Evaluation of Oceanic and Terrestrial Sources of Moisture for the North American Monsoon Using Numerical Models and Precipitation Stable Isotopes

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ABSTRACT

This work evaluates the oceanic and terrestrial moisture sources that contribute to North American monsoon (NAM) precipitation over a 30-yr period using the modified analytical dynamic recycling model. This computationally efficient modeling framework reveals previously overlooked moisture source regions such as Central America and the Caribbean Sea in addition to the well-known Gulf of California and Gulf of Mexico source regions. The results show that terrestrial evapotranspiration is as important as oceanic evaporation for NAM precipitation, and terrestrial sources contribute to approximately 40% of monsoonal moisture. There is a northward progression of terrestrial moisture sources, beginning with Central America during the early season and transitioning north into northern Mexico and the NAM region itself during the peak of the monsoon season. The most intense precipitation occurs toward the end of the season and tends to originate in the Gulf of California and the tropical Pacific, associated with tropical cyclones and gulf surges. Heavy stable isotopes of hydrogen and oxygen in precipitation ($\delta D$ and $\delta^{18}O$) collected for every precipitation event measured in Tucson, Arizona, for the period 1981–2008 complement the numerical results. The analysis shows that precipitation events linked to sources from the Gulf of Mexico and Caribbean Sea are more isotopically enriched than sources from the Gulf of California and tropical Pacific. It is also seen that terrestrial regions that derive their precipitation from the Gulf of Mexico are also more isotopically enriched than moisture sources from the Pacific.

1. Introduction

The North American monsoon (NAM) accounts for approximately 70% of the total annual precipitation in northwestern Mexico and 40%–50% of annual precipitation in the southwestern United States (Douglas et al. 1993). The onset of the NAM in early June is characterized by a westery-to-easterly shift in the midtropospheric winds over northern Mexico and heavy rainfall over western Mexico (Douglas et al. 1993; Stensrud et al. 1995; Adams and Comrie 1997; Higgins et al. 1997). As the season progresses, the region of heavy rainfall spreads northward along the western slopes of the Sierra Madre Occidental (SMO) into Arizona and New Mexico (Fig. 1).

The Gulf of Mexico (GOM) is an important moisture source for the NAM, as the positioning of the monsoon ridge and westward extension of the North Atlantic subtropical high help drive water vapor from the Gulf of Mexico and the Caribbean into the NAM region (Douglas et al. 1993; Schmitz and Mullen 1996; Adams and Comrie 1997; Higgins et al. 1997; Bosilovich et al. 2003). However, the elevated topography of the SMO acts as a barrier for lower-level moisture that comes from the Gulf of Mexico and blocks it from entering the NAM region. Consequently, the Gulf of California (GOC) and eastern tropical Pacific Ocean are also important sources for NAM precipitation (Hales 1972; Brenner 1974; Carleton 1986). One of the main mechanisms responsible for strong advection of moist tropical Pacific air channeled up the Gulf of California are “gulf surges,” characterized by strong south-southeast winds, a drop in temperature, and an increase in humidity over southern Arizona (Stensrud et al. 1997; Fuller and Stensrud 2000; Higgins et al. 2004; Douglas et al. 1993; Higgins et al. 1997). Tropical cyclones (TCs) originating in the eastern tropical Pacific can also contribute to NAM precipitation during the monsoon season (Douglas et al. 1993; Higgins et al. 1997). Furthermore, recent research has found that a large amount of gulf surge events are related to TCs,
indicating a role of TCs in surge initiation (Fuller and Stensrud 2000; Anderson et al. 2000; Douglas and Leal 2003; Higgins and Shi 2005). Thus, in general, the sources for NAM precipitation include a major source provided by the Gulf of California and eastern tropical Pacific at lower levels (below 850 mb) and a source provided by the Gulf of Mexico and the Caribbean Sea at upper levels (Carleton 1986; Carleton et al. 1990; Schmitz and Mullen 1996; Adams and Comrie 1997).

While oceanic sources are clearly important for monsoon rainfall, significantly less attention has been paid to terrestrial sources. Dominguez et al. (2008) argued that precipitation after monsoon onset dramatically increases the soil moisture content, and this moisture is later evaporated and can then significantly contribute to convective precipitation. A similar positive feedback between surface wetness and monsoon precipitation was identified by Small (2001) in a mesoscale modeling experiment. In an effort to explicitly quantify the moisture sources for the NAM, Bosilovich et al. (2003) performed a numerical simulation of the NAM water sources using three-dimensional tracers incorporated within a general circulation model. Surprisingly, they found that the continental sources provide much of the water for precipitation and suggested that precipitation recycling was an important factor contributing to monsoon intensity. However, this study was limited by uncertainties related to the global-scale modeling, including that the GCM used by Bosilovich et al. (2003) was unable to resolve the Gulf of California, which could significantly affect the source delineation.

In this study, we use the dynamical recycling model (DRM) to delineate and quantify the moisture sources of NAM precipitation. The DRM is a two-dimensional semi-Lagrangian analytical model (Dominguez et al. 2006; Dominguez and Kumar 2008) that has recently been modified to quantify moisture sources from different regions (Martinez and Dominguez 2014). Similar to more sophisticated three-dimensional Lagrangian methods, such as the Lagrangian Flexible Particle Dispersion Model (FLEXPART; Stohl and James 2004, 2005; Gimeno et al. 2010; Nieto et al. 2014) and the quasi-isentropic back-trajectory (QIBT) method (Dirmeyer and Brubaker 1999, 2007; Brubaker et al. 2001), the DRM can be used “offline” with different sources of atmospheric data, such as the North American Regional Reanalysis (NARR) used in this study [see Gimeno et al. (2012) for a review of the different methods to quantify moisture sources]. The DRM is computationally more efficient than FLEXPART and QIBT and has been shown to provide similar quantifications of moisture sources over the South American continent as the QIBT method (Martinez and Dominguez 2014). However, as with any two-dimensional analytical model, there is an assumption of a well-mixed atmosphere, which could cause incorrect estimates in regions where there is strong vertical wind shear or incomplete mixing (Goessling and Reick 2012). Some simple corrections have been incorporated into numerical two-dimensional models to alleviate this shortcoming (van der Ent et al. 2013). However, there is currently no analytical solution to the DRM that incorporates incomplete mixing, so the results from our analytical model must be interpreted as first-order estimates of moisture sources and are meant to guide further efforts that incorporate the full three-dimensional physics.
One of the main limitations of many numerically based moisture source studies of NAM precipitation is the lack of observational validation of the results. The heavy stable isotopes of hydrogen and oxygen in precipitation [δD (deuterium) and δ18O] are ideal observational tracers for sources of moisture because the isotopic composition depends in part on the temperature and humidity characteristics of the source region where the moisture originated, as well as on the changes of phase that the water within the air mass experiences as it moves over the continent and rains out (Gat and Carmi 1970). Within the United States, Welker (2000) shows that the average δ18O values of precipitation originating from the Pacific Northwest are depleted in heavy isotopes (i.e., more negative) as compared to precipitation originating from the Gulf of Mexico. In the southwestern United States, measurements of δD in water vapor during one premonsoon period show that most of the isotopic variability can be associated with changes in the advection of atmospheric moisture from different source regions (Strong et al. 2007). In their study, Strong et al. (2007) show that periods of high δD are linked to precipitation originating from the Gulf of Mexico, while low δD values originate from the Pacific. Similarly, in an analysis of isotopic composition of monsoon precipitation in Tucson, Arizona, Wright et al. (2001) show that isotopically depleted years are cooler and are associated with atmospheric circulation patterns that entrain more tropical moisture from the Pacific, while warmer, isotopically enriched years entrain less Pacific tropical moisture. It is important to note that the isotopic composition of water vapor originating through evapotranspiration (ET) from terrestrial regions reflects the characteristics of the precipitation that falls over land and is subsequently evaporated and transpired. These are a complex mixture of fractionating and nonfractionating processes (Yakir and Sternberg 2000). In this work, we use observations of isotopic composition of precipitation events measured over a 28-yr period in Tucson, Arizona, to complement the modified DRM model.

There are three main questions that we address in this study. 1) What are the main sources of moisture for NAM precipitation and their seasonal cycle? 2) What are the dominant modes of variability in source regions and associated synoptic patterns? 3) Can we use isotope information to provide information about source regions and complement the numerical results?

2. Data and methods
a. Model description

There are three primary methods used to quantify source–sink regions of atmospheric moisture: analytical or box models, numerical water vapor tracers, and physical water vapor tracers (Gimeno et al. 2012). The DRM is a two-dimensional analytical model initially designed for the study of local precipitation recycling (Dominguez et al. 2006). Much like other analytical models, which are mathematically derived from the equation of conservation of atmospheric moisture, this model assumes that the atmosphere is vertically well mixed. However, a significant difference is that the DRM takes the temporal change of moisture storage into account, while other similar models assume it to be negligible (Budyko 1974; Brubaker et al. 1993; Eltahir and Bras 1994) and hence are only valid at monthly or longer time scales. By applying a semi-Lagrangian scheme, the recycling ratio computed by the DRM can be expressed as

\[
R(x, \xi, \tau) = 1 - \exp \left[ - \int_0^{\tau} \frac{\varepsilon(x, \xi, t)}{\omega(x, \xi, t)} \, dt \right],
\]

where \( R \) is the recycling ratio; \( \varepsilon \) is the ET; and \( \omega \) is the precipitable water in the semi-Lagrangian coordinate system \( (x, \xi, \tau) \), representing \( x, y, \) and \( t \) dimensions. A more detailed derivation of this equation can be found in Dominguez et al. (2006). The DRM is not limited to the study of local recycling, as it can also be used to quantify the relative contributions from different sources to the atmospheric moisture over a given sink region (Martinez and Dominguez 2014). In the modified DRM the “recycling ratio” over a large domain can be decomposed into moisture contributions from several subregions (Martinez and Dominguez 2014). The modified DRM was successfully used in an application over South America (Martinez and Dominguez 2014). In the current paper, the sink is the NAM region, while the potential source regions encompass North America and the eastern Pacific and western Atlantic basins (Fig. 1). The core NAM region is defined based on both the North American Monsoon Experiment (NAME) Science and Implementation Plan and NAME precipitation zones, as defined by Castro et al. (2012). The NAM region (Fig. 1) includes southern Arizona in the United States and Sonora and Sinaloa in Mexico.

Throughout the manuscript we use the term “ratio contribution,” which refers to the averaged ratio of precipitation contributed by each source to the total precipitation over the NAM region. As the ratios are computed based on values for each grid cell, they are weighted by the precipitation rate of each grid and averaged over the NAM region. We also use the term “amount contribution,” which is the product of the ratio
contribution and area-averaged precipitation over the NAM region. The combination of the ratio and amount contribution provides a comprehensive picture of the moisture that originates from different sources in terms of precipitation intensity.

b. Input data

We use 30 years of NARR data (1979–2008) to drive the DRM (Mesinger et al. 2006). We limit our analysis to the summer monsoon period (from 16 June to 28 September) and do not use data after 2009 because several variables over Mexico had spatial inconsistencies, partly due to changes in the assimilation procedure (W. Ebisuzaki 2014, personal communication). Daily averaged precipitable water, zonal and meridional winds, daily accumulated precipitation, and ET are used as input to the DRM. The 3-hourly vertically integrated moisture fluxes are divided by 3-hourly precipitable water to give the zonal and meridional wind vertically weighted by the specific humidity at each level, to provide the back trajectories. In contrast to the other variables, the estimates of ET are subject to error because of a lack of observations (Nigam and Ruiz-Barradas 2006), and this makes ET the most uncertain variable in our moisture source analysis (Dominguez and Kumar 2008). Furthermore, even though precipitation is assimilated in the NARR, the quality of observations dramatically decreases south of the U.S.–Mexico border, so there are quality concerns about the NARR-derived ET. We compared NARR precipitation with that of the University of Delaware precipitation product (Legates and Willmott 1990) and found that the spatial distribution is similarly represented, but NARR tends to slightly underestimate precipitation, particularly in the states of Hidalgo, Michoacán, Guerrero, and Chiapas in Mexico (not shown). NARR ET follows the spatial distribution of NARR precipitation but is smaller in magnitude during July and August. This gives us some confidence in the realistic representation of ET.

c. Isotopic data

The Department of Geosciences at the University of Arizona has been analyzing the heavy stable isotopes of oxygen and hydrogen ($\delta^{18}O$ and $\delta D$) in liquid water for individual precipitation events over the Tucson area since 1981. Figure 2 shows the isotopic composition for all available summer (June–September) events. The stable isotope compositions are normally reported as $\delta$ values in units of parts per thousand ($\%\text{oo}$) relative to the standard mean ocean water (SMOW) composition; $\delta$ values are calculated as

$$\delta = 1000\left(\frac{R_s}{R_x} - 1\right),$$

where $R$ denotes the ratio of the heavy to light isotope and $R_s$ and $R_x$ are the ratios in the sample and standard (SMOW), respectively. Wright et al. (2001) used this same dataset (17 years in their case) to calculate seasonally averaged (July–August) precipitation isotopic composition. In this work, we will use individual events.

d. EOF analysis

For each of the 3150 days in the 30-yr period (105 days × 30 years), the DRM provides a ratio contribution for each grid cell. This contribution is the ratio of precipitation contributed by each particular grid to the NAM precipitation, as explained in section 2a, and varies from 0 to 1. In constructing a ratio matrix (a matrix of dimensions $t \times u$, where $t = 3150$ events and $u = 96673$, which is equal to 349 longitude × 277 latitude grid points), we subtract the time mean of each grid box to indicate contribution anomalies at each time step; thus, the magnitude of the contribution of each grid point is retained with its relatively positive or negative contribution at each time step. In a manner similar to Wei et al. (2012), we reduced the dimensionality of the data by performing an empirical orthogonal function (EOF) analysis on the ratio matrix. This provides the dominant modes of variability (EOFs) and their associated principal component (PC) time series. The PC time series can be used to determine days that are strong representatives of a particular mode. We determined that if a particular day has PC above (below) one standard deviation, it is representative of the positive (negative) phase of the mode. This criterion is used to
analyze the synoptic characteristics and cases associated with each mode of variability.

3. Results  

a. Climatology of intraseasonal NAM moisture sources

The 30-yr-averaged map of gridded ratio contribution during the monsoon season is shown in Fig. 3. Large contributions from the SMO (both western and eastern sides) and the Gulf of California are evident. Central America, the eastern tropical Pacific, the western Gulf of Mexico, and the Caribbean Sea are also important source regions. The NARR domain is subdivided into 15 representative subregions (Fig. 4a) that are part of three main zones: the Pacific (PAC), which includes the eastern tropical, lower, middle, and high Pacific and the Gulf of California; the Atlantic (ATL), which includes the Caribbean, Gulf of Mexico, and eastern Atlantic; and the terrestrial component (LAND), which includes Central America, Baja California, mountains (eastern slopes of the SMO), the western and eastern United States, and the NAM region. Note that the region defined as “eastern United States” includes a part of Mexico. The 30-yr climatology of the area-averaged amount of precipitation contributed by each of the subregions is shown in Figs. 4b–d, and the spatial pattern of contributions from representative subregions is shown in Fig. 5.

The seasonal variation of moisture contribution from the Gulf of Mexico and the Caribbean Sea is primarily driven by the climatological development of the monsoon ridge and the displacement of the North Atlantic subtropical high (Fig. 5a). The monsoon seasonal-averaged ratio contribution to NAM precipitation from the Gulf of Mexico and Caribbean Sea is similar with an average value of about 10% (Fig. 4b). By the end of June (26–30 June pentad), precipitation originating from both sources is primarily located in southern Mexico (Fig. 5a). As the monsoon develops, easterly moisture flux from the Caribbean Sea and, to a lesser extent, the Gulf of Mexico crosses the SMO and significantly contributes to NAM precipitation (21–25 July pentad and 15–19 August pentad). During the late monsoon season (9–13 September pentad), the dynamically favorable conditions for moisture advection into the NAM region diminish as the North Atlantic subtropical high retreats to its original position and the monsoon ridge dissipates. On the other hand, the moisture contributed by the Gulf of Mexico to precipitation along the southeastern coast of the United States and over the SMO increases dramatically.
The monsoon ridge also drives the seasonal variability of moisture from the Pacific zone (Fig. 5b). The eastern tropical Pacific and Gulf of California have similar contributions to NAM precipitation (~5%–7%), with a larger contribution per unit area from the Gulf of California given its much smaller spatial extent. Moisture advected from the eastern tropical Pacific contributes more to the total moisture than that from the Gulf of California during early July, especially to western Mexico (Fig. 4c). This situation is quickly reversed near the end of July because of the northward transport of moisture along the Gulf of California into the NAM region. Gulf surge events are likely responsible for much of this transport. These two sources contribute precipitation to a large area within the NAM region during September (Fig. 5b), and this is likely related to TC activities, including some that potentially “trigger” gulf surge events (Higgins and Shi 2005). The likelihood of TC landfall in the region is much greater during September and October when the monsoon ridge weakens and retreats southward, allowing the cyclones to recurve and affect terrestrial regions (Ritchie et al. 2011). This conclusion is supported by Fig. 5b, which shows the large contribution from western oceanic sources late in the monsoon, resulting in intense precipitation.

Terrestrial sources show a clear south-to-north progression. Intense precipitation over Central America is largely driven by the Caribbean low-level jet and begins in early April, with a maximum in mid-June (Amador 1998; Wang and Lee 2007; Durán Quesada et al. 2010). The increase in soil moisture associated with precipitation over Central America is then reevaporated and can contribute to precipitation northward driven by east-southeasterly wind. Consequently, early in the NAM, there is a large contribution from Central America (from 1 to 20 July in Fig. 4d). The contribution from the NAM region is small early in the season (from 16 June to 15 July in Fig. 4d), but increases continually because of the rapid increase in soil moisture over the western flank of the SMO. The recycling contribution then becomes as large as the contribution from Central America. In addition to Central America and the NAM region, there are two other important terrestrial sources: the eastern mountains of the SMO (MNT) and the eastern United States, which contribute ~8% and 6% of monsoon precipitation each (Fig. 4d).

Figure 6 summarizes the contributions (ratio and amount) from the PAC, LAND, and ATL regions. The results highlight the importance of terrestrial moisture sources for monsoonal rainfall, particularly during the mature stages of the monsoon in July and August, when roughly 40% of the precipitation is of terrestrial origin. Initially, the Pacific zone is the most important oceanic source, but the Atlantic zone quickly replaces it in early July, corresponding to the well-known transition to
easterly winds that characterizes the monsoon. Toward the end of the season, however, the Pacific again becomes more important than the Atlantic, as the monsoon signal diminishes and Pacific tropical cyclones greatly affect the NAM region during late September. During the period of peak precipitation (mid-August), terrestrial and Atlantic sources play a dominant role (Fig. 6).

**FIG. 5.** The 30-yr-averaged amount of precipitation (mm day$^{-1}$) contributed from important sources of the ATL, PAC, and LAND during different pentads: (a) from CARS and GOM; (b) from L-PAC, E-PAC, and M-PAC; and (c) from C-AMR, the NAM, MNT, E-US, and W-US. The 30-yr-averaged 500-mb geopotential heights (m) are shown as dashed contours. The NAM region is denoted by dotted area.
b. Dominant modes of moisture source variability and associated synoptic features

Using EOF analysis, the spatial patterns of the dominant modes of moisture source variability and their associated PC time series are evaluated (Fig. 7).

1) East–West Sources

The first EOF [Fig. 7a(1)] separates moisture sources from the east (primarily the Gulf of Mexico and the Caribbean Sea) from those of the west (eastern tropical Pacific, low and midlatitude Pacific, and the Gulf of California). The PC time series shows that sources from the west progressively become more important toward the end of the season [Fig. 7c(1)]. All events that score above (below) one standard deviation in the PC time series were classified as westerly (easterly) events (Fig. 8a). Westerly sources also account for the most intense precipitation events in the 30-yr period (Fig. 8a). Events from the east are more frequent during the first half of the monsoon period; however, they are on average less intense than those of Pacific origin [Figs. 8a(1), 8a(2)]. The negative to positive phase transition during the monsoon season is also illustrated by Fig. 7b(2).

2) North–South Sources

The second mode separates sources that originate north and south of approximately 25°N [Fig. 7a(2)]. Southerly sources dominate the beginning and end of the monsoon season and tend to be associated with heavier precipitation events during the end [Figs. 7c(2), 8b(1), 8b(2)]. Northerly sources (north of about 25°N) are frequent in the middle of the season, when southerly sources drop dramatically. This can be considered a reiteration of a northward transition of moisture sources to
NAM precipitation during the monsoon and a frequent impact of southern oceanic sources (probably the Pacific) during the late season, as stated in section 3a.

3) SMO–GOC SOURCES

The third EOF differentiates the moisture of mountainous origin around the SMO from those of the Gulf of California and adjacent regions. Negative EOF values are associated with sources over both eastern and western slopes of the SMO, which includes the southern NAM region (local recycling). Positive values cover the Gulf of California, the northern NAM, and the Pacific [Fig. 7a(3)]. The positive phase of this mode is associated with gulf surge patterns, as 69% of the major surges identified by Stutler (2013) occur during the positive phase of this mode. Precipitation of mountainous origin is, on average, less intense than that of GOC origin during the monsoon season [Fig. 8c(2)], as the western oceanic sources account for the most intense events toward the end of the monsoon (as was previously shown). However, precipitation originating as ET from the SMO becomes more frequent than that of oceanic origin during the peak monsoon period of August and early September [Fig. 8c(1)].

**Fig. 7.** The first three EOFs with their PC time series: [a(1)] the first EOF mode; [a(2)] the second EOF mode; [a(3)] the third EOF mode; [b(1)] the PC of the first EOF mode smoothed by 5-day averages; [b(2)] the seasonal cycle of PC1, averaged over 30 years; [c(1)] the PC of the second EOF mode smoothed by 5-day averages; [c(2)] the seasonal cycle of PC2, averaged over 30 years; [d(1)] the PC of the third EOF mode smoothed by 5-day averages; and [d(2)] the seasonal cycle of PC3, averaged over 30 years. The NAM region is suggested by the dotted area in [a(1)], [a(2)], and [a(3)].
Sample cases. We select two representative cases of EOF 1 (based on the value of their PC score) to analyze their associated synoptic patterns. The first case represents an anomalously high contribution from the Pacific zone (case 1), and the second case is for the Atlantic zone (case 2).

4) THE PACIFIC ZONE AS THE MAIN SOURCE

On 4 September 1998, 68% of the area-averaged precipitation over the NAM region originated from the Pacific zone (27% from the Gulf of California, 30% from the eastern tropical Pacific, and 20% from the low-latitude Pacific). This moisture contribution can be linked to TC activity in the region, as Hurricane Isis moved up the Gulf of California into the Mexican state of Sonora during the period of 1–3 September 1998 (www.nhc.noaa.gov/data/tracks/tracks-ep-1998b.png). The 850-mb geopotential heights and integrated moisture fluxes 3 days prior to the event show the evolution of a cyclone that originated in the tropical Pacific (Fig. 9a). The cyclone moved north, bringing moisture from the tropical oceans into the NAM region, and entraining evaporation from the Gulf of California along its path. Thus, a gulf surge was identified in the Yuma station as an anomalous moisture flux lasting 43 h (Stutler 2013). This event is TC related, according to the definition of Higgins and Shi (2005). In addition, much like the events depicted in Higgins and Shi (2005), there is another cyclone over the Gulf of Mexico off the east coast of Mexico [see Fig. 3 in Higgins and Shi (2005)]. This corresponds to Hurricane Earl, which affected the region between 31 August and 3 September 1998 (www.nhc.noaa.gov/data/tracks/tracks-at-1998.png). The ratio contribution maps from the eastern tropical Pacific, during the period of 2–4 September (Fig. 9b), show how the moisture from the south is able to penetrate northward into the NAM region. Moving northward along the cyclonic circulation, moisture from the tropical Pacific reached southern Arizona on 3 September and eventually penetrated into California and Utah.

5) THE ATLANTIC OCEAN AS THE MAIN SOURCE

The Atlantic zone was the dominant source of precipitation over the NAM region on 25 August 1996. During this day, 60% of the total precipitation was of Atlantic origin. Much like the Pacific case, this event was linked to TC Dolly, which made landfall over the Yucatan Peninsula, as depicted by the 850-mb geopotential height and vertically integrated moisture flux field (Fig. 9c). The westward movement of the TC created enhanced southeasterly flow and brought eastern oceanic moisture into Mexico and the central plains. The easterly transport channeled the moisture from the Gulf
of Mexico into the southwestern United States across Texas (Fig. 9d). A maximum ratio contribution of 33% from the Gulf of Mexico to precipitation was 2 days in advance of a maximum contribution from the Caribbean Sea of 34% on 25 August. The lag is mainly attributed to the larger distance of NAM from the Caribbean Sea.

c. Analysis of stable water isotopes

As shown before, for each summer day in the 1979–2008 period, we can delineate the regions that provide moisture for NAM precipitation. In addition, we have the $\delta^{18}O$ and $\delta^D$ composition of liquid water for all
storm events in the Tucson area since 1981. Consequently, for each monsoon storm event, we can evaluate the dominant sources of precipitation and how the isotopic composition is related to the source region. For example, during the event of 4 September 1998—described above as a day where a TC influenced the monsoon region—the measured $\delta^{18}O$ was $-14.2\%$ and $\delta D$ was $-96.5\%$. During this day, as mentioned above, we see that the moisture came predominantly from the tropical Pacific and the Gulf of California. This analysis can be done for all summer events that had measurements of isotopic composition in Tucson since 1981 (432 total events).

If we calculate the correlation coefficient between the isotopic compositions and the principal components for the three leading EOFs, we see statistically significant negative correlations between the $\delta^{18}O$ and $\delta D$ values and EOF 1 and, to a smaller degree, for EOF 3 (see Table 1). This indicates that moisture coming predominantly from the east will likely be more isotopically enriched than average, while moisture from the lower-latitude Pacific, Baja, Gulf of California, or NAM region (sources from the west) will be more depleted than average. The statistically significant correlation for EOF 3 indicates that moisture coming from the Gulf of California tends to be more isotopically depleted than moisture originating from terrestrial ET from the SMO, although the relationship is weaker than for EOF 1. We cannot use isotopes to distinguish the north–south sources that are depicted in EOF 2, as there is no statistical relationship.

We can also use the EOF analysis presented above and evaluate the isotopic composition for individual days that are representative of a strong positive or negative phase for each mode (Fig. 10, left). Not surprisingly, we find that sources from the east are more isotopically enriched than sources from the west (EOF 1), and sources from the SMO are more enriched than those from the Gulf of California (EOF 3). It is important to keep in mind that there is an observed “amount effect” where heavier precipitation events tend to have more negative isotopic compositions than lighter ones during the summertime over midlatitudes (Dansgaard 1964). This relationship is due to several processes involved in the isotopic variations of convective rainfall, but particularly important for arid and semiarid regions is the fact that, during lighter precipitation events, raindrops evaporate below cloud base and attain a more positive isotopic composition; this effect is reduced in very high intensity events (Dansgaard 1964). Consequently, we must evaluate whether the more negative isotopic compositions are simply due to heavier precipitation. To do this, we bin the storm events by intensity and evaluate the isotopic composition for each bin. While the heaviest events are clearly more negative, we see that at all levels of intensity, the easterly sources are more positive in $\delta^{18}O$ in EOF 1 and the SMO sources are more enriched in EOF 3. EOF 2 shows no clear signature, as was expected from the initial correlation analysis. As stated before, it is difficult to interpret the isotopic composition of terrestrial ET, but in the case of EOF 3, ET from the SMO is more enriched than moisture coming from the Gulf of California. Precipitation on the eastern side of the SMO largely originates from the Gulf of Mexico, which is isotopically more enriched than average. This moisture is then evaporated by the soil and transpired by vegetation and then transported to the NAM region. Transpiration at steady state is a nonfractionating process (Farquhar and Cernusak 2005), so transpired water from the SMO will have a very similar isotopic signature than that of the Gulf of Mexico.

### 4. Discussion and conclusions

In this work, we use the modified DRM to evaluate the moisture sources that contribute to summer NAM precipitation over a 30-yr period using the DRM and water stable isotopes. While most of the literature has focused on the relative role of the oceanic sources of monsoonal moisture—with particular emphasis on the relative influence of the Gulf of Mexico versus the Gulf of California—our study finds that moisture from terrestrial ET is in fact as important as oceanic evaporation for NAM precipitation. Much like the results from Bosilovich et al. (2003) using water vapor tracers in a GCM, we find that terrestrial sources contribute to approximately 40% of monsoonal moisture and are particularly important during the peak monsoon season. We find that during the early season (mid-June) Central America is an important source of moisture. As the season progresses, we find a northerward progression of terrestrial sources, and by midseason, local recycling and moisture from the SMO are also important sources of moisture. Dominguez et al. (2008) and Bosilovich et al. (2003) also found that local recycling peaks midseason. Interestingly, terrestrial sources have also been found to be very important contributors to precipitation during

### Table 1. Correlation coefficients between $\delta^{18}O$ and $\delta D$ and the PCs of the three dominant EOFs. The asterisks represent values that are statistically significant at the 99% level for a two-tailed test.

<table>
<thead>
<tr>
<th>PC</th>
<th>$\delta^{18}O$</th>
<th>$\delta D$</th>
</tr>
</thead>
<tbody>
<tr>
<td>PC1</td>
<td>$-0.304^*$</td>
<td>$-0.276^*$</td>
</tr>
<tr>
<td>PC2</td>
<td>$-0.023$</td>
<td>$-0.086$</td>
</tr>
<tr>
<td>PC3</td>
<td>$-0.171^*$</td>
<td>$-0.15^*$</td>
</tr>
</tbody>
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FIG. 10. The $\delta^{18}O$ grouped by (left) pentads (every other pentad marked by their starting dates) and (right) precipitation bins associated with three EOFs: (a) westerly and easterly sources, (b) northerly and southerly sources, and (c) the SMO and GOC sources. The “mn” indicates the pentad-averaged $\delta^{18}O$ for each phase of the modes.
the Southeast Asian summer monsoon (Wei et al. 2012; Drumond et al. 2011). However, the large contribution from terrestrial moisture does not necessarily lead to an added source of predictability (Wei et al. 2012). Implications for predictability for the NAM region will be explored in future work.

We examine the variability of moisture sources using EOF analysis. Each EOF mode suggests a “preferred direction of moisture sources.” Using this type of analysis, we find that the most intense NAM precipitation events occur toward the end of the season and tend to originate in the oceans west and southwest of the NAM region (Gulf of California and tropical Pacific). An example of this type of event occurred on 1–4 September 1998 (Figs. 9a,b), and it can be directly related to TC activity over the eastern tropical Pacific. Higgins and Shi (2005) show that gulf surge events (measured in Yuma, Arizona) that are directly related to TCs are associated with stronger and deeper plumes of tropical moisture and wetter conditions over the core monsoon region. In fact, Ritchie et al. (2011) find that, for locations in the southwestern United States (Phoenix, Tucson, and Albuquerque), TC remnants account for up to 30% of the annual rainfall. In contrast to the westerly sources, precipitation events of easterly origin (primarily Gulf of Mexico and Caribbean Sea) predominate during the peak of the season. However, TC activity in the western Atlantic basin can also lead to enhanced precipitation in the NAM region. This was the case during 21–26 August 1996 (Figs. 9c,d), where a TC that affected the Yucatan Peninsula brought moisture that was later advected into the NAM. In this case, the dominant moisture sources to the NAM were from the Gulf of Mexico and Caribbean Sea. The impact of TCs over the western Atlantic basin for monsoonal precipitation has not been previously studied in the literature, although Higgins and Shi (2005) allude to their possible influence.

Our analysis finds a general south-to-north progression in the sources of monsoonal rainfall. Southerly sources (low-latitude Pacific, Central American, and Caribbean) dominate the early season, but as the season progresses, source regions begin to shift north. The location of the anticyclonic circulation associated with the extension of the North Atlantic subtropical high is the most important driving factor for the relative contribution of northerly versus southerly sources. A southeastern location of the high tends to result in moisture coming preferentially from the south, while a northwestern location results in moisture originating north of 25°N. We also see that while, as stated above, oceanic sources are important in the early and late monsoon season, terrestrial sources dominate the midseason. However, the terrestrial horizontal flux of moisture is relatively small compared to the oceanic counterpart and terrestrial sources are in general not associated with the most intense precipitation events. This in part is due to the fact that most terrestrial moisture comes from NAM and the SMO region and must cross the SMO before entering the NAM region.

We use observations of heavy stable isotopes of hydrogen and oxygen ($^6$D and $^18$O) collected for every precipitation event measured in Tucson, Arizona, for the period 1981–2008. We compare these measurements with our analysis of moisture sources. This very long storm-scale observational dataset, as opposed to the more usual monthly or seasonal data, provides an invaluable resource to compare with our numerical results. We find that there is a clear isotopic distinction between “easterly” and “westerly” sources of moisture. Precipitation events linked to sources from the Gulf of Mexico and Caribbean Sea are more isotopically enriched than sources from the Gulf of California and tropical Pacific. We also see that terrestrial regions that derive their precipitation from the Gulf of Mexico are more isotopically enriched than moisture from the Gulf of California. This result is consistent with previous work using water vapor observations during a pre-monsoon season (Strong et al. 2007) and with work using seasonal precipitation observations during the monsoon period (Wright et al. 2001). However, our work is distinct because we have performed a climatological analysis linking storm-scale isotopic observations with their source regions. We hypothesize that the distinct isotopic signature between eastern and western sources is related to the rainout processes that the parcels undergo as they move into the NAM. We also find that precipitation of terrestrial origin from within the SMO region tends to be isotopically more enriched than that of the Gulf of California. Our hypothesis is that this reflects the influence of the Gulf of Mexico because precipitation within the SMO is primarily from the Gulf of Mexico and the transpiration process maintains the same isotopic signature of antecedent precipitation. However, a more detailed model of isotopic moisture using isotopic general circulation models (Jouzel et al. 2013) would be needed to test both of these hypotheses.

Finally, as stated before, our simple analytical DRM has the strong assumption of a well-mixed atmosphere. In any particular region, the degree of mixing in the atmosphere depends on the degree of vertical heterogeneities that arise because of changes in the direction of the horizontal winds in the vertical direction (wind shear) and the strength of vertical mixing due to convection, and in fact, very rarely is the atmosphere well mixed (Goessling and Reick 2012). Including the effect of shear in simple numerical models has been shown to
significantly improve the performance of these simple models (van der Ent et al. 2013). The NAM region is indeed a region of strong vertical shear, as low-level wind is generally southerly while winds above roughly 700 mb are predominantly easterly (Stensrud et al. 1997; Douglas and Leal 2003; Higgins et al. 2004). This is the reason why the general understanding has been that moisture at upper levels (above 700 mb) predominantly comes from the Gulf of Mexico, while moisture at low levels comes from the Gulf of California (Schmitz and Mullen 1996). To evaluate the potential impacts of the DRM’s well-mixed assumption, we calculated the vertical profile of zonal and meridional moisture fluxes averaged for selected days that were representative of the positive and negative phases of the first EOF. We chose this EOF because it clearly separates westerly from easterly origin (when shear is more likely to occur; Fig. 11). We see that, unlike the westerly events, easterly events show strong shear, with south-southwesterly flow below 750 mb and east-southeasterly flow above 750 mb. On average, the southeasterly flow dominates so the integral over the column would likely result in some

**FIG. 11.** The area-averaged vertical distribution of water vapor transport within the NAM region for the westerly and easterly cases. The vapor transport amounts are scaled to show the relative magnitude.
overestimation of the contribution from the area southeast of NAM and an underestimation of that from the Gulf of California and eastern tropical Pacific. Unfortunately, the DRM is an analytical model, and there is currently no analytical solution that accounts for vertical heterogeneities within the DRM framework. In our current and future work, we are including the three-dimensional aspect of moisture transport using water vapor tracers embedded within a high-resolution atmospheric model.

Our results are meant to be first-order estimates of moisture source regions for the NAM that can later be analyzed with other more detailed methods. One of the most important contributions to our work is that it shifts the attention of moisture sources from the traditional “Gulf of California” and “Gulf of Mexico” oceanic sources to other regions that have previously been overlooked, including the mountainous regions of the SMO and Central America.

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