Chapter 15

South Asian Summer Monsoon and subtropical deserts

Dr. K.P. Sooraj [Centre for Climate Change Research, Indian Institute of Tropical Meteorology, Ministry of Earth Sciences (IITM-MoES), Pune 411008, India]

Dr. Pascal Terray [Sorbonne Universites (UPMC, Univ Paris 06)-CNRS-IRD-MNHN, LOCEAN Laboratory, Paris, France]

Dr. Annalisa Cherchi [Institute of Atmospheric Sciences and Climate (ISAC-CNR), Bologna, Italy; Istituto Nazionale di Geofisica e Vulcanologia, INGV, Bologna, Italy]

Corresponding author address:

Sooraj K. P.

Centre for Climate Change Research, Indian Institute of Tropical Meteorology,

Ministry of Earth Sciences (IITM-MoES)

Pune 411008, India, e-mail:sooraj@tropmet.res.in

Abstract

The relationships between south Asian monsoon and Northern Hemisphere (NH) subtropical deserts have generated a lot of research in the recent times as both systems, despite of contrasting climates, are expected to be severely affected by anthropogenic climate change. This review envisages two pathways for the monsoon-desert relationship. The first one hypothesizes a significant influence of the monsoon on subtropical deserts whereby convection over the Indian Summer Monsoon (ISM) region induces Rossby-wave descent to its west. The second one proposes a very different perspective by emphasizing the potential role of NH deserts on ISM either through the changes of surface heating over the subtropical deserts or by dry air intrusions from arid regions into the monsoon domain. However, most current coupled climate models struggle to simulate realistically these monsoon-desert relationships due to various reasons, as documented in this chapter, calling for advances in coupled models with improved physical parameterizations.

Keywords: Indian summer monsoon, NH subtropical deserts, monsoon-desert relationship, anthropogenic climate change

15.1 Introduction

Monsoon and desert regions coexist at the subtropical latitudes of the African-Asian continent (e.g., Rodwell and Hoskins, 1996; Warner, 2004). The mutual association between these two contrasting climates has been studied in the past as well as in the recent times (e.g., Ramage, 1966; Charney, 1975; Charney et al., 1977; Shukla and Mintz, 1982; Sud and Fennessy, 1982; Smith, 1986a, 1986b; Mooley and Paolino, 1988; Sud et al., 1988; Parthasarathy et al., 1992; Yang et al., 1992; Webster, 1994; Rodwell and Hoskins, 1996, 2001; Sikka, 1997; Claussen, 1997; Bonfils et al., 2000; Douville et al., 2001; Xue et al., 2004; Yasunari et al., 2006; Wang, 2006; Wu et al., 2009; Biasutti et al., 2009; Lavaysse et al., 2009; Xue et al., 2010; Bollasina and Nigam, 2011a, 2011b; Bollasina and Ming, 2013; Tyrlis et al., 2013; Cherchi et al., 2014; Vinoj et al., 2014; Shekhar and Boos, 2017; Sooraj et al., 2019). As desertification is a fundamental process of the ongoing climate change (Cook and Vizy, 2015; Zhou, 2016; Wei et al., 2017) and climate projections of the south Asian monsoon remain uncertain (e.g., IPCC, 2013; Sabeerali et al., 2015; Annamalai et al., 2015; Sooraj et al., 2015; Krishnan et al., 2016; Kitoh, 2017; Singh and Achutarao, 2018; Wang et al., 2020), a renewed interest to understand the monsoon-desert relationships has grown. Furthermore, these two climate systems are affected by severe temperature, rainfall and radiation biases in current climate models (e.g., Bollasina and Ming, 2013; Levine et al., 2013; Sperber et al., 2013; Roehrig et al., 2013; Prodhomme et al., 2014; Sandeep and Ajayamohan, 2015; Samson et al., 2016; Haywood et al., 2016; Terray et al., 2018), and improving their representation is an important aspect to have better climate forecasts and projections (e.g., Cherchi et al., 2014; Terray et al., 2018; Sooraj et al., 2019).

Against the backdrop of this, we made an attempt to provide a comprehensive overview of the mutual relationships between these two contrasting climates thereby highlighting the underlying mechanisms. The chapter is organized as follows: Section 15.2 describes the salient climatological characteristics of the monsoon-desert system and highlights the historical background on the existence of subtropical deserts over African-Asian regions at the same latitude than the south Asian monsoon. Section 15.3 focuses on the south Asian monsoon (i.e., Indian Summer Monsoon, ISM) influence on the hot subtropical deserts, thus presenting the monsoon-desert paradigm using observation, reanalysis and coupled General Circulation Models (GCMs). Section 15.4 reviews the literature on the potential role of deserts in modulating the ISM. Finally, Section 15.5 encapsulates the main highlights as drawn from this Chapter review.

15.2 The Monsoon-Desert system: Background settings

The monsoon-desert system over African-Asian region is characterised by a sharp rainfall gradient during the boreal summer (e.g., from June to September) with heavy rainfall in the monsoon regions of the northern hemisphere (NH), but only sporadic and low rainfall in the adjacent arid regions (Fig. 15.1a). The contrasts between the two climates are further corroborated when considering other important parameters such as surface albedo or net radiation budget at the Top of the Atmosphere (TOA; Fig. 15.1b-c).

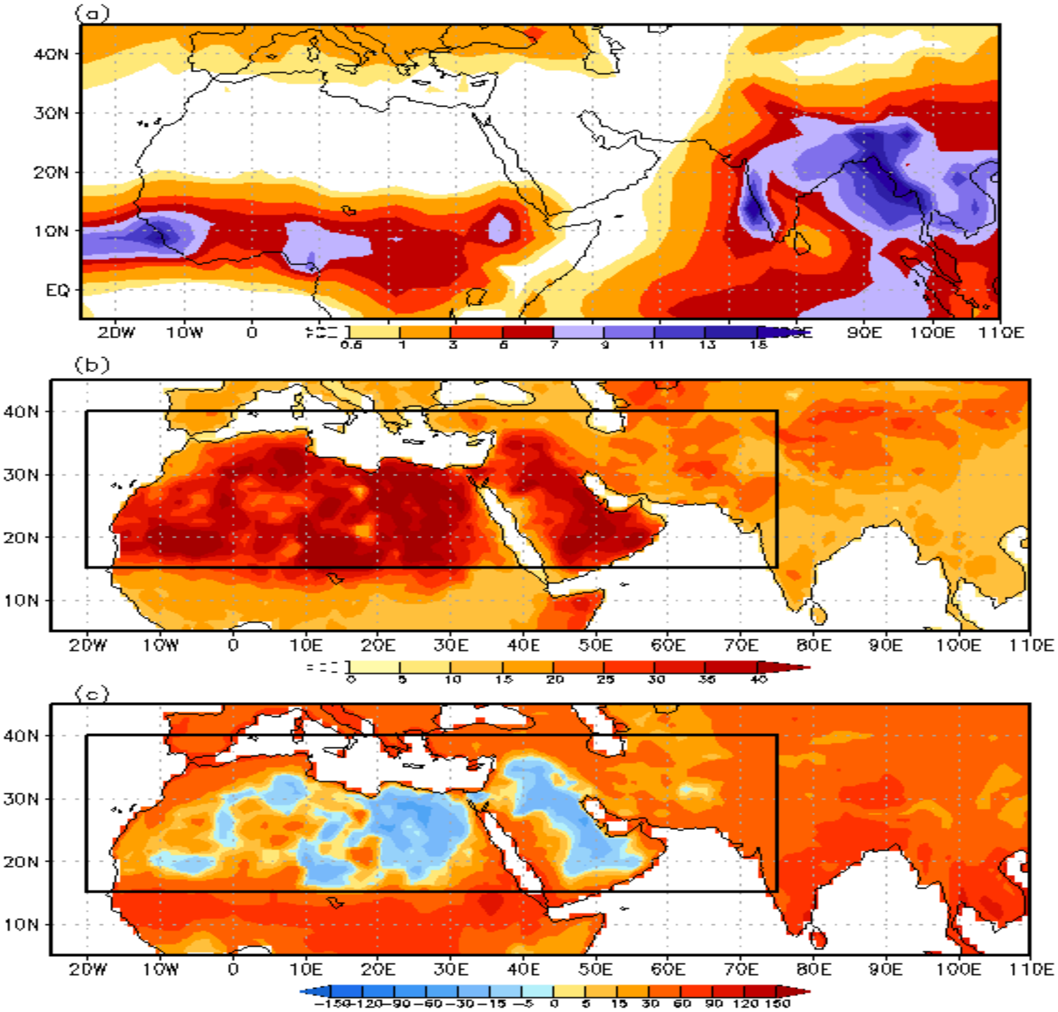

Figure 15.1: Climatological map of (a) rainfall (mm day^{-1}), (b) land surface albedo (%) and (c) net radiation budget at TOA (Wm^{-2}), for boreal summer period (June to September). In (a) rainfall climatology is computed for the 1986-2014 period from Global Precipitation Climatology Project (GPCP version 2.1; Huffman et al., 2009). In (b) and (c), albedo and radiation climatology is computed for the 2000-2018 period from the Clouds and the Earth's Radiant Energy System Energy Balanced and Filled (CERES-EBAF edition 4.0; Kato et al., 2018). In (b) and (c), the region highlighted in the black rectangle refers to "subtropical deserts".

The subtropical desert regions, with bright sandy surface terrains, clear sky conditions, high temperature, reduced soil moisture and lack of vegetation, are characterised by relatively high surface albedo (Fig. 15.1b; Sikka, 1997; Warner, 2004; Terray et al., 2018; Sooraj et al., 2019). Figure 15.1b shows two important examples for subtropical deserts: The Arabian-Iran-Thar desert located just to the west of the ISM system (Sikka, 1997) and the Sahara just to the north of the West African Monsoon (WAM) (Lavaysse et al., 2009). In this Chapter, these high albedo regions lying across north Africa and west Asia (i.e., the geographical region bounded by 20°W–75°E, 15°–40°N; Fig. 15.1b) are hereafter collectively referred to as "subtropical deserts" (or simply "arid regions").

As per the traditional theory dating back to the 1970s, the subtropical desert climates are associated with the descending branch of the Hadley circulation over the subtropics of the NH (Warner, 2004). However, NH Hadley circulation is weakest during boreal summer, which is completely out of synchronization with some of the observed summer climate features along the NH subtropics (e.g., the co-existence of both moist monsoon and desert climates at the same latitude). Consequently, this traditional view is now not well accepted in the literature (Yang et al., 1992; Rodwell and Hoskins, 1996; Wang, 2006; Wu et al., 2009). In a pioneering study, Charney (1975) made an attempt to explain the enhancement of subsidence over subtropical desert of the NH during boreal summer, by invoking a mechanism called biosphere-albedo feedback. As per their study, the pronounced reduction in vegetation cover (i.e., over-grazing) over subtropical deserts regions increases surface albedo, thus causing enhanced radiative cooling (Fig. 15.1c). This radiative loss is balanced by enhanced descent (Fig. 15.2), which in turn results in reduced rainfall, thus leading to further decrease in vegetation cover (i.e., desertification amplification). However, their mechanism ignored the possible influence of horizontal heat advection and hence found to be inappropriate over the NH subtropical deserts (e.g., Hoskins, 1986). Later, Yang et al. (1992) and Webster (1994) proposed another concept involving a closed “Walker type” circulation linking convection over south Asia to the subsidence over arid regions to its west. Nevertheless, subsequent studies (i.e., the seminal work of Rodwell and Hoskins, 1996, 2001; Hoskins, 1986) dispelled this notion, as their studies showed no signature of a closed overturning circulation. Based on the scale analysis of the thermodynamic equation, Rodwell and Hoskins (1996) also argued for the importance of horizontal heat advection for the existence of these subtropical desert regions. This currently recognized paradigm is often referred in the literature as the “monsoon-desert mechanism”, and is further described in Section 15.3.

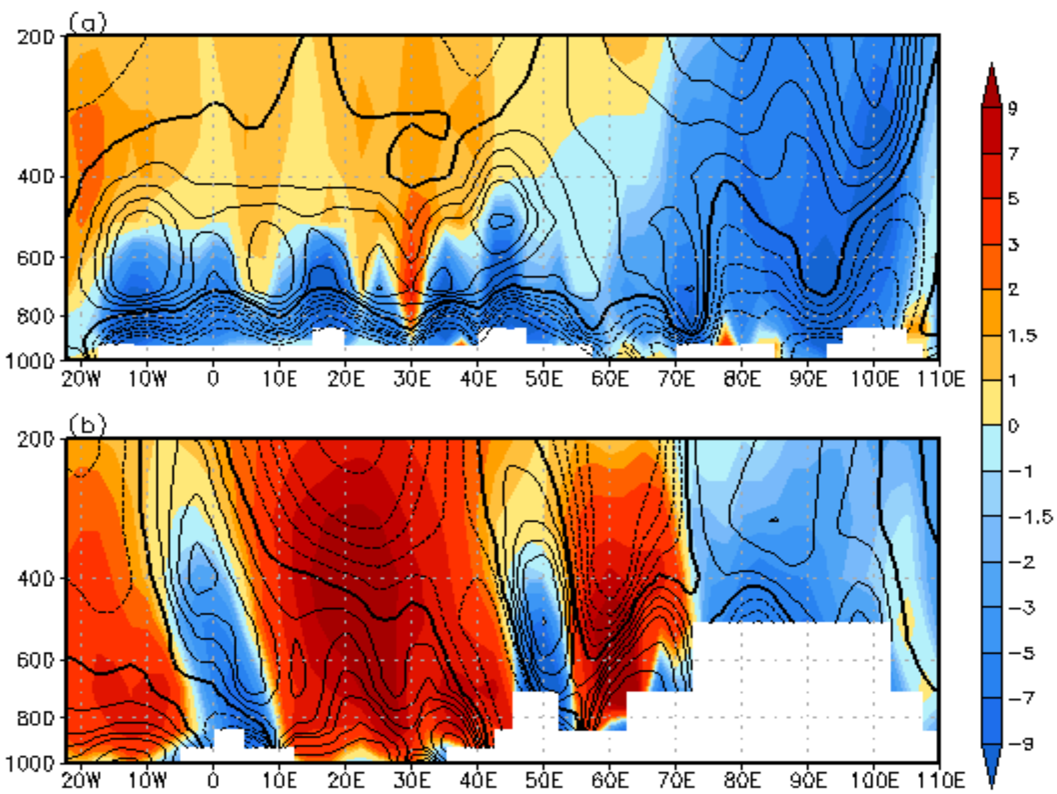

Figure 15.2: Vertical cross-section of atmospheric circulation in terms of vertical component of velocity (10^{-2} Pa s^{-1}, shaded) and horizontal wind divergence (10^{-6} s^{-1}, contours) during July, along a pressure-longitude plane averaged over two latitude bands (a) 20^0N and (b) 40^0N. The circulation fields are taken from the ERA-Interim reanalysis (Dee et al., 2011) and the climatology is computed for the 1986-2014 period. The negative (dashed) and positive (continuous) contours correspond, respectively, to absolute magnitudes of 1, 2, 3 and 4 units. The zero contours are highlighted in thick black color. Negative (positive) shading implies ascending (descending), while negative (positive) contours implies convergence (divergence). The presentation using July climatology follows the observational conjecture that it corresponds to the peak of monsoon activity (e.g., Tyrlis et al., 2013).

In contrast to the subtropical desert, the vegetated land surface over south Asian landmass shows a reduced surface albedo and the ISM region is radiatively surplus highlighting the role of clouds and moisture on the radiation balance (Fig. 15.1b-c; Sooraj et al., 2019). Furthermore, the ISM land region and the Bay of Bengal are characterized by strong ascending motion extending throughout the troposphere (see Fig. 15.2a), thus exemplifying the monsoon induced stratification due to the ISM rainfall and its associated diabatic heating (Fig. 15.1a). The corresponding low-level convergence is consistent with the thermo-dynamical response due to this diabatic heating (Fig. 15.2a; e.g., Neelin and Held, 1987).

The transition zone between this ISM convection center and the hot subtropical deserts to its west (i.e., extending from Mediterranean to west Asian landmass) is characterized by the existence of several regional heat lows with lower-level convergence and ascending motions (i.e., below 600-hPa) capped aloft by upper-level subsidence and divergence (i.e., mostly confined between 200 and 600-hPa) as displayed in Figure 15.2a. Figure 15.2b shows the intensification of these descending motions (extending throughout the troposphere) over west Asia and eastern Mediterranean regions at the northern boundary of the domain, thus highlighting the pronounced subsidence over these regions. Figure 15.2a-b highlights that the southern and northern regions of the hot subtropical deserts show totally different vertical structures of the local atmospheric circulation (Sooraj et al., 2019).

15.3 Monsoon influence over hot subtropical deserts

The idea that the existence of subtropical deserts is related to the ISM is dated back to mid-90s. Rodwell and Hoskins (1996) suggested a monsoon-desert mechanism whereby, in a linear modelling framework, remote diabatic heating in the Asian monsoon region induces a Rossby-wave pattern to the west, interacting with the southern flank of the mid-latitude westerlies and causing descent over eastern Sahara and the Mediterranean (Figs. 15.2 and 15.3). The associated atmospheric response has the form of an anticyclone at upper levels and a cyclone at lower levels, with a deepening of the isentropic surfaces due to the mid-tropospheric warming (Fig. 15.3a). When this far poleward thermal structure interacts with the southern flank of the mid-latitude westerlies, the air moves down the isentropes on their western side (Wang et al., 2012), as evident from Figure 15.3b where the northerly component of the westerly flow crosses the isentropic surfaces. Further, according to Rodwell and Hoskins (1996), the subsiding air is also of mid-latitude origin as revealed by their trajectory analysis. Regions of adiabatic descent are strengthened by "local diabatic enhancement" and longitudinal mountain chains induce a blocking of the westerly flow (Rodwell and Hoskins, 2001). The idea of the monsoon-desert mechanism linking the ISM to the Mediterranean has been then easily extended to other regions with Mediterranean-type of climates, like California and Chile, remotely forced by monsoon regions to the east (Rodwell and Hoskins, 2001). Overall, the theoretical framework based on these pioneering works is well established in terms of the origin of subtropical highs in the summer hemispheres (Cherchi et al., 2018).

In agreement with idealized model simulations, results focused on ERA40 reanalysis (Uppala et al., 2005) confirmed strong mid and upper-level warming spreading westward and causing significant depression of the isentropes, which are linked to Rossby wave activity away from the diabatic heating sources (Tyrlis et al., 2013). Over the eastern Mediterranean and Middle East, the subsidence and northerly flow (Etesian winds) are recognized as manifestations of the Rossby wave structure triggered by the ISM convection (Tyrlis et al., 2013; Rizou et al., 2018). In a similar framework, processes at work in the monsoon-desert mechanism have been analyzed in 20th century simulations from coupled GCMs participating to the 5th Coupled Model Intercomparison Project (CMIP5; Taylor et al., 2012), showing how few of them are able to simulate the mechanism for the correct reasons (Cherchi et al., 2014). CMIP5 coupled GCMs tend to underestimate (overestimate) ISM related diabatic heating at upper (lower) levels, resulting in a weaker forced response (Cherchi et al., 2014). Moreover, CMIP5 coupled GCMs with a severe dry bias over the ISM region depict the weakest mid-latitude winds and minimum descent over the Mediterranean, as well as little vertical variation in diabatic heating (Cherchi et al., 2014). On the other hand, when simulated precipitation over India improves in the coupled GCMs, the extratropical teleconnection with the Mediterranean region improves as well (Jin et al., 2019). In other words, the uncertainty associated with monsoon simulations needs to be considered in future climate projections even outside the monsoon domain. Interestingly, air-sea coupling seems also to be important to correctly represent the monsoon-desert teleconnections, as in coupled model simulations the divergence field associated with the ISM is more favorable for inducing westward Rossby wave propagation than in uncoupled simulations (Osso’ et al., 2019).

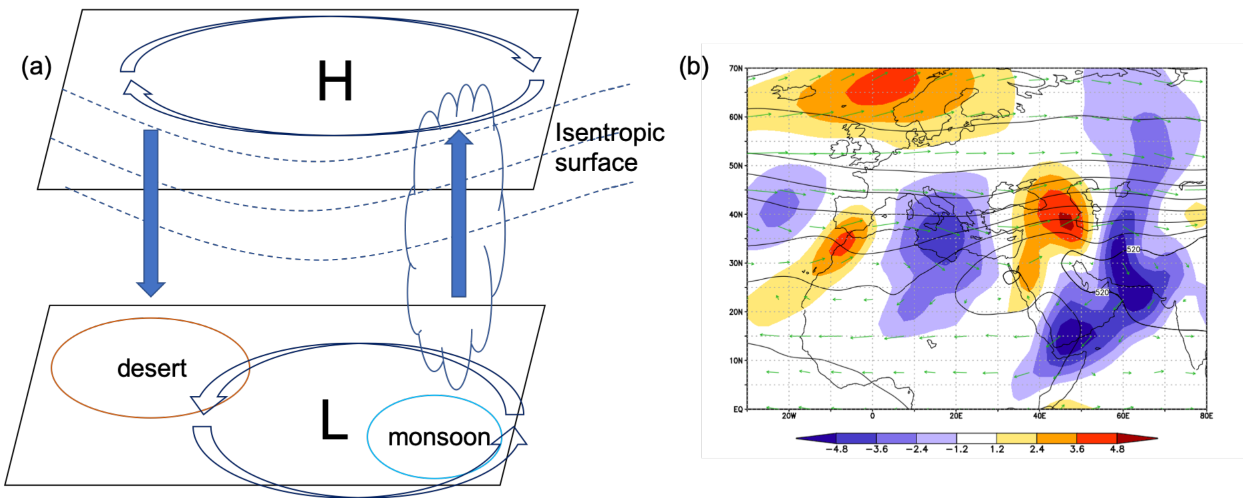

Figure 15.3: (a) Schematic diagram of the monsoon desert-mechanism with descent over the desert region (orange) induced by the heating over the monsoon convective region (cyan) interacting with local westerlies. [Adapted by permission from Wang et al., 2012]. (b) JJA mean wind (ms^{-1}, green vectors), meridional wind velocity (ms^{-1}, shaded), and pressure levels (hPa, contours with 50-hPa contour interval) on isentropic surfaces at 325K using NCEP/NCAR reanalysis dataset (Kalnay et al., 1996). The climatology is computed for the period 1958-2019.

Within boreal summer, descent enhancement over the Mediterranean and east Sahara has been observed during the onset of the ISM (Rodwell and Hoskins, 1996). In early July, when convection migrates over northern continental India, the Rossby wave structure amplifies impacting the circulation over the eastern Mediterranean and Middle East (Tyrlis et al., 2013). In the peak of the monsoon season, the combined diabatic heating pattern over the Arabian Sea and

Bay of Bengal regions exerts the largest descent over the eastern Mediterranean (Cherchi et al., 2014). As the monsoon activity is associated with active and break spells, it could be argued that successive Rossby wave pulses are released, inducing a cumulative effect over the region until the peak of the monsoon activity is reached in July (Tyrlis et al., 2013).

The processes recognized as part of the monsoon-desert mechanism vary at interannual timescales as well, with imprints of severe weak and strong ISMs noticeable over the Mediterranean (Cherchi et al., 2014). Interestingly, the monsoon forcing is more significant during strong ISMs, with enhanced subsidence over the Mediterranean region, than during weak ISMs (see Fig. 15.4). During a strong monsoon, upper tropospheric heating expands westward reaching a maximum over northern Arabian Peninsula modulating thermodynamic and dynamic patterns there and likely governing the occurrence of extremes over the region (Attada et al., 2019). ISM rainfall is significantly and negatively correlated with precipitation over Black Sea/Balkans region (Osso' et al., 2019). This kind of relationships suggests the possibility of using the ISM characteristics as potential predictors for the summer conditions over the Mediterranean region. At interannual to inter-decadal timescales, these dynamics are part of a larger picture involving North Africa (Liu et al., 2001; Wu et al., 2009; He et al., 2017) and portions of Eurasia via the so-called "silk road pattern" and "circumglobal teleconnection" (Lu et al., 2002; Enomoto et al., 2003; Ding and Wang, 2005; Saeed et al., 2014; Wang et al., 2017; Stephan et al., 2019, also see Chapter 13 and 14).

The monsoon-desert mechanism as first established using a linear modelling framework, is also supported by relating prehistoric lake-levels to Milankovitch-monsoon forcing (Rodwell and Hoskins, 1996) and extrapolated to the existence of "mega-deserts" and "mega-monsoon" areas in specific periods (Wang et al., 2014). Evidences of moist events over east Sahara have been observed (Gaven et al., 1981; Kowalski et al., 1989), consistent with shutting off of the monsoon-desert mechanism (Quade et al., 2018). Some of those wet events have been dated to correspond to minimum NH summertime insolation, linked with minimum intensity of ISM (Clemens et al., 1991). Some of these arguments have been confirmed with GCM studies (Claussen, 1994; Perez-Sanz et al., 2014).

As the ISM rainfall is projected to increase, the monsoon-desert teleconnection is consistent with the changes in 21st century projections over the Mediterranean region, at least for its central part corresponding to the largest increase in subsidence (Cherchi et al., 2016). However, other factors at play, i.e. like the warming and moistening of the troposphere under climate change, which enhance significantly the greenhouse effect over the deserts (Zhou, 2016; Wei et al., 2017), the North Atlantic Oscillation (Blade et al., 2012; Kalimeris and Kolios, 2019) or the changes in frequency/intensity of blocking systems (Masato et al., 2013; Tyrlis et al., 2015), may influence and shape the response in future climate projections. In future projections, the local atmospheric dynamics contribute in maintaining local temperature and precipitation balance over eastern and southern Mediterranean regions, suggesting a stronger influence of land surface warming on local atmospheric circulation and progressing desertification (Zhou, 2016; Wei et al., 2017; Barcikowska et al., 2020). In a climate change perspective, the influence from ISM on the Mediterranean region may have consequences also on the sea surface characteristics in terms of temperature and ecosystems (Kim et al., 2019).

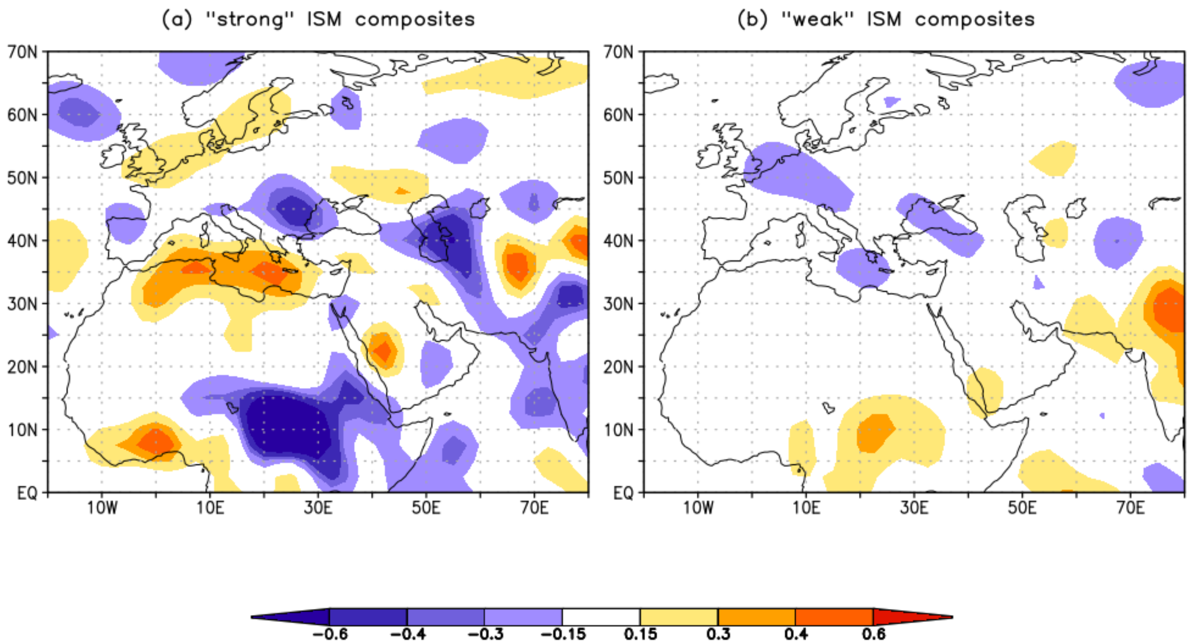

Figure 15.4: Composite of omega at 500 hPa (units hPa hr^{-1}) for (a) strong and (b) weak monsoon years for the boreal summer monsoon period (June to September), using NCEP/NCAR reanalysis dataset (Kalnay et al., 1996) for the period 1958-2019. Strong years are 1959, 1961, 1970, 1975, 1983, 1988, 1994 and weak years are 1965, 1966, 1968, 1972, 1974, 1979, 1982, 1985, 1986, 1987, 2002, 2004, 2009, 2014, 2015 (based on normalized All India Rainfall (AIR) index exceeding 1 standard deviation). The AIR index is taken from https://www.tropmet.res.in/~kolli/MOL/Monsoon/Historical/air.html.

15.4 Potential role of deserts in modulating ISM

The "monsoon-desert mechanism" described in the previous section, perceives the subtropical deserts of the NH to be a rather "passive" recipient in the relationship. However, from a different perspective, it is also argued that heat lows, changes of surface heating over the subtropical deserts and dry air intrusions (whether natural or anthropogenic) from arid regions into the monsoon domain can exert a significant control on the WAM and ISM systems, at both the intra-seasonal and seasonal time scales (Charney, 1975; Charney et al., 1977; Shukla and Mintz, 1982; Sud and Fennessy, 1982; Sud et al., 1988; Claussen, 1997; Bonfils et al., 2000; Douville et al., 2001; Xue et al., 2004; Yasunari et al., 2006; Xue et al., 2010; Krishnamurti et al., 2010; Bollasina and Nigam, 2011a, 2011b; Bollasina and Ming, 2013; Parker et al., 2016; Terray et al., 2018; Sooraj et al., 2019). For example, Sahelian Heat Low plays a key-role in the WAM evolution through its low-level cyclonic circulation and induced moisture convergence, and this is well established in observations, reanalysis and GCM simulations (Haarsma et al., 2005; Biasutti et al., 2009; Lavaysse et al., 2009; Shekhar and Boos, 2017). On similar lines, ISM, especially its onset and early part, is known to be influenced by the atmospheric variability over the subtropical desert regions (i.e., northwest part of India and west central Asia; Ramage, 1966; Smith, 1986a, 1986b; Mooley and Paolino 1988; Parthasarathy et al., 1992; Bollasina and Nigam, 2011b; Bollasina and Ming, 2013; Vinoj et al., 2014; Rai et al., 2015; Sooraj et al., 2019). During boreal summer, the monsoon depressions formed over the Bay of Bengal move northwestward across the Indian landmass, and eventually merge and dissipate in the heat-low region (Wang, 2006; Krishnamurti et al., 2013). The relationship between this seasonal heat low and ISM has been examined in perpetual boreal spring atmospheric GCM (i.e., AGCM) experiments by Bollasina and Ming, (2013). Remarkably, they found that the surface heating (i.e., with no seasonal variation of insolation in their perpetual experiments) over northwestern semi-arid areas is able to uniquely control the northwestward migration of ISM rainfall at seasonal time scale and of the monsoon depressions at intra-seasonal time scale.

Furthermore, recent modeling studies show increasing evidence of the impact of dust aerosols on the ISM at various time scales (i.e., from weekly to decadal) through aerosol radiative effects (Ramanathan et al., 2005; Lau et al., 2006; Meehl et al., 2008; Wang et al., 2009; Nigam and Bollasina, 2010; Bollasina et al., 2011; Vinoj et al., 2014; Jin et al., 2014, 2016a, 2016b; Solmon et al., 2015). For example, Vinoj et al. (2014) using AGCM sensitivity experiments argue that the presence of dust loading over North Africa and West Asian arid regions induced atmospheric heating over there, thus promoting abundant moisture transport into the ISM region, with associated enhanced rainfall (e.g., over Monsoon Core Region, MCZ). Thus, their study basically showed that the arid regions can also act as a dust induced atmospheric heat source (at least in a relative sense) during boreal summer and modulate ISM rainfall at the synoptic time scale. This is consistent with earlier studies (Smith 1986a, 1986b; Mohalfi et al., 1998), and also in line with other recent studies focusing on the impact of Middle East dust aerosols on ISM rainfall (Jin et al., 2014, 2015, 2016a; Solmon et al., 2015). However, the rainfall responses in each of these studies display heterogeneous distributions both in space and time (Solmon et al., 2015; Jin et al., 2016b; Sanap and Pandithurai, 2015). For example, Solmon et al. (2015) conducted a study (using a regional climate model) to examine the interaction between Middle East dust and ISM. Similar to Vinoj et al. (2014), they found an increase in rainfall restricted to the southern part of India with other parts, and central and northern India showing a significant decrease. Recently, Kumar and Arora, (2019) also claimed that enhanced dust forcing and associated warming over the Arabian Sea are unlikely to create a positive feedback on ISM rainfall, because of its limited spatial extent. To sum up, it is not altogether clear whether this part of the theory focusing on the role of Middle East dust on ISM is in definitive form.

This framework based on the relative heat source concept has also been extended to other time scales and to the ISM onset (Rai et al., 2015; Chakraborty and Agrawal, 2017; Samson et al., 2017; Terray et al., 2018; Sooraj et al., 2019). In particular, Samson et al. (2017) and Terray et al. (2018) demonstrated the sensitivity of NH monsoon regions (in particular African-Asian monsoon) to the land surface thermal forcing over these arid regions. Using regional and global coupled GCMs, respectively, they modified the land surface albedo using up-to-date satellite estimates. According to them, the persistent tropical rainfall errors in current coupled GCMs are partly associated with insufficient surface thermal forcing and incorrect representation of the surface albedo over the NH continents. Improving the parameterization of the land albedo in a regional coupled model (Samson et al., 2017) and two global coupled GCMs (i.e., SINTEX; Masson et al., 2012 and CFSv2; Saha et al., 2014; Terray et al., 2018), leads to a significant reduction of the model systematic dry bias over land. They further showed that African-Asian monsoon circulation is, partly, a response to the large-scale pressure gradient between the hot NH subtropical deserts and the relatively cooler oceans to the south. A concept, which may have implications for the ISM response in the context of climate change as desertification has been identified as a robust feature of global warming (Zhou, 2016; Wei et al., 2017).

In a companion modeling study, Sooraj et al. (2019) found that ISM evolution and intensity are significantly affected with opposite polarity to prescribed negative and positive surface albedo perturbations over the whole hot subtropical desert lying to the west of ISM, including the remote Sahara Desert. This is consistent with the hypothesis that the arid regions can also act as a relative heat source and modulate the ISM, but also the whole tropical climate during boreal summer (Terray et al., 2018). The darkening of the deserts (negative albedo perturbations) leads to advancement of the ISM onset by one month, with a rapid northward propagation of the rainfall band over the Indian domain (see Fig. 15.5). The brightening of the deserts (i.e., positive albedo perturbation) shows non-linear response in ISM rainfall and circulation with significantly larger amplitude (figure not shown).

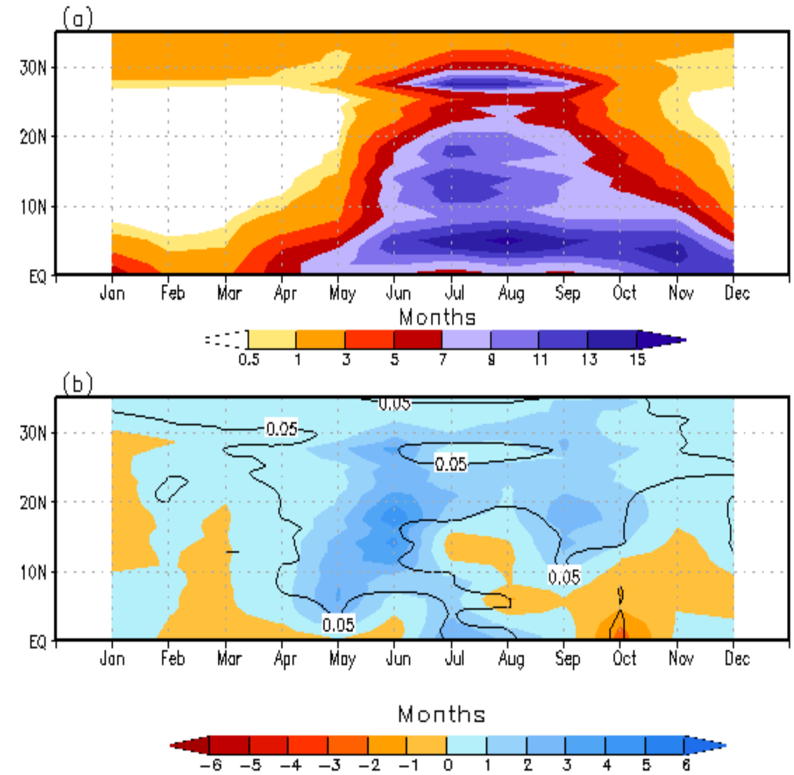

Figure 15.5: (a) Time-latitude evolution of rainfall climatology (mm day^{-1}) averaged along 70°-90°E (over both ocean and land points) from a control simulation performed with the SINTEX-F2 coupled model (Masson et al., 2012). (b) time-latitude evolution of anomalous rainfall response averaged along 70°-90°E from "Desert_m20" sensitivity experiment (see below). In (b), the responses that are above the 95% confidence level according to a permutation procedure with 9999 shuffles are encircled. "Desert_m20" is a sensitivity experiment performed with the SITEX-F2 coupled model in which the background land albedo has been artificially decreased by −20% over the whole hot subtropical desert extending up to the Sahara in the west (see highlighted box in Figure 15.1). [Adpated by permission from Sooraj et al., 2019]

Whilst the processes highlighted above (i.e., surface thermal forcing over arid regions) are mostly demonstrated at seasonal time scale, a recent observational study shows the evidence at the daily timescale as well (Sooraj et al., 2020). While examining the ISM rainfall extremes over the MCZ region at daily time scale, these authors found that a similar surface thermal signature over Indo-Pakistan Arid Region (IPAR) is among the best precursors of the ISM wet daily extremes at longer lead times (e.g., one or two weeks in advance), outperforming Sea Surface Temperature precursors based on the Monsoon Intra-Seasonal Oscillation (e.g., Wang et al., 2005, Roxy et al., 2017). With the additional role of moist processes, the study revealed the surprising existence of a strong water vapour positive feedback over the drier IPAR, at intraseasonal and daily time scales, in line with the strong longwave greenhouse effect as found over arid regions in the context of global warming (Zhou, 2016; Wei et al., 2017). Further, according to their study, the enhanced surface warming and amplified water vapor feedbacks may be another significant contributor to the recent increasing trend in rainfall wet extremes over Indian landmass. In the backdrop of global warming, the results from Sooraj et al. (2020) may have larger implications concerning the changes in ISM rainfall extremes as well as their potential predictability.

15.5 Summary and future perspectives

This chapter presents a comprehensive review on the monsoon-desert system focusing on the mutual relationships between these two contrasting climates, which, surprisingly, coexist at the same latitude of the NH, and highlights the underlying mechanisms. Such a review assumes significance, as recently there is a renewed interest to understand the close relationships between the two systems since both of them are expected to be severely affected by anthropogenic climate change in the forthcoming decades.

Firstly, the literature focusing on the monsoon influence on subtropical deserts is reviewed by highlighting the monsoon-desert mechanism whereby convection over ISM (and also the neighboring Bay of Bengal) induces strong descending motions over the NH subtropical deserts (i.e., to the west of ISM region), with the local subsidence and northerly flow (Etesian winds) being manifestations of the Rossby wave structure associated with ISM convection (Fig. 15.3). These different processes are further summarized in Figure 15.6. Hence, the theoretical framework, as suggested by earlier pioneering works (Rodwell and Hoskins, 1996, 2001), is now well established from more recent observational and modeling studies (e.g., Uppala et al., 2005; Tyrlis et al., 2013; Cherchi et al., 2014; Cherchi et al., 2018; Jin et al., 2019). Additional evidences are also presented to show that the monsoon-desert mechanism and the underlying processes operate at interannual timescales as well (Cherchi et al., 2014). However, most of the state-of-the-art coupled GCMs are unable to simulate this monsoon-desert relationship, partly due to the systematic monsoon dry bias affecting many current GCMs. For example, CMIP5 coupled GCMs with a severe dry bias over the ISM region depict the minimum descent over the subtropical deserts (Cherchi et al., 2014). In future projections, the monsoon-desert relationship remains elusive with ISM affecting mostly the central part of the Mediterranean region (Cherchi et al., 2016), despite that desertification and ISM rainfall are both projected to increase during the 21th century (Zhou, 2016; Wei et al., 2017; Wang et al., 2020). But, assessing the robustness of this counter-intuitive signal is challenging for several reasons. For example, it is not known if this paradox is related to the large uncertainty affecting ISM simulations (i.e., large biases in ISM mean characteristics as mentioned above) in current coupled GCMs or if it is the sign of the increasing role of radiative or surface land processes in shaping the climate of the deserts under global warming. Furthermore, the subtropical deserts are also affected by large temperature and radiation biases in current coupled GCMs (e.g., Samson et al., 2016; Terray et al., 2018). To sum up, both significant modeling developments, and an exhaustive analysis of all the external forcings at play (Blade et al., 2012; Kalimeris and Kolios, 2019; Masato et al., 2013; Tyrlis et al., 2015) are required to assess the fate of the monsoon-desert paradigm in our future world.

Secondly, we offered a different perspective by emphasizing the potential role of deserts in modulating ISM either through the changes of surface heating over the subtropical deserts or related to dry air intrusions from arid regions into the ISM domain (e.g., Krishnamurti et al., 2010; Bollasina and Nigam, 2011a, 2011b; Bollasina and Ming, 2013; Vinoj et al., 2014; Jin et al., 2014, 2016a; Solmon et al., 2015; Parker et al., 2016; Terray et al., 2018; Sooraj et al., 2019). Most of these studies, based on numerical modeling frameworks, show that the surface land warming paves the way for enhanced ISM rainfall through increased southwesterly monsoon flow and hence moist transport into the Indian continent. The associated processes are further summarized in Figure 15.6. For example, recent studies using fully coupled GCMs found that by darkening/brightening the subtropical deserts, the seasonality of ISM could be significantly modified (Fig. 15.5; e.g., Samson et al., 2017; Terray et al., 2018; Sooraj et al., 2019). Furthermore, a recent observational study provided new insights of the role of subtropical deserts (e.g., surface thermal forcing over IPAR) on the subseasonal modulations of ISM, and the occurrence of ISM daily rainfall extremes (Sooraj et al., 2020). These new studies challenge both the passive role of the desert as described in the monsoon-desert paradigm and the view that the lower tropospheric thermal contrast has only a minor role in the ISM evolution at different time scales from days to decades (Dai et al., 2013).

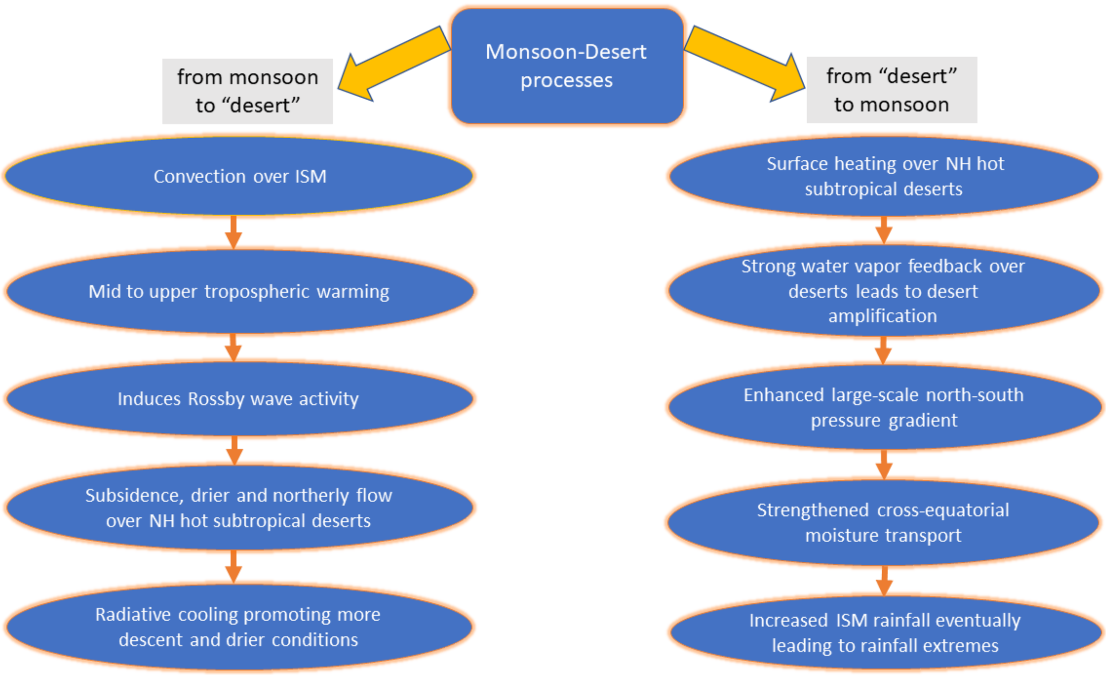

Figure 15.6: Schematic diagram summarizing the various interactive process and mechanisms in the monsoon-desert system over the African-Asian continent (i.e., from the monsoon to the "deserts" on the left and from the "deserts" to the monsoon on the right).

The subtropical deserts are particularly vulnerable to climate change (i.e., desert amplification with enhanced warming signal especially over the Sahara, the Arabian Peninsula and Middle-East) as suggested by several recent studies (e.g., Cook and Vizy, 2015; Zhou, 2016). The warming and moistening of the troposphere under climate change may in turn influence the local monsoon atmospheric circulation and, thus, eventually affect the monsoon-desert teleconnection in future climate. Further, the enhanced surface warming and amplified water vapor feedbacks over the arid regions adjacent to ISM (Sooraj et al., 2020) may have also significant implications for changes in frequency and intensity of ISM rainfall daily extremes under global warming scenario. However, as for the monsoon-desert mechanism, elucidating in a more robust way the potential role of the subtropical deserts on ISM will require both additional analysis of observations and improved GCMs with reduced rainfall biases, more detailed parameterizations for aerosols and improvements of the radiation codes embedded in these models.

Conflict of interest statement

The corresponding author states no conflict of interest on behalf of all authors.

Acknowledgement

Pascal Terray is funded by Institut de Recherche pour le Développement (IRD, France). The Centre for Climate Change Research (CCCR) at Indian Institute of Tropical Meteorology (IITM) is fully funded by the Ministry of Earth Sciences, Government of India.

References

Annamalai, H., Taguchi, B., Sperber. K.R., McCreary, J.P., Ravichandran, M., Cherchi, A., Martin, G., Moise, A., 2015. Persistence of Systematic errors in the Asian-Australian monsoon Precipitation in climate models: a way forward. Clivar. Exchanges. 66 doi:10.2172/1178403

Attada, R., Dasari, H.P., Parekh, A., Chowdary, J.S., Langodan, S., Knio, O., Hoteit, I., 2019. The role of the Indian summer monsoon variability on Arabian Peninsula summer climate. Clim. Dyn. 52, 3389-3404 doi: 10.1007/s00382-018-4333-x

Barcikowska, M.J., Kapnick, S.B., Krishnamurty, L., Russo, S., Cherchi, A., Folland, C.K., 2020. Changes in the future summer Mediterranean climate: contribution of teleconnections and local factors. Earth. Syst. Dyn. 11, 161-181 doi: 10.5194/esd-11-161-2020

Biasutti, M., Sobel, A.H., Camargo, S.J., 2009. The role of the Sahara low in summertime Sahel rainfall variability and change in the CMIP3 models. J. Clim. 22, 5755–5771. doi:10.1175/2009JCLI2969.1

Blade, I., Liebmann, B., Fortuny, D., van Oldenborgh, G.J., 2012. Observed and simulated impacts of the summer NAO in Europe: implications for projected drying in the Mediterranean region. Clim. Dyn. 39, 709-727 doi: 10.1007/s00382-011-1195-x

Bollasina, M., Ming, Y., 2013. The role of land-surface processes in modulating the Indian monsoon annual cycle. Clim. Dyn. 41(9–10),2497–2509. doi:10.1007/s00382-012-1634-3

Bollasina, M., Nigam, S., 2011a. The summertime “heat” low over Pakistan/northwestern India: evolution and origin. Clim. Dyn. 37, 957–970

Bollasina, M., Nigam, S., 2011b. Modeling of regional hydroclimate change over the Indian subcontinent: impact of the expanding Thar desert. J. Clim. 24, 3089–3106

Bollasina, M.A., Ming, Y., Ramaswamy, V., 2011. Anthropogenic aerosols and the weakening of the South Asian summer monsoon. Science. 334, 502–505, doi:10.1126/science.1204994

Bonfils, C., Noblet-Ducoudré, N.de., Braconnot, P., Joussaume, S., 2000. Hot desert albedo and climate change: Mid-Holocene monsoon in North Africa. J. Clim. 14, 3724–3737.

Chakraborty, A., Agrawal, S., 2017. Role of west Asian surface pressure in summer monsoon onset over central India. Environ. Res. Lett. 12

Charney, J.G., 1975. Dynamics of deserts and drought in Sahel. Quart. J. Roy. Meteor. Soc. 101: 193-202.

Charney, J., Quirk, W.J., Chow. S., Kornfield, J., 1977. A comparative study of the effects of albedo change on drought in semi-arid regions. J. Atmos. Sci. 34, 1366–1385.

Cherchi, A., Annamalai, H., Masina, S., Navarra, A.,2014. South Asian summer monsoon and the eastern Mediterranean climate: the monsoon-desert mechanism in CMIP5 simulations. J. Clim. 27, 6877-6903 doi: 10.1175/JCLI-D-13-00530.1

Cherchi, A., Annamalai, H., Masina, S., Navarra, A., Alessandri, A., 2016. Twenty-first century projected summer mean climate in the Mediterranean interpreted through the monsoon-desert mechanism. Clim. Dyn. 47, 2361-2371 doi: 101007/s00382-015-2968-4

Cherchi, A., Ambrizzi, T., Behera, S., Freitas, A.C.V., Morioka, Y., Zhou, T., 2018. The response of subtropical highs to climate change. Curr. Clim. Ch. Rep. doi: 10.1007/s40641-018-0114-1

Claussen, M., 1994. On coupling global biome models with climate models. Clim. Res. 4, 203-221

Claussen, M., 1997. Modeling biogeophysical feedback in the Africa and India monsoon region. Clim. Dyn. 13:247–257.

Clemens, S., Prell, W., Murray, D., Shimmield, G., Weedon, G., 1991. Forcing mechanisms of the Indian Ocean monsoon. Nature. 353, 720-725 doi: 10.1038/353720a0

Cook, K.H., Vizy, E.K., 2015. Detection and analysis of an amplified warming of the Sahara Desert. J. Clim. 28, 6560–6580, doi:10.1175/JCLI-D-14-00230.1

Dai, A., Li, H., Sun, Y., Hong, L.-C., Ho, Lin., Chou, C., and Zhou, T., 2013. The relative roles of upper and lower tropospheric thermal contrasts and tropical influences in driving Asian summer monsoons, J. Geophys. Res. Atmos. 118, 7024–7045, doi:10.1002/jgrd.50565.

Dee, D.P., Uppala, S.M., Simmons, A.J., Berrisford, P., Poli, P., Kobayashi, S., Andrae, U., Balmaseda, M.A., Balsamo, G., Bauer, P., Bechtold, P., Beljaars, A.C.M., van de Berg, L., Bidlot, J., Bormann, N., Delsol, C., Dragani, R., Fuentes, M., Geer, A.J., Haimberger, L., Healy, S.B., Hersbach, H., Hólm, E.V., Isaksen, L., Kållberg, P., Köhler, M., Matricardi, M., McNally, A.P., Monge-Sanz, B.M., Morcrette, J.-J., Park, B.-K., Peubey, C., de Rosnay, P., Tavolato, C., Thépaut, J.-N. and Vitart, F., 2011. The ERA-Interim reanalysis: Configuration 683 and performance of the data assimilation system. Quart. J. Roy. Meteorol. Soc. 137:553–597.

Ding, Q.H., Wang, B., 2005. Circumglobal teleconnection in the Northern Hemisphere summer. J. Clim. 18, 3483-3505 doi: 10.1175/JCLI3473.

Douville, H., Chauvin, F., Broqua, H., 2001. Influence of soil moisture on the Asian and African monsoons. Part I: Mean monsoon and daily precipitation. J. Clim. 14, 2381–2403

Enomoto, T., Hoskins, B. J., Matsuda,Y., 2003. The formation mechanism of the Bonin high in August. Quart. J. Roy. Meteor. Soc. 129, 157-178 doi: 10.1256/qj.01.211

Gaven, C., Hillaire-Marcel, C., Petit-Marie, N., 1981. A Pleistocene lacustrine episode in south-eastern Libya. Nature. 290, 131-133 doi: 10.1038/290131a0

Haarsma, R. J., Selten, F. M., Weber, S. L., Kliphuis, M., 2005. Sahel rainfall variability and response to greenhouse warming. Geophys. Res. Lett. 32, L17702

He, S., Yang, S., Li, Z., 2017. Influence of latent heating over the Asian and Western Pacific monsoon region on Sahel summer rainfall. Sci. Rep. 7, 7680 doi: 10.1038/s41598-017-07971-6

Haywood, J. M.,Jones, A., Dunstone, N., Milton, S., Vellinga, M., Bodas□Salcedo, A., Hawcroft, M., Kravitz, B., Cole, J., Watanabe, S., Stephens, G., 2016. The impact of equilibrating hemispheric albedos on tropical performance in the HadGEM2-ES coupled climate model, Geophys. Res. Lett. 43, 395–403, doi:10.1002/2015GL066903.

Hoskins, B. J., 1986. Diagnosis of forced and free variability in the atmosphere, pp. 57–63, in: Atmospheric and Oceanic Variability, edited by: Cattle, H., Royal Meteorological Society, Bracknell.

Huffman, G. J., Adler, R. F., Bolvin, D. T., Gu, G., 2009. Improving the global precipitation record: GPCP Version 2.1. Geophy. Res. Lett. 36,L17808. doi:10.1029/2009GL040000

IPCC, 2013. Fifth Assessment Report of the Intergovernmental Panel on Climate Change, www.ipcc.ch/ipccreports/ar4-wg1.htm

Jin, L., Zhang, H., Moise, A., Martin, G., Milton, S., Rodriguez, J., 2019. Australia-Asian monsoon in two versions of the UK Met Office Unified Model and their impacts on tropical-extratropical teleconnections. Clim. Dyn. 53, 4717-4741 doi: 10.1007/s00382-019-04821-1

Jin, Q., Wei, J., Yang, Z.L., 2014. Positive response of Indian summer rainfall to Middle East dust. Geophys. Res. Lett. 41,4068–4074. https://doi.org/10.1002/2014GL059980

Jin, Q., Wei, J., Yang, Z.L., Pu, B., Huang, J., 2015. Consistent response of Indian summer monsoon to Middle East dust in observations and simulations. Atmos. Chem. Phys. 15,9897–9915. https://doi.org/10.5194/acp-15-9897-2015

Jin, Q., Yang, Z.-L., Wei, J., 2016a. High sensitivity of Indian summer monsoon to Middle East dust absorptive properties. Sci. Rep. 6, 30690, doi:10.1038/srep30690.

Jin, Q., Yang, Z.-L., Wei, J., 2016b. Seasonal responses of Indian summer monsoon to dust aerosols in the Middle East, India, and China. J. Clim. 29, 6329–6349

Kalimeris, A., Kolios, S., 2019. TRMM-based rainfall variability over the central Mediterranean and its relationship with atmospheric and oceanic climatic modes. Atm. Res. 230, 104649 doi: 10.1016/j.atmosres.2019.104649

Kalnay, E., Kanamitsu, M., Kirtler, R., Collins, W., Deaven, D., Gandin, L., Iredell, M., Saha, S., White, G., Woollen, J., Zhu, Y., Chelliah, M., Ebisuzaki, W., Higgins, W., Janowiak, J., Mo, K. C., Ropelewski, C., Wang, J., Leetma, A., Reynolds, R., Jenne, R., Joseph, D., 1996. The NCEP/NCAR 40-year reanalysis project. Bull. Amer. Meteor. Soc. 77, 437-470

Kato, S., Rose, F. G., Rutan, D. A., Thorsen, T. J., Loeb, N. G., Doelling, D. R., et al 2018. Surface irradiances of Edition 4.0 Clouds and the Earth’s Radiant Energy System (CERES)

Energy Balanced and Filled (EBAF) data product. J. Clim. 31, 4501–4527. doi: 10.1175/JCLI-D-17-0523.1

Kim, G-U., Seo K-H., Chen, D., 2019. Climate change over the Mediterranean and current destruction of marine ecosystem. Sci. Rep. 9, 18813 doi: 10.1038/s41598-019-55303-7

Kitoh, A., 2017. The Asian monsoon and its future change in climate models: a review. J. Meteor. Soc. Japan. 95, 7-33, doi:10.2151/jmsj.2017-002.

Kowalski, K., Van Neer, W., Bochenski, Z., Mlynarski, M., Rsebik-Kowalska, B., Szyndlar, Z., Lavaysse, C., Flamant, C., Janicot, S., Parker, D.J., Lafore, J.P., Sultan, B., Pelon, J., 2009. Seasonal evolution of the West African heat low: a climatological perspective. Clim. Dyn. 33, 313–330

Krishnamurti, T.N., Thomas, A., Simon, A., Kumar, V., 2010. Desert air incursions, an overlooked aspect, for the dry spells of the Indian summer monsoon. J. Atmos. Sci. 67, 3423–3441

Krishnamurti, T.N., Stefanova, L., Misra, V., 2013. Tropical meteorology (pp 331). Springer. New York, NY.

Krishnan, R., Sabin, T.P., Vellore, R., Mujumdar, M., Sanjay, J., Goswami, B.N., Hourdin, F., Dufresne J-L., Terray, P., 2016. Deciphering the desiccation trend of the South Asian monsoon hydroclimate in a warming world. Clim. Dyn. 47(3–4),1007–1027. https://doi.org/10.1007/s00382-015-2886-5

Kumar, S., Arora, A., 2019. On the connection between remote dust aerosol and Indian summer monsoon. Theor. Appl. Climatol. 137, 929–940. https://doi.org/10.1007/s00704-018-2647-6

Lau, K. M., Kim, M. K., Kim, K. M., 2006. Asian summer monsoon anomalies induced by aerosol direct forcing: The role of the Tibetan Plateau. Clim. Dyn. 26, 855–864, doi:10.1007/s00382-006-0114-z.

Lavaysse, C., Flamant, C., Janicot, S., Parker, D.J., Lafore, J.P., Sultan, B., Pelon, J., 2009. Seasonal evolution of the West African heat low: a climatological perspective. Clim. Dyn. 33: 313–330

Levine, R.C., Turner, A.G., Marathayil, D., Martin, G.M., 2013. The role of northern Arabian Sea surface temperature biases in CMIP5 model simulations and future predictions of Indian summer monsoon rainfall. Clim. Dyn. 41: 155–172

Liu, P., Wu, G., Sun, S., 2001. Local meridional circulation and deserts. Adv. Atmos. Sci. 18, 864-872 doi: 10.1007/BF03403508

Lu, R.Y., Oh, J.H., Kim, B. J., 2002. A teleconnection pattern in upper-level meridional wind over the North African and Eurasian continent in summer. Tellus. 54A: 44-55 doi: 10.3402/tellusa.v54i1.12122

Masato, G., Hoskins, B. J., Woollings, T., 2013. Winter and summer northern hemisphere blocking in CMIP5 models. J. Clim. 26, 7044-7059 doi: 10.1175/JCLI-D-12-00466.1

Masson, S., Terray, P., Madec, G., Luo, J. J., Yamagata, T., Takahashi, K., 2012. Impact of intra-daily SST variability on ENSO characteristics in a coupled model. Clim. Dyn. 39,681-707

Meehl, G. A., Arblaster, J. M., Collins, W. D., 2008. Effects of black carbon aerosols on the Indian monsoon. J. Clim. 21, 2869–2882, doi:10.1175/2007JCLI1777.1

Mohalfi, S., Bedi, H.S., Krishnamurti, T.N., Cocke, S.D., 1998. Impact of shortwave radiative effects of dust aerosols on the summer season heat low over Saudi Arabia. Mon. Wea. Rev. 126, 3153–3168

Mooley, D.A., Paolino, D.A., 1988. A predictive monsoon signal in the surface level thermal fields over India. Mon. Wea. Rev. 116,256–264

Neelin, J.D., Held, I.M., 1987. Modeling tropical convergence based on the moist static energy budget. Mon. Wea. Rev. 115:3–12

Nigam, S., Bollasina, M., 2010. ‘‘Elevated heat pump’’ hypothesis for the aerosol-monsoon hydroclimate link: ‘‘Grounded’’ in observations? J. Geophys. Res. 115, D16201, doi:10.1029/2009JD013800.

Osso, A., Shaffrey, L., Dong, B., Sutton, R., 2019. Impact of air-sea coupling on Northern Hemisphere summer climate and the monsoon-desert teleconnection. Clim. Dyn. 53, 5063-5078 doi: 10.1007/s00382-019-04846-6

Parker, D.J., Willetts, P., Birch, C., Turner, A.G., Marsham, J. H., Taylor, C.M., Kolusu, S., Martin, G. M., 2016. The interaction of moist convection and mid-level dry air in the advance of the onset of the Indian monsoon. Quart. J. Roy. Meteor. Soc. 142, 2256–2272, https://doi.org/10.1002/qj.2815.

Parthasarathy, B., Rupakumar, K., Munot, A.A., 1992 . Surface pressure and summer monsoon rainfall over India. Adv. Atmos. Sci. 9,359–366

Perez-Sanz, A., Li, G., Gonzalez-Samperiz, P., Harrison, S. P., 2014. Evaluation of modern and mid-Holocene seasonal precipitation of the Mediterranean and northern Africa in the CMIP5 simulations. Clim. Past. 10, 551-568 doi: 10.5194/cp-10-551-2014

Prodhomme, C., Terray, P., Masson, S., Izumo, T., Tozuka, T., Tamagata, T., 2014. Impacts of Indian Ocean SST biases on the Indian Monsoon as simulated in a global coupled model. Clim. Dyn. 42:271–290

Quade, J., Dente, E., Armon, M., Ben Dor, Y., Morin, E., Adam, O., Enzel, Y., 2018. Megalakes in the Sahara? A review. Quart. Res. 90, 235-275 doi: 10.1017/qua.2018.46

Rai, A., Saha, S.K., Pokhrel, S., Sujith, K., Halder, S., 2015. Influence of pre-onset land-atmospheric conditions on the Indian summer monsoon rainfall variability. J. Geophys. Res. Atmos. 120:4551–4563

Ramage, C.S., 1966. The summer atmospheric circulation over the Arabian Sea. J. Atmos. Sci. 23, 144–150.

Ramanathan, V., Chung, C., Kim, D., Bettge, T., Buja, L., Kiehl, J. T.,Washington, W. M, Fu, Q., Sikka, D. R., Wild, M., 2005. Atmospheric brown clouds: Impacts on South Asian climate and hydrological cycle. Proc. Natl. Acad. Sci. USA, 102, 5326–5333, doi:10.1073/pnas.0500656102.

Rizou, D., Flocas, H.A., Hatzaki, M., Bartzokas, A., 2018. A statistical investigation of the impact of the Indian monsoon on the eastern Mediterranean circulation. Atmosphere. 9 doi: 10.3390/atmos9030090

Rodwell, M.J., Hoskins, B.J., 1996. Monsoons and the dynamics of deserts. Quart. J. Roy. Meteor. Soc. 122, 1385-1404

Rodwell, M.J., Hoskins, B.J., 2001. Subtropical anticyclones and summer monsoons. J. Clim. 14, 3192-3211

Roehrig, R., Bouniol, D., Guichard, F., Hourdin, F., Redelsperger, J.L., 2013 The present and future of the West African monsoon: a process-oriented assessment of CMIP5 simulations along the AMMA Transect. J. Clim. 26: 6471–6505

Roxy, M.K., Ghosh, S., Pathak, A., Athulya, R., Mujumdar, M., Murtugudde, R., Terray, P., Rajeevan, M., 2017. A threefold rise in widespread extreme rain events over central India. Nat. Commun. 1-11. doi:10.1038/s41467-017-00744-9

Sabeerali, C.T., Rao, S.A., Dhakate, A.R., Salunke, K., Goswami, B.N., 2015. Why ensemble mean projection of south Asian monsoon rainfall by CMIP5 models is not reliable? Clim. Dyn. 45, 161–174

Saeed, S., Lipzig, N.V., Muller, W.A., Saeed, F., Zanchettin, D., 2014. Influence of the circumglobal wave train on European summer precipitation. Clim. Dyn. 43, 503-515 doi: 10.1007/s00382-013-1871-0

Saha, S., Moorthi, S.,Wu, X.,Wang, J., Pan, H.-L.,Wang, J., Nadiga, S., Tripp, P., Behringer, D., Hou, Y.T., Chuang, H.Y., Iredell, M., Ek, M., Meng, J., Yang, R., Mensez, M.P., Dool, H.V.D., Zhang, Q., Wang, W., Chen, M. and Becker, E., 2014. The NCEP climate forecast system version 2. J. Clim. 27,2185–2208

Samson, G., Masson, S., Durand, F., Terray, P., Berthet, S., Jullien, S., 2017. Role of land surface albedo and horizontal resolution on the Indian Summer Monsoon biases in a coupled ocean-atmosphere tropical-channel model. Clim. Dyn. doi:10.1007/s00382-016-3161-0

Sanap, S.D., Pandithurai, G., 2015. Inter-annual variability of aerosols and its relationship with regional climate over Indian subcontinent. Int. J. Climatol. 35,1041–1053. https://doi.org/10.1002/joc.4037

Sandeep, S., Ajayamohan, R., 2015. Origin of cold bias over the Arabian Sea in Climate Models. Sci. Rep. 4, 6403. https://doi.org/10.1038/srep06403

Shekhar, R., Boos, W.R., 2017. Weakening and Shifting of the Saharan Heat Low Circulation During Wet Years of the West African Monsoon. J. Clim. 30, 7399-7422

Shukla, J., Mintz, Y., 1982. Influence of land-surface evaporation on Earth's climate. Science. 215, 1498–1501

Sikka, D.R., 1997. Desert climate and its dynamics. Curr. Sci. 72, 35–46.

Singh, R., AchutaRao, K., 2018. Quantifying uncertainty in twenty-first century climate change over India. Clim. Dyn. 52(7–8), 3905–3928. https://doi.org/10.1007/s00382-018-4361-6

Smith, E.A., 1986a. The structure of the Arabian heat low. Part I: surface energy budget. Mon. Wea. Rev. 114, 1067–1083.

Smith, E.A., 1986b. The structure of the Arabian heat low. Part II: bulk tropospheric heat budget and implications. Mon. Wea. Rev. 114, 1084–1102

Solmon, F., Nair, V.S., Mallet, M., 2015. Increasing Arabian dust activity and the Indian summer monsoon. Atmos. Chem. Phys. 15, 8051–8064. https://doi.org/10.5194/acp-15-8051-2015

Sooraj, K.P., Terray, P., Mujumdar, M., 2015. Global warming and the weakening of the Asian summer monsoon circulation: assessments from the CMIP5 models. Clim. Dyn. 45, 233–252.

Sooraj, K.P., Terray, P., Masson, S., Cretat, J., 2019. Modulations of the Indian summer monsoon by the hot subtropical deserts: insights from coupled sensitivity experiments. Clim. Dyn. 52, 4527–4555. https://doi.org/10.1007/s00382-018-4396-8.

Sooraj, K.P., Terray, P., Shilin, A., Mujumdar, M., 2020. Dynamics of rainfall extremes over India: A new perspective. Int. J. Climatol. 40: 5223– 5245. https://doi.org/10.1002/joc.6516

Sperber, K.R., Annamalai, H., Kang, I.S., Kitoh, A., Moise, A., Turner, A.G., Wang, B., Zhou, T., 2013. The Asian summer monsoon: an intercomparison of CMIP5 vs. CMIP3 simulations of the late 20th century. Clim. Dyn. 41: 2711–2744. doi:10.1007/s00382-012-1607-6

Stephan, C.C., Klingaman, N.P., Turner, A.G., 2019. A mechanism for the recently increased interdecadal variability of the Silk Road Pattern. J. Clim. 32, 717-736 doi: 10.1175/JCLI-D-18-0405.1

Sud, Y.C., Fennessy, M., 1982. A study of the influence of surface albedo on July circulation in semi-arid regions using the GLAS GCM. Int. J. Climatol. 2, 105–125.

Sud, Y.C., Shukla, J., Mintz, Y., 1988. Influence of land surface roughness on atmospheric circulation and precipitation: A sensitivity study with a general circulation model. J. Appl. Meteor. 27, 1036–1054.

Taylor, K., Stouffer, R., Meehl, G., 2012. An overview of CMIP5 and the experiment design. Bull. Am. Meteor. Soc. 93, 485-498 doi: 10.1175/BAMS-D-11-00094.1

Terray, P., Sooraj, K.P., Masson, S., Krishna, R.P.M., Samson, G., Prajeesh, A.G., 2018. Towards a realistic simulation of boreal summer tropical rainfall climatology in state-of the-art climate coupled models. Clim. Dyn. 50, 3413–3439 doi:10.1007/s00382-017-3812-9

Tyrlis, E., Lelieveld, J., Steil, B., 2013. The summer circulation over the eastern Mediterranean and the Middle East: influence of the South Asian monsoon. Clim. Dyn. 40, 1103-1123 doi: 10.1007/s00382-012-1528-4

Tyrlis, E., Tymvios, F.S., Giannakopoulos, C., Lelieveld, J., 2015. The role of blocking in the summer 2014 collapse of Etesians over the eastern Mediterranean. J. Geophys. Res. Atm. 120, 6777-6792 doi: 10.1002/2015JD023543

Uppala, S.M., Kallberg, P.W., Simmons, A.J., et al 2005. The ERA-40 Reanalysis. Quart. J. Roy. Meteor. Soc. 131, 2961-3012 doi: 10.1256/qj.04.176

Vinoj, V., Rasch, P. J., Wang, H., Yoon, J. H., Ma, P. L., Landu, K., Singh, B., 2014. Short term modulation of Indian summer monsoon rainfall by West Asian dust. Nature. Geo. Science. doi:10.1038/NGEO2017

Wang, B., 2006. The Asian Monsoon. Springer, Chichester.

Wang, B., Biasutti, M., Byrne, M., Castro, C., Chang, C. P., et al., 2020. Monsoons Climate Change Assessment. Bull. Amer. Meteor. Soc. doi: https://doi.org/10.1175/BAMS-D-19-0335.1.

Wang, B., Liu, J., Kim, H.J., Webster, P.J., Yim, S.Y., 2012. Recent change of the global monsoon precipitation (1979-2008). Clim. Dyn. 39, 1123-1135 doi: 10.1007/s00382-011-1266-z

Wang, B., Webster, P.J., Teng, H., 2005. Antecedents and self-induction of active-break south Asian monsoon unraveled by satellites. Geophys. Res. Lett. 32, 4–7 doi:10.1029/2004GL020996

Wang, C., Kim, D., Ekman, A. M. L., Barth, M. C., Rasch, P. J., 2009. Impact of anthropogenic aerosols on Indian summer monsoon. Geophys. Res. Lett. 36, L21704 doi:10.1029/2009GL040114.

Wang, L., Xu, P., Chen, W., Liu, Y., 2017. Interdecadal variations of the Silk Road Pattern. J. Clim. 30, 9915-9932 doi: 10.1175/JCLI-D-17-0340.1

Wang, P.X., Wang, B., Cheng, H., Fasullo, J., Guo, Z.T., Kiefer, T., Liu, Z.Y., 2014. The global monsoon across timescales: coherent variability of regional monsoons. Clim. Past. 10, 2007-2052 doi: 10.5194/cp-10-2007-2014

Warner, T.T., 2004. Desert Meteorology Cambridge University Press, London, p 612

Webster, P.J., 1994. The role of hydrological processes in ocean atmosphere interactions. Rev. Geophys. 32(4), 427–476

Wei, N., Zhou, L., Dai, Y., Xia, G., Hua, W., 2017. Observational Evidence for Desert Amplification Using Multiple Satellite Datasets. Sci. Rep. 2043 doi:10.1038/s41598-017-02064-w

Wu, G.X., Liu, Y., Zhu, X., Li, W., Ren, R., Duan, A., Liang, X., 2009. Multi-scale forcing and the formation of subtropical desert and monsoon. Ann. Geophys. 27, 3631-3644 doi: 10.5194/angeo-27-3631-2009

Xue, Y., Juang, H.M.H., Li, W. P., Prince, S., Defries, R., Jiao, Y., Vasic, R., 2004. Role of land surface processes in monsoon development: East Asia and West Africa. J. Geophys. Res. (Atmos). 109, 03105–03128

Xue, Y., De, Sales F., Vasic, R., Mechoso, C. R., Prince, S. D., Arakawa, A., 2010. Global and temporal characteristics of seasonal climate/vegetation biophysical process (VBP) interactions. J. Clim. 23, 1411–1433

Yang, S., Webster, P.J., Dong, M., 1992. Longitudinal heating gradient: another possible factor influencing the intensity of the Asian summer monsoon circulation. Adv. Atmos. Sci. 9, 397-410

Yasunari, T., Saito, K., Takata, K., 2006. Relative roles of large-scale orography and land surface processes in the global hydroclimate, Part I: Impacts on monsoon systems and the Tropics. J. Hydrometeor. 7: 626–641.

Zhou, L., 2016. Desert amplification in a warming climate. Sci. Rep. 6. doi:10.1038/srep31065

Figure captions:

Figure 15.1: Climatological map of (a) rainfall (mm day^{-1}), (b) land surface albedo (%) and (c) net radiation budget at TOA (Wm^{-2}), for boreal summer period (June to September). In (a) rainfall climatology is computed for the 1986-2014 period from Global Precipitation Climatology Project (GPCP version 2.1; Huffman et al., 2009). In (b) and (c), albedo and radiation climatology is computed for the 2000-2018 period from the Clouds and the Earth's Radiant Energy System Energy Balanced and Filled (CERES-EBAF edition 4.0; Kato et al., 2018). In (b) and (c), the region highlighted in the black rectangle refers to "subtropical deserts".

Figure 15.2: Vertical cross-section of atmospheric circulation in terms of vertical component of velocity (10^{-2} Pa s^{-1}, shaded) and horizontal wind divergence (10^{-6} s^{-1}, contours) during July, along a pressure-longitude plane averaged over two latitude bands (a) 20°N and (b) 40°N. The circulation fields are taken from the ERA-Interim reanalysis (Dee et al., 2011) and the climatology is computed for the 1986-2014 period. The negative (dashed) and positive (continuous) contours correspond, respectively, to absolute magnitudes of 1, 2, 3 and 4 units. The zero contours are highlighted in thick black color. Negative (positive) shading implies ascending (descending), while negative (positive) contours implies convergence (divergence). The presentation using July climatology follows the observational conjecture that it corresponds to the peak of monsoon activity (e.g., Tyrlis et al., 2013).

Figure 15.3: (a) Schematic diagram of the monsoon desert-mechanism with descent over the desert region (orange) induced by the heating over the monsoon convective region (cyan) interacting with local westerlies. [Adapted by permission from Wang et al., 2012]. (b) JJA mean wind (ms^{-1}, green vectors), meridional wind velocity (ms^{-1}, shaded), and pressure levels (hPa,

contours with 50-hPa contour interval) on isentropic surfaces at 325K using NCEP/NCAR reanalysis dataset (Kalnay et al., 1996). The climatology is computed for the period 1958-2019.

Figure 15.4: Composite of omega at 500 hPa (units hPa hr^{-1}) for (a) strong and (b) weak monsoon years for the boreal summer monsoon period (June to September), using NCEP/NCAR reanalysis dataset (Kalnay et al., 1996) for the period 1958-2019. Strong years are 1959, 1961, 1970, 1975, 1983, 1988, 1994 and weak years are 1965, 1966, 1968, 1972, 1974, 1979, 1982, 1985, 1986, 1987, 2002, 2004, 2009, 2014, 2015 (based on normalized All India Rainfall (AIR) index exceeding 1 standard deviation). The AIR index is taken from https://www.tropmet.res.in/~kolli/MOL/Monsoon/Historical/air.html.

Figure 15.5: (a) Time-latitude evolution of rainfall climatology (mm day^{-1}) averaged along 70°-90°E (over both ocean and land points) from a control simulation performed with the SINTEX-F2 coupled model (Masson et al., 2012). (b) time-latitude evolution of anomalous rainfall response averaged along 70°-90°E from "Desert_m20" sensitivity experiment (see below). In (b), the responses that are above the 95% confidence level according to a permutation procedure with 9999 shuffles are encircled. "Desert_m20" is a sensitivity experiment performed with the SITEX-F2 coupled model in which the background land albedo has been artificially decreased by −20% over the whole hot subtropical desert extending up to the Sahara in the west (see highlighted box in Figure 15.1). [Adpated by permission from Sooraj et al., 2019]

Figure 15.6: Schematic diagram summarizing the various interactive process and mechanisms in the monsoon-desert system over the African-Asian continent (i.e., from the monsoon to the "deserts" on the left and from the "deserts" to the monsoon on the right).