

# DECADAL VARIATIONS AND TRENDS IN SNOWMELT AND STREAMFLOW TIMING: GLOBAL AND NORTH AMERICAN PATTERNS IN THE 20<sup>TH</sup> CENTURY

Michael D. Dettinger<sup>1</sup>, Daniel R. Cayan<sup>1,2</sup>, Henry Diaz<sup>3</sup>, and Iris Stewart<sup>2</sup>

<sup>1</sup>*U.S. Geological Survey, La Jolla, California USA*

<sup>2</sup>*Climate Research Division, Scripps Institute of Oceanography, La Jolla, California*

<sup>3</sup>*Climate Diagnostics Center, Boulder, Colorado USA*

One of the most robust projections of how climate change could affect rivers and high-altitude regions is that warming trends would result in earlier snowmelt and thus, for many rivers, earlier and smaller snowmelt-fed peak discharges. Such a change is of widespread concern because snowpacks traditionally have provided important natural reservoirs of water in the high-altitude basins through the cool seasons (when irrigation and other demands are small) and into the warm seasons (when streamflows can be most beneficially exploited).

In light of this projection, historical discharge records from rivers around the world (1) have been analyzed for trends in streamflow timing. In recent decades in cool climates and high-altitude regions around the world, the seasonal peak flows in many of the rivers in the high and middle latitudes in both Northern and (less robustly) Southern Hemispheres have come earlier, and are a smaller part of each year's total. In particular, when these fractions are analyzed in terms of nonparametric Kendall's tau trend statistics, significant ( $p < 0.05$ ) trends in the fraction of each year's flow that occurs between April and July (one measure of tendencies for late snowmelt discharges to dominate annual hydrographs) are found in long-term (20+ years) discharge records from rivers throughout eastern Europe and western Russia, across Canada, through the western Rocky Mountains, and along the Mississippi River. A similar array of rivers shows trends at even higher significance levels ( $p < 0.01$ ) when the fraction of annual flows during the local peak-flow season (the 3 months with highest long-term average flows) at each river is considered, instead of comparing April-July fractional flows at every river.

These trends towards smaller fractions of the discharge during the long-term average peak-discharge seasons are explained (in large part) by corresponding trends towards earlier flows overall, with highly significant ( $p < 0.01$ ) trends toward earlier "centers of mass" of annual hydrographs occurring in most of the same high-latitude and high-altitude snowmelt-fed rivers (Fig. 1). The snowmelt contributions and peak of these dozens of rivers are tending to occur earlier in the water year, which means that--increasingly--a smaller part of the overall flow is available for water-resources management during the seasons when the snowmelt flows historically have occurred.

For the period 1945 to 1993, historical streamflow records were analyzed for 650 rivers in the conterminous United States that have unmanaged flow. Of these rivers, flows in 25% have trended significantly ( $p < 0.01$ ) towards earlier peak seasonal flows; only 5% (mostly along the East Coast) have trended towards later flows. In the same 650 rivers, the amplitudes of seasonal-flow cycles declined throughout the northern half of the conterminous United States. In the western United States, where the trends have been examined in still greater detail, the trends are associated with significant winter and spring warming (on order of 2°C) since late 1940s, and with decadal and longer changes

in the air-sea climate of the North Pacific basin (2). All of these trends are reflected also in decadal trends in which springtime greenup and blooming in two regional phenological networks arrive earlier now than in the 1950s (3).

Notably, both the streamflow-timing trends and phenological trends in the western United States have been stronger on average at middle-altitude measurement sites than at higher altitude sites. For example, the beginning of major spring snowmelt has arrived earlier by an average of 0.43 days/yr since 1955 in western rivers for gages at altitudes less than 1 km, whereas at higher gages, the trend has been 0.16 days/yr earlier. Lilac first-bloom dates have trended earlier by 0.19 days/yr in plants below 1 km and by 0.12 days/yr in higher plants. This altitude dependence of the timing trends is in agreement with results of climate-change watershed simulations and discharge-record analyses in the Sierra Nevada of California, which indicated that streamflow timing in the highest watersheds (where, even with modest warming, winter and spring temperatures remain well below freezing) and lowest watersheds (where temperatures are at or above freezing for long periods even without additional warming) are likely to be less sensitive to global warming than are middle-altitude settings.

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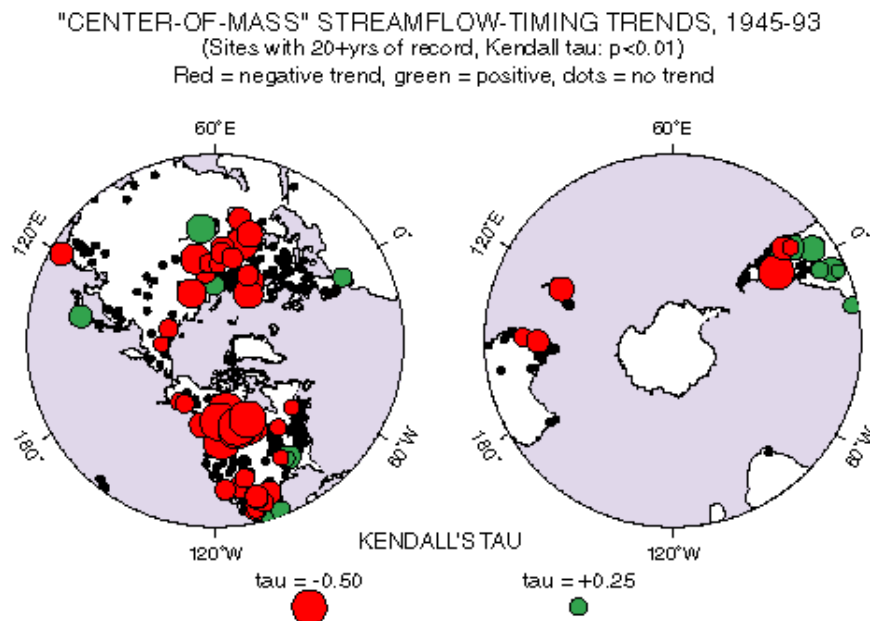


Fig. 1 -- Global trends in the timing of streamflow, as measured by the flow-weighted average day of flows in extratropical rivers; red filled circles denote retrogression of the annual hydrograph.