ANALYSIS OF METEOROLOGICAL AND HYDROLOGICAL EXTREMES IN THE INDIAN SUBCONTINENT UNDER PRESENT AND FUTURE CONDITIONS

PECHLIVANIDIS I.G., OLSSON J. and ARHEIMER B.

Swedish Meteorological and Hydrological Institute, Norrköping, Sweden
E-mail: ilias.pechlivanidis@smhi.se

ABSTRACT

The Indian subcontinent poses extraordinary challenges to understand, quantify and predict hydro-climatic extremes (e.g. floods and droughts). The strong hydro-climatic gradient due to monsoon and the geographic features is linked to extreme weather events which threat life and significantly affect the country's economy. Climate change is expected to change the frequency and magnitude of the extreme weather events, consequently affecting river flow characteristics. In here, we investigate meteorological and hydrological extremes under the present and future climatic conditions driven by three emission scenarios (RCP2.6, RCP4.5, and RCP8.5). The use of different emission scenarios allows for the assessment of uncertainty of future impacts. Climate projections from the CORDEX-South Asia framework have been bias-corrected using the DBS (Distribution Based Scaling) method and used to force the HYPE (HYdrological Predictions for the Environment) hydrological model to generate projections of river flow. We calculate the 12-month Standard Precipitation Index (SPI) for various regions of different hydro-climatic conditions and investigate the changes of SPI from the present (1976-2005) to the mid (2021-2050) and end (2071-2100) century climate. In addition, Sen's non-parametric estimator of slope is used to calculate the magnitude of trend in high flows (99^{th} percentile) at three main river systems, whose statistical significance is assessed by the Mann–Kendall test. Overall, SPI differs between emission scenarios and future periods, whereas its value is dependent on the region's hydro-climatic gradient. The high uncertainty in the climate projections is propagated in the hydrological impact model, and as a result the trend in high flows is subject to the climate projection. In general, results from all scenarios indicate increase in high flows with the changes becoming more remarkable at the end of the century.

Keywords: Hydrological modelling, HYPE, climate change impacts, extremes, India, CORDEX

1. Introduction

The large increase in the atmospheric concentrations of greenhouse gases has led to the global climate change phenomenon which is expected to have a strong impact on water resources on the local, regional and global scales. Climate change can strongly alter the flow regimes and magnitude of extreme events, e.g. floods and droughts, and further cause great damage to the society and even endanger human lives. Assessment of future climate change impacts on water resources commonly involves climate variables (i.e. precipitation, temperature) from global circulation models (GCMs) in combination with hydrological models (Pechlivanidis *et al*., 2011). To downscale the GCM output and thus provide high-resolution meteorological inputs to hydrological models, regional climate models (RCMs) have been developed. In a collective scientific effort, the World Climate Research Programme (WCRP) has recently launched a framework, called COordinated Regional climate Downscaling EXperiment (CORDEX), to generate and evaluate fine-scale ensembles of RCM projections globally (Giorgi *et al*., 2009).

RCMs often show large bias in the magnitude and spatial distribution of precipitation and, to a lesser extent, temperature at the regional and/or local scale. A solution to the problem of RCM misrepresentation is to bias correct the RCM data to make them reproduce historical observed statistics to the degree possible (Wetterhall *et al*., 2012). Bias correction often includes an implicit downscaling component, in that higher-resolution reference observations are used when fitting the RCM mapping functions. Bias correction generally preserves the variability described by different climatic conditions generated by RCM projections; however, the RCM may perform differently depending on season or governing atmospheric circulation.

India is a developing country with nearly two-thirds of the population depending directly on the climate- and water-sensitive sectors. The region is characterised by a strong hydro-climatic gradient due to the monsoon and the geographic features; hence posing extraordinary scientific challenges to understand, quantify and predict future availability of water resources. In here, we investigate the impacts of climate change in India and aim in particular to answer the following questions: i) what is the quantified impact of climate change on India's hydro-climatic extremes? and ii) how does the potential impact vary in different climatic regions (i.e. tropical, humid subtropical and montane)?

2. Study area and data

2.1. Study area

India is the seventh-largest country by area and the second-most populated country with over 1.2 billion people. The country covers an area of about 3.3 million km^2 and some of its river basins extend into several neighbouring countries (i.e. China, Nepal, Pakistan, and Bangladesh; see Figure 1). Major rivers of Himalayan origin that are mainly located in India include the Ganga and the Brahmaputra, both of which drain into the Bay of Bengal. The spatiotemporal variation in climate is perhaps greater than in any other area of similar size in the world. The climate is strongly influenced by the Himalayas and the Thar Desert in the northwest, both of which drive the monsoons. In terms of spatial variability, the rainfall pattern roughly reflects the different climate regimes of the country, which vary from humid in the northeast (rainfall occurs about 180 days/year), to arid in northwest (20 days/year). Moreover, India is characterised by strong temperature variations in different seasons ranging from a mean temperature of about 10 °C in winter to about 32 °C in pre-monsoon season.

2.2. Meteorological reference data – Climate projections

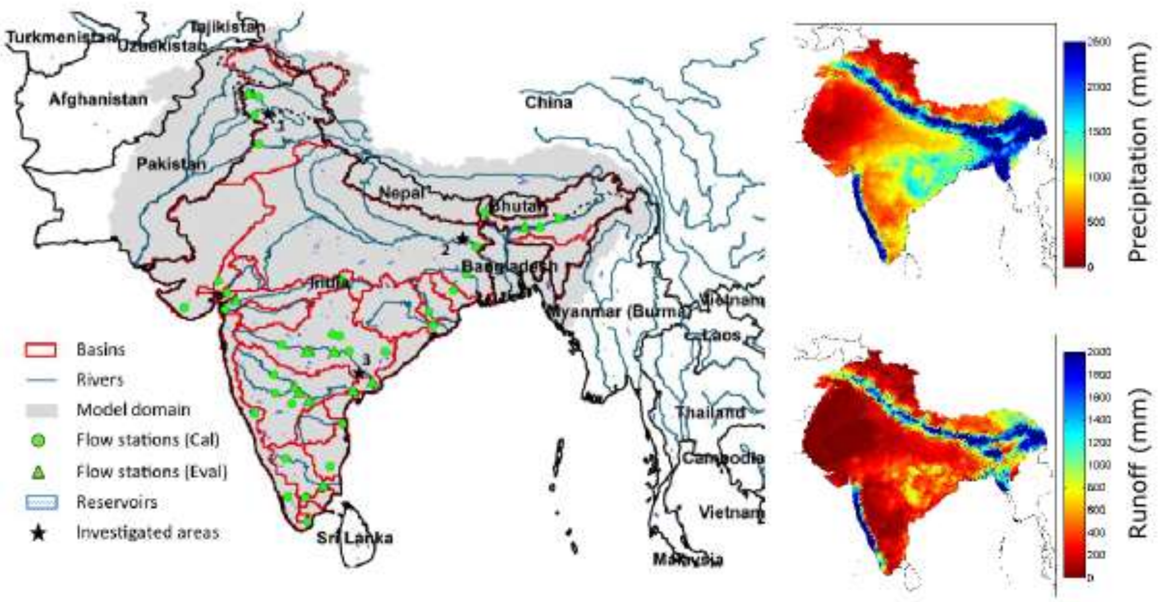

Figure 1: Map of the Indian subcontinent (model domain). Specific investigations are conducted at river-basins with a star (1 - Chenab (Indus), 2 - Ganga and 3 - Godavari).

Daily precipitation inputs for the period 1971-2005 (here used as reference period) are obtained from the Asian Precipitation – Highly Resolved Observational Data Integration Towards Evaluation of Water Resources (APHRODITE) project (Yatagai *et al*., 2012) at 0.25° resolution.

Similarly, AphroTEMP provides daily temperature inputs for the same period at 0.5° resolution. APHRODITE and AphroTEMP (in the following jointly denoted APHRODITE) are the only long-term continental-scale gridded datasets that are based on a dense network of daily data for Asia including the Himalayas.

Our ensemble of three climate projections consists of modelling chains that use the same GCM (EC-EARTH) and RCM (RCA4), but three different representative concentration pathways, RCPs. RCPs are numbered after their increased radiative forcing until year 2100 (+2.6, +4.5, and +8.5 W/m^2, respectively). The RCM projections (mean daily precipitation and temperature) were bias corrected against the APHRODITE dataset using the Distribution Based Scaling, DBS, statistical method (Yang *et al*., 2010). In brief, DBS aims to map the quantile distributions of precipitation and temperature in the RCM data to those of the reference data. The analysis is based on three 30-year periods: reference (1976-2005), mid-century (2021-2050), and end-century (2070-2099) period.

3. Methodology

3.1. The India-HYPE model

The Hydrological Predictions for the Environment, HYPE, model is a semi-distributed rainfall-runoff model capable of describing the hydrological processes at the basin scale. The model represents processes for snow accumulation and melting, evapotranspiration, soil moisture, discharge generation, groundwater recharge, and routing through rivers and lakes. In this model setup, we use global datasets to extract the information required for hydrological applications. The HYPE model is set up for the entire Indian subcontinent (4.9 million km^2) divided into 6010 sub-basins, i.e. with an average size of 810 km^2, and is referred to as India-HYPE (Pechlivanidis and Arheimer, 2015). The model runs at a daily time step using APHRODITE as input data. The bias-corrected projections were used to force the hydrological model for the assessment of climate change impacts on water resources.

3.2. Climate change impact assessment

Trend analysis of high flows

The non-parametric Mann-Kendall (MK) test was used to statistically assess the existence of monotonic linear or non-linear trend of high flows (defined as the 99th percentile of flow in every year) over time (1976-2100). The Sen's slope (also known as the Kendall slope) is an unbiased estimator of the true slope in simple linear regression and was used in here.

Standard Precipitation Index

The Standardised Precipitation Index (SPI) is defined as the number of standard deviations that the observed cumulative precipitation at a given time scale would deviate from the long-term mean. Positive SPI values indicate greater than median precipitation, and negative values indicate less than median precipitation. Because the SPI is normalised, wetter and drier climates can be represented in the same way, and wet periods can also be monitored using the SPI. For instance, a drought event occurs at any time the SPI is continuously negative and reaches an intensity of −1.0 or less. The event ends when the SPI becomes positive.

4. Results

The trend analysis and 12-month SPI for the rivers Chenab (tributary of Indus), Ganga and Godavari are presented in Figure 2. Clear increasing trends were detected in high flows for all RCP scenarios (Fig. 2 a-c). The Sen's slopes vary between the climatologic regions, with the smaller slopes occurring in the montane climate (Chenab river). As expected, the slopes increase for the severe RCP8.5 scenario, which projects a high increase in precipitation and consequently runoff generation (Pechlivanidis *et al*., 2015).

Clear increasing trends were detected for the Ganga and Godavari rivers for all RCPs. The hydrological response in these rivers is mainly rain-fed dominated, and hence the increase in precipitation over the mid- and end-century in these regions will influence the magnitude (and frequency) of high flows.

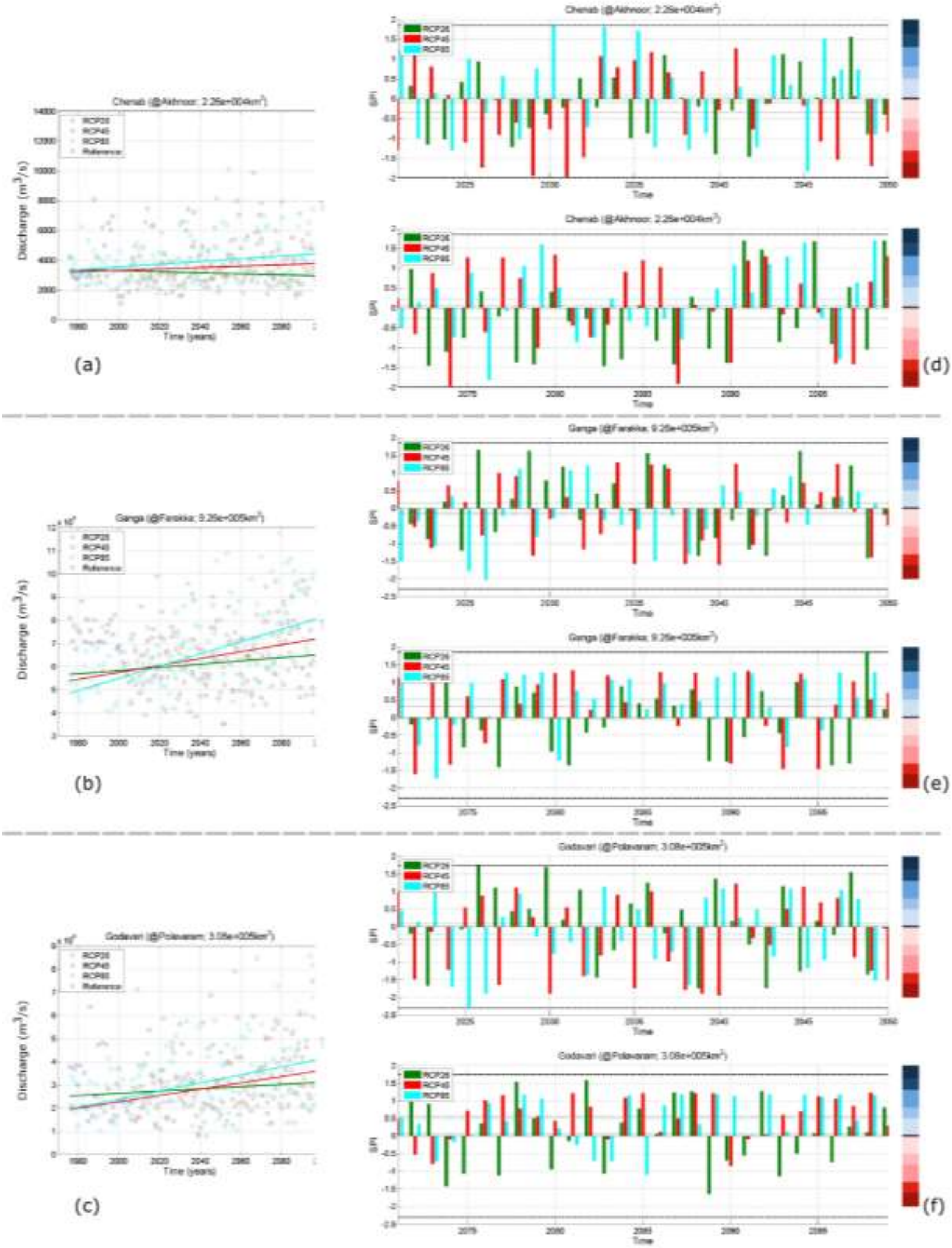

Figure 2: Trend in high flows (a-c) and the 12-month SPI (d-f) for mid- and end-century for Indus, Ganga, and Godavari. The blue/red colour-scales define the severity of SPI.

Figure 2 (d-f) illustrates the deviation in wet/dry (and their severity) years. Overall, SPI differs between RPCs and future periods, whilst similarly to the trends in high flows, the SPI magnitude and frequency is dependent on the region's hydro-climatic gradient. In general, results from all scenarios indicate more frequent wet years (SPI > 0) with the changes becoming remarkable at the end of the century. In addition, it is interesting to note that extreme SPI values (>1.5 or <-1.5) are more frequent during the mid-century for the Ganga and Godavari river basins.

5. Conclusions

This study focuses on the analysis of the extremes in three major Indian rivers of different hydro-climatic characteristics. It is clear that the uncertainty in the climate projections, as represented here in terms of RCPs, is propagated in the hydrological model and consequently affects the model results.

- In general an increasing trend in high flows is observed for all rivers and RCPs; however its significance depends on the regional hydro-climatic characteristics.
- The trend in slope is also dependent on the RCPs with higher trends being observed for RCP8.5 compared to RCP4.5 and RCP2.6.
- Magnitude and frequency of SPIs vary between RCPs and future periods. Wet years will be more frequent at the end of the century particular at the tropical and humid subtropical regions.

REFERENCES

1. Giorgi, F., Jones, C., Asrar, G.R., 2009. Addressing climate information needs at the regional level: the CORDEX framework. WMO Bull. 58, 175–183.
2. Graham, L.P., Hagemann, S., Jaun, S., Beniston, M., 2007. On interpreting hydrological change from regional climate models. Clim. Change 81, 97–122. doi:10.1007/s10584-006-9217-0
3. Pechlivanidis, I.G., Arheimer, B., 2015. Large-scale hydrological modelling by using modified PUB recommendations: India-HYPE. Hydrol. Earth Syst. Sci. Discuss. 12, 2885–2944. doi:10.5194/hessd-12-2885-2015
4. Pechlivanidis, I.G., Jackson, B., McIntyre, N., Wheater, H.S., 2011. Catchment scale hydrological modelling: A review of model types, calibration approaches and uncertainty analysis methods in the context of recent developments in technology and applications. Glob. NEST 13, 193–214.
5. Pechlivanidis, I.G., Olsson, J., Bosshard, T., Sharma, D., Sharma, K.C., 2015. Multi-basin modelling of future hydrological fluxes in the Indian subcontinent. J. Hydrol. Reg. Stud. Under Revi.
6. Wetterhall, F., Pappenberger, F., He, Y., Freer, J., Cloke, H.L., 2012. Conditioning model output statistics of regional climate model precipitation on circulation patterns. Nonlinear Process. Geophys. 19, 623–633. doi:10.5194/npg-19-623-2012
7. Yang, W., Andréasson, J., Graham, P.L., Olsson, J., Rosberg, J., Wetterhall, F., 2010. Distribution-based scaling to improve usability of regional climate model projections for hydrological climate change impacts studies. Hydrol. Res. 41, 211–229. doi:10.2166/nh.2010.004
8. Yatagai, A., Kamiguchi, K., Arakawa, O., Hamada, A., Yasutomi, N., Kitoh, A., 2012. APHRODITE: Constructing a long-term daily gridded precipitation dataset for Asia based on a dense network of rain gauges. Bull. Am. Meteorol. Soc. 93, 1401–1415. doi:10.1175/BAMS-D-11-00122.1