Hydrol. Earth Syst. Sci. Discuss., https://doi.org/10.5194/hess-2017-296
Manuscript under review for journal Hydrol. Earth Syst. Sci.
Discussion started: 6 June 2017

Hydrology and Earth System Sciences
Open Access
Discussions

Precipitation Pattern in the Western Himalayas revealed by Four Datasets

Hong Li[1], Jan Erik Haugen[2], and Chongyu Xu[3]

[1]The Norwegian Water Resources and Energy Directorate, Norway
[2]Norwegian Meteorological Institute, Norway
[3]University of Oslo, Norway

Correspondence to: Hong Li (holi@nve.no)

Abstract. Data scarcity is the biggest problem for scientific research related to hydrology and climate studies in the great Himalayas Region. High quality precipitation data are among the most difficult to obtain due to sparse network, cold climate and high heterogeneity in topography. This paper examines four different types of datasets, including interpolated gridded data based on ground observations (IMD, $1^{\circ}\times1^{\circ}$ and APHRODITE, $0.25^{\circ}\times0.25^{\circ}$), reanalysis data (ERA-interim, $0.75^{\circ}\times0.75^{\circ}$) and high resolution simulation by a regional climate model (WRF, $0.15^{\circ}\times0.15^{\circ}$). In Northern India of the Western Himalayas, the four datasets show a similar spatial pattern and temporal variation during the period 1981-2007, though the absolute values vary significantly (497-819 mm/year) mainly due to the data source and the methods of data generation. The differences are particularly large in July and August at the windward slopes and the high elevation area. All the datasets show a wetter summer and drier winter during the period, though most of the trends in monthly precipitation are not significant. The comparison between two periods of 1981-1985 and 2003-2007 shows an increase in summer and a decrease in winter with large variations. Between the periods, the runoff is expected to increase which is likely to result in more and bigger floods in the downstream areas according to the IMD, APHRODITE and WRF datasets, whereas the ERA-interim dataset reveals a tendency toward longer low flow periods and more droughts. All the datasets can give a good overview of the precipitation, but because of coarse spatial resolution and small size of basins in this area, future work such as local correction is necessary for hydro-glacial modelling.

1 Introduction

The great Himalayas Region is the largest cryosphere outside the polar areas and is the source of many rivers which supply water to more than 800 million people (Hegdahl et al., 2016; Li et al., 2015). Local populations largely depend on precipitation and rivers for drinking water, hygiene, industry, fishing, and also for agriculture and hydro-power generation, which are the main sectors of local economy (Ménégoz et al., 2013). Therefore, it is very important to understand changes and distribution of precipitation, their impacting factors as well as their implication for the survival of glaciers.

Precipitation is one of the most important elements in meteorology and hydrology and it is very relevant to human activities. In recent years, with the development of space-borne measurements and computing technologies, gridded precipitation datasets have been widely generated and attracted much interest. Compared to traditional ground stations, gridded data cover a large area, sometimes even the globe, and disclose the spatial variability. Additionally, gridded data are generally produced by researchers for scientific purposes and the data are free accessible for scientific research. Gridded precipitation data have been extensively used where high quality *in situ* measurements are not available.

The work presented in this paper is a part of the INDICE project (The response of the hydrological system in India to climate change, https://www.nve.no/hydrology/indice-project/). The overall aim of the project is to understand impacts of climate change on glaciers in the Western Himalayas and subsequent effects on water resource availability and socio-economic status of the local community. The first difficulty for achieving this goal is a lack of high quality data, particularly precipitation, for hydrological studies. Therefore, it is an important step to evaluate the existing types of datasets for spatial pattern and temporal changes of precipitation. Implications for glacier survival are also concerned. Due to the fact that this project eventually interests in glacier and hydrological impacts, we only select datasets at a daily time step, which is most often used in hydrological simulations. Additionally, we purposely select data covering a long period and from various sources which are widely used, including observations, reanalysis and climate simulations.

There have been quite a few studies about precipitation over the great Himalayas Regions (Yatagai et al., 2012; Ménégoz et al., 2013; Palazzi et al., 2013). The available gridded precipitation data fall into four types: satellite images, interpolated observations, reanalysis and model simulations. However, all estimations are also generally very uncertain due to the complex climate dynamics and local topography and the precipitation rates differ widely among the four types and even among different products of the same type. The satellite data show discrepancies due to platforms and characteristics of sensors. Reflectance from land surface, particularly snow and ice, can cause distinctive biases (Yin et al., 2008). The gridded observations are generally believed the most reliable. However, great cautions has to be paid when using such data due to inadequacy of interpolating methods and unavoidable inferiors inherited from gauge measurements. For example, underestimation of precipitation can be 58% of annual total precipitation in the cold Alaska region due to wind, wetting loss and trace precipitation (Yang et al., 1998). High resolution climate models provide an alternative perspective and the models are competitive in aspect of high spatial and temporal resolution, identification of precipitation forms (Ménégoz et al., 2013), consistency with other parameters and measurable uncertainties. On the other hand, the gridded simulation data may misrepresent the reality and suffer from inadequacy of boundary and forcing conditions. Reanalysis data are a combination of observations from many sources and dynamic models, but users should be cautious because of continuous changes in observing systems and systematic errors of used models (Dee et al., 2011). Additionally, uncertainties in reanalysis data are difficult to understand and quantify (Dee et al., 2011).

In this study, four datasets of three types (interpolated observations, reanalysis and modelling data) for a period of 27 years (1981-2007) over the Western Himalayas are used, which is the first of its kind in this region in aspect of number of datasets and data length. The purpose is to compare the datasets and to understand implications of the differences when using them in glacier and hydrological studies.

Hydrol. Earth Syst. Sci. Discuss., https://doi.org/10.5194/hess-2017-296
Manuscript under review for journal Hydrol. Earth Syst. Sci.
Discussion started: 6 June 2017

Hydrology and Earth System Sciences
Open Access
Discussions

2 Study Area

The study area lies in the northern part of the Indian Himalayan Region (Figure 1). The highest point is 7677 meters above sea level (m a.s.l.), located in the north-eastern region. The low elevation part lies in the south-western region, which adjoins Pakistan. The climate is affected by monsoon and western disturbance. In summer, from May to October, warm moisture from the Indian Ocean moves northwards and turns west when it hits the high mountains. This interaction brings plenty of precipitation. Precipitation at high mountains falls as snow in winter from November to April. Along the course of the moist wind, precipitation decreases from east to west. In winter, the climate is controlled by western turbulence. The mid-latitude low pressure systems bring some snowfall (Ménégoz et al., 2013), but winter is generally quite dry, especially in the coldest region.

This area is the source of the Indus River and the Ganges River, which are transboundary among China, India, Pakistan and Bangladesh. Additionally, these two rivers have very high hydropower potential. How to explore hydropower is continuously negotiated among the involved countries, which makes the study area very political sensitive.

In the great Himalayas Region, there are many glaciers and most of them are not regularly monitored. These glaciers are the key indicators of regional climate change and water resources. The fates of the glaciers are world-widely concerned by scientific and public communities. Fortunately, the Chhota Shigri glacier in the study area has been observed since 1962 and it is representative in term of mass balance for the Western Himalayas glaciers (Azam et al., 2014). Analysis of precipitation data contributes to research of the Chhota Shigri glacier as well as other glaciers in the Western Himalayas.

3 Data

3.1 IMD dataset

The IMD dataset is produced by the India Meteorological Department for the whole India. This dataset covers years from 1951 to 2007 and has a spatial resolution of $1° \times 1°$. The data is interpolated by the Shepard method (Shepard, 1968) from weather stations. Rajeevan et al. (2006) compared the IMD dataset with the Variablity Analysis of Surface Climate Observations (VASClimo) dataset and they concluded that the IMD dataset was more accurate in terms of spatial variation. The IMD dataset is extensively used in climate related research and applications, such as validation of climate models (Bollasina et al., 2011; Wiltshire, 2014) and monsoon variability and predictions (Goswami et al., 2006).

The number of used stations varies during the period of 1981-2007 as well as across the region. During this period, the average number of stations per grid point varies from 0.2 to 4.4 and on average 2.99 stations are used per grid point (Rajeevan et al., 2006). Spatially, more stations are used in the central south; less stations near the borders of India and in the northern part. No observations are available near the latitude of 35.5°N and its north.

3.2 APHRODITE dataset

The APHRODITE (Asian Precipitation—Highly Resolved Observational Data Integration Towards Evaluation of Water Resources) dataset is interpolated by the Sphere map method based on data collected at 5,000–12,000 stations (Yatagai et al., 2012). The interpolated parameter is the precipitation anomaly or ratio, instead of the precipitation amount and a weighting function is based on the angular distance with modification considering topography (Yatagai et al., 2012). The dataset covers Asia over the period of 1951-2007. Different versions of the APHRODITE dataset has been used to determine of Asian monsoon precipitation change, hydrological modelling (Pechlivanidis and Arheimer, 2015; Xu et al., 2016), verification of high-resolution model simulations and satellite precipitation estimates (Kamiguchi et al., 2010). In this research, we use the latest version (V1101) for monsoon Asia at a spatial resolution of 0.25°×0.25° (Dimri et al., 2013).

The APHRODITE dataset involves the largest number of gauge observations and has been claimed better than the MRI/JMA AGMC model at a spatial resolution of 20 km, which has the highest resolution of AGCM used to study global warming (Yatagai et al., 2005). The dataset represents the orographic precipitation pattern and heavy rainfall spreads across the Himalayas (Yatagai et al., 2012) and is believed to be one of the most realistic precipitation datasets for Asia (Ménégoz et al., 2013).

3.3 ERA-interim dataset

The ERA-interim dataset is the precipitation product of the ERA-Interim (Dee et al., 2011), which is a spatially and temporally complete data set of multiple climate variables at high spatial and temporal resolution. The ERA-Interim is global atmospheric reanalysis produced by the ECMWF (European Centre for Medium-Range Weather Forecasts). The dataset dates back to 1979 and is updated with approximately 1 month delay from real-time. The model output is on T255 spectral resolution but our downloaded product is on a Gaussian grid (with a resolution of 0.7×0.7° at the Equator) with a 3-hour time resolution. The data assimilation system is based on a 2006 release of the IFS (Cy31r2) (Dee et al., 2011) and precipitation is adjusted based on GPCP v2.1 before release. This dataset has been widely used as boundary and forcing conditions for regional climate models (Dimri et al., 2013; Katragkou et al., 2015).

Due to the fact that variability of precipitation is very high over the study area, the spatial resolution of the ERA-interim dataset is limited in representing the spatial variability (Ménégoz et al., 2013; Dimri et al., 2013). The large differences compared to the in situ measurements are attributed to the lack of observations in high altitude areas.

3.4 WRF dataset

The WRF dataset is generated by a regional climate model, the Weather Research & Forecasting Model (v3.7.1). The model is a limited-area, non-hydrostatic, primitive-equation model with multiple options for various physical parameterization schemes. The model can generate atmospheric simulations using real data (observations, analyses) or idealized conditions and has been used in climate simulation in Asia and other areas. Selection of the physical parameterization scheme in the Himalayas is not

Hydrol. Earth Syst. Sci. Discuss., https://doi.org/10.5194/hess-2017-296
Manuscript under review for journal Hydrol. Earth Syst. Sci.
Discussion started: 6 June 2017

optimized due to the complex topography (Maussion et al., 2011). Therefore, we use a configuration for EURO-CORDEX by Katragkou et al. (2015) with small modifications, as shown in Table 1.

This climate model has been proved to be able to produce the regional precipitation at a fine scale, but has been criticized to be moist biased compared with satellite data, the IMD and the APHRODITE datasets particularly in winter for high altitude (Maussion et al., 2011; Srinivas et al., 2013; Li et al., 2016). However, the daily runoff simulation by WRF-hydro by Li et al. (2016) agrees well with the observed discharge in the Beas Basin (32°N, 77°E), which confirms the precipitation simulations reversely.

4 Spatial variation

The four datasets show similar spatial pattern of annual precipitation (Figure 2). The highest precipitation locates at the foothill of the mountains and stretches from southeast to northwest. With increasing spatial resolution, the spatial variability increases from the IMD dataset to the WRF dataset. The coefficient of variation is 0.5, 0.6, 0.7 and 1.1 respectively for the IMD, ERA-interim, APHRODITE and WRF datasets. Visually, the high precipitation locations (the foothills of the mountains and the southeastern corner) are most clearly shown by the WRF dataset.

Both the IMD and APHRODITE datasets originate from station observations. The APHRODITE dataset has a finer spatial resolution and uses much more stations, particularly also observations from Nepal, Bhutan and China. Compared with the IMD dataset, the APHRODITE dataset indeed has a much higher estimation at the foothills of the mountains, which seems more realistic (Yatagai et al., 2012). However, the APHRODITE dataset has the lowest annual total amount, only 61% of the IMD dataset. A low precipitation area (less than 300 mm/year) is located in the north-eastern corner. The elevation of this area is 4650 m a.s.l. and ranges from 906 to 7677 m a.s.l. The temperature is -2.35 °C of annual mean and as low as -16.81 °C in January (AphroTemp, Yatagai et al., 2012). In winter, the precipitation mainly falls as snow and thus the rain gauges tend to significantly underestimate the precipitation. In contrast, the IMD dataset uses only the observations at the low valley area of India with a relatively higher precipitation (Rajeevan et al., 2006).

The ERA-interim and WRF datasets are products with different dynamical models, whereas the ERA-interim precipitation dataset has been adjusted to the GPCC monthly precipitation dataset. ERA-interim and WRF are similar in terms of annual total amount (ERA-interim: 718 mm/year, WRF: 688 mm/year) and spatial pattern partially due to the fact that in this area the observations that are assimilated into reanalysis systems are sparse and unevenly distributed. Spatial resolution of regional climate models is definitely important in the mountainous areas (Ménégoz et al., 2013). The regional climate models forced by the ERA-interim are claimed to produce more realistic results than the ERA-interim precipitation dataset due to their higher resolution (Polanski et al., 2010; Maussion et al., 2011; Dimri and Niyogi, 2013; Dimri et al., 2013).

The four datasets show a similar spatial pattern in all four seasons, but the WRF dataset shows a relatively high contribution in spring and low contribution in winter (Figure 3). The products from dynamic models do not suffer from the undercatch problem, which exists in the other three datasets. For the low contribution in winter, the possible reason is that there is less moisture available by simulations compared to the observations shown by Dimri and Niyogi (2013) using HadRM3 and REMO.

The summer monsoon and winter monsoon respectively bring the precipitation in summer and winter. Here we select two months in each season to examine the precipitation pattern against elevation. As shown in Figure 4, precipitation in both seasons shows the similar pattern – "curved sword". For instance, the summer precipitation increases with the elevation at the low area (100 - 800 m a.s.l). However, at approximately 700 m a.s.l, the range of precipitation becomes large. It resembles the grip part of a sword. At 2500 m a.s.l, the precipitation is at a high level (250 mm/month). At high area, the precipitation decreases with elevation. This curved sword pattern is more clear in summer than in winter and there is a large variation between datasets. It should be noted here that the presented elevations are slightly lower than the actual values due to spatial interpolation.

The effects of the Himalayan topography on precipitation are clearly shown in Figure 5. The summer monsoon comes from the southeast and the precipitation decreases along the path. Over the flat topography, the precipitation decreases with latitude since the strength of monsoon decreases with distance from its source. As the monsoon gets closer to the mountains, the precipitation starts to increase. As the air parcel is lifted to high levels, the climate gets dry and cold. The winter monsoon travels from the northwest (Dimri and Niyogi, 2013) and it is much colder and drier than the summer monsoon. Therefore, the precipitation occurs mainly along the up-slope. The magnitude is also small and decreases along the path of winter monsoon. In winter, the highest precipitation occurs in the windward of the up-slope region, but it is 0.5 or 1.5 degree (around 55-110 km) far away from the mountains in summer. Bookhagen and Burbank (2006) analyzed a decade of TRMM data and also found the highest annual precipitation is offset by a few 10s of km south of either high topography or relief. This offset has only been found over tall and broad mountain regions rather than narrow mountain peaks (Dimri and Niyogi, 2013).

The differences among the datasets are significant, particularly at the high elevation. The WRF dataset gives much more precipitation in summer and where elevation is below 3000 m a.s.l. The WRF model has been reported to be moist biased in summer (Srinivas et al., 2013; Li et al., 2016) and it is often cited as orographic bias which described as strong over-prediction of precipitation rates along windward slopes while predicted snowfall lies under measured values along leeward slopes (Maussion et al., 2011). However, it is not fair to interpret as model errors rather than inaccuracy in measurements. Discharge measurements are generally more qualified than precipitation in the snow and ice dominated area (Henn et al., 2015; Kretzschmar et al., 2016). Therefore, the quality of runoff simulation can infer by the forcing precipitation data. Li et al. (2016) used the WRF-Hydro (v3.5.1) modeling system in the Beas Basin, which is a main tributary of the Indus River in Northern India, and they found that the distribution of simulated daily discharge values agreed well with the gamma distribution from observed discharge. This finding provides confidence of the WRF simulation though they used a slightly different setting.

Hydrology and Earth System Sciences
Open Access
Discussions

5 Temporal Variation

The inter-annual patterns are very similar as indicated by high correlations between pairs of datasets, shown in Table 2. The correlation between the IMD and APHRODITE datasets is the highest, reaching 0.91. This is due to the fact that they are both interpolated from ground observations. The WRF dataset has low correlation with all other datasets, since the WRF model produces much higher variability than other datasets.

The intra-annual cycle is also similar in terms of temporal distribution (Figure 6). The WRF and APHRODITE datasets give respectively the highest and lowest variability, which is mainly reflected in the summer months. During the period of 1981-2007, the winter gets drier whereas the summer gets wetter. Such changes would lead to strong negative mass balance conditions of glaciers, which is discussed in the next section. It is worthy to note that only three of the trends (May by the WRF dataset; June by the IMD and ERA-interim datasets) are statistically significant at the 95% confidence level by the Mann-Kendall test.

6 Implications for glaciers

Temperature in combination with precipitation controls survival of glaciers. For this purpose, we compare mean temperature and precipitation for the first and last five years, namely 1981-1985 and 2003-2007. For temperature, two datasets are selected: the temperature results by the same simulation of the WRF precipitation dataset and the temperature dataset produced by the same methods and stations as the APHRODITE dataset. The reasons to use only two temperature datasets are two-fold. One is because temperature is generally better measured and less variable than precipitation, so the two datasets are enough to give a good overview. The second reason is that the precipitation analysis has shown that WRF and APHRODITE represent highest and lowest precipitation of the four datasets and other two datasets are between them.

The WRF model is able to reproduce the dry and wet lapse rates and shows a high correlation between temperature and elevation (Figure 7). For the periods of 1981-1985 and 2003-2007, the temperature increases 0.91 °C in winter and 0.26 °C in summer. Such changes lead to the elevation of freezing point (0 °C) moving up 125 meters in winter and 32 meters in summer. The APHRODITE shows the similar effects, but the magnitudes are more striking.

All the datasets show a dominant decrease in winter precipitation (Figure 8). The most notable changes are given by the observations, the IMD and APHRODITE datasets. Shown by the IMD dataset, the precipitation decreases 42 mm/month, which accounts for 38% of the mean winter precipitation from 1981 to 1985. These two datasets also indicate more decrease at high elevation than low elevation, though there are large variations. However, the WRF dataset shows an opposite pattern.

For the summer precipitation, the datasets are not consistent. The ERA-interim dataset shows a decrease in general and the decrease is high at the low elevation whereas the other three datasets show an increase and the increase is high at the low elevation (Figure 9).

The comparison of the two periods shows an unfavourable condition for the glaciers: less accumulation and faster melting due to decreasing winter precipitation and increasing temperature (Figure 7). Moreover, the area between 4900 m a.s.l., which is the equilibrium line altitude (ELA) of the Chhota Shigri glacier (see Azam et al., 2012, Figure 2), and 5200 m a.s.l. is relatively large compared with the areas in other elevation zones. Therefore, as the climate gets warmer, the ELA will further move up. Such a nonlinear characteristic of elevation distribution leads to a significant reduction in the accumulation area and small storage buffer of permanent snow and ice. Additionally, precipitation at the low elevation tends to increase in summer shown by the IMD, APHRODITE and WRF datasets. Such changes cause fast response of discharge at downstream of the basins. Therefore, the downstream regions are more likely to experience more frequent and bigger floods. However, the changes shown by the ERA-interim dataset likely result in longer low flow period and more droughts.

7 Conclusions

Data scarcity is the biggest problem for hydrological research in the Great Himalayas region. High quality precipitation data are among the most difficult to obtain due to the sparse network, cold climate and high heterogeneity in topography. This paper examines the spatial and temporal pattern of precipitation in this region based on different types of datasets, including interpolated gridded data based on ground observations (IMD, $1^\circ \times 1^\circ$ and APHRODITE, $0.25^\circ \times 0.25^\circ$), reanalysis data (ERA-interim, $0.75^\circ \times 0.75^\circ$) and high resolution simulation by a regional climate model (WRF, $0.15^\circ \times 0.15^\circ$) in Northern India of the Western Himalayas during the period 1981-2007.

The four datasets are similar in terms of spatial pattern and temporal variation, though the absolute values vary significantly (497-819 mm/year) mainly due to the data source and the methods of data generation. The differences are particularly large in July and August at the windward slopes and the high elevation areas. The datasets indicate a wetter summer and drier winter during the period, though most of the trends in monthly precipitation are not significant. The comparison between two periods of 1981-1985 and 2003-2007 shows precipitation increased in summer precipitation and decreased in winter. Combining with the increasing temperature, the runoff responses are expected to get faster and the downstream areas are likely to experience more and bigger floods. The four datasets can give a good overview of the precipitation, but because of spatial resolution and small size of basins in this area, future work such as local corrections is necessary for hydro-glacial modelling.

Acknowledgements. This study is funded by the Research Council of Norway through the research program NORKLIMA under grant the project 216546. We thank India Meteorological Department and Sonia Grover at Water Resources Division at TERI (India), European Centre for Medium-Range Weather Forecasts and the APHRODITE (http://www.chikyu.ac.jp/precip/english/products.html) for provision of data. We thank Oskar Landgren at the Norwegian Meteorological Institute for assistance in modelling and data analysis as well as review of the manuscript. The model simulation was done when the first author worked at the Norwegian Meteorological Institute.

Conflict of Interest

No conflict of interest.

8 Code availability

9 Data availability

The ERA-interim and APRODITE data are available from the data provider sites. The WRF data are available via https://archive.norstore.no/pages/public/about.jsf.

Author contributions. Hong Li: model simulation, data analysis and draft. Jan Erik Haugen: model simulation and results analysis. Chongyu Xu: draft review and manuscript modification.

References

Azam, M. F., Wagon, P., Ramanathan, A., Vincent, C., Sharma, P., Arnaud, Y., Linda, A., Pottakkal, J. G., Chevallier, P., Singh, V. B., and Berthier, E.: From balance to imbalance: a shift in the dynamic behaviour of Chhota Shigri glacier, western Himalaya, India, Journal of Glaciology, 58, 315–324, 2012.

Azam, M. F., Wagnon, P., Vincent, C., Ramanathan, A., Linda, A., and Singh, V. B.: Reconstruction of the annual mass balance of Chhota Shigri glacier, Western Himalaya, India, since 1969, Annals of Glaciology, 55, 69–80, 2014.

Bollasina, M. A., Ming, Y., and Ramaswamy, V.: Anthropogenic Aerosols and the Weakening of the South Asian Summer Monsoon, Science, 2011.

Bookhagen, B. and Burbank, D. W.: Topography, relief, and TRMM-derived rainfall variations along the Himalaya, Geophysical Research Letters, 33, L08 405, 2006.

Dee, D. P., Uppala, S. M., Simmons, A. J., Berrisford, P., Poli, P., Kobayashi, S., Andrae, U., Balmaseda, M. A., Balsamo, G., Bauer, P., Bechtold, P., Beljaars, A. C. M., van de Berg, L., Bidlot, J., Bormann, N., Delsol, C., Dragani, R., Fuentes, M., Geer, A. J., Haimberger, L., Healy, S. B., Hersbach, H., Hólm, E. V., Isaksen, L., Kållberg, P., Köhler, M., Matricardi, M., McNally, A. P., Monge-Sanz, B. M., Morcrette, J.-J., Park, B.-K., Peubey, C., de Rosnay, P., Tavolato, C., Thépaut, J.-N., and Vitart, F.: The ERA-Interim reanalysis: configuration and performance of the data assimilation system, Quarterly Journal of the Royal Meteorological Society, 137, 553–597, 2011.

Dimri, A. P. and Niyogi, D.: Regional climate model application at subgrid scale on Indian winter monsoon over the western Himalayas, International Journal of Climatology, 33, 2185–2205, 2013.

Dimri, A. P., Yasunari, T., Wiltshire, A., Kumar, P., Mathison, C., Ridley, J., and Jacob, D.: Application of regional climate models to the Indian winter monsoon over the western Himalayas., The Science of the total environment, 468-469 Su, S36–47, 2013.

Goswami, B. N., Venugopal, V., Sengupta, D., Madhusoodanan, M. S., and Xavier, P. K.: Increasing Trend of Extreme Rain Events Over India in a Warming Environment, Science, 2006.

Hegdahl, T. J., Tallaksen, L. M., Engeland, K., Burkhart, J. F., and Xu, C.-Y.: Discharge sensitivity to snowmelt parameterization: a case study for Upper Beas basin in Himachal Pradesh, India, 2016.

Henn, B., Clark, M. P., Kavetski, D., and Lundquist, J. D.: Estimating mountain basin-mean precipitation from streamflow using Bayesian inference, Water Resources Research, 51, 8012–8033, 2015.

Kamiguchi, K., Arakawa, O., Kitoh, A., Yatagai, A., Hamada, A., and Yasutomi, N.: Development of APHRO_JP, the first Japanese high-resolution daily precipitation product for more than 100 years, Hydrological Research Letters, 4, 60–64, 2010.

Katragkou, E., García-Díez, M., Vautard, R., Sobolowski, S., Zanis, P., Alexandri, G., Cardoso, R. M., Colette, A., Fernandez, J., Gobiet, A., Goergen, K., Karacostas, T., Knist, S., Mayer, S., Soares, P. M. M., Pytharoulis, I., Tegoulias, I., Tsikerdekis, A., and Jacob, D.: Regional climate hindcast simulations within EURO-CORDEX: evaluation of a WRF multi-physics ensemble, Geoscientific Model Development, 8, 603–618, 2015.

Kretzschmar, A., Tych, W., Chappell, N. A., and Beven, K. J.: Reversing hydrology: quantifying the temporal aggregation effect of catchment rainfall estimation using sub-hourly data, Hydrology Research, 2016.

Li, H., Xu, C.-Y., Beldring, S., Tallaksen, L., and Jain, S. K.: Water Resources under Climate Change of Himalayan Basins, Water Resources Management, 2015.

Li, L., Gochis, D. J., Sobolowski, S., and Mesquita, M. d. S.: Evaluating the present annual water budget of a Himalayan headwater river basin using a high-resolution atmosphere-hydrology model, in: EGU General Assembly Conference Abstracts, vol. 18, 2016.

Maussion, F., Scherer, D., Finkelnburg, R., Richters, J., Yang, W., and Yao, T.: WRF simulation of a precipitation event over the Tibetan Plateau, China – an assessment using remote sensing and ground observations, Hydrology and Earth System Sciences, 15, 1795–1817, 2011.

Ménégoz, M., Gallée, H., and Jacobi, H. W.: Precipitation and snow cover in the Himalaya: from reanalysis to regional climate simulations, Hydrology and Earth System Sciences, 17, 3921–3936, 2013.

Palazzi, E., von Hardenberg, J., and Provenzale, A.: Precipitation in the Hindu-Kush Karakoram Himalaya: Observations and future scenarios, Journal of Geophysical Research: Atmospheres, 118, 85–100, 2013.

Pechlivanidis, I. G. and Arheimer, B.: Large-scale hydrological modelling by using modified PUB recommendations: the India-HYPE case, Hydrology and Earth System Sciences, 19, 4559–4579, 2015.

Polanski, S., Rinke, A., and Dethloff, K.: Validation of the HIRHAM-simulated Indian summer monsoon circulation, Advances in Meteorology, 2010.

Rajeevan, M., Bhate, J., Kale, J. D., and Lal, B.: High resolution daily gridded rainfall data for the Indian region: Analysis of break and active monsoon spells, Current Science, 2006.

Shepard, D.: A two-dimensional interpolation function for irregularly-spaced data, in: Proceedings of the 1968 23rd ACM national conference, pp. 517–524, 1968.

Srinivas, C. V., Hariprasad, D., Bhaskar Rao, D. V., Anjaneyulu, Y., Baskaran, R., and Venkatraman, B.: Simulation of the Indian summer monsoon regional climate using advanced research WRF model, International Journal of Climatology, 33, 1195–1210, 2013.

Wiltshire, A. J.: Climate change implications for the glaciers of the Hindu Kush, Karakoram and Himalayan region, The Cryosphere, 8, 941–958, 2014.

Xu, H., Xu, C.-Y., Chen, S., and Chen, H.: Similarity and difference of global reanalysis datasets (WFD and APHRODITE) in driving lumped and distributed hydrological models in a humid region of China, Journal of Hydrology, 542, 343–356, 2016.

Yang, D., Goodison, B. E., Ishida, S., and Benson, C. S.: Adjustment of daily precipitation data at 10 climate stations in Alaska: Application of World Meteorological Organization intercomparison results, Water Resources Research, 34, 241–256, 1998.

Yatagai, A., Xie, P., and Kitoh, A.: Utilization of a new gauge-based daily precipitation dataset over monsoon Asia for validation of the daily precipitation climatology simulated by the MRI/JMA 20-km-mesh AGCM, Sola, 2005.

Yatagai, A., Kamiguchi, K., Arakawa, O., Hamada, A., Yasutomi, N., and Kitoh, A.: APHRODITE: Constructing a Long-Term Daily Gridded Precipitation Dataset for Asia Based on a Dense Network of Rain Gauges, Bulletin of the American Meteorological Society, 93, 1401–1415, 2012.

Yin, Z.-Y., Zhang, X., Liu, X., Colella, M., and Chen, X.: An Assessment of the Biases of Satellite Rainfall Estimates over the Tibetan Plateau and Correction Methods Based on Topographic Analysis, Journal of Hydrometeorology, 9, 301–326, 2008.

Hydrol. Earth Syst. Sci. Discuss., https://doi.org/10.5194/hess-2017-296
Manuscript under review for journal Hydrol. Earth Syst. Sci.
Discussion started: 6 June 2017

Hydrology and Earth System Sciences
Discussions

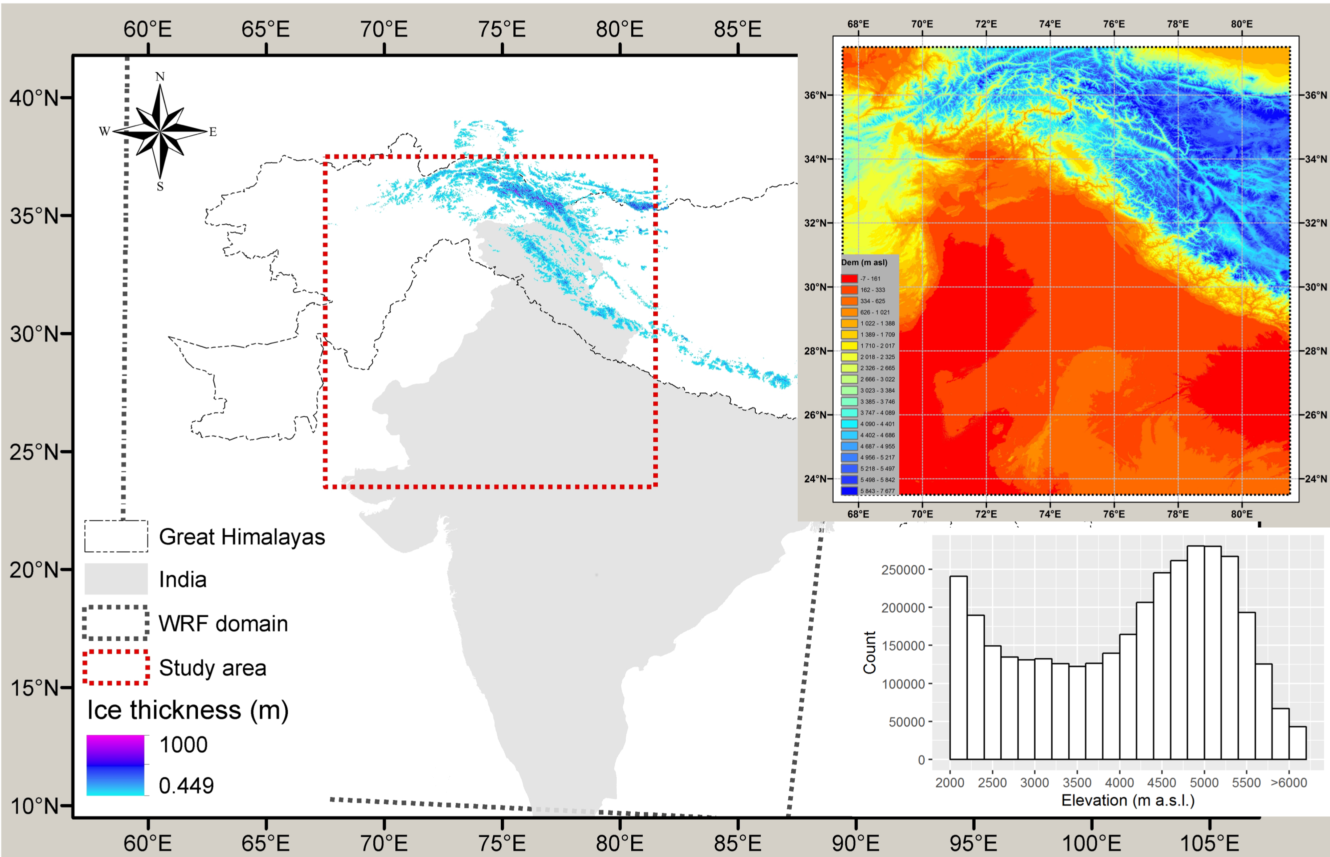

Figure 1. The location and elevation of the study area. The elevation source is HydroSHEDS (http://hydrosheds.org/).

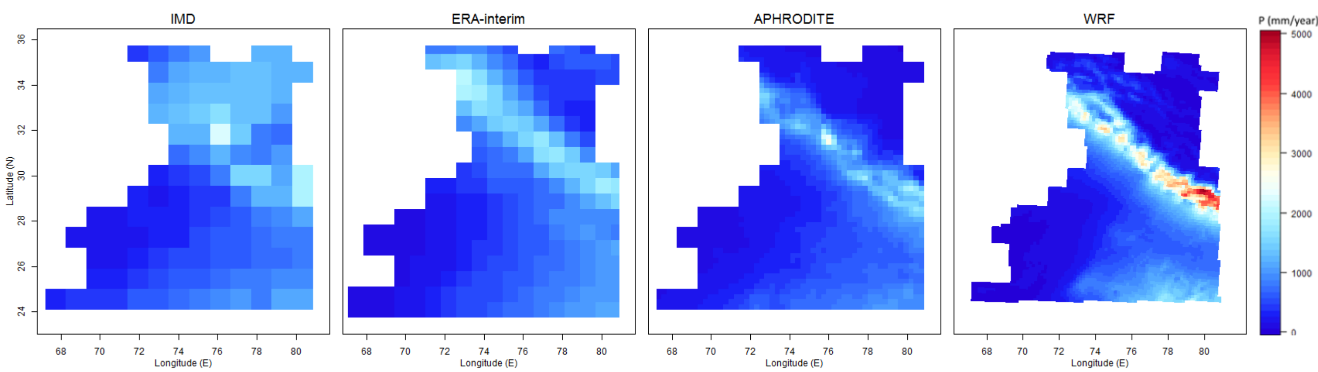

Figure 2. Annual precipitation.

Hydrol. Earth Syst. Sci. Discuss., https://doi.org/10.5194/hess-2017-296
Manuscript under review for journal Hydrol. Earth Syst. Sci.
Discussion started: 6 June 2017

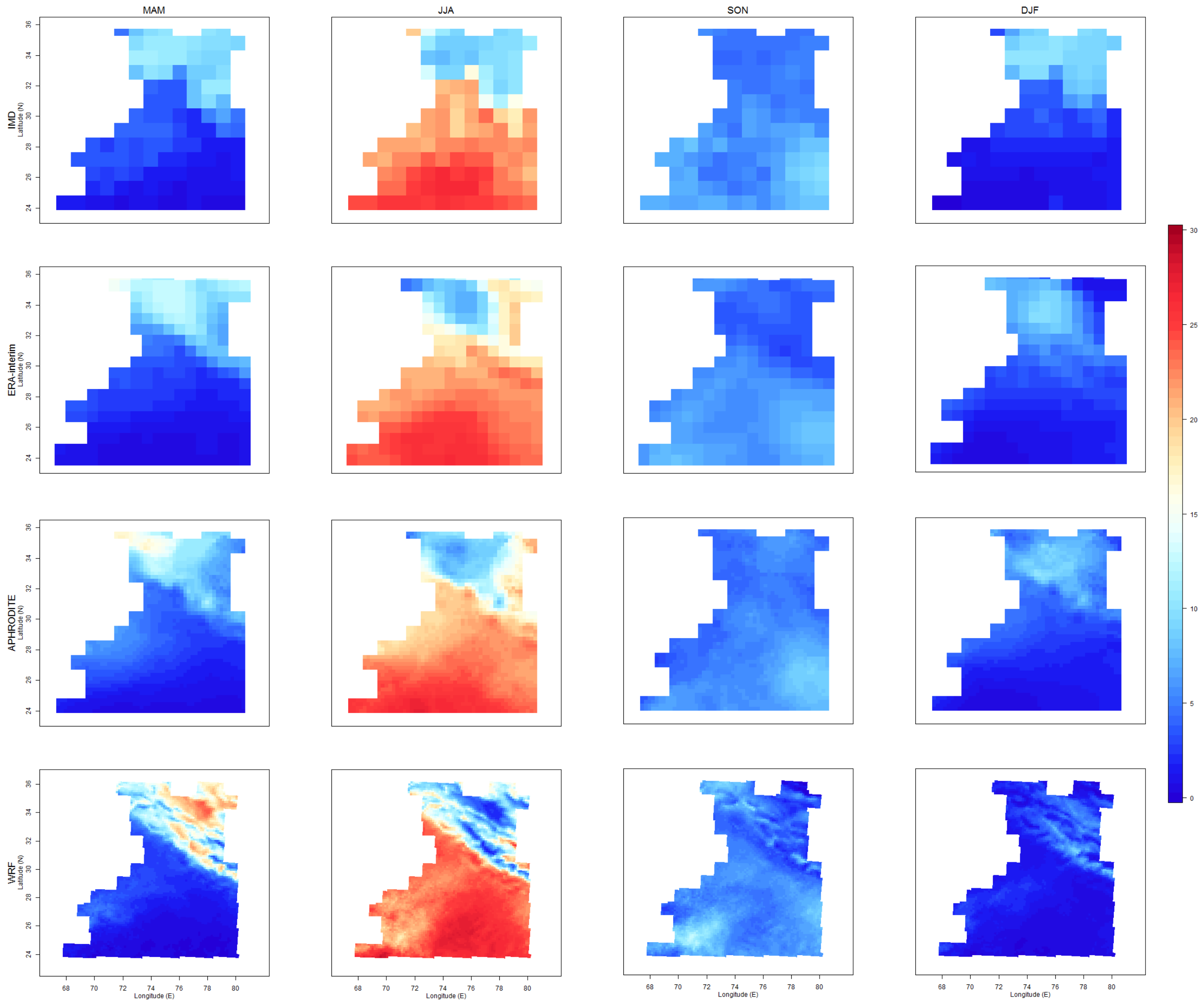

Figure 3. Seasonal contributions (%) to annual precipitation.

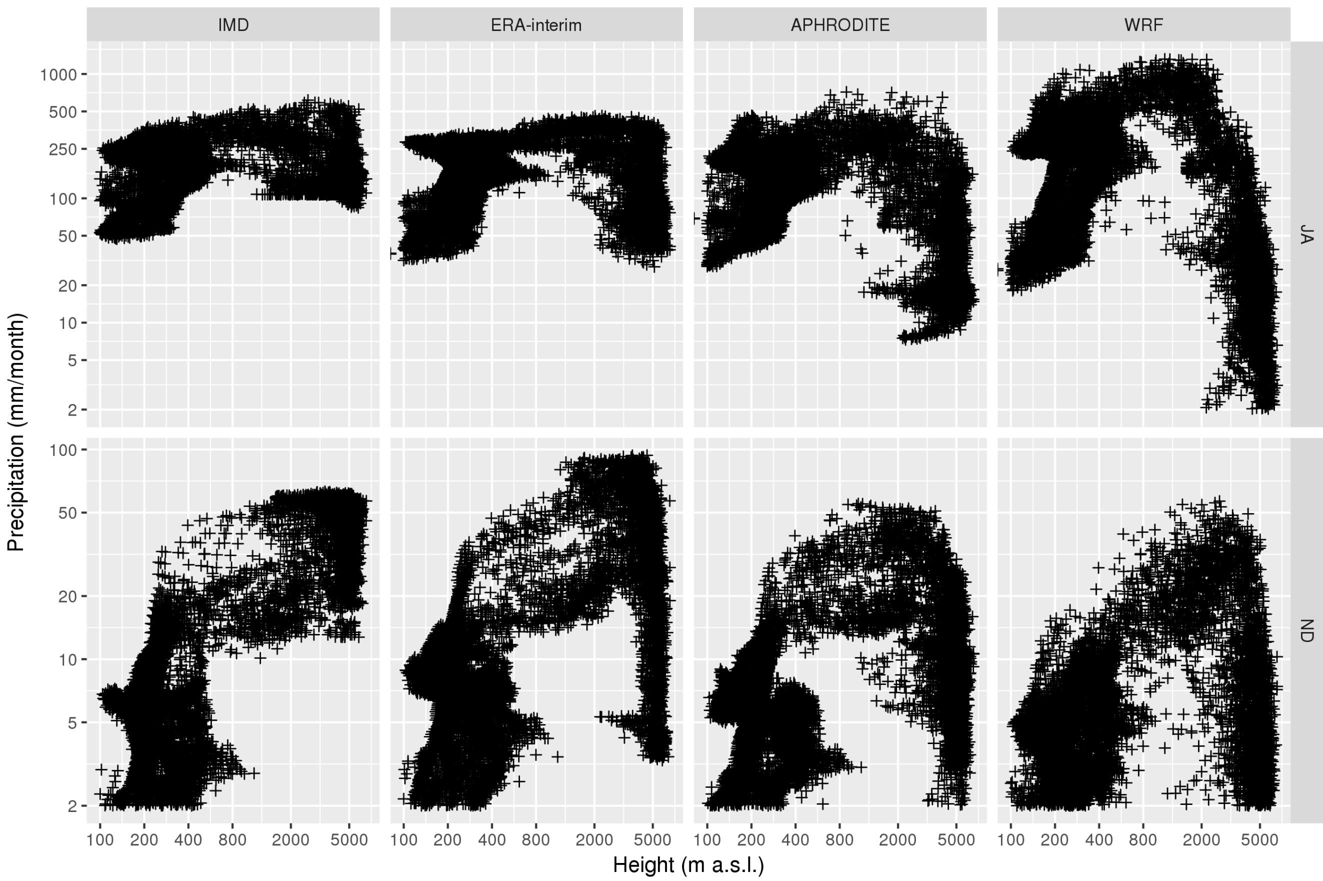

Figure 4. JA (July, August – top) and ND (November, December – bottom) precipitation against elevation. Note that axes are not linear.

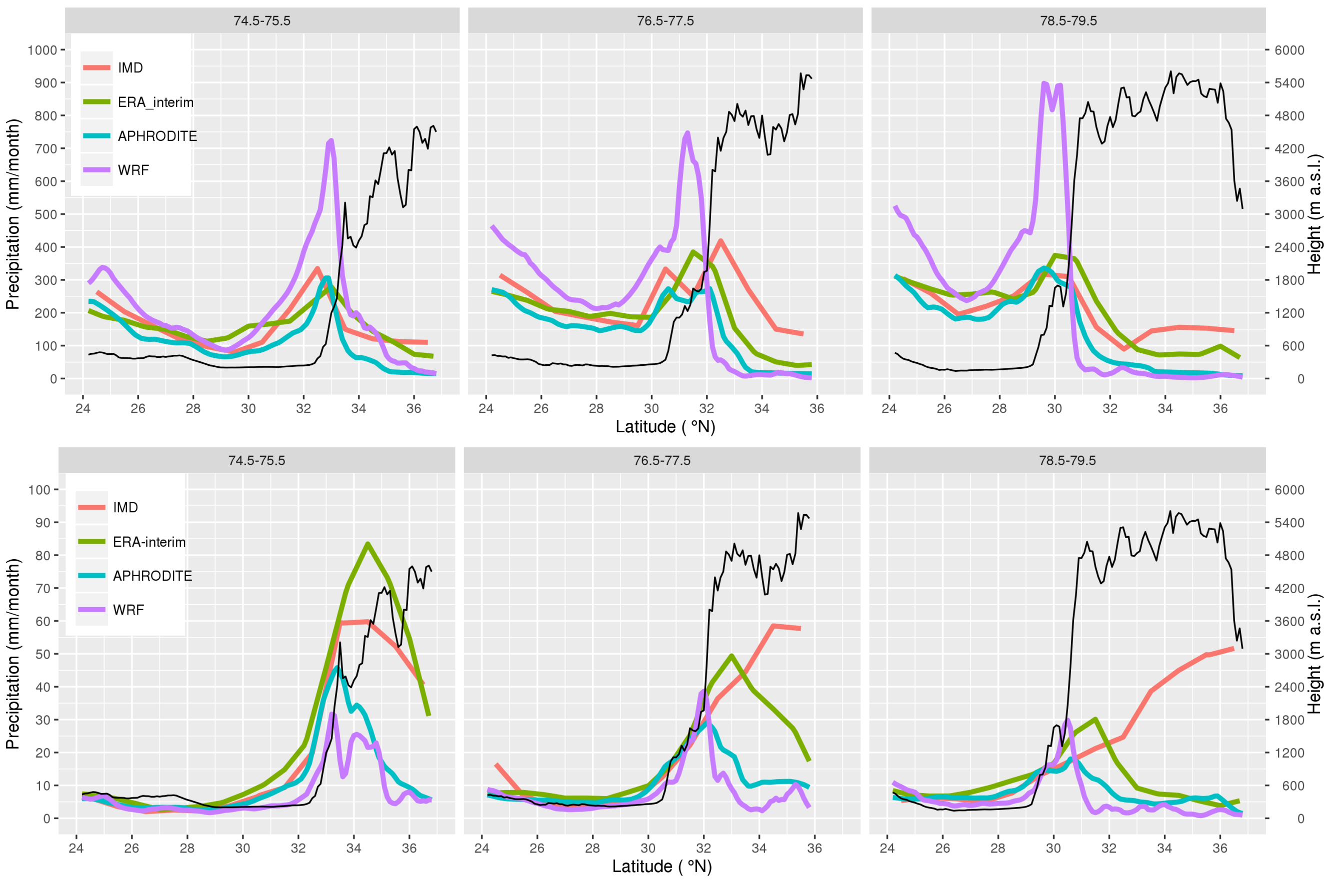

Figure 5. JA (July, August – top) and ND (November, December – bottom) precipitation elevation (mean in the selected longitude box) from west to east.

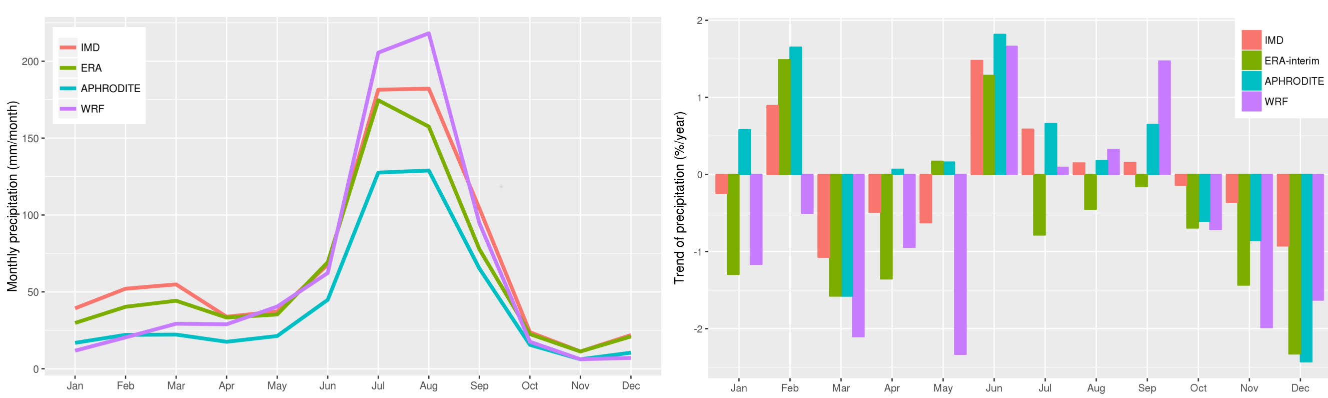

Figure 6. Monthly precipitation (left) and the trend during 1981-2007 (right).

Hydrol. Earth Syst. Sci. Discuss., https://doi.org/10.5194/hess-2017-296
Manuscript under review for journal Hydrol. Earth Syst. Sci.
Discussion started: 6 June 2017

Hydrology and Earth System Sciences
Open Access
Discussions

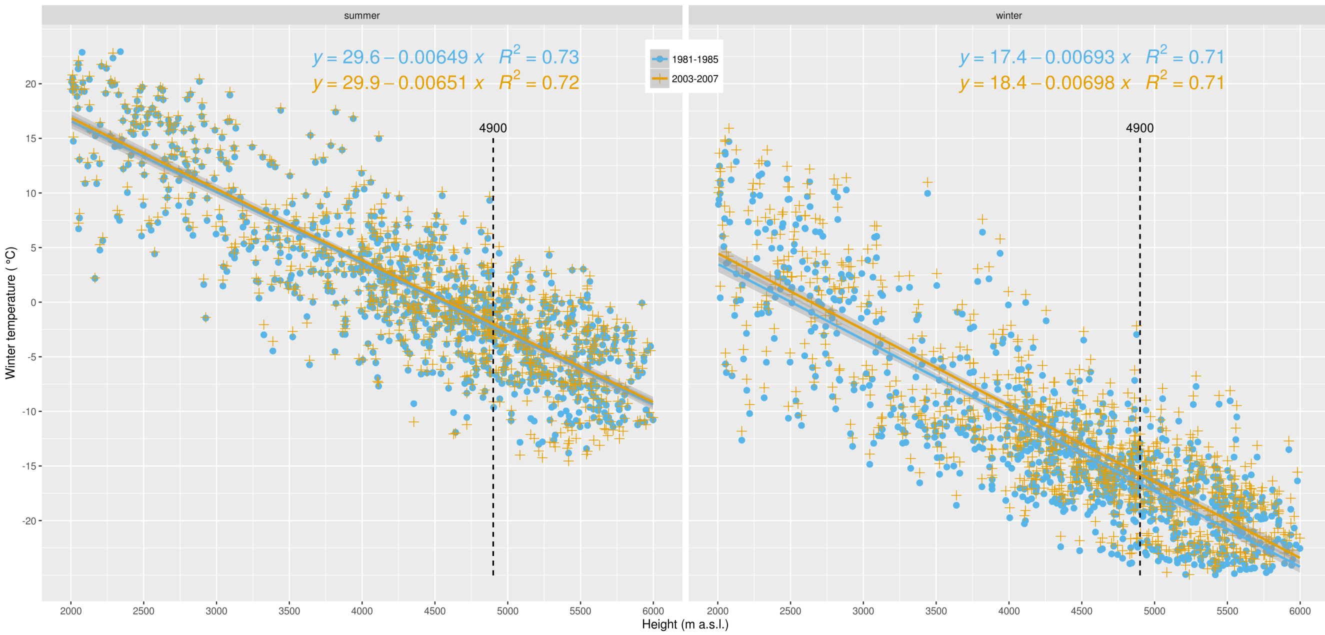

Figure 7. Mean temperature and its regression lines for the periods of 1981-1985 and 2003-2007 by the WRF simulation.

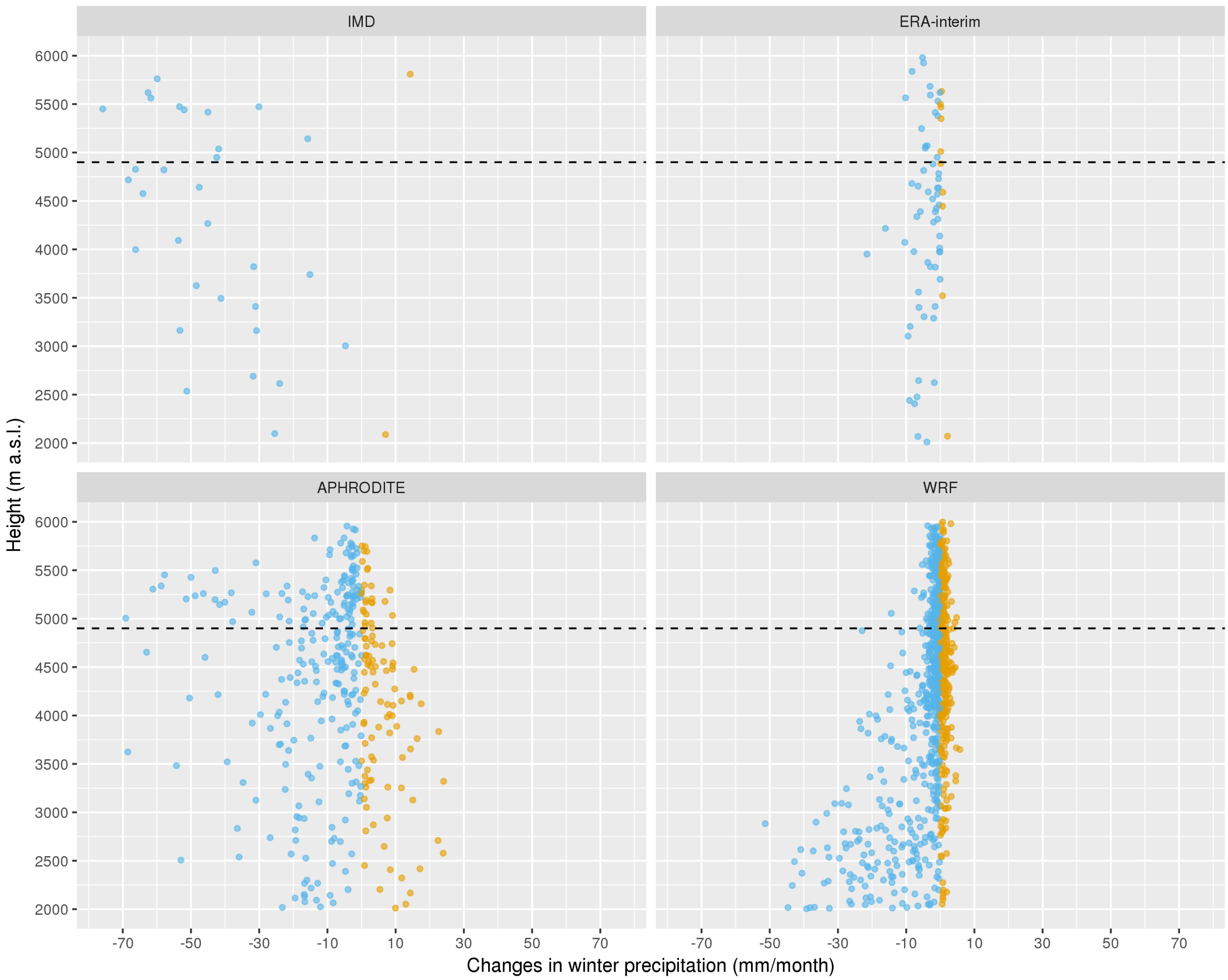

Figure 8. Changes in winter precipitation (2003-2007 minus 1981-1985) against elevation.

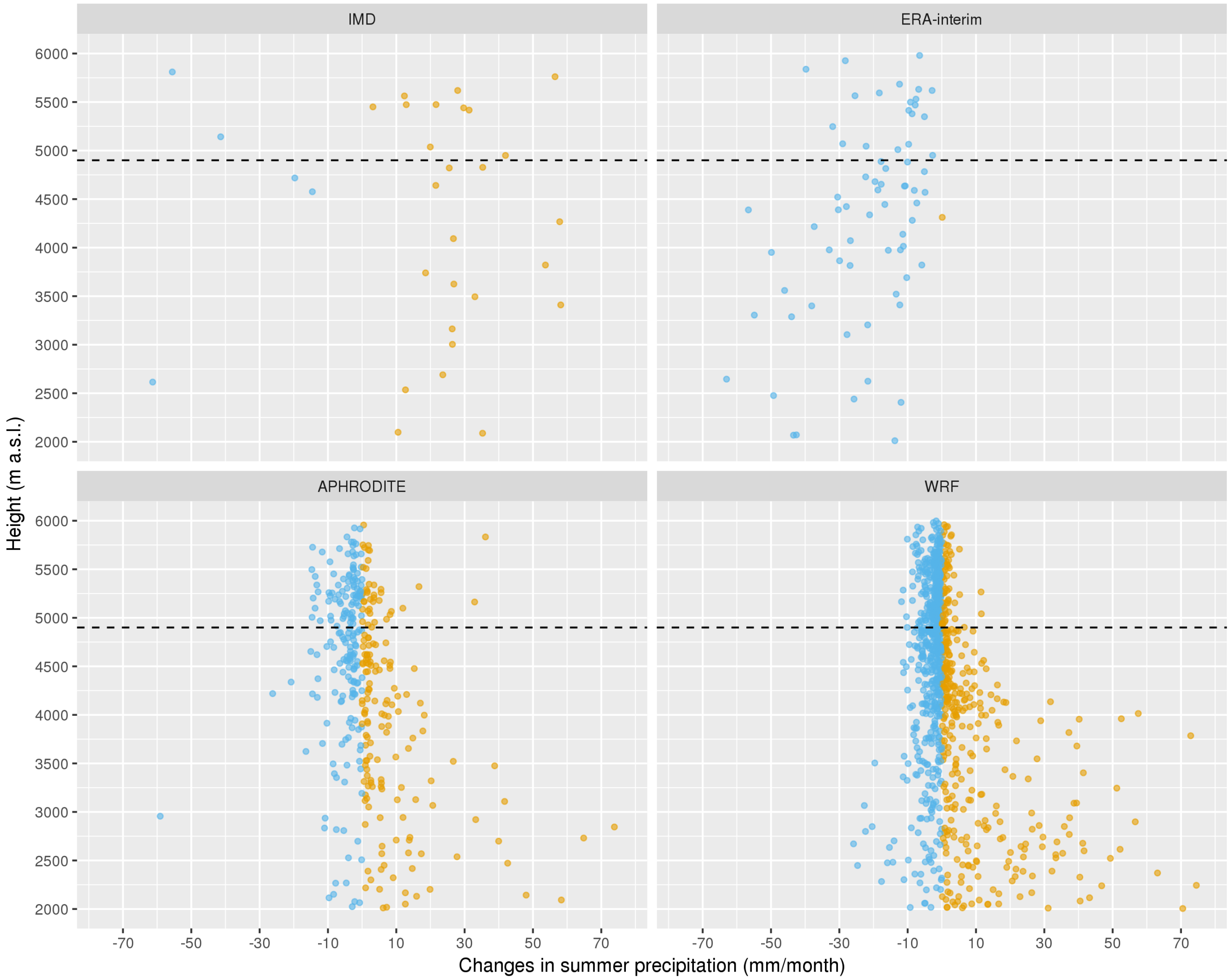

Figure 9. Changes in summer precipitation (2003-2007 minus 1981-1985) against elevation.

Hydrol. Earth Syst. Sci. Discuss., https://doi.org/10.5194/hess-2017-296
Manuscript under review for journal Hydrol. Earth Syst. Sci.
Discussion started: 6 June 2017

Table 1. The main configuration of the climate model

Time and Domain	
Period	1979-2007
Region	59-91E, 9-46N
Horizontal grid spacing	16,306 km
Dimension	(193, 241, 38)
Model top pressure	50 hPa
Physics	
Microphysics	Thompson scheme
Radiation	CAM
Surface-layer	Monin-Obukhov (Janjic) scheme
Boundary-layer	Mellor-Yamada-Janjic TKE scheme
Cumulus	Kain-Fritsch (new Eta) scheme
Land surface	Unified Noah land-surface model
Lateral boundaries	
Forcing	ERA-Interim 0.75° ×0.75°, 6 hourly

Table 2. Pearson's correlation of annual precipitation series

Data \ Data	IMD	ERA-interim	APHRODITE	WRF
IMD	-	0.86	0.91	*0.64*
ERA-interim	0.86	-	0.86	*0.64*
APHRODITE	0.91	0.86	-	*0.59*
WRF	*0.64*	*0.54*	*0.59*	-