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Abstract

Runoff from snowmelt is regarded as a vital water source for people and ecosystems throughout the Northern Hemisphere (NH). Numerous studies point to the threat global warming poses to the timing and magnitude of snow accumulation and melt. But analyses focused on snow supply do not show where changes to snowmelt runoff are likely to present the most pressing adaptation challenges, given sub-annual patterns of human water consumption and water availability from rainfall. We identify the NH basins where present spring and summer snowmelt has the greatest potential to supply the human water demand that would otherwise be unmet by instantaneous rainfall runoff. Using a multi-model ensemble of climate change projections, we find that these basins – which together have a present population of ~2 billion people – are exposed to a 67% risk of decreased snow supply by 2060. Further, in the multi-model mean, 68 basins (with a present population of >300 million people) transition from having sufficient rainfall runoff to meet all present human water demand to having insufficient rainfall runoff. However, internal climate variability creates irreducible uncertainty in the projected future trends in snow resource potential, with about 90% of snow-sensitive basins showing potential for either increases or decreases over the near-term decades. Our results emphasize the importance of snow for fulfilling human water demand in many NH basins, and highlight the need to account for the full range of internal climate variability in developing robust climate risk management decisions.

Introduction

The accumulation of snow is a vital source of water for natural systems and humans (Viviroli et al. 2007; Barnett et al. 2005; Rood et al. 2008; Westerling et al. 2006; Pierson et al. 2013; Kurz et al. 2008). For humans, snow is a crucial natural reservoir (Barnett et al. 2005), providing both flood control and water storage by capturing water in solid form in cold months and releasing it in warm months, concurrent with higher agricultural and evapotranspirative demands (Barnett et al. 2008; Viviroli et al. 2007; Hayhoe et al. 2004). Snow can also serve as a sentinel system, providing a benchmark by which the advance of global warming can be measured (Renard et al. 2008; Barnett et al. 2008).

Yet analyses reveal that the relationship between snow and warming is more complex than monotonic declines, particularly given that trend detection in mountainous regions is challenging (Viviroli et al. 2011; Brown & Mote 2009). In the Western US, for example, increases in freezing elevations (Ashfaq et al. 2013), decreases in snowfall-to-rainfall ratios (Knowles et al. 2006), earlier snowmelt runoff (Rauscher et al. 2008), and decreases in snowfall (Pederson et al. 2013), have been observed together with long-term increases in snow accumulation (Kapnick & Hall 2010; Mote 2006; Howat & Tulaczyk 2005). Further, despite projected snow declines by the end of the century (Diffenbaugh et al. 2012), the magnitude of internal climate variability suggests that some NH regions may experience increases in both mean (Mankin & Diffenbaugh 2014) and extreme (O'Gorman 2014) snowfall for at least the next half century or more, complicating decisions around new water infrastructure or flood management. The implications of a varied snow response for humans and ecosystems will therefore be a function of both the undetermined mix of human-induced climate change and natural climate variability, and the present importance of snow in basin-scale hydrology.

While a number of studies demonstrate that snow supply is vital and likely to decline by mid-century (Diffenbaugh et al. 2012; Barnett et al. 2005; Rauscher et al. 2008; Ashfaq et al. 2013; Mankin & Diffenbaugh 2014), assessments of snow as a source of water supply are largely inferred from supply-side measures such as the ratio of total annual snowfall to runoff (Barnett et al. 2005), or the fraction of annual streamflow pulsed in the warm season (Stewart et al. 2004). Analyses of present snow supply are helpful for identifying the spatial pattern of snow's importance in the overall hydrological cycle (Barnett et al. 2008; Barnett et al. 2005; Viviroli et al. 2007). However, global warming will not influence the supply of snow or the timing or magnitude of snowmelt runoff equally for all basins (Rauscher et al. 2008; Brown & Mote 2009; Viviroli et al. 2011; Ashfaq et al. 2013; Adam et al. 2009). Because we do not know snow's relative importance to each region's water supply portfolio, we also do not know the differential risks this heterogeneous response presents to regional water availability in snow-dominated regions.

Human water demand, which is shaped by both basin-scale hydroclimate and the water-demanding activities of people, is supplied by groundwater and surface and subsurface runoff from both rainfall and snowmelt. Given the NH distributions of human water demand, where does snowmelt runoff have the potential to be critical for water supply? Here we present a quantification of the potential for observed and projected snowmelt runoff to fulfill NH spring and summer human water demand. In calculating this "snow resource potential," we reconcile the timing and magnitude of each basin's unique sub-annual patterns of snowmelt and rainfall runoff, as well as "human blue water demand" (surface and groundwater consumption, (Hoekstra et al. 2012)). We focus explicitly on human demand, noting that ecosystems also place important and varied demands on snow accumulation and melt (Rood et al. 2008; Tague & Peng 2013; Westerling et al. 2006; Pierson et al. 2013), and are also highly exposed to changes in snow hydrology (Rood et al. 2008; Westerling et al. 2006; Pierson et al. 2013; Kurz et al. 2008).

Methods

We perform our analysis at the basin scale. We focus on identifying those basins likely to be most sensitive to changes in snowmelt runoff, given both the magnitude of human blue water demand (hereafter "demand"), and the potential for snow to supply the fraction of demand that would otherwise be unfulfilled by instantaneous rainfall runoff. We partition mean basin-scale total runoff (surface and subsurface) into contributions from snowmelt and rainfall (Supplementary Material), and remove the amount of monthly demand that could be fulfilled by rainfall runoff, as discussed below. The remaining demand is 'unmet', and needs to be supplied by alternative sources, such as from groundwater, surface reservoirs, and/or snowmelt. We then calculate the percentage of cumulative spring and summer unmet demand that could be supplied by cumulative spring and summer snowmelt runoff, which we call the "snow resource potential". This snow resource potential will exceed 100% if snowmelt runoff exceeds unmet demand. This partitioning separates those basins where spring and summer rains are theoretically sufficient for human needs, versus those where snow contributions could play a critical role in supplying water in both the present and future climates.

We calculate monthly snowmelt runoff (mm) at the grid-point scale. We use the human blue water footprint (Hoekstra & Mekonnen 2012) to estimate NH basin-scale dependence on snow as a water resource. The blue water footprint refers to human surface and subsurface water consumption across industrial, domestic, and agricultural uses, and was estimated for 1996-2005 at 5-arc-minute-resolution (Hoekstra & Mekonnen 2012). We calculate the basin-scale area-weighted blue water footprint (mm/month) minus the historical mean (1955-2005) monthly rainfall runoff (mm/month) to calculate the human water demand that remains in a given month. When remaining demand is a positive amount, we term this remaining blue water footprint "unmet demand".

To estimate the potential for NH snowmelt runoff to supply basin-scale unmet demand, we calculate the ratio between the cumulative boreal spring and summer (March-August) snowmelt runoff and cumulative unmet demand (Fig. 1). When expressed as a percentage, we call this measure the "snow resource potential".

We estimate March-August rainfall runoff, snowmelt runoff, unmet demand, and snow resource potential for the "historical" (1955-2005) and "future" (2006-2080) periods in reanalysis (historical) and in transient climate simulations (historical and future). For the historical period, we rely on version 2 of the Global Land Data Assimilation System (GLDAS) – a 0.25° gridded reanalysis of surface land variables – to provide estimates of observed land surface processes (Rodell & Houser 2004). The estimates from this dataset provide an observed climatological baseline against which to evaluate projected future changes.

We use two global climate model ensembles forced in the IPCC AR5 RCP8.5 emissions pathway (Riahi et al. 2011) to simulate both historical and future snowmelt runoff and rainfall runoff (Supplementary Material). RCP8.5 provides the emissions pathway most similar to observations since 2005 (Peters et al. 2013). We use these two ensembles forced in RCP8.5 to capture several different sources of uncertainty in the projections of future climate. The first is the Coupled Model Intercomparison Project (CMIP5) (Taylor et al. 2012), which includes GCMs that simulate coupled interactions among the atmosphere, ocean, land, and sea ice at varying resolutions (Flato et al. 2013; Taylor et al. 2012). We use one run from the 19 CMIP5 models that provide the requisite output fields providing a 19-member CMIP5 ensemble (Table S1). The second ensemble is NCAR's single-model "large ensemble" (LENS), which consists of 30 simulations of the Community Earth System Model (CESM) (Kay et al. 2014). CESM is a coupled atmosphere-ocean-land-sea-ice model that simulates climate at 1°×1° atmospheric resolution. LENS encompasses 30 simulations of the climate from 1920-2080, using both observed and projected (RCP8.5) forcing. Each LENS member is initialized with the same ocean and sea-ice conditions, with the only difference being small perturbations to the initial atmospheric state.

In analyzing both CMIP5 and LENS in a single forcing pathway, our estimations of risk of future declines in the snow resource potential come from two sources of ensemble uncertainty. CMIP5 provides a range from an undetermined combination of model structure and internal variability, while the LENS provides an estimate of "irreducible" uncertainty from CESM's representation of internal climate variability (Deser, Knutti, et al. 2012; Kay et al. 2014; Mankin & Diffenbaugh 2014; Deser, Phillips, et al. 2012). Internal variability exerts a large influence on long-term hydroclimate and snow accumulation (Rauscher et al. 2008; Kapnick & Delworth 2013; Mankin & Diffenbaugh 2014), which can create an irreducible range of uncertainty on multi-decadal time scales.

We convert all gridded data to mm/month and compute area-weighted averages for basins demarcated by a modified version of the Simulated Topological Network 30p (STN-30p) (Vörösmarty et al. 2000) (Supplementary Material). STN-30p is a 0.5° resolution dataset representing the spatial extent of drainage basins. We modify STN-30p using the coastal basins of (Meybeck et al. 2006) to aggregate small coastline basins into larger basins following the methods of (Viviroli et al. 2007). We analyze basins with centroids >10˚N latitude, and mask small basins for which the GLDAS 0.25 data are too coarse, providing 421 NH basins for our analysis. Gridded human population estimates for 2015 are retrieved from the Center for International Earth Science Information Network (CIESIN et al. 2005).

We calculate basin-scale monthly-mean linear trends in snowmelt runoff and rainfall runoff from 2006-2080 in each of the CMIP5 and LENS realizations, yielding time trend coefficients based on the 75-year basin-scale time series. We express each simulation's linear time trend relative to its respective historical (1955-2005) monthly mean climatology. We present these time trends as percent change per 50 years. To account for biases in the CMIP5 and LENS simulations, we project these relative changes in snowmelt runoff and rainfall runoff onto the GLDAS historical monthly mean climatology. We multiply each realization's monthly relative trend (fraction of that realization's historical mean) by the GLDAS monthly value. We add this relative change to the GLDAS baseline monthly mean, providing 49 estimates of absolute change (19 CMIP5, 30 LENS) in future monthly snowmelt runoff and rainfall runoff in each basin. We then estimate the future unmet demand and snow resource potential for each realization, and difference it from the GLDAS-based observational baseline. This method is similar to the statistical change factor method used to downscale climate data (Minville et al. 2008; Chen et al. 2011); however, rather than projecting onto daily-scale observations, we add the relative changes in the future monthly means to observed monthly means. Following the IPCC (Diffenbaugh et al. 2014; Collins et al. 2014), risks are calculated as the percent of the ensemble that agrees on the direction of change.

Results

We show the basin-scale evolution of spring and summer snowmelt runoff and unmet demand for the San Joaquin, Colorado, Syr Darya, and Indus basins (Fig. 1a-d). The observed seasonal relationship between snowmelt runoff and unmet demand is basin-dependent. For instance, in the agriculturally intensive San Joaquin, unmet demand begins to accumulate in May as snowmelt runoff slows. The mismatch in runoff timing suggests the importance of storage reservoirs to supplying water during the dry season, which is also when agricultural demand, and thus unmet demand, is highest. By August, the snow resource potential is ~17% of unmet demand. In contrast, in the Indus basin, where the sub-annual evolution of human water demand and rainfall runoff is quite different than the San Joaquin, the August snow resource potential is ~180%.

Snowmelt runoff is a spatially dominant feature of the NH spring and summer hydrological regime: 305 of the 421 basins have March-August snowmelt runoff. Yet despite snowmelt runoff's ubiquity, more than two-thirds of NH basins (280 of 421) have sufficient spring and summer rainfall runoff to meet all spring and summer human demand (Fig. 1e). Of these 421 basins, we identify 97 snow-sensitive basins (i.e., basins with both climatological spring-summer snowmelt runoff and unmet demand). These basins are presently home to ~1.9 billion people. The snow-sensitive basins are geographically limited to approximately 25-45°N (near the sub-tropical high pressure centers) (Fig. 1e). Notable exceptions are the extremely high latitudes, where human populations are low and all human water demand can be met by runoff from snowmelt.

For many snow-sensitive basins, spring-summer snowmelt runoff exceeds unmet demand many times over, meaning that even large decreases in snow supply may not pose risks for human water consumption. However, at least 46 basins have snowmelt runoff fulfilling unmet demand. These 46 basins are currently home to 1.5 billion people. For example, in the Ganges-Brahmaputra, where 700 million people live, ~76% of unmet demand can be supplied by snowmelt runoff. In the Shatt al-Arab basin that spans much of the Middle East, the snow that accumulates in the Zagros Mountains can supply ~56% of the spring and summer total unmet demand for its ~67 million people.

Using the LENS and the CMIP5 model projections, we examine the risks of increases in unmet demand and decreases in snow resource potential (Fig. 2a-b). Decreases in spring and summer rains pose the risk that some basins that currently have enough rainfall to meet human water demand (hatched basins in Fig. 1e) may transition to having unmet demand by 2060 (grey basins in Fig. 2a and b), even without considering possible future increases in human demand. In the CMIP5 ensemble-mean, 68 basins (with >319 million people) transition from sufficient to insufficient rainfall runoff for human consumption, including the Mississippi basin in central North America. In LENS, 31 basins (totaling ~100 million people presently) transition to having net unmet demand profiles in the future (Fig. 2b).

The 97-basin mean risk of decreased snow resource potential is greater than 60%: it is 67% for CMIP5, and 64% for LENS. A decrease in the snow resource potential is governed by a combination of sub-annual changes in rainfall runoff (which can change the spring and summer unmet demand profile), and by changes in the magnitude and timing of snowmelt. We therefore calculate the joint risk of combined decreases in snowmelt runoff and increases in unmet demand (Fig. 2c-d). In CMIP5, 20 basins (with ~27 million people) exhibit >50% risk of both increased unmet demand and decreased snowmelt runoff, while in LENS, 6 basins (with >10 million people) have >50% risk (Fig. 2c-d) by 2060.

While the risk of decreasing snow resource potential is large in many basins (Fig. 2), there is substantial uncertainty in the fraction of unmet demand that is likely to be met by snowmelt runoff by 2060 (denoted by basin stippling in Fig. S1b,c, which shows the CMIP5 and LENS ensemble mean projections). Indeed, for both the multi-model CMIP5 ensemble and the single-model LENS ensemble, the majority (~90%) of snow-dependent basins span positive and negative changes in the snow resource potential (Fig. 3a-f). Only three basins show declines across all realizations in both ensembles, all three of which exhibit low snow volumes in the baseline climate: on the Iberian and Italian peninsulas (the Duero-Adour and Central Apennines respectively), and in the Rio Grande basin spanning Texas and Mexico. The lack of unequivocal robustness in both the CMIP5 and LENS ensemble-mean responses highlights the large variations in the long-term future snow resource potential. In particular, the fact that the single-model LENS ensemble does not simulate a consistent sign of change in a number of basins suggests that much of the uncertainty in future snow resource potential can arise from internal variability.

To quantify the potential basin-scale interactions of rainfall and snowmelt runoff in determining future snow resource potential, we calculate the seasonal average (March-August) ensemble-mean trends in snowmelt and rainfall runoff in CMIP5 and LENS (Fig. 4). For snowmelt runoff, the ensembles show similar patterns of high-latitude increases and mid-latitude decreases (Fig. 4a-b). Along with projected increases in warm-season precipitation, there is an increase in spring and summer rainfall runoff in the high and mid-latitudes (Fig. 4c-d). For most basins, decreases in snowmelt runoff are associated with increases in rainfall runoff, suggesting that at least some of the decrease in snowmelt runoff results from a transition of precipitation from snowfall to rainfall. The exception is a collection of basins in Central America, the Mediterranean, and Central Asia that exhibit declines in both snowmelt and rainfall runoff. Like the ensemble-mean changes in the snow resource potential, there are large uncertainties in the magnitude of the ensemble-mean trends in rainfall and snowmelt runoff, indicated by the vast stippled areas in Figure 4. For both rainfall runoff and snowmelt runoff, the variability in the seasonal trends within LENS spans a large percentage of the CMIP5 variability, including many of the snow-sensitive basins identified in our analysis, particularly around the Western US and the Mediterranean (Fig. 4e-f). As with the snow resource potential, the fact that the LENS range spans a large fraction of the CMIP5 range suggests that much of the multi-model uncertainty could arise from internal climate variability.

To identify the basins that are most likely to be sensitive to snow supply changes, we highlight key results for basins that meet the following criteria: (1) basins with a March-August snow resource potential of 1-250% in the observed historical baseline, and (2) a present population of over 1 million people. Together, these criteria focus our analysis on large or population-dense basins. In particular, the 1-250% inclusion criterion emphasizes places where snowmelt runoff has a non-zero potential to supply unmet demand but does not exceed unmet demand so many times over that the basin is potentially insensitive to changes in snowmelt or rainfall runoff.

We find that 32 basins, encompassing ~1.45 billion people, meet these criteria (Table 1, map inset). Particularly sensitive basins include the Kizil Irmak (basin ID 14), Asi (basin ID 15), Asksu (basin ID 16), and Aegean (basin ID 11) in the Mediterranean region, and the Ebro-Duero (basin ID 9) on the Iberian Peninsula. These five regions show 100% risks of declining snow resource potential across the 19 CMIP5 models. In contrast, the highly populous Indus river basin (~270 million) has lower risks of decreased snow resource potential, in part due to modest increases in rainfall runoff projected in LENS, and modest but uncertain increases in snowmelt runoff in the CMIP5.

Discussion

Our measure of snow resource potential is defined by two requisite factors: that NH spring and summer snowmelt runoff is a climatological feature of the hydrological basin, and that human water consumption exceeds water available from instantaneous rainfall runoff. This formulation allows us to focus explicitly on the potential of the snow resource to supply human water demand that is not met by rainfall. However, because snow is not the only source of water storage for humans, and because snow is also critical for fulfilling water demanded by ecosystems, a number of caveats beyond the assumption of the RCP8.5 scenario must be considered.

First is that our measure does not consider the needs of each basin's environmental runoff requirements, nor how changes in snowmelt timing will affect ecosystems and their required nutrient loadings (Pierson et al. 2013). Warmer temperatures imply greater potential evapotranspiration and probable changes in soil moisture during the dry season (Seneviratne et al. 2010). Further, a snow-to-rain phase change could potentially decrease streamflow (Berghuijs et al. 2014), suggesting the possibility of net runoff decreases in warming basins irrespective of precipitation changes. Neither the ecological contributions to total water demand nor the ecological consequences of these shifts in basin hydrology are captured in our analysis.

Second is our treatment of the human dimension. Total human population – and thereby total water demand – will almost certainly increase in the future. However, we do not predict changes in total population or the geographic distribution of people, nor the changes in consumption patterns that are likely to accompany future socioeconomic changes. To do so would introduce additional sources of uncertainty, whereas our aim is to isolate the uncertainty from climate change. The likelihood that population growth and economic development increase human water demand in the future implies that our analysis provides a lower bound on the risks that global warming will present to snow resource potential, as increasing population and/or per capita consumption will further increase the total amount of water required to meet human demand.

Third is that our measure of snow resource potential quantifies the size of the snow water resource given climatological factors and present human water demand, but does not consider whether basin-scale water availability is sustainably managed. The basins that we identify as being sensitive to snow changes, for example, may have sufficient surface storage infrastructure or groundwater resources to ensure water supply during months of shortfall, rendering snowmelt runoff less critical for meeting unmet demand. Conversely, a number of rainfall-sufficient basins (hatched regions in Figs. 1-3) may be reliant on the extra volume of water provided by snowmelt runoff for hydropower or other managed systems (Rauscher et al. 2008), or may not be positioned to collect and store all the rainfall runoff within the basin. Furthermore, our analysis of the most sensitive basins includes a minimum population criterion of 1 million people (Table 1). It is possible that adjacent basins with smaller populations could together represent areas of equivalent exposure when considered together as a contiguous unit. If basin-scale population densities of at least 5 people per km^2 are considered rather than population totals, four additional basins meet the inclusion criteria presented in Table 1.

It should be noted that the assumption of the RCP8.5 pathway, which is the highest available in the AR5, could influence not just the risks of decreased snow resource potential for basins, but also the relative magnitudes of the basin-scale uncertainties between the CMIP5 and LENS. Presumably, the expression of internal variability in both ensembles will represent an increasing fraction of total uncertainty under lower emissions trajectories. How this will change the relative magnitudes of uncertainty between the CMIP5 and a LENS-like experiment requires further testing.

Fourth, there are several spatial and temporal factors that influence our analysis, and therefore our results. Because we consider the size of the snowmelt resource over a

6-month window (March-August), the temporal scale we consider is too coarse to identify subtler, but potentially critical, shifts in snowmelt runoff peaks that change dry season lengths (Rauscher et al. 2008; Ashfaq et al. 2013). There are also considerable sub-basin heterogeneities (such as from topography or soil heterogeneity) that can influence the timing and magnitude of observed water availability at smaller temporal scales (Rauscher et al. 2008; Adam et al. 2009). The scale at which snow and snowmelt runoff are resolved in models is also a critical limitation (Pavelsky et al. 2012; Ashfaq et al. 2013; Rauscher et al. 2008). The CMIP5 ensemble has divergent estimates of snow accumulation (Diffenbaugh et al. 2012). Sources of model divergence in estimates of snow include (1) simulations of synoptic-scale atmospheric processes that create snowfall, model representations of topography (Mote 2006), and fine-scale processes that are parameterized at sub-grid-scales in the models, such as snow albedo and cloud feedbacks (Qu & Hall 2013; Qu & Hall 2006). Such limitations influence model bias and therefore, ensemble-mean bias. This is a justification for examining the full distribution of snow-related changes produced by the both the CMIP5 and LENS and comparing their relative spans as in Fig. 4. However, it should be emphasized that neither ensemble explicitly resolves all of the processes that create snowfall and snowmelt.

The different means by which models treat these snow-related processes is often cited as the reason for the large multi-model uncertainty in CMIP5 (Rauscher et al. 2008; Ashfaq et al. 2013). However, our results suggest that irreducible uncertainty from model representations of internal variability at coarse spatial scales can span a similarly large uncertainty (Fig. 4e-f). It is important to note that the similar range of uncertainty in future snowmelt in the LENS and CMIP5 in some basins may not hold for simulations at finer scales that better resolve the atmosphere and land surface (Rauscher et al. 2008). In higher resolution simulations, the magnitude of warming appears to be sufficiently large to overwhelm fine-scale precipitation variability arising from complex topography (Ashfaq et al. 2013). It remains, however, that the large uncertainties within the single-model LENS ensemble highlight the potential for internal variability to exert a large influence on monthly-scale hydroclimate, and therefore risks of declines in snow resource potential. Furthermore, the magnitude of the LENS uncertainty suggests the possibility that, for some climate impacts, the fraction of total CMIP5 ensemble uncertainty contributed by internal variability may be larger than the fraction contributed by model differences.

Conclusions

Our estimate of snow resource potential provides a meaningful baseline for quantifying the risk that different regions face from changes in climate (such as from global warming or internal climate variability) and/or changes in demand (from population or land-use change). It can also be reconciled against analyses of basin-scale vulnerability and adaptation capacity (World Water Assessment Programme 2009).

We conclude that, should greenhouse gas emissions continue along their recent trajectory, which is at or above the RCP8.5 scenario analyzed here (Peters et al. 2013), the risks of declines in snow resource potential exceed 67% in snow-sensitive basins, potentially impacting spring and summer water availability for nearly 2 billion people. In the CMIP5 ensemble-mean, global warming also shifts an additional 68 basins to have spring and summer rainfall runoff that is insufficient to meet human water demand, even without accounting for increases in demand that are likely to arise from population growth and economic development. These basins are particularly critical, as emerging increases in unmet demand must be supplied by alternative sources, in many cases within the context of decreasing snow resource potential.

Our results highlight the basins where future snow changes pose the greatest risk to people's present water demand patterns. We present these risks in the context of climate uncertainty, including the irreducible uncertainty from internal climate variability. Given present demand, this irreducible range is sufficient to create ambiguity in the sign of decadal trends in future snow resource potential. A number of other uncertainties exist in future water resources from snow, many of which reside in the human dimension, including where and how people manage and respond to water resources in a changing climate. Our results provide critical context for climate risk management (Kunreuther et al. 2013; Milly et al. 2008) and robust adaptation decisions (Kunreuther et al. 2013; Milly et al. 2008; Lempert & Collins 2007) that require identification of critically snow-dependent basins and quantification of irreducible uncertainty in future climate trajectory.

References

Adam, J.C., Hamlet, A.F. & Lettenmaier, D.P., 2009. Implications of global climate change for snowmelt hydrology in the twenty-first century. *Hydrological Processes*, 972(December 2008), pp.962–972. Available at: http://onlinelibrary.wiley.com/doi/10.1002/hyp.7201/full [Accessed February 15, 2014].

Ashfaq, M. et al., 2013. Near-term acceleration of hydroclimatic change in the western U.S. *Journal of Geophysical Research: Atmospheres*, 118(January), pp.1–18. Available at: http://doi.wiley.com/10.1002/jgrd.50816 [Accessed October 6, 2013].

Barnett, T.P. et al., 2008. Human-induced changes in the hydrology of the western United States. *Science (New York, N.Y.)*, 319, pp.1080–1083. Available at: http://www.ncbi.nlm.nih.gov/pubmed/18239088 [Accessed March 14, 2013].

Barnett, T.P., Adam, J.C. & Lettenmaier, D.P., 2005. Potential impacts of a warming climate on water availability in snow-dominated regions. *Nature*, 438(7066), pp.303–9. Available at: http://www.ncbi.nlm.nih.gov/pubmed/16292301 [Accessed March 1, 2013].

Berghuijs, W., Woods, R. & Hrachowitz, M., 2014. A precipitation shift from snow towards rain leads to a decrease in streamflow. *Nature Climate Change*, (May), pp.18–21. Available at: http://www.nature.com/nclimate/journal/vaop/ncurrent/full/nclimate2246.html [Accessed May 27, 2014].

Brown, R.D. & Mote, P.W., 2009. The Response of Northern Hemisphere Snow Cover to a Changing Climate. *Journal of Climate*, 22(8), pp.2124–2145. Available at: http://journals.ametsoc.org/doi/abs/10.1175/2008JCLI2665.1 [Accessed March 26, 2013].

Chen, J., Brissette, F.P. & Leconte, R., 2011. Uncertainty of downscaling method in quantifying the impact of climate change on hydrology. *Journal of Hydrology*, 401(3-4), pp.190–202. Available at: http://linkinghub.elsevier.com/retrieve/pii/S0022169411001351.

CIESIN, FAO & CIAT, 2005. Gridded Population of the World: Future Estimates (GPWFE).

Collins, M. et al., 2014. Long-term Climate Change: Projections, Commitments and Irreversibility. *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*.

Diffenbaugh, N.S. et al., 2014. Cross-chapter box on the regional climate summary figures. In C. B. Field et al., eds. *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge & New York: Cambridge University Press, pp. 137–141.

Diffenbaugh, N.S., Scherer, M. & Ashfaq, M., 2012. Response of snow-dependent hydrologic extremes to continued global warming. *Nature Climate Change*, 3(11), pp.379–384. Available at: http://www.ncbi.nlm.nih.gov/pubmed/24015153 [Accessed September 22, 2013].

Flato, G. et al., 2013. *Evaluation of Climate Models*,

Hayhoe, K. et al., 2004. Emissions pathways, climate change, and impacts on California. *Proceedings of the National Academy of Sciences of the United States of America*, 101(34), pp.12422–7. Available at: http://www.pubmedcentral.nih.gov/articlerender.fcgi?artid=514653&tool=pmcentrez&rendertype=abstract.

Hoekstra, A.Y. et al., 2012. Global monthly water scarcity: blue water footprints versus blue water availability. *PloS one*, 7(2), p.e32688. Available at: http://www.pubmedcentral.nih.gov/articlerender.fcgi?artid=3290560&tool=pmcentrez&rendertype=abstract [Accessed March 24, 2014].

Hoekstra, A.Y. & Mekonnen, M.M., 2012. The water footprint of humanity. *Proceedings of the National Academy of Sciences of the United States of America*, 109(9), pp.3232–7. Available at: http://www.pubmedcentral.nih.gov/articlerender.fcgi?artid=3295316&tool=pmcentrez&rendertype=abstract [Accessed May 23, 2014].

Howat, I.M. & Tulaczyk, S., 2005. Trends in spring snowpack over a half-century of climate warming in California, USA. *Annals of Glaciology*, 40(1), pp.151–156. Available at: http://openurl.ingenta.com/content/xref?genre=article&issn=0260-3055&volume=40&issue=1&spage=151.

Kapnick, S.B. & Delworth, T.L., 2013. Controls of Global Snow under a Changed Climate. *Journal of Climate*, 26(15), pp.5537–5562. Available at: http://journals.ametsoc.org/doi/abs/10.1175/JCLI-D-12-00528.1 [Accessed October 30, 2013].

Kapnick, S.B. & Hall, A., 2010. Observed Climate–Snowpack Relationships in California and their Implications for the Future. *Journal of Climate*, 23(13), pp.3446–3456. Available at: http://journals.ametsoc.org/doi/abs/10.1175/2010JCLI2903.1 [Accessed April 28, 2013].

Kay, J.E. et al., 2014. The Community Earth System Model (CESM) Large Ensemble Project: A Community 4 Resource for Studying Climate Change in the Presence of Internal Climate Variability. *Bulletin of the American Meteorological Society*.

Knowles, N., Dettinger, M. & Cayan, D.R., 2006. Trends in snowfall versus rainfall in the western United States. *Journal of Climate*, 19, pp.4545–4559. Available at: http://journals.ametsoc.org/doi/abs/10.1175/JCLI3850.1 [Accessed November 3, 2013].

Kunreuther, H. et al., 2013. Risk management and climate change. *Nature Climate Change*, 3(5), pp.447–450. Available at: http://www.nature.com/doifinder/10.1038/nclimate1740 [Accessed January 23, 2014].

Kurz, W.A. et al., 2008. Mountain pine beetle and forest carbon feedback to climate change. *Nature*, 452(7190), pp.987–90. Available at: http://www.ncbi.nlm.nih.gov/pubmed/18432244 [Accessed January 26, 2014].

Lempert, R.J. & Collins, M.T., 2007. Managing the risk of uncertain threshold responses: comparison of robust, optimum, and precautionary approaches. *Risk analysis: an official publication of the Society for Risk Analysis*, 27(4), pp.1009–26. Available at: http://www.ncbi.nlm.nih.gov/pubmed/17958508 [Accessed October 11, 2014].

Mankin, J.S. & Diffenbaugh, N.S., 2014. Influence of temperature and precipitation variability on near-term snow trends. *Climate Dynamics*. Available at: http://link.springer.com/10.1007/s00382-014-2357-4 [Accessed October 21, 2014].

Meybeck, M., Dürr, H.H. & Vörösmarty, C.J., 2006. Global coastal segmentation and its river catchment contributors: A new look at land-ocean linkage. *Global Biogeochemical Cycles*, 20(1), pp.1–15.

Milly, P.C.D. et al., 2008. Stationarity Is Dead: Whither Water Management ? *Science (New York, N.Y.)*, 319(February), pp.573–574.

Minville, M., Brissette, F. & Leconte, R., 2008. Uncertainty of the impact of climate change on the hydrology of a nordic watershed. *Journal of Hydrology*, 358(1-2), pp.70–83. Available at: http://linkinghub.elsevier.com/retrieve/pii/S002216940800262X.

Mote, P.W., 2006. Climate-Driven Variability and Trends in Mountain Snowpack in Western North America. *Journal of Climate*, 19, pp.6209–6220.

O'Gorman, P.A., 2014. Contrasting responses of mean and extreme snowfall to climate change. *Nature*, 512(7515), pp.416–418. Available at: http://dx.doi.org/10.1038/nature13625.

Pavelsky, T.M. et al., 2012. Changes in orographic precipitation patterns caused by a shift from snow to rain. *Geophysical Research Letters*, 39(18), p.n/a–n/a. Available at: http://doi.wiley.com/10.1029/2012GL052741 [Accessed October 25, 2013].

Pederson, G.T., Betancourt, J.L. & McCabe, G.J., 2013. Regional patterns and proximal causes of the recent snowpack decline in the Rocky Mountains, USA. *Geophysical Research Letters*, p.n/a–n/a. Available at: http://doi.wiley.com/10.1002/grl.50424 [Accessed April 1, 2013].

Peters, G.P. et al., 2013. The challenge to keep global warming below 2 °C. *Nature Climate Change*, 3(1), pp.4–6. Available at: http://www.nature.com/doifinder/10.1038/nclimate1783 [Accessed January 27, 2014].

Pierson, D.C. et al., 2013. Changes in the timing of snowmelt and the seasonality of nutrient loading: can models simulate the impacts on freshwater trophic status? *Hydrological Processes*, 27(21), pp.3083–3093. Available at: http://doi.wiley.com/10.1002/hyp.9894 [Accessed February 5, 2014].

Qu, X. & Hall, A., 2006. Assessing Snow Albedo Feedback in Simulated Climate Change. *Journal of Climate*, 19, pp.2617–2630.

Qu, X. & Hall, A., 2013. On the persistent spread in snow-albedo feedback. *Climate Dynamics*, (April 2013). Available at: http://link.springer.com/10.1007/s00382-013-1774-0 [Accessed September 18, 2013].

Rauscher, S.A. et al., 2008. Future changes in snowmelt-driven runoff timing over the western US. *Geophysical Research Letters*, 35(16), p.L16703. Available at: http://doi.wiley.com/10.1029/2008GL034424 [Accessed October 25, 2013].

Renard, B. et al., 2008. Regional methods for trend detection: Assessing field significance and regional consistency. *Water Resources Research*, 44(8), pp.1–17.

Riahi, K. et al., 2011. RCP 8.5-A scenario of comparatively high greenhouse gas emissions. *Climatic Change*, 109, pp.33–57.

Rodell, M. & Houser, P., 2004. The global land data assimilation system. *Bulletin of the American Meteorological Society*, (March), pp.381–394. Available at: http://journals.ametsoc.org/doi/abs/10.1175/BAMS-85-3-381 [Accessed June 30, 2014].

Rood, S.B. et al., 2008. Declining summer flows of Rocky Mountain rivers: Changing seasonal hydrology and probable impacts on floodplain forests. *Journal of Hydrology*, 349(3-4), pp.397–410. Available at: http://linkinghub.elsevier.com/retrieve/pii/S0022169407006920 [Accessed November 2, 2013].

Seneviratne, S.I. et al., 2010. Investigating soil moisture-climate interactions in a changing climate: A review. *Earth-Science Reviews*, 99(3-4), pp.125–161. Available at: http://dx.doi.org/10.1016/j.earscirev.2010.02.004.

Stewart, I.T., Cayan, D.R. & Dettinger, M.D., 2004. Changes in snowmelt runoff and timing in Western North America under a "business as usual" climate change scenario. *Climatic Change*, 62, pp.217–232.

Tague, C. & Peng, H., 2013. The sensitivity of forest water use to the timing of precipitation and snowmelt recharge in the California Sierra: Implications for a warming climate. *Journal of Geophysical Research: Biogeosciences*, 118(2), pp.875–887. Available at: http://doi.wiley.com/10.1002/jgrg.20073 [Accessed September 16, 2013].

Taylor, K.E., Stouffer, R.J. & Meehl, G. a., 2012. An Overview of CMIP5 and the Experiment Design. *Bulletin of the American Meteorological Society*, 93(4), pp.485–498. Available at: http://journals.ametsoc.org/doi/abs/10.1175/BAMS-D-11-00094.1 [Accessed February 27, 2013].

Viviroli, D. et al., 2011. Climate change and mountain water resources: overview and recommendations for research, management and policy. *Hydrology and Earth System Sciences*, 15(2), pp.471–504. Available at: http://www.hydrol-earth-syst-sci.net/15/471/2011/ [Accessed May 28, 2013].

Viviroli, D. et al., 2007. Mountains of the world, water towers for humanity: Typology, mapping, and global significance. *Water Resources Research*, 43, p.W07447. Available at: http://doi.wiley.com/10.1029/2006WR005653 [Accessed June 1, 2013].

Vörösmarty, C.J. et al., 2000. Geomorphometric attributes of the global system of rivers at 30- minute spatial resolution (STN-30). *Journal of Hydrologygy*, 237, pp.17–39.

Westerling, A.L. et al., 2006. Warming and earlier spring increase western U.S. forest wildfire activity. *Science (New York, N.Y.)*, 313(5789), pp.940–3. Available at: http://www.ncbi.nlm.nih.gov/pubmed/16825536 [Accessed October 17, 2013].

World Water Assessment Programme, 2009. *The United Nations World Water Development Report 3: Water in a Changing World*, Paris, London: UNESCO, Earthscan. Available at: http://www.esajournals.org/doi/abs/10.1890/1051-0761(2001)011[1027:WIACW]2.0.CO;2.

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Table captions

Table 1 Risk profiles of snow-dependent basins. We show the 32 snow-dependent basins that meet the following criteria: (1) observed late 20th C. snowmelt runoff is 1-250% of unmet demand, making it potentially sensitive to changes in water supply and (2) more than 1 million inhabitants presently exist. For these 32 basins, totaling 1.45 billion people, we show the observed snow resource potential, the risk of decreases in this measure in both the CMIP5 and LENS ensembles and the percent of the CMIP5 multi-model uncertainty that the LENS ensemble spans.

Figure captions

Fig. 1 Basin-scale snowmelt runoff supply of human water demand. **a-d**, 1955-2005 March through February cumulative unmet demand (UD), orange, and snowmelt runoff (snmQ), light blue, both referenced to the right axis (mm) and their ratio (snmQ/UD), dark blue, referenced to the left axis (snmQ/UD), for example basins: the San Joaquin [a], Colorado [b], Syr Darya [c] and Indus [d]. In each panel, August is highlighted in red to show the value plotted in [e], which is the August snmQ/UD cumulative ratio multiplied by 100, or what we term, the "snow resource potential". **e**, The snow resource potential. Blue-stripped regions indicate basins for which instantaneous monthly rainfall runoff is sufficient to meet all March-August basin-scale demand. White regions have no snowmelt runoff.

Fig. 2 Risks of decreased March-August snowmelt supply and increased unmet demand by 2060. For the CMIP5 (left column, [a,c]) and the LENS (right column, [b,d]), we show the risks of decreases in snowmelt resource potential in [a,b]. Basins with blue lines indicate basins for which future rainfall runoff is sufficient to meet present human water demands. **c-d**, Basins with joint risks for both snowmelt decreases and unmet demand increases. Grey basins in [a] and [b] indicate basins that shift from sufficient to insufficient rainfall runoff to meet water demand in the ensemble-mean. These basins are projected to be snowmelt dependent. Their ensemble-mean snow resource potential projections are shown in Fig. S1.

Fig. 3 Ensemble range in snow resource potential change. For each ensemble, CMIP5 (left column, [a,c,e]) and the LENS (right column, [b,d,f]) we show the full ensemble range in the change of future snowmelt supply potential differenced from the present potential, expressed as percentage points: the basin minimum [a-b], the ensemble mean [c-d], and the basin maximum [e-f]. Grey basins are those for which future rainfall runoff is insufficient to meet human water demand.

Fig. 4 Ensemble-mean trends from CMIP5 and LENS. **a-b**, March-August ensemble-mean linear snowmelt runoff trends, estimated from 2006-2080 in the CMIP5 [a] and LENS [b], expressed as percent change per 50 years. **c-d**, As in [a] and [b] but for rainfall runoff. **e-f**, The percent of the variability in CMIP5 trends in snowmelt runoff [e] and rainfall runoff [f], spanned by the LENS ensemble. Stippled basins in [a-d] indicate basins for which the ensemble-mean trend is less than 1 SD of the ensemble variability.

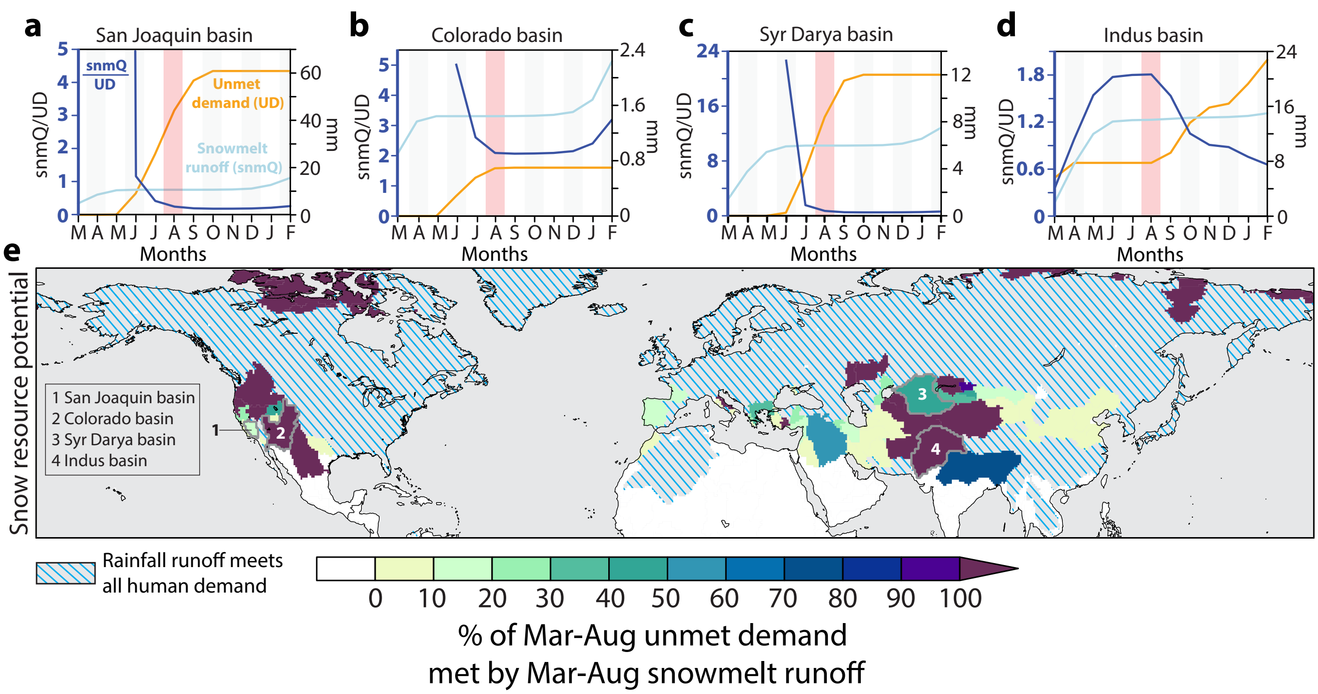


Fig. 1 Basin-scale snowmelt runoff supply of human water demand. **a-d**, 1955-2005 March through February cumulative unmet demand (UD), orange, and snowmelt runoff (snmQ), light blue, both referenced to the right axis (mm) and their ratio (snmQ/UD), dark blue, referenced to the left axis (snmQ/UD), for example basins: the San Joaquin [a], Colorado [b], Syr Darya [c] and Indus [d]. In each panel, August is highlighted in red to show the value plotted in [e], which is the August snmQ/UD cumulative ratio multiplied by 100, or what we term, the "snow resource potential". **e**, The snow resource potential. Blue-stripped regions indicate basins for which instantaneous monthly rainfall runoff is sufficient to meet all March-August basin-scale demand. White regions have no snowmelt runoff.

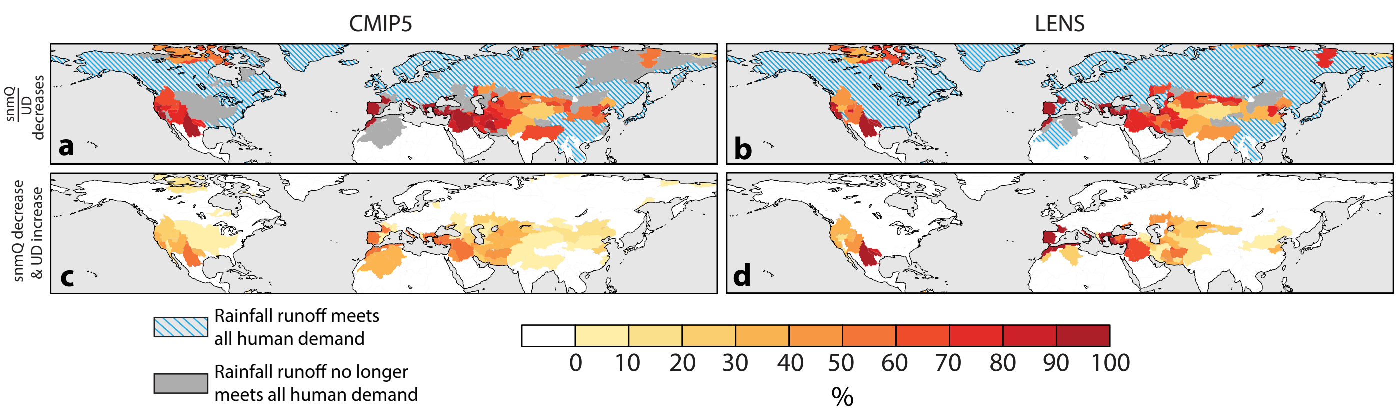
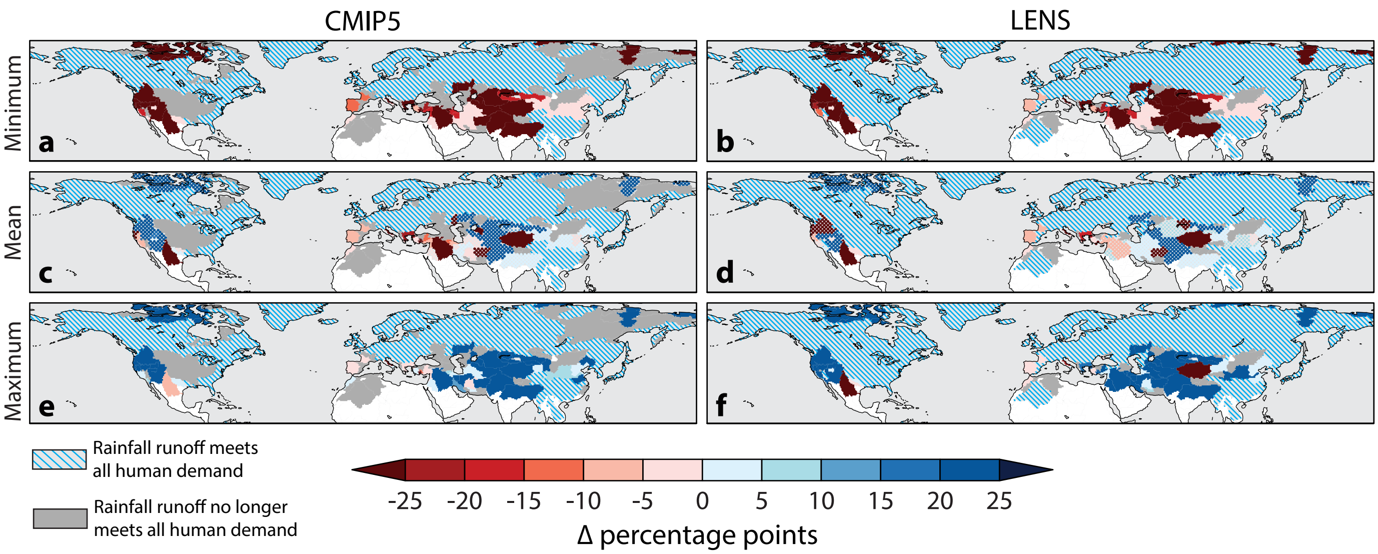


Fig. 2 Risks of decreased March-August snowmelt supply and increased March-August unmet demand by mid-century. For the CMIP5 (left column, [a,c]) and the LENS (right column, [b,d]), we show the risks of decreases in snowmelt resource potential in [a,b]. Basins with blue lines indicate basins for which future rainfall runoff is sufficient to meet present human water demands. **c-d**, Basins with joint risks for both snowmelt decreases and unmet demand increases. Grey basins in [a] and [b] indicate basins that shift from sufficient to insufficient rainfall runoff to meet water demand in the ensemble-mean. These basins are projected to be snowmelt dependent. Their ensemble-mean snow resource potential projections are shown in Fig. S1.



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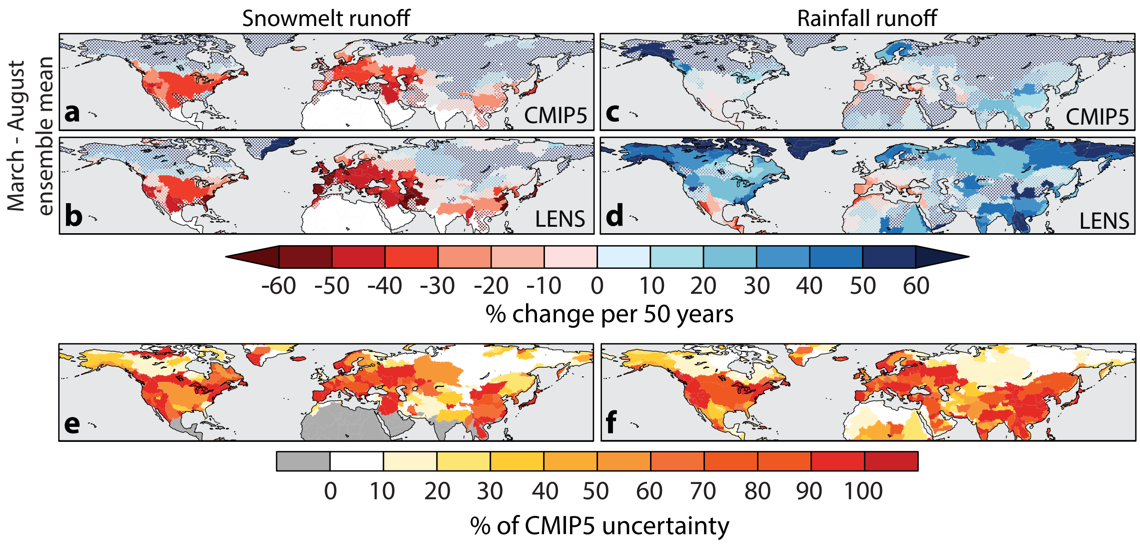

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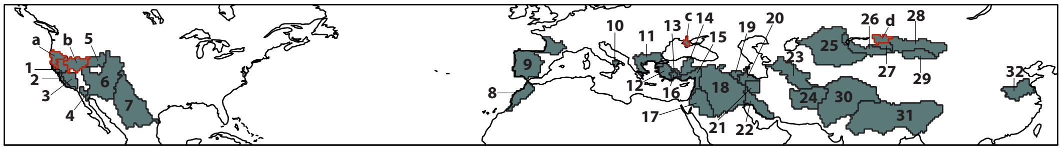

#	Name	Population (mil.)	snmQ/UD index (%)	CMIP Risk (%)	LENS Risk (%)
1	Sacramento	4.93	25	95	87
2	Coastal California	3.73	2	89	73
3	San Joaquin	6.30	17	95	90
4	Colorado (South)	1.21	1	74	50
5	Upper Great Basin	2.44	46	63	50
6	Colorado	9.65	207	74	50
7	Rio Grande	16.46	114	95	100
8	Atlas	25.48	2	95	100
9	Ebro-Duero	32.20	10	100	100
10	South Apennines	1.13	3	95	97
11	Aegean	12.14	35	100	97
12	Buyuk Menderes	9.74	8	95	100
13	Sakarya	1.29	179	95	70
14	Kizil Irmak	6.38	24	100	80
15	Asi	19.19	15	100	97
16	Aksu	1.97	151	100	90
17	Dead Sea	15.71	1	84	77
18	Shatt al Arab	67.44	56	95	73
19	Urmia	5.25	26	68	57
20	South Caspian	8.41	18	95	67
21	Masileh	21.23	16	79	70
22	Karun	13.85	1	79	70
23	Garagum	9.68	3	79	73
24	Farah	12.74	164	79	70
25	Syr Darya	27.14	50	58	60
26	Ili	4.46	34	47	50
27	Alakol	1.72	44	53	47
28	Dzungarian	10.74	16	53	73
29	Upper Ili	1.11	2	68	67
30	Indus	269.43	105	37	33
31	Ganges	696.82	77	63	47
32	Huai	131.59	1	58	37

Table 1 Risk profiles of snow sensitive basins. We show the 32 snow sensitive basins that meet the following criteria: (1) observed late 20th C. snowmelt runoff is 1-250% of unmet demand, making it sensitive to changes in water supply and (2) more than 1 million inhabitants. For these 32 basins, totaling 1.45 billion people, we show the observed snowmelt dependency, the risk of decreases in this measure in both the CMIP5 and LENS ensembles. Outlined in red are the four additional basins that do not meet the 1M inhabitant threshold, but have population densities >5 people/km^2: [a] Klamath Basin (snmQ/UD: 125%; CMIP Risk: 79%; LENS Risk: 93%); [b] Western Great Basin (snmQ/UD: 239%; CMIP Risk: 74%; LENS Risk: 33%); [c] North Black Sea-Crimea (snmQ/UD: 2%; CMIP Risk: 94%; LENS Risk: 100%); and [d] Western Dzungarian (snmQ/UD: 95%; CMIP Risk: 47%; LENS Risk: 73%).

Supplemental Material for:

The potential for snow to supply human water demand in the present and future

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Supplementary Methods

Calculation of snowmelt and rainfall runoff

We focus our analysis on the six months of boreal spring and summer for two reasons. First, in the NH, boreal spring and summer are when water demands are highest (Hoekstra et al. 2012). Second, because the snow season length varies by altitude and latitude, it is necessary to capture a large calendar window of NH snowmelt (Mankin & Diffenbaugh 2014). Glacial contributions are relatively small at the basin scales that we consider, with the exception of very dry regions, such as the Aral and Syr Darya basins (Kaser et al. 2010; Viviroli et al. 2011). We therefore do not consider glacial melt in this analysis.

Snowmelt runoff (surface and subsurface) is not standard output from most coordinated climate model experiments. Instead, the land surface components in climate models often provide the snowmelt rate. Typically, snowmelt runoff is estimated as some function of temperature and elevation (Viviroli et al. 2007), while high-resolution daily-scale snowmelt runoff estimates can be estimated with a snowmelt runoff model (SRM), forced with observations or a climate model (Ashfaq et al. 2010; Rauscher et al. 2008; Immerzeel et al. 2010). However, because of the computational cost to provide a large number of simulations with an SRM and the coarse temporal and spatial scales we analyze, we estimate snowmelt runoff directly from the monthly values of snowmelt rate fields from 49 ensemble members at the basin-scale.

At each grid-point for each ensemble member, we estimate a "snow runoff coefficient" in a manner similar to the calculation made by an SRM (Martinec et al. 2008). We use the ratio of grid-scale snowmelt flux to rainfall flux to estimate the coefficient, which approximates the ratio of snowmelt runoff ($Q_{snowmelt}$) to rainfall runoff (Q_{rain}), β:

$$\frac{Q_{snowmelt}}{Q_{rain}} \approx \frac{snowmelt\ rate}{rainfall\ rate} = \beta$$

We interpret total runoff as the basin-scale precipitation that does not evaporate. We therefore do not distinguish the different runoff pathways (surface versus subsurface) such runoff takes. Thus total runoff is the sum of runoff from rainfall and from snowmelt, ($Q_{total} = Q_{snowmelt} + Q_{rain}$), the above relation above gives,

$$Q_{total} = \beta \cdot Q_{rain} + Q_{rain}.$$

Therefore, rainfall runoff can be calculated as

$$Q_{rain} = \frac{Q_{total}}{(1+\beta)}$$

and snowmelt runoff can be calculated as

$$Q_{snowmelt} = Q_{total} - Q_{rain}.$$

Details of the CMIP5 and LENS climate simulations

Analysis of snowmelt contributions to total runoff requires fields from either land-ice or land surface models, limiting our analysis to 19 CMIP5 models (Table S1). To ensure that the CMIP5 fields can be readily compared within each basin, we interpolate all CMIP5 models to 1°×1° in the horizontal via a patch recovery method (Gu et al. 2004).

Both CMIP5 and LENS are run using observed greenhouse gas concentrations over the historical period and the RCP8.5 forcing pathway (Riahi et al. 2011) over the 21st century. RCP8.5 prescribes an additional 8.5 $W \cdot m^{-2}$ of radiative forcing over the pre-industrial radiative balance (~1370 CO_2-equivelent) by 2100 (Moss et al. 2010). CMIP5 shows a median global mean warming of ~3.5°C by 2080 (Rogelj et al. 2012) (relative to the late-20th century baseline). Some CMIP5 GCMs also include upper atmospheric dynamics, interactive carbon cycle, and land vegetation (Taylor et al. 2012; Flato et al. 2013).

Variables used in GLDAS reanalysis and the CMIP5 and CESM LENS simulations

From the GLDAS, we use the sum of monthly surface and subsurface runoff (Qs + Qsb), snowmelt rate (Qsm), and rainfall rate (Rainf) to calculate snowmelt runoff ($Q_{snowmelt}$) and unmet demand. From CMIP5, we use precipitation (pr) and snowfall flux (prsn) to estimate the rainfall rate, and total runoff (mrro) and snowmelt (snm) to estimate snowmelt runoff and rainfall runoff. From LENS, we use the sum of surface and subsurface runoffs (QRGWL, QDRAI, and QOVER), as well as snowmelt (QSNOMELT) and the rainfall rate (RAIN).

References

Ashfaq, M. et al., 2010. Influence of climate model biases and daily-scale temperature and precipitation events on hydrological impacts assessment: A case study of the United States. *Journal of Geophysical Research*, 115(D14), p.D14116. Available at: http://doi.wiley.com/10.1029/2009JD012965 [Accessed May 4, 2014].

Flato, G. et al., 2013. *Evaluation of Climate Models*,

Gu, H., Zong, Z. & Hung, K.C., 2004. A modified superconvergent patch recovery method and its application to large deformation problems. *Finite Elements in Analysis and Design*, 40(5-6), pp.665–687.

Hoekstra, A.Y. et al., 2012. Global monthly water scarcity: blue water footprints versus blue water availability. *PloS one*, 7(2), p.e32688. Available at: http://www.pubmedcentral.nih.gov/articlerender.fcgi?artid=3290560&tool=pmcentrez&rendertype=abstract [Accessed March 24, 2014].

Immerzeel, W.W., van Beek, L.P.H. & Bierkens, M.F.P., 2010. Climate change will affect the Asian water towers. *Science*, 328(5984), pp.1382–5. Available at: http://www.ncbi.nlm.nih.gov/pubmed/20538947 [Accessed February 5, 2014].

Kaser, G., Grosshauser, M. & Marzeion, B., 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), pp.20223–7. Available at: http://www.pubmedcentral.nih.gov/articlerender.fcgi?artid=2996705&tool=pmcentrez&rendertype=abstract [Accessed January 27, 2014].

Mankin, J.S. & Diffenbaugh, N.S., 2014. Influence of temperature and precipitation variability on near-term snow trends. *Climate Dynamics*. Available at: http://link.springer.com/10.1007/s00382-014-2357-4 [Accessed October 21, 2014].

Martinec, J., Rango, A. & Roberts, R., 2008. *Snowmelt Runoff Model (SRM) User's Manual, Special Report 100*,

Meybeck, M., Dürr, H.H. & Vörösmarty, C.J., 2006. Global coastal segmentation and its river catchment contributors: A new look at land-ocean linkage. *Global Biogeochemical Cycles*, 20(1), pp.1–15.

Moss, R.H. et al., 2010. The next generation of scenarios for climate change research and assessment. *Nature*, 463(7282), pp.747–56. Available at: http://www.ncbi.nlm.nih.gov/pubmed/20148028 [Accessed February 27, 2013].

Rauscher, S.A. et al., 2008. Future changes in snowmelt-driven runoff timing over the western US. *Geophysical Research Letters*, 35(16), p.L16703. Available at: http://doi.wiley.com/10.1029/2008GL034424 [Accessed October 25, 2013].

Riahi, K. et al., 2011. RCP 8.5-A scenario of comparatively high greenhouse gas emissions. *Climatic Change*, 109, pp.33–57.

Rogelj, J., Meinshausen, M. & Knutti, R., 2012. Global warming under old and new scenarios using IPCC climate sensitivity range estimates. *Nature Climate Change*, 2(4), pp.248–253. Available at: http://www.nature.com/doifinder/10.1038/nclimate1385 [Accessed February 28, 2013].

Taylor, K.E., Stouffer, R.J. & Meehl, G. a., 2012. An Overview of CMIP5 and the Experiment Design. *Bulletin of the American Meteorological Society*, 93(4), pp.485–498. Available at: http://journals.ametsoc.org/doi/abs/10.1175/BAMS-D-11-00094.1 [Accessed February 27, 2013].

Viviroli, D. et al., 2011. Climate change and mountain water resources: overview and recommendations for research, management and policy. *Hydrology and Earth System Sciences*, 15(2), pp.471–504. Available at: http://www.hydrol-earth-syst-sci.net/15/471/2011/ [Accessed May 28, 2013].

Viviroli, D. et al., 2007. Mountains of the world, water towers for humanity: Typology, mapping, and global significance. *Water Resources Research*, 43, p.W07447. Available at: http://doi.wiley.com/10.1029/2006WR005653 [Accessed June 1, 2013].

Supplementary table

	Model Name
1	CCSM4
2	CESM1-BGC
3	CESM1-CAM5
4	CESM1-WACCM
5	CMCC-CMS
6	CanESM2
7	GFDL-ESM2G
8	GFDL-ESM2M
9	GISS-E2-H-CC
10	GISS-E2-R
11	GISS-E2-R-CC
12	MIROC-ESM
13	MIROC-ESM-CHEM
14	MIROC5
15	MPI-ESM-LR
16	MPI-ESM-MR
17	bcc-csm1-1
18	bcc-csm1-1-m
19	inmcm4

Table S1 Models used from the CMIP5 ensemble.

Supplementary figure

Fig. S1 Present and future March-August snow resource potential. a, 1955-2005 mean snowmelt to unmet demand ratio (same as Fig. 1e). b, The CMIP5 ensemble mean 2060 projection. c, The LENS ensemble mean 2060 projection. Stippled basins in [b] and [c] indicate where the ensemble mean is less than 1 SD of the ensemble variability. Note that grey basins in Fig. 2a and b have their snowmelt supply potentials shown here.

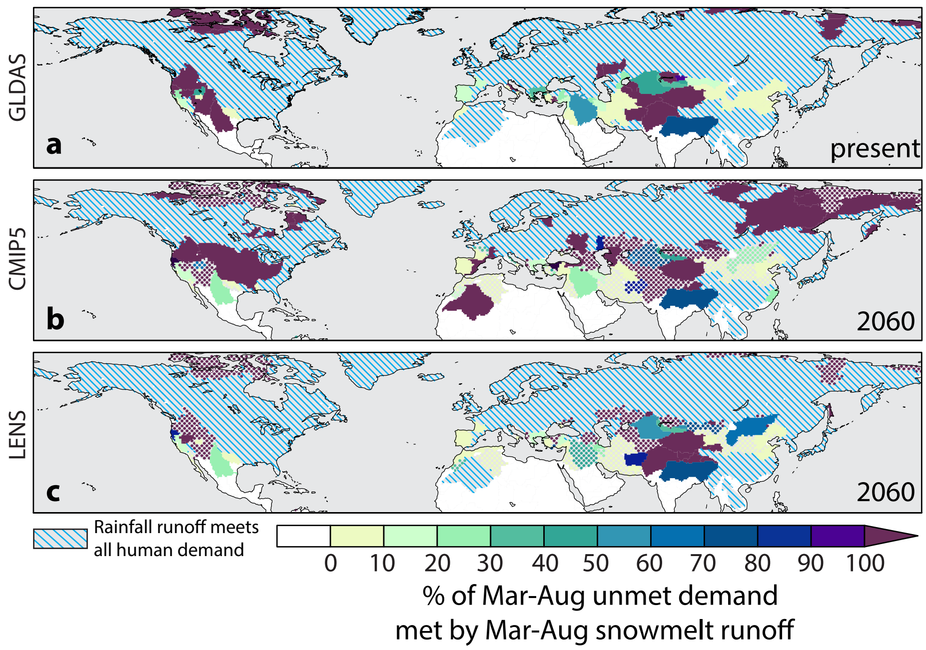

Fig. S1 Present and future March-August snow resource potential. **a,** 1955-2005 mean snowmelt to unmet demand ratio (same as Fig. 1e). **b,** The CMIP5 ensemble mean 2060 projection. **c,** The LENS ensemble mean 2060 projection. Stippled basins in [b] and [c] indicate where the ensemble mean is less than 1 SD of the ensemble variability. Note that grey basins in Fig. 2a and b have their snowmelt supply potentials shown here.