

CLIMATE CHANGE

Impacts in the third dimension

Despite reports of no trends in snow- and rainfall, rivers in the northwest USA have run lower and lower in recent decades. A closer look at high- and low-altitude precipitation suggests that observational networks have missed a decline in mountain rain and snow that can explain the discrepancy.

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Mountain catchments are key sources for river water and water supply. In the western US, for example, they contribute as much as 75% of surface-water and groundwater supplies. High-altitude catchments play this crucial role as they tend to receive more precipitation than surrounding lowlands. And mountain precipitation often forms thick snowpacks, which hold water in deep freeze until the following warm season. As the weather warms, just in time to meet high water demand, melt water feeds the streams. When a long-term decline in streamflow trends was diagnosed in the Pacific Northwest^{1,2} in the late 2000s despite widespread reports that precipitation showed no corresponding trend^{3,4}, the discrepancy was cause for concern. Writing in *Science*, Luce and colleagues⁵ suggest that a decline in high-mountain precipitation resulted from a climate-change-induced slow-down in the westerly winds that normally bring mountain rain and snow.

Mountains receive more precipitation than surrounding lowlands, because winds and storms that encounter high topography are forced up in altitude so that they can pass over them. On the way up, they cool, and copious amounts of water vapour condense and fall as precipitation on and around the mountains. This effect, generally referred to as orographic enhancement of precipitation, is more or less additional to any precipitation that the storms would generate even in the absence of mountains. This orographic enhancement is approximately^{6,7} the product of three factors: horizontal wind speed, the amount of water vapour in the air and the slope of the mountain faces (which determines how quickly the air is lifted).

Luce and colleagues⁵ find that high-altitude winds over the Pacific Northwest have declined in the past few decades, to a degree that would be expected to reduce the amount of orographic precipitation in the mountain ranges there. They note that the winds have been slowing down just enough to cause rates of precipitation decline that

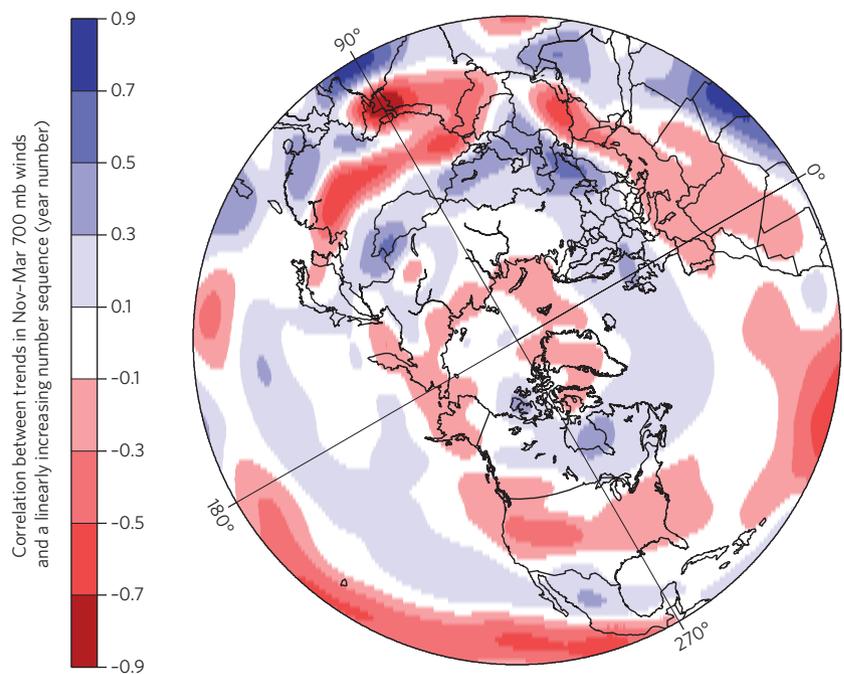


Figure 1 | Changing winds. Between 1950 and 2012, zonal winds at altitudes of about 3 kilometres above sea level (at atmospheric pressures of 700 mb) have slackened over some mid-latitude land areas (red shades). Luce and colleagues⁵ suggest that the slowing winds have led to significantly reduced high-altitude precipitation in the Pacific Northwest, and perhaps elsewhere. Such a reduction could result from a reduction in the orographic enhancement of precipitation by weakening high-altitude winds, a change that has not been picked up by the sparse networks of mountain observations.

would in turn explain the observed decline in streamflows. Previously, the most common explanations for the differing precipitation and streamflow trends were possible unaccounted-for impacts of land and water use, or potential increases in evaporation or sublimation rates in response to rising temperatures so that less water reaches the region's streams and rivers^{2,8}. The observation of Luce and colleagues offers a novel, and very plausible, alternative explanation. Based on radiation-balance considerations, Luce and colleagues also argue that the effects of warming alone would probably not have been large enough to explain observed streamflow declines in the Pacific Northwest, although this argument does not seem to

exhaust all options for warming-induced flow reductions.

If Luce and colleagues are correct, then important (15%) declines in orographic precipitation must have been missed by the observational network. This is a very real possibility. In the western US, as in mountain regions around the globe, harsh weather conditions, complex topography and long distances from larger human settlements have historically limited the numbers and often the quality of high-altitude weather stations. As a result, long-term declines in precipitation at high altitudes in the Pacific Northwest could well have gone unnoticed — ironically, precisely in the areas that provide most of the water.

The complexity of interactions between large-scale wind fields, precipitation patterns and river-based water supplies in the Pacific Northwest should stand as a stark warning for designers and operators of climate networks in mountainous regions. Declines in mountain precipitation in response to slackening winds, if widespread, could threaten the sources of many river systems globally, and potentially could change the timing and character of many downstream flows. Future flooding, drought, wildfire, ecosystems and other landscape features might be affected by a transition from high-altitude snow to low-altitude rain in ways that would challenge long-established ecosystems and water management systems. In this context, expansion of mountain-based networks of observations of surface weather and streamflow, as well as conditions in the atmosphere above, will be essential for resource and hazard managers striving to accommodate uncertain future climate changes and impacts.

Luce and colleagues take the argument further by suggesting that the slowing winds reflect large-scale atmospheric-circulation changes associated with shifting or slackening mid-latitude zones of westerly winds and storm tracks. They hypothesize that these storm-track changes might be related to differences between tropical versus polar warming trends, which might be associated

directly with anthropogenic global warming. But, when mapped at a hemispheric scale, the particular patch of declining winds that Luce and his colleagues studied (Fig. 1) can be seen to be localized near the Pacific Northwest. Hemispherically, the trends in westerly wind speeds are seen to be quite complex and variable, and, if anything, might be more focused (and explained) by changing continental climate gradients. Thus, it is not yet clear how much the decline in high-altitude precipitation change in the Pacific Northwest can be generalized.

The kinds of changes reported by Luce and colleagues, when viewed at global scales, are complex and uncertain. Global climate models of the current generation smooth over mountain topographies to a great extent; for example, the highest altitudes in the western US in the majority of global models are less than half the height of the highest mountain ranges there. Thus, orographic enhancements are dampened considerably in the models, and consequently the models are unlikely to faithfully capture the kinds of changes in precipitation in mountainous regions reported by Luce and his colleagues.

Luce and colleagues⁵ identify potentially very important changes in high-altitude precipitation and wind patterns that are already underway in at least one corner of the world, the Pacific Northwest. These

changes have mostly been missed by current observational networks and climate simulations, and show no immediate signs of being simple or uniform at the largest scales. In this context, more attention to the crucial third dimension — high altitudes — will be needed in our climate models, and even more so in our observational networks, if we are going to recognize and prepare for long-term climate changes in mountainous regions. In the end, we cannot adapt to something we cannot observe or predict. □

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References

1. Luce, C. H. & Holden, Z. A. *Geophys. Res. Lett.* **36**, L16401 (2009).
2. Fu, G., Barber, M. & Chen, S. *Hydrol. Proc.* **24**, 866–878 (2010).
3. Mote, P. W., Hamlet, A. F., Clark, M. P. & Lettenmaier, D. P. *Bull. Am. Meteorol. Soc.* **86**, 39–49 (2005).
4. Barnett, T. P. *et al. Science* **319**, 1080–1083 (2008).
5. Luce, C. H., Abatzoglou, J. T. & Holden, Z. A. *Science* **342**, 1360–1364 (2013).
6. Rhea, J. O. & Grant, L. O. in *Advanced Concepts and Techniques in the Study of Snow and Ice Resources: Interdisciplinary Symposium December 1973, Proceedings* (eds Santeford, H. S. & Smith, J. L.) 182–192 (1974).
7. Neiman, P. J., White, A. B., Ralph, F. M., Gottas, D. J. & Gutman, S. I. *Water Management* **162**, 83–94 (2009).
8. Das, T., Pierce, D. W., Cayan, D. R., Vano, J. A. & Lettenmaier, D. P. *Geophys. Res. Lett.* **38**, L23403 (2011).

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