Received: 10 July 2019 | Revised: 31 October 2019 | Accepted: 1 December 2019 | Published on: 22 December 2019

DOI: 10.1002/met.1869

COMMENTARY

Meteorological Applications RMetS

Variability of integrated precipitable water over India in a warming climate

Anoop Kumar Mishra

Centre for Remote Sensing and Geoinformatics, Sathyabama Institute of Science and Technology, Chennai, India

Correspondence
Anoop Kumar Mishra, Centre for Remote Sensing and Geoinformatics, Sathyabama Institute of Science and Technology, Chennai 600119, India.
Email: daksha112@gmail.com

Funding information
Ministry of Earth Sciences, Grant/Award Number: MoES/16/27/2014-RDEAS

Abstract

Changes in precipitation patterns as a result of increased atmospheric water vapour in a warming environment over the Indian region have been reported in the past few decades. However, these studies have not focused much on exploring the changes in atmospheric water vapour in a changing climate. The present study focuses on examining the variability of integrated precipitable water (IPW) over the Indian region derived from the Modern Era Retrospective-Analysis for Research and Application (MERRA 2) model in a warming environment. The results suggest that the IPW has increased significantly in recent decades. Changes in the IPW are consistent with changes in regional warming over India. The results also point out an increase of about 4.98% ± 1.26% in the IPW for a 1°C increase in regional warming. The variability of IPW has been examined in a warming climate. An increase in regional temperature shows coherent variation with IPW. A decadal increase of about 1.69% has been reported in the IPW.

KEYWORDS

integrated water vapor, model observations, precipitation extremes

1 | INTRODUCTION

Atmospheric water vapour plays a critical role in governing precipitation patterns (Trenberth *et al.*, 2003; Mishra and Liu, 2014; Mishra, 2019). Mishra and Liu (2014) reported an increase in heavy precipitation and a reduction in light and moderate precipitation as a result of increased atmospheric water in a warming environment. An increase of about 7% in atmospheric water vapour for a 1°C increase in global temperature has been observed by Trenberth *et al.* (2003). Changed precipitation patterns may be attributed to increased atmospheric water vapour. Atmospheric water vapour has increased over various parts of the globe (Ross and Elliott, 1996; Zhai and Eskridge, 1997; Trenberth *et al.*, 2005). Ross and Elliott (1996) used 21 years of radiosonde observations from stations in North America to show a decadal increase of about 3–7% in atmospheric water vapour over these stations. A positive correlation between atmospheric water vapour and temperature was derived over China using radiosonde data (Zhai and Eskridge, 1997) An increasing decadal trend of about 1.3% in column integrated water vapour was derived over global ocean using a special sensor microwave imager (SSM/I) (Trenberth *et al.*, 2005). Wang *et al.* (2018) linked the changes in precipitation patterns with shifts in regional atmospheric water vapour. Increased atmospheric water vapour over various parts of the globe shows large variability. The present paper is the first attempt to examine the variability of integrated water vapour over the Indian region in a warming environment. It quantifies the impact of warming on changes in integrated precipitable water (IPW) over India using data from the Modern Era Retrospective-Analysis for Research and Application (MERRA 2) model.

2 | DATA AND METHODOLOGY

Temperature data from the Global Historical Climatology Network (GHCN) were used. The GHCN provides monthly temperature data for 7,280 global stations from 226 countries. Data for the period 1980–2018 (39 years) were used in the present study. Homogeneity adjustments to remove non-climatic influences that may bias the observed temperature record were performed. An annual uncertainty of about 0.1°C is reported from these data. Monthly data are available from this source at 0.5 × 0.5° (Lawrimore *et al*., 2011). Temperature data from the MERRA-2 were also used to examine the impact of warming on the IPW. For the results, see the additional supporting information. The IPW from the surface up to 500 mb were used to explore the variability in a changing climate. An inter-annual difference technique adopted by Mishra and Liu (2014) was used to quantify the impact of warming on the IPW. The present analysis reveals that changes in the IPW show a coherent variation with warming (see below). The difference between the integrated precipitable water (ΔIPW) of any two years is plotted against the difference in temperature (ΔT) to explore the relationship between changes in the IPW and temperature. An advantage of this technique over a time-series technique is a significant reduction of the scattering of points and the convergence of ($\Delta IPW/\Delta T$) towards a constant value when ΔT increases.

The total number of data points used in this method is $(t - 1)/2$ times more than those used in the time-series technique (where t is the number of years). A p-value is derived for the significance test.

3 | RESULTS AND DISCUSSION

The IPW data for the period 1980–2018 derived from MERRA-2 were used to explore the changes in the IPW in recent decades. Figure 1 illustrates the seasonal changes during the southwest monsoon season in the IPW from 1980–1998 to 1999–2018. The southwest monsoon season in India starts with the onset of the southwest monsoon winds in June and continues till mid-September. This is called the rainy season in most of the Indian region. The IPW shows an increase in recent decades, especially over the central, northeastern and western parts of the India.

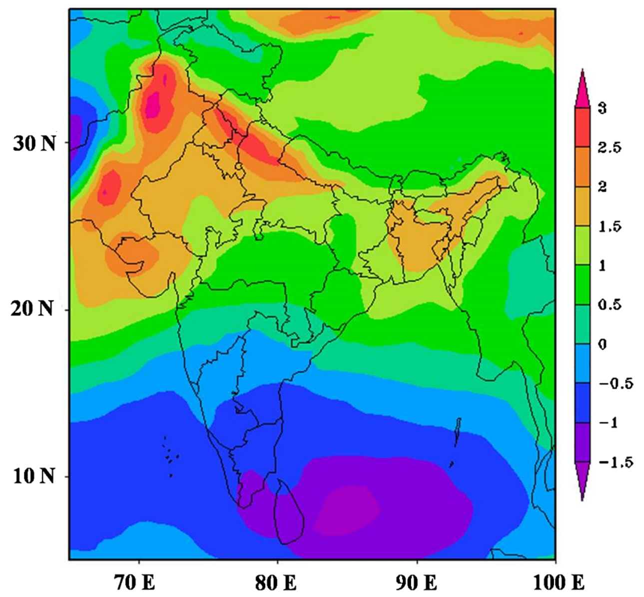

FIGURE 1 Difference in the integrated precipitable water (IPW) (kg·m^{-2}) from 1980–1998 to 1999–2018 ($IPW_{1999–2018}$ − $IPW_{1980–1998}$) from Modern Era Retrospective-Analysis for Research and Application (MERRA 2) model reanalysis

Furthermore, the northeastern, western and central north parts of India show increases in the range of 1.5–3.0 kg·m^{-2} in the IPW over recent decades. The southern part of the Indian region shows a decrease in the IPW during the southwest monsoon season. Note that the southern part of India receives the majority of its rainy spells in the northeast monsoon season between October and March (Singh *et al*., 2017). Figure 2 shows the variation of the IPW with regional temperature over the Indian region.

The National Climate Data Center (NCDC)-derived temperatures from the GHCN were used. The IPW shows large inter-annual variation with an increasing trend. The percentage anomaly is calculated from the absolute amount by normalizing the total integrated water vapour of the corresponding year. Normalization can filter out the fluctuations caused by the inter-annual variability in integrated water vapour and thus gives more self-consistent results. A 13-point filter was also used to eliminate small-scale fluctuations/noise Regional temperature shows coherent variation with the IPW. The peaks and troughs of the IPW match well with those in regional temperature. An increasing trend in the IPW is consistent with Wang and Zhang (2008). The trend in water vapour is statistically significant at the 95% confidence level. A rise in tropospheric water vapour may result in increases in both the frequency and intensity of heavy precipitation (Mishra and Liu, 2014). It is reported that

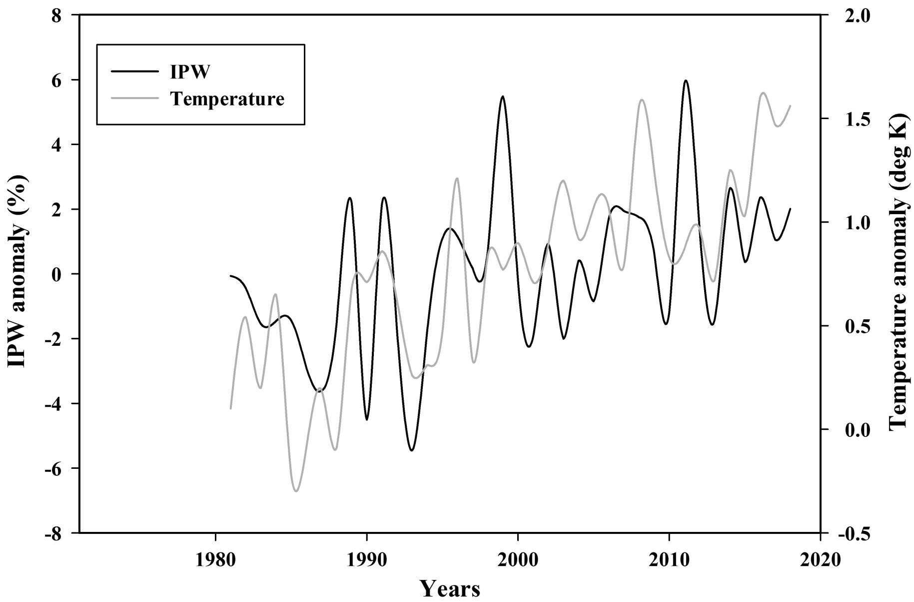

FIGURE 2 Variation of the integrated precipitable water (IPW) (anomaly with respect to the period 1980–2018) with regional temperature (anomaly with respect to the 1910–2000 average)

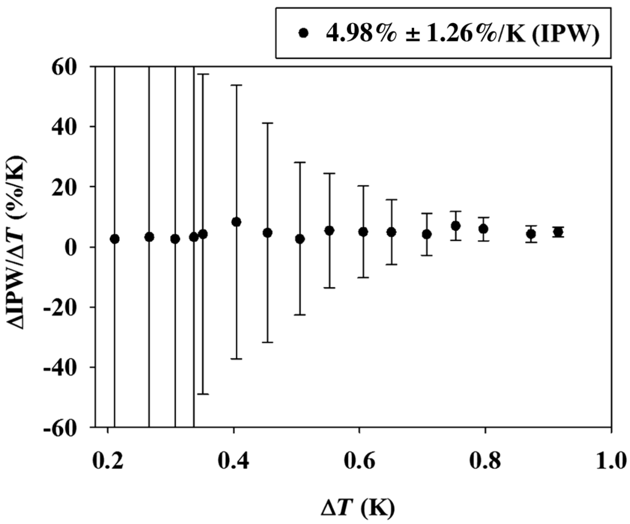

FIGURE 3 ΔIPW/ΔT as a function of ΔT, where ΔIPW is the difference between the integrated precipitable water (IPW) of any two years in the period 1980–2018; and ΔT is the difference in regional temperatures of the same two years. The vertical bar denotes the 1 SD (standard deviation) for the data points of an individual group. About 46 data points were averaged in an individual group

tropospheric warming can increase the availability of atmospheric water vapour.

An inter-annual difference technique (Mishra and Liu, 2014) was adopted to quantify the impact of warming on the IPW. The difference in the IPW is linearly proportional to the temperature difference. The difference in the IPW (ΔIPW) of any two years is divided by the difference in temperature (ΔT) and plotted against ΔT. The results are shown in Figure 3.

A statistically meaningful ΔIPW/ΔT (4.98%/K) is achieved at high values of ΔT near 0.87 K. Figure 3 shows that the IPW over the region has increased by about 4.98% $\pm$ 1.26% for a 1°C increase in regional warming. A decadal increase of 0.34 K has been observed over India. Thus, the IPW shows a decadal increase of about 1.69% over India (4.98 $\times$ 0.34). An increase in the IPW is consistent with an increase in heavy precipitation over India in a warming environment (Mishra and Liu, 2014; Mishra, 2019). Furthermore, temperature data from the MERRA-2 are also used to examine the impact of warming. For the results, see the additional supporting information. It can be seen that the anomaly in the IPW is consistent with temperature. Furthermore, an increase of about 5.14% $\pm$ 1.18% in the IPW for a 1°C increase in regional warming is observed when temperature from the MERRA-2 is used. In comparison, an increase of about 4.98% $\pm$ 1.26% in the IPW is observed with the GHCN data. Thus, uncertainty in the trend is minimized when the IPW and temperature observations from the same data source are used.

Temperature data from MERRA-2 have also been used to analyze the variability and results are presented in supplementary material. It can be seen that anomaly in IPW is more consistent with temperature.Furthermore, an increase of about 5.14% $\pm$ 1.18% in IPW for one degree increase in regional warming is observed when temperaure from MERRA-2 is used. In comparison, anincrease of about 4.98% $\pm$ 1.26% in IPW is observed with GHCN data. Thus uncertainty in trend is minimized when IPW and temperature observations from same data source have been used.

4 | CONCLUSIONS

The study explores the variability of the integrated precipitable water (IPW) in a warming environment.

Changes in the IPW are quantified against changes in temperature using an inter-annual difference technique. The convergence of the mean changes in integrated water vapour ($\Delta IPW/\Delta T$) towards a constant near $\Delta T = 0.92$ K is intriguing (Figure 3). This has a very interesting implication, which is that changes in integrated water vapour can be forecasted with a fair degree of confidence (i.e. a smaller deviation) given the future temperature predicted accurately by reanalysis. The study reports a strong dependence of the IPW on warming over India. The increased IPW due to anthropogenic warming may cause an increase in flood disasters as a result of intensified precipitation events. Thus, the study highlights the importance of mitigation and adaptation actions against flood-related disasters which may increase in number and severity in a warming environment.

ACKNOWLEDGEMENTS

The Ministry of Earth Sciences (MoES), Delhi, is sincerely acknowledged for providing financial support (order number MoES/16/27/2014-RDEAS) for this research.

ORCID

Anoop Kumar Mishra https://orcid.org/0000-0001-8313-7499

REFERENCES

Lawrimore, J.H., Menne, M.J., Gleason, B.E., Williams, C.N., Wuertz, D.B., Vose, R.S. and Rennie, J. (2011) An overview of the global historical climatology network monthly mean temperature data set, version 3. *Journal of Geophysical Research – Atmospheres*, 116(D19), 1–18.

Mishra, A. and Liu, S.C. (2014) Changes in precipitation pattern and risk of drought over India in the context of global warming. *Journal of Geophysical Research – Atmospheres*, 119(13), 7833–7841. https://doi.org/10.1002/2014JD021471.

Mishra, A.K. (2019) Quantifying the impact of global warming on precipitation patterns in India. *Meteorological Applications*, 26 (1), 1–8. https://doi.org/10.1002/met.1749.

Ross, R.J. and Elliott, W.P. (1996) Tropospheric water vapor climatology and trends over North America: 1973–93. *Journal of Climate*, 9(12), 3561–3574.

Singh, P., Gnanaseelan, C. and Chowdary, J.S. (2017) North-east monsoon rainfall extremes over the southern peninsular India and their association with El Niño. *Dynamics of Atmospheres and Oceans*, 80, 1–11.

Trenberth, K.E., Dai, A., Rasmussen, R.M. and Parsons, D.B. (2003) The changing character of precipitation. *Bulletin of the American Meteorological Society*, 84, 1205–1217. https://doi.org/10.1175/BAMS-84-9-1205.

Trenberth, K.E., Fasullo, J. and Smith, L. (2005) Trends and variability in column-integrated atmospheric water vapor. *Climate Dynamics*, 24, 741–758. https://doi.org/10.1007/s00382-005-0017-4.

Wang, J., and Zhang, L. (2008) Systematic errors in global radiosonde precipitable water data from comparisons with ground-based GPS measurements. *Journal of Climate*, 21(10), 2218–2238.

Wang, X., Pang, G., Yang, M., Wan, G. and Liu, Z. (2018) Precipitation changes in the Qilian Mountains associated with the shifts of regional atmospheric water vapour during 1960–2014. *International Journal of Climatology*, 38(12), 4355–4368.

Zhai, P. and Eskridge, R.E. (1997) Atmospheric water vapor over China. *Journal of Climate*, 10, 2643–2652. https://doi.org/10.1175/1520-0442(1997)010<2643:AWVOC>2.0.CO;2.

SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of this article.