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Analysis of Kenya's Atmospheric Moisture Sources and Sinks

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ABSTRACT: Achievement of the United Nations Sustainable Development Goals (SDGs) is contingent on understanding the potential interactions among human and natural systems. In Kenya, the goal of conserving and expanding forest cover to achieve SDG 15 "Life on Land" may be related to other SDGs because it plays a role in regulating some aspects of Kenyan precipitation. We present a 40-yr analysis of the sources of precipitation in Kenya and the fate of the evaporation that arises from within Kenya. Using MERRA-2 climate reanalysis and the Water Accounting Model 2 layers, we examine the annual and seasonal changes in moisture sources and sinks. We find that most of Kenya's precipitation originates as oceanic evaporation but that 10% of its precipitation originates as evaporation within Kenya. This internal recycling is concentrated in the mountainous and forested Kenyan highlands, with some locations recycling more than 15% of evaporation to Kenyan precipitation. We also find that 75% of Kenyan evaporation falls as precipitation elsewhere over land, including 10% in Kenya, 25% in the Democratic Republic of the Congo, and around 5% falling in Tanzania and Uganda. Further, we find a positive relationship between increasing rates of moisture recycling and fractional forest cover within Kenya. By beginning to understand both the seasonal and biophysical interactions taking place, we may begin to understand the types of leverage points that exist for integrated atmospheric water cycle management. These findings have broader implications for disentangling environmental management and conservation and have relevance for large-scale discussions about sustainable development.

KEYWORDS: Water budget/balance; Water vapor; Atmosphere–land interaction; Biosphere–atmosphere interaction; Climate services; Ecosystem effects; Regional effects; Africa; Water resources; Evapotranspiration; Precipitation

1. Introduction

a. *Global and regional drivers of moisture recycling in East Africa*

Understanding precipitation, its patterns, and the drivers of changes in these patterns is critical for advancing sustainable land and water management globally, and especially in sub-Saharan Africa (Opiyo et al. 2015; Kenya Ministry of Environment and Natural Resources 2016). In Kenya specifically, fundamental understanding of the atmospheric water cycle is essential for revealing how precipitation is connected to local and global geophysical processes (Otte et al. 2017). Insights around the origin and fate of atmospheric water are especially important in systems with substantial populations engaged in spatially extensive, rainfed livelihoods, such as Kenya's pastoral and rainfed agricultural regions (Samberg et al. 2016; Galvin et al. 2020; Keys and Falkenmark 2018). Moreover, while global analyses provide initial evidence about the importance of Kenyan evaporation for regional precipitation in central Africa (Keys et al. 2016), it is unclear whether Kenyan evaporation is indeed important for local, Kenyan precipitation.

In broad terms, global patterns of water evaporating, flowing through the atmosphere, and falling out elsewhere as precipitation, are well documented and generally understood (Koster et al. 1986). This atmospheric water cycle is also often referred to as moisture recycling, especially when describing this process over the terrestrial surface (van der Ent et al. 2010; Tuinenburg et al. 2014). While knowledge gaps persist in areas of precipitation physics and cloud microphysics, general understanding of atmospheric water has improved over the past several decades (Trenberth et al. 2011). In East Africa specifically, moisture recycling has been evaluated using isotopic analysis, regional climate models, and global moisture tracking procedures. Stable isotope analysis found that the Indian ocean is a dominant source of rainfall for much of East Africa (Levin et al. 2009). This is corroborated by findings that large- and medium-scale jet dynamics are an

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important driver of moisture transport, including the Findlater jet and the Madagascar tip jet (Schumacher et al. 2020), transporting moisture broadly from the Indian Ocean to East Africa. Tropical cyclones from the Indian Ocean were also identified as contributors of precipitation for southern Kenya specifically (Schumacher et al. 2020). Additionally, research into central African moisture recycling dynamics, including the origins of moisture for the Congo River, have demonstrated the strong relationships with east-to-west equatorial moisture transport (Sorí et al. 2017), as well as the strong contribution from African land sources (Dyer et al. 2017). Detailed analyses of atmospheric processes related to Kenya's long rainy season (and its wet and dry periods more broadly) have shown the importance of large-scale atmospheric circulation for determining rainfall variability in Kenya (Dyer and Washington 2021).

b. *Forest cover changes and the atmospheric water cycle*

Land surface–atmosphere interactions that result in terrestrial moisture recycling are well studied at global (Kleidon et al. 2000; Dirmeyer et al. 2009; Seneviratne et al. 2013) and regional scales (Swann et al. 2015; Wei et al. 2012; Halder et al. 2016). A central finding of this literature is that anthropogenic land-use decisions, such as deforestation, can have significant impacts on the timing and magnitude of evaporation and corresponding precipitation (Spracklen and Garcia-Carreras 2015), though this coupling between the land surface and the atmosphere varies globally depending on spatial scale and geographic location (Comer and Best 2012; Berg et al. 2016; Keune et al. 2018).

In terms of forest cover change, the scale of deforestation (or afforestation) can matter considerably. For example, smaller patches of deforestation can lead to small-scale vertical heating instabilities, with potential increases in local precipitation (Lawrence and Vandecar 2015). However, when deforestation occurs at larger spatial scales the consequences for downwind precipitation are decidedly negative (Spracklen et al. 2018). Conversely, recent work exploring increases to forest cover find corresponding increases in downwind precipitation. Meier et al. (2021) find that increases in European forest area can have pronounced increases on downwind rainfall, particularly during winter months. Pranindita et al. (2021) reveal that forested areas in Europe provide an important buffering effect during European heatwaves, by contributing a stable supply of moisture to the atmosphere despite circulation-driven decreases in oceanic moisture transport.

Terrestrial moisture recycling is understudied in East Africa, relative to the tropics more broadly (Spracklen et al. 2018), and especially relative to tropical locations such as the Amazon (Spracklen and Garcia-Carreras 2015; Staal et al. 2015). Thus far, existing work has revealed portions of Kenya's atmospheric water cycle, including detailed atmospheric dynamics and correlations with broader Earth system processes. We identify a complimentary need for understanding the spatially explicit sources of Kenya's precipitation and sinks of Kenyan evaporation. Such an understanding is necessary given the local and regional importance of vegetation for fostering moisture recycling (Keys et al. 2016; Staal et al. 2015, 2020). Currently, substantial land-use changes are occurring in Kenya (Pellikka et al. 2009; Ronoh et al. 2018; Kweyu et al. 2020), and in East Africa more broadly (Aleman et al. 2018; McNicol et al. 2018; Fisher et al. 2011; Kalisa et al. 2019). Thus, it is critical to provide a baseline understanding of how Kenya's forests may contribute to local hydrological and ecological resilience. That spatially extensive forest changes may be interlinked with the atmospheric water cycle underlines the need for integrated tools to disentangle these patterns.

c. *Concepts for atmospheric water management*

The precipitationshed and the evaporationshed are two concepts for analyzing the origin of precipitation falling in a location, as well as the fate of evaporation traveling elsewhere (Keys et al. 2012; van der Ent and Savenije 2013). These frameworks have been examined for interannual robustness and across multiple climate datasets (Keys et al. 2014). Likewise, these methods have been used to study human interactions with the atmospheric water cycle in a variety of contexts, including the impacts of land-use change on water flows (Wang-Erlandsson et al. 2018), vulnerability of agricultural areas in Bolivia (Weng 2020), and the role of forests in fostering agricultural resilience (Mu et al. 2021). Likewise, other work has explored management and governance dimensions specifically using the precipitationshed and the evaporationshed framework (Keys et al. 2017; Wierik et al. 2020).

d. *Sustainable development in the context of changing forests*

As countries globally aim to achieve the United Nations Sustainable Development Goals (SDGs), a set of 17 interconnected goals targeted at all aspects of sustainable economic and social development, there are specific goals that may have unexpected interactions with one another. SDG 15 "Life on Land" is aimed at terrestrial biodiversity conservation, with one of the key indicators (15.1.1) aimed at increasing "forest area as a proportion of total land area." As such, there are active efforts to halt deforestation, reforest cleared areas, and afforest hitherto unforested areas. The consequences of increasing forest cover tend to decrease surface and groundwater availability, with considerable variation across biomes, aridity, and tree species (Brown et al. 2005; Farley et al. 2005). However, another key consequence of expanding forest cover is to strengthen the land's role in determining downwind precipitation. There is evidence that forests can stabilize ecosystem processes and atmospheric water recycling, since forests provide consistent transpiration, especially through dry seasons, given they can tap into deep soil moisture (Wang-Erlandsson et al. 2016; Staal et al. 2020; Pranindita et al. 2021). This constant transpiration could provide more stable precipitation downwind, possibly improving the corresponding reliability of agricultural production (Weng et al. 2019).

Thus, as countries progress toward SDG15, they may synergistically make progress toward some other SDGs, such as climate regulation (SDG13) and reduction in hunger (SDG2). Additionally, forest conservation in the forested mountainous regions of southwestern Kenya (i.e., Kenya's water towers) may also be critical for maintaining freshwater supplies for surface runoff (SDG6) (Vogl et al. 2017; Wamucii et al. 2021). Kenya currently has between 6% and 7% of its area covered by forest, and as part of its national goals related to SDG achievement, it aspires for a national forest cover goal of 10% by 2030 (Kenya Ministry of Environment and Natural Resources 2016). To provide a scientific backstop to this development and conservation agenda, it would be valuable to understand how forests interact with the atmospheric water cycle.

e. *Outline of paper*

Here, we explore the moisture recycling dynamics in East Africa, with a focus on Kenya. We will employ both the precipitationshed and the evaporationshed to understand the spatially explicit origin and fate of Kenya's atmospheric water. We also aim to understand whether Kenyan moisture recycling has distinct differences between dry and wet years, and whether and how forest cover (including in Kenya's mountainous regions) is related to stronger or weaker moisture recycling patterns in Kenya. Such an understanding will highlight which parts of Kenya are disproportionately exposed to changes in forest cover-related moisture recycling. We discuss our findings in the context of ongoing sustainable development agendas, as well as exploring what the next steps may be for disentangling the society–land–atmosphere interactions within Kenya and beyond its borders.

2. Data and methods

a. *Moisture tracking model and data*

We employ the Modern-Era Retrospective Analysis for Research and Applications, version 2 (MERRA-2), climate reanalysis dataset (Gelaro et al. 2017), specifically variables pertaining to the atmospheric water cycle (Supplemental Table 1 in the online supplemental material). The MERRA-2 water cycle representation has been examined globally and in regional detail and reveals both improvements and continued challenges relative to both past and contemporary reanalysis data products (Bosilovich et al. 2017).

The Water Accounting Model 2 layers (WAM-2layers) is a global, Eulerian moisture tracking model that reconstructs the atmospheric water cycle—from water's evaporative origin on the planet, through the atmosphere, and to its fate elsewhere as precipitation (van der Ent et al. 2014). The WAM-2layers is a flexible model that can be used with gridded climate data of varying resolutions (Findell et al. 2019; Guo et al. 2020). Past work compared global and regional results of using the WAM-2layers with the ERA-Interim climate reanalysis (Dee et al. 2011) relative to the MERRA, version 1.0, climate reanalysis (Rienecker et al. 2011), and found strong global fidelity between the two datasets as well as strong regional similarities, with some isolated differences (Keys et al. 2014).

There are 11 MERRA-2 variables that are used as input for the updated WAM-2layers and are summarized in Supplemental Table 1. The three-dimensional data were downloaded on a model-level grid, rather than pressure level, to avoid issues related to moisture being lost in high-altitude regions during the WAM-2layers runs (van der Ent et al. 2014; Keys et al. 2014). All data are publicly accessible and were downloaded from the NASA Goddard Earth Sciences (GES) Data and Information Services Center (DISC). All data were downloaded at the 0.5° latitude × 0.625° longitude MERRA-2 spatial resolution, for the period 1980–2019. The two-dimensional variables were downloaded at the 1-h temporal resolution, and the three-dimensional variables were downloaded at the 6-h resolution. We detail key metadata for each of the data types used in the analysis in Supplemental Table 1.

The WAM-2layers was modified to accommodate the different input data. Specifically, changes were made to how the model reads in the vertical flux data (i.e., column water, evaporation, and precipitation), to the time step of some calculations (reflecting the MERRA-2 time discretization), and to the atmospheric boundary separating the upper and lower levels of the atmosphere. (A list of the specific changes to the python code can be found in the online supplemental material.) The WAM-2layers has two key steps. First, we calculated "fluxes and states" of the water balance globally. This step tracked water for every grid cell as it originated on the land surface as evaporation, its trajectory through the lower and upper layers of the atmosphere, and where the water precipitated (either in the same grid cell or elsewhere). To preserve that atmospheric water balance, the input data are discretized from either 6- or 1-hourly data, down to a 7.5-min time step. Longer time steps would risk missing water passing quickly through small grid cells, since the horizontal distance between degrees of longitude becomes smaller in moving poleward from the equator. Shorter time steps allow the WAM-2layers to account for water moving through smaller grid cells (van der Ent et al. 2010).

In the second step, we used the fluxes and states information to either 1) track the evaporation of a specific location forward to its fate as precipitation (i.e., stepping forward in time), or 2) track the precipitation of a specific location backward to its origin as evaporation (i.e., stepping backward in time). Thus, the WAM-2layers was first run for 40 years at the global scale, to calculate the fluxes and states for all locations. Second, the WAM-2layers was used to track a country-specific run for Kenya, tracking moisture both forward and backward in time.

We note that, although higher-resolution datasets are available, computational limitations (both in data storage and length of time for analysis) made these data optimal for the present set of research questions, especially given the interest in regional-scale patterns and processes at scales of months or longer (Keys et al. 2014; Findell et al. 2019; Guo et al. 2020).

b. *Calculation of moisture recycling ratios*

Previous work introduced the idea of terrestrial moisture recycling ratios (e.g., van der Ent et al. 2010). Evaporation recycling ratios are defined as the fraction of precipitation arising from a specific location's evaporation, ϵ_c. In general, terrestrial evaporation recycling ratios are defined as

$$\epsilon_c = \frac{E_c}{E_c + E_o},$$

where E_c is the evaporation arising from terrestrial (i.e., land) sources, E_o is the evaporation arising from oceanic sources, and ϵ_c is the ratio of terrestrial to oceanic sources. Precipitation recycling ratios are defined as the fraction of evaporation that falls as precipitation on a specific location, or ρ_c. In general, terrestrial precipitation recycling ratios are defined as

$$\rho_c = \frac{P_c}{P_c + P_o},$$

where P_c is the evaporation arising from terrestrial (i.e., land) sources, P_o is the evaporation arising from oceanic sources, and ρ_c is the ratio of terrestrial to oceanic sources. We note specifically in this paper when the definition of moisture recycling ratios departs from these definitions.

c. Forest cover data

To examine the correspondence between Kenyan forest cover and terrestrial moisture recycling ratios (for both precipitation and evaporation), we needed a gridded dataset of fractional forest cover. We used the Global 1-km Consensus Land Cover dataset (Tuanmu and Jetz 2014), which integrates multiple global remote sensing-derived land-cover products, in 12 land classes. For our purposes, we specifically calculated the fractional extent of four forest types (evergreen/deciduous needle leaf trees, evergreen broadleaf trees, deciduous broadleaf trees, and mixed/other trees) at a 1 km resolution. We then created a single raster layer representing overall forest cover within each pixel (sum of the fractional extents of all four forest cover types), and upscaled the resulting raster to a $0.5° \times 0.625°$ grid using bilinear interpolation.

We compared the fractional tree cover from the Consensus Land Cover with the corresponding precipitation and evaporation moisture recycling ratios. We did this both in terms of 1) the fraction of local precipitation from land evaporation, and 2) the fraction of local evaporation that later falls on land as precipitation. We used Spearman's rank correlation coefficient, which is suitable for comparing monotonic relationships (e.g., when one variable increases, we want to identify whether the other variable also increases, and vice versa).

We note that we did not use the MERRA-2 land-cover map, in part because it is based on a land-cover product developed in the early 1990s (Reichle et al. 2017), and we wanted to use a forest product that fell more clearly in the midst of our analysis period. Later in the paper, we discuss the advantages and disadvantages of this approach, and point to potential advancements that can be made in future work.

d. Detecting the difference between dry-, neutral-, and wet-year moisture recycling

We aimed to examine the difference between dry, neutral, and wet year moisture recycling for Kenya, to understand whether Kenya is more or less dependent on terrestrial sources of moisture in years with different moisture regimes. To do this, we employed the same methods as described in Keys et al. (2018). We first calculated the total annual rainfall in Kenya for the 40 years of analysis. Second, we split this time series into dry, neutral, and wet years by finding the mean annual precipitation for Kenya, and subtracting this from the annual values,

$$P_A = P_Y - \overline{P},$$

where P_Y is the precipitation for current year, $\overline{P}$ is the mean precipitation for all years, and P_A is the anomalous precipitation for that year. We then split this time series of anomalies into thirds, with the bottom third representing "dry years," the middle third representing "neutral years," and the top third representing "wet years." Using the dry and wet years, we identified the mean evaporation recycling ratio at the monthly time scale. Last, we performed a two-sided Student's t test, to determine whether the terrestrial moisture recycling ratios in the dry years were different from the wet years, using the 90% confidence interval.

We also calculated the difference in evaporation contribution during dry and wet years and weighted each grid cell by its importance to Kenya's precipitation. For every location in the precipitationshed (and for the dry, neutral, and wet years), we divided the evaporation contribution by total precipitation falling in Kenya. Formally,

$$E'_i = E_i / P_{\text{sink}},$$

where E_i is the annual average evaporation contributed to Kenyan precipitation at location i, P_{sink} is the annual average precipitation falling in Kenya, and E'_i is the weighted evaporation contribution from location i. In this way, the evaporation was weighted by its importance to Kenya's precipitation. We then found the fractional difference between dry year and wet year evaporation contribution throughout Kenya's precipitationshed by calculating

$$E'_{\text{diff}} = \frac{(E'_{i,\text{wet}} - E'_{i,\text{dry}})}{E'_{i,\text{wet}}}.$$

e. Comparison of MERRA-2 results with ERA-Interim results

ERA-Interim is the climate reanalysis dataset used in the original WAM-2layers (van der Ent et al. 2013; van der Ent 2016). Thus, we complement the MERRA-2-based moisture recycling analysis with a comparison of a country-based analysis of moisture recycling, which employed the ERA-Interim reanalysis and the WAM-2layers (Link et al. 2020). We note that we do not expect the moisture recycling results to be identical, since the underlying model physics and parameterizations that produced the MERRA-2 and ERA-Interim are distinct (Table 1).

f. Seasonal definition for Kenya

Aligning our definitions to existing literature about subannual seasonal changes between hot, cool, dry, and wet conditions, we

TABLE 1. Evaluation of Kenya-moisture recycling results between this study and the Link et al. (2020) ERA-Interim-based analysis. The Link et al. results were reported for the 2001–18 time period, and so the MERRA-2 results were computed for the same time frame.

Moisture recycling ratio	MERRA-2 (this study)	ERA-Interim (Link et al. 2020)
Fraction of Kenya's precipitation from all land sources	16.0%	22.9%
Fraction of Kenya's precipitation from Kenyan sources.	7.7%	9.2%

use a Kenya-specific terminology to refer to these seasons. We describe Kenya's moisture sources during their four seasons (Table 2), based on Galvin et al. (2001).

3. Results

a. *Origin of Kenya's precipitation*

We use the concept of the precipitationshed to represent the upwind locations that contribute evaporation to Kenya's precipitation. The ocean is an important source of moisture for Kenya, with 85% of average annual precipitation originating from oceanic evaporation (Fig. 1). However, 15% of average annual precipitation originates as terrestrial evaporation within Kenya, primarily from the Kenyan highlands. During all seasons, the Kenyan highlands remain a key source of moisture for Kenyan precipitation (Fig. 2). At the beginning of the calendar year, during the hot dry season [December–February (DJF)], oceanic moisture sources tend to come from the northeast, including the Somali coastline and the Arabian Sea. During the long rainy season [March–May (MAM)], moisture sources are closer to the Kenyan coastline in the Indian Ocean. During the cool dry season [June–September (JJAS)], moisture originates from the southeast, including from the northern coast of Madagascar, and the coastline of Tanzania. Finally, in the short rainy season [October–November (ON)], dominant moisture sources are the coastline of Kenya, the western Indian Ocean, and the coastal waters of Somalia.

b. *Fate of Kenya's evaporation*

We use the concept of the evaporationshed to represent the downwind locations that receive precipitation from Kenya's evaporation. Evaporation arising in Kenya travels in a westerly direction, crossing much of central Africa (Fig. 3). We find that over 70% of Kenyan evaporation falls as precipitation over land, including ~10% in Kenya, ~25% in the Democratic Republic of the Congo, ~5% falling in each of Tanzania and Uganda, and ~2%–3% in each of the Republic of Congo, Gabon, and South Sudan. Some locations receive more than 10% of local precipitation from Kenyan evaporation, including the Kenyan highlands and eastern Uganda. As with the sources of precipitation, the Kenyan highlands receive a significant fraction of precipitation from recycled Kenyan

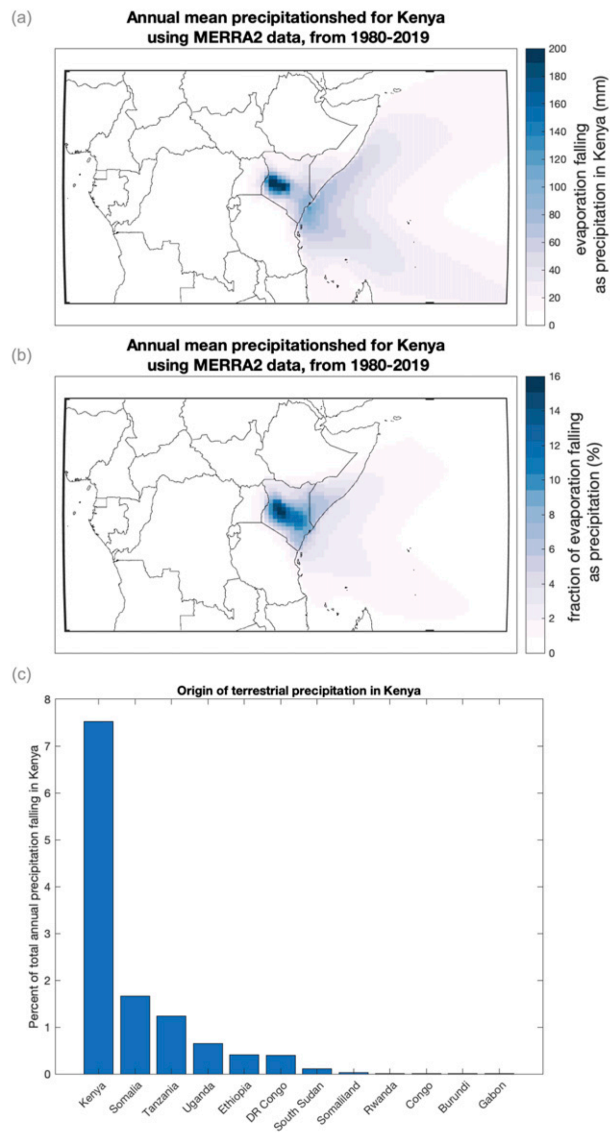

FIG. 1. The origin of Kenya's terrestrial precipitation: (a) the amount of source evaporation arising from a given grid cell that later contributes to Kenyan precipitation, (b) the fraction of local evaporation from a given grid cell that later contributes to Kenyan precipitation, and (c) the evaporative sources of Kenyan precipitation, arising from Kenya and neighboring countries.

TABLE 2. Regionally relevant names of subannual seasons in Kenya.

Calendar months	Seasonal name
DJF	Hot dry
MAM	Long rainy
JJAS	Cool dry
ON	Short rainy

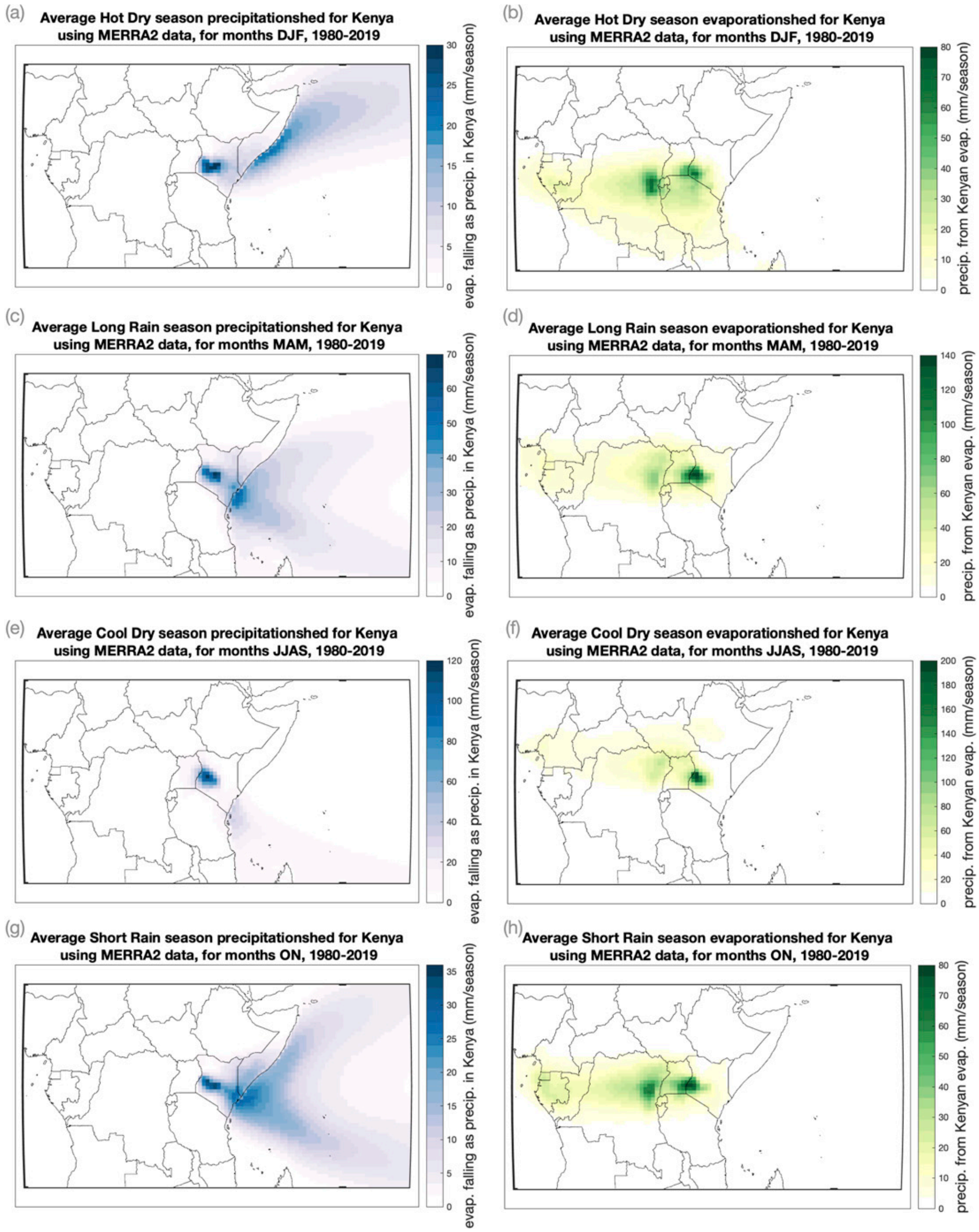

FIG. 2. Seasonal moisture recycling for Kenya's (a),(b) hot dry, (c),(d) long rain, (e),(f) cool dry, and (g),(h) short rain seasons (see Table 2 for seasonal definition).

evaporation during all seasons of the year (Fig. 2). During the hot dry season, the central western region of Kenya and the Lake Kivu region both receive a large fraction of Kenyan evaporation. During both the long rainy and the cool dry season, the border between Kenya and Uganda receives the largest fractions of Kenyan evaporation. Then, during the short rainy season, the key recipients of Kenyan evaporation shift to eastern Uganda and west of Lake Edward.

c. Dry- versus wet-year dynamics of Kenyan moisture recycling

On the basis of the 40-yr analysis of Kenyan moisture recycling (including all global sources of Kenyan precipitation, and all global sinks of Kenyan evaporation), we examined the seasonal cycle of moisture recycling in Kenya, among dry, normal, and wet years (Fig. 4). During wet years, terrestrial moisture recycling is increased significantly (with the dots in

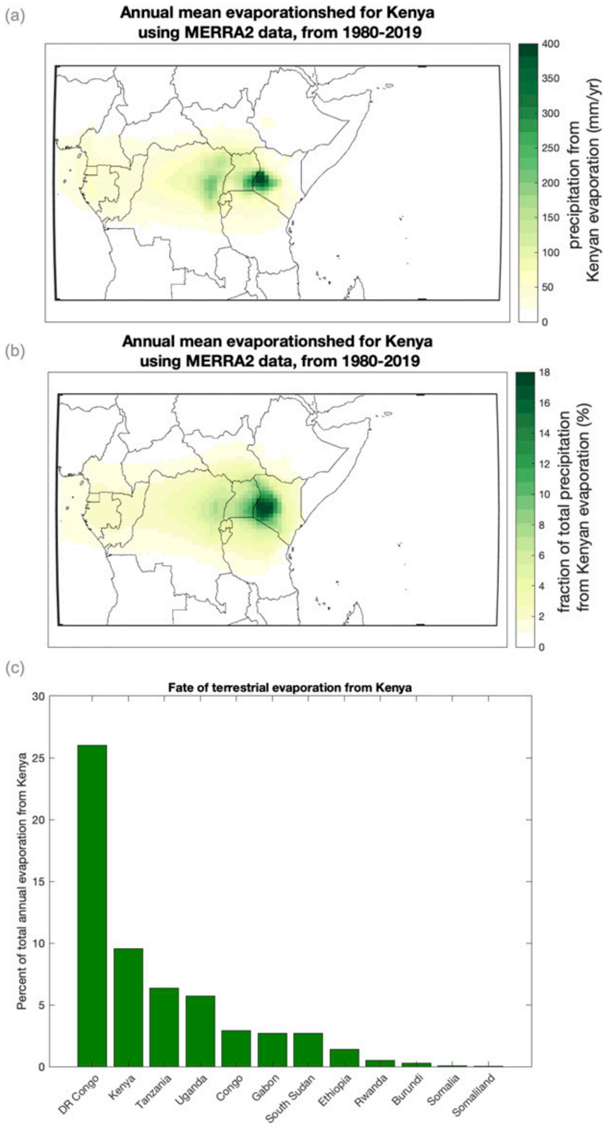

FIG. 3. The fate of Kenya's evaporation, represented as (a) the amount of precipitation that is received in a given grid cell from upwind Kenyan evaporation, (b) the fraction of local precipitation in a given grid cell that is received from upwind Kenyan evaporation, and (c) as the fraction of precipitation falling among countries originating as Kenyan evaporation.

Fig. 4 indicating those months that are significantly different from their dry year values). Specifically, precipitation arising from land evaporation is significantly higher in wet years than dry years, during the long rainy (MAM) and cool dry (JJAS) periods.

We can visualize the relative importance of a given source of moisture during dry and wet years (see methods section 2d). The map of percent difference in weighted contribution to Kenya's precipitation reveals the areas that are relatively more important during wet years (the blue areas in Fig. 5), versus the areas that are relatively more important during dry years (the red areas in Fig. 5). During wet years,

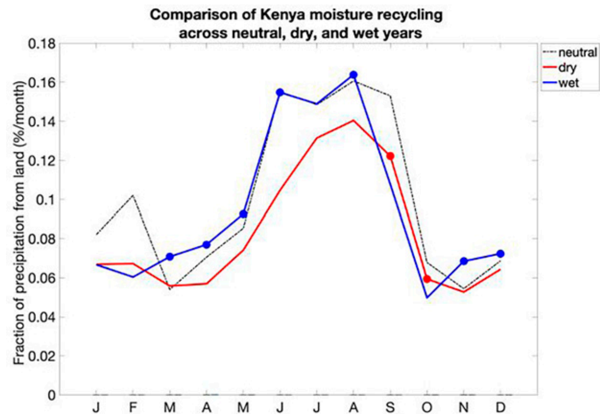

FIG. 4. Seasonal cycle of terrestrial moisture recycling in Kenya corresponding to wet, neutral, and dry conditions as defined by total annual precipitation (see section 2).

evaporation from the terrestrial surface of most of Kenya is relatively more important, as is the Indian Ocean farther from the African coastline. Conversely, during dry years, evaporation from the coastal waters of East Africa, as well as the Arabian Sea become relatively more important for Kenyan precipitation.

d. Forests as important sources and sinks of Kenyan moisture recycling

For both source and sink relationships, a positive though weak relationship exists between trees and moisture recycling (Fig. 6; Table 3). This suggests that Kenya's forests may serve a functional role for the atmospheric water cycle, particularly for evaporation that will later fall on land elsewhere. This positive relationship is not simply a signal of trees being located in places that receive rain (indeed, trees generally must receive a minimum amount of rainfall; Sankaran et al. 2005), but rather that tree-covered areas in Kenya both receive relatively more precipitation from upwind land and send relatively more precipitation to other land areas. We emphasize that the fraction of moisture being recycled is not solely related to the underlying vegetation, but a combination of many factors, including position of the terrestrial location relative to prevailing winds, the distance of the location from the ocean, the presence of topography that might affect broadscale circulation patterns, and adjacent terrestrial vegetation.

4. Discussion

a. Kenya and forest-based moisture recycling

The regional patterns of moisture sources that we identify in this research are corroborated by others. In an analysis of the Kilimanjaro region that borders Kenya and Tanzania, Otte et al. (2017) found that at the beginning of the calendar year, moisture sources showed a tendency to arise from the northeast of Kenya, traveling south during the calendar year, mirroring the results described herein. Research examining the sources of precipitation in the Congo River basin

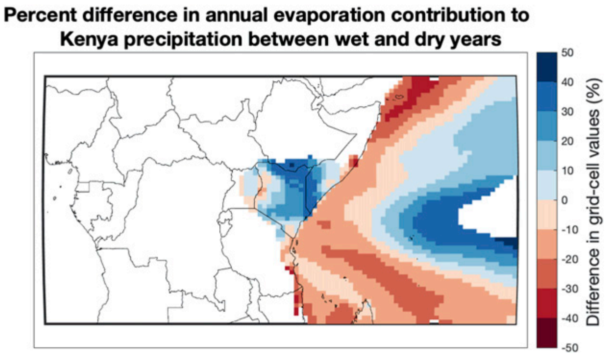

FIG. 5. The difference between the driest and wettest years of evaporation contribution to Kenyan precipitation.

corroborate our findings that Kenyan evaporation contributes moisture to the Congo region, and central Africa more broadly. Soría et al. (2017) found that East Africa and the Indian Oceans play major roles in contributing moisture to the Congo. Findings are demonstrated in Dyer et al. (2017) showing similar seasonal patterns, emphasizing the seasonal oscillation for major moisture sources from north to south.

b. *Water towers in East Africa*

Existing work has shown the importance of East Africa's mountains as sources of water for cities, agriculture, and biodiversity (Wolanski and Gereta 2001). For example, the Mau River provides drinking water to wildlife, livestock, and people first in the forests, then in rangelands, and finally flowing to Lake Victoria (Dybas 2011). The Upper Tana River basin covers Mount Kenya and the Aberdare highlands (Apse et al. 2015). It is a critical area for water supply to the city of Nairobi, supports an important agricultural area, and supplies one-half of the country's hydropower output (Vogl et al. 2017).

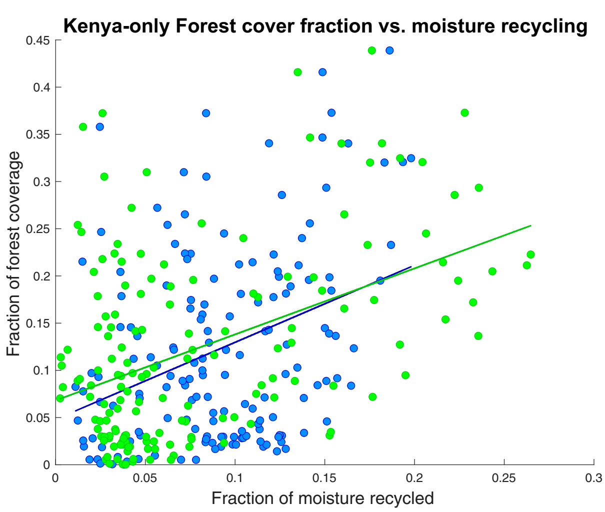

FIG. 6. The relationship between moisture recycling ratios for a given location in Kenya and the corresponding fraction of that location covered by forests (including evergreen trees, deciduous trees, and mixed forests). Blue is the ratio for "precipitation from land," green is the ratio for "evaporation to land," and linear-fit trends lines are included.

TABLE 3. Spearman rank correlation coefficient (i.e., Spearman's rho) between the fractional forest cover in Kenya and the corresponding moisture recycling data.

Correlation of fractional forest cover with . . .	Spearman's rho
Precipitation that came from land upwind	0.29
Evaporation that will later fall on land	0.31

Given that this surface water ultimately originates as precipitation in these water towers, we emphasize the importance of understanding the interconnections between forest cover and moisture recycling. We show a general pattern of forests being positively correlated with higher moisture recycling ratios. Likewise, the significantly greater importance of terrestrial moisture recycling during wet years (as compared with neutral or dry years), suggests that during the times when the most water is falling and potentially stored in these high-elevation areas, forests are critical.

c. *Transboundary reality of SDG achievement*

While arid and semiarid northern counties within Kenya seem to gain little from Kenyan sources of moisture, a substantial portion of Kenyan evaporation later falls as precipitation in southern Kenya. This is especially true during the hot dry season. Thus, the positive effects of reforestation and afforestation may correspond in an indirect way to knock-on benefits for SDGs that are related to a stable atmospheric water cycle, including hunger and poverty goals (SDG1 and SDG2), as well as freshwater and climate regulation (SDG6 and SDG13). Moreover, this work highlights both the seasonally varying and transboundary role that Kenyan moisture recycling plays. In the context of the SDGs, as well as other global biodiversity goals, the fact that moisture recycling crosses administrative borders underscores the need to achieve the SDGs not just at country-specific levels, but at regional scales as well. For example, we show that parts of eastern Uganda receive more than 10% of annual average precipitation from Kenyan evaporation. This geophysical connection could contribute to stronger social, political, and economic connections that could foster cross-border collaboration on SDG progress (Keys et al. 2017; Keys and Wang-Erlandsson 2018).

d. *Limitations*

While the findings of this work are robust and correspond well with other studies examining the atmospheric water cycle in East Africa, we acknowledge some of the limitations. First, MERRA-2 is known to have a bias in the amount of precipitation that falls in certain high-altitude regions (such as the Andes mountains) as well as some tropical areas (Bosilovich et al. 2017). Likewise, it may have comparatively higher evaporation rates in the oceans, slightly skewing the results to overemphasize nonterrestrial moisture recycling (and correspondingly, underemphasize terrestrial moisture recycling). Given this, we have included comparisons with a high-resolution version of the ERA-Interim dataset and show broadly comparable results. Furthermore, other analyses that employ high-resolution ERA-Interim data, albeit approaching the question from a much more focused, atmospheric-dynamics perspective, highlight broadly similar findings to ours (Dyer and Washington 2021). While beyond the scope of this work, other reanalysis products, such as ERA5, could be used to assess these (and earlier) findings. In addition, it will be critical to understand how moisture recycling may change with climate change, especially in the tropics. While some work has examined moisture recycling changes under climate change (Findell et al. 2019), it remains underexplored, especially interdisciplinary analyses focused on social, ecological, and geophysical interactions.

We also note the uncertainties introduced by comparing forest cover from a static data product and moisture recycling ratios across a wider range of time. While it makes sense to summarize long-term moisture recycling patterns in terms of interannual averages (to reveal the long-term patterns of moisture flow, rather than overemphasizing interannual variability), the underlying land cover and the average moisture recycling behavior do not perfectly correspond to one another.

e. *Future work*

Although this work provides important, long-term context for understanding Kenya's moisture recycling patterns, seasonal variation, and the potential relationship of moisture recycling with forest cover, there are several important next steps. First, substantial advances could be made in simulating the dynamic interaction of land cover with moisture recycling, by exploring land-use change questions with a dynamic Earth system model. Such an approach would permit a broader view of interactions arising from land-cover change, expanding beyond changes in evaporation and transpiration to include changes in sensible and latent heat partitioning, as well as changes in boundary layer dynamics (Findell et al. 2019). Second, if such a model incorporated a water tagging feature that allowed for moisture tracking within the model, dynamic questions of forest cover change could be explored specifically in the context of moisture recycling (Dyer et al. 2017).

In addition to simulation of key dynamic land–atmosphere processes, Earth system modeling would also provide the ability to unpack what aspects of deforestation were the primary drivers of changes in land–atmosphere interactions. For example, simulations of control, deforestation and afforestation scenarios would allow for the cataloging of changes in albedo, soil moisture depth, surface roughness, and sensible versus latent heat flux partitioning. Improving the fundamental understanding of key drivers and interactions could provide better insight into the physical relationship of tree cover with regional-scale moisture recycling, as well as provide interdisciplinary insight for water and land resource managers.

While there are straightforward reasons why forests would be disproportionate sources of evaporation for downwind precipitation, it is somewhat less clear why precipitation in Kenyan forests might disproportionately arise from upwind land. Future work should investigate the detailed characteristics of the moisture sources of Kenyan forests, to determine the underlying mechanisms that give rise to this relationship. This mechanistic understanding could shed light on how the relationship is modulated, whether geophysically (e.g., via topography or prevailing winds), ecologically (e.g., via ecosystem phenology), or anthropogenically (e.g., via land-use change).

Given both the higher moisture recycling ratios present in areas with greater fractional forest cover and the fact that 10% of Kenya's evaporation returns as precipitation within Kenya, it is worth considering what may happen if forest cover changes in the future. It is well understood that forested areas in Kenya are critical reserves for biodiversity as well as providing numerous ecosystem services (Kogo et al. 2019). Despite this, the pressing need for expanded economic prosperity in Kenya often relies on agricultural expansion into areas that might otherwise be forested.

In the context of such development, it is critical to examine the tradeoffs or synergies that may emerge from pursuing different paths of forest cover change. These must be assessed in terms of more than the direct economic benefits flowing from agricultural expansion alone. Additionally, the indirect cobenefits ought to also be considered—such as desirable changes in moisture recycling. Conversely, trade-offs might emerge from changes in forest cover, such as increased sedentarization of pastoral populations who can no longer access restricted forests. Some analyses have been completed in the past that answer parts of these questions (Galvin et al. 2001; Sircely et al. 2019), though a coupled analysis has yet to be done that also considers both changes in forest cover and the corresponding changes in moisture flow.

5. Conclusions

We find that the forested Kenyan highlands provide considerable terrestrial moisture recycling, evaporating water that will fall within Kenya's borders. This is in addition to the fact that they are essential sources of surface water regulation and biodiversity preservation. More generally, we show that Kenyan evaporation is recycled internally to provide 10% of Kenyan precipitation. While most of Kenya's precipitation arises from the adjacent Indian Ocean (~85%), more than 70% of Kenya's evaporation will later fall on land. Wet years are associated with significantly higher terrestrial moisture recycling, especially during the long rainy and cool dry seasons. The combination of forests as important conduits of moisture recycling and wet years being disproportionately reliant on terrestrial sources of moisture, suggests that more work needs to be done to disentangle this relationship. Moreover, this understanding is especially critical in the context of rapidly changing land cover as the Kenyan government strives to deliver a sustainable and prosperous future for the Kenyan population.

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Data availability statement. All data for the MERRA-2 reanalysis were downloaded from the National Aeronautics and Space Administration Goddard Earth Sciences (GES) Data and Information Services Center (DISC). (https://disc.gsfc.nasa.gov/). The WAM-2layers was originally downloaded from the GitHub repository (https://github.com/ruudvdent/WAM2layersPython). A beta release of the WAM-2layers updated to accommodate MERRA-2 data and tailored for the Kenya-specific analysis, can be downloaded from this GitHub repository (https://github.com/pkeys/WAM2layersPythonMerra2). The Global 1-km Consensus Land Cover dataset is available for download at EarthEnv (https://www.earthenv.org/). The moisture recycling data for this analysis, specifically the 40-yr data for the sources of Kenyan precipitation and the sinks of Kenyan evaporation, are saved in the permanent data repository Mountain Scholar (https://hdl.handle.net/10217/235433).

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