



A Review of Drought in the Middle East and Southwest Asia

MATHEW BARLOW,^{*} BENJAMIN ZAITCHIK,⁺ SHLOMIT PAZ,[#] EMILY BLACK,[@]
JASON EVANS,[&] AND ANDREW HOELL^{**}

^{*}*Department of Environmental, Earth, and Atmospheric Sciences, University of Massachusetts Lowell, Lowell, Massachusetts*

⁺*Department of Earth and Planetary Sciences, Johns Hopkins University, Baltimore, Maryland*

[#]*Department of Geography, University of Haifa, Haifa, Israel*

[@]*Department of Meteorology, University of Reading, Reading, United Kingdom*

[&]*Climate Change Research Centre, University of New South Wales, Kensington, Australia*

^{**}*Department of Geography, University of California, Santa Barbara, Santa Barbara, California*

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ABSTRACT

The Middle East and southwest Asia are a region that is water stressed, societally vulnerable, and prone to severe droughts. Large-scale climate variability, particularly La Niña, appears to play an important role in regionwide droughts, including the two most severe of the last 50 years—1999–2001 and 2007/08—with implications for drought forecasting. Important dynamical factors include orography, thermodynamic influence on vertical motion, storm-track changes, and moisture transport. Vegetation in the region is strongly impacted by drought and may provide an important feedback mechanism. In future projections, drying of the eastern Mediterranean region is a robust feature, as are temperature increases throughout the region, which will affect evaporation and the timing and intensity of snowmelt. Vegetation feedbacks may become more important in a warming climate. There are a wide range of outstanding issues for understanding, monitoring, and predicting drought in the region, including dynamics of the regional storm track, the relative importance of the range of dynamical mechanisms related to drought, the regional coherence of drought, the relationship between synoptic-scale mechanisms and drought, the predictability of vegetation and crop yields, the stability of remote influences, data uncertainty, and the role of temperature. Development of a regional framework for cooperative work and dissemination of information and existing forecasts would speed understanding and make better use of available information.

1. Introduction

The Middle East and southwest Asia are a highly water-stressed region with reduced societal resilience resulting from economic and political challenges. As a result, severe drought in the region can have complex impacts, ranging beyond direct impacts on crops and livestock to an array of indirect impacts associated with sanitation, nutrition, loss of livelihood, displaced populations, and international disputes. As an example, the catastrophic 1999–2001 drought resulted in impacts spanning crop failures; widespread livestock death; significant population migrations; increases in diseases

(polio, cholera, diphtheria, typhoid, and tuberculosis); soil and land cover degradation; loss of orchards and fruit trees both as a result of direct drought impacts and through use as fuel; desiccation of internationally important wetlands; increase in household debt, with a disproportionate impact on women and children; and international boundary disputes over both river flows and refugees (Agrawala et al. 2001; Lautze et al. 2002). In terms of standardized precipitation deficits, this regional drought comprised the most severe area of drought in the world during this period (Fig. 1). (Datasets are described in figure captions.) Moreover, future drought impacts may be even worse, as consensus model projections suggest an overall drying trend for much of the region (IPCC 2013a). Understanding the dynamics, predictability, and trends of droughts in this region is, therefore, a critically important problem. This review assesses the current understanding of drought in this sensitive region with regard to both the

Corresponding author address: Mathew Barlow, Department of Environmental, Earth, and Atmospheric Sciences, 1 University Ave., University of Massachusetts Lowell, Lowell, MA 01854.
E-mail: mathew_barlow@uml.edu

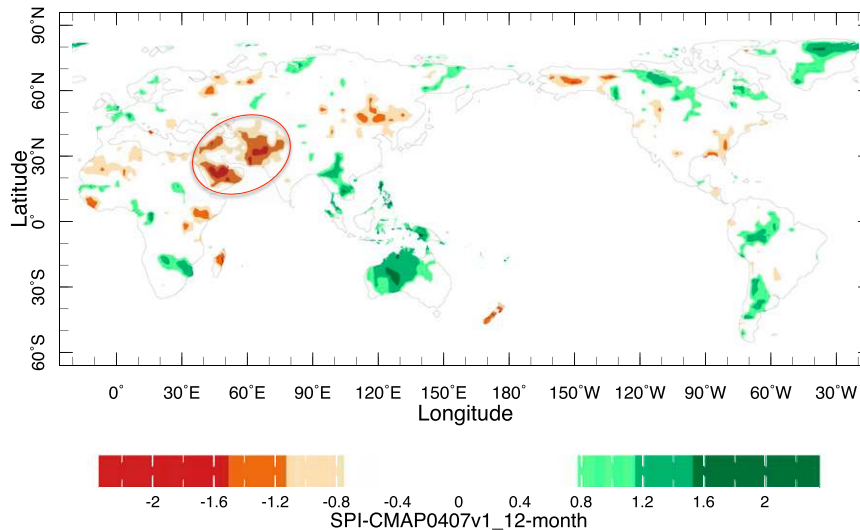


FIG. 1. The 1999–2001 drought, as measured by the 12-month standardized precipitation index (SPI), calculated based on precipitation from the CPC Merged Analysis of Precipitation (CMAP; Xie and Arkin 1996, 1997), relative to the 1979–2010 period. The red oval denotes the focus area for this review.

historical record and future projections and identifies outstanding questions. In addition to drought research, previous results with respect to the region's climatology, hydrology, vegetation, and precipitation processes that are not focused specifically on drought but are relevant to understanding drought are also surveyed.

The terms “Middle East” and “southwest Asia” both have varying definitions. For the purposes of this study, the region considered extends from the east coast of the Mediterranean Sea through Pakistan, along with the Arabian Peninsula, and includes the following countries (Fig. 2): Israel, Lebanon, Syria, Jordan, Saudi Arabia, Oman, Qatar, the United Arab Emirates, Kuwait, Bahrain, Yemen, Iraq, Iran, Afghanistan, Tajikistan, Uzbekistan, Kyrgyzstan, Turkmenistan, and Pakistan. This area is chosen to be relatively broad while considering an area of generally similar climate (although ranging from Mediterranean climate to semiarid and arid conditions) that is influenced by regionwide drought mechanisms. The region includes an arc of relatively fertile land, the Fertile Crescent, which is indicated schematically on Fig. 2 along with the definitions of Middle East and southwest Asia used in this review.

As discussed further in the next section, the climate of the region is generally semiarid to very arid, including several deserts, but annual precipitation does exceed 60 cm along the eastern Mediterranean region and on many of the mountain slopes in the region and ranges as high as 180 cm in a small region on the southern coast of the Caspian Sea. Over much of the region, precipitation primarily comes during the cold season (November–

April) from synoptic storms, although there are exceptions, including the importance of the summer monsoon in Pakistan and southeastern Afghanistan and the extension of the African summer monsoon/intertropical convergence zone (ITCZ) into the southern coast of the Arabian Peninsula. Because of its common importance for most of the region, drought variability associated with cold season precipitation processes is a particular focus of this review.

Large-scale and subsistence farming as well as pasturing are common throughout the region (e.g., Ryan et al. 2012; Ramankutty et al. 2008), so the region's precipitation, though modest in many areas, is very important. The combined effects of water scarcity (Oki and Kanae 2006) and frequent drought over the Middle East and central-southwest Asia (Mishra and Singh 2010) affect crop yields and the regional economy (Kaniewski et al. 2012), which increases the potential for the loss of life and property (Agrawala et al. 2001).

Despite the aridity of the region, it is generally well populated outside of the highest mountains and desert regions, with an estimated population density (Fig. 3, top) similar to the southeast United States or South Africa. Within the region, there are areas of high poverty and societal vulnerability; one measure of poverty, infant mortality, is shown in Fig. 3, bottom. This vulnerability is particularly evident during severe droughts, as noted above. Moreover, given the long-standing socio-political tensions in several areas of the region in an environment of limited resources, drought variability may raise the risk of regional conflicts (El Kharraz et al. 2012;

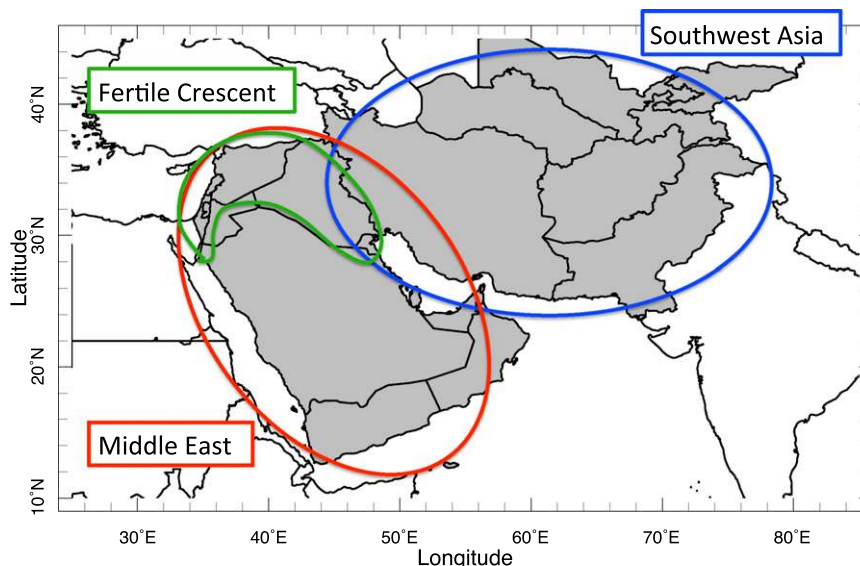


FIG. 2. Countries considered here (in gray) along with approximate definitions of three subdomains often focused on in regional studies (Middle East, in red; Fertile Crescent, in green; and southwest Asia, in blue). Definitions of these regions vary considerably: more expansive definitions of the Middle East include the entire domain; more restrictive definitions focus on the coastal countries. The region as a whole is also sometimes referred to as western Asia.

Selby and Hoffmann 2012; Fröhlich 2013; Gleick 2014; Kelley et al. 2015). In terms of the impacts of drought, therefore, the region is particularly important because of the intersection of population, vulnerability, drought severity, and potential aridification under climate change.

Here we review the current state of understanding of drought in the region, considering regional climate in section 2, historical drought episodes in section 3, drought dynamics in section 4, predictability in section 5, and trends and projections in section 6. The review concludes with a summary, including critical research questions for future studies of drought in the region.

2. Regional climate

To provide context for the consideration of drought dynamics, an overview of the regional climate is given. The spatial distribution and seasonality of precipitation, vegetation, and hydrology are reviewed, as well as the primary atmospheric circulation and precipitation mechanisms that constitute the processes through which drought can be expressed.

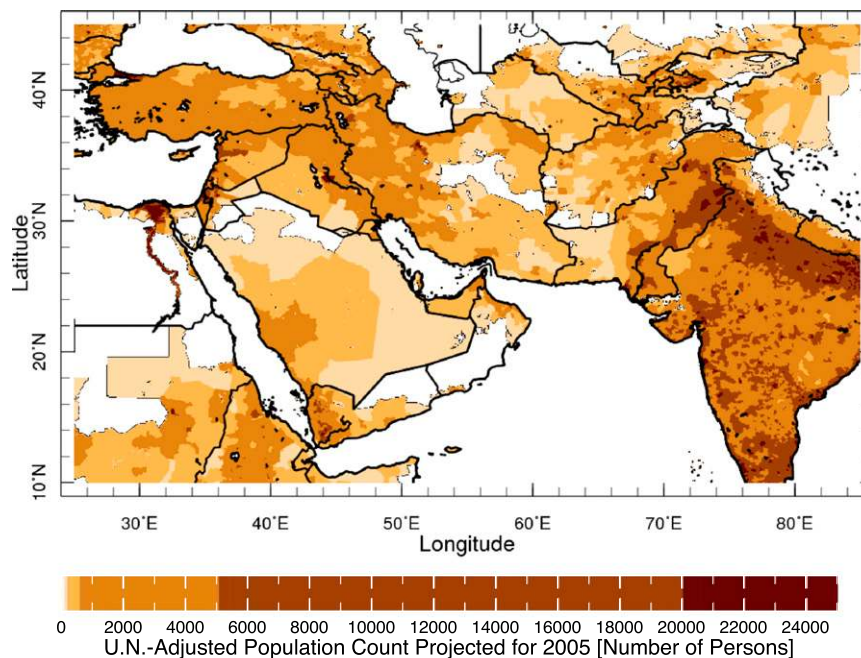
a. Distribution and seasonality of precipitation, hydrology, and vegetation

The annual mean precipitation is shown in Fig. 4a. The largest amounts occur in five main areas: the coastal eastern Mediterranean Sea, the western slopes of the Zagros Mountains in Iran and Iraq, the south coast of

the Caspian Sea, the slopes of the mountain complex on the western edge of the Tibetan Plateau (the Hindu Kush, the Pamir, and the Tian Shan ranges), and the southern tip of the Arabian Peninsula. There is also significant precipitation in the Fertile Crescent, which arcs from the coastal Mediterranean Sea across southeastern Turkey, northern Syria and Iraq, and into northeastern Iran along the western Zagros (Fig. 2). The spatial distribution of precipitation is closely linked to the very significant topography of the region (Fig. 4b), especially the western slopes of the mountains, as much of the regional precipitation occurs during the cold season as a result of orographic capture from eastward-moving storm systems (Martyn 1992) guided by the upper-tropospheric westerlies (Krishnamurti 1961; Schiemann et al. 2009). The distribution of precipitation is a strong control on regional vegetation (Fig. 4c), which has implications for drought feedbacks, as discussed in section 4e. The region also includes areas of little to no precipitation, including several major deserts (nomenclature varies): the Negev in southern Israel; the Syrian Desert, inland from the coastal Mediterranean Sea; the Arabian Desert, over much of the Arabian Peninsula; the Iranian salt deserts in interior and eastern Iran; the Thar Desert in northwestern India and parts of eastern Pakistan; the Registan Desert centered on southwestern Afghanistan; and the Kara-Kum, centered in Turkmenistan.

Throughout the Middle East and southwest Asia, interannual variability in rainfall is high. The ratio of the standard deviation to the mean (the coefficient of

Population Estimate



Poverty Estimate (infant mortality rate)

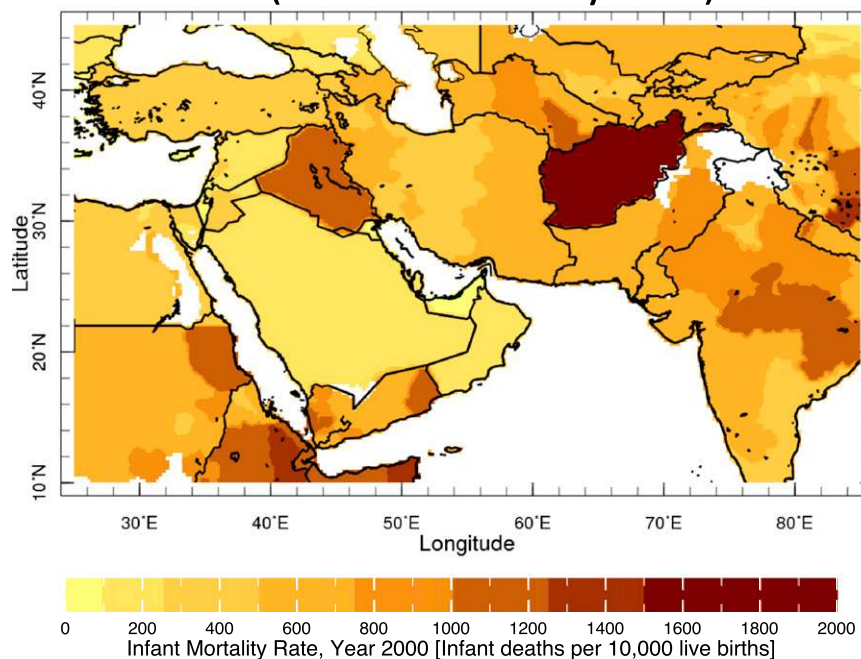


FIG. 3. (top) Population count and (bottom) poverty estimates. Estimated infant mortality rate (infant deaths per 10 000 live births) is used here as a measure of poverty. The unit of population is number of persons and the unit of infant mortality rate is infant deaths per 10 000 live births. Both the population data and the infant mortality rate are from the Center for International Earth Science Information Network (CIESIN), Columbia University ([Center for International Earth Science Information Network 2005](#)).

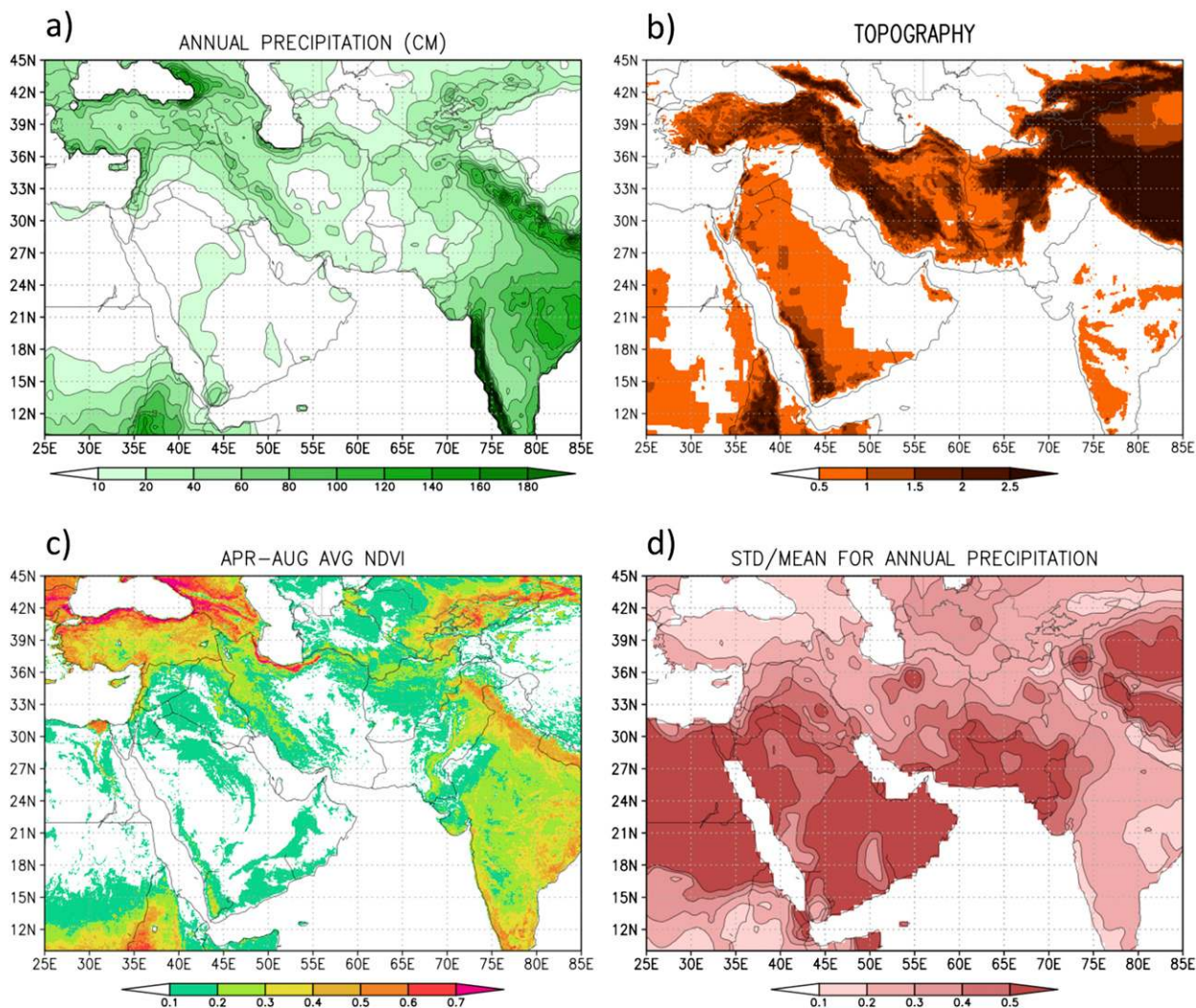


FIG. 4. (a) Annual mean precipitation (cm), (b) elevation (km), (c) growing season vegetation, and (d) coefficient of variation for annual precipitation (ratio of the standard deviation to the mean). The contour intervals for precipitation and elevation are 10 cm and 0.5 km, respectively. The growing season vegetation is estimated by April–August normalized difference vegetation index (NDVI). Both NDVI and the coefficient of variation are unitless ratios, with contour intervals of 0.1 in both cases. The NDVI is shaded from light green (least vegetative vigor) to red (most vigor) to allow visual discrimination of the large range in vegetative vigor over the region. The GPCC version 6 dataset (Schneider et al. 2014; Rudolf et al. 2003) is used for precipitation, with the averaged calculated for the 1951–2010 period. The Global Inventory Modeling and Mapping Studies (GIMMS) NDVIg dataset (Pinzon et al. 2005; Tucker et al. 2005), produced by the Global Land Cover Facility (GLCF) at the University of Maryland, College Park, is used for NDVI for the 1981–2006 period. The ETOPO5 dataset (NOAA 1988) is used for topography.

variation) for annual precipitation is shown in Fig. 4d, with most of the region having values larger than 20% (and often much larger). Most of the highest values are in regions with little to no precipitation or at the margins of those regions (cf. Fig. 4a). As an example of variability, the annual precipitation for Jerusalem is shown in Fig. 5 for 1950–2012; the standard deviation is 31% of the mean, and the annual values span more than a fivefold range in that period, from a minimum of 21 cm to a maximum of 113 cm.

Analysis of precipitation is limited by sparse observations and the presence of steep precipitation gradients associated with the extreme terrain. Figure 6 shows the amount of monthly station observations that underlie the gridded data in the GPCC dataset for the 1951–2010 period, as used in Fig. 4 and Table 1. In addition to the poor spatial coverage in many parts of the domain, there is considerable temporal variability in coverage as well (Hoell et al. 2015). A comprehensive analysis of available precipitation data for the entire region has not yet

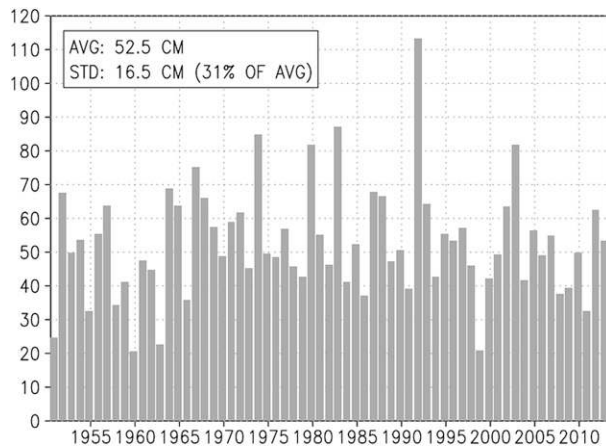


FIG. 5. Annual precipitation (cm) in Jerusalem for 1950/51–2012/13. The precipitation data were obtained from the Israel Meteorological Service.

been done, but the northern part of the domain was considered in [Schiemann et al. \(2008\)](#), Kuwait was considered in [Marcella and Eltahir \(2008\)](#), Saudi Arabia in [Almazroui \(2011\)](#), and Iran in [Katirae-Boroujerdy et al. \(2016\)](#) for a range of different datasets and sources. In general, data agreement among observed gridded datasets is good enough for qualitative identification of wet

and dry years but has a large range of uncertainty for quantitative analysis; model products and satellite estimates can provide value, especially in real-time monitoring, but have even more uncertainty. The high values of precipitation along the southern shore of the Caspian Sea are poorly represented in some observed gridded data as well as in model and satellite estimates. Despite the uncertainties, the large-scale variability appears to be well captured by the available data in the high mountains, where the precipitation is mainly from synoptic-scale systems that are well observed upstream and with precipitation strongly constrained by the orography. That is, while the spatial details of the pattern may not be well resolved, the basin-averaged amounts appear to be adequately represented ([Schär et al. 2004](#); [Barlow and Tippett 2008](#)).

The seasonal cycle of precipitation is shown in [Fig. 7](#), in terms of both seasonal amount (left panels) and percentage of annual mean (right panels; brown shading indicates seasonal values less than one-quarter of the annual mean, and green shading indicates values more than one-quarter of the annual mean). There are three main precipitation mechanisms in the region: cold season synoptic precipitation, which is important for much of the region; summer monsoon precipitation, which is

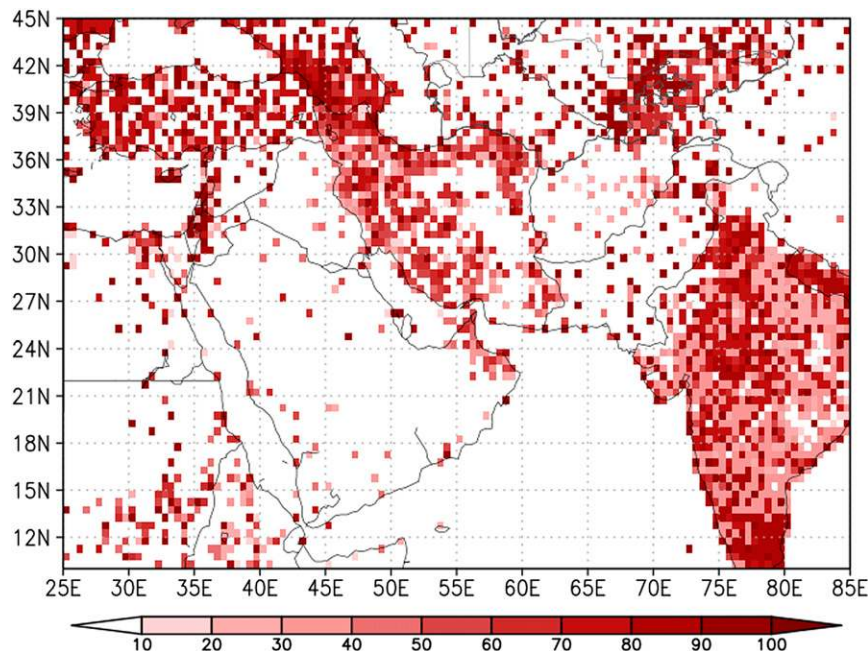


FIG. 6. Station data availability underlying the GPCC version 6 dataset, as in [Fig. 4](#), for the 1951–2010 period, on the 0.5°-resolution grid. The availability is given in terms of the percent of months in the 60-yr period that have at least one station report per grid box for each month. That is, a value of 100 for an individual grid box indicates that for each month in the period, there was at least one station report within the area of the grid box, whereas a value of 0 indicates that all the monthly values in the period for that grid box were based on interpolation.

TABLE 1. Cross correlation of country-averaged annual precipitation for 1951–2010. Correlations ≥ 0.5 shown in bold and results are rounded to one decimal for clarity. Precipitation is from the GPCC dataset, as in Fig. 4.

	Saudi Arabia														United Arab Emirates			
	Kyrgyzstan	Turkmenistan	Uzbekistan	Tajikistan	Afghanistan	Pakistan	Syria	Lebanon	Israel	Iraq	Iran	Jordan	Kuwait	Qatar	Emirates	Bahrain	Oman	Yemen
Kyrgyzstan	1.0	0.6	0.7	0.8	0.0	−0.3	0.2	0.1	−0.1	0.0	0.1	0.1	0.0	−0.1	−0.1	−0.1	−0.2	0.0
Turkmenistan	0.6	1.0	0.9	0.7	0.3	0.0	0.4	0.4	0.1	0.2	0.3	0.4	0.1	0.1	0.1	0.1	−0.1	0.0
Uzbekistan	0.7	0.9	1.0	0.8	0.2	0.0	0.3	0.3	0.0	0.1	0.2	0.3	0.0	0.0	0.0	0.0	0.0	−0.1
Tajikistan	0.8	0.7	0.8	1.0	0.2	−0.2	0.3	0.2	0.0	0.2	0.3	0.3	0.0	0.1	0.1	0.1	−0.1	0.0
Afghanistan	0.0	0.3	0.2	0.2	1.0	0.5	0.2	0.1	0.2	0.4	0.3	0.6	0.1	0.3	0.4	0.5	0.4	0.3
Pakistan	−0.3	0.0	0.0	−0.2	0.5	1.0	−0.1	0.0	0.0	0.2	0.0	0.1	0.1	0.1	0.3	0.3	0.2	0.4
Syria	0.2	0.4	0.3	0.3	0.2	−0.1	1.0	0.8	0.6	0.4	0.7	0.6	0.7	0.4	0.2	0.2	0.1	0.2
Lebanon	0.1	0.4	0.3	0.2	0.1	0.0	0.8	1.0	0.7	0.2	0.5	0.4	0.6	0.2	0.1	0.0	0.1	0.0
Israel	−0.1	0.1	0.0	0.0	0.2	0.0	0.6	0.7	1.0	0.2	0.6	0.4	0.8	0.2	0.1	0.1	0.0	0.2
Saudi Arabia	0.0	0.2	0.1	0.2	0.4	0.2	0.4	0.2	0.2	1.0	0.5	0.6	0.3	0.5	0.6	0.6	0.4	0.4
Iraq	0.1	0.3	0.2	0.3	0.3	0.0	0.7	0.5	0.6	0.5	1.0	0.8	0.6	0.6	0.2	0.4	0.3	0.2
Iran	0.1	0.4	0.3	0.3	0.6	0.1	0.6	0.4	0.4	0.4	0.8	1.0	0.4	0.7	0.4	0.6	0.5	0.3
Jordan	0.0	0.1	0.0	0.0	0.1	−0.1	0.7	0.6	0.8	0.3	0.6	0.4	1.0	0.2	0.1	0.2	0.1	0.0
Kuwait	−0.1	0.1	0.0	0.1	0.3	0.1	0.4	0.2	0.2	0.5	0.6	0.7	0.2	1.0	0.3	0.3	0.1	0.2
Qatar	−0.1	0.1	0.0	0.1	0.4	0.3	0.2	0.1	0.1	0.6	0.2	0.4	0.1	0.3	1.0	1.0	1.0	0.4
United Arab Emirates	−0.1	0.1	0.0	0.1	0.5	0.3	0.3	0.0	0.1	0.6	0.4	0.6	0.2	0.3	0.8	1.0	0.7	0.2
Bahrain	−0.1	0.1	0.0	0.1	0.4	0.2	0.2	0.1	0.1	0.6	0.3	0.5	0.1	0.3	1.0	1.0	0.7	0.3
Oman	−0.2	−0.1	−0.1	−0.1	0.3	0.4	0.1	0.0	0.0	0.4	0.2	0.3	0.0	0.1	0.4	0.5	0.3	1.0
Yemen	0.0	0.0	−0.1	0.0	0.1	0.1	0.2	0.1	0.2	0.4	0.2	0.2	0.2	0.2	0.2	0.1	0.6	1.0

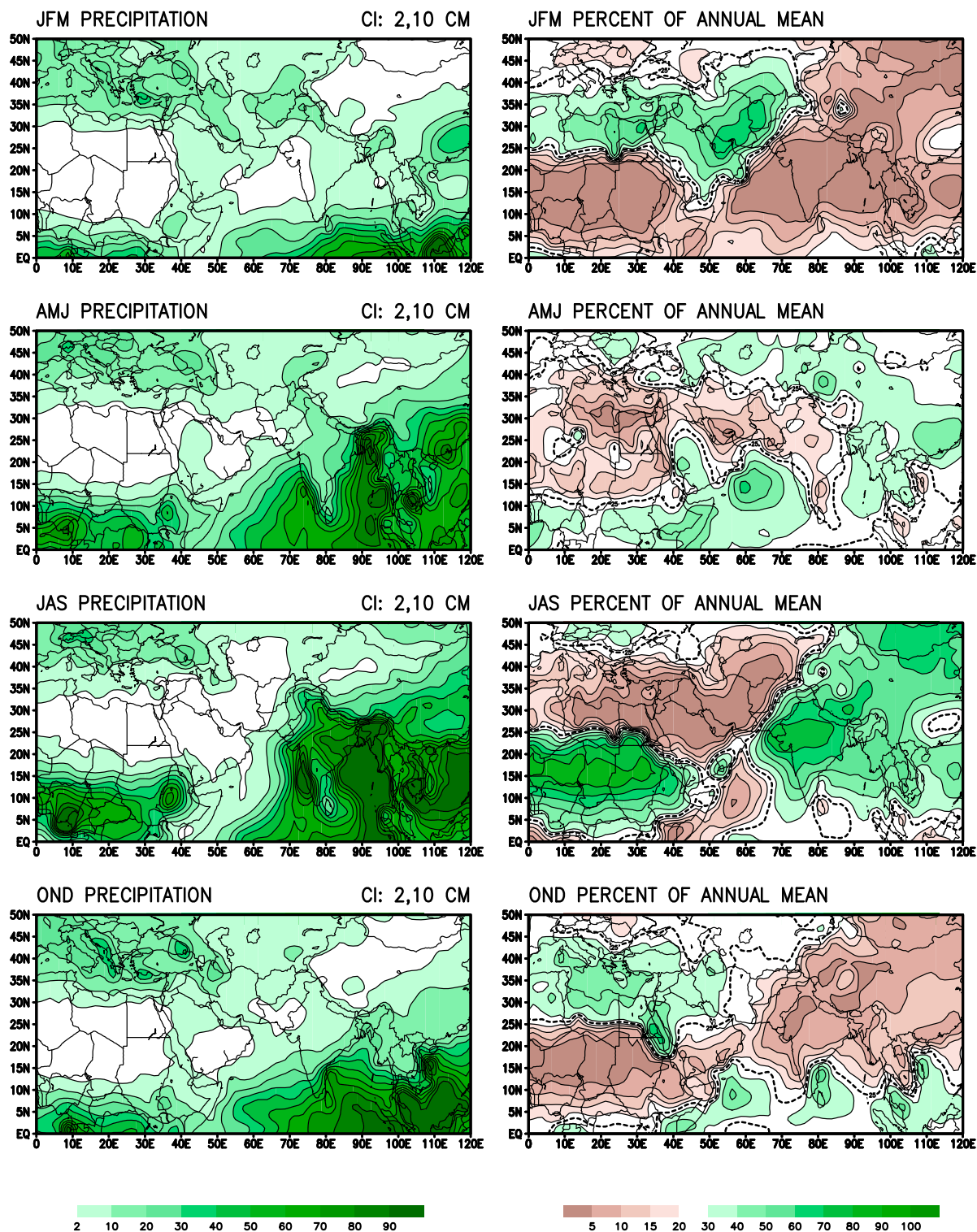


FIG. 7. Seasonal cycle of precipitation, in terms of (left) total values and (right) percent of annual mean. The total values are shown in intervals of 10 cm, with an additional first interval of 2 cm. The percent of annual mean is shown in intervals of 5% and brown shading for values <25% (the point at which all seasons would be contributing equally) and in intervals of 10% and green shading for values >25%. Calculations are based on CMAP (Xie and Arkin 1996, 1997) for the 1979–2010 period. The CMAP dataset is used here to allow inclusion of ocean precipitation.

important for Pakistan and southeastern Afghanistan; and warm season African monsoon–ITCZ precipitation extending into the southern tip of the Arabian Peninsula from Africa.

Terrestrial hydrological dynamics in the region are extremely diverse and cannot be addressed comprehensively in this review. In general, the prevailing hydrology follows precipitation gradients, with major rivers originating in relatively moist highland zones and often flowing into semiarid or arid regions. In the high mountains of the region, precipitation occurs primarily during the cold season, as snow. As there is little precipitation during the warm season, the spring melt is a primary driver of peak river flows (Schär et al. 2004; Barlow and Tippett 2008). The headwaters of the Tigris and Euphrates Rivers are in the Anatolia Plateau of Turkey and the Zagros Plateau of Iran. These mountain ranges have been found to play a key role in the production of precipitation in the Fertile Crescent region (Evans et al. 2004; Alijani 2008) and, by extension, water resources in the region. Note that the headwaters are partially out of the domain considered here so that a full consideration of hydrological drought for the Fertile Crescent requires consideration of the remote precipitation in Turkey. The waters of the Tigris and Euphrates support extensive irrigation developments in all riparian states and feed the marshlands of southern Iraq, both of which have been found to affect the local climate through their influence on evaporation (Evans and Zaitchik 2008; Marcella and Eltahir 2012b). There has not been much study of soil moisture in the region, but winter and spring precipitation and temperature have a strong influence on soil moisture in the Euphrates plain (Zaitchik et al. 2007) and likely many other parts of the region as well.

Notably, the region includes several major transboundary rivers, including the Indus, the Jordan, the Tigris and Euphrates, and the Amu Dar'ya and Syr Dar'ya, all of which are subject to intense water demands, resulting in considerable political tension. On the northern border of the region, the Aral Sea, fed by the Amu Dar'ya and Syr Dar'ya, was originally the fourth largest lake in the world but was reduced to 10% of its original size by 2007 as a result of the introduction of intensive agricultural practices (Micklin 1988; Micklin and Aladin 2008).

The geographic distribution, seasonality, and interannual variability of precipitation have a clear signal in vegetation cover and variability across the region. The growing season vegetation, as broadly represented by the April–August normalized difference vegetation index (NDVI), is shown in Fig. 4c. The largest values of April–August NDVI are in a narrow band along the

southern shore of the Caspian Sea in association with the largest values of precipitation in that region, as well as in the valleys of the Pamir and Tian Shan Mountains. In addition to the local correspondence with precipitation, there are notable anthropogenic fingerprints in the distribution of vegetation. This is true in large rivers with significant vegetation that has an irrigated or nonlocal relationship with precipitation, including the valleys of the Indus, Amu Dar'ya, Syr Dar'ya, Tigris, and Euphrates. Note that, although NDVI is an estimate of vegetative vigor, it does not necessarily reflect the most societally important areas of vegetation, given the widespread subsistence agriculture and livestock grazing through the region that occur in only moderately vegetated areas. Agriculture is sufficiently intensive in the former Soviet Union countries that changes in vegetation associated with the dissolution of the Soviet Union are evident (Kariyeva and van Leeuwen 2012).

b. Circulation and precipitation mechanisms

The upper-level winds, sea level pressure (SLP), and synoptic variability are shown in Fig. 8 for average January conditions (Figs. 8a,c,e) and July conditions (Figs. 8b,d,f). The synoptic variability is shown in terms of 2–8-day-filtered upper-level meridional wind variance, which is a good indicator of upper-level synoptic transient activity in the region, as discussed further below.

At the largest scales, the circulation changes from a cold season regime under the influence of the westerlies and associated synoptic activity to a warm season regime under the influence of the Indian monsoon. The strong westerly jet and associated synoptic activity during the cold season are seen in Figs. 8a and 8e, respectively, and the extension of the northwestern-most branch of the monsoon into northern Pakistan and southeastern Afghanistan is seen in the July–September panels of Fig. 7.

Cold season synoptic precipitation is important over much of the region and has been studied by several authors. Reconciling these previous synoptic analyses of extratropical cyclones and cyclone tracks into an overall picture is challenging, however, because of differences in spatial domain, methodology, and terminology. The transient analysis of Hoskins and Hodges (2002) provides a large-scale, general view. Over the region, they identified a prominent maximum of vertical velocity variance at midlevels and a local branch of transient activity in both meridional wind and potential temperature of the 2-PVU ($1 \text{ PVU} = 10^{-6} \text{ m}^{-2} \text{ s}^{-1} \text{ K kg}^{-1}$) surface at upper levels, similar to the branch of transient activity shown in Fig. 8e. Their dynamically oriented analysis found that the principal track at upper levels is from the Atlantic and the principal track at lower levels

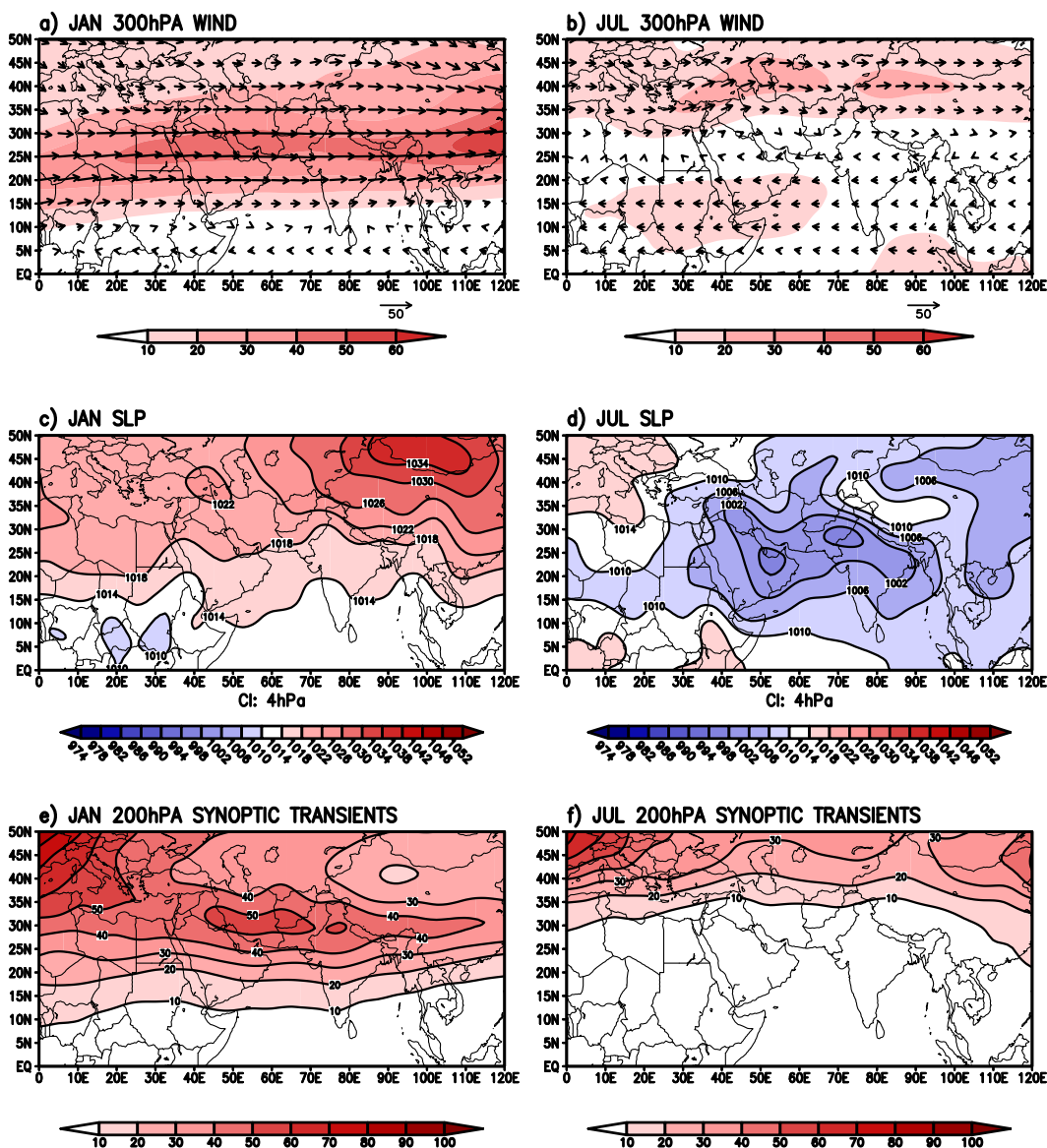


FIG. 8. (left) January and (right) July circulation fields: (a),(b) 300-hPa wind (vectors and speed colored shading); (c),(d) SLP; and (e),(f) 200-hPa synoptic transients. A 2–8-day-filtered 200-hPa meridional wind variance is used as the estimate of upper-level synoptic transients. The contour interval for wind speed is 10 m s^{-1} , SLP is 4 hPa, and synoptic transients is $10 \text{ m}^2 \text{ s}^{-2}$. The calculations are based on the NCEP–NCAR reanalysis (Kalnay et al. 1996) for the 1951–2010 period.

is from the Mediterranean Sea—these results provide a reasonable regional-scale perspective.

More local analyses have shown considerable detail in the structures of these general paths. The cyclone tracks affecting the Fertile Crescent can be grouped into two main routes: south of Turkey toward the Caspian Sea and near Jordan or Syria toward the Persian Gulf (Trigo et al. 1999). Systems are relatively frequent but precipitation occurs only with strong surface frontal activity associated with the strongest systems (Trigo et al. 1999).

For the Middle East, Cyprus lows are more important for precipitation than are Black Sea or Atlas lows. Troughs traveling along the subtropical jet stream can also generate isolated thunderstorms without strong surface fronts via inducing onshore flows from the Persian Gulf (Trigo et al. 2010). A local maximum of cyclogenesis associated with the relatively warm surface of the Caspian Sea and with Caucasus lee waves modulates the pressure field over the southern part of western Asia (Lambert et al. 2002; Paz et al. 2003). Occasionally, Red

Sea troughs propagate from the south, and when they coincide with extratropical cyclones entering from the west, there can be devastating floods. This happened, for example, in November 1994 (Krichak et al. 2000; Ziv et al. 2005a). At the margins of the rainy season, Red Sea troughs play a greater role, with most rainy events resulting from a northward extension of this low (Tsvieli and Zangvil 2005). Both the eastern Mediterranean upper trough and the Red Sea trough are important along the southeastern coast of the Arabian Peninsula (Charabi and Al-Hatrushi 2010). Tropical cyclones are also an infrequent source of precipitation in that region (Al-Rawas and Valeo 2009).

The synoptic tracks affecting the southwest Asia part of the domain have not been studied as much as the Middle East part of the domain. Barlow et al. (2006) showed, for heavy precipitation events in Afghanistan, a westerly track into southwest Asia consistent with the branch of transient activity shown in Fig. 8e, as did Cannon et al. (2016) for precipitation in the western Himalayas and Karakoram.

In the summer, the Indian monsoon, in addition to directly affecting northern and southeastern Pakistan, appears to also remotely influence precipitation over the northern part of the domain via an influence on temperature and stability (Schiemann et al. 2007). It has also been suggested that the Indian monsoon may remotely force subsidence over the region (Rodwell and Hoskins 1996, 2001), with orographic interaction playing an important role (Rodwell and Hoskins 2001; Tyrlis et al. 2013; Simpson et al. 2015), and observational data supports this relationship during the monsoon onset (Saini et al. 2011) and peak phase (Ziv et al. 2004). However, this influence occurs after most of the seasonal decline in precipitation has already occurred for much of the region. The degree to which the end of the wet season is due to an increase in inhibiting factors, such as the remote forcing of the monsoon or its tropical precursors, versus a decrease in precipitation-generating factors, such as the northward retreat and weakening of the storm track, is not yet clear.

While orography plays a primary role in generating precipitation via upslope lifting, it can play that role only if sufficient water vapor is transported into the area. The water vapor transport pathways were investigated explicitly in Evans and Smith (2006) for the Fertile Crescent. They showed that most precipitation events in that area are dominated by water vapor coming from the west over the Mediterranean Sea. However, the largest precipitation events were dominated by water vapor coming from the south where the Red Sea and Persian Gulf play a role as source regions. These southerly dominated events are able to transport large amounts of

water vapor into the Fertile Crescent through the formation of a mountain barrier jet west of the Zagros Mountains (Evans and Alsamawi 2011). This mountain barrier jet occurs over a relatively small spatial scale such that current global climate models (GCMs) are unlikely to represent the phenomena and hence are probably unable to produce an important class of precipitation event for the Fertile Crescent. Given the extreme terrain throughout most of the region and the scarcity of observations, it is not clear that current gridded global analyses adequately represent regional moisture fluxes.

The seasons in the Persian Gulf area of the region are sometimes divided into the northeast monsoon (December–March), the spring transition (April–May), the southwest monsoon (June–September), and the fall transition (October–November; Walters and Sjöberg 1988), as this area transitions from low-level northeasterly flow in the cold season to low-level southwesterly flow in the warm season. For the full study region, at low levels the northeastern extent is at the margin of the Siberian high during winter and the southern extent is under the influence of a shallow low pressure area over Saudi Arabia and southern Pakistan, typically identified as a thermal low. Over Saudi Arabia, field work shows that within the low pressure area there is subsidence to within 1 km of the surface and then ascent below that (Blake et al. 1983). However, the interaction of orography with remote dynamic forcing may contribute more to the center of the low pressure system over southern Pakistan and northwestern India than does direct sensible heating from the surface (Bollasina and Nigam 2011).

During summer, a low-level jet forms over the Persian Gulf, with orography, mountain slope, and land–sea breeze playing a role in the formation and strength of the jet (Giannakopoulou and Toumi 2012).

3. Historical droughts

This section reviews historical droughts as identified in the previous literature and in a drought disaster database.

In the 1940s–present period, the two most severe droughts for the region as a whole appear to be the 1999–2001 (Agrawala et al. 2001; Barlow et al. 2002; Lotsch et al. 2005; Trigo et al. 2010; Kaniewski et al. 2012; Hoell et al. 2012) and 2007/08 droughts (Trigo et al. 2010; Kaniewski et al. 2012; Hoell et al. 2012). (The 1999–2001 period given for the first drought indicates the period of broadest impact, but the drought extended from 1998 to 2002 for some areas of the region.) Information about more local droughts as well as droughts

TABLE 2. Drought disasters as listed in the EM-DAT disaster database (Centre for Research on the Epidemiology of Disasters 2014).

Kyrgyzstan	2009
Turkmenistan	
Uzbekistan	2000/01
Tajikistan	2000/01, 2008
Afghanistan	1969, 1971–73, 2000–02, 2006, 2008, 2011
Pakistan	1999–2003
Syria	1999–2000, 2008–10
Lebanon	
Israel	1999
Saudi Arabia	
Iraq	1969–71, 1998–2001
Iran	1964, 1999–2001
Jordan	1999, 2000
Kuwait	
Yemen	1969–71, 1975, 1977

prior to the 1940s is sparse and difficult to compare based on different definitions and data periods. As summarized in Bruins (1999), the largest precipitation deficits in Jerusalem for the 1846–1993 period are 1932/33, 1950/51, and 1959/60, all of which were less than 50% of average. For Israel as a whole, based on a hydrologic measure for the 1937–84 period, 1950/51, 1958/59, 1972/73, and 1978/79 were strong drought years. More recently, the period 2004/05–2008/09 was also very dry. The driest years for the Jordan valley identified in Black (2012) for the 1950–99 period are 1960, 1963, 1966, 1970, 1973, 1979, 1986, 1987, and 1999. Section 4d provides some new analysis of regional droughts for the 1951–2010 period in the context of regional coherence.

For an impacts-oriented perspective on historical droughts in the region, drought disasters from the Emergency Events Database (EM-DAT), the Office of U.S. Foreign Disaster Assistance/Centre for Research on the Epidemiology of Disasters (OFDA/CRED) international disaster database (Centre for Research on the Epidemiology of Disasters 2014), are shown in Table 2. A disaster is defined in this database as meeting one of the following criteria: 10 or more people reported killed, 100 or more people reported affected, declaration of a state of emergency, or a call for international assistance. While there may be some reporting issues with this database, the occurrence of a drought disaster generally tracks precipitation anomalies for Asia (Barlow et al. 2006), so it appears to be reasonable. Based on the drought disaster data, the 1999–2001 and 2007/08 droughts are the most represented, sometimes extended to 1999–2002 and 2007–10, along with more local droughts: 1969, 1971–73, and 2006 for Afghanistan; 1969–71 for Iraq; 1964 for Iran; and 1969–71, 1975, and 1977 for Yemen. Given that Yemen has a different primary

precipitation mechanism (African monsoon/summer ITCZ) from the rest of the region, it may be expected to have different drought events. Because of the geography and precipitation mechanism, it seems likely that these droughts may be synchronized with drought events in the greater Horn of Africa, but this has not been studied explicitly.

The historical droughts listed in this section were identified based on different metrics, periods, and areas within the region. A comprehensive ranking of historical drought episodes in the region, accounting for data issues, and especially with respect to the pre-1969 record, is not possible based on the previous literature but would be very useful for assessing the dynamical influences on the region, within-region relationships, and associated predictability.

4. Drought dynamics

This section reviews results related to the dynamics of drought in the region, in terms of large-scale teleconnection patterns, synoptic regimes and climatological features, mechanisms of tropical forcing, regional coherence, vegetation, and dust.

a. Large-scale teleconnection patterns

Several large-scale teleconnection patterns have been shown to have an influence on precipitation in different areas of the region:

- North Atlantic Oscillation (NAO) (Cullen and deMenocal 2000; Aizen et al. 2001; Cullen et al. 2002; Mann 2002; Krichak et al. 2002; Syed et al. 2006; Charabi and Al-Hatrushi 2010; Black 2012; Donat et al. 2014; Al Senafi and Anis 2015; Athar 2015),
- El Niño–Southern Oscillation (ENSO) (Price et al. 1998; Barlow et al. 2002; Nazemosadat and Ghasemi 2004; Mariotti et al. 2005; Syed et al. 2006; Mariotti 2007; Hoell et al. 2014a; Hoell et al. 2014b; Niranjana and Ouarda 2014; Donat et al. 2014; Yin et al. 2014; Krichak et al. 2014; Al Senafi and Anis 2015; Athar 2015),
- Madden–Julian oscillation (MJO) (Barlow et al. 2005; Nazemosadat and Ghaedamini 2010; Barlow 2011; Hoell et al. 2012; Tippett et al. 2015; Pourasghar et al. 2015),
- east Atlantic–western Russia (EA/WR) pattern (Krichak et al. 2002; Ziv et al. 2006; Yosef et al. 2009; Black 2012; Yin et al. 2014; Krichak et al. 2014)
- Indian Ocean dipole (IOD) (Chakraborty et al. 2006; Pourasghar et al. 2012; Al Senafi and Anis 2015; Athar 2015),
- North Sea–Caspian pattern (NCP) (Kutiel and Benaroch 2002; Kutiel et al. 2002; Yosef et al. 2009)

- North Africa/western Asia (NAWA) index (Paz et al. 2003; Tourre and Paz 2004)
- Mediterranean oscillation index (Yosef et al. 2009; Ziv et al. 2014),
- Pacific warm pool index (Lotsch et al. 2005; Ziv et al. 2006),
- Atlantic multidecadal oscillation (AMO) (Sheffield and Wood 2008),
- Atlantic tripole index (Lotsch et al. 2005),
- Circumglobal teleconnection (CGT) (Feldstein and Dayan 2008),
- Polar–Eurasia pattern (Yin et al. 2014), and
- west Pacific oscillation (WPO) (Aizen et al. 2001).

The strengths of these teleconnections vary considerably within the region. There are also indications of variations in the temporal stability of these relationships (Ropelewski and Halpert 1987; Price et al. 1998; Marcella and Eltahir 2008; Krichak et al. 2014)—although there are perhaps some indications that using a definition based on sea surface temperatures (SSTs) of NAO-like variability gives a stronger, more stable result than a more traditional atmospheric-based definition. ENSO has also been linked to variations in river flow (Barlow and Tippet 2008), soil moisture (Sheffield and Wood 2008), and NDVI (Kariyeva and van Leeuwen 2012) in the region.

For ENSO, it appears that the state of the western Pacific may be an important additional factor (Barlow et al. 2002; Hoerling and Kumar 2003; Hoell and Funk 2013). As noted previously, two of the most severe widespread droughts for the region were during 1999–2001 and 2007/08, both of which were associated with La Niña conditions, a warm western Pacific, and similar hemispheric wind patterns (Agrawala et al. 2001; Barlow et al. 2002; Trigo et al. 2010; Hoell et al. 2012; Hoell et al. 2014a).

For many of these teleconnection studies, the influence on precipitation has been evaluated only for subareas of the full region considered in this review. Moreover, aside from the influence of the tropical Pacific in the 1999–2001 and 2007/08 drought events, the role of these teleconnections in individual drought episodes has not been closely analyzed.

b. Synoptic regimes and climatological features

In an analysis of wet and dry years for the Jordan valley, Black (2012) found that the synoptic regimes noted previously in section 2 were also important in interannual variability and were modulated by the NAO. A wet-minus-dry composite showed that precipitation departures over the Jordan valley were out of phase with precipitation departures over southern

Europe and associated with changes in storm-track structure over the Mediterranean Sea.

A major part of eastern Mediterranean precipitation is controlled by a large-scale process associated with two main anticyclonic centers: the Azorian and Siberian highs. During periods with intensive anticyclones over central Europe, the area gets drier (Kutiel and Paz 1998; Krichak et al. 2000). During these dry spells, positive SLP and midlevel height (H-500) anomaly patterns prevail over eastern Europe while negative SLP and H-500 anomalies are found over southwestern and western Europe. A more intensive anticyclonic system over central Europe during dry eastern Mediterranean seasons suggests an intensification of the westward advection of dry Asian air masses into the area (Krichak et al. 2000).

c. Mechanisms of tropical forcing

While there is not yet a complete understanding of the dynamical pathways by which tropical variability can influence the region, there have been several studies of the influence of tropical convection occurring over a region extending from the eastern Indian Ocean to the western Pacific Ocean. Enhanced tropical Indo–west Pacific Ocean convection results in diabatic heating increases, which excites baroclinic (Barlow et al. 2002, 2005, 2007; Barlow 2011; Hoell et al. 2012, 2013) and barotropic (Hoell et al. 2013) stationary Rossby waves over central-southwest Asia and the Middle East. The mean wind appears to be important in increasing the northward extent of the classic Gill–Matsuno response to tropical forcing, which assumes a resting basic state (Barlow 2011; Adames and Wallace 2014). The stationary Rossby waves thermodynamically interact with the mean climate, resulting in modifications to the mid- and upper-tropospheric temperature advection, which is balanced by precipitation-suppressing subsidence (Barlow et al. 2005; Hoell et al. 2012; Hoell et al. 2014b). Anticyclonic circulation associated with Rossby waves also reduces the flux of moisture into the region from tropical Africa and the Arabian Peninsula (Mariotti et al. 2002, 2005; Mariotti 2007; Barlow and Tippet 2008; Hoell et al. 2014b). The Indo–west Pacific convection also appears to excite eastward-traveling barotropic Rossby waves that can travel across the Northern Hemisphere and influence the Middle East and central-southwest Asia from the west (Hoell et al. 2013). Additionally, a hemispherically symmetric influence from ENSO has been proposed in Seager et al. (2003, 2005), resulting from interaction between the tropically forced subtropical jet anomalies and transient activity.

Thus, there are indications that tropical Indo-Pacific Ocean anomalies can influence the region with a

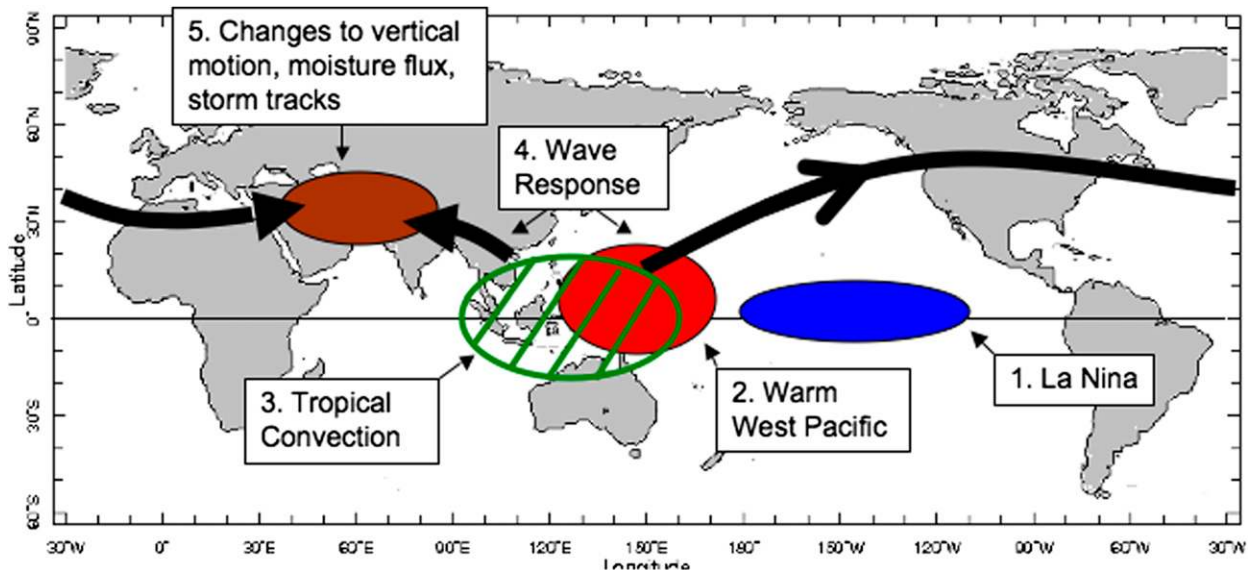


FIG. 9. Schematic of drought mechanisms for the 1999–2001 and 2007/08 severe regional droughts.

modified Gill–Matsuno-like response to the west, a response to the east that propagates around the hemisphere, and a hemispherically symmetric response. Over the region, these wind circulations modify mid-level vertical velocity, moisture flux, and storm tracks, as shown schematically in Fig. 9—these mechanisms appear to be operating in both major regional droughts of the last 50 years, although the relative importance of the three different mechanisms has not yet been evaluated.

d. Regional coherence

While there are at least two major factors that link the region as a whole—the widespread nature of the most severe drought episodes and the importance of cold season synoptic precipitation across most of the region—the amount of regional coherence in year-to-year variability is less clear. To provide a very simple first view of this, annual precipitation is averaged over each country and then correlated with every other country for the 1951–2010 period based on the GPCC data; these cross correlations are shown in Table 1. For clarity, the correlations are shown to only one significant digit, and values equal to or greater than 0.5 are shown in bold. The amount and spatial distribution of station data underlying this analysis change considerably over the period (Hoell et al. 2015), and so, while the results are consistent with previous work, they should be interpreted with some caution. In this calculation with annual data, the northern tier of countries (Uzbekistan, Kyrgyzstan, Turkmenistan, and Tajikistan) is distinct from the others. The countries of the Fertile Crescent

are generally closely related but do not clearly form a distinct group; instead, they form a chain of relationships, gradually changing from east to west. Afghanistan is correlated at 0.5 or higher only for Iran, Pakistan, and the United Arab Emirates. Pakistan is correlated at 0.5 or higher only for Afghanistan, which is expected, given the large contribution of the summer monsoon to Pakistan's precipitation (the mutual correlation is 0.79 considering only the November–April months). Yemen is also correlated at 0.5 or higher only for a single other country in the domain, Oman, which is also expected, given the different precipitation mechanism for the southern tip of the Arabian Peninsula (the African monsoon/ITCZ). The countries of the Arabian Peninsula, in general, are not well correlated to the rest of the region, except for Iran.

From this simple analysis, it appears that none of the domains usually discussed in the literature is a close match to the spatial relationships of precipitation variability, at least in the annual mean, although the entire domain can be coherent in severe episodes. This complexity is consistent with the wide range of regional and large-scale influences on the region, as discussed in the previous three subsections.

For the same period of 1951–2010, the yearly variation in the number of countries with precipitation deficits is shown in Fig. 10 for three deficit thresholds: less than average (light brown), less than 90% of average (medium brown), and less than 75% of average (dark brown). A number of widespread droughts occur during the period, with at least 16 of the 19 countries reporting less-than-average precipitation for 11 of the years (1958, 1960, 1962,

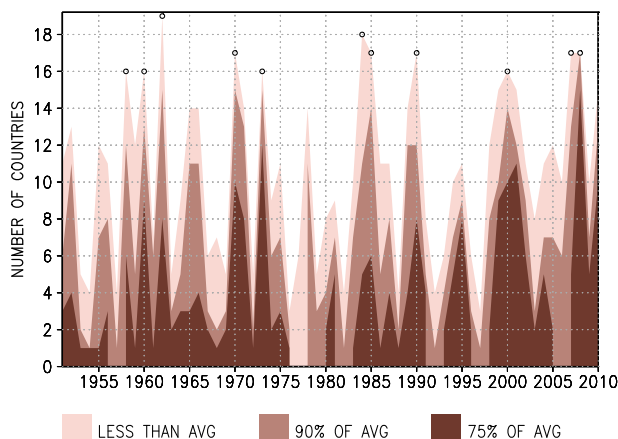


FIG. 10. Number of countries in the region (of 19 total) experiencing annual precipitation deficits during the 1951–2010 period. The three brown shades (light, medium, and dark) indicate the number of countries with annual precipitation below, 90%, and 75% of average. The calculations are based on GPCP version 6 data on the 0.5° grid, averaged over the land area of each country. The open circles indicate years where at least 16 of the 19 countries had less-than-average precipitation.

1970, 1973, 1984, 1985, 1990, 2000, 2007, and 2008) and more than half the countries reporting less than 75% of average precipitation for 6 of the years (1970, 1973, 2000, 2001, 2008, and 2010). A composite of the SST anomalies for the 11 yr with at least 16 of 19 countries drier than average is shown in Fig. 11. The pattern of cold SST anomalies in the central and eastern Pacific and warm SST anomalies in the western Pacific and eastern Indian Ocean, as discussed in the previous section relative to severe droughts, holds also for this composite based on the regional coherence of precipitation deficits. The pattern is not sensitive to the choice of deficit threshold or number of countries, although composites that include more of the weaker droughts in the early part of the period have a smaller magnitude of the SST anomalies than composites based on the stronger, more recent droughts.

In terms of year-to-year variability, the precipitation of individual countries is most closely linked to geographic neighbors with gradual changes in the strength of the relationships over distance. As a result, there do not appear to be clear subdivisions within the region for interannual variability, although the northeastern-most countries show the most separation from the others. In terms of more severe drought, there is considerably more spatial coherence. Given the complexity of these relationships as well as data issues, a careful analysis of the spatial patterns of precipitation variability by season would be useful to determine drought-relevant subdivisions within the

region, as well as how best to define the boundaries of the region.

e. Vegetation

Within the semiarid climate zone, which spans a broad swath of the region from the Mediterranean coast in the west to Pakistan in the east, dry seasons and years with below-average precipitation lead to dieback in seasonal grasslands and frequent crop failure in rain-fed agricultural regions (Lotsch et al. 2005; Thenkabail et al. 2004). These lands are also subject to degradation, such as when overgrazing of drought-prone grasslands results in soil nutrient loss and a long-term decline in vegetation cover (Evans and Geerken 2004).

This spatial and temporal variability in vegetation invites consideration of the influence that vegetation might have on the onset and evolution of droughts in the region. Proposed drought–vegetation feedbacks include energy balance feedback pathways mediated by surface albedo (e.g., Charney 1975) or by changes in the Bowen ratio (e.g., Betts and Ball 1998), moisture convergence feedbacks associated with transpiration rate (e.g., Dirmeyer 1994), aerodynamic effects of surface roughness (e.g., Sud et al. 1988), influence on mesoscale atmospheric circulations (e.g., Avissar and Liu 1996), and influence on infiltration of precipitation into the soil (e.g., Scheffer et al. 2005). In drylands, vegetation also has an important soil-stabilizing effect. Loss of vegetation due to climate variability, human-induced land cover change, or land degradation can result in an increase in wind erosion and lofting of dust aerosols into the atmosphere, which can inhibit precipitation by warming and stabilizing the atmosphere and by reducing the amount of solar radiation that reaches the surface. Large portions of southwest Asia are prone to dust storms, suggesting that vegetation influences on dust lofting could have a significant impact on precipitation processes.

While variable vegetation cover and frequent dust storms are signs that southwest Asia could be highly sensitive to vegetation–drought feedbacks, precipitation variability in the region is also largely controlled by powerful large-scale dynamics, as discussed in the previous section. The realization of significant vegetation impacts on drought, then, depends on the relative strength of local versus remote forcings on regional hydrometeorology.

Southwest Asia has not been a particularly strong focus for studies of land–atmosphere feedbacks, but a number of global and regionally focused studies offer insight on potential mechanisms for vegetation–drought feedbacks in the region. Global modeling studies of land–atmosphere coupling strength indicate that portions of southwest Asia have potential for local precipitation

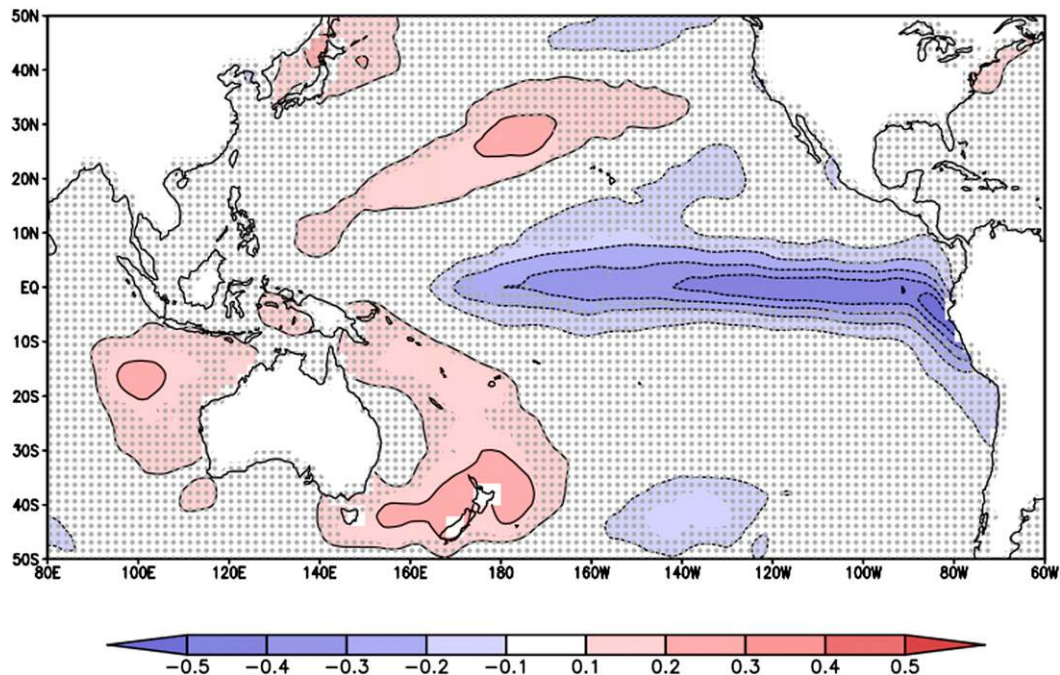


FIG. 11. Composite of SST anomalies ($^{\circ}\text{C}$) for the 11 yr in the 1951–2010 period when at least 16 of the 19 countries in the region reported annual precipitation less than average (the open circles in Fig. 10), based on the GPCC version 6 precipitation data. The shading interval is 0.1°C and gray stippling is shown over regions not significant at the 5% level.

feedbacks. [Koster et al. \(2004\)](#) found that modeled coupling strength was weak in arid portions of the region but stronger in some semiarid and subhumid portions of the Arabian Peninsula, Pakistan, Kyrgyzstan, and Tajikistan. This pattern is consistent with results in other regions, which indicate that soil moisture coupling is strongest in transitional climate zones in which soil moisture variability is significantly correlated with changes in evapotranspiration. The [Koster et al. \(2004\)](#) simulations address soil moisture feedbacks, not vegetation feedbacks, and so are not designed to capture the influence that vegetation itself has on albedo, transpiration of subsurface moisture, or surface roughness.

Southwest Asia appears more prominently in a global modeling study by [Zeng and Yoon \(2009\)](#), which used a coupled atmosphere–ocean–land–vegetation model that, when accounting for vegetation albedo effects, indicated that the world’s warm deserts might expand by 34% in the twenty-first century. A significant portion of this expansion was indicated to occur in marginal lands of southwest Asia—primarily in the southern Arabian Peninsula and in the Fertile Crescent and Anatolia regions of Turkey, Syria, and Iraq. In a regional modeling study of drought, [Zaitchik et al. \(2007\)](#) found that under drought conditions vegetation dieback in the semiarid zone of Syria and Iraq leads to an increase in albedo, a

reduction in sensible heat flux, and a tendency toward lower surface temperatures, a shallower planetary boundary layer, and reduced cloud cover. In the cooler, generally more humid highlands of Iran, in contrast, drought had no discernible impact on surface albedo, but it did cause a soil-moisture-mediated increase in the Bowen ratio, resulting in elevated surface temperatures and a deep, dry planetary boundary layer that also inhibited cloud formation. Modeling experiments also suggest a feedback on the regional summer monsoon circulation associated with expansion of the Thar Desert ([Bollasina and Nigam 2011](#)).

Compared to surface energy balance effects, the potential for vegetation to influence precipitation in southwest Asia through bulk humidity feedbacks would appear to be more modest. [Dirmeyer and Brubaker \(2007\)](#) performed a global evaluation of precipitation recycling, diagnosed through back-trajectory analysis of a global reanalysis dataset, and found that recycling ratios across southwest Asia are among the lowest in the world—generally below 4%, and less than 6% everywhere but in the high mountains of Pakistan. Against this background, it is unlikely that the humidity effects of drought-induced changes in transpiration flux would have a large impact on atmospheric saturation and the potential for precipitation recycling.

f. Dust

Finally, several studies have examined the influence that dust has on meteorological conditions in southwest Asia. The Arabian Peninsula and other arid to semiarid portions of southwest Asia are significant sources of dust aerosols, and the column-integrated dust load over the region is among the highest in the world, particularly in boreal summer (Miller et al. 2004). This dust load results in an increase in atmospheric radiative heating and an associated reduction in solar radiation reaching the surface. The result is a cooler surface and a potential for drought-enhancing feedback due to reduced evapotranspiration or stabilization of the lower atmosphere, though interaction with large-scale dynamics can actually produce a positive precipitation feedback in desert regions like the Arabian Peninsula (Miller et al. 2004). Ganor et al. (2010) observed 966 dust days in the eastern Mediterranean region during 1958–2006. They showed that the total incidence of dust days in the region increased in recent decades with an average rate of an additional 2.7 dust-storm days per decade. In a set of regional climate modeling studies, Marcella and Eltahir (2010, 2012a) found that accurate simulation of summertime temperatures in southwest Asia requires proper representation of the radiative effects of dust. They found no significant influence of vegetation on dust emissions in their simulation, largely because the Arabian Desert, in which vegetation cover is almost totally absent, is the dominant dust source. Nevertheless, further studies that consider interannual variability in vegetation cover and dust transport processes are recommended, particularly given the recent increase in dust events noted by Ganor et al. (2010) and the potential for drought–desertification feedbacks in marginal lands.

5. Predictability

The overall predictability of drought in the region has not yet been well established. However, at least three of the factors discussed in the previous section—the influence of the tropical oceans, the importance of snowmelt to river flows and vegetation, and the influence of a predictable mode of intraseasonal variability (the MJO)—all suggest the possibility of considerable predictability of various aspects of drought, some of which have been verified for parts of the region.

The link to the tropical oceans has been used as a basis for statistical correction of model output, which has been shown to increase predictive skill for seasonal winter precipitation forecasts in northeastern Afghanistan, northern Pakistan, and the northern tier of the domain (Uzbekistan, Tajikistan, and Kyrgyzstan; Tippett et al. 2003, 2005). The

degree to which model improvements could extend the area of predictability or ocean information could be used directly for forecasting in the region is not yet clear.

Snowmelt is a primary driver of river flows in the high mountains of the region, and, while good observations of snowpack accumulation are not currently available, operationally available data for cold season precipitation have been shown to be an effective indirect measure of snowpack and can serve as a skillful basis for river flow forecasts for the Amu Dar'ya and Syr Dar'ya and nearby rivers, either by accumulating precipitation within a basin (Schär et al. 2004) or by using statistical relationships (Barlow and Tippett 2008). Accumulated precipitation is also highly correlated with levels of the large basin of the Aral Sea (Nezlin et al. 2004). The potential of this approach for other rivers in the region has not yet been evaluated.

The importance of snowmelt to vegetation in the high mountains of the Hindu Kush, the Pamir, and the Tian Shan ranges results in a lagged relationship between cold season precipitation and subsequent growing season vegetation (Nezlin et al. 2005; Barlow and Tippett 2008; Gessner et al. 2013) that could potentially serve as a basis for prediction. In the different hydrological context of the Jordan River region, vegetation shows the highest correlation to the 6-month accumulated value of a drought index (Törnros and Menzel 2014), also suggesting some potential for prediction.

There also appears to be the potential for predicting vegetation in the high mountain regions based on snowmelt (Barlow and Tippett 2008).

As noted in the previous section, the MJO has a strong influence on precipitation in much of the region. The MJO, a predictable mode of tropical atmospheric variability (e.g., Waliser et al. 2003) with time scales from approximately 30 to 60 days, can result in heavy flooding events even in the midst of a severe drought season or, conversely, enhancement of the drought, depending on the MJO phase (Hoell et al. 2012). There appears to be predictability of these drought breaks and enhancements out to at least two weeks (Barlow et al. 2005).

Overall for the region, there appear to be a number of sources of potential drought predictability for seasonal precipitation, river flows, and vegetation, as well as for intraseasonal breaks and enhancements of drought. However, there has been only a very limited assessment of the operational predictability associated with these factors.

6. Trends and projections

Much of the Middle East and southwest Asia lies on the northern edge of the subtropics, an area that is

projected to become more arid as a result of the strengthening and expansion of the Hadley cell under global warming (IPCC 2007, 2013b). This first-order view, however, is a broad generalization that does not capture the climatic diversity and complexity of the region. As described above, the Middle East and southwest Asia span the intersection of powerful climatic features from the west (NAO; midlatitude storm tracks), east (southwest Asian and Indian monsoon influences), north (Siberian high), and south (ITCZ; Indian Ocean modes) and are also influenced by global-scale variability associated with ENSO and the strength of the atmospheric general circulation. Projections of regional climate under global warming (IPCC 2013a) must consider and accurately capture how the strength of these diverse influences will evolve, as well as the manner in which these changes and the effects of secular warming will interact with the diverse internal geography of the region. In this regard, subregions within the Middle East and southwest Asia may respond to global climate change in very different ways.

a. Middle East

For the eastern Mediterranean region, the large-scale drying projection is reinforced by a number of factors. First, the NAO is projected to become more positive in the future (Christensen et al. 2013), a trend that would be expected to reinforce drying of the region (e.g., Kelley et al. 2012) if synoptic dynamics are relatively stationary under climate change. Climate model projections indicate, however, that the mechanisms of future change are dynamically distinct from the mechanisms of present-day interannual variability. Under present-day climate conditions, dry years are a product of a change in the orientation of storm tracks—partially associated with NAO variability—that causes the dominant storm track to strengthen and focus to the north. Additionally, models project that the storm track will be weakened in general (Lionello and Giorgi 2007; Pinto et al. 2007), leading to widespread drying in southern Europe and the Middle East (Black et al. 2009) that is independent from interannual NAO variability. This projection is consistent with analyses indicating that climate change is causing a shift in the dominant precipitation mechanism from frontal precipitation associated with storm tracks to forced convective events that depend on the upslope flow of moist air masses (Evans 2009). It is also consistent with the fact that both global climate models (Evans 2009, 2010) and high-resolution regional climate simulations (Black 2009; Kitoh et al. 2008; Jin et al. 2010; Lionello and Giorgi 2007; Mariotti et al. 2008; Seager et al. 2014) project significant drying of the eastern Mediterranean region under future climate.

Thus, both the projected NAO trend and the projected weakening of the storm track are consistent with observations and model predictions for a drier Mediterranean region and Middle East.

Atmospheric dynamics associated with the Mediterranean Sea also have a significant influence on the eastern Mediterranean region and the Middle East. Shohami et al. (2011) found an increase of the SLP over the whole Mediterranean basin and weakening of the Eurasian thermal high during the winter, accompanied by a rising 500-hPa geopotential height during the years 1984–2003. This trend is projected also for future scenarios by Giorgi and Lionello (2008), who show in their models an area of increased SLP during winter, and thus increased anticyclonic circulation, centered over the central Mediterranean Sea. These reduced conditions for cyclogenesis and specific humidity explain their findings of an increase in the warming conditions during the summer and transitional seasons over the eastern Mediterranean region and Middle East and the less favorable conditions for precipitation generation through the winter and the transitional seasons. Shohami et al. (2011) also found an increase in the summer–autumn SST. This suggests a decrease in the cooling effect of the Mediterranean Sea eastward, and a lengthening of the summer season into autumn (Shohami et al. 2011).

In addition to these external global and synoptic-scale drivers of climate, the eastern Mediterranean region and Fertile Crescent regions are characterized by significant topography and surface variability that is relevant to climate projections. Perhaps most dramatically, the region is located on a steep climatic gradient, ranging from a dry summer subtropical (Mediterranean) climate in its north to semiarid and arid conditions in the south. This transition between two climate zones serves as an important indicator of climatic sensitivity (Shohami et al. 2011), as soil moisture and vegetation respond quickly and dramatically to external climate forcing (Zaitchik et al. 2007). This sensitivity is associated with a mutual enhancement (positive feedback) between droughts and heat waves that has been identified in the region, and that may cause both heat and drought to intensify more strongly than would be predicted on the basis of large-scale warming alone (IPCC 2012). A global climate model used by Kitoh et al. (2008) projected precipitation decrease in the Fertile Crescent region with more severe changes in streamflow, which may result in substantial damage to rain-fed agriculture in the Mesopotamia area. Moreover, the study projects that by the end of this century the Fertile Crescent will lose its current shape and may disappear.

The influence that topography has on the distribution of rainfall, meanwhile, is evident in any analysis of

present-day precipitation processes, and the interaction of synoptic- and mesoscale atmospheric circulations with topography is expected to affect the regional expression of climate change. For example, while regional climate model (RCM) projections for the region agree with GCM projections in their broad features, the higher resolution of RCMs allows them to capture topographically driven atmospheric dynamics such as the Zagros Mountain barrier jet (Evans 2008). RCM simulations project that the number of precipitation events associated with the barrier jet will increase in the future, shifting the distribution of precipitation toward large, southerly dominated rainfall events. This shift has the potential to increase the vulnerability of the region to drought owing to the interannual variability in the number of these events. Atmospheric circulations and precipitation processes in the Fertile Crescent are also known to be affected by the Lebanon and Anti-Lebanon Mountains, which act as a rain barrier on eastward-moving storm systems (Evans et al. 2004), and by elevated heating from the Zagros Plateau, which enforces atmospheric subsidence on the Tigris–Euphrates lowlands (Zaitchik et al. 2007). If future changes in atmospheric circulation alter the interaction between storm tracks and these topographic features then it is possible that rainfall patterns within the Middle East will change in a manner that is nonstationary with respect to large-scale dynamics.

Observational support for these detailed precipitation projections is, unfortunately, limited, in large part because in situ meteorological data are sparse over much of the region. These data limitations give rise to inconclusive trend analysis. For example, atmospheric reanalyses indicate an increased drying during winter over the eastern Mediterranean region and the Middle East, and an analysis of available meteorological station data by Alpert et al. (2002) showed that more stations in the eastern Mediterranean region showed decreases in precipitation than increases, though the results were mixed across stations. In contrast, Zhang et al. (2005) examined both surface station records and gridded precipitation analyses for the Middle East and found insignificant negative precipitation trends. They concluded that precipitation was characterized by strong interannual variability without any significant trend in any of the precipitation indices analyzed. It is possible that these seemingly contradictory results reflect the fact that high variance in precipitation data is masking substantial trends (Morin 2011). There are some areas of the Arabian Peninsula that have a downward trend in precipitation (AlSarmi and Washington 2011, 2014; Almazroui et al. 2012). Hoerling et al. (2012) used an intercomparison of several observational datasets to show an overall

drying of the coastal Mediterranean Sea from 1902 to 2010, although the signal was somewhat mixed for the coastal Middle East. They then conducted a series of modeling runs that suggested that roughly half of the observed trend in that period was due to anthropogenic forcing and also that three aspects of SST forcing were important to the drying trend: uniform overall warming, warming of the tropics relative to the Northern Hemisphere extratropics, and warming of the tropical Indian Ocean relative to the tropical Pacific Ocean.

The likelihood that modern-day climate change will produce a drying trend in the eastern Mediterranean region and Fertile Crescent is of particular concern because the region is already under significant water stress. Groundwater aquifers are being rapidly depleted (e.g., Voss et al. 2013), and flow volume in vital waterways like the Jordan River has reduced substantially in recent years (Wade et al. 2010). Projections based on a hydrologic discharge model coupled to regional climate model output suggest decreases in Tigris–Euphrates basin discharge of 19%–58% (Bozkurt et al. 2015). Even in the absence of climate change, demographic factors are expected to push Jordan into a state of absolute water poverty by 2020 (Nortcliff et al. 2011).

The potential for climate change to influence precipitation patterns and societal well-being in the region is also dramatically evident in the prehistorical record. The late Holocene climates of the Near East were analyzed by Enzel et al. (2003), who connected geologic data, probable atmospheric circulation at synoptic and global scales, and the hydrology (lake level) of the Dead Sea. They found evidence that prolonged and severe droughts have affected the Dead Sea basin, and the Levant as a whole, several times during the Holocene period. The most probable cause for these droughts is that the 500-hPa and SLP patterns were not conducive for cyclones migrating all the way to the eastern Mediterranean Sea. The authors emphasize two prominent lake-level falls as a result of droughts, which could have been associated with cultural transitions in the Near East. The first is documented in the ~2200 BC transition from the early to middle Bronze Age in the Levant, which coincides with the collapse of the Akkadian Empire. The second lake-level fall occurred between the late fifth and late eighth century AD and coincided with the collapse of the agricultural, water-harvesting Byzantine society and the Arab expansion into the Levant from the arid area of current Saudi Arabia (e.g., deMenocal 2001; Weiss and Bradley 2001).

The analysis by Enzel et al. (2003) bears important lessons for current and future water resources. Today, even with water supply buffered by intensive groundwater use and storage management, 2 or 3 years with

mean annual rainfall below the long-term mean over the Levant will cause a severe meteorological drought. This drought will be transformed quickly into hydrologic and socioeconomic droughts.

Compared to precipitation trends and projections, changes in temperature are relatively straightforward. In an analysis of the observational record, [Saaroni et al. \(2003\)](#) found significant temperature increase during summer in the eastern Mediterranean region and Middle East. Similarly, [Zhang et al. \(2005\)](#) found statistically significant and spatially coherent trends in temperature indices corresponding to a warming trend in the region from Turkey to Iran and from Georgia to the southern tip of the Arabian Peninsula. Significant increases in the number of warm days and significant decreases in the number of cold days were detected, while the increasing trends in the number of warm days were much stronger. Increases in temperature have implications for evaporative demand and are thus an important consideration in drought projections.

Analysis of observed trends shows increased surface warming during the summer months and the transitional seasons ([Saaroni et al. 2003](#); [Ziv et al. 2005b](#)). [Shohami et al. \(2011\)](#) explain the increased summer heat by demonstrating the weakening of the Persian trough, implying the reduction of its cooling effect over the eastern Mediterranean region and Middle East during summer ([Saaroni et al. 2010](#)). Under future climate, models predict continued warming with particularly pronounced changes in the summer season ([Ulbrich et al. 2006](#); [Giorgi and Lionello 2008](#)).

b. Southwest Asia

Precipitation projections for southwest Asia are less confident than for the coastal Middle East. The area of projected precipitation decreases over the Mediterranean Sea extends weakly into southwest Asia but is bracketed with possible precipitation increases at the northern and southern extents of the domain ([Christensen et al. 2013](#); [Polade et al. 2014](#)). In an analysis of AR4 coupled model runs by [Kim and Byun \(2009\)](#), drought in the region increased in intensity, frequency, and duration, although again that signal was strongest at the coastal Mediterranean Sea and decreased to the east. The consistency of projected changes between models is also less in this region, and the strength and exact location of the changes appear to be sensitive to model resolution ([Christensen et al. 2013](#)), presumably because of the complex topography. Moreover, this is a region where models have not been fully validated ([Christensen et al. 2013](#)), and there are still some issues with the models' basic seasonal cycle of precipitation ([Flato et al. 2013](#)).

In the easternmost portions of southwest Asia, the Indian monsoon is an important source of precipitation ([section 2a](#)), while in the rest of the region the monsoon may play a suppressing role ([section 2b](#)). The influence that current and future climate change may have on the Indian monsoon is a critical area of research and one that is plagued by significant uncertainties. While a number of historical analyses suggest that South Asian monsoon precipitation has declined in the period since 1950, there are problems of disagreement between datasets and periods of analysis ([Turner and Annamalai 2012](#)). GCMs differ widely in their projection of future change. In the multimodel average, models included in phase 3 of the Coupled Model Intercomparison Project (CMIP3), project an increase in mean South Asian monsoon precipitation ([Stowasser et al. 2009](#)). But there is little model consensus in the western reaches of the monsoon zone that are most relevant to southwest Asia, and when the CMIP3 ensemble is trimmed to include only the models with the most reasonable representation of monsoon, the projection is actually for a slight decrease in mean annual monsoon precipitation in the western monsoon zone ([Turner and Annamalai 2012](#)), with considerable uncertainty in both the magnitude and sign of change. Results from the more recent CMIP5 experiment similarly show an increase in the mean South Asian monsoon precipitation but with a wide spread among model projections ([IPCC 2013a](#); [Menon et al. 2013](#)). While there are dynamical explanations for an increase in South Asian monsoon precipitation under greenhouse-gas-induced warming—warmer tropical SSTs, increased atmospheric water vapor over the Indian Ocean ([Douville et al. 2000](#)), and increased land–sea temperature contrasts ([Sutton et al. 2007](#)) could all contribute to a stronger monsoon—models and theory both suggest that more complex feedbacks might have countervailing effects, and the impact that aerosols have had and will continue to have on monsoon strength is an area of active research ([Turner and Annamalai 2012](#)). GCMs also tend to project an increase in interannual variability of South Asian monsoon precipitation ([Kitoh et al. 1997](#); [Turner et al. 2007](#); [Menon et al. 2013](#)), which could lead to more frequent drought years even if precipitation increases in the mean. GCMs are inconclusive on intraseasonal variability ([Turner and Annamalai 2012](#)), which can be particularly important for floods and episodic droughts.

In the historical record for precipitation, it is difficult to make a confident trend assessment, owing in part to data limitations, although there do appear to be areas of negative precipitation trends in the region ([Dai 2013](#); [Golian et al. 2015](#)).

For temperature, both observations and projections exhibit strong warming (Hartmann et al. 2013; Christensen et al. 2013). Even in the absence of large precipitation changes, the existing and expected future temperature changes have considerable implications for drought in the region because of the associated changes in evaporation, in the timing and amount of seasonal snowmelt, and in glacier melt. Projections of decreases in soil moisture and increases in measures of drought that account for the role of temperature (Dai 2013) are larger and more confident than those of precipitation. Additionally, projected increases in temperature and associated reductions in seasonal snowpack and retreat of permanent glaciers provide reason to expect that rivers originating in the Hindu Kush and Himalaya Mountains may experience significant changes in seasonality and total discharge in a warmer world (Singh and Bengtsson 2004; Aizen et al. 2006, 2007; Sorg et al. 2012; Immerzeel et al. 2012; Diffenbaugh et al. 2013; Sorg et al. 2014), with implications for downstream drought vulnerability

7. Summary and outstanding questions

The Middle East and southwest Asia are a region that is water stressed, societally vulnerable, and prone to severe droughts. A warming trend is already evident and a drying trend looks likely for much of the region in the future, in association with climate change. Water politics in the region are further challenged by the transboundary nature of many of the region's rivers and drainage basins. The Middle East and southwest Asia are, therefore, a critical area for understanding drought. Here, the previous literature relevant to drought dynamics, predictability, and trends has been reviewed and outstanding questions identified.

Dynamically, the region is at a crossroads of regional influence from the Mediterranean Sea, Europe, and Asia, as well as large-scale influence from the Atlantic Ocean, Mediterranean Sea, Indian Ocean, and Pacific Ocean sectors. This results in complicated precipitation relationships most of the time but can result in regionally coherent drought when one of the sectors is exerting a particularly large influence or when the sectors are acting in concert. The Pacific sector, in terms of the combination of La Niña with warm waters in the western Pacific and eastern Indian Oceans, appears to play the strongest role in forcing regionwide drought, including the two most severe of the last 50 years—1999–2001 and 2007/08. The relative role of the western Pacific Ocean compared to the eastern Indian Ocean in these episodes, as well as the relationship of those regions to decadal variability and trends, particularly in terms of how other modes can contribute to the cold

central Pacific–warm western Pacific pattern, is not well understood. Additionally, multiple factors have been identified as important in these episodes for suppressing precipitation, including thermodynamic forcing of mid-level vertical motion, moisture transport, and storm-track strength and position, but the relative importance of these factors is not yet clear. The sparseness of precipitation data makes assessing the long-term stability of the links particularly challenging. A number of more local droughts have been identified in the literature (section 3), but the dynamics of most of those droughts and their regional coherence are not yet clear. Previous work has spanned a diverse range of drought metrics, spatial domains, and time periods, and more uniform analyses would likely be very helpful. There is considerable literature on precipitation mechanisms and the links between large-scale variability and regional synoptic systems (sections 2b, 4a, and 4b), which is a promising base for future work but which has not yet been widely applied to understanding drought episodes. Investigating the nature of the local storm-track system, in terms of the difference between lower-level measures and mid- and upper-level measures, the differences in its structure from the canonical Pacific and Atlantic storm tracks, and the role and dynamical underpinnings of its life cycle and the onset of the dry season, is a particularly interesting question for understanding regional precipitation and, ultimately, drought. The role of temperature and evaporation in regional drought is expected to be important but has not yet received much attention. In summary, a complex range of dynamical influences have been shown to have at least some influence on the precipitation of the region, both locally and regionwide (particularly the tropical Pacific and Indian Oceans), although the relationship to individual drought episodes has not been well explored beyond some large-scale aspects of the regionwide 1999–2001 and 2007/08 droughts.

The region appears to have considerable potential predictability of various aspects of drought because of the influence of the tropical oceans; the importance of snowmelt; and the influence of a predictable mode of intraseasonal variability, the MJO. The operational predictive skill from these relationships, however, has been explored in only a few limited cases, such as statistical correction of model winter seasonal precipitation forecasts in the northern part of southwest Asia and peak-flow seasonal forecasts of the Amu Dar'ya and Syr Dar'ya. The link to tropical oceans suggests both that model forecast skill may improve with model improvements and that the state of the tropical oceans, current and predicted, could be used directly to forecast seasonal precipitation in the region. Accurate representation of the Asian jet structure is a key issue for models

because of the importance of jet interaction with the stationary wave response to tropical forcing. Snowmelt, which in some parts of the region provides much of the available surface water during the growing season, has shown predictability for the major rivers in the northeast part of the domain, but whether a similar approach would work for other rivers in the region has not been tested, in part owing to the difficulty of obtaining river gauge data. The snowmelt also appears to be linked to vegetative vigor in the region and so may provide utility in crop forecasting, although this has also not been tested beyond some simple correlations. Snowmelt has so far been considered primarily in terms of precipitation, and the role of temperature in the timing of the melt in the spring and in terms of reducing the snowpack during winter has not been fully examined. Given the increasing temperature trends in the region and the importance of the snowpack, this is a key question. Vegetation in the region is closely linked to precipitation and may also play a feedback role. Finally, even when predictions can be accurately made—and informal forecasts of drought for 2007/08 were made based on the state of the Pacific Ocean at the time—effectively communicating forecasts in a region with multiple challenges (historic tensions, shared resources, and political instability) is a profound challenge. In summary, there are multiple sources of potential predictability, but the currently achievable skill of such forecasts is not fully known and effectively communicating those predictions will be challenging.

In terms of current trends and future projections, recent observations show a significant temperature increase in the Middle East and southwest Asia, with a rise in the number of warm days and heat-wave events. Observed changes in precipitation are less clear, owing in part to data scarcity. In future projections, drying of the eastern Mediterranean region is a robust feature, as are temperature increases for most of the region, which will affect the timing of the hydrological cycle and the critically important snowmelt even if precipitation remains unchanged. Projections of precipitation changes are more study dependent, probably related to differences in models' ability to accurately reproduce regional precipitation mechanisms, although an increase in variability appears likely. Stronger drought events together with vegetation–albedo feedback may increase the potential for desert expansion under conditions of global warming. In summary, current warming and expected future warming is robust for much of the region, important changes in the hydrological cycle are expected as a result of the warming influence on snowpack, and future precipitation decreases seem likely for the part of the domain under the influence of eastern

Mediterranean climate. Data scarcity and model validation are significant limitations on our understanding of both historical and projected trends.

Data scarcity, within-region relationships, and communication are common themes among the outstanding questions. Regional coordination efforts that would help address these issues include a regional, high-resolution reanalysis to provide circulation and moisture data at a resolution sufficient to adequately resolve the topography and small-scale circulation features, such as low-level jets, and to provide a detailed estimate of uncertainty; a comparison of all available precipitation products for the region as whole, in combination with data recovery efforts; and development of a regional framework for cooperative work, water resource management, assessment of climate change risk, and the development and dissemination of forecasts.

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