WATER RESOURCES

Hydrologic connectivity constrains partitioning of global terrestrial water fluxes

Stephen P. Good,[1,2]* David Noone,[3] Gabriel Bowen[1,4]

Continental precipitation not routed to the oceans as runoff returns to the atmosphere as evapotranspiration. Partitioning this evapotranspiration flux into interception, transpiration, soil evaporation, and surface water evaporation is difficult using traditional hydrological methods, yet critical for understanding the water cycle and linked ecological processes. We combined two large-scale flux-partitioning approaches to quantify evapotranspiration subcomponents and the hydrologic connectivity of bound, plant-available soil waters with more mobile surface waters. Globally, transpiration is 64 ± 13% (mean ± 1 standard deviation) of evapotranspiration, and 65 ± 26% of evaporation originates from soils and not surface waters. We estimate that 38 ± 28% of surface water is derived from the plant-accessed soil water pool. This limited connectivity between soil and surface waters fundamentally structures the physical and biogeochemical interactions of water transiting through catchments.

Continental precipitation is routed through soils, plants, and streams on its return to the oceans or atmosphere. This hydrologic routing within catchments determines peak and baseflow stream discharge, plant productivity, and surface water quality. Over the long term, changes in water storage are minimal, and precipitation entering catchments exits as either runoff or evapotranspiration (*1*). Further partitioning evapotranspiration flux into evaporation and transpiration subcomponents is essential for understanding links between ecologic and hydrologic systems, because biologic water use is inexorably coupled with ecosystem productivity (*2*).

At plot scales, transpiration and evaporation fluxes can be directly measured by hydrometric devices such as lysimeters, leaf cuvettes, and sap flow probes, yet these techniques remain difficult to implement at watershed, regional, or continental scales (*3*–*6*). The classic hydrologic paradigm of translatory flow links these fluxes and posits that infiltration entering the soil column, where it may be used by vegetation, displaces previously held water deeper into the profile and eventually into streams (*7*). Observed preferential flow paths at hillslope scales (*8*, *9*) and geochemical evidence (*10*, *11*) point to the possibility that soil water used by plants remains separated from water rapidly passing though soils and into open channels. If this hydrologic separation is established as a generalized phenomena across catchments, models may require a more complex representation of water movement and associated soil biogeochemistry (*12*).

Two distinct stable isotope techniques have emerged as solutions for flux partitioning at regional to global scales (*5*). Both approaches leverage differences between the ratio of heavy to light isotopes of water (e.g, D/H) in transpiration, which is often assumed to be unchanged relative to soil source waters (*13*), and evaporation, which is D-depleted relative to source waters because of the lower vapor pressure and diffusivity of the rare isotopologue (*14*). Runoff-based techniques use differences in the isotope ratios of precipitation inputs and outflowing runoff from hydrologic basins to partition evapotranspiration, with larger differences indicating more evaporation from surface waters (*3*, *15*, *16*). Evapotranspiration-based techniques involve directly measuring the isotopic ratio of upward vapor flux over a region and comparing it to estimated values for the evaporation and transpiration flux end members (*17*–*19*). Though useful, both approaches suffer from key deficiencies. Runoff techniques are unable to consider partial evaporation of soil waters before plant uptake if the remaining water is not discharged to surface waters (*20*, *21*). In contrast, evapotranspiration techniques provide information only within the measurement's flux footprint, and results are difficult to extrapolate across regions of heterogeneous surface cover or to areas with open surface water, which typically lie beyond the footprint of conventional flux-monitoring stations.

We established a unified framework for hydrologic partitioning that reconciles runoff and

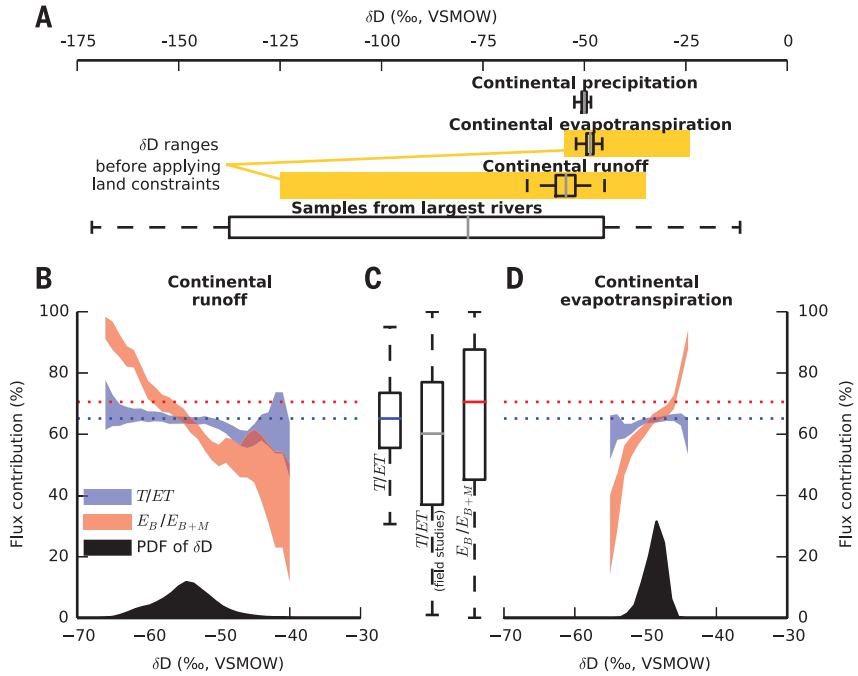

Fig. 1. Continental hydrologic partitioning constrained by the global D/H ratios. (**A**) Estimated global precipitation, evapotranspiration, and runoff δD values compared with values from 23 of the 200 largest rivers (*23*). Box plots depict median, 25th, and 75th percentiles of simulations, whereas yellow boxes depict the range based only on an ocean and atmosphere mass balance. Isotope values are reported in δ notation, where $\delta D = R/R_{VSMOW} - 1$, with R the D/H isotope ratio (VSMOW, Vienna standard mean ocean water). (**B**) Relationship between runoff δD and the transpired fraction of evapotranspiration, T/ET (blue); the fraction of evaporation (E) from soils, E_B/E_{B+M} (red) (B, bound waters; M, mobile waters); and a kernel density estimate, PDF of δD, of the distribution global runoff (black). Red and blue shaded areas show mean values, smoothed with a 5‰ moving window, ± 2 SE; and dotted lines show median percentages across all simulations. (**C**) Box plot of T/ET from this study, T/ET from field studies (*4*), and E_B/E_{B+M} from this study. (**D**) The same as (B) for continental evapotranspiration δD values.

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evapotranspiration isotope approaches by quantifying the connectivity between soil matrix waters and mobile surface waters. This "hydrologic connectivity" is formally defined as the fraction of mobile surface water derived from bound waters (water that resides in the soil matrix and is available to support plant transpiration) as opposed to mobile waters (water that rapidly bypasses soils via preferential flow paths and does not mix with bound waters) (*22*). In a fully connected system, consistent with the translatory flow paradigm, water accessible to plants and subjected to soil evaporation also moves into streams. In a disconnected system characterized by preferential flow, soil waters do not interact with surface waters, and therefore water entering streams and rivers has an isotopic composition equivalent to that of rainfall. This theoretical framework can be applied, using established models for isotopic fractionation and data on isotopic inputs (precipitation) and outputs (runoff and evapotranspiration), to constrain the partitioning of hydrologic fluxes into the subcomponents of transpiration, evaporation of bound water in soils, and evaporation from mobile surface waters.

We recently determined the D/H isotope ratios of continental runoff and evapotranspiration (*23*), independent of terrestrial hydrologic partitioning, via an isotopic mass balance of the oceans and atmosphere. This ocean-atmosphere approach used satellite retrievals of marine surface-level D/H isotope ratios in water vapor (*24*) to estimate oceanic evaporation isotope ratios. Combining these with over-ocean precipitation isotope ratios modeled based on monitoring station data (*25*), we calculated the isotope ratios of continental fluxes as the residuals of each isotopologue mass balance. Here, over-land precipitation isotope ratios (*25*) were combined with bulk land-atmosphere water fluxes in gridded simulations of all terrestrial flux subcomponents and their isotope ratios to calculate the global terrestrial water isotope budget (*22*). In determining this budget, the fluxes of soil evaporation, surface water evaporation, and hydrologic connectivity were found so that the isotope ratios of continental runoff and evapotranspiration fluxes were consistent with the ocean-atmosphere mass balance (*23*).

When implementing this framework, constraints on possible runoff, interception, transpiration, and evaporation fluxes within the terrestrial hydrologic cycle (e.g., transpiration may not exceed evapotranspiration) limit the range of continental output flux isotope ratios relative to the previous ocean-atmosphere study (Fig. 1A). For global runoff isotope values, the revised results are within the range of observed large river values (*23*). Few direct observations of evapotranspiration isotope values are available for comparison with our result, and large uncertainties persist in accurately measuring this flux (*5*, *26*). Our simulations show that if the value of global runoff is more D-enriched, less transpiration and more surface water evaporation are required to balance the global isotope budget (Fig. 1B). Conversely, if the isotopic value of global evapotranspiration is more D-enriched, more transpiration and soil evaporation are required to meet observational constraints (Fig. 1D). Overall, the fraction of evaporation occurring in soils is more sensitive to runoff and evapotranspiration composition than is the transpired fraction.

Globally, the transpired fraction of evapotranspiration is estimated to be 56 to 74% (25th to 75th percentiles), with a median of 65% and mean of 64%. A previous estimate of global partitioning (*3*), which did not incorporate the evaporation of bound soil water and its connectivity to mobile water, suggested a value of 80 to 90%. Subsequent critiques and revisions of that study have obtained estimates similar to those reported here, though with greater uncertainty (*6*, *20*). The estimated transpired fraction described here is relatively insensitive to the hydrologic connectivity, which reflects the strong constraint imposed by the high isotope value of global evapotranspiration on the magnitude of this relatively D-enriched flux. We find that the global fraction of evaporation occurring in soils is 45 to 88%, with a median of 71% and a mean of 65%. Based on our simulations, we estimate hydrologic connectivity to be 14 to 59%, with a median of 31% and mean of 38%, which suggests a pervasive disconnect between water bound in soils and water entering streams, although not a complete separation.

Although local runoff D/H ratios in our model are typically larger then local precipitation D/H ratios, the flux weighted D/H ratio of global runoff is smaller than that of global continental precipitation because of spatial patterns in continental precipitation D/H composition and hydrologic routing. Locally, the evaporation of bound soil waters raises the isotope value of transpiration flux because plant roots will withdraw D-enriched soil waters. The positive-skewed distribution of simulation results with a low average hydrologic connectivity reflects the fact that at smaller connectivity values, the flux entering surface waters has decreased D/H ratios because more water is bypassing soils that are D-enriched. Thus, simulations with substantial soil evaporation are consistent with a global evapotranspiration flux that is enriched in D relative to precipitation, and simulations with low connectivity are consistent with a global runoff flux that is more depleted in D than precipitation. In contrast to the transpired fraction, the bound-water evaporation percentage is weakly correlated with connectivity (Fig. 2).

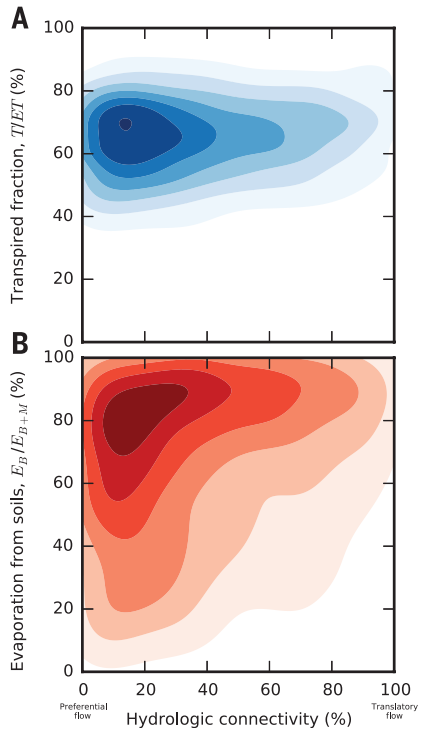

Fig. 2. Relationship between hydrologic connectivity and hydrologic partitioning. This is a bivaraite kernel density plot showing the distribution of results from Monte Carlo simulations of D/H ratios in the continental water cycle, with darker shaded areas more likely. (**A**) The transpired fraction of total evapotranspiration, *T*/*ET* and (**B**) the fraction of soil and surface water evaporation that occurs from soils, E_B/E_{B+M}.

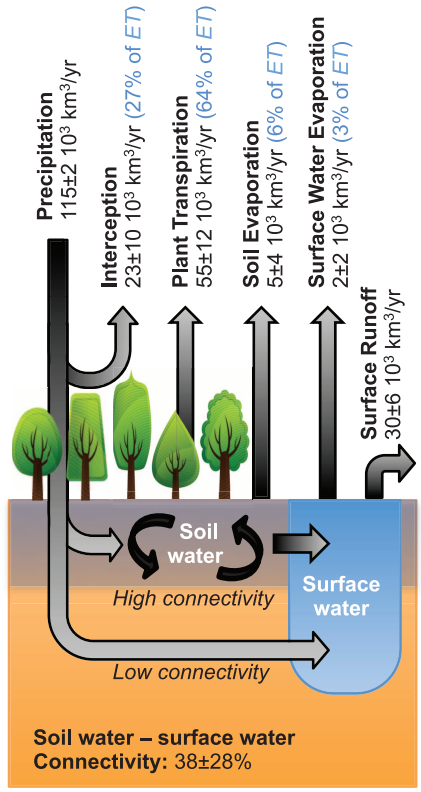

Fig. 3. Partitioned continental hydrologic fluxes. Terrestrial precipitation (annual mean ± 1 SD) not intercepted by vegetation mixes into soils or flows into surface waters. Soil water is withdrawn by plant roots via transpiration, subjected to evaporation, and leaks into the surface water. Of the flux entering the surface waters, our results suggest that 38% is derived from the soils, with the remainder being consistent with precipitation routed directly via preferential flow paths. Surface water that does not evaporate returns to the ocean as runoff.

This suggests predictive limits of our approach, in that more-connected systems with more soil evaporation and less-connected systems with less soil evaporation will produce similar continental output flux isotope ratios.

The terrestrial hydrologic partitioning estimated here corresponds to a total transpiration of 55,000 ± 12,000 km^3 per year (mean ± 1 SD), a total soil evaporation of 5000 ± 4000 km^3 per year, and a total surface water evaporation of 2000 ± 2000 km^3 per year, assuming an interception of 23,000 ± 10,000 km^3 per year (*27*) and a continental precipitation of 115,000 ± 2000 km^3 per year (*28*) (Fig. 3). The transpired fraction determined here is consistent with previous meta-analyses (Fig. 1C) and places an observational constraint on transpiration estimates from global Earth system models, which range between 38 and 80% (*4–6*, *29*). The fraction of total evapotranspiration flux occurring from surface waters, 2.9%, is also consistent with values from global Earth system models, which range from 2 to 4% when reported (*29*). Globally, tropical forests provide the bulk of continental transpiration, although these regions contribute modest amounts of soil and surface water evaporation as well.

Transpiration fluxes form the primary link between the water and carbon cycles, with water lost from plant stomata during carbon assimilation (i.e., plant water use efficiency) being a critical factor determining ecosystem function and productivity. Although we estimate that plant transpiration is a majority of the evapotranspiration flux, our results demonstrate that previous partitioning approaches may overestimate the contribution of transpiration, because they do not consider evaporation from multiple catchment water pools and their connectivity. Furthermore, isotopic partitioning approaches are sensitive to bulk flux estimates and their uncertainties, as well as assumptions about interception rates, with larger interception isotopically indistinguishable from increased transpiration because both fluxes are often assumed to be unfractionated relative to their source waters (*6*, *20*). Because a majority of evaporation occurs from soils and not open waters, more knowledge is needed of the role of ecosystem structure and microclimate in determining sub-canopy evaporation rates.

Finally, the partial hydrologic disconnect between bound and mobile waters, which our estimates suggest is substantial and pervasive at the global scale, has implications for prediction and monitoring of both water quantity and quality within streams and rivers. The hydrologic and hydrochemical properties of surface water systems are strongly influenced by physical flow paths within the near surface, and the low connectivity found here suggests, for example, that stream biogeochemistry may be less sensitive to soil zone processes than it would be if hydrologic connectivity were higher. Although we determined a single average connectivity value, connectivity varies with geography and in time as preferential flow paths are activated and deactivated throughout the year (*30*). Indeed, the relation between the connectivity metric and soil-water transit time distributions is likely to be complex. Given the ubiquitous nature of both water quantity and water quality issues affecting watersheds worldwide, an improved understanding of hydrologic connectivity at variety of temporal and spatial scales is essential.

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ACKNOWLEDGMENTS

This project was funded by the NSF Macrosystems Biology program, grant EF-01241286, and the U.S. Department of Defense. D.N. acknowledges the support of the NSF Climate and Large Scale Dynamic program as part of a Faculty Early Career Development award (AGS-0955841). Support and resources from the Center for High Performance Computing at the University of Utah are also gratefully acknowledged. Bulk flux data used in this study are available online from NASA (http://precip.gsfc.nasa.gov/, http://gmao.gsfc.nasa.gov/merra/) and the Woods Hole Oceanographic Institute (http://oaflux.whoi.edu/). Global surface vapor isotope data are available as supplementary information in (*23*). The model code and input data files used in this study are available at http://waterisotopes.org.

SUPPLEMENTARY MATERIALS

www.sciencemag.org/content/349/6244/175/suppl/DC1
Materials and Methods
Figs. S1 to S3
References (*31–37*)

7 January 2015; accepted 2 June 2015
10.1126/science.aaa5931

CLIMATE CHANGE

Climate change impacts on bumblebees converge across continents

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For many species, geographical ranges are expanding toward the poles in response to climate change, while remaining stable along range edges nearest the equator. Using long-term observations across Europe and North America over 110 years, we tested for climate change–related range shifts in bumblebee species across the full extents of their latitudinal and thermal limits and movements along elevation gradients. We found cross-continentally consistent trends in failures to track warming through time at species' northern range limits, range losses from southern range limits, and shifts to higher elevations among southern species. These effects are independent of changing land uses or pesticide applications and underscore the need to test for climate impacts at both leading and trailing latitudinal and thermal limits for species.

Biological effects of climate change threaten many species (*1*), necessitating advances in techniques to assess their vulnerabilities (*2*). In addition to shifts in the timing of species' life cycles, warming has caused range expansion toward the poles and higher elevations (*3–6*). Climate impacts could cause losses from parts of species' trailing range margins (*7*), but those losses are infrequently observed (*4*). Such responses depend on species' traits, such as

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Science **349**, 175 (2015);
DOI: 10.1126/science.aaa5931

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