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Approaching moisture recycling governance

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ABSTRACT

The spatial and temporal dynamics of water resources are a continuous challenge for effective and sustainable national and international governance. The watershed is the most common spatial unit in water resources governance, which typically includes only surface and groundwater. However, recent advances in hydrology have revealed 'atmospheric watersheds' – otherwise known as precipitationsheds. Water flowing within a precipitationshed may be modified by land-use change in one location, while the effect of this modification could be felt in a different province, country, or continent. Despite an upwind country's ability to change a downwind country's rainfall through changes in land-use or land management, the major legal and institutional implications of changes in atmospheric moisture flows have remained unexplored. Here we explore potential ways to approach what we denote as moisture recycling governance. We first identify a set of international study regions, and then develop a typology of moisture recycling relationships within these regions ranging from bilateral moisture exchange to more complex networks. This enables us to classify different types of possible governance principles and relate those to existing land and water governance frameworks and management practices. The complexity of moisture recycling means institutional fit will be difficult to generalize for all moisture recycling relationships, but our typology allows the identification of characteristics that make effective governance of these normally ignored water flows more tenable.

1. Introduction

The challenges of global environmental governance are growing more complex as the exponentially increasing threats of climate change, land-use change, population pressure, and changing consumption patterns interact (Steffen et al., 2015a,b; Richardson et al., 2009). Some of the most urgent and pressing challenges that humanity must collectively address are related to the water cycle (Savenije et al., 2014), since water links different groups of people and economic sectors together. Trans-boundary water issues are well-studied when it relates to surface water, like rivers and lakes, or groundwater, such as shared aquifers (e.g. Falkenmark, 2003). However, transboundary water management has so far not taken changes to atmospheric water flows into account (e.g. the recycling of evaporation to precipitation). It is now well-known that humans modify the amount and timing of water that enters the atmosphere as evaporation (e.g. Gordon et al., 2005; Van der Ent et al., 2014). These modifications have primarily been driven by anthropogenic land-use change, such as large-scale irrigation or deforestation, which modifies the amount of evaporation entering the atmosphere (e.g. Tuinenburg et al., 2014; Swann et al., 2015). This modified amount of evaporation can lead to changes in water vapor in the atmosphere, and also to changes in precipitation downwind (e.g. Bagley et al., 2014; Spracklen and Garcia-Carreras, 2015; Keys et al., 2016). This process of evaporation entering the atmosphere, traveling with the prevailing winds, and eventually falling out as rain is known as moisture recycling.

Moisture recycling is an increasingly well-understood phenomenon. A key insight from this body of research is that a large fraction of precipitation falling on land originates as evaporation from other land surfaces rather than from over the oceans, the land based result of this evaporation is referred to as terrestrial moisture recycling. Globally, terrestrial moisture recycling accounts for 40% of the precipitation that falls on land, and in many places can account for as much as 75% of annual precipitation (e.g. Van der Ent et al., 2010). Keys et al. (2012) introduced the concept of the precipitationshed to better explain how a specific location is dependent on rain that comes from evaporation from a different place (Fig. 1A). A precipitationshed can thus be seen as a 'watershed of the sky in that it describes how upwind and downwind

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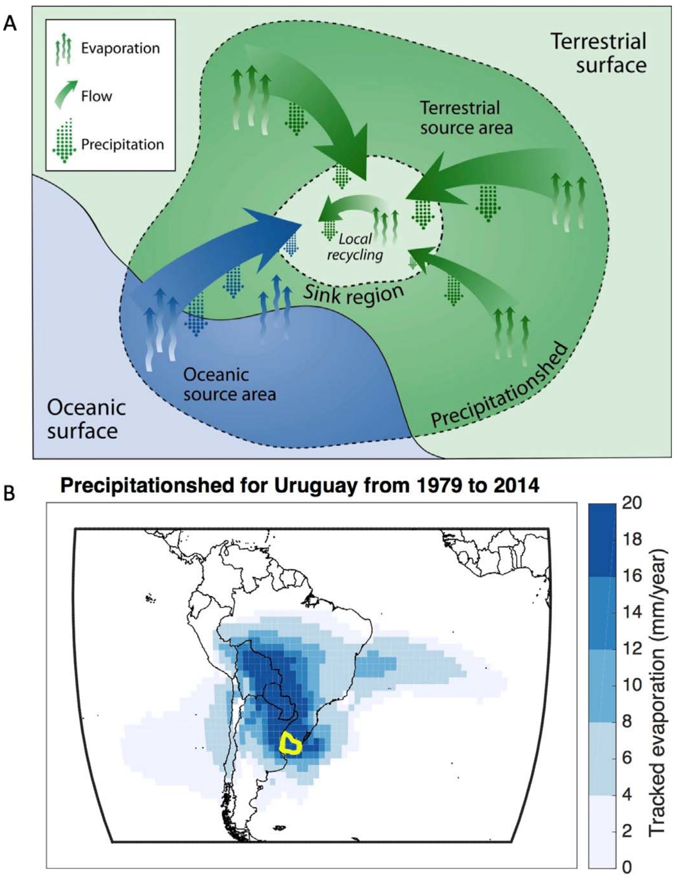

Fig. 1. The precipitationshed; Conceptual diagram of a precipitationshed (A), and the actual precipitationshed for Uruguay (B). In panel B, the yellow circle encloses Uruguay, and corresponds to the selected sink region where precipitation is falling, and the shaded area corresponds to regions that contribute evaporation to Uruguay (i.e., source region). Panel A was originally published in Keys et al. (2012) in Biogeosciences, and shared here under the Creative Commons Attribution 3.0 License. Figure will appear in color in the online version.

regions are connected through the flows of water vapor, similar to how upstream and downstream areas are connected. The precipitationshed for Uruguay is shown as an illustrative example of the spatial size and shape (Fig. 1B).

Downwind areas whose precipitation originates as upwind evaporation over land can be vulnerable to land-use changes (Keys et al., 2012). There exists a large body of research exploring land-use change impacts on terrestrial moisture recycling relationships. Evaluations of land-use change in the Amazon, the USA, China, the Sahel, and India have revealed that the consequences for moisture recycling are not uniform (e.g. Dirmeyer and Brubaker, 1999; Dominguez et al., 2006; Lo and Famiglietti, 2013; Bagley et al., 2014; Badger and Dirmeyer, 2015; Salih et al., 2013; Swann et al., 2015; Keys et al., 2016). In some monsoon regions, increases in evaporation from intense irrigation have led to changes in circulation, and decreases in downwind precipitation (Tuinenburg et al., 2014; Krakauer et al., 2016). However, in general, land-use changes that decrease evaporation (e.g. deforestation) tend to decrease precipitation downwind, while land-use changes that increase evaporation (e.g. irrigation) tend to increase precipitation downwind.

The societal implications and governance challenges of these changes are less known. In some seminal work, Dirmeyer et al. (2009) examined the ‘import’ and ‘export’ of moisture among countries, with some emphasis on the flows of moisture among countries with differing economic indicators. Other work has examined the social implications of changes to moisture recycling, including effects on downwind agricultural yields (Bagley et al., 2012) and rainfed farming hotspots (Keys et al., 2012).

Despite the fact that many studies accept that human actions can, and more importantly do, modify moisture recycling patterns, there has been little study of what this means from the perspective of transboundary water governance. The implications for *intentional* modification of moisture recycling in terms of either management or governance has been ignored (except in some highly theoretical cases; e.g. Layton and Ellison, 2016). There has been some work exploring the implications of weather modification, particularly in the arid western United States, on cloud seeding operations (Chu et al., 2014; Xue et al., 2014) and the legal implications of such practices (Brown, 2011). However, cloud seeding operates on very short time scales, such as the scale of storm systems, rather than the longer timescales at which land-use change and moisture recycling phenomena occur.

This paper aims to contribute to the understanding around transboundary governance of moisture recycling. By governance we mean the attempts for steering social and environmental processes among countries and their sometimes-conflicting objectives (Galaz, 2014). We provide a brief glossary in Table 1, to clarify key terms.

This paper will be structured around the following questions:

Table 1
Definitions of key terms used in this research.

Term	Definition
Moisture recycling	The process of evaporation arising from the surface of the Earth traveling through the atmosphere and returning elsewhere as precipitation.
Water vapor	The gas phase of water; this is what is tracked using moisture tracking models, such as the WAM-2layers.
Source region	This refers to the source of evaporation (in a moisture recycling context); refer to Fig. 1.
Sink region	This refers to the sink of precipitation (in a moisture recycling context); refer to Fig. 1. A user-selected region for which the source of precipitation is tracked and determined. When evaporation in a sink region provides moisture for rainfall within itself, a sink region may overlap with its source region.
Evaporation	This refers to all water that changes from liquid to gas phase, as it enters the atmosphere. This includes water evaporating from the surface of soils and plant leaves, as well as water that leaves vegetation as transpiration. We use evaporation synonymously with evapotranspiration.
Precipitation	This refers to all water that changes from gas to liquid, as it exits the atmosphere. This includes water precipitating as rain, snow, ice, and other forms (hail, sleet, and graupel).
Precipitationshed	An area B that is upwind of region A, that provides evaporation for A's precipitation. The extent of precipitationshed is determined by the area that contributes moisture (source region) to a selected region (sink region).
Governance	Attempts for steering social and environmental processes at the international level through institutional development, including the interplay between state and non-state actors, and their sometimes-conflicting objectives.
Complex system	A system with many parts that interact to produce system-wide behavior that cannot easily be explained in terms of interactions between the individual constituent elements.
Institutions	The rules that shape human society and interaction, including official (e.g. laws) and unofficial (e.g. norms, customs) rules.
Actor	Individuals or groups that behave as single entities in international issues.
Management	The efficient and effective deployment and allocation of an organization's resources when and where they are needed. Such resources may include financial resources, human skills, or information technology.
Norms	The shared values, ideals, and expectations for appropriate behavior held by a group.