Prior results indicate an amplified annual mean warming trend over the Sahara, with temperature trends that are 2–4 times that of the tropical mean rate. Trend analysis is conducted using five atmospheric reanalyses and three observational datasets to better understand the seasonality and physical processes of this amplified warming and the implications for Sahel precipitation. The seasonality of the amplified warming is maximum during July–October with a minimum during June. Two processes related to the amplified warming are identified. A “dry process” supports amplified warming over the Sahara when there is limited latent heating and/or evaporation to cool the surface and distribute heat to the atmosphere. In this mechanism, the warming results from changes in the upward longwave and downward longwave fluxes that are tightly coupled to each other. The second, termed a “wet process,” occurs during the summer West African monsoon season. In this mechanism there are increases in the low- and midlevel atmospheric moisture over the Sahara that add to the surface warming by increasing the longwave downward radiation. This additional atmospheric moisture is transported over the Sahara because of a strengthening of the thermal low/Saharan high circulation system. A positive feedback mechanism is discussed in which enhanced moisture transport due to the stronger Saharan warming leads to increased Sahel rainfall that further strengthens the meridional temperature and height gradients by cooling the Sahel surface, further enhancing moisture transport into the region. Both processes contribute to the amplified warming, with the amplification being greater during the summer.

1. Introduction

A recent study by Cook and Vizy (2015, hereinafter CV15) reported on an amplified warming trend over the Sahara Desert when analyzing annual mean fields from three atmospheric reanalyses and two observational datasets. They found that for the 1979–2012 period, annual-mean surface temperatures over the Sahara have increased at a rate that is 2–4 times that of the tropical-mean temperature trend. Here we expand on that study to examine the seasonality of this trend to deepen our physical understanding of the amplification processes and the implications for Sahel rainfall. Variations in meridional temperature gradients, such as those that accompany the amplified Sahara warming, are known to be closely connected with tropical rainfall variations across sub-Saharan northern Africa (e.g., Patricola and Cook 2007, 2008; Biasutti et al. 2009; Lavaysse et al. 2010; Cook and Vizy 2013; Vizy et al. 2013), so it is important to understand the seasonality of the Saharan warming to improve prediction.

The background is reviewed in section 2. A description of the datasets analyzed is presented in section 3, and the analysis methodology is discussed in section 4. Results are presented in section 5, and conclusions are summarized in section 6.

2. Background

CV15 analyze annual mean, linear surface temperature trends in three atmospheric reanalyses, namely the European Centre for Medium-Range Weather Forecasts interim reanalysis (ERA-Interim, hereinafter ERAI; Dee et al. 2011), the National Centers for Environmental Prediction (NCEP)–U.S. Department of Energy (DOE) AMP-2 reanalysis (NCEP2; Kanamitsu et al. 2002), and the National Aeronautics and Space Administration (NASA) Modern-Era Retrospective Analysis for Research and Applications (MERRA; Rienecker et al. 2011), and two observational datasets, namely the Climatic Research Unit Time Series (TS)
Observational dataset, version 3.21 (CRU; Mitchell and Jones 2005), and the Global Historical Climate Network merged land–ocean analysis (GHCN; Peterson and Vose 1997, Jones and Moberg 2003). Consistent across all five datasets, annual mean surface temperatures in the Sahara Desert (20°–30°N, 10°W–30°E) were found to be increasing at a rate that was 2–4 times faster than the tropical mean temperature during the 1979–2012 period. An evaluation of trends in the annual mean surface heat balance identified the disabling of evaporation as the primary factor in the amplification. Processes related to solar forcing and the water vapor–temperature feedback did not emerge as relevant for the accelerated warming. In particular, while all three atmospheric reanalyses produce the amplified Sahara warming signal, they disagree about the role of trends in the annual-mean column water vapor. In NCEP2, column water vapor over the Sahara averaging region has a positive trend that is accelerated compared with the tropical mean, but the MERRA column water vapor trends over the Sahara are much smaller than for the tropical mean. Column water vapor trends over the Sahara are negative in ERAI, compared with a zero trend in the tropical mean.

The importance of Saharan warming is underlined by the many studies that relate summertime rainfall variations over sub-Saharan northern Africa to the strength of the Saharan heat low. As discussed by Webster (1987), land–sea thermal contrast plays a pivotal role in the development of summer monsoon systems, including the West African monsoon. A warmer Sahara is thought to be associated with a stronger Sahara heat low accompanied by an enhancement of the Sahel low-level thermal gradient and stronger low-level westerly/southwesterly moisture transport, and hence precipitation, over the Sahel and southern Sahara (Patricola and Cook 2007; Biasutti et al. 2009; Lavaysse et al. 2010; Vizy et al. 2013). This mechanism can operate across a wide range of time scales, explaining past (e.g., Patricola and Cook 2007, 2008) and present-day rainfall variability over the region (Lavaysse et al. 2010). This mechanism could also become more influential in the future because of global warming (Haarsma et al. 2005; Biasutti et al. 2009; Vizy et al. 2013).

Evan et al. (2015) used three Algerian observing stations and one atmospheric reanalysis (MERRA) to study the processes associated with the observed rainfall recovery from the 1980s Sahelian drought. Unlike CV15, who investigate annual mean temperature trends, Evan et al. (2015) focus on the months of July and August, which are part of the 3-month Sahel wet season. Their analysis indicates that increases in July and August temperatures over the western Sahara (20°–30°N, 7°W–5°E) in the last 30 years are forced by anomalous nighttime heating of the surface by atmospheric water vapor. Evan et al. (2015) do not evaluate whether this seasonal warming is amplified relative to the rest of the tropics, as this was not the purpose of their study.

The results of Evan et al. (2015) do not disagree with those of CV15 since they do not evaluate the amplification; that is, they do not compare heating rates and mechanisms over the Sahara with those of the tropics in general and, of course, the water vapor–temperature feedback occurs throughout the globe. The two studies also use different averaging regions and time means (Lavaysse 2015). However, the reliance on one reanalysis in Evan et al. (2015) is of concern, especially for water vapor (e.g., Jiang et al. 2015) and because the MERRA used is known to have limitations for trend analysis due to discontinuities in water vapor values associated with changes in the observing system (Bosilovich et al. 2011; Rienecker et al. 2011; Robertson et al. 2011). MERRA2 has been developed to address some of these issues (Molod et al. 2015). Nonetheless, certain disparities in these results suggest that more work is needed to develop a more complete understanding of the amplified warming over the Sahara and its influence on Sahel rainfall.

3. Datasets

To provide checks on the data and a measure of confidence, the following five atmospheric reanalyses are analyzed for the 1979–2015 period:

- National Centers for Environmental Prediction (NCEP)–U.S. Department of Energy (DOE) AMIP-II reanalysis (NCEP2; Kanamitsu et al. 2002), with 2.5° resolution upper air and ~1.8° resolution surface;
- European Centre for Medium-Range Weather Forecasts interim reanalysis (ERAI; Dee et al. 2011), with 1.5° horizontal resolution;
- National Aeronautics and Space Administration (NASA) Modern-Era Retrospective Analysis for Research and Applications (MERRA; Rienecker et al. 2011), with 0.5° latitude × 2/3° longitude horizontal resolution;
- NASA Modern-Era Retrospective Analysis for Research and Applications, version 2 (MERRA2; Bosilovich et al. 2015), with 0.5° latitude × 0.625° longitude; and
- Japan Meteorological Agency’s Japanese 55-Year Reanalysis (JRA-55; Kobayashi et al. 2015), with 1.25° resolution.

MERRA2 and JRA-55 were not analyzed in CV15, but are included here to improve our understanding of the uncertainty in the trends on monthly to seasonal time
scales. Since resolution is similar among the reanalyses, they are retained on their own grids to prevent loss of information.

In addition to reanalyses, land surface temperature and precipitation estimates from various observational datasets are used. One is the 1979–2015 Global Historical Climate Network merged land–ocean analysis (Peterson and Vose 1997; Jones and Moberg 2003). Although the 5° resolution is coarser than the other datasets, the GHCN covers both tropical land and ocean points so it provides an opportunity to compare surface air temperature amplification rates for the Sahara with respect to tropical mean. The Climatic Research Unit TS observational dataset, version 3.23 (Harris et al. 2014), for 1979–2014 is also analyzed. This gridded dataset, with 0.5° resolution, uses more than 4000 land-based weather stations to provide monthly land surface air temperature and precipitation estimates. Also utilized is the Global Precipitation Climatology Project monthly precipitation dataset, version 2.2 (GPCP; Adler et al. 2003). This 2.5° resolution dataset provided monthly precipitation estimates from 1979–2014 by combining observations and satellite precipitation data.

4. Methodology

The analysis here follows that of CV15 in comparing trends in surface temperature among various tropical averaging regions. Area-averaged values are calculated for the tropics (all land and water between 30°S and 30°N), tropical land (all land between 30°S and 30°N), and the Sahara Desert (20°–30°N, 10°W–30°E). In addition, spatial distributions are evaluated at monthly mean time scales in contrast to the annual-mean approach of CV15.

Also as in CV15, a diagnosis of surface heat balance trends is used to understand the surface temperature trends. The surface heat balance equation is

\[ C \frac{dT_{\text{sfc}}}{dt} = \text{SW}_{\text{abs}} + \text{LW}_{\text{down}} - \text{LW}_{\text{up}} - \text{SH} - \text{LH} - D, \]  

(1)

where \( T_{\text{sfc}} \) is surface temperature and \( C \) is the heat capacity of the surface given by

\[ C = cph, \]  

(2)

where \( h \) is the depth to which heat penetrates the surface, \( c \) is the specific heat, and \( \rho \) is the density of the surface material. Also, \( \text{SW}_{\text{abs}} \) is the solar radiation absorbed at the surface, \( \text{LW}_{\text{down}} \) is the longwave back radiation emitted by atmospheric greenhouse gases, \( \text{LW}_{\text{up}} \) is the longwave radiation emitted from Earth’s surface, \( \text{SH} \) is the sensible heat, and \( \text{LH} \) is the latent heat; \( D \) represents the redistribution of heat within the surface primarily by downward vertical diffusion and ocean currents. With the exception of \( D \), each term on the right-hand side of Eq. (1) is provided as output in the reanalyses.

Equation (1) is reorganized as

\[ [R] = [\text{SW}_{\text{abs}}] + [\text{LW}_{\text{down}}] - [\text{LW}_{\text{up}}] - [\text{SH}] - [\text{LH}]. \]  

(3)

where the square brackets indicate the annual, seasonal, or monthly mean. The residual \([R]\) is the sum of the heat storage term \( C \partial T_{\text{sfc}}/\partial t \), \( D \), and numerical error. As discussed in CV15, the heat storage term is small compared with the terms on the right-hand side of Eq. (3) and the accuracy of reanalyses, and this requires an equilibrium approach for the annual mean. For example, to estimate an upper-end value for the Sahara Desert, let \( h \approx 4 \text{ cm}, c \approx 840 \text{ J kg}^{-1} \text{ K}^{-1}, \) and \( \rho \approx 2.65 \times 10^{3} \text{ kg m}^{-3} \) in Eq. (2), and assume a temperature trend of 0.5 \text{ K decade}^{-1}. Then, \( C \partial T_{\text{sfc}}/\partial t \approx 1.4 \times 10^{-4} \text{ W m}^{-2} \) while many of the terms on the right-hand side of Eq. (1) are on the order of tens or hundreds of watts per meter squared. Likewise, CV15 finds that \( D \) is generally small over land (i.e., the Sahara) for the annual mean, but for subannual time scales (i.e., monthly) \( D \) may be more important. Each term on the right-hand side of Eq. (1) depends on the surface temperature directly or indirectly, and the adjustment of the surface heat balance occurs on time scales that are typically much smaller than the monthly to annual time scales considered here.

5. Results

a. Annual mean analysis

With three additional years and two additional reanalyses, the annual-mean results presented in CV15 are briefly updated. Table 1 shows area-averaged, climatological, annual-mean surface temperatures and trends for the five atmospheric reanalyses and the observations (when output is available). For the reanalyses surface skin temperature is utilized, while the CRU and GHCN measure surface air temperature at approximately 2-m height.

Consistent with the CV15 results, annual mean surface temperature warming trends for the tropics are significant for all five reanalyses; JRA-55 has the smallest trend at +0.07 \text{ K decade}^{-1} and MERRA2 has the largest trend at +0.15 \text{ K decade}^{-1}. Tropical land warming trends are also significant, and generally larger than the trends for
TABLE 1. Climatological annual average mean and trends for surface temperature for the tropics, tropical land, and Sahara averaging region. Statistically significant values at the 90%, 95%, and 98% confidence interval are respectively shown in bold, bold italics, and bold with asterisks after accounting for autocorrelation using the Zwiers and von Storch (1995) two-stage table lookup test procedure.

<table>
<thead>
<tr>
<th></th>
<th>ERAI</th>
<th>JRA-55</th>
<th>MERRA</th>
<th>MERRA2</th>
<th>NCEP2</th>
<th>GHCN</th>
<th>CRU</th>
</tr>
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<tr>
<td>Tropical mean surface temperature (K)</td>
<td>298.84</td>
<td>298.08</td>
<td>299.01</td>
<td>298.81</td>
<td>298.43</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Tropical mean surface temperature trend (K decade$^{-1}$)</td>
<td>0.09*</td>
<td>0.07*</td>
<td>0.10*</td>
<td>0.15</td>
<td>0.10*</td>
<td>0.13*</td>
<td>—</td>
</tr>
<tr>
<td>Tropical land mean surface temperature (K)</td>
<td>297.49</td>
<td>297.13</td>
<td>298.06</td>
<td>297.71</td>
<td>295.98</td>
<td>—</td>
<td>297.39</td>
</tr>
<tr>
<td>Sahara mean surface temperature trend (K decade$^{-1}$)</td>
<td>0.14*</td>
<td>0.20*</td>
<td>0.13*</td>
<td>0.21</td>
<td>0.14*</td>
<td>—</td>
<td>0.19*</td>
</tr>
<tr>
<td>Sahara mean surface temperature (K)</td>
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<td>297.82</td>
<td>298.85</td>
<td>297.70</td>
<td>293.28</td>
<td>—</td>
<td>297.58</td>
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<td>Sahara amplification factor relative to the tropics</td>
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<td>0.36</td>
<td>0.32*</td>
<td>0.35</td>
<td>0.48</td>
<td>0.36</td>
<td>0.38</td>
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<tr>
<td>Sahara amplification factor relative to tropical land</td>
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<td>1.8</td>
<td>2.5</td>
<td>1.6</td>
<td>3.4</td>
<td>2.8</td>
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</tr>
</tbody>
</table>

the tropics. The ranges in trends among the reanalyses are consistent with the observed tropical trend from GHCN and the tropical land trend from CRU.

The warming trends of annual mean surface temperature for the Sahara are greater than the trends for both the tropical mean and tropical land, ranging from +0.22 K decade$^{-1}$ for ERAI to +0.48 K decade$^{-1}$ for NCEP2. All the Sahara warming trends except for NCEP2 are significant, despite NCEP2 having the largest magnitude of the seven datasets analyzed. Again these trends for the Sahara are similar to those calculated in CV15.

The last two rows of Table 1 provide measures of the trend amplification for the annual mean Saharan warming relative to the entire tropics and relative to tropical land. Relative to the tropics, the annual mean Saharan warming trend is 2.3–5.1 times greater, with warming in NCEP2 and JRA-55 amplified more than the other three reanalyses. (CV15 report an annual mean Saharan warming amplification that is 3.2–6.1 times the tropical mean.) If tropical land is utilized as a basis instead, then the amplification factor is lower, ranging from 1.5 to 3.4 times greater. Thus, amplified warming over the Sahara is reduced when the three most recent years are factored in as the tropical trend is increasing more than the Sahara trend.

JRA-55 has the largest amplification factor when it is calculated relative to the tropics (i.e., 5.1), but the amplification relative to tropical land alone is similar to ERAI and MERRA2. This may be because, unlike the other reanalyses that are forced with SSTs from the NOAA daily Optimum Interpolation Sea Surface Temperature data (OISST; Reynolds et al. 2007), prescribed SSTs in JRA-55 are from the Centennial In Situ Observation-based Estimates (COBE; Ishii et al. 2005), which are based on in situ measurements and do not include satellite-derived SST estimates.

We characterize the Saharan surface temperature amplification relative to the entire tropics below except when comparing with the CRU land-only observations. The Sahara constitutes a significant percentage (~8%) of the total land area between 30°S and 30°N, so using trends from the entire tropics provides an estimate that is less strongly influenced by the Sahara. The spatial distribution of the amplification is not impacted, only the magnitude.

Figure 1 shows the distribution of the annual-mean tropical amplification factor for the datasets. Common among the reanalyses is that strong amplified warming is associated with orography, but the reanalyses do not agree regionally on its location. Spatial variations among the reanalyses are associated with the Saharan trends as the tropical mean trends are uniformly applied. This finding agrees with studies that suggest that there is stronger amplified warming in high-elevation regions associated with greenhouse gas forcing (e.g., Beniston et al. 1997; Beniston 2003; Seidel and Free 2003; Wang et al. 2014; Pepin et al. 2015). It is unclear why there is not better agreement among the reanalyses; perhaps differences in spatial resolution and/or biases in the atmospheric moisture field over the region play a role.

The spatial patterns of the amplification factors for CRU and GHCN are fairly homogenous. The CRU observations use no satellite data, so the homogeneity reflects the lack of available observations over the Sahara. The GHCN observations use satellite information, but the resolution is coarse (~5° resolution). This suggests that GHCN and CRU may not be particularly useful for understanding spatial variations within the Sahara averaging region.

An evaluation of the annual-mean surface heat balance trends (not shown) produces results consistent with the mechanisms identified in CV15 (see Table 3 therein, and the associated discussion). In summary, the largest trends in the surface heat balance components for the tropical mean are positive latent heat flux trends balanced by negative trends in $R$ [Eq. (3)], presumably associated with the redistribution of heat within the ocean. In contrast, for the Sahara Desert, trends in both the latent heat flux and the redistribution of heat within...
the surface are extremely small. Trends in the upward longwave and downward longwave fluxes are greatest, and they are statistically significant across all of the re-analyses (with the exception of the upward longwave flux in NCEP2). The amplified Sahara warming (in the annual mean) results from the tight coupling between the upward and downward longwave radiation, presumably triggered by increases in greenhouse gases, in the absence of latent heat fluxes and the surface redistribution of heat. This “dry process” mechanism promotes amplified warming over the Sahara in the annual mean analysis presumably because the dry season is longer than the 4-month wet summer monsoon season over northern Africa. Trends in the sensible heat flux are small, and trends in the solar flux are inconsistent across reanalyses despite having the Sahara amplification in each.

As discussed in section 2, CV15 conclude that enhanced longwave back radiation due to positive column water vapor trends does not play a role in the amplification...
of the annual mean warming signal over the Sahara. Despite agreement that Sahara temperatures exhibit amplified warming, there was no agreement among the reanalyses used in that study (ERAI, NCEP2, and MERRA) about trends in column precipitable water. Since Evan et al. (2015) point to an important role for this mechanism in summer warming (but not amplification) over the western Sahara, termed here as a “wet process,” we present updated annual-mean results here with the longer time period and additional reanalyses.

Figure 2 shows the area-averaged, annual-mean 1979–2015 precipitable water time series for the tropical and Sahara regions in each of the five reanalyses. Dashed lines indicate linear trends. ERAI (Fig. 2a) has a negative trend in precipitable water of \(-0.10 \text{ mm decade}^{-1}\) over the Sahara, while the other reanalyses (Figs. 2b–e) indicate positive trends. Since JRA-55, MERRA2, and NCEP2 have linear Saharan trends that are positive and greater than the positive tropical mean trends, increases in precipitable water over the Sahara could contribute to the amplified Sahara warming according to these reanalyses, but this is not the case according to ERAI and MERRA.

Since all five reanalyses exhibit amplified Sahara warming, and the three reanalyses with Sahara precipitable water trends exceeding their tropical trends do not necessarily have higher amplification factors (Table 1), these results are consistent with CV15’s conclusion that an amplified water vapor–temperature feedback is not primarily responsible for the amplified Sahara warming in the annual mean. Even if we neglect NCEP2 as an older-generation product (Trenberth et al. 2005, 2011) and MERRA because of its known issues with the representation of atmospheric water vapor (Bosilovich et al. 2011; Rienecker et al. 2011; Robertson et al. 2011), we are left with the same conclusion.

Given the pronounced seasonality of the northern Africa climate, the large-scale, annual mean perspective of CV15 and the above analysis may be inadequate for a more refined understanding of the physical processes associated with the amplified Sahara warming (i.e., “dry” vs “wet” processes) and, especially, for understanding its implications for seasonal Sahel rainfall. We are particularly concerned about the large averaging region, and that annual averaging can mask seasonally varying physical processes associated with circulation and column water vapor trends. The Sahara amplification is investigated on seasonal time scales below to advance our understanding.

b. Seasonal analysis

Figure 3a shows 1979–2015 monthly mean surface temperature trends for the tropics (dashed lines) and the Sahara averaging region (solid lines) for the various datasets. Monthly surface temperature trends for the tropical mean are fairly consistent over the annual cycle. Generally, the smallest (largest) trends occur in January (October). JRA-55 trends are consistently the smallest among the reanalyses, while MERRA2 trends are the largest. ERAI, MERRA, and NCEP2 are similar to one another.

The seasonal cycle for the Saharan monthly surface temperature trends is similar among four of the reanalyses, with NCEP2 being the exception. The largest values occur during late boreal summer (August and September) with possibly a secondary maximum in the spring, the latter being dataset dependent. There is also good agreement among the reanalyses that the smallest warming trend occurs during June. There is a consensus among all of the reanalyses that the Saharan warming trend exceeds the tropical warming trend for all months except for June in ERAI and MERRA2.

CRU and GHCN observations have more subdued monthly surface temperature trends than the reanalyses. Unlike the reanalyses, there is not a distinct maximum peak during the summer, instead monthly trends generally fall between \(+0.3\) and \(+0.4 \text{ K decade}^{-1}\) for most months. This absence of a summertime peak may be related to limitations of these observational datasets over the data-sparse Sahara. In particular, station information from outside the Sahara is being used to help fill in areas of the Sahara that are missing station data. Because of this, caution should be taken when interpreting CRU and GHCN estimates. Both GHCN and CRU indicate a minimum warming trend in June, consistent with the reanalyses.

Figure 3b shows 1979–2015 monthly mean precipitable water trends for the same averaging regions from the reanalyses. While all of the reanalyses indicate positive precipitable water trends over the Sahara that exceed the tropical trend during the boreal summer, coinciding with the Saharan warming trend peak (Fig. 3a), they differ somewhat in the magnitude and duration of this precipitable water trend maximum. For example, the positive precipitable water trend in ERAI is limited to August–September and has a smaller magnitude \((+0.51 \text{ mm decade}^{-1})\), whereas the other four reanalyses suggest a longer lasting peak (i.e., July–October) with peak magnitudes ranging from \(1.05 \text{ mm decade}^{-1}\) in NCEP2 to \(1.60 \text{ mm decade}^{-1}\) in MERRA2. Outside of these months precipitable water trends are similar to the tropical precipitable water trend or they are negative. Finally, the MERRA precipitable water trend for the tropical mean is an outlier relative to the other reanalyses. This again is due to the discontinuities in the atmospheric water vapor time
FIG. 2. Trends in the annual mean precipitable water (mm) over the tropics (red) and Sahara (blue) averaging regions for (a) ERAI, (b) JRA-55, (c) MERRA, (d) MERRA2, and (e) NCEP2. Values shown have subtracted the climatological mean value which is given in each panel along with the trend (mm decade$^{-1}$).
series in MERRA (Bosilovich et al. 2011; Rienecker et al. 2011; Robertson et al. 2011), but it is not an issue over the Sahara.

To summarize the seasonal cycles of surface temperature and precipitable water trends, Figs. 3c and 3d show the monthly multireanalysis mean surface temperature and precipitable water trends, respectively. This reanalyses ensemble mean produces a positive Saharan surface temperature trend that exceeds the tropical warming trend in all months. The seasonality of the signal is clarified, with a Saharan warming trend minimum in June and maximum in July–October. During other months the Saharan warming trend is fairly constant around +0.3 K decade\(^{-1}\) and amplified with respect to the tropical mean by 0.22 K decade\(^{-1}\). Furthermore, the summer Saharan surface warming trend peak is associated with a positive precipitable water trend peak during July–September that exceeds the tropical precipitable water trend. This suggests that changes in atmospheric water vapor content are further enhancing the amplified warming signal in the reanalyses, contributing to the larger Saharan warming trends during these summer months relative to the dry season months of November–May when the amplified...
Saharan warming results only from the dry processes discussed in CV15. Since the dry process mechanism is well explained by CV15, the analysis below focuses on months in Fig. 3c when the Sahara warming trend deviates most from its dry season warming trend, namely during July–September when it is amplified the most, and on June.

The following analysis of the July–September and June periods includes only ERAI, JRA-55, and MERRA2. These reanalyses are selected because they are newer, often referred to as second-generation reanalyses. They also encompass the surface temperature and precipitable trends ranges shown in Fig. 3, and are not known to have the issues discussed earlier in NCEP2 and MERRA.

Figures 4a–d show July–September climatological surface air temperature for CRU, and surface skin temperatures for ERAI, JRA-55, and MERRA2, respectively, while Figs. 4e–h show surface temperature trends. The climatologies agree that the warmest surface temperatures (i.e., greater than 308 K) occur west of 10°E over the western Sahara. The datasets are also in consensus that surface temperature trends exceed +0.2 K decade⁻¹ over much of the Sahara, with the largest positive trends...
generally east of 10°E. The +0.2 K decade $^{-1}$ threshold is important here because it signifies that the Saharan temperature trend exceeds the surface temperature trend for the tropics from all of the datasets. The location of the maximum positive warming trend varies. For example, it is positioned over the Tibesti Mountains of northern Chad and southern Libya in MERRA2 and JRA-55, over northern Sudan in CRU, and over the central and eastern Sahel in ERAI. Over the western Sahel all of the datasets indicate a cooling trend that is most pronounced in JRA-55, and confined west of 0° longitude in ERAI.

To better understand the July–September temperature trends shown in Fig. 4, climatologies and trends in the surface heat balance components are shown in Fig. 5. Figure 5a shows climatological values for the combined radiative terms, $SW_{net} + LW_{net}$, for ERAI, JRA-55, and MERRA2, while Figs. 5b and 5c show the climatological values for $SW_{net}$ and $LW_{net}$ individually. All reanalyses show that the combined $SW_{net} + LW_{net}$ over the Sahara is positive, ranging between +40 and +90 W m$^{-2}$, indicating a net radiative heating of the surface as the positive $SW_{net}$ exceeds the negative $LW_{net}$ over the Sahara. There is much more structure in the ERAI and MERRA2 $SW_{net} + LW_{net}$ field, which is due to $SW_{net}$.

Figures 5d and 5e show July–September climatologies for the $LW_{down}$ and $LW_{up}$ terms for the three reanalyses.
The largest values of $LW_{\text{down}}$ occur west of 10°E over the western Sahara and south of 20°N over the Sahel, and values are generally lower to the north and east of the topography (i.e., the Ahaggar, Tibesti, and Marra Mountains) of interior northern Africa. The largest magnitudes of $LW_{\text{up}}$ are over the western Sahara coinciding with the location of the warmest surface temperatures (Figs. 4a–d).

The other terms of the surface heat balance [Eq. (3)], namely $LH$, $SH$, and $R$ (not shown), are at least one order of magnitude smaller than $SW_{\text{net}}$, $LW_{\text{down}}$, and $LW_{\text{up}}$ (Fig. 5) over the Sahara. As noted by CV15, the small values of the latent heat flux lead to the annual-mean amplification of Sahara warming since these values are much larger in the topical mean. Sensible heat fluxes and $R$ are also small over the Sahara.

Figures 6a–e show July–September trends for $SW_{\text{net}} + LW_{\text{net}}$, $LW_{\text{net}}$, $LW_{\text{down}}$, and $LW_{\text{up}}$ from the reanalyses. Trends in the net radiative flux, $SW_{\text{net}} + LW_{\text{net}}$, (Fig. 6a) vary among the reanalyses with ERAI
indicating negative (i.e., cooling) trends over much of the northern and eastern Sahara, JRA-55 indicating significant positive trends over the southwestern Sahara and negative trends over the eastern Sahara, and MERRA2 indicating positive trends over much of the Sahara. For ERAI, the negative $\text{SW}_{\text{net}} + \text{LW}_{\text{net}}$ trends over the northern Sahara are associated with negative $\text{SW}_{\text{net}}$ trends (Fig. 6b), while the negative $\text{SW}_{\text{net}} + \text{LW}_{\text{net}}$ trends over the eastern Sahara are associated with negative trends in both $\text{SW}_{\text{net}}$ and $\text{LW}_{\text{net}}$ (Fig. 6c). For JRA-55, $\text{LW}_{\text{net}}$ trends are most influential over the southwestern Sahara, and are associated with significant positive trends in $\text{LW}_{\text{down}}$ (Fig. 6d), and are reinforced by negative $\text{LW}_{\text{up}}$ trends (Fig. 6e) over the western Sahel. Over the eastern Sahara, negative $\text{LW}_{\text{net}}$ trends dominate the $\text{SW}_{\text{net}} + \text{LW}_{\text{net}}$ trend, suggesting increased heat loss from the surface associated with positive (i.e., cooling) $\text{LW}_{\text{up}}$ trends. For MERRA2, the positive $\text{SW}_{\text{net}} + \text{LW}_{\text{net}}$ trends over the Sahara associated with positive $\text{LW}_{\text{down}}$ trends are large enough to offset surface cooling associated with positive $\text{LW}_{\text{up}}$ trends and negative $\text{SW}_{\text{net}}$ trends.

July–September trends for LH, SH, and $R$ are shown in Figs. 7a–c, respectively. All three reanalyses generally agree that LH trends are small over most of the Sahara but are larger south of 20°N over the Sahel. The exception is over southern Algeria in JRA-55, where positive trends (i.e., enhanced cooling) occur. ERAI and JRA-55 indicate negative (i.e., warming) SH trends over southern Libya and Egypt, while MERRA2 produces positive (i.e., cooling) SH trends. Trends in $R$ are small for JRA-55 and MERRA2 over the entire Sahara, but larger for ERAI.

To summarize Figs. 6 and 7, July–September surface warming trends in ERAI are primarily due to a decrease in SH and $R$ heat losses from the surface as the trend in $\text{SW}_{\text{net}} + \text{LW}_{\text{net}}$ is negative and LH trends are negligible over the Sahara. In contrast, warming associated with positive $\text{LW}_{\text{net}}$ trends due to an increase in $\text{LW}_{\text{down}}$ is more influential in JRA-55 west of 20°E, and MERRA2 over the majority of the Sahara. East of 20°E for JRA-55, positive $\text{SW}_{\text{net}}$ trends and reduced heat loss from the surface by SH are influential. These contrasting results suggest two different surface heat balance scenarios, one associated with a limited increase in atmospheric moisture content (i.e., ERAI) and the other associated with a marked increase in atmospheric moisture (i.e., JRA-55 and MERRA2). This difference needs to be further examined to understand which scenario is more plausible.

Figures 8a–c show July–September precipitable water trends for the total atmospheric column from
the reanalyses. The trend pattern for ERAI (Fig. 8a) indicates strong drying over the eastern and central Sahel with weaker drying extending poleward to the orography around 20°N. North of the topography there is a weak positive precipitable water trend (i.e., < +0.8 mm decade⁻¹) over the northern Sahara. JRA-55 (Fig. 8b) and MERRA2 (Fig. 8c) precipitable water trends are in better agreement with one another than with ERAI. Both indicate significant positive trends in precipitable water over the Sahara that exceed the tropical mean trend value, although the trend in JRA-55 is more concentrated west of 20°E, while the trend in the MERRA2 extends across the entire Sahara.

Fig. 8. July–September 1979–2015 precipitable water trends (mm decade⁻¹) through the entire atmospheric column for (a) ERAI, (b) JRA-55, and (c) MERRA2. (d)–(f) The precipitable water at low levels between 1000 and 800 hPa, and (g)–(i) the precipitable water at midlevels between 400 and 800 hPa, for the same three reanalyses, respectively. Stippling denotes significance at the 90% level of confidence after accounting for autocorrelation. July–September mean tropical trends for each panel are denoted in the upper-right corner.
The analysis of the precipitable water trends is expanded to evaluate July–September trends at low levels, between 1000 and 800 hPa (Figs. 8d–f), and midlevels, between 800 and 400 hPa (Figs. 8g–i), to determine the levels at which the moisture changes are occurring. For ERAI, the drying trend over the central and eastern Sahel is primarily associated with precipitable water changes at low levels; the drying shown in Fig. 8d accounts for 50%–90% of the total drying trend shown in Fig. 8a. There is also evidence of a weak, low-level drying trend over Libya and Egypt, but this is mostly offset by an increase in precipitable water at midlevels (Fig. 8g).

Precipitable water changes in JRA-55 are dominated by changes at low levels over the western and central Sahel extending to the Marra Mountains at 20°E (Fig. 8e). Here, low-level trends account for 60%–90% of the total positive precipitable water trends shown in Fig. 8b. The eastward and northward extension of the positive trend appears to be limited by the orography. Over the Sahara north and east of the topography, low-level precipitable water trends are small with a weak low-level drying trend over Egypt and Sudan consistent with ERAI. Midlevel precipitable water changes are most important over the northern and eastern Sahara (Fig. 8h), accounting for nearly all (i.e., 70%–100%) of the positive precipitable water trend shown in Fig. 8b, even when offset by the low-level drying trend over Egypt and Sudan.

MERRA2 precipitable water changes are more similar to JRA-55 than ERAI. At low levels (Fig. 8f) there are positive precipitable water trends extending across the Sahel to the Sudan, but the magnitudes of these trends are less than half those of JRA-55, and they account for a smaller percentage (i.e., 30%–60%) of the total precipitable water trend compared to JRA-55. MERRA2 indicates that, over the northern Sahara, a higher percentage of the positive precipitable water trend (i.e., 30%–50%) is due to changes at low levels with the rest associated with midlevel positive precipitable water trends (Fig. 8i). Unlike for ERAI and JRA-55, there is no evidence of weak low-level drying over the eastern Sahara of Egypt.

Precipitable water trends are next compared to available observations to assess which trend pattern is more plausible. Unfortunately, there is not a reliable gridded observational dataset of precipitable water available covering the same time period to compare with the reanalyses. Here we use precipitation as a proxy for precipitable water. Figures 9a and 9b show July–September climatological precipitation for the CRU and GPCP precipitation datasets, while Figs. 9c and 9d show July–September precipitation trends. Since almost all of the July–September rainfall occurs south of 20°N, we cannot comment on the reliability of the precipitable water trends directly over the Sahara, but we can comment on the trends over the Sahel. CRU and GPCP both agree that precipitation trends are positive across the entire Sahel, with negative rainfall trends in the vicinity of the Guinean and Cameroon Highlands. This indicates that the amplified warming over the Sahara is associated with enhanced summertime rainfall over the Sahel. A comparison with Figs. 8a–c indicates that the precipitable water trend patterns in JRA-55 and MERRA2 are consistent with the observed rainfall trend pattern, but this is not the case for ERAI. As a result, we place more confidence in JRA-55 and MERRA2 precipitable water trends, and less confidence in ERAI trends. Furthermore, this difference among the reanalyses is consistent with ERAI having a much smaller summer amplified warming signal compared to JRA-55 and MERRA2. It is unclear why ERAI produces a drying trend over the Sahel, but it warrants further attention in future work.

Since it does not rain much (if at all) during the summer over the Sahara (Fig. 9) and the surface is dry with little to no evaporation, the only way precipitable water can increase over the Sahara is by transport via the regional circulation. Figures 10a–c show 925-hPa July–September climatological geopotential heights and moisture flux transport, qv, for the reanalyses. While there are some differences in the magnitudes among the reanalyses, the primary circulation features include a monsoon trough extending across the continent centered along 19°N just south of the orography, and a ridge of higher heights centered over Tunisia and the Mediterranean Sea. These features are accompanied by strong, low-level southwesterly moisture flux from the Gulf of Guinea into the monsoon trough over West Africa, as well as strong northerly moisture flux over the eastern Sahara of Egypt and Libya on the eastern flank of the high pressure ridge.

July–September 925-hPa geopotential height and qv trends for the three reanalyses are shown in Figs. 10d–f. All three reanalyses are in agreement, with positive geopotential height trends south of 20°N and negative trends north of 20°N. This trend pattern can be interpreted as a northward shift of the monsoon trough during the summer, and is consistent with the results of Shekhar and Boos (2016, manuscript submitted to J. Climate). Low-level circulation changes that accompany this shift are associated with enhanced westerly/southwesterly moisture flux transport west of 15°E over the northern Sahel and southern Sahara, and reduced low-level moisture flux transport from the Gulf of Guinea onto the Guinean Coast. These results are consistent with Pu and Cook (2012), who discuss the relationship between the low-level West
African westerly jet and Sahel rainfall variability on interannual to decadal time scales, and help explain the Sahel rainfall recovery (Figs. 9c,d).

Over the northeastern Sahara there is a weakening of the low-level northerly moisture flux over Libya and Egypt associated with a weakening of the ridge over the Mediterranean Sea. The low-level moisture flux transport is also diverted eastward toward the Arabian Peninsula, as denoted by the easterly component of the $q_v$ trend vectors, suggesting that warming over the Arabian Peninsula may also be influencing the low-level circulation over the easternmost Sahara. Overall, these changes signify a weakening in the low-level moisture advection over the northeastern Sahara from the Mediterranean Sea, confirming that the increases in precipitable water are primarily associated with midlevel changes over this region.

Figures 11a–c show 600-hPa July–September climatological geopotential heights and $q_v$ for the three reanalyses, while Figs. 11d–f show their trends. The dominant circulation feature in the climatology is the Saharan high centered over the northwestern Sahara (Figs. 11a–c). Anticyclonic flow around this midlevel high is associated with northwesterly/northerly moisture flux transport over Libya and Egypt on its eastern flank, and strong easterly moisture flux transport over the Sahel on its southern flank.

In terms of the midtropospheric geopotential height and $q_v$ trends, JRA-55 and MERRA2 (Figs. 11e,f) are fairly similar, with positive height trends over southern Algeria indicating a deepening of the Saharan high/thermal low system over the western Sahara accompanied by enhanced westerly/northwesterly $q_v$ over the northern and northeastern Sahara. Thus, there is an increased moisture flux transport from the northwestern Sahara and Mediterranean Sea over the northeastern Sahara associated with the strengthening of the Saharan high. Over the Sahel between 15° and 20°N, $q_v$ is also enhanced, and is associated with an intensification of the African easterly jet (AEJ), which is consistent with findings in CV15. The intensification of the AEJ is

![Fig. 9. July–September climatological precipitation (mm day$^{-1}$) for the (a) CRU and (b) GPCP observational datasets. Also shown are July–September precipitation trends (mm day$^{-1}$ decade$^{-1}$) for the (c) CRU, and (d) GPCP datasets. Stippling denotes significance at the 90% level of confidence after accounting for autocorrelation.](image_url)
helping to transport moisture out of the central Sahel at midlevels, in agreement with Cook (1999), who discusses the role of the AEJ in influencing precipitation over the Sahel.

ERAI midtropospheric trends are a little different from JRA-55 and MERRA2 (Fig. 11d), as the maximum positive height trends are centered farther to the southeast over southern Chad instead of over southern Algeria. As a
result, trends in $qv$ over the Sahel in ERAI differ from JRA-55 and MERRA2 with only a weak intensification of the AEJ. Over the Mediterranean Sea, negative height trends are also a little stronger, resulting in enhanced westerly moisture transport over the northern Sahara. The amount of moisture transported over the northern Sahara is much less than it is for the other two reanalyses. Finally, we briefly examine the amplified warming signal minimum over the Sahara in June in Fig. 3. Figures 12a–d show June climatological surface temperatures for CRU, ERAI, JRA-55, and MERRA2, while Figs. 12e–h show the corresponding trends. All of the datasets indicate the largest warming trends over the western Sahara and Morocco, and over Chad and Sudan,
but the magnitudes of the warming trends are less than the July–September trends (Fig. 4). Elsewhere over the Sahara, trends are less than the tropical mean trend. All the reanalyses also indicate a weak cooling trend for the central Sahara, though it is more spatially confined to Libya in MERRA2 and JRA-55.

Figures 13a–c show June 600-hPa climatological geopotential heights and $qv$ for the reanalyses, while Figs. 13d–f show the corresponding trends. All three reanalyses agree that positive 600-hPa geopotential height trends are collocated with the surface temperature maxima, while there are negative height trends over the northeastern Sahara and eastern Mediterranean Sea. This pattern indicates a westward shift of the Saharan high at midlevels during June. Associated with this westward repositioning of the Saharan high, northerly/northwesterly moisture flux into the northeastern Sahara of Libya and Egypt decreases, resulting in less midlevel moisture advection relative to July–September. That being said, it is still not completely clear how these changes are associated with a minimum in the amplified warming over the Sahara. To better understand these relationships requires additional analysis at submonthly time scales, which is beyond the scope of this current study.

6. Summary and conclusions

Five atmospheric reanalyses (ERAi, JRA-55, MERRA, MERRA2, and NCEP2) and three observational datasets...
(CRU, GHCN, and GPCP) are examined to evaluate the seasonality of the 1979–2015 Sahara Desert amplified warming signal to deepen our physical understanding of the amplification processes and the implications for Sahel rainfall.

At the annual mean time scale there is strong agreement among the reanalyses and observational datasets analyzed that the Sahara Desert is warming faster than the tropical mean warming rate. This amplification is estimated to be 2.3–5.1 times greater than the tropical mean trend for the 1979–2015 period, which is consistent with CV15, who use a shorter analysis period (i.e., 1979–2012) and examined fewer datasets. While there are differences among the datasets regarding the spatial

FIG. 13. As in Fig. 11, but for June.
distribution of the annual mean amplified warming (Fig. 1), the largest amplification occurs over the central Saharan orography, which agrees with studies that suggest that elevation is an influential factor for amplified warming associated with greenhouse gas forcing (Beniston et al. 1997; Beniston 2003; Seidel and Free 2003; Wang et al. 2014; Pepin et al. 2015).

An evaluation of the annual-mean surface heat balance trends confirms that the amplified warming is associated with the mechanism described by CV15. For the tropical mean, the largest trends in the surface heat balance components are positive latent heat flux trends balanced by negative trends in the residual term, presumably associated with the redistribution of heat within the ocean. In contrast, for the Sahara Desert, trends in both the latent heat flux and the redistribution of heat within the surface are extremely small and the warming results from changes in the upward longwave and downward longwave fluxes, which are tightly coupled to each other. Furthermore, based on the reanalyses analyzed here, it is inconclusive whether the changes in downward longwave fluxes are due to changes in column water vapor trends at the annual mean time scale. In this case three reanalyses (i.e., JRA-55, MERRA2, and NCEP2) suggest that it could be playing a role, while the other two reanalyses indicate the opposite (i.e., ERAI and MERRA). This result is also consistent with CV15.

Analyzing trends of the annual mean values does not take into account the distinct seasonality of the northern African climate, and it may mask seasonally varying physical processes. Here, the Sahara amplification is investigated on seasonal time scales. Results from this analysis indicate that, aside for June in ERAI and MERRA2, the Saharan warming trend exceeds the tropical mean warming trend in all months. An ensemble mean of the reanalyses (Fig. 3c) indicates that the Saharan warming trend is amplified and fairly uniform at about +0.3 K decade$^{-1}$ from October to May. During June, the warming trend decreases to less than +0.2 K decade$^{-1}$, which is only 50% greater than the tropical mean trend for this month. The Saharan warming trend in July–October is much larger than the annual rate, peaking in September at around +0.5 K decade$^{-1}$ and associated with an increase in atmospheric water vapor content over the Sahara during the summer (Fig. 3d). Thus, the enhanced precipitable water during July–September is associated with an additional amplification of the Saharan surface temperature, above the expected level of the amplified warming during the dry season.

An evaluation of the July–September surface radiation balance for ERAI, JRA-55, and MERRA2 results in two different surface heat balance scenarios. The Saharan warming trend in ERAI is primarily due to a decrease in SH and $R$ loss from the surface as there is a strong drying trend over the Sahel in this reanalysis and a limited increase in atmospheric moisture content over the Sahara (Fig. 8a). In contrast, while there are some spatial differences, the Saharan warming trends in JRA-55 and MERRA2 are associated with positive LW$_{\text{net}}$ trends due to an increase in LW$_{\text{down}}$ over most of the Sahara. In both of these reanalyses there is a significant increase in precipitable water over the Sahel and Sahara in the summer (Figs. 8b,c).

Observed July–September precipitation trends in CRU and GPCP are used as a proxy for observations of precipitable water trends over the Sahel to evaluate which of the above trend scenarios is more plausible. Results from this comparison indicate that July–September Sahel precipitable water trends in JRA-55 and MERRA2 are consistent with the observed Sahel rainfall recovery over the past 37 years shown in Fig. 9 and discussed in the literature (Nicholson 2005; Hagos and Cook 2008; Lebel and Ali 2009; Evan et al. 2015; Sanogho et al. 2015; Dong and Sutton 2015; Park et al. 2016). This is not the case for ERAI, however, where Sahel precipitable water trends are negative (i.e., drying). Thus, more confidence is placed in the MERRA2 and JRA-55 surface heat balance trend patterns.

The positive atmospheric moisture trend over the Sahara is associated with increases at both low levels (i.e., from the surface to 800 hPa) and midlevels (i.e., 800–400 hPa), with orography playing a pivotal role. South and west of the Atlas, Ahaggar, Tibesti, and Marra Mountains, low-level precipitable water changes are most important, while precipitable water trends north and east of these mountain ranges are primarily associated with changes at midlevels.

The changes in atmospheric moisture content can be related to changes in the thermal low/Saharan high circulation system that dominates the summer climatology over the Sahara. At low levels, increases in precipitable water over the southern Sahara and western Sahel are associated with a northward shift of the low-level thermal low trough (Fig. 10) and, hence, an increase in low-level westerly/southwesterly moisture transport from the Atlantic due to a stronger meridional height gradient between the strongly warming Sahara and the Sahel. This additional low-level moisture over the Sahel is associated with increased Sahel rainfall (the Sahel rainfall recovery), which in turn cools the surface over the Sahel and further intensifies the meridional surface temperature gradient between the Sahara and Sahel. At midlevels, the increase in precipitable water over the northeastern Sahara is associated with an intensification of the Saharan high, which is the divergent outflow of the thermal low system. The stronger anticyclone is associated with an increase in moisture flux transport.
over the northeastern Sahara from the northwestern Sahara and Mediterranean Sea. Thus, there is a positive feedback during the summer months by which Saharan surface warming is amplified even more than during the dry season due to the increased transport of moisture over the Sahara via the intensification of the thermal low/Saharan high circulation system. Future work is still needed to develop a more complete understanding of the Sahel rainfall increase by evaluating the atmospheric moisture budget.

The minimum amplified warming during June is also briefly examined. Results indicate that the midtropospheric Saharan high is shifted westward toward 10°W, accompanied by weaker midtropospheric atmospheric moisture flux over the northeastern Sahara during June, but it is still not completely clear how this is associated with a minimum in the amplified warming. Additional analysis at submonthly time scales is needed in the future to reconcile why the amplified warming in June is much less than during the other months of the year.

This study shows that two processes are operating over the annual cycle to cause the observed amplification of Saharan surface warming. The first is a “dry process” that promotes amplified warming over the Sahara relative to the rest of the tropics when latent heating/evaporative cooling is disabled during November–May. The second is a “wet process” that occurs during the summer months with a peak during August. Increases in atmospheric moisture content over the Sahara amplify surface warming by increasing the longwave back radiation. Both regimes are contributing to the overall amplified warming over the Sahara from 1979–2015, with the amplification being much greater during the summer.

Finally, the relevance of these results may not be limited to the Sahara. Other arid regions of the world including Australia, the Kalahari of southern Africa, western Pakistan/northern India, and the southwestern United States have atmospheric circulation features including a thermal low system develop during the warm season. More work is needed to better understand how the dry and wet processes operate to impact amplified warming over these regions.

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