**Evolution and current state of our understanding of the role
played in the climate system by land surface processes in semi-arid regions**

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ABSTRACT

The role of the land surface in climate and weather has been a major research focus since the 1970s. Since that time our understanding of the issue has greatly changed and many new themes in several disciplines are being considered. This article summarizes the changes in our understanding that have taken place in research on this topic and reviews principally papers that have appeared in the last two decades. Several other papers provide comprehensive reviews of literature that appeared prior to that time. The major changes that have occurred include 1) more sophisticated and rigorous analysis of desertification, 2) increased emphasis on hydrological processes, including the role of groundwater, 3) use of multi-model ensembles and regional models, 4) the emergence of the domain of ecohydrology, with emphasis on detailed feedbacks between water availability and vegetation, 5) examination of the hypothesis that vegetation feedback can produce abrupt climate change, 6) emphasis on the impacts on convective or synoptic-scale systems, and 7) consideration of the impact of aerosols, including the Saharan Air Layer. With the exception of desertification, each of these topics is reviewed.

1. INTRODUCTION

The earth as a whole receives on average 341 W/m² at the top of the atmosphere. Less than 23% of this radiation is absorbed in the atmosphere (Trenberth et al. 2009). Some two-thirds of the atmospheric heating is via heat fluxes from the earth's surface. Over half of that is supplied via the latent heat release when water vapor extracted from the surface condenses in the atmosphere as clouds. Surface fluxes are modulated by the characteristics of the land surface, including vegetation (biosphere), soils (lithosphere), ice (cryosphere), and water (hydrosphere) (Fig. 1). Clearly, the land surface has a major impact on the atmosphere and global climate system.

This impact has long been recognized in a general sense, but the idea of land-surface characteristics influencing weather events or climatic variability is a much more recent one. The first suggestion of this influence in the meteorological literature may have been in papers by Namias (1952, 1955, 1960), who suggested that soil moisture was a factor in North American droughts. Nevertheless, this concept of land-atmosphere interaction received little attention until Jule Charney published his seminal paper on drought and desertification (Charney 1975). The impetus for his paper was the occurrence of a major drought in the African Sahel at the same time that the desertification concept became popularized (e.g, UNEP 1977) and satellite photos demonstrated the large-scale impact of land surface changes (Fig. 2). An example of the latter is the classic photo from Otterman (1974), showing that the border between the Negev and Sinai deserts was visible via contrasts in surface albedo. The borders between Namibia and Angola and Afghanistan and the former Soviet Union were similarly apparent (Nicholson 2011).

Both Charney and Otterman focused on the question of anthropogenic changes in surface albedo. Charney (1975) suggested that overgrazing in the Sahel had exposed highly reflective

1 soil, changing the atmospheric radiation balance in a way that enhanced the subsidence in this
2 region, thereby increasing aridity. Fig. 3 illustrates typical radiation budgets over the Sahara and
3 over a grassland similar to that of the Sahel. The net radiative loss at the top of the atmosphere
4 would increase with the increased surface albedo. To restore the radiative balance, adiabatic
5 heating via subsidence would be required to offset the radiative loss resulting from the higher
6 albedo.

7 The ensuing studies of this issue were primarily model simulations with exaggerated
8 surface changes; observations of the phenomenon were few (Nicholson et al. 1998, Nicholson
9 2002). The mainstream meteorological community did not readily accept the idea that land
10 surface changes could significantly affect climatic variability. The situation began to change
11 with the inception in 1983 of the International Satellite Land Surface Climatology Project
12 (ISLSCP) led by Ichiaque Rasool and Hans-Jürgen Bolle (Fig. 4) and the development of
13 models that explicitly treated vegetation characteristics, beginning with the pioneering work of
14 Deardorff (1977, 1978). The BATS model (Biosphere-Atmosphere Transfer Scheme) of Robert
15 Dickinson et al. (1986) and the SiB (Simple Biosphere) of Piers Sellers et al. (1986) both
16 appeared in the mid-1980s, almost simultaneous with the First ISLSCP Field Experiment (FIFE)
17 (Hall and Sellers 1995). This experiment focused on land-atmosphere interaction in the U. S.
18 Great Plains and was followed by two additional ISLSCP experiments, HAPEX-Sahel in Africa
19 (Goutourbe et al. 1997) and BOREAS, in the northern United States and Canada (Sellers et al.
20 1997). The impact on the scientific community is clear from Fig. 4, which shows the number of
21 papers published each year under the topics of land-atmosphere feedback, soil moisture
22 feedback, land-atmosphere interaction, and albedo-drought feedback, as found by searching in

1 the Web of Science. This search by is by no means exhaustive, since not all papers are captured
2 by these specific "topics". However, the general trends shown by the figure are representative.

3 While albedo was implicated as a major factor in the early papers, it soon became evident
4 that the real driver of land-atmosphere interaction is soil moisture. The albedo mechanism fell
5 out of favor for several reasons, most notably the recognition that the changes of this parameter
6 were smaller than had been assumed (Nicholson et al. 1998, Ba et al. 2001). The role of soil
7 moisture got a boost from the first observational study to clearly demonstrate the impact of soil
8 moisture on storm systems (Taylor and Lebel 1998). Charney's continued work (Charney et al.
9 1977) included soil moisture and identified three major areas major where land-atmosphere
10 interaction appeared to have the potential to influence climate: the U. S. Great Plains, India, and
11 the West African Sahel. While Charney had initially theorized that land surface changes in the
12 Sahel could initiate drought, these soil moisture studies modified this idea to the concept of land-
13 atmosphere feedbacks enhancing the persistence of drought. Several studies suggested that the
14 multi-decadal persistence of dry or wet conditions in the Sahel was a result of such feedback
15 (e.g., Courel et al. 1984, Nicholson 1989, Lare and Nicholson 1994, Zeng et al. 1999, 2000).
16 Simple studies of the influence of soil moisture gave way to more complex theory concerning
17 hydrological feedbacks, land-atmosphere coupling, and the impact of these changes on storm
18 systems and convection.

19 At the same time, ideas about desertification were rapidly changing. Various works
20 showed that original estimates of the process were greatly exaggerated and that much of the
21 assumed degradation was actually drought induced (e.g., Tucker et al. 1991, Dean et al. 1995,
22 Nicholson et al. 1998, Prince et al. 1998, Prince 2002, Wessels et al. 2004). The very
23 generalized studies of desertification that initially appeared in the literature were replaced by

1 more sophisticated studies of land use change and its impact, changes in vegetation productivity
2 (Fig. 5), the impact of mineral dust, and soil moisture-vegetation feedbacks (Reynolds and
3 Stafford-Smith 2002). Several exciting areas emerged that are related to this last topic: patch
4 dynamics and self-organization, bi-stability of ecosystems, critical transitions and catastrophic
5 shifts, abrupt climate change. Fig. 6 presents an overview of this evolution of the research on
6 land-atmosphere interaction, commencing with the early topics of albedo and desertification.

7 This review will introduce these new paradigms and summarize the most recent research
8 carried out on land-atmosphere interaction, considering all of the topics in Fig. 6 with the
9 exception of land use change. Detailed reviews of the earlier studies of land-atmosphere
10 interaction can be found in Entekhabi (1995), Betts et al. (1996), Nicholson et al. (1998), and
11 Nicholson (2000, 2001, 2013), and Giannini et al. (2008). This review will concentrate on
12 studies that have appeared in the last decade or two. During this time period the nature of
13 research on land surface feedback on climate has shifted markedly and the concept of land-
14 atmosphere interaction has become generally accepted throughout the meteorological
15 community. Two decades ago that was not the case. The major changes in the nature of the
16 research include

- 17
- 18 1) more sophisticated and scientifically rigorous analysis of desertification;
 - 19 2) increased emphasis on hydrological processes, including the role of groundwater;
 - 20 3) use of multi-model ensembles and evaluation of model performance
 - 21 4) the use of regional climate models instead of global models.
 - 22 5) the emergence of the domain of ecohydrology, which considers detailed feedbacks among
 - 23 water availability and vegetation;

- 6) examination of the hypothesis that vegetation feedback can produce abrupt climate change;
- 7) emphasis on the impacts on individual convective or synoptic systems as opposed to seasonal or large-scale climate; and
- 8) consideration of the impact of aerosols, including the Saharan Air Layer.

This article is structured around the above themes, with the exception of desertification. Recent research in each area is summarized, along with some of the major findings and unanswered questions. Desertification is not included because several other publications have appeared that provide excellent reviews (e.g., Thomas and Middleton 1994, Warren 1996, Nicholson et al. 1998, Nicholson 2011, Imeson 2011, d'Odorico et al. 2013, Reynolds and Stafford-Smith 2002). Overall hundreds if not thousands of papers relevant to land-atmosphere interaction have appeared over the last two decades. An attempt has been made to focus on those that have the broadest significance. That is why land use change is not emphasized: the results are very specific to the case evaluated. To further narrow down the scope, papers dealing with Sahelian West Africa are emphasized, as that is the area where the greatest amount of research on the topic has been carried out. Because of the emphasis on that region, the discussion of aerosol impact excludes the products of biomass burning. The author apologizes in advance for any significant studies that may have been overlooked in this review.

2. HYDROLOGICAL THEORY

It is well established that soil moisture is a major player in land-atmosphere feedback. Recent studies have emphasized characterizing the temporal and spatial patterns of soil moisture

1 and identifying the areas of strongest interaction between land surface and the atmosphere. A
2 topic recently introduced into is the role of ground water in this interaction.

3 4 2.1 Bimodal distribution of soil moisture

5 An important characteristic of soil moisture that several studies have demonstrated is its
6 bimodal distribution in time. This characteristic, which is a result of various feedback
7 mechanisms in the surface water balance, is particularly strong in arid and semi-arid regions.
8 This distribution, shown mainly by numerical models, complements the bi-stability of vegetation
9 regimes in semi-arid regions, and helps to explain this particular characteristic of dryland
10 vegetation (see section 5.2).

11 Rodriguez-Iturbe et al. (1991) and Entekhabi et al. (1992) developed a simple soil
12 moisture model that included recycling. It provided evidence that the land-atmosphere system
13 can exhibit a two preferential states corresponding to wet and dry modes of soil moisture.
14 Bimodality increased with increasing aridity. d'Odorico et al. (2000), using a stochastic water
15 balance model, concluded that the probability distribution of soil moisture can be unimodal or
16 bimodal, depending on the underlying climate, soil, and vegetation properties. Daly et al. (2009)
17 demonstrated a mechanism by which bimodality can also result in humid regions, when a
18 shallow water table allows for interactions between the saturated and unsaturated zone of the
19 soil. d'Odorico and Porporato (2004) and Yin et al. (2014) produced further evidence of the
20 bimodality of soil moisture.

21 Those authors also provided both theoretical and experimental evidence that summer soil
22 moisture anomalies affect the probability of subsequent rainfall occurrence in the mid-latitudes.
23 This is consistent with the observational evidence of this effect that Taylor and Lebel (1998)

1 produced for the tropical West African Sahel, which is also a region of summer rainfall. As a
2 result of the dependence of rainfall on antecedent soil moisture, two preferential states or "wet"
3 and "dry" arise in the summer soil moisture field. Intermediate conditions have a lower
4 probability of occurrence. The inter-dependence of rainfall and soil moisture that leads to this
5 bimodality results in a positive feedback that can help explain the persistence of summer
6 drought, a characteristic noted long ago by Karl (1983), Karl et al. (1987), and Diaz (1983). This
7 bimodality can be produced by the combination of meteorological conditions in conjunction with
8 the non-linearity of soil moisture response to these conditions (Teuling et al. 2005).

10 2.2 Self-organization of rainfall and soil moisture fields

11 The spatial fields of both rainfall and soil moisture exhibit preferred spatial structures.
12 Rodriguez-Iturbe et al. (1998a,b) examined the spatial structure of rainfall fields as they evolve
13 over time, using daily data from a river basin in Arkansas. The results of the study provided
14 observational evidence of the self-organization of rainfall fields. They showed that the spatial
15 variance follows a power law at all scales of observation, with variance increasing with the mean
16 rainfall accumulated during a rain event. d'Odorico and Rodriguez-Iturbe (2000) singled out the
17 most important physical mechanisms of land-atmospheric interaction that operate at the local or
18 mesoscale and govern the dynamic evolution of soil moisture fields. As with rainfall fields, the
19 spatial correlation of soil moisture remains unchanged with the time or space scale of
20 observation (Rodriguez-Iturbe et al. 1995) and follows a power law of decay (Fig. 7). These
21 results suggest that local dynamics play a key role in this self-organization, although the overall
22 synoptic driving mechanisms of the rainfall are crucial.

2.3 Asymmetric recovery from dry versus wet soil moisture anomalies

The bimodality of soil moisture is not the only hydrological feedback mechanism that tends to enhance the persistence of drought. Another feedback mechanism is related to the inverse relationship between soil temperature and moisture and the fact that different factors govern evapotranspiration in soil-controlled versus atmospheric controlled cases (Brubaker and Entekhabi 1996a,b). In the case of soil control, soil moisture is the limiting factor in evapotranspiration. Under atmospheric control, radiation, wind and atmospheric humidity determine the magnitude of evapotranspiration. The result is that a return to "normal" is prolonged in the drought case, compared to the case of anomalously wet soil.

2.4 Degree of land-atmosphere coupling

Some of the earliest meteorological models suggested that land-atmosphere interactions would be particularly strong in certain geographical regions. Charney et al. (1977), for example, identified the Sahel, northwestern India, and the U. S. Great Plains as such regions. Brubaker et al. (1993) suggested that moisture recycling, the amount of evapotranspiration from a region that remains within the region, could identify such regions. Since then considerable effort has been placed on using this and other metrics to quantify the degree of land-atmosphere coupling and identify the "hotspots" of land-atmosphere interaction. These "hot spots" are invariably characterized by evapotranspiration rates that show large temporal variability and strong sensitivity to soil moisture (Guo et al. 2006).

Interest in this topic has increased, in part because models suggest this interaction may increase in the future and play a role in the development of future climate (Dirmeyer et al. 2012, 2013a,b, 2014). Seneviratne et al. (2006a), for example, concluded that land-atmosphere

1 feedback is responsible for much of the projected increase in summer temperature variability in
2 Europe. Williams and Kniveton (2012) surmise that land-atmosphere coupling will also play a
3 role in future climate development over Southern Africa.

4 The mechanisms of interaction involve surface coupling in the hydrologic cycle and its
5 influence on the planetary boundary layer, a key to the coupling of the land surface with
6 convection. Metrics used for the surface coupling include covariances among soil moisture,
7 evaporation, vegetation, precipitation and recycling (Brunsell 2006, Notaro 2008, Campo et al.
8 2009, van den Hurk and van Meijgaard 2010). Metrics used to examine the coupling to the
9 boundary layer include the association between boundary layer development and surface
10 variables such as diurnal temperature, evaporation and humidity; lifting condensation level; and
11 convective triggering potential (Santanello et al. 2009, 2011, Findell and Eltahir 2003). It
12 appears that, in general, surface coupling effects are most important under drier conditions and
13 coupling to the boundary layer becomes more important under wetter conditions (Santanello et
14 al. 2013).

15 Findell and Eltahir (2003) categorized surface-boundary layer interactions via four
16 classes of convective regimes. These are 1) atmospheric conditions favor deep convection over
17 wet soils (positive feedback), 2) convection is favored over dry soils (negative feedback), 3)
18 atmospheric conditions generally suppress convection, and 4) convection is atmosphere-
19 controlled. The categorization was based on a variable termed convective triggering potential
20 and a low-level humidity index. Ferguson and Wood (2011) used this same framework and
21 applied it to seven years of satellite data to identify predominant coupling signals.

22 An important finding of the studies of surface effects is that the degree of coupling is
23 greatest under conditions of medium soil moisture content and is weakest under extremely dry or

wet conditions (Seneviratne et al. 2006b, Lintner et al. 2013, Guo and Dirmeyer 2013). This is one of the reasons that the magnitude of land-atmosphere coupling is seasonally varying (van den Hurk and van Meijgaard 2010) and also varies from year to year, as soil moisture values move away from the sensitive range (Guo and Dirmeyer 2013). Thus, in wet regions, the coupling is higher in dry periods, while in dry regions the coupling is stronger during anomalously wet periods (Wei and Dirmeyer 2012). Overall, the coupling is greatest in transition zones between wet and dry climates (Guo et al. 2006), because soil moisture values are often in the sensitive range.

Dirmeyer et al. (2009) synthesized several approaches to quantifying land-atmosphere coupling, applying data from observations and reanalyses to atmospheric tracer models and stand-alone land surface schemes. Based on the results, they summarized the necessary criteria for strong surface-atmosphere interaction: These include 1) persistence of soil moisture anomalies, 2) strong and consistent regulation of evaporation by soil moisture, and 3) reinforcement of water cycle anomalies via recycling. This produces in most locations a strong seasonality in the degree of coupling (Fig. 8). In North America it appears to be larger in late spring and summer than in the winter or early spring months (Misra and Dirmeyer 2009, Zeng et al. 2010a, Guo et al. 2012). In the Sahel it appears to be greatest in April and May, just before the monsoon season begins (Yamada et al. 2013). In both winter and summer monsoon regions the coupling is probably strongest towards the end of the rainy season, as rainfall tapers off, but in the grasslands of the Great Plains and South America it may be strong throughout the year (Dirmeyer et al. 2009).

2.5 Groundwater

1 Within the last decade the importance of groundwater in land-atmosphere interactions has
2 become recognized. Its major importance appears to be its roles in modulating the spatial
3 distribution of soil moisture and surface fluxes (Miguez-Macho et al., 2007, 2008) and
4 promoting a hydrologic memory within the land surface. It can influence dust generation in
5 deserts (Elmore et al. 2008). The introduction of groundwater dynamics also improves the
6 performance of climate models (Maxwell et al. 2007, Yuan et al. 2008), which may lead to
7 improvements in seasonal forecasting.

8 The hydrologic memory in ground water exists because surface pulses of moisture reach
9 the water table with considerable lag. Leung et al. (2011) pointed out that, because of its slow
10 response time, groundwater may play a role in long time-scale processes such as multi-year
11 drought. Using regional climate simulations, they showed that groundwater dynamics tend to
12 influence the partitioning of soil moisture between the surface and subsurface, but not total soil
13 moisture amount. However, this partitioning strongly affects surface latent and sensible heat
14 fluxes. Consequently, groundwater depth provides important feedback on cloudiness, diurnal
15 temperature range, surface temperature and cloud height. The impact of soil moisture on
16 atmospheric processes tends to be higher where the water table is deep because interactions
17 between groundwater and soil moisture are weak in this case. This increases the sensitivity of
18 the system to soil moisture. Lo and Famiglietti (2010) demonstrated that groundwater's impact
19 on surface hydrological memory can be positive, negative or neutral. It appears to be most
20 important in transition regions between areas of deep and shallow water tables.

21 Fan et al. (2007) used a groundwater flow model to examine water table dynamics in the
22 U.S. The study's results suggested that water table depth exhibits spatial organization at
23 watershed, regional, and continental scales. This may have implications for the organization of

1 soil moisture fields and soil moisture memory. Maxwell et al. (2007) provide further support for
2 this. They combined a 3D groundwater flow model and surface water routing with a mesoscale
3 atmospheric model. The fully coupled model showed spatial and temporal correlations between
4 surface variables, atmospheric boundary layer characteristics, and water table depth. It also
5 maintained a realistic soil moisture distribution, which the atmospheric model could not.

6 Anyah et al. (2008) used a regional climate-hydrologic system model to investigate the
7 role played by water table dynamics in controlling soil moisture, evapotranspiration (ET),
8 boundary layer dynamics and precipitation. The study compared the results for two regions with
9 shallow water tables, humid locations in the eastern U.S. and semi-arid locations in the western
10 U.S. Water table fluctuations enhanced ET in the west, but not in the east, where soil water is
11 not the limiting factor. The enhanced ET led to higher convective precipitation via local
12 feedback processes and moisture recycling.

13 Jiang et al. (2009) examined the combined effect of vegetation and groundwater
14 dynamics on warm season precipitation in the Central U. S. These factors appeared to increase
15 the persistence of intraseasonal precipitation, and possibly enhance precipitation as well. They
16 also enhanced the coupling between soil moisture and lifting condensation level. The impact of
17 groundwater was found to be significant when the soil moisture is relatively dry. This is
18 consistent with the results of Anyah et al. (2008), who found impact limited to areas where ET is
19 soil-controlled.

20 Bierkens and van den Hurk (2007) used a stochastic model of soil moisture-precipitation
21 feedback augmented with a groundwater model to investigate the impact of groundwater on the
22 persistence of rainfall. The degree of persistence was found to increase with the groundwater
23 residence time.

3. MODELING LAND-ATMOSPHERE INTERACTION

The vast majority of studies of land-atmosphere interaction have been carried out using numerical models. The reason is clear. The factors influencing climate or weather systems are manifold. With observations it is hard to design an experiment that will equivocally isolate the impact of the land surface. Moreover, soil moisture measurements are scarce on most continents (Seneviratne et al. 2006b). While early modeling studies were generally performed with a single general atmospheric circulation model, often coupled to an explicit land/vegetation model, more recent trends have been to utilize multi-model ensembles and regional models. Observations show strong biases in individual models in near-surface temperature and humidity (Dirmeyer et al. 2006), so that multimodel means improve performance. This approach provides more confidence in the results by reducing the dependence of results on model biases and inadequacies. It also facilitates the evaluation of model performance.

3.1 Estimating land-atmosphere coupling from multi-ensemble modeling

Because of a lack of appropriate observations, most studies of land-atmosphere interaction have been carried out with general circulation models. Unfortunately, the results tended to be model-dependent (Koster et al. 2002). To further explore this dependency, the Global Land-Atmosphere Coupling Experiment (GLACE) was carried out using 12 atmospheric general circulation models (AGCMs) (Koster et al. 2006, Guo et al. 2006). In this experiment, land-surface atmosphere was quantified using a parameter that expresses the inter-model differences that are assumed to result from the land-atmosphere forcing in the individual models. The derived coupling strength varied greatly among the models, but the spatial patterns of

coupling showed strong agreement among them. This allowed the major "hot spots" to identified (Fig. 9). These included (Koster et al. 2004) the central US Great Plains, the West African Sahel, and northwestern India, the same regions identified earlier by Charney et al. (1977) as being particularly sensitive to land-surface forcing.

Notaro (2008) examined land-atmosphere coupling via soil moisture in 19 climate models used in the IPCC Four Assessment Report. He used statistical correlations to determine "hot spots", lagged co-variance ratios between soil moisture and precipitation and autocorrelation of soil moisture (a measure of soil moisture memory). Although the same "hot spots" identified by the GLACE models stood out, additional boreal summer "hot spots" over northern Brazil and western Eurasia were identified. The study also suggested that "hot spots" existed in the austral summer over each continent. Zeng et al. (2010a) obtained similar results using reanalysis products and observations.

A key aspect of land-atmosphere interaction is soil moisture memory. As part of GLACE, Seneviratne et al. (2006b) compared the soil memory in eight atmospheric GCMs (AGCMs). With this variable, they found similar results among the models. They also showed that soil moisture memory is controlled by the sensitivity of evaporation to soil moisture, which decreases with soil moisture content, and by the sensitivity of runoff to soil moisture, which increases with soil moisture.

3.2 Model Evaluation

Important contributions of GLACE were to determine the consistency of model simulations of coupling effects and to determine reasons for the spread of model results. Using GLACE data, Seneviratne et al. (2006b) compared soil moisture memory in 8 AGCMs and got

1 similar results from each. They found that moisture memory in models is controlled by the
2 sensitivity of evaporation to soil moisture, which decreases with increasing soil moisture, and by
3 runoff's sensitivity to soil moisture, which increases with increasing soil moisture. The
4 implication is that sensitivity is greatest in areas of medium soil moisture content. The
5 differences among models was shown to be largely a result of soil water-holding capacity. Much
6 more research is needed to accurately characterize this parameter.

7 Several other studies concluded that the model's ability to capture the evaporative process
8 is the key to model performance. Dirmeyer et al. (2006) and Guo et al. (2006) suggested that the
9 surface evaporation response to soil moisture and radiation explains the model spread in land-
10 atmosphere interaction. An evaporation rate that varies strongly and consistently with soil
11 moisture gives higher land-atmosphere coupling strength. Hohenegger et al. (2009) suggested
12 that the spread of model results depends on the parameterization of both evaporation and
13 convection.

14 Ferguson et al. (2012) compared remotely sensed and modeled estimates of soil moisture,
15 evaporative fraction, and lifting condensation level. The study evaluated coupling strength in a
16 number of river basins. Remote sensing yielded substantially weaker coupling than did models.
17 However, there was agreement with respect to the rank order of basins with respect to coupling
18 strength.

20 3.3. Use of Regional Climate Models

21 Perhaps the most important result of the use of regional models to study land surface
22 processes is the consensus that interactive land surface schemes improve the performance of
23 climate models (Druryan et al. 2004, Steiner et al. 2009, van den Hurk and van Meijgaard 2010,

Konare et al. 2008). They generally improve the simulation of hydrological processes and circulation features and enhance predictive capacity (e.g., Campo et al. 2009, Mueller et al. 2014). The impact of atmospheric dynamics can be considerable (Campo et al. 2009). There are, however, exceptions. For example, Roundy et al. (2014) found that land surface coupling skewed results in the NCEP Climate Forecast System model towards a wet regime, making it difficult to predict drought with this model.

A number of regional model simulations have examined the West African Sahel. Steiner et al. (2009) coupled a new land surface model (CLM3) to a regional climate model, the RegCM3, and demonstrated improvement in modeling West African climate, compared to earlier runs utilizing the BATS land surface scheme. Seasonal timing and location of rainfall, surface temperature gradients, and upper-level winds more closely matched observations. Drier soil conditions triggered the improvement, clearly indicating the impact of the surface on regional-scale circulation and precipitation. Druyan et al. (2004), using the regional model of NASA/GIS, similarly showed an acute sensitivity of the mean circulation of the West African monsoon to land surface processes. Flaounas et al. (2012) applied the weather research forecasting model (WRF) to examine the sensitivity on monsoon onset to various surface forcings. Hagos et al. (2014) found that soil moisture modulates precipitation via its impact on the latitude and intensity of the AEJ. This occurred only in moderate soil moisture regimes, consistent with studies (e.g., Seneviratne et al. 2006b) reviewed in section 2.4. Impact was lacking in the extreme dry and wet cases because these are energy- and moisture-limited, respectively.

Regional models have also been applied to address the potential impact of aerosols, deforestation and desertification. Coupling a regional climate model to a dust model, Konare et al. (2008) showed that dust tended to reduce precipitation in the Sahel. However, it also

improved the model simulation of the monsoon, including the African and Tropical Easterly Jets. Using a regional model, Abiodun et al. (2008) also concluded that deforestation and desertification would impact the African Easterly Jet (AEJ), a result of reduced monsoon flow. However, as with early studies of these phenomena, the surface changes imposed in the model were highly unrealistic.

Some regional modeling studies have addressed the relative impact of surface changes versus atmospheric dynamics. To quantify coupling over West Africa, van den Hurk and van Meijgaard (2010) used two of the criteria proposed by Dirmeyer et al. (2009): persistence of soil moisture anomalies and recycling. They concluded that coupling is strong along the northern edge of the West African monsoon during June-July-August and just north of the equator over central Africa during March-April-May. They also concluded that overall the impact of surface conditions on precipitation dynamics is not particularly strong, being overridden by large-scale dynamics. This is consistent with the conclusion of Rowell et al. (1995) who found some sensitivity of the West African monsoon to soil moisture, but concluded that SST variations dwarfed the signal. Moufouma-Okia and Rowell (2010) used the Hadley Center regional model to investigate the impact of soil moisture on the West African monsoon. Initial soil moisture anomalies affected intra-seasonal, interannual and spatial variations in precipitation, but the influence was markedly lower than that of the lateral boundary conditions of the model.

4. ECOHYDROLOGY

In the 1990s the term "ecohydrology" was coined to describe the merger of the disciplines of ecology and hydrology (King and Caylor 2011). This field of study examines the mutual interactions between the hydrologic cycle and ecosystems (Porporato and Rodriguez-

1 Iturbe 2002, Newman et al. 2006). While studies of this interaction are numerous in both the
2 hydrological and ecological communities, ecohydrology encompasses primarily dynamic
3 processes and feedback and the development of an integrative framework for studying the
4 intersection of climate, water and vegetation at various spatial scales. At the core are the
5 hydrologic mechanisms of climate-soil-vegetation dynamics that control ecological patterns and
6 processes. Soil moisture is the key to addressing this (Rodriguez-Iturbe 2000).

7 Dolman et al. (2014) trace the origins of this field back to the seminal paper of John
8 Monteith (1965). In that paper Monteith transformed the Penman equation for
9 evapotranspiration to a formulation that explicitly includes the contribution of vegetation.
10 Emerging from this early idea was a broader concept of plant-water interaction, a field that has
11 grown tremendously in the last 15 years. An outgrowth of that field is the concept of abrupt
12 vegetation change and abrupt climate change. These topics, which fit into the domain of
13 ecohydrology, are considered in the following two sections. The current section covers the
14 evolution of concepts within ecohydrology.

15 Traditionally, ecohydrological research has focused on the earth's drylands, arid and
16 semi-arid ecosystems where ecological processes are water-limited. Water-vegetation
17 interaction is especially intense in dryland ecosystems because of the scarcity of water and its
18 intermittent and unpredictable appearance (Porporato and Rodriguez-Iturbe 2002). The
19 interactions are also extremely complex in these environments because vegetation is both cause
20 and effect of water availability and the structure of vegetation is extremely heterogeneous. This
21 poses a challenge in creating representative spatial averages of water balance, soil moisture, and
22 ecohydrological processes at the landscape or catchment scale (Caylor et al. 2006, Thompson et
23 al. 2011).

Several important papers have addressed theoretical frameworks for understanding ecohydrological processes in the drylands. Turnbull et al. (2012) deal with their stability. They theorize that the dynamics of ecosystem change, in the face of external forces, are determined by the type and strength of feedbacks between the hydrologic cycle and ecological processes. Stabilizing feedbacks are critical for maintaining a healthy ecosystem, but they can be disrupted by external factors. The system can recover as long as amplifying feedbacks do not develop. Noting the complexity of both hydrologic and ecological systems, Jenerette et al. (2012) suggest that an understanding can be derived by treating them as complex adaptive systems. Such systems are characterized by feedbacks, thresholds, hysteresis, and self-organization of both vertical and horizontal structure on multiple scales. This concept of self-organization is treated in section 5.1.

In most cases, ecohydrology in water-limited environments involves processes at the surface and within the unsaturated zone of the soil. There are some exceptions, however, where groundwater recharge occurs (Liu 2011). In humid regions, groundwater interactions with the unsaturated zone must also be taken into account (Rodriguez-Iturbe et al. 2007, Laio et al. 2009, Tamea et al. 2009). Li et al. (2012) further suggested that pedological processes must be figured into the interactions.

Newman et al. (2006) pointed out the need to develop integrated and interdisciplinary approaches to studying the links between hydrology and ecology. King and Caylor (2011) conclude that this has not yet been done adequately. They considered the question as to whether most ecohydrological research is based on methodological strengths from the two parent fields or merely includes an overlap of the two disciplines. They found that few studies integrated the strongest methodological approaches of both disciplines. They identified this as a weakness to

overcome in order to understand the coupled functioning of ecological and hydrological systems. Other critical issues in ecohydrology include its application to climate change and resource sustainability (Wang et al. 2012, Porporato and Rodriguez-Iturbe 2013) and the development of ecohydrology on a global scale, a goal made possible by the development of satellite remote sensing of surface processes (Dolman et al. 2014).

5. PLANT-WATER RELATIONSHIPS IN ECOSYSTEMS

Many of the works cited previously have made it clear that dryland regions are most sensitive to land-atmosphere interaction. It is here where the moisture is sporadically available in time and space and where surface moisture is the limiting factor in vegetation growth and evapotranspiration. For this reason, the current discussion will focus on arid and semi-arid regions.

5.1 Vegetation-climate interaction and the dynamics of dryland ecosystems

A common characteristic of savannas and arid lands is the heterogeneity, or "patchiness" of the vegetation cover (Fig. 10). Localized patches of high biomass concentrations are interspersed with relatively bare ground (Rietkerk et al. 2000). The patches are induced mainly by water stress (Klausmeier 1999, Rietkerk et al. 2004, Gilad et al. 2007, Barbier et al. 2006) and take on very different spatial form and ecological function, depending on species and various environmental factors (Meron et al. 2007).

Specific feedbacks between vegetation and moisture shape the development of regular, organized patterns of patchiness. These feedbacks are often interactive (Scheffer et al. 2005, Dekker et al. 2007, Gutiérrez-Jurado et al. 2006 Baudena et al. 2008, Schymanski et al. 2009).

1 The relevant feedbacks with vegetation cover include soil moisture, shading, and nutrient
2 retention (Koster et al. 2004, Scheffer et al. 2005, d'Odorico et al. 2007, Dekker et al. 2007,
3 2010). Any vegetation cover reduces thermal amplitude, radiation exposure, wind desiccation
4 and soil erosion (Kefi et al. 2007). It modifies moisture availability by extracting soil water,
5 intercepting precipitation, and modulating percolation and runoff (Gutiérrez-Jurado et al. 2006).
6 In drylands water tends to flow from sparsely to densely vegetated patches or from intercanopy
7 to canopy spaces. The patches collect not only water but also nutrients, essentially becoming
8 "islands of fertility" (Ridolfi et al. 2008) (Fig. 11).

9 The patchiness can be "self-organized", i.e., resulting from dynamic processes within the
10 ecosystem, rather than imposed externally. Two opposing feedbacks control the water balance in
11 the patches (e.g., Rietkerk et al. 2004, Lejeune et al. 2002, Gilad et al. 2007). Infiltration
12 concentrates water at the vegetation patch, accelerating vegetation growth. At the same time,
13 water uptake by the vegetation acts to deplete water near the patch. The dominant feedback is
14 generally a function of scale. Facilitation among plants occurs near the patches, but competition
15 prevails at a distance from the patch. These feedbacks are important in understanding several
16 aspects of ecosystems, including the existence of savanna vegetation (Sankaran et al. 2004,
17 Meyer et al. 2007) and the concept of abrupt transitions or catastrophic shifts in ecosystems
18 (Section 6).

20 5.2 The emerging concept of "patch dynamics"

21 Patch dynamics is a new and potentially unifying mechanism to explain the tree-grass
22 coexistence in savannas (Wiegand et al. 2005, 2006, Meyer et al. 2007). A given site is a two-
23 phase vegetation mosaic: individual or aggregated woody plants and intercanopy space

1 (Breshears and Barnes 1999). Savanna environments exist along a forest/grass continuum. The
2 underlying concept of patch dynamics is that a savanna consists of patches in which a cyclical
3 succession between woody and grassy dominance proceeds spatially asynchronously. The four
4 classic savanna factors (herbivory, fire, nutrients, and water) are all candidates for the
5 disturbance that drives the successional cycles.

6 The position along the continuum depends in large part on soil moisture availability,
7 which changes in response to feedbacks and water stress (Lefever and Lejeune 1997,
8 Klausmeier, 1999, Rietkerk et al. 2004). Five basic vegetation states exist along the rainfall
9 gradient: uniform vegetation, gaps, stripes, spots, and bare soil (Meron et al. 2007) (Fig. 12).

10 A number of studies have attempted to predict the occurrence and nature of changes
11 along this continuum. One hypothesis is that two stable states may occur, separated by an
12 unstable equilibrium. Such a state of "bistability" exists as a result of positive feedback resulting
13 from local facilitation (Kefi et al. 2007, Rietkerk and van de Koppel 1997). The implication is
14 that discontinuous transitions ("catastrophic shifts" can occur) from a small change in some
15 parameter (Scheffer and Carpenter 2003) (Fig. 13). The heterogeneity of typical dryland
16 vegetation cover could facilitate such shifts (van Nes and Scheffer 2005). Various models
17 attempt to determine whether continuous or discontinuous transitions will occur (e.g., Kefi et al.
18 2006, Rietkerk et al. 2002, 2004).

19 Patchiness is considered to be an indicator of the potential for such transitions, with
20 certain shapes predicting imminent discontinuous transition towards the bare state. Once this
21 state exists, the feedbacks between trees and grasses that sustain the savanna environment are no
22 longer possible, resulting in irreversible change.

A corollary to "patch dynamics" is that very rapid transitions from wet and vegetated ground to dry and bare ground could occur in presence of an external climate trigger (Rietkerk and van de Koppel 1997, Janssen et al. 2008). When critical thresholds in the climate-vegetation system are surpassed, catastrophic shifts in the vegetation state can occur (Rietkerk et al. 2011). Warning signals of such a shift, such as slow response to disturbances or changes in spatial characteristics, may be evident (Carpenter et al. 2011, Kefi et al. 2013, 2014).

6. ABRUPT CHANGE

An outgrowth of the research on land-surface processes has been the hypothesis that land-atmosphere interactions can lead to abrupt climate change. The issue has been related primarily to the question of the creation of the Sahara Desert, but it has implications for the Sahel as well (Patricola and Cook 2008). Reviews are provided by Rietkerk et al. (2011) and Kabat et al. (2004).

This question results from contemporaneous findings in climatology, paleoclimatology, and ecology. At issue is how rapidly the Sahara emerged towards the end of the Holocene. In mid-Holocene, around 6000 years ago, the present day Sahara was a savanna environment. An analysis of dust in a sediment core from the Atlantic just off the West African coast (Fig. 14) suggests that the transition from savanna to desert may have occurred within a few hundred years (deMenocal et al. 2000). While that finding contradicts the more conventional view of progressive change (Fig. 15) and a much later timing of the termination of the African humid period (e.g., Kroepelin et al. 2008, Amaral et al. 2013), climate models that include interactive vegetation are able to replicate such an abrupt transition (Claussen 1997, Liu et al. 2007). These also show an accompanying feedback of the vegetation on precipitation.

The hypothesis of abrupt climate change developed at roughly the same time as ecological theory predicting the potential for catastrophic shifts, as described above. This gave credence to the concept of land-atmosphere interactions provoking abrupt climate change. However, this whole question is complicated by the fact that abrupt transitions, or bifurcations (Matyasovszky et al. 2013, Bathiany et al. 2012), characterize other aspects of the climate system. Dust in Atlantic sediment cores shows that Heinrich stadials, which are associated with cold North Atlantic sea-surface temperatures, trigger abrupt increases in aridity and wind strength in the Sahel (Collins et al. 2013). This is indicative of a strong influence of the Atlantic Meridional Overturning Circulation (MOC) on the position of this boundary. A global atmosphere-ocean-sea ice model predicts that a transition from glacial to warm climate can take place in as little as 200 years, with the MOC setting the time scale (Rose et al. 2012). Lenton et al. (2008) discuss these and other potential "tipping points" in the climate system, critical thresholds at which a small perturbation can have a major impact on the system.

7. IMPACT OF THE LAND SURFACE OF CONVECTION AND STORMS

Some of the most promising working on land surface processes is studies linking them to convection. In semiarid regions the surface fluxes of heat and moisture are strongly impacted by the occurrence of convective rainfall (Clark et al. 2004), but the so-produced surface anomalies also influence the development of convective rainfall. The relevant characteristic is not the overall state of the land surface, but the spatial heterogeneity of the characteristics of moisture and temperature that play a role (e.g., Taylor et al. 2005, 2011a, Gantner and Norbert 2010). This conclusion, also reached long ago in early modeling experiments (e.g., Anthes 1984), has stood the test of time.

The issue, however, is complex. The impact of the heterogeneity depends on a number of factors, such as ambient conditions, spatial scale, stage of convection, nature of storm system, and so on. Taylor et al. (2011b) provide an excellent review of recent perspectives on the topic. This current review focuses on land-atmosphere interactions in the Sahel (section 7.1), but results from other regions are also considered (section 7.2). Finally, the impact of soil moisture on predictability is briefly examined (section 7.3).

7.1 Land-Atmosphere Interactions in the Sahel

Most of the work on the links between the land surface and convection has been done with model simulations. These have concluded that surface flux anomalies related to soil moisture and temperature can induce secondary circulations that affect boundary layer depth, impact cloud development and trigger convection (Adler et al. 2011a,b). These anomalies can also trigger the development of secondary Mesoscale Convective Complexes (MCSs) from a parent MCS (Birch et al. 2013). The surface fluxes have an impact on the diurnal cycle of convection (Mohr et al. 2003).

The coupling of the atmosphere and land surface also appears to produce unstable modes that do not exist in the atmosphere-only part of the system (Parker 2008). The result is wave disturbances, the propagation of which is governed by the spatial configuration of atmospheric and soil moisture anomalies. Lavender et al. (2010) investigated whether soil moisture-atmosphere coupling plays a role in the 15-day westward propagating mode of intraseasonal rainfall variability in the West African monsoon. They found that the mode can exist without this coupling, but the coupling produces a positive feedback that enhances and further organizes the mode.

1 In the Sahel rainfall-induced anomalies can persist for several days after a storm, long
2 enough to modify the overlying boundary layer (Schwendike et al. 2010). Boundary layer
3 changes are linked mainly to long length scales of surface heterogeneities (Clark et al. 2004)
4 because advective effects may override the influence of the land-surface at smaller scales (Taylor
5 et al. 1997). Squall-line rainfall, on the other hand, shows the strongest response to anomalies on
6 small length scales comparable to that of convection.

7 Observational studies have produced convincing evidence of the impact of land-surface
8 heterogeneities on convection in the semi-arid Sahel, particularly the drier northern sector. The
9 first of these was that of Taylor and Lebel (1998), who used data from the HAPEX-Sahel field
10 experiment of 1992 (Goutourbe et al. 1994). They found that the probability of rainfall at a
11 given location was strongly correlated with that location having received antecedent rainfall from
12 a previous event (Fig. 16). In other words, once a location has received significant rainfall, it is
13 more likely than other locations to receive rainfall from subsequent disturbances that pass by.
14 The sparse vegetation in the Sahel likewise influences the activity of African Easterly Waves
15 (AEWs). Both models and observations show that the sparseness results in a warmer and deeper
16 planetary boundary layer (PBL), ultimately resulting in greater AEW activity and more long-
17 lived rain events associated with the waves (Taylor and Clark 2001).

18 More recent observational studies have provided more detail into the mechanisms
19 involved in the feedback. Soil moisture has considerable impact on convection-related
20 parameters, especially over complex and heterogeneous terrain (Hauck et al. 2011). For example,
21 a high soil moisture content lowers the lifting condensation level and the level of free convection
22 (Barthlott et al. 2011). There is also low convective inhibition over dry patches (to initiate
23 convection) and high convective available potential energy (CAPE, for the initiation of

precipitation) (Froidevaux et al. 2014). It also increases the relative magnitudes of sensible and latent heat exchange at the surface and increases the thermal stability of the lower atmosphere. With increased evaporation, sensible heat transfer is reduced and the surface is cooler, which has a negative impact on convection (Kanamitsu and Mo 2003, Cook et al. 2006).

A number of studies present evidence that soil moisture anomalies also impact precipitation. In the Sahel dry anomalies (areas of higher temperature and lower moisture than the surroundings) can be several hundred kilometers and larger. These “hot spots” generate anomalous heat lows during the day and cyclonic vorticity at night (Taylor et al. 2005). The vortices may influence the characteristics of African easterly waves in the northern Sahel and thereby influence rainfall. These vortices are thus both a cause and effect of the rainfall (Taylor 2008). Soil moisture anomalies on the scale of 10 to 40 kilometers appear to exert strong control on storm initiation (Taylor et al. 2011a). Storm initiation occurs preferentially downwind of anomalously dry soils with positive surface temperature anomalies (Fig. 17) and in areas of strong negative temperature gradients (Fig. 18). An interesting case study of such an effect was made for a convective system that occurred over northern Mali during the AMMA Special Observing Period (Taylor et al. 2010). The impacts of soil moisture patches are evident even at scales of 100 to 200 km (Taylor and Ellis 2006, Wolter et al. 2010). The initiation of convection by such patches is favored when the soil inhomogeneity is superimposed upon a convergence zone (Kluepfel et al. 2012). However, the process is also affected by other factors, such as humidity in the boundary layer and by CAPE (Kluepfel et al. 2011).

The impact of soil moisture heterogeneities is strongly dependent on the stage of convection and the impact on precipitation is different for initiation versus modification of an existing rain cell (Barthlott and Kalthoff 2011). Convection is often initiated over strong

1 moisture gradients or over the dry “hot spots” (Huang and Margulis 2013). Wet soils, compared
2 to dry, tend to suppress the initiation of afternoon or evening convection in the Sahel (Taylor and
3 Ellis 2006, Cook et al. 2006). However, dry soil appears to weaken mature systems (Gantner
4 and Kalthoff 2010) while moisture soil will enhance mature convective systems (Taylor et al.
5 2010). Froidevaux et al. (2014) concluded that, while convection is initiated over dry patches,
6 further downstream intensification of the convection occurs over wet patches. They also found
7 that this is the case only when the mid-level wind is strong enough to force the system to
8 propagate. Otherwise, precipitation is overall weaker and falls preferentially over the dry areas.

9 Unfortunately, these conclusions cannot be generalized and examples are found of both
10 positive and negative feedback between soil moisture and precipitation (Findell et al. 2011). An
11 excellent example comes from the southwestern United States. In agreement with Cook et al.
12 (2006), Kanamitsu and Mo (2003) suggested that wet soil moisture anomalies set up patterns of
13 convergence and divergence that are not conducive to precipitation and also increase
14 atmospheric stability. However, they found that in summer over Arizona and New Mexico the
15 altered circulation increases moisture transport from the Gulf of California. This overrides the
16 negative feedback of the wet anomaly and increases precipitation. A more conclusive
17 understanding of the feedback might be gained by considering the background state in which it
18 occurs, particularly the relative availability of sensible and latent heat for the triggering of
19 convection (Tawfik and Dirmeyer 2014), and by separating considering the question of feedback
20 impact on triggering versus amplification of convection (Findell et al. 2011, Gianotti et al. 2014,
21 Tawfik and Dirmeyer 2014, Dirmeyer et al. 2014).

22 Another of the still open questions is whether the feedback between the land surface and
23 convection merely modifies the spatial distribution of rainfall or affects the overall amount as

well. In modeling studies by Lauwaet et al. (2009, 2010) the surface changes introduced did not influence the amount of rainfall, despite the changes in surface fluxes and CAPE. Model simulations of Gantner and Norbert (2010) suggest that the lack of a net impact may be a result of the contrasting impact on developing versus mature convective systems. The triggering of convection was favored by drier surfaces and/or soil moisture inhomogeneities, but mature systems weakened when they approached drier surfaces. Gaertner et al. (2010) found that introducing a soil moisture perturbation into a model had different effects at different scales: a reduction in rainfall over the wet path itself but a net increase in rainfall over a larger area. Moufouma-Okla and Rowell (2010), using a regional climate model, found that soil moisture anomalies had little impact on the overall amount of rainfall, creating only small and random intraseasonal, interannual and spatial variations. However, they noted that the conclusion may be model dependent or influenced by the initial soil moisture data introduced into the model. Hence the question is still very open.

7.2 Other Studies of Soil Moisture Impact

The impact of soil moisture has also been examined for tornadoes, hurricanes, heat waves, and drought. Cheresnick and Basara (2005), in a case study of a tornado that occurred in Minnesota in 2001, concluded that evapotranspiration over the Great Plains added to the severity of the storm. Kellner et al. (2012) and Evans et al. (2011) demonstrated that the inland reintensification of Tropical Storm Erin, in 2007, was probably a result of soil moisture effects. Bozeman et al. (2012) came to a similar conclusion concerning Tropical Storm Fay, which also intensified inland over the U.S. However, Erlingis and Barrow (2014) showed that pre-storm soil moisture dryness is associated with higher rainfall from the nocturnal mesoscale convective

1 systems in the U. S. Great Plains. This effect can be modified by synoptic and mesoscale
2 dynamics. Using a 50-year observational data set, Koster et al. (2003) similarly concluded that
3 precipitation-induced soil moisture anomalies can affect subsequent precipitation. Schär et al.
4 (1999), using a regional model, found that soil moisture plays a critical role in the summertime
5 precipitation climate in western Europe.

6 Fischer et al. (2007a,b) examined European heat waves in four years and determined that
7 soil moisture/temperature interactions may have accounted for 50% to 80% of the number of hot
8 days. Stefanon et al. (2014) likewise found positive feedback over the plains regions of Europe,
9 but noted that soil moisture tended to reduce the heat wave intensity over mountains and near the
10 coast because of mesoscale circulations induced by the soil moisture anomalies. Using the
11 Canadian regional Climate Model (CRCM5) to investigate soil moisture-atmosphere interactions
12 of the U. S. Great Plains, Diro et al. (2014) found that land-atmosphere coupling increases the
13 interannual variability of maximum temperatures, the number of hot days, and the frequency and
14 duration of hot spells. Berg et al. (2014) showed that soil moisture dynamics enhance both mean
15 temperature and its variance over "hotspots" of land-atmosphere coupling. They showed that
16 higher order moments, skewness and kurtosis, also differ in model simulations with and without
17 interactive soil moisture. This suggests that soil moisture has an asymmetric effect on negative
18 and positive extremes of the probability density function of surface temperature.

19 More controversial is the impact of soil moisture on drought. Meng et al. (2014)
20 evaluated soil moisture feedback in the 2002 drought in Australia. In contrast to results for the
21 Sahel, they found a positive feedback loop such that reduced soil moisture tended to reduce
22 precipitation, further reducing the soil moisture. That is consistent with earlier studies showing
23 drought being sustained by soil moisture feedback in the U. S. Great Plains (see Salvucci et al.

2002 for review). Examining the spatial covariance of soil moisture indices related to convective potential, Roundy et al. (2013) found evidence of a strong coupling in the southeastern United States. Barreiro et al. (2014) found that simulations of interannual variability of rainfall over Argentina were improved with when an interactive land surface scheme was included. However, some recent research tends to suggest that the feedback on interannual variability and drought is relatively weak. Philips and Klein's (2014) observational study found relatively weak soil moisture feedback on convection in the southern Great Plains, although the feedback increased as conditions became drier. Diro et al. (2014) found that the sensitivity of temperature to land-atmosphere coupling is much greater than that of precipitation. Zeng et al. (2010b), using a regional climate model, found that the impact on intra-annual precipitation variability in China is only about 6%.

A limitation to most of the observational studies of soil moisture feedback is that they are based on correlations, which do not indicate causality. This is particularly true when one of the variables being correlated is characterized by persistence (Alfieri 2008, Guillod et al. 2014). For this reason Salvucci et al. (2002) re-evaluated the question of soil moisture feedback in the Great Plains, examining rainfall and soil moisture data from numerous stations in Illinois and using a statistical method that is unaffected by this persistence. The result was that they could not reject the null hypothesis that soil moisture does not influence precipitation.

7.3 Application to prediction

The idea of a soil moisture memory impacting meteorological processes is appealing, as it suggests that antecedent soil moisture might have some applications to prediction. Numerous studies have provided evidence that soil moisture anomalies do enhance forecast skill on

seasonal to seasonal time scales (Koster et al. 2011). Collins et al. (2014) indicated that accurate soil moisture is a prerequisite for reliable seasonal forecasts for the U. S. Great Plains. Conil et al. (2007, 2009) concluded that soil moisture provides a significant but small amount of forecast skill for summer rainfall in the mid-latitudes. Wet soil moisture anomalies generally have a stronger influence than dry anomalies (Koster et al. 2011). In parts of North America soil moisture has a strong influence on surface temperature prediction up to two months in advance (Koster et al. 2010). Philippon and Fontaine (2002) showed a correlation between soil moisture in the boreal autumn rainy season along the Guinea Coast and rainfall in the Sahel, to the north, in the following year. Douville et al. (2007), however, suggested that this result was a statistical artifact and that soil moisture memory over West Africa is too short to provide forecast skill.

The impact of soil moisture on prediction varies with the season. It provides predictive skill once strong land-atmosphere coupling is established, often in the late spring or summer (Guo et al. 2011, 2012). Over West Africa the soil memory decreases rapidly during the dry season, but it can contribute to predictability at the end of and just after the rainy season (Douville et al. 2007).

Koster and Suarez (2003) found that the impact of land surface initialization on seasonal forecasting was generally limited to the "hot spots" characterized by strong soil moisture anomalies and strong sensitivity of evaporation to soil moisture and precipitation to evaporation. For a strong impact further conditions include a boundary layer that is sensitive to surface flux variations, strong memory in the soil moisture, and a strong coupling between surface fluxes and subsurface moisture (Dirmeyer et al. 2013). The extent to which these conditions are met can explain some of the differences between models regarding the importance of soil moisture for prediction.

1 An additional factor related to soil moisture is its impact on vegetation, suggesting that
2 interactive vegetation might be very important in seasonal forecasting. However, Gao et al.
3 (2008) concluded that the treatment of vegetation in the forecast model appears to have only
4 minor impact on seasonal predictability. This issue requires further examination.

6 8. MINERAL AEROSOLS AND THE SAHARAN AIR LAYER

7 The atmosphere contains particulates generated by biomass burning and by deflation of
8 the earth's surface by wind. The latter process, which generates inorganic mineral dust, is
9 particularly important in semi-arid regions. Roughly half of the mineral dust residing in the
10 atmosphere is generated over West Africa. While both types of particulates have significant
11 impact on atmospheric heating, research on climatic impacts has focused on mineral dust. This
12 review is confined to its role. The reader is also referred to Choobari et al. (2014) for a detailed
13 state-of-the art review of the impact of mineral dust on the climate system.

15 8.1 The Saharan Air Layer

16 The daytime Sahelo-Saharan boundary layer has a split structure with a well-mixed, near-
17 surface convective layer lying beneath a deep residual layer that is more stably stratified
18 (Messenger et al. 2010). This residual layer, termed the Saharan Air Layer or SAL, is hot and dry
19 and characterized by a red haze (Fig. 19). The haze is due to mineral dust eroded from the
20 Sahelian land surface (Ntchayi-Mbourou et al. 1998). Much of the dust is fine material eroded
21 from the dry remnants of Holocene lakes that once spread across the Sahel (Prospero et al. 2002).
22 African Easterly Waves (AEWs) play an important role in the mobilization of the dust, although
23 extra-tropical disturbances also play a role in the western Sahel (Knippertz and Todd 2010).

1 Some 20% of the dust entrainment into the atmosphere over North Africa is linked to AEWs
2 (Jones et al. 2003).

3 The east-west extent of the SAL is typically 2000-3000 km, but it can extend some 5000
4 km, covering an area about the size of the contiguous United States (Karyampudi et al. 1999,
5 Dunion and Velden 2004). Where the SAL meets the eastern Atlantic it resides between roughly
6 900mb/1800 m and 500 mb/5500 m (Carlson and Prospero 1972). It extends even higher over
7 the continent, where its depth decreases from north to south (Parker et al. 2005). The SAL is
8 bound by subsidence inversions at its top and bottom (Carlson and Prospero 1972) (Fig. 19).
9 These inversions help maintain the integrity of the layer. The dust that defines the layer also
10 helps to maintain its thermal structure (Wong et al. 2009).

11 The SAL has significant impact on meteorological processes over the Sahel by way of its
12 radiative effect, its thermal character, and its dryness. This being recognized, several
13 meteorological experiments over the Atlantic and West Africa were carried out to better
14 understand the role of the SAL (Zipser et al. 2009). For the most part, the dust acts as an
15 "elevated heat pump" (Lau et al. 2009), warming the mid-troposphere but cooling the surface
16 (Reale et al. 2011, Solomon et al. 2012). Maximum heating is in the layer 850 mb to 700 mb
17 (Huang et al. 2009a). The SAL impacts the African Easterly Jet (AEJ), African Easterly Wave
18 development (Thorncroft et al. 2003) and probably the development of tropical cyclones and
19 hurricanes over the Atlantic (Dunion and Velden 2004). Karyampudi and Carlson (1988) claim
20 that it is important if not critical in the initial development of AEWs.

21 The impact of the SAL on the atmosphere is manifold. It increases the vertical shear
22 associated with the AEJ, warms the air aloft and thereby increases the stability of the lower
23 atmosphere, and it reduces relative humidity, a result being the creation of downdrafts (Dunion

1 and Velden 2004, Wu et al. 2006). The SAL further influences the AEJ via the low static
2 stability of the air mass. This creates a negative PV anomaly and anticyclonic relative vorticity
3 on the poleward side of the jet. The low is a key part of the PV-sign reversal that characterizes
4 the instability of the AEJ (Thorncroft et al. 2003, Hsieh and Cook 2008). Dust outbreaks into the
5 layer shift the ITCZ over the Atlantic Ocean northward, enhancing precipitation along the ITCZ
6 (Wilcox et al. 2010). A further effect of the presence of the SAL is that the air below 700 mb is
7 drier and warmer. This raises the lifting condensation level and the level of free convection,
8 requiring additional energy for convection to occur (Wong and Dessler 2005).

9 The impact of the SAL on tropical storms has been hotly debated and the results of many
10 studies are contradictory. Early papers suggested that this layer would enhance tropical
11 cyclogenesis and intensification (Karyampudi and Carlson 1988, Karyampudi et al. 1999,
12 Karyampudi and Pierce 2002). A larger number of papers have suggested a negative influence
13 (Dunion and Velden 2004, Jones et al. 2007, Shu and Wu 2009, Lau and Kim 2007a,b, Reale et
14 al. 2009, Sun et al. 2008, 2009) (Fig. 20). Studies of individual hurricanes suggest that, by
15 reducing sea-surface temperatures over the eastern tropical Atlantic, the SAL suppresses both
16 rainfall and hurricane development (Lau and Kim 2007a,b, Evan et al. 2006, 2008, Wu 2007, Wu
17 et al. 2006).

18 Braun (2010) re-examined these studies and concluded that the role of the SAL in
19 convection and storm development has probably been over-emphasized. Sippel et al. (2011), for
20 example found that the SAL has its greatest impact north of the AEJ, where convection is weak
21 and commonly dry. Its influence appears to be weak south the AEJ, the region where most
22 AEWs develop and convection is most active. Clearly the links among the SAL, the AEJ, and
23 developing tropical cyclones and hurricanes is not straight-forward.

Lau et al. (2009) propose a paradigm that helps to explain the disparity in various results. The changes in sea-surface temperature over the eastern tropical Atlantic induced by the SAL modulate the Hadley and Walker circulations over West Africa. The result is reduced rainfall in the eastern Atlantic and Gulf of Guinea, but enhanced convection over West Africa. This is consistent with many of the observational results.

8.2 Mechanisms of the impact of mineral dust

The main impact of mineral dust is on the atmospheric radiation budget. The radiative effects depend on the composition of the dust, i.e., on its relative role in absorbing versus reflecting radiation (see review in Nicholson 2000). Hence the radiative effects are different for the mineral-based Saharan dust and the smoke introduced by biomass burning (Huang et al. 2009b).

The particulates affect clouds by serving as ice nuclei and cloud condensation nuclei (DeMott et al. 2003, Hui et al. 2008, Jenkins et al. 2008, Zhang et al. 2007, Wiacek et al. 2010). They also influence cloud dynamics, the rate of droplet formation, and the vertical structure of latent heat release (Khain et al. 2005, Koren et al. 2005). Rosenfeld et al. (2001) suggested that the microphysical effects are associated with reduced precipitation efficiency and hence with reduced rainfall. However, the microphysical effects of mineral dust are complex and cannot be generalized, as they depend vary much on other ambient conditions. For this reason, the impact can be very different in the initial and mature stages of convection (Tao et al. 2007). Overall, the influence of aerosols on precipitation represents the joint impact of the nucleation and dynamic effects. For this reason, diverse results have been produced concerning the impact of mineral dust on weather systems.

Dust over West Africa also influences atmospheric circulation. It appears to intensify the African Easterly Jet (Reale et al. 2011), consistent with the mid-level heating, and weaken the Tropical Easterly Jet (Konare et al. 2008). Evaluating 22 years of data, Jones et al. (2004) provide observational evidence that mineral dust can increase the amplitude of AEWS over the Atlantic, presumably via radiative forcing. Peng et al. (2012) reached a similar conclusion, but suggested that the intensity of the effect depends on initial environmental conditions. Dust outbreaks also affect the Saharan Heat Low (Lavaysse et al. 2011). The radiative effect increases its thickness, but the impact of the dust also affects the heat low via its influence on the AEJ and AEWs.

8.3 Impact on precipitation

Klueser and Holzer-Popp (2010) provided observational evidence that mineral dust changes cloud properties over the Sahel in ways that are consistent with the suppression of convection. Most studies conclude that the net effect is to reduce precipitation over the Sahel (Klueser and Holzer-Popp 2010, Solomon et al. 2008, 2012), particularly that associated with deep convection (Huang et al. 2009a). The modeling study of Yoshioka et al. (2007) suggested that the radiative forcing of mineral aerosol is to reduced precipitation in the ITCZ, including the Sahel region, and reduce it south of the ITCZ. They concluded that the mineral dust may contribute as much as 30% of the precipitation difference between wet and dry years in the Sahel

Some have reached the opposite conclusion. Lau et al. (2009), suggest that the dust can strengthen the monsoon and shift it northward. This implies an increase in rainfall over the Sahel. Some of the data sets evaluated by Klueser and Holzer-Popp (2010) likewise suggested an increase in cloud cover and convection. Jenkins et al. (2008) concluded that the mineral

aerosols coming off of West Africa can invigorate the cloud bands and increase lightning activity in this region in tropical storms (Jenkins and Pratt 2008). Huang et al. (2009a,b) derived observational evidence that mineral dust and biomass burning reduce rainfall further south, near the Guinea Coast, in late boreal autumn and winter by as much as 50%. Over the Atlantic the reduction was most evident in the case of moderate rain rates (10-20 mm/day) (Huang et al. 2009c). In the case of light rain, the dust could actually enhance rainfall.

9. SYNTHESIS OF RESULTS

There is an overwhelming body of evidence that land surface characteristics have an impact on dynamical processes in the atmosphere. A consensus has been reached on many aspects of land-atmosphere interaction. There are numerous examples of the impact of soil moisture and aerosols on individual systems, from tornadoes and hurricanes to the mesoscale systems that prevail in regions such as the Sahel and the U. S. Great Plains, but many aspects of land-atmosphere interaction are still controversial.

One important result is the consensus that there exist "hotspots" where land-atmosphere coupling is particularly strong. These locations are generally characterized by strong soil moisture memory, surface control of evaporation, moderate magnitudes of soil moisture, and a high degree of precipitation recycling. Thus, the most important areas of coupling are large semi-arid expanses such as the Sahel. The impact of soil moisture is greatest under moderate conditions; it is weak for very dry and very wet soils. For this reason, the degree of coupling varies seasonally and also from year-to-year. It is also influenced by groundwater.

In many of these locations, land surface effects clearly have an impact on convection. The heterogeneity of characteristics, including soil moisture gradients, is particularly important.

1 There is considerable evidence from the Sahel that convection tends to be preferentially initiated
2 over dry soil and that soil moisture distribution plays a role in storm evolution and the
3 distribution of precipitation. Overall, the importance and degree of land-surface effects appears
4 to depend on the stage of development of individual systems. It is, however, not clear if the
5 overall amount of precipitation is affected by land-atmosphere coupling. The conclusions based
6 on the Sahel are not necessarily transferable to other locations. In some cases, the spatial
7 distribution of surface characteristics can set up secondary circulations that impact storm
8 systems.

9 An interesting result to emerge is the self-organization of vegetation, soil moisture
10 distribution, and precipitation. That is, the spatial distribution of these variables can be
11 organized from dynamic feedback processes within the system, rather than being externally
12 imposed. For example, there are feedbacks between vegetation cover and soil moisture, shading,
13 and nutrient retention. These lead to the development of the patchiness of vegetation cover in
14 dryland regions. The nature and sign of the feedback depends on the distance from the patch, so
15 that feedbacks are different in canopy versus intercanopy space.

16 Related to these feedbacks is the concept of "patch dynamics". The underlying
17 assumption is that there is a cyclical succession between woody and grassy dominance, with
18 vegetation patterns shifting along a continuum between woody and grass cover. According to
19 theory, the vegetation states between complete cover of trees or grass are unstable, thus allowing
20 for abrupt, catastrophic shifts in vegetation cover to occur. This concept has been applied to
21 understanding the development of the Sahara at the end of the African humid period, but that
22 particular issue is highly controversial.

One of the more controversial questions is the impact of land surface processes on drought. It has long been assumed that soil moisture affects the persistence and magnitude of drought. However, this view has been challenged by some recent studies. The evidence is often based on lag correlations, which are affected by autocorrelation of the individual parameters. Likewise, there is disagreement on the degree of soil moisture memory. In most cases, it is too short to have a significant impact on interannual variability.

The impact of mineral aerosols on tropical cyclones and hurricanes has also been hotly debated. This issue is closely linked to land-atmosphere coupling, in that surface characteristics modulate the mobilization of mineral dust. Mechanisms include both nucleation of ice and droplets and radiative effects. Individual case studies have demonstrated a tendency for aerosols to suppress hurricane development. However, the effect depends also on other ambient characteristics of the storms.

10. RESEARCH NEEDS

Our understanding of land-atmosphere interactions has been advanced through improvements in numerical modeling, such as the use of multi-model ensembles and regional models and incorporating groundwater and surface water routing into models. However, several gaps in our knowledge still exist in our understanding of the effects of land-surface processes on precipitation. This is clearly underscored by the contradictory findings on some issues, such as the sign of the feedback between soil moisture and precipitation, between mineral dust and precipitation, and between mineral dust and tropical storms. Another case in point is the weak performance of many models of land-atmosphere interaction, particularly with respect to applying the land surface memory to seasonal

1 prediction. Current needs include additional confirmation of land surface effects through
2 observational evidence, more rigorous statistical evaluation of results, and a comprehensive
3 theoretical framework that adequately treats the non-linearity of feedbacks among the relevant
4 processes. Such a framework could help to settle some of the open questions, such as the
5 sign of feedbacks.

6 A good basis for such a framework may be the three conditions identified by Koster
7 and Suarez (2003) as prerequisites for the land-surface to impact precipitation. These
8 include a strong initial soil moisture anomaly, strong sensitivity of evaporation to soil
9 moisture, and strong sensitivity of precipitation to evaporation. The first relates the
10 variability and memory of soil moisture as well as to the transformation of precipitation to
11 soil moisture. The second is the coupling between the land and the atmospheric boundary
12 layer (ABL). The third is the coupling between the ABL and the troposphere. The question
13 of the impact of mineral dust on convection, while related to ABL/troposphere coupling, is
14 closely linked to processes within the troposphere. In view of that and its manifold effects,
15 a separate framework is required for a comprehensive understanding of its impacts.

16 Most of the research has focused on the land/ABL coupling. Consequently the
17 processes linking surface fluxes and soil moisture are reasonably well understood.
18 However, soil moisture is extremely sensitive to the structure of the relationships between
19 evaporative fraction (ratio of latent heat to net radiation) and soil moisture and between
20 the runoff ratio and soil moisture (Koster and Mahanama 2012). The efficiency of
21 evaporation varies with the character of vegetation, while the efficiency of runoff
22 generation varies the character of precipitation. These relationships must be evaluated
23 jointly (Dirmeyer 2011a).

1 There is large uncertainty in the evaporative fraction (Guillod et al. 2014) and
2 critical thresholds separating, for example, soil versus atmosphere control or surface runoff
3 versus infiltration are not well established. This stems in part from the failure to
4 adequately parameterize the spatiotemporal distribution of storm precipitation as model
5 input, although this reasonably well established. However, failure to adequately address
6 the contributions of groundwater to soil moisture or the contributions of interception and
7 detention water to evaporation also play a role.

8 Perhaps the least understood part of this scheme is the ABL/troposphere coupling.
9 In particular, the link between the evaporative fraction and subsequent precipitation is
10 poorly understood (Guillod et al. 2014). Improvements in this aspect of coupling require
11 further research into the impact of condensation and latent heat release on thermal
12 stability of the boundary layer (Tawfik and Dirmeyer 2014) or into such effects as
13 entrainment of dry air (van Heerwaarden et al. 2009) or moisture advection (Kanamitsu
14 and Mo 2003). Related to this coupling is two additional issues: the impact of land-surface
15 processes on trigger convection versus modulating its intensity, and the question of
16 whether land-surface processes might overall enhance or merely redistribute precipitation.

17 With respect to models, major difficulties include the coupling with observations
18 and the inconsistency among models in the definition of hydrologic parameters and
19 quantities. Validation is hindered by the fact that measurements of soil moisture, surface
20 flux, surface meteorology, and boundary layer structure (i.e., radiosonde measurements)
21 are seldom co-located. Moreover, the space scales of these measurements are generally not
22 consistent with the spatial resolution of models. Soil moisture in models is essentially a

1 model-dependent construct that is quite different from soil moisture in nature. The
2 definition of "wetness" is inconsistent among models, as well (Koster et al. 2009).

3 The latter is an important point because model input is often model generated since
4 soil moisture observations are not readily available in most locations and precipitation
5 data are extremely sparse from many regions of the world. Fortunately, this situation is
6 changing as a result of satellites geared towards global monitoring of both variables at
7 high-resolution, The Soil Moisture Active Passive (SMAP) for soil moisture (Entekhabi et al.
8 2011) and the Global Precipitation Mission (Hue et al. 2014).

9 What is needed is improved standardization of parameters or at least recognition of
10 the fact that output produced by one model is not intrinsically transferable to another
11 model (e.g., model produced soil moisture fields). Nevertheless, differences among model
12 simulations or output appear to be due much more to differences in the atmospheric
13 models than in the land surface schemes coupled to them (Wei and Dirmeyer 2010, Wei et
14 al. 2010a,b). Hence progress in understanding land surface effects is dependent on
15 atmospheric model improvement as well. Ideally, the land and atmospheric models should
16 be jointly developed, as opposed to merely coupled.

17 Above all, better observations are needed. The new satellites will help but ground
18 truth still needs to be established. In particular, runoff and stream flow measurements and
19 gauge data are needed. Accurate precipitation measurements are critical for model
20 performance (Dirmeyer 2011b). Uncertainties in soil moisture are overwhelmingly due to
21 uncertainties in precipitation (Wei et al. 2008). In many cases, extensive data exists but has
22 not been available outside the country where collected. International data exchange needs
23 to be promoted.

1 Most of our understanding of the impact of the land surface on the atmosphere has
2 been gained theoretically. Observations of its impact are few, in part because it is difficult
3 to effectively separate processes. For example, some of the apparent evaporative
4 fraction/precipitation relationships that have been observed can be explained by the
5 persistence of precipitation (Salvucci et al. 2002, Guillod et al. 2014) or may be statistical
6 artifacts (Douville et al. 2007).

7 Our understanding of land-surface processes has expanded tremendously over the
8 last two to three decades. Much of the advancement has been achieved via community-
9 wide efforts, such as ISLSCP and field experiments within it, GLACE, the Global SOil
10 Wetness Project (GSWP, Dirmeyer 2011b), or the Global Land-Atmosphere System Study
11 (GLASS). van den Hurk et al. (2011) give a review of some of these programs. The impact
12 is clear from Fig. 4, with increases in relevant publications following field experiments like
13 FIFE, HAPEX-Sahel, or BOREAS or following the GLACE experiment of 2006. Continued
14 community-wide effort is needed to adequately deal with the research needs in the area of
15 land-atmosphere interaction.

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FIGURES:

1. Schematic of the forcings and fluxes at the top and bottom of the earth's atmosphere.

2. Satellite photo showing strong albedo contrast along the Sinai/Negev border (within indicated oval). Photo courtesy of NASA.

3. Schematic illustration of the surface energy balance over the barren Sahara and over the Sahelian savanna. T is surface temperature, LW is longwave radiation from the surface; LW counter-radiation is emitted by the atmosphere, and A_s is surface albedo.

4. Number of publications appearing per year covering the topics of soil moisture-feedback, land-atmosphere feedback, land-atmosphere interaction, or albedo-drought feedback. These were taken from the Web of Science, search with the afore-mentioned four topics. The commencement of ISLSCP and the timing of three ISLSCP experiments is also indicated.

5. Changes in rain-use efficiency over West Africa 1981 to 1999. Green is increased, red is decreased, indicating degradation/desertification (from Prince et al. 2007). Light green indicates increasing but non-significant trends and pink indicates decreasing but non-significant trends.

6. Flow chart of the evolution of research on land-atmosphere interaction.

7. Correlation function of the soil moisture field (from Rodriguez-Iturbe et al. 1995)

1 8. Soil moisture memory (in days) for areas where land-atmosphere coupling appears to be
2 significant (from Dirmeyer et al. 2009). Data are shown for four seasons.

3
4 9. Regions of strong land-atmosphere coupling strength during June-to-August, averaged across
5 results from 12 AGCMs (from Koster et al. 2004). Color key is a dimensionless coupling
6 strength.

7
8 10. Semi-arid ecosystems are generally characterized by a patchy vegetation cover.

9
10 11. Dryland regions are characterized by "islands of fertility" which concentration moisture and
11 nutrients via run-in and provide shading. Bare patches in between are regions of high radiation
12 and evaporation, excess heat, and runoff.

13
14 12. Modeled representation of patchiness in dryland ecosystems. Black indicates maximum
15 vegetation cover and white indicates minimum cover. Feedbacks govern shifts between varying
16 degrees of patchiness, including shifts between spots, labyrinths, and gaps (from Rietkerk et al.
17 2004).

18
19 13. The concept of catastrophic shifts in ecosystems (Rietkerk et al. 2004). Ecosystems may
20 undergo a predictable sequence of self-organized spatial patterns as they approach a critical
21 transition.

1 14. Comparison of radiative forcing over the Sahara during the Holocene and dust in an Atlantic
2 sediment core off the coast of West Africa (red dot in the photo). The abrupt shift in dust and the
3 lack of correspondence with radiative forcing might be interpreted as evidence of a positive
4 feedback (from deMenocal et al. 2000).

5
6 15. Holocene evolution of lakes and rainfall. Top: lake stands in the Sahara-Sahel region (8-
7 28N, 20W - 40E). Bottom: oxygen-isotope record of summer rainfall above Qunf Cavae, Oman
8 (from Liu et al. 2007 and Fleitmann et al. 2007). These clearly suggest a gradual end to the
9 African humid period of the Holocene and the development of the Sahara.

10
11 16. Accumulated 30-day rainfall totals in the Sahel region (top) and (bottom) daily rainfall at two
12 pairs of gauges during the HAPEX Sahel experiment, July 14 to August 12, 1992. Darkest
13 shading indicates monthly rainfall in excess of 225 mm; lightest indicates monthly rainfall less
14 than 135 mm. In both cases, the gauges are ~10 km apart, and the climatological gradient is
15 small and in the opposite direction of that shown (from Taylor and Lebel 1998).

16
17 17. Temperature and soil moisture anomalies from the seasonal mean versus distance from the
18 point of initiation of mesoscale systems (from Taylor et al. 2011a). Colors indicate the
19 temperature anomaly in degrees K. Contours indicate the volumetric soil moisture anomaly (%).

20
21 18. Distribution of last surface temperature anomaly gradients associated with initiation of
22 mesoscale convective systems in the Sahel. Frequency of along-wind gradients (K/100km)
23 located 10 km downstream of the initiation point (black stepped line). Expected frequency is

1 shown in gray. Areas of enhanced/reduced probability of initiation are shown in orange/grey
2 (from Taylor et al. 2011a).

3
4 19. (left) Conceptual model of the Saharan air layer (SAL) (from Carlson and Prospero 1972).
5 The Saharan air layer (dark shading, indicating intense dust layer) is trapped between two
6 temperature inversions. (right) High clouds over the northern Sahel mixed with red Sahelian
7 dust (photo courtesy of Carol Breed).

8
9 20. Evolution of storm intensity for six hurricanes and one tropical storm. Red is when the storm
10 is under the influence of the Saharan Air Layer (SAL) and green is when it is not under the
11 influence of the SAL (from Dunion and Velden 2004).

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Figure 1

Figure 2

Figure 3

Saharan Surface

$T = 60^{\circ}\text{C}$

Solar Radiation

LW Radiation

$A_s = 0.5$

LW counter
radiation

20%

R_{net}

Albedo

Sahelian Grassland Surface

$T = 30^{\circ}\text{C}$

Solar Radiation

LW Radiation

$A_s = 0.2$

LW counter
radiation

20%

Albedo

Figure 4

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