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PAGES 193–200

A Close Look at Oceanic Sources of Continental Precipitation

PAGES 193–194

Globally, the hydrological cycle is characterized by the evaporation of about 500,000 cubic kilometers of water per year, of which 86% is from the oceans and 14% is from the continents [*Quante and Matthias,* 2006]. Most of the water that evaporates from the oceans (90%) is precipitated back into them, while the remaining 10% is transported to the continents, where the water precipitates. About two thirds of this precipitation is recycled over the continents, and only one third runs off directly into the oceans.

Because societies rely on secure water resources, it is important to understand the processes that govern the atmospheric transport of moisture [*Trenberth et al.*, 2003] and how they are related to precipitation over land. Research on these processes is also related to studies on the energetic coupling of the land-atmosphere system, as well as to paleoclimatology; studies on the latter aim to extract information on past states of the climate system from records such as those of ice cores and stalagmites.

However, determining the exact sources of continental precipitation can be tricky—moisture that evaporates in a region is not the single origin of the precipitation that falls in that region [*Trenberth and Guillemot,* 1998]. Thus, scientists must first understand whether water vapor present in the atmosphere at a given point is from local evaporation (recycling) or is transported from remote sources (advection). However, considerably more difficult than estimating the ratio between advected and recycled moisture is understanding where water evaporates to and how the resulting water vapor is transported through the atmosphere on global and local scales.

Water Vapor Distribution

The general distribution of water vapor follows that of temperature, because equilibrium vapor pressure increases markedly with temperature according to the Clausius-Clapeyron equation. Consequently, water vapor concentrations decrease rapidly with height.

Through satellite measurements and models, scientists can learn more about water vapor concentrations at different latitudes and altitudes. For example, near the surface, where most water vapor resides, concentrations vary by more than 3 orders of magnitude, from 10 parts per million by volume in the coldest regions to as much as 5% in the warmest [*Quante and Matthias,* 2006]. The tropical atmosphere contains more than 3 times as much water vapor as the extratropical. In the midlatitudes the water vapor distribution is subject to intense day-to-day variations, responding strongly to the passage of cyclones.

Data from remote sensing instruments reveal that at any time, there are typically three to five major filamentary structures in each hemisphere that transport large amounts of water vapor in narrow streams from the tropics to higher latitudes. *Newell et al.* [1992] termed these features “atmospheric rivers,” because they transport quantities of water similar to those of the world’s largest rivers. Through these, water vapor can be transported over long distances—for example, at 35° latitude in both hemispheres, 95% of water vapor present in the atmosphere arrived through these filaments [*Ralph et al.*, 2005]. In contrast to real rivers, however, these conceptual atmospheric rivers change their location every day, responding to the meteorological situation.

Precipitation Associated With Major Oceanic Sources: The Global Scale

To quantify atmospheric water vapor transport, one must first identify where water evaporates to. Unfortunately, few direct measurements of evaporation exist. In the absence of global measurements, indirect methods must be used. Isotopic analysis has been the traditional method used

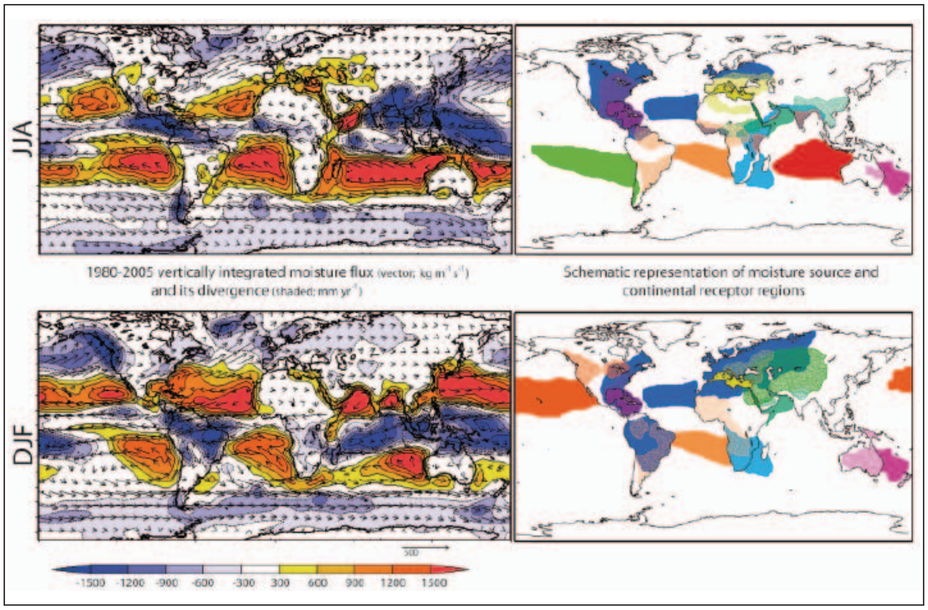

Fig. 1. (left) Vertically integrated moisture flux for 1980–2005, seen as vectors (measured in kilograms per meter per second), and its divergence, seen as warm and cool colors (measured in millimeters per year) for summer (June, July, August; JJA) and winter (December, January, February; DJF). Data are from http://www.cgd.ucar.edu/cas/catalog/newbudgets/index.html#AtD. (right) Schematic representation of moisture source and continental receptor regions is shown in the same colors as the corresponding oceanic source regions for JJA and DJF. Overlapping regions are shown with texture. From Gimeno et al. *[2010b, Figure 4].*

By L. Gimeno, R. Nieto, A. Drumond, A. M. Durán-Quesada, A. Stohl, H. Sodemann, and R. M. Trigo

to identify the origin of the moisture that feeds precipitation. This method is based on knowing the relationship between the relative proportions of certain isotopes of oxygen and hydrogen, which depend on the conditions (height, temperature, or distance from the coast) under which the water evaporated to the atmosphere. However, such analyses are limited without some idea of large-scale movements of water vapor.

A powerful snapshot of evaporation and precipitation can be seen from diagnosing the vertically integrated moisture flux from atmospheric data. Regions of divergence or convergence of moisture flux values must reflect forces of net evaporation or precipitation [*Trenberth and Guillemot,* 1998]. Figure 1 (left) shows global maps during boreal summer (June, July, August; JJA) and winter (December, January, February; DJF) of vertically integrated moisture flux and its divergence, which indicate the main net moisture sources (warm colors) on a global scale, found within the Indian, North and South Pacific, and North and South Atlantic oceans. Several smaller regions also contribute significantly, such as the Caribbean, Mediterranean, and Red seas, as well as the Agulhas Current region (in the waters surrounding South Africa).

Knowledge of the source regions for continental precipitation not only helps researchers to understand extreme precipitation events [e.g., *Stohl et al.,* 2008] but also helps to uncover precipitation patterns on climatological time scales. Different approaches can be used to quantify the amount of moisture advected in the atmosphere and its trajectories to different regions. In addition to studies of moisture flux budgets from and to certain regions [e.g., *Chen et al.,* 1994], other approaches involve tracing water from its source region using Eulerian forward modeling [e.g., *Koster et al.,* 1986] and the increasingly popular Lagrangian backward modeling [*Dominguez et al.,* 2006; *Dirmeyer and Brubaker,* 2007]. Recently, several methods have been developed for diagnosing specific humidity variations along a large number of trajectories to identify moisture source and sink regions and their relationships with one other [*Stohl and James,* 2004; *Drumond et al.,* 2008; *Gimeno et al.,* 2010a]. Isotopic measurements [*Wright al.,* 2001], in conjunction with flux analysis, modeling, and humidity studies, help to cement results. Furthermore, improvements have also been made in deriving quantitative moisture source information [*Sodemann et al.,* 2008].

From these data, relationships can be made between evaporation source regions and continental precipitation. Figure 1 (right) summarizes the main oceanic moisture sources and the associated continental receptor regions of the evaporated moisture, diagnosed with the Lagrangian method of *Stohl and James* [2004]. The productivity of major oceanic moisture sources for continental precipitation is not evenly distributed—some specific oceanic sources generate more continental precipitation than others [*Gimeno et al.,* 2010b]. As seen in the figure, the northern Atlantic subtropical ocean provides moisture for precipitation over vast geographical areas (from Mexico to large parts of Eurasia) in DJF. The small enclosed Red Sea source provides disproportionally large amounts of moisture that precipitate between the Gulf of Guinea and Indochina (JJA) and the African Great Lakes and Asia (DJF). Another key regional source for Europe and northern Africa (JJA) is the Mediterranean. Vast continental areas lack appreciable direct water transport from any major oceans, usually corresponding to some of the most arid inland regions (e.g., inner Asia) unless continental moisture recycling can compensate (albeit partly) for the lack of a direct oceanic moisture source (e.g., in eastern Siberia).

Some landmasses obtain moisture evaporated in the same hemisphere (e.g., northern Europe or eastern North America), while others receive moisture from both hemispheres with large seasonal variations (e.g., northern South America). Monsoon regimes in India, tropical Africa, and the North American Great Plains are fed by moisture provided from a large number of source regions, highlighting the complex nature of precipitation.

Implications of Climate Change

Climate change scenarios suggest that the high sensitivity of saturation vapor pressure to temperature will result in an intensified hydrological cycle with increased evaporation and precipitation rates in a warmer world [*Held and Soden,* 2006; *Intergovernmental Panel on Climate Change* (*IPCC*), 2007]. However, that is just part of the story, as changing circulation patterns will lead to large regional changes of the moisture budget.

Some regional changes are already being observed. For example, recent changes in atmospheric circulation patterns are partially responsible for declining precipitation trends over regions such as the Iberian Peninsula, southwestern United States, and Australia, areas thought to be prone to a higher frequency of droughts in the future according to climate projections [e.g., *IPCC,* 2007]. It seems plausible that regions receiving moisture from several different oceanic source regions are less susceptible to shifts in circulation regimes than regions relying on water vapor from only one source. Thus, analysis of where water in precipitation originates may help to identify regions that are at risk in a changing climate.

Future Challenges

Fundamentally, precipitation does not reveal from which oceanic basin it once evaporated. Thus, major challenges for moisture source diagnostics as they become more widely used are to further establish their validity and evaluate underlying assumptions. Stable water isotope measurements are one possible means of providing source-related information for validating such diagnostics [*Pfahl and Wernli,* 2009]. However, understanding the relation between water isotope signatures and precipitation sources is far from complete, and isotope fractionation during air mass transport may be overwriting source signatures [*Sodemann et al.,* 2008]. The prospect of better understanding how moisture sources affect precipitation isotopes is of crucial importance for the interpretation of many paleoclimate archives, such as ice cores and cave sediments. Therefore, future research needs to combine moisture source diagnostics with all other available information, including stable water isotope modeling and measurements.

Another reason that understanding source-to-sink relationships in the atmospheric water cycle is so important is extreme weather events. For example, convergence and transport from regions of high water vapor may trigger rainfall extremes and cause floods [*Stohl et al.,* 2008], while the absence of moisture transport to continental regions may play a key role in the buildup and persistence of continental drought [*Seneviratne et al.,* 2006; *Hoerling and Kumar,* 2003]. This coupling of the ocean-land-atmosphere system via the atmospheric water cycle needs to be understood because each of its elements may undergo change, with potentially severe consequences for society.

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NEWS

NASA Selects Asteroid Mission for New Frontiers Program

PAGE 194

NASA has selected an unmanned mission to study and return samples from a carbonaceous asteroid as the third mission in its New Frontiers Program, the agency announced on 25 May. The Origins-Spectral Interpretation-Resource Identification-Security-Regolith Explorer (OSIRIS-REx) is scheduled for a 2016 launch from Cape Canaveral, Fla., and a 2023 return to Utah's Test and Training Range. It will be the first U.S. mission to return samples from an asteroid to Earth and the first to return asteroid samples that could help scientists understand organics on Earth.

The mission aims to sample the approximately 1900-foot-diameter asteroid, 1999 RQ36, which is named for the year it was discovered. This asteroid is "kind of a time capsule from 4.5 billion years ago, when the solar system formed," according to OSIRIS-REx principal investigator Michael Drake, director of the Lunar and Planetary Laboratory at the University of Arizona, Tucson, which NASA selected to lead the mission. The NASA Goddard Space Flight Center, Greenbelt, Md., is managing the mission, and Lockheed Martin will build the spacecraft. The mission is expected to cost $800 million, excluding the $1 billion launch vehicle.

"We are bringing back what we believe is the type of material that led to the organics on Earth, that led to the building blocks for life, that led to us. Nothing like that exists right now," Drake said, adding that amino acids are known to exist in space and scientists expect to find them on the asteroid. "We're bringing back something essentially untouched by human hands, which has not seen the Earth's biota and will be a pristine sample of what's out there. In detail, I can't tell you where this goes, because like all exploration and discovery, you can predict the kinds of things you'll find, complicated organics that might help us understand the building blocks of life, but until you see what's there you don't actually know where the science is going to take you in detail."

Whereas Japan's Hayabusa space probe returned with a very small sample of the stony Itokawa asteroid in June 2010, OSIRIS-REx is expected to bring back a minimum of 60 grams of material from asteroid 1999 RQ36. That amount would satisfy the mission's science requirements, with some leftover to archive for future study, Drake explained. However, he said, it is possible the spacecraft could return with up to 2 kilograms of material. "The reason for bringing back far more material than we need for scientific study is to ensure [that] the next generation—as science progresses and civilization marches on—will have materials that are unique, that don't exist currently on Earth at all, to study," he said.

The spacecraft will carry several instruments on board including the OSIRIS-REx Camera Suite, the OSIRIS-REex Visible-Infrared Spectrometer, the OSIRIS-REx Thermal Emission Spectrometer, the OSIRIS-REex Laser Altimeter, and a student-built X-ray imaging spectrometer, to measure the composition of the asteroid.

After OSIRIS-REex orbits and extensively maps the asteroid's surface, the science team will choose a location for sampling. The probe will not actually land on the surface. "A better analogy is that we kiss the surface," explained Drake. "A very slow approach of about 10 centimeters per second. The contact itself is about 5 seconds. Most of [the] sample is collected in the first second." The sample will be collected by the spacecraft's arm. "Think of a pogo stick you could bend," he said. The sample will be stored in a capsule similar to that used by the NASA Stardust spacecraft, which returned to Earth in 2006 with the first comet particles, from comet Wild 2.

OSIRIS-REex will arrive at 1999 RQ36 in 2019 and will send a stream of data back to Earth. However, samples won't be returned until 2023 because of orbiter mechanics and the optimal timing for an efficient return.

The mission "ushers in a new era of planetary exploration," according to Jim Green, director of NASA's Planetary Science Division. He added, "The knowledge from the mission also will help us to develop methods to better track the orbits of asteroids."

NASA administrator Charles Bolden said, "This is a critical step in meeting the