2016, it is good only during January-June in addition to exceptionally good near September 2014.

Finally, it may be observed that the ERA-interim reanalysis data of meridional wind velocity (12UT) at ~3 km altitude above the mean seal level show alternating positive (southerly) and negative values,resembling the atmospheric Rossby waves in the sub tropical region during 1-6 September 2014 (Fig. 14~~3~~),. The meridional winds associated with Rossby waves could be easily noted to have their extensions in both the Arabian Sea and Bay of Bengal, indicating that water vapour from both the regions was attracted towards the Jammu and Kashmir, India region as the converging point of Rossby waves was located near this region. It may be easily noticed that the waves got strengthened on 4thand weakened on 5th and ultimately dissipated on 6th September. This dissipation of Rossby waves led to the dumping of the attracted water vapour over this region leading to the historical-record heavy-flooding during this period. This is one clear example of how synoptic scale Rossby waves can reorganize water vapour over large scale and lead to extreme rainfall event. It is well known that subtropical westerly jet is one of many important sources of Rossby waves in the mid to tropical latitudes. If the subtropical jet drifts climatically northward then the surface weather events associated with them also will drift similarly which will lead to unusual weather changes climatically.

Interestingly from the published reports, it can be found that there is a close association between changes in Rossby wave breaking events and climatic variations and variations in the stratospheric dynamics (Barnes and Polvani 2013; Lu et al. 2014).Climatic merdional shift, which is in response to the enhanced polar vortex and upper-tropospheric baroclinicityarising due to global warming, of the tropospheric jet has been successfully linked to climatic changes in Rossby wave breaking events caused by baroclinic instabilities (Wittman et al., 2007; Kunz et al., 2009; Rivière, 2011; Wilcox et al., 2012). The climatic increase in the tropospheric warming arising due to baroclinic forcing of Rossby waves is more prominent in the mid-latitudes than in the tropical regions(Allen et al., 2012; Tandon et al., 2013).This mid-latitude warming plays an important role in driving the poleward jet shift responding to climate change(Ceppi et al., 2014).It is to be remembered that the combined action of tropospheric baroclinic forcing (warming) and stratospheric polarvortex can gradually move the subtropical jet from about 27° to 54° (Garfinkel and Waugh, 2014). Using Global circulation models (GCM), linear wave theory predicts that in response to increased greenhouse gas (GHG) forcing, mid-latitude eddy-driven jets, arising due to strong coupling between synoptic scale eddy activity and jet streams in both the hemispheres, will be climatically

shiftedpoleward(Fourth report of Intergovernmental Panel on Climate Change (IV-IPCC), Meehl et al., 2007).However, mid-latitude Rossby waves and the associated wave dissipation in the subtropical region are predicted to move climatically equatorward due to the spherical geometry of the Earth (Hoskins et al., 1977; Edmon et al., 1980). This propagation of location of wave breaking towards the equator will have climatic impact on the proper relation between upper troposphere PV variations associated with Rossby waves and the associated surface weather parameters in the subtropical latitude regions. This may be one of the reasons that during 1999-2010, the relation between PV and precipitation became poor as observed in the present study.

Regarding surface temperature, except for its linear long term trend, there is no clear evidence of strong link between variations in the upper tropospheric potential vorticities and surface temperature for all the six stations mentioned. It seems that climatic variations in the upper tropospheric vorticities have significantly less influence on surface temperature variations.

5. Conclusions

Studies of climatic change in the surface temperature and precipitation over the Jammu and Kashmir, India region of the western Himalayas are carried out for a period of 37 years during 1980-2016. Analyses of the observations revealan increase in the annual temperature by 0.8°C. Higher increase in temperature is noted for stations located at higher altitudes and that isaccompanied by~~with~~ an insignificant decrease in annual precipitation. Long-term variation of winter temperature and precipitationhas good correlation with winter NAO index. Additionally, WRF model simulations showgood correlationof 0.85 with the observed data. It is found that in the recent decades, precipitation associated with both the monsoon and western disturbances has been decreasing significantly. While the monsoon deficiency is associated with decreasing difference in surface temperature between the Indian landmass and nearby Indian O~~o~~cean, the deficiency associated with western disturbances during winter is due to the climatic northward displacement of subtropical jet. This subtropical jet wind helps to drag moisture associated with disturbances to the Himalayan region. Regarding historical extreme weather eventassociated with September 2014 floods in Jammu and Kashmir, it is found that breaking of intense Rossby wave activity over Kashmir played an important role as the wave could drag lots of water vapor from both the Bay of Bengal and Arabian Sea and dump them here through its breaking during the first week of September, 2014, leading to the extreme rainfall event measuring more than 620 mm in some parts of the South Kashmir.

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Table:

Table 1. Annual and Seasonal temperature trend in Kashmir Valley during 1980-2016~~0~~

Table 2. Annual and Seasonal Precipitation trends in Kashmir valley during 1980-2016~~0~~

~~Table 3. Mean temperature increase at each station from 1980 to 2010~~

~~Table 1~~4: ~~Statistics of temperature at all the six stations of Kashmir (1980-2010)~~

~~Table 2~~5: ~~Statistics of precipitation at all the six stations of Kashmir (1980-2010)~~

Table 3: ~~.~~ Mean temperature increase at each station from 1980 to 2010

Stations (Mann Kendall test)	Temperature Trends	Annual	Min	Max	Winter	Spring	Summer	Autumn	Abrupt Change (student's T test
Gulmarg Critical Values a=0.10 (1.654) a=0.05(1.96) a=0.01(2.567)	Increasing trend	S=0.01	S=0.01	S=0.1	S=0.05	S=0.01	NS	S=0.05	1995
	Z statistics	3.976	3.059	1.564	2.43	2.806	0.486	2.159	
Pahalgam	Increasing trend	S=0.01	S=0.01	S=0.01	S=0.01	S=0.01	S=0.1	S=0.05	1995
	Z statistics	4.119	3.6	3.519	3.118	3.438	1.71	2.416	
Srinagar	Increasing trend	S=0.05	S=0.1	S=0.01	S=0.05	S=0.05	S=0.1	NS	1995
	Z statistics	2.108	1.392	2.804	1.992	2.413	0.374	0.198	

Kupwara	Increasing trend	S=0.01	S=0.1	S=0.01	S=0.05	S=0.01	S=0.1	S=0.1	1995
	Z statistics	3.433	1.819	3.246	1.988	2.719	1.78	1.865	
Kokarnag	Increasing trend	S=0.01	S=0.05	S=0.01	S=0.01	S=0.01	S=0.1	S=0.1	1995
	Z statistics	3.467	2.363	3.11	3.195	3.195	1.46	0.68	
Qazigund	Increasing trend	S=0.1	S=0.1	S=0.1	S=0.05	S=0.05	NS	S=0.1	1995
	Z statistics	1.717	1.77	1.68	2.026	2.236	-0.714	-1.501	

Table 1: Annual and Seasonal temperature trend in Kashmir Valley

Stations	Temperature Trend	Annual S%	Min S%	Max S%	Winter S%	Spring S%	Summer S=%	Autumn S=%	Abrupt Change
Gulmarg	+	**S=99**	**S=99**	S=90	**S=95**	**S=95**	NS	**S=99**	1995
Pahalgam	+	**S=99**	**S=99**	**S=99**	**S=99**	**S=99**	S=90	**S=95**	1995
Srinagar	+	**S=95**	**S=95**	**S=99**	S=90	**S=95**	NS	NS	1995
Kupwara	+	**S=99**	**S=95**	**S=99**	S=90	**S=99**	S=90	**S=95**	1995
kokarnag	+	**S=99**	**S=99**	**S=99**	**S=99**	**S=99**	NS	S=90	1995
Qazigund	+	**S=95**	S=90	**S=95**	S=90	**S=95**	NS	S=90	1995

+ Increase; S= significance level ; NS = Insignifance; Bold= high significance

Table 2: Annual and Seasonal Precipitation trends in Kashmir valley.

Stations	Precipitation Trend	Annual S%	Winter S%	Spring S%	Summer S=%	Autumn S=%	Abrupt Change
Gulmarg	-	**S=95**	S=90	**S=99**	NS	NS	1995
Pahalgam	-	S=90	S=90	**S=99**	NS	NS	1995
Srinagar	-	**S=95**	NS	**S=99**	NS	NS	1995
Kupwara	-	S=90	S=90	**S=99**	NS	NS	1995
kokarnag	-	S=90	S=90	**S=95**	NS	NS	1995
Qazigund	-	**S=95**	NS	**S=99**	NS	NS	1995

- Decreasing; S= significance level ; NS = Insignifance; Bold = high significance

Stations (Mann Kendall test)	Precipitation Trends	Annual	Winter	Spring	Summer	Autumn	Abrupt Change (student's T test
Gulmarg Critical Values a=0.10 (1.654) a=0.05(1.96) a=0.01(2.567)	decreasing trend	S=0.05	S=0.1	S=0.01	NS	NS	1995
	Z statistics	-1.988	-1.53	-2.515	-0.445	-0.394	
Pahalgam	decreasing trend	S=0.1	S=0.1	S=0.05	NS	NS	1995
	Z statistics	-1.442	-1.136	-2.151	-0.556	0.034	

Srinagar	decreasing trend	S=0.05	NS	S=0.01	NS	NS	1995
	Z statistics	-2.532	0.051	-2.060	-0.105	-1.003	
Kupwara	decreasing trend	S=0.1	S=0.1	S=0.01	NS	NS	1995
	Z statistics	-1.962	-0.817	-2.919	-0.986	-0.153	
Kokarnag	decreasing trend	S=0.1	S=0.1	S=0.05	NS	NS	1995
	Z statistics	-1.326	-1.53	-2.276	0.186	-0.119	
Qazigund	decreasing trend	S=0.05	NS	S=0.05	NS	NS	1995
	Z statistics	-1.275	-0.764	-2.413	0.359	-0.232	

~~Table 3: Mean temperature increase at each station from during 1980-2016~~0~~.~~

~~Stations~~	~~Elevation in meters~~	~~Topography~~	~~Increase annual temperature in °C~~
~~Pahalgam~~	~~2600mts~~	~~Located on mountain top~~	~~1.13~~
~~Gulmarg~~	~~2740mts~~	~~Located on mountain top~~	~~1.04~~
~~Srinagar~~	~~1600mts~~	~~Located on plane surface in an urbanized area~~	~~0.55~~

Kupwara	1670mts	Located on plane surface bounded on three sides by mountains	0.92
Kokarnag	2000mts	Located on plane surface	0.99
Qazigund	1650mts	Located on plane surface	0.78

Table 14: sStatistics of temperature at all the six stations of Kashmir (1980-2010)

Gulmarg Temperature		Test statistic	Critical values			Result
			(Statistical table)			
			a=0.1	a=0.05	a=0.01	
Annual	Mann-Kendall	2.923	1.645	1.96	2.576	S (0.01)
	Linear Regression	3.12	1.699	2.045	2.756	S (0.01)
	Student's t	-2.564	1.697	2.042	2.75	S (0.05)
Maximum		1.782	1.645	1.96	2.576	S (0.1)
		1.942	1.699	2.045	2.756	S (0.1)
		-2.114	1.697	2.042	2.75	S (0.05)
Minimum		3.059	1.645	1.96	2.576	S (0.01)
		3.79	1.699	2.045	2.756	S (0.01)
		-3.194	1.697	2.042	2.75	S (0.01)

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~~Winter~~	~~2.43~~	~~1.645~~	~~1.96~~	~~2.576~~	~~S (0.05)~~
	~~2.259~~	~~1.699~~	~~2.045~~	~~2.756~~	~~S (0.05)~~
	~~-2.805~~	~~1.697~~	~~2.042~~	~~2.75~~	~~S (0.01)~~
~~Spring~~	~~2.006~~	~~1.645~~	~~1.96~~	~~2.576~~	~~S (0.05)~~
	~~2.224~~	~~1.699~~	~~2.045~~	~~2.756~~	~~S (0.05)~~
	~~-2.025~~	~~1.697~~	~~2.042~~	~~2.75~~	~~S (0.1)~~
~~Summer~~	~~0.986~~	~~1.645~~	~~1.96~~	~~2.576~~	~~NS~~
	~~0.829~~	~~1.699~~	~~2.045~~	~~2.756~~	~~NS~~
	~~-1.193~~	~~1.697~~	~~2.042~~	~~2.75~~	~~NS~~
~~Autumn~~	~~2.859~~	~~1.645~~	~~1.96~~	~~2.576~~	~~S (0.01)~~
	~~2.32~~	~~1.699~~	~~2.045~~	~~2.756~~	~~S (0.05)~~
	~~-2.322~~	~~1.697~~	~~2.042~~	~~2.75~~	~~S (0.05)~~
~~**Pahalgam Temperature**~~					
~~Annual~~	~~4.119~~	~~1.645~~	~~1.96~~	~~2.576~~	~~S (0.01)~~
	~~3.996~~	~~1.645~~	~~1.96~~	~~2.576~~	~~S (0.01)~~
	~~-1.985~~	~~1.696~~	~~2.04~~	~~2.745~~	~~S (0.1)~~
~~Maximum~~	~~3.519~~	~~1.645~~	~~1.96~~	~~2.576~~	~~S (0.01)~~
	~~4.457~~	~~1.697~~	~~2.042~~	~~2.75~~	~~S (0.01)~~
	~~-3.152~~	~~1.696~~	~~2.04~~	~~2.745~~	~~S (0.01)~~
~~Minimum~~	~~3.6~~	~~1.645~~	~~1.96~~	~~2.576~~	~~S (0.01)~~
	~~4.553~~	~~1.697~~	~~2.042~~	~~2.75~~	~~S (0.01)~~
	~~-1.554~~	~~1.696~~	~~2.04~~	~~2.745~~	~~NS~~
~~Winter~~	~~3.811~~	~~1.645~~	~~1.96~~	~~2.576~~	~~S (0.01)~~
	~~3.856~~	~~1.697~~	~~2.042~~	~~2.75~~	~~S (0.01)~~
	~~-2.482~~	~~1.696~~	~~2.04~~	~~2.745~~	~~S (0.05)~~
~~Spring~~	~~3.438~~	~~1.645~~	~~1.96~~	~~2.576~~	~~S (0.01)~~
	~~4.597~~	~~1.697~~	~~2.042~~	~~2.75~~	~~S (0.01)~~
	~~-3.166~~	~~1.696~~	~~2.04~~	~~2.745~~	~~S (0.01)~~
~~Summer Temperature~~	~~1.719~~	~~1.645~~	~~1.96~~	~~2.576~~	~~S (0.1)~~
	~~1.915~~	~~1.697~~	~~2.042~~	~~2.75~~	~~S (0.1)~~
	~~-1.451~~	~~1.696~~	~~2.04~~	~~2.745~~	~~NS~~
~~Autumn Temperature~~	~~2.416~~	~~1.645~~	~~1.96~~	~~2.576~~	~~S (0.05)~~
	~~2.46~~	~~1.697~~	~~2.042~~	~~2.75~~	~~S (0.05)~~
	~~-1.823~~	~~1.696~~	~~2.04~~	~~2.745~~	~~S (0.1)~~
~~**Kokarnag Temperature**~~					
~~Annual~~	~~3.62~~	~~1.645~~	~~1.96~~	~~2.576~~	~~S (0.01)~~
	~~3.998~~	~~1.699~~	~~2.045~~	~~2.756~~	~~S (0.01)~~
	~~-2.194~~	~~1.697~~	~~2.042~~	~~2.75~~	~~S (0.05)~~

~~Maximum~~	~~3.11~~	~~1.645~~	~~1.96~~	~~2.576~~	~~S (0.01)~~
	~~3.622~~	~~1.699~~	~~2.045~~	~~2.756~~	~~S (0.01)~~
	~~-3.104~~	~~1.697~~	~~2.042~~	~~2.75~~	~~S (0.01)~~
~~Minimum~~	~~2.763~~	~~1.645~~	~~1.96~~	~~2.576~~	~~S (0.01)~~
	~~2.776~~	~~1.699~~	~~2.045~~	~~2.756~~	~~S (0.01)~~
	~~-1.28~~	~~1.697~~	~~2.042~~	~~2.75~~	~~NS~~
~~Winter~~	~~3.195~~	~~1.645~~	~~1.96~~	~~2.576~~	~~S (0.01)~~
	~~3.518~~	~~1.699~~	~~2.045~~	~~2.756~~	~~S (0.01)~~
	~~-1.632~~	~~1.697~~	~~2.042~~	~~2.75~~	~~NS~~
~~Spring~~	~~3.195~~	~~1.645~~	~~1.96~~	~~2.576~~	~~S (0.01)~~
	~~3.469~~	~~1.699~~	~~2.045~~	~~2.756~~	~~S (0.01)~~
	~~-2.133~~	~~1.697~~	~~2.042~~	~~2.75~~	~~S (0.05)~~
~~Summer~~	~~1.462~~	~~1.645~~	~~1.96~~	~~2.576~~	~~NS~~
	~~1.108~~	~~1.699~~	~~2.045~~	~~2.756~~	~~NS~~
	~~-1.527~~	~~1.697~~	~~2.042~~	~~2.75~~	~~NS~~
~~Autumn~~	~~1.680~~	~~1.645~~	~~1.96~~	~~2.576~~	~~S(0.1)~~
	~~1.023~~	~~1.699~~	~~2.045~~	~~2.756~~	~~NS~~
	~~-0.315~~	~~1.697~~	~~2.042~~	~~2.75~~	~~NS~~
~~**Kupwara Temperature**~~					
~~Annual~~	~~3.433~~	~~1.645~~	~~1.96~~	~~2.576~~	~~S (0.01)~~
	~~3.745~~	~~1.699~~	~~2.045~~	~~2.756~~	~~S (0.01)~~
	~~-2.384~~	~~1.697~~	~~2.042~~	~~2.75~~	~~S (0.05)~~
~~Maximum~~	~~3.246~~	~~1.645~~	~~1.96~~	~~2.576~~	~~S (0.01)~~
	~~3.842~~	~~1.699~~	~~2.045~~	~~2.756~~	~~S (0.01)~~
	~~-3.303~~	~~1.697~~	~~2.042~~	~~2.75~~	~~S (0.01)~~
~~Minimum~~	~~1.819~~	~~1.645~~	~~1.96~~	~~2.576~~	~~S (0.1)~~
	~~2.331~~	~~1.699~~	~~2.045~~	~~2.756~~	~~S (0.05)~~
	~~-1.485~~	~~1.697~~	~~2.042~~	~~2.75~~	~~NS~~
~~Winter~~	~~1.785~~	~~1.645~~	~~1.96~~	~~2.576~~	~~S (0.1)~~
	~~1.797~~	~~1.699~~	~~2.045~~	~~2.756~~	~~S (0.1)~~
	~~-1.643~~	~~1.697~~	~~2.042~~	~~2.75~~	~~NS~~
~~Spring~~	~~2.719~~	~~1.645~~	~~1.96~~	~~2.576~~	~~S (0.01)~~
	~~2.98~~	~~1.699~~	~~2.045~~	~~2.756~~	~~S (0.01)~~
	~~-3.297~~	~~1.697~~	~~2.042~~	~~2.75~~	~~S (0.01)~~
~~Summer~~	~~1.785~~	~~1.645~~	~~1.96~~	~~2.576~~	~~S (0.1)~~
	~~2.605~~	~~1.699~~	~~2.045~~	~~2.756~~	~~S (0.05)~~
	~~-2.477~~	~~1.697~~	~~2.042~~	~~2.75~~	~~S (0.05)~~
~~Autumn~~	~~2.085~~	~~1.645~~	~~1.96~~	~~2.576~~	~~S (0.05)~~
	~~2.003~~	~~1.699~~	~~2.045~~	~~2.756~~	~~S (0.05)~~
	~~-1.917~~	~~1.697~~	~~2.042~~	~~2.75~~	~~S (0.1)~~

~~Srinagar Temperature~~					
~~Annual~~	~~2.108~~	~~1.645~~	~~1.96~~	~~2.576~~	~~S (0.05)~~
	~~2.243~~	~~1.699~~	~~2.045~~	~~2.756~~	~~S (0.05)~~
	~~-2.133~~	~~1.697~~	~~2.042~~	~~2.75~~	~~S (0.05)~~
~~Maximum~~	~~2.804~~	~~1.645~~	~~1.96~~	~~2.576~~	~~S (0.01)~~
	~~3.27~~	~~1.699~~	~~2.045~~	~~2.756~~	~~S (0.01)~~
	~~-2.456~~	~~1.697~~	~~2.042~~	~~2.75~~	~~S (0.05)~~
~~Minimum~~	~~-1.791~~	~~1.645~~	~~1.96~~	~~2.576~~	~~S(0.1)~~
	~~-1.799~~	~~1.699~~	~~2.045~~	~~2.756~~	~~S(0.1)~~
	~~Infinity~~	~~1.697~~	~~2.042~~	~~2.75~~	~~S (0.01)~~
~~Winter~~	~~1.694~~	~~1.645~~	~~1.96~~	~~2.576~~	~~S(0.1)~~
	~~1.871~~	~~1.699~~	~~2.045~~	~~2.756~~	~~S(0.1)~~
	~~-0.454~~	~~1.697~~	~~2.042~~	~~2.75~~	~~NS~~
~~Spring~~	~~2.413~~	~~1.645~~	~~1.96~~	~~2.576~~	~~S (0.05)~~
	~~2.164~~	~~1.699~~	~~2.045~~	~~2.756~~	~~S (0.05)~~
	~~-2.523~~	~~1.697~~	~~2.042~~	~~2.75~~	~~S (0.05)~~
~~Summer~~	~~1.374~~	~~1.645~~	~~1.96~~	~~2.576~~	~~S(0.1)~~
	~~1.273~~	~~1.699~~	~~2.045~~	~~2.756~~	~~S(0.1)~~
	~~-0.174~~	~~1.697~~	~~2.042~~	~~2.75~~	~~NS~~
~~Autumn~~	~~0.918~~	~~1.645~~	~~1.96~~	~~2.576~~	~~NS~~
	~~1.099~~	~~1.699~~	~~2.045~~	~~2.756~~	~~NS~~
	~~-0.73~~	~~1.697~~	~~2.042~~	~~2.75~~	~~NS~~
~~Qazigund Temperature~~					
~~Annual~~	~~2.057~~	~~1.645~~	~~1.96~~	~~2.576~~	~~S (0.05)~~
	~~1.961~~	~~1.645~~	~~1.96~~	~~2.576~~	~~S (0.05)~~
	~~Infinity~~	~~1.697~~	~~2.042~~	~~2.75~~	~~S (0.01)~~
~~Maximum~~	~~1.983~~	~~1.645~~	~~1.96~~	~~2.576~~	~~S (0.05)~~
	~~1.844~~	~~1.699~~	~~2.045~~	~~2.756~~	~~S(0.05)~~
	~~-0.034~~	~~1.697~~	~~2.042~~	~~2.75~~	~~NS~~
~~Minimum~~	~~1.683~~	~~1.645~~	~~1.96~~	~~2.576~~	~~S (0.1)~~
	~~1.683~~	~~1.645~~	~~1.96~~	~~2.576~~	~~S (0.1)~~
	~~Infinity~~	~~1.697~~	~~2.042~~	~~2.75~~	~~S (0.01)~~
~~Winter~~	~~2.023~~	~~1.645~~	~~1.96~~	~~2.576~~	~~S (0.05)~~
	~~1.843~~	~~1.699~~	~~2.045~~	~~2.756~~	~~S (0.1)~~
	~~-0.838~~	~~1.697~~	~~2.042~~	~~2.75~~	~~NS~~
~~Spring~~	~~2.036~~	~~1.645~~	~~1.96~~	~~2.576~~	~~S (0.05)~~
	~~1.922~~	~~1.699~~	~~2.045~~	~~2.756~~	~~S (0.1)~~
	~~-1.996~~	~~1.645~~	~~1.96~~	~~2.576~~	~~S (0.05)~~
~~Summer~~	~~1.714~~	~~1.645~~	~~1.96~~	~~2.576~~	~~S(0.1)~~

	-1.124	1.699	2.045	2.756	NS
	0.808	1.697	2.042	2.75	NS
Autumn	-1.802	1.645	1.96	2.576	S (0.1)
	-1.74	1.699	2.045	2.756	S (0.1)
	1.55	1.697	2.042	2.75	NS

Table 25: Statistics of precipitation at all the six stations of Kashmir (1980-2010)

Gulmarg precipitation		Test statistic	Critical values		Result	
			(Statistical table)			
		a=0.1	a=0.05		a=0.01	
Annual	Mann-Kendall	-1.915	1.645	1.96	2.576	S(0.1)
	Linear regression	-2.442	1.699	2.045	2.756	S (0.05)
	Student's t	3.214	1.697	2.042	2.75	S (0.01)
Winter		-0.193	1.645	1.96	2.576	S(0.1)
		0.186	1.699	2.045	2.756	S(0.1)
		1.946	1.697	2.042	2.75	S (0.1)
Spring		-2.515	1.645	1.96	2.576	S (0.01)
		-2.922	1.699	2.045	2.756	S (0.01)
		3.209	1.697	2.042	2.75	S (0.01)
Summer		-1.445	1.645	1.96	2.576	NS
		-0.803	1.699	2.045	2.756	NS
		-0.629	1.697	2.042	2.75	NS
Autumn		-1.394	1.645	1.96	2.576	NS
		-1.428	1.699	2.045	2.756	NS
		1.001	1.697	2.042	2.75	NS
Pahalgam precipitation						
Annual		-0.425	1.645	1.96	2.576	NS
		-0.702	1.699	2.045	2.756	S=(0.1)
		1.773	1.697	2.042	2.75	S (0.1)
Winter		-0.176	1.645	1.96	2.576	S(0.1)
		0.104	1.699	2.045	2.756	NS
		1.946	1.697	2.042	2.75	S (0.1)
Spring		-2.915	1.645	1.96	2.576	S (0.01)
		-2.851	1.699	2.045	2.756	S (0.01)
		2.479	1.697	2.042	2.75	S (0.05)

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~~Summer~~	~~1.156~~	~~1.645~~	~~1.96~~	~~2.576~~	~~NS~~
	~~1.535~~	~~1.699~~	~~2.045~~	~~2.756~~	~~NS~~
	~~-1.387~~	~~1.697~~	~~2.042~~	~~2.75~~	~~NS~~
~~Autumn~~	~~0.034~~	~~1.645~~	~~1.96~~	~~2.576~~	~~NS~~
	~~0.348~~	~~1.699~~	~~2.045~~	~~2.756~~	~~NS~~
	~~-0.622~~	~~1.697~~	~~2.042~~	~~2.75~~	~~NS~~
~~**Kokarnag precipitation**~~					
~~*Station*~~ ~~Annual Precipitation~~	~~-1.326~~	~~1.645~~	~~1.96~~	~~2.576~~	~~S=(0.1)~~
	~~-1.436~~	~~1.645~~	~~1.96~~	~~2.576~~	~~S=(0.1)~~
~~Winter precipitation~~	~~-1.93~~	~~1.645~~	~~1.96~~	~~2.576~~	~~S(0.1)~~
	~~-1.592~~	~~1.699~~	~~2.045~~	~~2.756~~	~~NS~~
~~Spring Precipitation~~	~~-2.176~~	~~1.645~~	~~1.96~~	~~2.576~~	~~S (0.05)~~
	~~-2.525~~	~~1.699~~	~~2.045~~	~~2.756~~	~~S (0.05)~~
~~Summer Precipitation~~	~~0.187~~	~~1.645~~	~~1.96~~	~~2.576~~	~~NS~~
	~~-0.154~~	~~1.699~~	~~2.045~~	~~2.756~~	~~NS~~
~~Autumn Precipitation~~	~~-0.901~~	~~1.645~~	~~1.96~~	~~2.576~~	~~NS~~
	~~-0.903~~	~~1.645~~	~~1.96~~	~~2.576~~	~~NS~~
~~**Srinagar precipitation**~~					
~~Annual~~	~~-2.532~~	~~1.645~~	~~1.96~~	~~2.576~~	~~S (0.05)~~
	~~-2.931~~	~~1.699~~	~~2.045~~	~~2.756~~	~~S (0.05)~~
	~~3.094~~	~~1.697~~	~~2.042~~	~~2.75~~	~~S (0.01)~~
~~Winter~~	~~-1.096~~	~~1.645~~	~~1.96~~	~~2.576~~	~~NS~~
	~~-1.071~~	~~1.649~~	~~2.045~~	~~2.756~~	~~NS~~
	~~0.584~~	~~1.697~~	~~2.042~~	~~2.75~~	~~NS~~
~~Spring~~	~~-2.906~~	~~1.645~~	~~1.96~~	~~2.576~~	~~S (0.01)~~
	~~3.741~~	~~1.699~~	~~2.045~~	~~2.756~~	~~S (0.01)~~
	~~3.205~~	~~1.697~~	~~2.042~~	~~2.75~~	~~S (0.01)~~
~~Summer~~	~~-1.105~~	~~1.645~~	~~1.96~~	~~2.576~~	~~NS~~
	~~-0.92~~	~~1.699~~	~~2.045~~	~~2.756~~	~~NS~~
	~~0.673~~	~~1.697~~	~~2.042~~	~~2.75~~	~~NS~~
~~Autumn~~	~~-1.003~~	~~1.645~~	~~1.96~~	~~2.576~~	~~NS~~
	~~-1.014~~	~~1.645~~	~~1.96~~	~~2.576~~	~~NS~~
	~~0.761~~	~~1.697~~	~~2.042~~	~~2.75~~	~~NS~~
~~**Qazigund Precipitation**~~					
~~Annual~~	~~-2.275~~	~~1.645~~	~~1.96~~	~~2.576~~	~~S(0.05)~~
	~~-1.976~~	~~1.645~~	~~1.96~~	~~2.576~~	~~S(0.05)~~

	~~1.946~~	~~1.697~~	~~2.042~~	~~2.75~~	~~S (0.1)~~
~~Winter~~	~~-0.746~~	~~1.645~~	~~1.96~~	~~2.576~~	~~NS~~
	~~-0.733~~	~~1.645~~	~~1.96~~	~~2.576~~	~~NS~~
	~~-0.315~~	~~1.696~~	~~2.04~~	~~2.745~~	~~NS~~
~~Spring~~	~~-2.587~~	~~1.645~~	~~1.96~~	~~2.576~~	~~S(0.01)~~
	~~-2.706~~	~~1.645~~	~~1.96~~	~~2.576~~	~~S(0.01)~~
	~~-0.773~~	~~1.696~~	~~2.04~~	~~2.745~~	~~NS~~
~~Summer~~	~~0.859~~	~~1.645~~	~~1.96~~	~~2.576~~	~~NS~~
	~~0.567~~	~~1.645~~	~~1.96~~	~~2.576~~	~~NS~~
	~~-1.078~~	~~1.696~~	~~2.04~~	~~2.745~~	~~NS~~
~~Autumn~~	~~-0.632~~	~~1.645~~	~~1.96~~	~~2.576~~	~~NS~~
	~~-0.702~~	~~1.645~~	~~1.96~~	~~2.576~~	~~NS~~
	~~0.525~~	~~1.696~~	~~2.04~~	~~2.745~~	~~NS~~
~~**Kupwara Precipitation**~~					
~~Annual~~	~~-1.962~~	~~1.645~~	~~1.96~~	~~2.576~~	~~S (0.1)~~
	~~-1.059~~	~~1.645~~	~~1.96~~	~~2.576~~	~~S (0.1)~~
	~~3.045~~	~~1.699~~	~~2.045~~	~~2.756~~	~~S (0.01)~~
~~Winter~~	~~-0.117~~	~~1.645~~	~~1.96~~	~~2.576~~	~~NS~~
	~~0.195~~	~~1.645~~	~~1.96~~	~~2.576~~	~~S(0.1)~~
	~~2.479~~	~~1.697~~	~~2.042~~	~~2.75~~	~~S (0.05)~~
~~Spring~~	~~-2.962~~	~~1.645~~	~~1.96~~	~~2.576~~	~~S (0.01)~~
	~~-3.059~~	~~1.645~~	~~1.96~~	~~2.576~~	~~S (0.01)~~
	~~1.773~~	~~1.697~~	~~2.042~~	~~2.75~~	~~S (0.1)~~
~~Summer~~	~~-0.153~~	~~1.645~~	~~1.96~~	~~2.576~~	~~NS~~
	~~-0.084~~	~~1.645~~	~~1.96~~	~~2.576~~	~~NS~~
	~~0.143~~	~~1.697~~	~~2.042~~	~~2.75~~	~~NS~~
~~Autumn~~	~~-0.153~~	~~1.645~~	~~1.96~~	~~2.576~~	~~NS~~
	~~-0.084~~	~~1.645~~	~~1.96~~	~~2.576~~	~~NS~~
	~~-0.031~~	~~1.697~~	~~2.042~~	~~2.75~~	~~NS~~

Table 3: Mean temperature increase at each station from during 1980-2016.

Stations	Elevation in meters	Topography	Increase annual temperature in °C
Pahalgam	2600mts	Located on mountain top	1.13
Gulmarg	2740mts	Located on	1.04

		mountain top	
Srinagar	1600mts	Located on plane surface in an urbanized area	0.55
Kupwara	1670mts	Located on plane surface bounded on three sides by mountains	0.92
Kokarnag	2000mts	Located on plane surface	0.99
Qazigund	1650mts	Located on plane surface	0.78

Figure captions:

Fig. 1.Geographical setting and topographic map (elevationin meter is above mean sea level) of the Kashmir Valley along with marked locations of six meteorological observation stations: Srinagar, Gulmarg, Pahalgam, Kokarnag, Qazigund and Kupwara

Fig. 2 (a-g).Trends in surface temperature (°C) at the six interested locations of the Kashmir valley. (a) for annual mean temperature, (b) maximum temperature, (c) minimum temperature, (d) winter mean temperature during December-February, (e) spring mean temperature (March-May), (f) summer mean temperature (June-August) and (g) autumn mean temperature (September-November).

Fig. 3 (a-e). Same as Fig. 2 but for precipitation (mm) and only for means of (a) annual, (b) winter, (c) spring, (d) summer and (e) autumn.

Fig. 4 (a).Cumulative testing for defining change point of temperature (averaged for all the six stations of the Kashmir valley), (b) same as (a) but for precipitation, (c) Comparison of trends of Kashmir temperature with North

Atlantic Ocean (NAO index (d) same as (c) but for precipitation, (e) regression analysis of winter temperature and (f) regression analysis of winter precipitation.

Fig. 5. (a).Comparision between observed and WRF model (location of Kokarnag is considered) simulated annually averaged temperature (averaged for all the stations) variations for the years 1980-2016~~0~~, (b) same as (a) but for spring season, (c) for summer, (d) for autumn, (e) winter, (f) for minimum temperature and (g) maximum temperature

Fig. 6.Same as Fig. 5 but for precipitation. Here the minimum and maximum precipitation are not considered because it cannot be defined them properly in a day.

Fig. 7~~6~~ (a-f).Observed monthly-averaged surface temperature and precipitation and ERA-interim potential vorticities at the 350 K potential temperature and 200 ~~mb~~ hPalevel pressure surfaces for the station, Srinagar during the years 1980-2016~~0~~.

Fig. 8~~7~~ (a-f).Same as the Fig. 6 but for Kokarnag.

Fig. 9~~8~~ (a-f).Same as the Fig. 7 but for Kupwara.

Fig. 10~~9~~ (a-f).Same as the Fig. 8 but for Pahalgam.

Fig. 11~~0~~ (a-f).Same as the Fig. 9 but for Qazigund.

Fig. 12~~1~~ (a-f).Same as the Fig. 10 but for Gulmarg.

Fig. 13~~2~~ (a-f).Same as the Fig. 11 but for all the stations and during the years 2011-2016.

Fig. 14~~3~~. (a-f).Synopitc scale ERA-interim meridional wind velocity covering the Jammu and Kashmir region for sis days from 01 to 06 September 2014 (historical record flooding rainfall over this region).