Book: Bird Migration Across the Himalayas: wetland functioning amidst mountains and glaciers

Chapter 11: Hydrology and glaciology of the Himalayas: their influence on wetlands

Bodo Bookhagen

Institute of Earth- and Environmental Science, University of Potsdam, Karl-Liebknecht-Str. 24/25, 14467 Potsdam-Golm, Germany

Keywords

Monsoon, Winter Westerlies, Runoff, High Mountain Asia, Snow Cover, Snow Water Equivalent (SWE)

Abstract

This chapter analyzes the impact of monsoonal runoff and glacial discharge on hydrology and wetlands in the Himalaya. The runoff generated from liquid and solid precipitation as well as from glaciers is an integral part of the mountain range's hydrology. Importantly, rainfall and glacial contribution to discharge varies along the strike of the Himalaya: The western areas receive a significant amount of snowfall during winter westerly disturbances and consequently annual discharge in this region may be comprised of 50+% snowmelt. In contrast, the central and eastern Himalaya receive more monsoonal rainfall and the landscape's topography does not allow for large glaciers or extensive snow storage. The runoff in this region is dominated by monsoonal rainfall, and annual snowmelt contribution is less than 25%. Nevertheless, runoff in the Himalaya mountain range heavily depends on transiently stored moisture in the form of snow, glaciers, and permafrost; runoff generation for all Himalayan catchments is dominated by snow melt during the pre-monsoon season (April-June). This chapter will review climatic and hydrologic influences and provide a regional assessment of monsoonal, glacial and snow-melt contribution to Himalayan hydrology. The water provided through these pathways are integral for maintaining healthy wetland environments.

Climate and Hydrology in the Himalaya

River runoff or discharge in mountain rivers depends on precipitation and transiently-stored water, such as groundwater and permafrost. Liquid precipitation (rainfall) generates runoff with short lag times, whereas solid precipitation in the form of snow can have lag times of up to 6 months – for example snowfall in the winter melts during spring and summer. The significant lag time of winter precipitation is a key process to maintain year-round runoff in mountain rivers and surrounding environments. A change from solid to liquid precipitation will change the timing of runoff, although the total annual runoff may remain the same. The time lag between seasonal snowfall and snowmelt sustains runoff during the drier summer months. A warmer climate could change the timing of melt and the volume of the snowpack, and would have significant consequences for ecologic and commercial water resources, particularly in year-round water provisioning. Among the world's snow-dominated regions, the western Himalaya and central Asia are susceptible to changes in the timing of snowmelt, as reservoir capacity is currently not sufficient to buffer large seasonal shifts in the hydrograph [e.g., *Barnett et al.*, 2005; *Hijioka et al.*, 2014; *Immerzeel et al.*, 2013]. The climatic zones in a mountain range are thus an integral part of the hydrology with cascading effects on downstream areas, including wetlands [e.g., *Immerzeel et al.*, 2010; *Urrutia and Vuille*, 2009].

During the past century, glaciers around the world have shrunk, with an acceleration in glacial shrinking during the last decade of the 20th and the first decade of the 21st century [e.g. *Baraer et al.*, 2012; *Bolch et al.*, 2012; *Kaser*, 1999; *Oerlemans*, 2005; *Price and Weingartner*, 2012; *Vaughan et al.*, 2013]. Glacial runoff and snowmelt are an important source of clean water and provide a significant part of the annual hydrologic budget in some regions [e.g. *Archer and Fowler*, 2004; *Bookhagen and Burbank*, 2010; *Immerzeel et al.*, 2010; *Radic and Hock*, 2011]. However, the contribution of transiently stored moisture to runoff is difficult to determine and varies from year to year. Our understanding of mountain hydrology is limited due to harsh condition in high mountain regions, especially in High Mountain Asia that has large areas above 5 km elevation. Remote-sensing studies can help to assess general trends in snowmelt contribution, glacial area, elevation changes, and velocities, but in-situ field work adds crucially important measurements unavailable at the scale of most remotely sensed datasets [e.g. *Boers et al.*, 2014b; *Bookhagen and Burbank*, 2006; 2010; *Draganits et al.*, 2014; *Quincey et al.*, 2007; *Scherler et al.*, 2011a; b].

There is a clear distinction between runoff generated from snowmelt and that from glaciers: Snowmelt-runoff generally occurs early in the season with the increase in solar radiation during spring time, while Glacial-derived runoff occurs during the (late) summer season when most snow is melted and glacial ice is exposed. While glaciers are important for water resources in some tropical regions, especially the central Andes, the seasonal snow cover in the Himalaya generally provides a larger water-volume storage system [e.g. *Bookhagen and Burbank*, 2010; *Immerzeel et al.*, 2013; *Jeelani et al.*, 2012; *Kaser et al.*, 2010]. For example, river systems in the western and northwestern Himalaya, such as the Indus, derive more than 50% of their annual runoff from snow-melt water [e.g., *Archer and Fowler*, 2004; *Bookhagen and Burbank*, 2010; *Immerzeel et al.*, 2013], but only a few percent runoff is derived from glacial-melt water [*Jeelani et al.*, 2012]. The Himalaya have seasonal snow cover, especially in the western and northwestern Himalaya, at elevations above 4 or 5 km (cf. **Error! Reference source not found.**).

It is difficult to measure the water volume stored in snow. Snow-cover measurements based on optical or near-infrared satellite imagery only indicate areal extent, but not snow volume (depth). For example, a thin persistent snow layer may have the same signal as thick seasonal cover, but their water equivalents differ significantly. Snow water equivalent (SWE) measurements give a better estimate of the amount of water stored in high elevation areas. There are two primary methods used to derive snow-water equivalents: (1) direct measurements of remote-sensing derived SWE, and (2) SWE modeling using a variety of optical remote sensing and field-based input parameters. Direct measurements are useful, but do not have high spatial resolution and are hampered by technical difficulties [e.g. *Pulliainen and Hallikainen*, 2001; *Tedesco et al.*, 2015; *Tedesco et al.*, 2004], while modeled outputs are reliant on insufficient in-situ data and usually don't provide real-time estimation. Both approaches have difficulties that limit our understanding of SWE in High Mountain Asia. But the few robust studies clearly show that snowmelt and glacier melt play a key role in the hydrology and climate ofthe Himalaya.

Datasets and Methods

The analysis and synthesis presented in this paper relies on several field and remotely-sensed datasets. Glacial extents were derived from the Randolph Glacier Inventory (RGI), a community based dataset of global glacier outlines (Version 3.2) [*Arendt et al.*, 2012] (**Error! Reference source not found.**). These data are referred to as RGI V3.2. Rainfall data were based on the Tropical Rainfall Measurement Mission (TRMM) product 3B42 [*Boers et al.*, 2014a; *Bookhagen*, 2010; *Bookhagen and Strecker*, 2010; *Huffman et al.*, 2007] This product has a 3-hour temporal resolution (data were aggregated to daily time steps) and a spatial resolution of 0.25°x0.25° (about 25x25 km^2) with an observational range from 1998 to 2014. In addition, high-spatial resolution TRMM 2B31 data were used to identify orographic rainfall. These data are based on the raw orbital observations that have been interpolated to regularly-spaced 5km grids [*Bookhagen and Burbank*, 2006; *Bookhagen and Strecker*, 2008; *Bookhagen and Burbank*, 2010; *Bookhagen and Strecker*, 2012]. A comparison of station data and gridded rainfall data for the Himalaya and South America indicate that TRMM 3B42 and TRMM 2B31 perform reasonably well [e.g. *Andermann et al.*, 2011; *Boers et al.*, 2014a; *Bookhagen and Strecker*, 2008; *Bookhagen and Burbank*, 2010; *Carvalho et al.*, 2012].

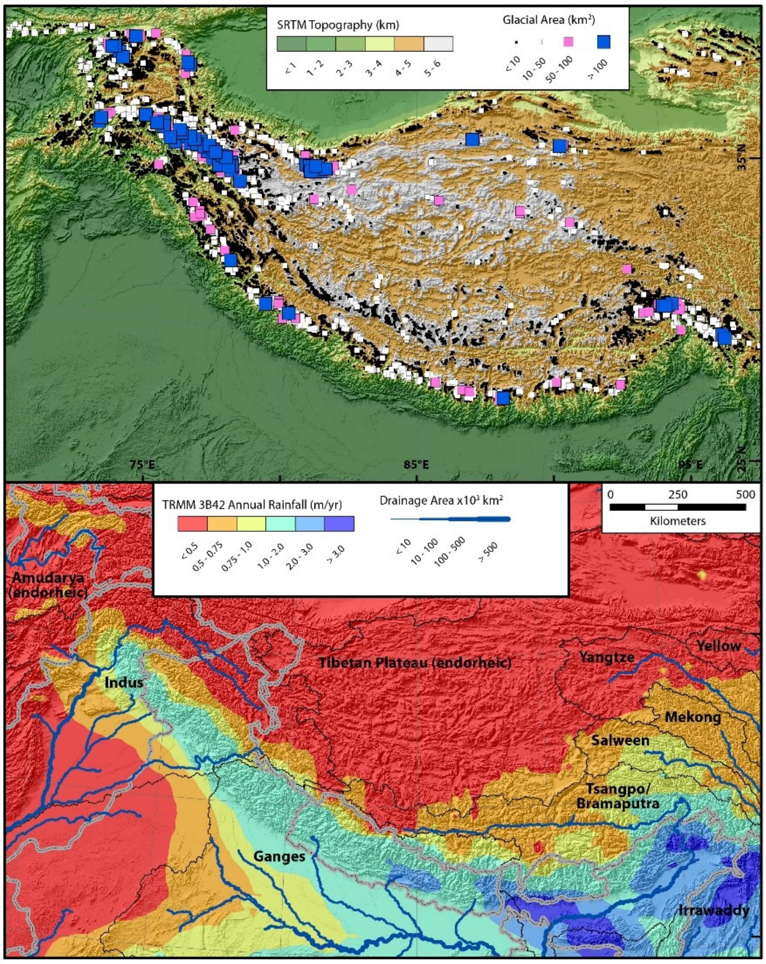

Figure 1: Top panel shows topography based on SRTM Data and present-day glacial distribution following the Randolph Catalog V3.2 [*Arendt et al.*, 2012] and glacial areas of individual, continuous glaciers are color-coded square markers. Note the high glacial density and large glacial areas in the western and northwestern Himalaya. Bottom panel shows mean annual rainfall based on TRMM 3B42 satellite data (1998-2014) [*Bookhagen and Burbank*, 2010; *Huffman et al.*, 2007]. Rivers are delineated in blue with line width corresponding to catchment area (based on hydrologically-corrected SRTM data). Catchments are outlined in black with bold catchment names and international borders are gray.

Climatic, Topographic, and Hydrologic Gradients in the Himalaya

Despite the uniformly high topography of the Himalaya, the Himalaya are a climatologically and hydrologically diverse system (Figure 1). This section describes climatic and hydrologic gradients (i.e., their changes in space and time) and summarizes hydrologic results. The hydrology and its seasonality have profound impact on wetland formation and their spatial and temporal extent [*Bunn and Arthington*, 2002; *Tockner and Stanford*, 2002].

Two principle climate regimes dominate the Himalaya: the Indian Summer Monsoon (ISM) and the Winter Western Disturbances (WWD). During the summer months the monsoon is driven by the temperature difference between ocean and land, resulting in an atmospheric pressure gradient [*Clemens et al.*, 1991; *Webster et al.*, 1998]. During the monsoon season (June to September), wind systems transport moisture-laden air from the Bay of Bengal towards the northwest along the southern Himalayan front. When these air masses interact with topography, they are forced to rise and cool; they subsequently lose the ability to store moisture and create the typical heavy monsoonal rainfall [*Bookhagen and Burbank*, 2006; 2010]. In the western Himalaya, monsoonal precipitation is significantly less than in the eastern and central Himalaya, primarily because of the increasing distance from the Bay of Bengal [e.g. *Bookhagen et al.*, 2005; *Wulf et al.*, 2010].

During winter, the pressure gradient that drives the Monsoon reverses, resulting in WWD—westerly upper tropospheric synoptic-scale waves [e.g. *Cannon et al.*, 2015; *Wulf et al.*, 2010]. In contrast to the ISM, western disturbances travel at higher altitudes and are therefore susceptible to orographic capture and intensification at high elevations [*Lang and Barros*, 2004; *Winiger et al.*, 2005; *Wulf et al.*, 2010]. The WWD are responsible for much of the winter precipitation in the western and northwestern Himalaya. These regions receive higher snowfall than the central or eastern Himalaya, as demonstrated by the significantly greater snow covered area [*Immerzeel et al.*, 2009; *Wulf et al.*, 2010]. Consequently, snowmelt contributions to annual river runoff in the western Himalaya are considerably greater than in the eastern and central Himalaya where monsoonal rainfall is the dominant source of river runoff [e.g. *Bookhagen and Burbank*, 2010; *Immerzeel et al.*, 2009; *Jeelani et al.*, 2012] (Figure 2).

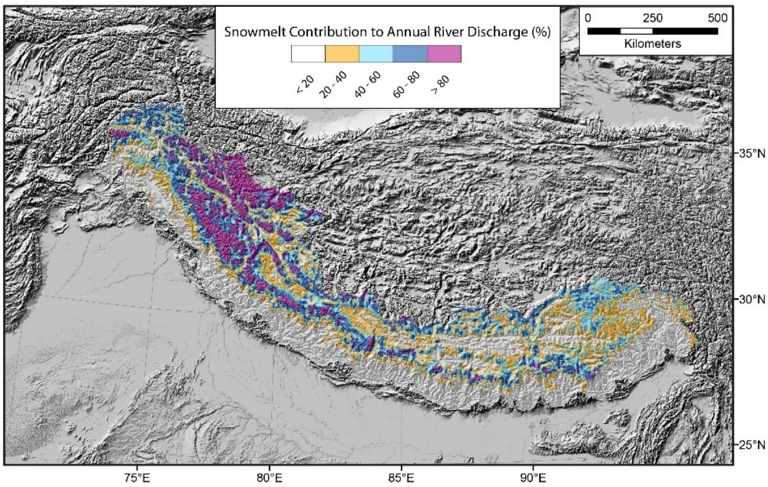

Figure 2: The geographic distribution of snowmelt contribution to annual river discharge for main Himalayan catchments. Model results were derived from calibrated and validated satellite products and degree-day runoff modeling at monthly temporal and 1000-m spatial resolution (modified after *Bookhagen and Burbank* [2010]). There exists high snowmelt contribution in the western Himalaya (e.g., the Indus and Sutlej catchments). Areas with significant annual snowmelt contribution to river runoff are located at high elevations in difficult-to-access regions with few to no monitoring stations.

The WWD are responsible for much of the seasonal snow accumulation in the northwestern Himalaya [*Cannon et al.*, 2015; *Dimri*, 2007; *Winiger et al.*, 2005; *Wulf et al.*, 2010]. Still, the Indian summer monsoon can generate high elevation snow to the central and eastern Himalaya and the Tibetan Plateau [*Bookhagen and Burbank*, 2010; *Putkonen*, 2004; *Winiger et al.*, 2005; *Wulf et al.*, 2010]. However, seasonal snow cover is more spatially extensive and longer lasting in the western Himalaya than in the central and eastern Himalaya; snow volume also peaks much later in the western Himalaya [*Immerzeel et al.*, 2009]. Furthermore, snowlines are lower in the western Himalaya [*Scherler et al.*, 2011b]. These findings are consistent with the different hypsometry (more area at higher elevation) in the western and northwestern Himalaya and the general storm tracks of the WWD. Throughout the Himalaya, seasonal snow cover has been reduced over the past 15 years, but has increased in the Karakoram [*Immerzeel et al.*, 2009; *Tahir et al.*, 2011]. This finding has been debated, but appears to be consistent with the so-called Karakoram glacier anomaly—a region of positive glacier mass balance either as a result of increased wintertime precipitation or decreased summer temperature [e.g., *Bolch et al.*, 2012; *Gardelle et al.*, 2013; *Hewitt*, 2005; *Immerzeel et al.*, 2013; *Scherler et al.*, 2011b]. Positive mass balances indicate that glaciers are gaining mass (i.e. water volume) and is often correlated with glacial area; however, it is important to note that this relation is different for transient glacial system that adjust to new environmental (e.g., climatic) conditions.

The combination of changes in topography and atmospheric influence along strike of the Himalaya results in different hydrologic compartments (Figures 1 to

3). The northwestern (Karakoram) and western Himalaya are characterized by large areas above 5 km elevation and thus have a large potential area for glacial coverage and snow-water storage. These areas are presently heavily snow covered and glacierized (Figure 1), but were even more so in the past [e.g., *Amidon et al.*, 2013; *Scherler et al.*, 2010]. This area shows the highest glacial and snowmelt runoff in the Himalaya with contributions to annual discharge exceeding 50% [*Bookhagen and Burbank*, 2010; *Immerzeel et al.*, 2009; *Jeelani et al.*, 2012] (cf. Figure 2). In order to demonstrate the large-scale climatic and topographic gradients and their impact on glaciers and snow cover, a west-to-east profile was constructed that averages values along the Himalayan arc in north-south direction (Figure 3). The focus is on areas above 500 m elevations; hence low-elevation areas such as the Ganges foreland and Indus plain were excluded. Emphasis is put on data close to the main Himalayan arc, excluding the Tibetan plateau. This analysis reveals that the maximum elevations along the Himalayan arc remain roughly similar and vary between 6 and 8 km, but the area above 5 km varies widely and hence modifies conditions for cryospheric processes (Figure 3). These data are an approximation of the hypsometric differences between the eastern and western Himalaya. A clear west-to-east gradient exists for snow-covered areas and snow-water equivalent with high amounts of both in the west. There, about half of the annual precipitation falls as snow during WWD resulting in significant snow cover and depth. In addition, the potential area that can be glaciated, for example delineated by the area above 5 km elevation, is much larger in the western Himalaya than in the east. Rainfall in the Himalayan foreland shows a clear east-to-west gradient with more rainfall in the eastern regions closer to the moisture source of the Bay of Bengal [*Bookhagen and Burbank*, 2010], but rainfall in the mountainous Himalaya is more evenly distributed and doesn't show a strong gradient, although rainfall to the west of the Shillong Plateau at 93°E is higher than elsewhere in the Himalaya (Figure 3) [*Bookhagen and Burbank*, 2010; *Bookhagen et al.*, 2005].

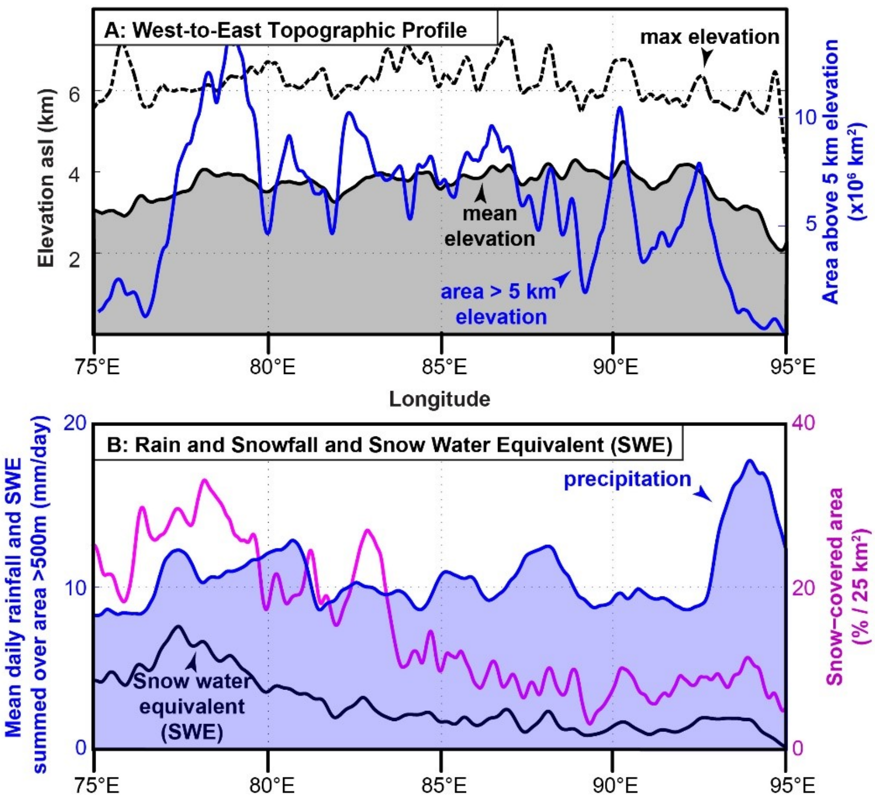

Figure 3: West-to-east profile along the Himalayan arc showing topographic and climatic data. Top panel shows maximum and mean topographic elevation (peaks have been smoothed and show 5-km running means) in dashed and solid black lines, respectively. Blue line indicates the area above 5 km elevation, which serves as a rough estimator for snow cover and glacial extent. Note the large area consecutive above 5 km to the West of 80°E, which corresponds to the Karakoram Himalaya. Bottom panel shows climatic data for the same area with mean daily rainfall and snow water equivalent (SWE) in blue colors. SWE is significantly larger in the Karakoram and western Himalaya than in the central or eastern Himalaya. Similarly, the snow-covered area exhibits a steep East-to-West gradient with higher year-around snow cover in the western areas.

Environmental changes and trends in snow cover and glacial areas

The release of glacial melt water crests in the summer and early autumn and can be critical for both agricultural practices and natural ecosystems [e.g., *Alford and Armstrong*, 2010; *Bolch et al.*, 2012; *Ficke et al.*, 2007; *Kapnick et al.*, 2014; *Menon* *et al.*, 2013; *Sultana et al.*, 2009; *Valentin et al.*, 2008; *Wulf et al.*, 2010]. As a result, changes in the melt water regime due to climate warming will have consequences for environment and ecosystem services, particularly for the western and northwestern Himalaya. Melting glaciers can also increase the risk of ice/snow avalanches and glacial lake outburst floods [*Quincey et al.*, 2007; *Richardson and Reynolds*, 2000]. However, it is unlikely that significant changes in annual runoff will occur soon, although shrinkage outside the Karakoram will increase the seasonality of runoff with impacts on agriculture and hydropower generation [e.g., *Kapnick et al.*, 2014]. Glaciers in the western Himalaya are larger than those in the central or eastern Himalaya, and thus will have a slower response time to climatic shifts (Figure 1).

Most Himalayan glaciers are losing mass at rates similar to glaciers around the globe, except for the Karakoram area [e.g., *Bolch et al.*, 2012; *Gardelle et al.*, 2013; *Hewitt*, 2005; *Kääb et al.*, 2012; *Scherler et al.*, 2011b]. Despite recent efforts, the climatic and cryospheric processes in the high-elevation Himalaya are still poorly understood. This is partly due to the difficultly inherent in accessing this region, but also due to the size and topographic complexity of glaciers and the multi-country setting of this region [*Hewitt*, 2014]. In the western Himalaya, glaciers are, in general, receding, but not responding uniformly to climate warming [*Hewitt*, 2014; *Kargel et al.*, 2011; *Scherler et al.*, 2011b]. Regional patterns have been detected, but even these have inconsistencies as a result of local variations in climate. Current observations suggest that most glaciers were in retreat since about 1850 in the central and eastern Himalaya and the outer Tien Shan, but slower retreat, standstill, and advances have been observed in the Karakoram [e.g., *Bolch et al.*, 2012; *Gardelle et al.*, 2012; *Kääb et al.*, 2012; *Scherler et al.*, 2011b; *Smith et al.*, 2014]. The causes for the Karakoram anomaly are debated with speculations including seasonality differences [*Kapnick et al.*, 2014] or increased winter precipitation and/or cooler summers that might be responsible for glacier stability or expansion [*Gardelle et al.*, 2012; *Hewitt*, 2014].

The interplay of snowmelt and glacial melt waters and runoff generated from rainfall are the key hydrologic processes in this area and control wetland formation. Wetland areas in the western and northwestern Himalaya heavily depends on seasonal water storage in the form of snow and ice, and are important for the pre-monsoon and post-monsoon season: Snowmelt generated in the pre-monsoon season and glacial melting in the post-monsoon season. These areas are not heavily influenced by rainfall and depend heavily on transiently stored waters and environmental changes will have significant impacts. Predicted climate changes suggest earlier snow melt waters, which may leave less runoff during the summer season, when wetland environments are most active. In contrast, wetland areas in the central and eastern Himalaya receive their runoff from rainfall during the monsoon season and thus exhibit different seasonality and high dependence on monsoon variability.

An additional, important impact of snow- and glacial melt waters is their sediment-free water. Runoff generated from heavy rainfall events is often associated with heavy suspended sediment concentration [*Wulf et al.*, 2010; 2012]. The sediment is often deposited in low-slope environments, such as wetlands, and while they form an integral part of the biodiversity of these areas, increased sediment flux leads to a decrease in wetland activity.

Bibliography

Alford, D., and R. Armstrong (2010), The role of glaciers in stream flow from the Nepal Himalaya, *The Cryosphere Discuss.*, *4*(2), 469-494.

Amidon, W. H., B. Bookhagen, J. P. Avouac, T. Smith, and D. Rood (2013), Late Pleistocene glacial advances in the western Tibet interior, *Earth and Planetary Science Letters*, *381*, 210-221.

Andermann, C., S. Bonnet, and R. Gloaguen (2011), Evaluation of precipitation data sets along the Himalayan front, *Geochemistry Geophysics Geosystems*, *12*.

Archer, D. R., and H. J. Fowler (2004), Spatial and temporal variations in precipitation in the Upper Indus Basin, global teleconnections and hydrological implications, *Hydrology and Earth System Sciences*, *8*(1), 47-61.

Arendt, A., A. Bliss, T. Bolch, and J. G. Cogley (2012), Randolph Glacier Inventory - A Datast of Global Glacier Outlines: Version 3.2, edited, *Global Land Ice Measurements from Space, Boulder Colorado, USA. Digital Media*.

Baraer, M., B. G. Mark, J. M. McKenzie, T. Condom, J. Bury, K. I. Huh, C. Portocarrero, J. Gomez, and S. Rathay (2012), Glacier recession and water resources in Peru's Cordillera Blanca, *Journal of Glaciology*, *58*(207), 134-150.

Barnett, T. P., J. C. Adam, and D. P. Lettenmaier (2005), Potential impacts of a warming climate on water availability in snow-dominated regions, *Nature*, *438*(7066), 303-309.

Boers, N., B. Bookhagen, J. Marengo, N. Marwan, J.-S. von Storch, and J. Kurths (2014a), Extreme rainfall of the South American monsoon system: A dataset comparison using complex networks, *Journal of Climate*.

Boers, N., A. Rheinwalt, B. Bookhagen, H. M. J. Barbosa, N. Marwan, J. Marengo, and J. Kurths (2014b), The South American rainfall dipole: A complex network analysis of extreme events, *Geophysical Research Letters*, *41*(20), 7397-7405.

Bolch, T., et al. (2012), The State and Fate of Himalayan Glaciers, *Science*, *336*(6079), 310-314.

Bookhagen, B. (2010), Appearance of extreme monsoonal rainfall events and their impact on erosion in the Himalaya, *Geomatics Natural Hazards & Risk*, *1*(1), 37-50.

Bookhagen, B., and D. W. Burbank (2006), Topography, relief, and TRMM-derived rainfall variations along the Himalaya, *Geophysical Research Letters*, *33*(8).

Bookhagen, B., and M. R. Strecker (2008), Orographic barriers, high-resolution TRMM rainfall, and relief variations along the eastern Andes, *Geophysical Research Letters*, *35*(6).

Bookhagen, B., and D. W. Burbank (2010), Toward a complete Himalayan hydrological budget: Spatiotemporal distribution of snowmelt and rainfall and their impact on river discharge, *Journal of Geophysical Research-Earth Surface*, *115*.

Bookhagen, B., and M. R. Strecker (2010), Modern Andean rainfall variation during ENSO cycles and its impact on the Amazon Basin, in *Neogene history of Western Amazonia and its significance for modern diversity*, edited by H. V. C. Hoorn, F. Wesselingh, Blackwell Publishing, Oxford.

Bookhagen, B., and M. R. Strecker (2012), Spatiotemporal trends in erosion rates across a pronounced rainfall gradient: Examples from the southern Central Andes, *Earth and Planetary Science Letters*, *327*, 97-110.

Bookhagen, B., R. C. Thiede, and M. R. Strecker (2005), Abnormal monsoon years and their control on erosion and sediment flux in the high, and northwest Himalaya, *Earth and Planetary Science Letters*, *231*(1-2), 131-146.

Bunn, S. E., and A. H. Arthington (2002), Basic principles and ecological consequences of altered flow regimes for aquatic biodiversity, *Environmental Management*, *30*(4), 492-507.

Cannon, F., L. V. Carvalho, C. Jones, and B. Bookhagen (2015), Multi-annual variations in winter westerly disturbance activity affecting the Himalaya, *Climate Dynamics*, *44*(1-2), 441-455.

Carvalho, L. M. V., C. Jones, A. N. D. Posadas, R. Quiroz, B. Bookhagen, and B. Liebmann (2012), Precipitation Characteristics of the South American Monsoon System Derived from Multiple Datasets, *Journal of Climate*, *25*(13), 4600-4620.

Clemens, S., W. Prell, D. Murray, G. Shimmield, and G. Weedon (1991), FORCING MECHANISMS OF THE INDIAN-OCEAN MONSOON, *Nature*, *353*(6346), 720-725.

Dimri, A. P. (2007), A study of mean winter circulation characteristics and energetics over southeastern Asia, *Pure and Applied Geophysics*, *164*(5), 1081-1106.

Draganits, E., S. Gier, C.-C. Hofmann, C. Janda, B. Bookhagen, and B. Grasemann (2014), Holocene versus modern catchment erosion rates at 300 MW Baspa II hydroelectric power plant (India, NW Himalaya), *Journal of Asian Earth Sciences*, *90*, 157-172.

Ficke, A. D., C. A. Myrick, and L. J. Hansen (2007), Potential impacts of global climate change on freshwater fisheries, *Reviews in Fish Biology and Fisheries*, *17*(4), 581-613.

Gardelle, J., E. Berthier, and Y. Arnaud (2012), Slight mass gain of Karakoram glaciers in the early twenty-first century, *Nature Geoscience*, *5*(5), 322-325.

Gardelle, J., E. Berthier, Y. Arnaud, and A. Kaab (2013), Region-wide glacier mass balances over the Pamir-Karakoram-Himalaya during 1999-2011, *Cryosphere*, *7*(4), 1263-1286.

Hewitt, K. (2005), The Karakoram anomaly? Glacier expansion and the 'elevation effect,' Karakoram Himalaya, *Mountain Research and Development*, *25*(4), 332-340.

Hewitt, K. (2014), *Glaciers of the Karakoram Himalaya*, Springer, Dordrecht.

Hijioka, Y., E. Lin, J. J. Pereira, R. T. Corlett, X. Cui, G. E. Insarov, R. D. Lasco, E. Lindgren, and A. Surjan (2014), Asia, in *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part B: Regional Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, edited by V. R. Barros, et al., pp. 1327-1370, Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Huffman, G. J., R. F. Adler, D. T. Bolvin, G. Gu, E. J. Nelkin, K. P. Bowman, Y. Hong, E. F. Stocker, and D. B. Wolff (2007), The TRMM multisatellite precipitation analysis (TMPA): Quasi-global, multiyear, combined-sensor precipitation estimates at fine scales, *Journal of Hydrometeorology*, *8*(1), 38-55.

Immerzeel, W. W., L. P. H. van Beek, and M. F. P. Bierkens (2010), Climate Change Will Affect the Asian Water Towers, *Science*, *328*(5984), 1382-1385.

Immerzeel, W. W., F. Pellicciotti, and M. F. P. Bierkens (2013), Rising river flows throughout the twenty-first century in two

Himalayan glacierized watersheds, *Nature Geoscience*, *6*(9), 742-745.

Immerzeel, W. W., P. Droogers, S. M. de Jong, and M. F. P. Bierkens (2009), Large-scale monitoring of snow cover and runoff simulation in Himalayan river basins using remote sensing, *Remote Sensing of Environment*, *113*(1), 40-49.

Jeelani, G., J. J. Feddema, C. J. van der Veen, and L. Stearns (2012), Role of snow and glacier melt in controlling river hydrology in Liddar watershed (western Himalaya) under current and future climate, *Water Resources Research*, *48*.

Kääb, A., E. Berthier, C. Nuth, J. Gardelle, and Y. Arnaud (2012), Contrasting patterns of early twenty-first-century glacier mass change in the Himalayas, *Nature*, *488*(7412), 495-498.

Kapnick, S. B., T. L. Delworth, M. Ashfaq, S. Malyshev, and P. C. D. Milly (2014), Snowfall less sensitive to warming in Karakoram than in Himalayas due to a unique seasonal cycle, *Nature Geoscience*, *7*(11), 834-840.

Kargel, J. S., J. G. Cogley, G. J. Leonard, U. Haritashya, and A. Byers (2011), Himalayan glaciers: The big picture is a montage, *Proceedings of the National Academy of Sciences of the United States of America*, *108*(36), 14709-14710.

Kaser, G. (1999), A review of the modern fluctuations of tropical glaciers, *Global and Planetary Change*, *22*(1-4), 93-103.

Kaser, G., M. Grosshauser, and B. Marzeion (2010), Contribution potential of glaciers to water availability in different climate regimes, *Proceedings of the National Academy of Sciences of the United States of America*, *107*(47), 20223-20227.

Lang, T. J., and A. P. Barros (2004), Winter storms in the central Himalayas, *Journal of the Meteorological Society of Japan*, *82*(3), 829-844.

Menon, A., A. Levermann, and J. Schewe (2013), Enhanced future variability during India's rainy season, *Geophysical Research Letters*, *40*(12), 3242-3247.

Oerlemans, J. (2005), Extracting a Climate Signal from 169 Glacier Records, *Science*, *308*(5722), 675-677.

Price, M. F., and R. Weingartner (2012), Global change and the world's mountains, *Mountain Research and Development*, *32*(S1), S3-S6.

Pulliainen, J., and M. Hallikainen (2001), Retrieval of regional Snow Water Equivalent from space-borne passive microwave observations, *Remote Sensing of Environment*, *75*(1), 76-85.

Putkonen, J. K. (2004), Continuous snow and rain data at 500 to 4400 m altitude near Annapurna, Nepal, 1999-2001, *Arctic Antarctic and Alpine Research*, *36*(2), 244-248.

Quincey, D. J., S. D. Richardson, A. Luckman, R. M. Lucas, J. M. Reynolds, M. J. Hambrey, and N. F. Glasser (2007), Early recognition of glacial lake hazards in the Himalaya using remote sensing datasets, *Global and Planetary Change*, *56*(1-2), 137-152.

Radic, V., and R. Hock (2011), Regionally differentiated contribution of mountain glaciers and ice caps to future sea-level rise, *Nature Geosci*, *4*(2), 91-94.

Richardson, S. D., and J. M. Reynolds (2000), An overview of glacial hazards in the Himalayas, *Quaternary International*, *65-6*, 31-47.

Scherler, D., B. Bookhagen, and M. R. Strecker (2011a), Hillslope-glacier coupling: The interplay of topography and glacial dynamics in High Asia, *Journal of Geophysical Research-Earth Surface*, *116*.

Scherler, D., B. Bookhagen, and M. R. Strecker (2011b), Spatially variable response of Himalayan glaciers to climate change affected by debris cover, *Nature Geoscience*, *4*(3), 156-159.

Scherler, D., B. Bookhagen, M. R. Strecker, F. von Blanckenburg, and D. Rood (2010), Timing and extent of late Quaternary glaciation in the western Himalaya constrained by Be-10 moraine dating in Garhwal, India, *Quaternary Science Reviews*, *29*(7-8), 815-831.

Smith, T., B. Bookhagen, and F. Cannon (2014), Improving semi-automated glacial mapping with a multi-method approach: areal changes in Central Asia, *The Cryosphere Discuss.*, *8*(5), 5433-5483.

Sultana, H., N. Ali, M. M. Iqbal, and A. M. Khan (2009), Vulnerability and adaptability of wheat production in different climatic zones of Pakistan under climate change scenarios, *Climatic Change*, *94*(1-2), 123-142.

Tahir, A. A., P. Chevallier, Y. Arnaud, and B. Ahmad (2011), Snow cover dynamics and hydrological regime of the Hunza River basin, Karakoram Range, Northern Pakistan, *Hydrology and Earth System Sciences*, *15*(7), 2275-2290.

Tedesco, M., C. Derksen, J. S. Deems, and J. L. Foster (2015), Remote sensing of snow depth and snow water equivalent, in *Remote Sensing of the Cryosphere*, edited, pp. 73-98, John Wiley & Sons, Ltd.

Tedesco, M., J. Pulliainen, M. Takala, M. Hallikainen, and P. Pampaloni (2004), Artificial neural network-based techniques for the retrieval of SWE and snow depth from SSM/I data, *Remote Sensing of Environment*, *90*(1), 76-85.

Tockner, K., and J. A. Stanford (2002), Riverine flood plains: present state and future trends, *Environmental Conservation*, *29*(3), 308-330.

Urrutia, R., and M. Vuille (2009), Climate change projections for the tropical Andes using a regional climate model: Temperature and precipitation simulations for the end of the 21st century, *Journal of Geophysical Research-Atmospheres*, *114*.

Valentin, C., et al. (2008), Runoff and sediment losses from 27 upland catchments in Southeast Asia: Impact of rapid land use changes and conservation practices, *Agriculture Ecosystems & Environment*, *128*(4), 225-238.

Vaughan, D. G., et al. (2013), Observations: Cryosphere, in *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, edited, Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Webster, P. J., V. O. Magana, T. N. Palmer, J. Shukla, R. A. Tomas, M. Yanai, and T. Yasunari (1998), Monsoons: Processes, predictability, and the prospects for prediction, *Journal of Geophysical Research-Oceans*, *103*(C7), 14451-14510.

Winiger, M., M. Gumpert, and H. Yamout (2005), Karakorum-Hindukush-western Himalaya: assessing high-altitude water resources, *Hydrological Processes*, *19*(12), 2329-2338.

Wulf, H., B. Bookhagen, and D. Scherler (2010), Seasonal precipitation gradients and their impact on fluvial sediment flux in the Northwest Himalaya, *Geomorphology*, *118*(1-2), 13-21.

Wulf, H., B. Bookhagen, and D. Scherler (2012), Climatic and geologic controls on suspended sediment flux in the Sutlej River Valley, western Himalaya, *Hydrol. Earth Syst. Sci. Discuss.*, *9*, 541–594.