A mechanism for land–ocean contrasts in global monsoon trends in a warming climate

J. Fasullo

Abstract A central paradox of the global monsoon record involves reported decreases in rainfall over land during an era in which the global hydrologic cycle is both expected and observed to intensify. It is within this context that this work develops a physical basis for both interpreting the observed record and anticipating changes in the monsoons in a warming climate while bolstering the concept of the global monsoon in the context of shared feedbacks. The global-land monsoon record across multiple reanalyses is first assessed. Trends that in other studies have been taken as real are shown to likely be spurious as a result of changes in the assimilated data streams both prior to and during the satellite era. Nonetheless, based on satellite estimates, robust increases in monsoon rainfall over ocean do exist and a physical basis for this land–ocean contrast remains lacking. To address the contrast's causes, simulated trends are therefore assessed. While projections of total rainfall are inconsistent across models, the robust land–ocean contrast identified in observations is confirmed. A feedback mechanism is proposed rooted in the facts that land areas warm disproportionately relative to ocean, and onshore flow is the chief source of monsoonal moisture. Reductions in lower tropospheric relative humidity over land domains are therefore inevitable and these have direct consequences for the monsoonal convective environment including an increase in the lifting condensation level and a shift in the distribution of convection generally towards less frequent and potentially more intense events. The mechanism is interpreted as an important modulating influence on the "rich-get-richer" mechanism. Caveats for regional monsoons exist and are discussed.

Keywords Monsoon · Climate change · Tropical convection

1 Introduction

Monsoon rainfall is critical both for tropical economies and ecosystems and its prediction in the context of climate change is a scientific challenge of considerable importance. A concept that has emerged in recent years to describe coherent low frequency variability among the various regional monsoons is that of a global monsoon in which the seasonal overturning circulation and rainfall vary in a coherent fashion across the Tropics (e.g. Trenberth et al. 2000). While the concept of a global monsoon continues to be explored, and its relevance to some modes of variability is known to be weak (e.g. El Niño-Southern Oscillation), it has proven useful in describing and understanding other aspects of variability (Wang and Ding 2008). Moreover, the concept may be useful in describing common sensitivities of the various monsoon systems in a changing climate. In this context, it is argued here that the global monsoon concept is particularly applicable to extent that the various monsoons, despite their regional distinctions, are driven by shared feedbacks and common

J. Fasullo (✉)
CAS/NCAR, National Center for Atmospheric Research,
3090 Center Green Dr., Boulder, CO 80301, USA
e-mail: fasullo@ucar.edu

forcings. But what are these shared feedbacks and what role would they be expected to play in shaping the future monsoon?

The global hydrologic cycle has received considerable scrutiny, both in regards to its present day variability and future evolution, and several common themes have emerged. Increased tropospheric temperatures and net evaporation in a warmer climate imply an increase in atmospheric water holding capacity and cycling, and thus a potential for increased rainfall. At the same time, basic constraints on tropical dynamics are expected to weaken its zonal circulations (Vecchi et al. 2006; Ma et al. 2011), and these are key components of the monsoons generally (Webster and Yang 1992; Webster et al. 1998; Sun et al. 2010). In the net, and on a global scale, the balance of these influences leads to a robust intensification of the hydrologic cycle in conjunction with the changing surface Bowen ratio and net radiative balance. While the intensification does not scale with Clausius-Clapeyron, it is nonetheless significant and projected consistently across models (e.g. Allen and Ingram 2002; Held and Soden 2006). Also in line with these expectations are recent observations from various surface (Huntington 2006) and satellite based estimates (Syed et al. 2010; Zhou et al. 2011), which have demonstrated an intensification of the hydrologic cycle. Nonetheless, as these records are relatively brief and the density of observational stations has evolved over time, the representativeness and accuracy of reported trends remains somewhat uncertain.

Developing hydrologic constraints on a regional scale, particularly over monsoonal land domains, has been problematic. Simple scaling arguments, such as those that have been used successfully over the oceans (e.g. Held and Soden 2006), remain elusive both over land globally and on regional scales. A challenge has in part arisen from the large internal variability that is characteristic of regional rainfall (e.g. Deser et al. 2011), but the additional physical complexity of the land-monsoon hydrologic environment has also played a confounding role. For example, vegetation-convective interactions and land-surface hydrology play key roles in moisture cycling and these are not generally well simulated by models (Dai 2011). Moreover, significant uncertainty arises from the influence of aerosols in the monsoon environments (Lau and Kim 2006; Ramanathan et al. 2001; Nigam and Bollasina 2010) and even the gross scale nature of the aerosol impact on rainfall remains unclear (e.g. Khain 2009). Accompanying these uncertainties, future projections of monsoon intensity over land vary widely across models (Kim et al. 2008). Interpretation of these projections is clouded further by diagnoses of recent monsoon variability, including reanalysis-based studies that have identified substantial weakening of the land monsoon (e.g. Chase et al. 2003) and satellite

analyses, which while finding no trend over land identify a strengthening over ocean (Wang and Ding 2006).

Several questions therefore arise. Are observations, and particularly reanalyses, suitable for evaluating trends in the global monsoon and do they provide a meaningful basis for evaluating model simulations? How does hydrologic variability globally relate to the regional monsoons? Can models, despite their various errors and uncertainties, contribute to the development and understanding of the global monsoon concept and future monsoon evolution?

In addressing these questions, it is useful to first consider the shared features of the various monsoon systems. Most basically, the existence of a land–ocean contrast is fundamental to many monsoons and feedbacks in the water cycle, and particularly clouds, play a central role in establishing their span, strength, and variability (e.g. Webster et al. 1998). At the same time, a robust and disproportionate warming of tropical land regions is a ubiquitous feature of a warming climate (e.g. Joshi et al. 2008; Boer 2011) and so the question arises as to how this fundamental characteristic of a changing climate may influence monsoon variability? Fasullo (2010) investigated the consequences of the land–ocean contrast in warming on the annual mean global energy budget and found a particularly strong response at low latitudes, related to the increased aridity of the boundary layer over land and its impacts on clouds and radiation that have direct consequence for radiative equilibration of the climate system. Fundamental to the contrast was the limited availability of moisture over land and the inextricable constraints it imposed on convection and clouds. But what are the consequences for rainfall and what insights into the already stated questions and the global monsoon concept might be gained from these constraints?

To investigate these questions, reanalysis and satellite data are used in conjunction with a suite of global coupled model simulations. The data and methods used are addressed in Sect. 2 while in Sect. 3 the suitability of reanalyses for exploring the global monsoon is assessed. In Sect. 4, projections of the global monsoon are examined with the goal quantifying the large inter-model spread in monsoon projections and aspects of their associated land–ocean contrasts. Results from these sections as they relate to the major science questions is discussed in Sect. 5 and conclusions and related future work are presented in Sect. 6.

2 Methods and data

2.1 Reanalyses

Estimates of global monsoon intensity over recent decades are computed from a suite of reanalyses produced by the

major meteorological centers (NCEP (NOAA), ECMWF, JMA, and NASA). Trenberth et al. (2011) provides an assessment of these products, particularly as related to the hydrological cycle and land–ocean exchanges. The first generation of atmospheric reanalyses was produced in the mid-1990s at the National Center for Environmental Prediction/National Center for Atmospheric Research (NCEP/ NCAR, Kalnay et al. 1996) and assimilated few hydrological fields. It did not use SSM/I data or satellite water vapor channels. Hence the reanalysis is data sparse across the monsoon domains with the result that the moisture fields are largely produced by the reanalysis model and are severely deficient in their spatial and temporal variability. Variability in the reanalysis' hydrologic fields is influenced strongly by changes in the assimilated data stream and their projection onto the model convective physics and not by natural variability (Trenberth et al. 2005, 2011).

Two second generation products, the ERA-40 (Uppala et al. 2005) and the JMA 25-year reanalysis (JRA-25) (Onogi et al. 2007) addressed flaws in the earlier reanalyses, but many problems persisted, particularly in regards to the assimilation of water vapor data and model flaws. For this study, E-P from ERA40 is also computed based on the method described in Trenberth et al. (2002).

Several improved reanalyses have recently become available including the NCEP Coupled Forecast System Reanalysis and Reforecast (CFSRR, Saha et al. 2010), MERRA (NASA's Modern-Era Retrospective Analysis for Research and Applications (Rienecker et al. 2011), and ECMWF's ERA-Interim (Simmons et al. 2007). There are three main differences from the first generation efforts including increased resolution, improved initialization and assimilation techniques, and the incorporation of additional satellite radiances. The newer reanalyses also incorporate many important model improvements, the use of four-dimensional variational (4D-Var) data assimilation, and various other changes in their analysis methodology. MERRA provides various quantities that are used to calculate E-P, without going through the mass correcting procedure that is necessary in the other reanalyses, made possible by MERRA's use of the incremental analysis update procedure that evolves the fields smoothly. In addition, an extended reanalysis for the twentieth century and beyond (20thC), based on specified SSTs and surface pressure reports, has been performed with the ensemble Kalman filter (Compo et al. 2011), using a recent data assimilation system. Because data are assimilated only at the surface, the atmospheric increments only affect the free atmosphere indirectly in this reanalysis and changes in the data stream have an indirect but potentially large impact on hydrologic variability, particularly as it relates to the monsoons.

In general, all of these reanalysis are known not to balance or satisfy basic moisture constraints (Trenberth et al. 2011). Trenberth et al. (2005) evaluated precipitable water from NCEP reanalyses, ERA-40, and SSM/I, and identified spurious variability in trends in all reanalyses, with only SSM/I providing reliable trends over the ocean. Trenberth et al. (2011) also provides other examples of pervasive problems in spin up of the hydrological cycle, and its treatment in reanalyses and both generally and in regards to trends. Based on these works, there is the expectation that diagnoses of global monsoon trends using reanalyses may be problematic.

2.2 Satellite retrievals

A general lack of ground-based measurements has meant that most tropical precipitation estimates are based on various algorithms applied to satellite data and then merged into synthesized products such as the Global Precipitation Climatology Project (GPCP, Huffman et al. 2009). The temporal sampling limitations from two instantaneous precipitation rates per day from polar orbiters are offset by geostationary satellites, but with less accurate infrared sensors. Nonetheless, comparisons of GPCP and other datasets (Adler et al. 2001; Yin et al. 2004) reveal large discrepancies over tropical oceans of order 10–15%. The aliasing of such biases onto trends in the tropics is a major contributor to uncertainty in monitoring the monsoons (Arkin et al. 2010). Nonetheless, errors in simulated rainfall are often substantially larger than that contained in satellite products and GPCP has a variety of legitimate uses in validation of both models and the reanalyses.

2.3 Model simulations

Simulations of the World Climate Research Programme's (WCRP's) Coupled Model Intercomparison Project phase 3 (CMIP3) multi-model dataset (Meehl et al. 2007) are used to assess future projections. The simulations represent the combined effort of sixteen modeling centers using a total of two-dozen coupled climate models in a variety of configurations and under a range of forcing scenarios. The projections of the twenty-first century based on forcing of the SRES-A1B scenario are used here and benefit from employing a fully coupled and interactive ocean model. This scenario is selected as it offers the greatest number of available model runs. All fields in the archive are considered but some models have incomplete information. Where available, one member (run1) of each model ensemble is chosen for this analysis and an estimate of internal variability is obtained from the ensemble of a single model (NCAR CCSM3) for which multiple ensemble members are available.

A variety of derivative fields central to tropical convection and rainfall are computed from the CMIP3 archive. These include the lifting condensation level (LCL) and convective available potential energy (CAPE). For continuous projections of the CMIP3 archive, only monthly fields are available and are thus used for these computations. In computing LCL, a parcel from the lowest model pressure level data, at or above the reported surface pressure, is ascended along a dry adiabat until it reaches the level of saturation, defined as the LCL. Computations of CAPE involve lifting the parcel beyond that point, to the level at which it is neutrally buoyant while integrating its buoyancy along its full vertical trajectory. The effects of heat release associated with the latent heats of fusion and vaporization are both considered during the parcel ascent.

3 The global monsoon as diagnosed from reanalyses

The proliferation of reanalysis in recent years provides an important opportunity to evaluate the robustness of their resolved variability. Figure 1 shows the evolution of global monsoon rainfall over land in several reanalyses and in GPCP using the method of regional monsoon identification developed by Wang and Ding (2006) as applied individually to each dataset. While the regions defined by this method are similar across the datasets, reported variations and trends can vary widely. To provide a satellite-based context for these variations, GPCP shows some significant interannual variability but no significant trend over land since 1979, consistent with the results of Wang and Ding (2006). Thus, the large variations that exist in present-day global-land monsoon are associated with internal variability and these render undetectable any forced component of variability that may exist. Despite the lack of a trend, this period contains a contemporaneous rapid increase of global surface temperature and thus, according to GPCP, the absolute magnitude of the global-land monsoon's sensitivity to global temperature is likely to be weak.

Several remarks can be made on the reanalyses' depictions of the global monsoon that provide insight into their suitability for global change studies. A study identifying a significant weakening trend based on NCEP data used fields spanning the pre-satellite era (Chase et al. 2003). From these reports of monsoon weakening, both theoretical expectations and models were called into question. But how reliable are trends in estimates of global monsoon intensity from reanalyses, particularly prior to 1979?

The 20thC, ERA40, and NCEP products offer the opportunity to compare the robustness of various trends from 1958 to 1979 (intervals denoted by "A" in Fig. 1). While NCEP shows a marked weakening of the monsoons (-3.0 mm day^{-1} c^{-1}), other reanalyses show a very
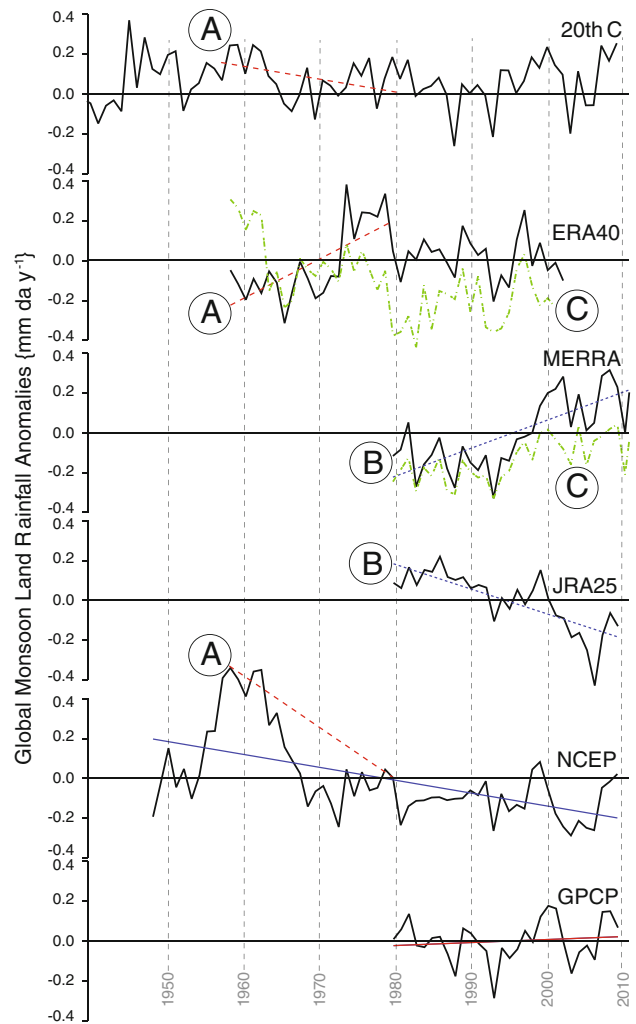

Fig. 1 The evolution of global monsoon rainfall over land as estimated from various reanalyses and GPCP. Several identifiably spurious features exist including contradictory trends prior to (A) and during the satellite era (B), and inconsistencies with moisture convergence estimated from the mass-corrected atmospheric moisture budget (C)

different evolution. In part these differences may arise from a general lack of observational data in the monsoon regions, particularly prior to 1968 (e.g. Yang et al. 2002), and thus the reanalysis fields are largely model generated, influenced only weakly by observational constraints. Spurious trends therefore are likely to be induced as observations become available. In the 20thC reanalysis, the weakening from 1958 to 1979 is substantially smaller (-0.5 mm day^{-1} c^{-1}) as the reanalysis altogether fails to capture the broad peak in rainfall resolved in NCEP near 1960. Estimates from ERA40 contrast even more markedly, with a substantial contemporaneous increase in rainfall ($+2.0$ mm day^{-1} c^{-1}). Interestingly both the NCEP and ERA40 trends are statistically significant though clearly they are not both physically tenable. While ERA40

incorporated many improvements not considered in the NCEP reanalysis methodology, it remains an open question as to whether any of the reanalyses provide a reasonable depiction of nature during this period, as only sparse surface monitoring of rainfall can be used to evaluate the reanalysis. Notwithstanding this uncertainty, it is clear that some of the reanalyses, if not all, are discernibly wrong and there is no objective justification for placing confidence in any of their reported trends.

In comparing the various reanalyses during the satellite era (labels "B" in Fig. 1), other important contrasts can also be identified. Despite methodological improvements and the incorporation of water vapor channels by more recent reanalyses (Trenberth et al. 2011), trends during the satellite era are mutually inconsistent as MERRA shows a strong positive trend from 1979 to 2010 while JRA25 shows a contemporaneous and robust weakening. Both trends are verifiably false based on retrievals from GPCP and spurious increases in MERRA's hydrologic cycle in the late 1990s are known to relate to changes in assimilated satellite radiances (Trenberth et al. 2011). Moreover, interannual variability represented across reanalyses during the satellite era is poor generally. Separate evaluation of CFSRR and ERAI (not shown) reveal similar shortcomings with even subtle changes in the density of assimilated radiances, and particularly those relating to water vapor (e.g. SSM/I), having a major effect on monsoon intensity in both reanalysis products (Trenberth et al. 2011).

Inconsistencies within a single reanalysis are also evident and can be highlighted by comparing moisture convergence derived from the atmospheric budget, plus the forecasted evaporation component, with simulated precipitation. These intervals are indicated by "C" in Fig. 1. Variations in the budget, if correctly closed, would mirror those in precipitation. Instead, trends and variability in both MERRA and ERA40 budgets contrast strongly with simulated rainfall and a broad divergence between the forecast and assimilated fields is evident. Since the moisture budget is computed from fields directly assimilated by the reanalyses, as opposed to precipitation that is a model forecast product, more confidence can be placed in the budget estimates. Nonetheless, agreement among even the various budget fields and retrievals from GPCP is weak, particularly in regards to trends, and these too are therefore likely to be flawed as indicators of the global monsoon. Thus, it is clear that reanalyses, even when considered across the satellite era, are both mutually and internally inconsistent and are discernibly inappropriate for evaluating trends in the global monsoon. They are also not suitable for evaluating simulations or theoretical scalings of the global monsoon in a warming climate. Rather, it is likely that satellite derived diagnoses, though imperfect, provide the best estimate of present-day global monsoon variability.

4 CMIP3 projections

Model-median projections of summer rainfall normalized by the increase in global temperature are shown in Fig. 2 where trends for June through September (JJAS) and December through February (DJF) are used to denote the respective northern and southern hemisphere summer monsoon seasons. The corresponding present-day global monsoon domains based on GPCP rainfall also shown. Regions where trends agree in sign across at least 75% of models are shown by stippled and hatched domains. Robust increases in rainfall are evident in the Inter-Tropical Convergence Zone (ITCZ) in the Indian and Pacific tropical oceans and in southeast Asia including the monsoonal ocean domains of the southwest Asian, East Asian, and Australian monsoon systems. Increases in model median rainfall are also evident across most other monsoonal ocean domains while robust reductions in rainfall are projected in many subtropical ocean domains, though these are not generally monsoonal. As noted in earlier studies (e.g. Kim et al. 2008), trends over monsoon land regions are

Fig. 2 The multi-model twenty-first century trend in summer season rainfall based on the CMIP3 SRES-A1b scenario model runs and normalized by global mean warming. Zonal mean values for ocean (blue), land (red), and the globe, along with their interquartile ranges (lines) are also shown. Stippling (hatching) denotes regions where positive (negative) trends are consistent in at least ¾ of models
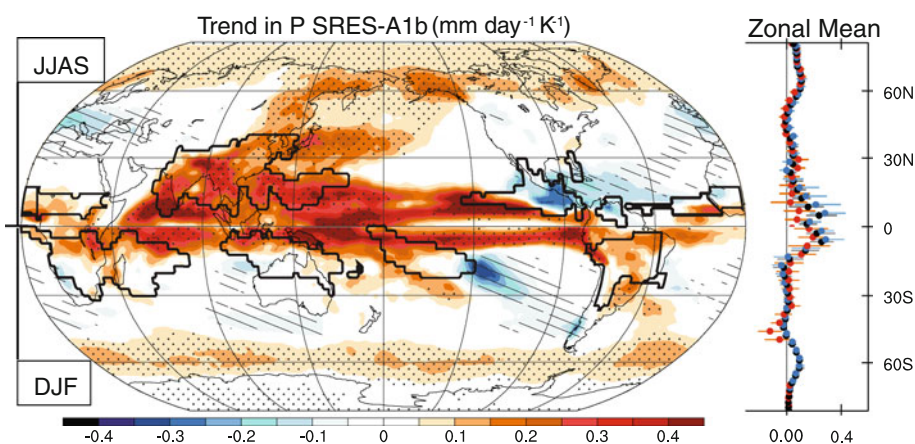
inconsistent across both models and regions generally, with increases in some regions, such as India, South America, and Africa, and small increases or decreases in other domains such as North America and Australia. Trends in monsoon rainfall over land are generally not robust across models with widespread disagreement on even the sign of such trends. In the zonal mean, substantial increases in tropical ocean rainfall are evident in all models, with even the lower quartile exhibiting a positive trend at low latitudes, in contrast to higher latitudes where trends are small generally. In tropical land regions, trends span a relatively broad range and include both increases and decreases with an interquartile range that spans zero at most latitudes. The large inter-model spread is associated in part with internal variability, as the trends are based on a single ensemble member, making assessment of the contrast at regional and zonal mean scales a challenge. It is estimated here, based on the ensemble spread in estimates of the global monsoon from the NCAR CCSM3, internal variability makes a significant contribution to the spread in rainfall trends ($\sigma = 0.04$ mm day^{-1} K^{-1}). Nonetheless, a contrast between land and ocean regions emerges at low latitudes that differs markedly in character from high latitudes, where zonal mean changes over land and ocean agree closely. The question therefore arises as to what environmental changes and physical constraints may exist to influence the land–ocean contrast and to what degree they are relevant to the monsoon convective environments.

To quantify and explore the simulated behavior in monsoon domains, Table 1 shows the difference in simulated mean state and projected sensitivities averaged over global land and ocean monsoonal domains. The mean state is useful in interpreting trends as strong linkages between them are known to exist, such as for example as implied by the "rich-get-richer" mechanism of tropical convection whereby regions that are convectively active in the current climate experience a disproportionate strengthening under warming (e.g. Neelin 2007; Chou et al. 2009). Due to their higher latitudes and elevations, land monsoon regions are generally cooler at the surface (298.7 ± 1.3 K) than their ocean counterparts (301.2 ± 0.8 K) and they experience

lower relative humidity ($73.0 \pm 3.5\%$ vs. $82.9 \pm 2.6\%$). The vertical structure of the troposphere is also distinct with lower LCL pressure (743 ± 268 hPa vs. 819 ± 303 hPa) and smaller values of CAPE (51.1 ± 45.0 J vs. 747 ± 512 J). Associated with their aridity and relative stability, land regions also have less cloud amount than ocean regions ($67.5 \pm 8.6\%$ vs. $70.7 \pm 9.2\%$) and lower precipitation (6.4 ± 0.6 mm day^{-1} vs. 7.8 ± 1.0 mm day^{-1}).

Trends in temperature show a disproportionate warming of monsoonal land domains relative to their ocean counterparts with a median contrast of 0.27 K per degree of warming globally and an interquartile range of 0.19 to 0.34 K K^{-1} (Table 1). Associated with this warming is a general tendency towards increased aridity, with all models showing reductions in RH at 925 hPa and an interquartile range of the contrast with ocean domains of -0.9 to -0.1% K^{-1}. Figure 3 shows the regional structure of trends in RH. At all latitudes, decreases in RH over land are projected, with robust reductions within the monsoonal domains of the Americas, East Asia, Australia, and West Africa. In contrast, trends in ocean monsoon domains are small and positive generally with portions of the many monsoonal ocean domains exhibiting positive trends that are robust across models.

The decrease in lower tropospheric RH exerts an inhibiting effect on convection generally, and mandates an increase in the LCL height (i.e. a decrease in its pressure) as the boundary layer becomes more arid. The median contrast in LCL trends between land and ocean is -1.6 hPa K^{-1} with an interquartile range or -2.4 to 0 hPa K^{-1}, and a net reduction in the LCL pressure level occurs in all but a few models (Table 1). Regional trends in the LCL are shown in Fig. 4. Due to its explicit reliance on humidity, LCL exhibits a strong spatial correlation with RH (Fig. 3) and all monsoon land domains, except for northwestern India, exhibit a lifting of the LCL in the model median. Trends over land contrast with those over ocean, which experience a robust lowering of the LCL (i.e., increase in pressure) in most of the tropics and subtropics, including their monsoonal domains (Fig. 5).

Table 1 Median linear trends and their interquartile range in SRES-A1b twenty-first century projections

Land–ocean contrast	T (K)	P (mm day^{-1})	RH925 (%)	LCL (mb)	CLT (%)	CAPE (J)
Mean state	−2.59	−1.40	−9.97	−75.7	−3.24	−696
{25%, 75%}	{−3.12, −1.86}	{−2.2, −0.5}	{−12.0, −7.8}	{−99, −73}	{−6.0, −0.2}	{−1,022, −264}
Trends	+0.27	−0.06	−0.64	−1.63	−0.50	−187
{25%, 75%}	{0.19, 0.34}	{−0.13, 0.08}	{−0.89, −0.07}	{−2.4, 0}	{−0.74, −0.05}	{−249, −59}
		[0.04]				

Trends are normalized by global temperature change to remove the variance induced from contrasts in their climate sensitivity. Internal variability in rainfall, defined as the standard deviation across multiple NCAR CCSM3.0 ensemble members, is shown in bold brackets

Fig. 3 The multi-model twenty-first century trend in summer season 925 hPa relative humidity based on the CMIP3 SRES-A1b scenario model runs and normalized by global mean warming. Zonal mean values for ocean (*blue*), land (*red*), and the globe, along with their interquartile ranges (*lines*) are also shown. *Stippling* (hatching) denotes regions where positive (negative) trends are consistent in at least ¾ of models
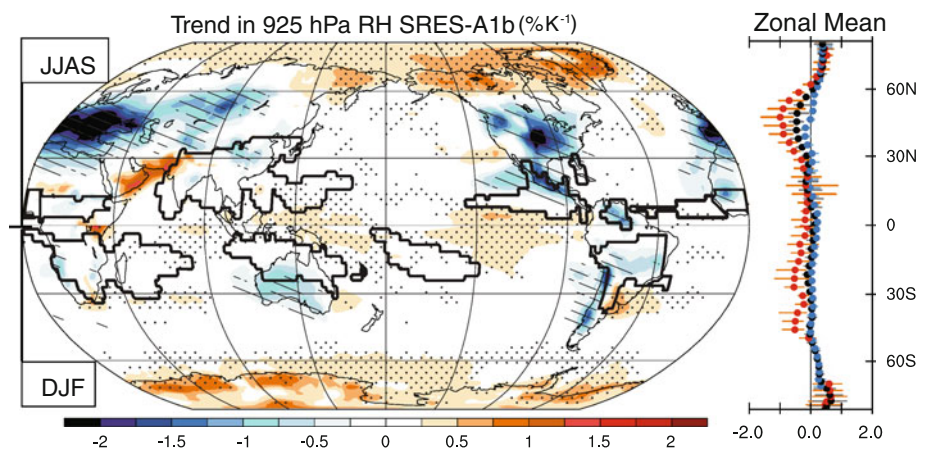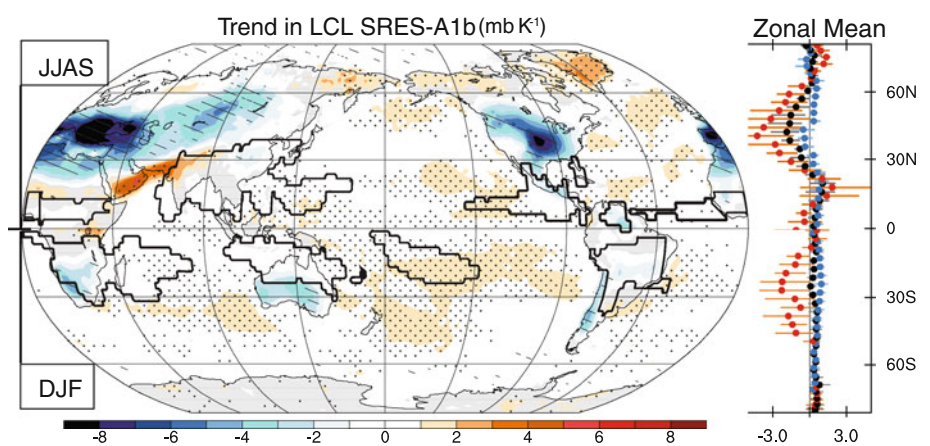
Fig. 4 The multi-model twenty-first century trend in summer season lifting condensation level based on the CMIP3 SRES-A1b scenario model runs and normalized by global mean warming. Zonal mean values for ocean (*blue*), land (*red*), and the globe, along with their interquartile ranges (*lines*) are also shown. *Stippling* (hatching) denotes regions where positive (negative) trends are consistent in at least ¾ of models

Fig. 5 The multi-model twenty-first century trend in summer season cloud amount based on the CMIP3 SRES-A1b scenario model runs and normalized by global mean warming. Zonal mean values for ocean (*blue*), land (*red*), and the globe, along with their interquartile ranges (*lines*) are also shown. *Stippling* (hatching) denotes regions where positive (negative) trends are consistent in at least ¾ of models
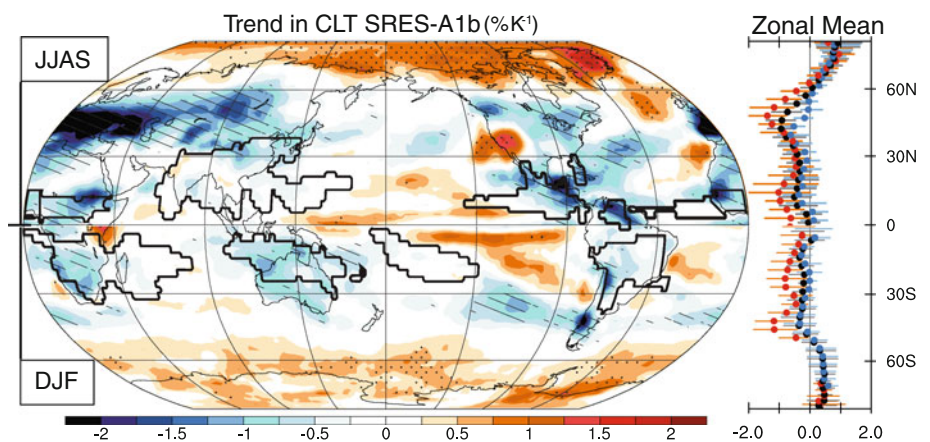
Reflecting the combined effects of boundary layer humidity and temperature, land–ocean contrasts in CAPE projections are substantial. Climate change is known to be associated generally with an increase in static stability across the tropics in association with an amplified hydrologic cycle and related warming in the middle and upper troposphere (e.g. O'Gorman and Schneider 2009). However less well documented is the variability of convective instability and this is identified here as a key influence in driving land–ocean monsoonal contrasts. Figure 6 shows trends in CAPE during summer. The contrast between land and ocean domains is pronounced. As a consequence of their trends towards greater aridity, and despite their disproportionate warming, land monsoon domains experience much smaller increases in CAPE than do ocean domains. The model median land–ocean contrast in projected CAPE

Fig. 6 The multi-model twenty-first century trend in summer season CAPE based on the CMIP3 SRES-A1b scenario model runs and normalized by global mean warming. Zonal mean values for ocean (*blue*), land (*red*), and the globe, along with their interquartile ranges (*lines*) are also shown. *Stippling* (hatching) denotes regions where positive (negative) trends are consistent in at least ¾ of models
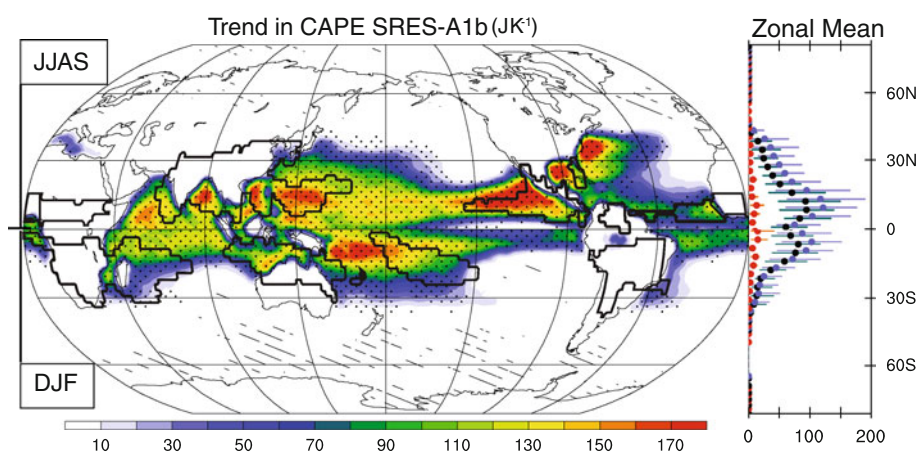
is -187 J K^{-1} with an interquartile range of -59 to -249 J K^{-1}. Trends in CAPE over tropical oceans are pronounced generally and increases over monsoonal ocean domains are particularly strong. The increases result from the combined warming and moistening of the boundary layer, which enhances buoyancy during the vertical ascent of convecting parcels, despite an increase in static stability. In the deep tropics (15°N–15°S) the increases over ocean are particularly large and robust across models with even the 25% tile model increase in the zonal mean exceeding 40 J K^{-1}. A stark contrast is evident with land regions, where increases are small generally and even the sign of simulated trends is ambiguous across models. In none of the global land monsoonal domains are robust increases evident nor do increases over land exceed those over ocean.

Consistent with the combined influence of these trends on the convective environment, reductions in cloud amount are simulated generally under warming (Trenberth and Fasullo 2009) and decreases in cloud amount are known to exhibit a robust land–ocean contrast in the annual mean (Fasullo 2010). Here, summer mean cloud amount is shown to exhibit similar behavior with reductions over land exceeding those over ocean by -0.5% K^{-1}. The regional structure of these trends is shown in Fig. 6. Land monsoon regions including those in the Americas, Australia, and Africa, exhibit marked and robust decreases in cloud amount across models. Reductions are also evident in some monsoonal ocean domains, though generally these are weaker and less robust across models than those over land.

5 Summary and discussion

Reconciling the observational record with a theoretical understanding of the monsoons is prerequisite to interpreting both current trends and future projections. Studies that report substantial weakening of the monsoons are

difficult to reconcile with a broader perspective on the water cycle as the monsoons are a central component of the global hydrologic cycle, which has independently been observed to strengthen with warming in a manner generally consistent with expectations. Here reanalyses are shown to be fundamentally inconsistent in their depiction of monsoon trends and reports of weakening based on reanalyses are likely to be in error. It is argued here that from an observational standpoint, reliable estimates of global monsoon variability can best be gained from the satellite record and that the robust feature of this record is the existence of a land–ocean contrast in rainfall trends, not in a shift in absolute magnitude. This contrast is characterized by a significant strengthening of the oceanic monsoon component accompanying weak and insignificant trends over land that are obscured in part by significant internal variability. In this regard, the satellite record is found to be qualitatively consistent with model simulations, which show a robust land–ocean contrast in monsoon trends. An outstanding goal is therefore to provide a theoretical basis for this contrast.

Towards this end, and in order to promote a physical basis for the global monsoon concept, the role of common feedbacks is emphasized and explored. The analysis establishes a mechanism based on the canonical land–ocean contrast in warming constrained by limitations on moisture availability over land as summarized in Fig. 7. The mechanism is rooted in the fact that the monsoons depend primarily on the onshore flow of moisture from ocean regions. The enhanced warming of land domains relative to ocean therefore mandates a disproportionate increase in saturation specific humidity relative to that over ocean (Fig. 7-1) and as a result, a reduction in the RH of the onshore flow is expected. Based on the model median contrast in warming of 0.27 K per degree of warming globally, this reduction is about 1.8% K^{-1} due to the roughly 7% K^{-1} scaling of the Clausius-Clapeyron relationship, and this matches closely with the simulated land–
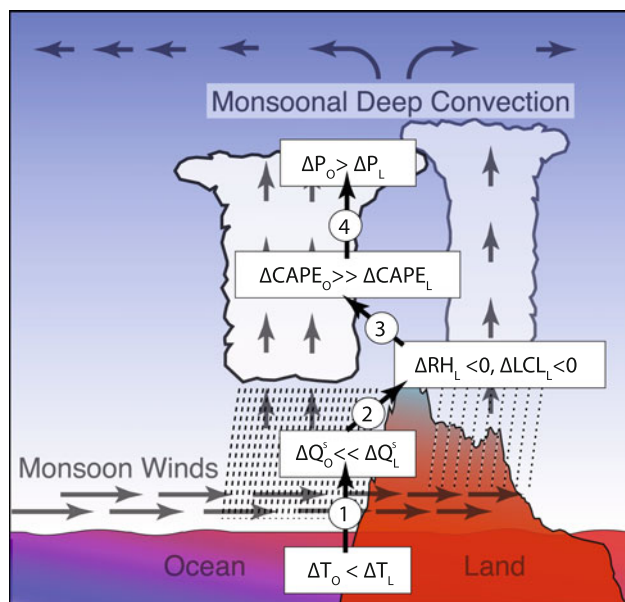
Fig. 7 Conceptual model of processes driving land–ocean contrasts in global monsoon rainfall in a warming climate

ocean contrast in RH of 1.6% K^{-1} (Table 1). Increased aridity in the global-land monsoon land is therefore both qualitatively and quantitatively consistent with expectations based on the constrained onshore monsoonal flow. The inextricable consequence of RH reductions in the boundary layer over land is the lifting of the LCL (Fig. 7-2). In conjunction with an increase in static stability, associated with a warming climate identified in previous work, boundary layer land–ocean contrasts lead to muted increases in CAPE over land relative to those over ocean, which are found to be both significant in magnitude and robust across models (Fig. 7-3). These shifts in the monsoonal convective environment are also associated with a land–ocean contrast in rainfall, which while containing considerable spread both across region and model, is nonetheless found to be evident in the median simulated response.

The mutual relationships for the fields assessed can in instances be complex. For example, substantial decreases in RH and CLT characterize most land monsoon domains, yet total rainfall nonetheless increases in some regions. The contrast between trends in RH, CLT, and rainfall is particularly pronounced over South America and central Africa. Similarly, significant and robust increases in rainfall exist in some land monsoon regions in which CAPE fails to exhibit a robust increase. These differences underscore the fact that LCL and CAPE are not comprehensive determinants of rainfall variability but rather are merely influencing factors. As it is constrained explicitly by the fields available in the CMIP3 archive, the current analysis is incomplete to the extent that overriding

influences exist and these will be important considerations for follow on work.

There are also regional exceptions to the proposed mechanism and chief amongst these is the southwest Asian monsoon, which experiences a considerable increase in projected rainfall over land that is robust across models in some regions. Other components of the proposed mechanism in Southeast Asia, such as a reduction in RH and lifting of the LCL over land, are also not universally valid. However, the Indian monsoon is unique in that the center of its diabatic heating and rainfall occur over the Bay of Bengal, and these drive monsoonal flow over both the land and ocean domains. Thus the sensitivity of its deep convection to land-surface constraints is limited, as the center of its deep convection resides primarily over ocean.

A basis that is useful for understanding aspects of simulated trends in rainfall is the so-called rich-get-richer mechanism whereby regions that are convectively active in the present day experience a disproportionate increase in intensity under warming (e.g. Neelin 2007; Chou et al. 2009). More recent work has emphasized the role of surface temperature, rather than rainfall, in governing future trends (Xie et al. 2010), though qualitatively these descriptions are similar for the monsoon domains, as the warmest regional SSTs tend to coincide with the regions of strongest deep convection. The question therefore arises as to how to view the current mechanism in this context. While it is true that ocean monsoonal domains tend to have greater instability and rainfall in the present-day climate than do land domains (e.g. Table 1), significant rainfall and instability nonetheless exist for both (e.g. Table 1). However, future projections demonstrate a disproportionate destabilization of ocean regions and it is not possible generally to account for future trends based on present day magnitudes alone. Moreover, the rich-get-richer mechanism does not address the moisture limitations that are inherent to the land surface. Thus, in this context, the mechanism proposed here is viewed as a modulating influence on the rich-get-richer mechanism.

Notwithstanding the implications of the mechanism proposed here, major outstanding issues remain relating to future projections. As the mechanisms explored here do not constrain total rainfall but merely influence its land–ocean contrast, chief amongst the outstanding issues is the estimation of absolute rainfall trends over land, which is a more relevant parameter to impact assessment. Continued efforts to constrain accurately projected rainfall amounts will therefore be essential for adaptation efforts. Moreover, the influence of aerosols on projected trends remains a major uncertainty. There is confidence that the trends reported here are not governed by aerosols, as the contrast exists in simulations in which aerosols are increasing, decreasing, or altogether absent. However it remains a

major uncertainty as to how aerosols with modulate both the land–ocean contrast in rainfall and its absolute intensity and this influence remains a subject of ongoing research.

6 Conclusions and future work

Using reanalysis and satellite data in conjunction with climate projections of the CMIP3 archive, a perspective has been advanced here that reconciles the apparent disagreements between observed and simulated monsoon variability in a warming environment. Reanalyses have been found to be unreliable for assessing these trends and instead satellite retrievals are deemed to be the most appropriate means for diagnosing monsoon rainfall trends in a warming climate. A key feature of trends diagnosed from satellite retrievals is the land–ocean contrast in which robust increases evident over ocean accompany relatively stable conditions over land. Model simulations are found to replicate this contrast and a mechanism has been proposed and evaluated that both explains the observed and simulated behavior and promotes the concept of the global monsoon. The mechanism is rooted in the contrast in warming between land and ocean, constraints on moisture due to the land surface, and their implications for boundary layer humidity and the monsoonal hydrologic and convective environments. The mechanism accounts for various simulated trends and these are demonstrated to be robust across models, notwithstanding the large internal variability inherent to rainfall.

Major challenges remain in predicting the future monsoons. Chief among these, and central to the evaluation of impacts, is the projection of absolute rainfall amounts over the land monsoon domains. Towards this end, the identification of model biases responsible for the wide spread that exists in future monsoon projections will be key. Developing observational constraints and improved physical parameterizations to reduce these errors and improve model fidelity remains a major priority. Improving our understanding and simulation of the various modes governing monsoon rainfall is also a major objective as systematic biases in tropical propagating modes and air-sea interactions, particularly as they relate to ENSO and the Pacific cold tongue bias, remain large. The additional fields incorporated in the upcoming CMIP5 release are likely to contribute substantially to an improve understanding of these effects.

References

Adler RF, Kidd C, Petty G, Morrissey M, Goodman H (2001) Intercomparison of global precipitation products: the Third Precipitation Intercomparison Project (PIP-3). Bull Am Meteorol Soc 82:1377–1396

Allen MR, Ingram WJ (2002) Constraints on future changes in climate and the hydrologic cycle. Nature 419:224–232. doi:10.1038/nature01092

Arkin PA, Smith T, Sapiano MRP, Janowiak J (2010) The observed sensitivity of the global hydrological cycle to changes in surface temperature. Environ Res Lett 5. doi:10.1088/1748-9326/5/3/035201

Boer GJ (2011) The ratio of land to ocean temperature change under global warming. Clim Dyn. doi:10.1007/s00382-011-1112-3

Chase TN, Knaff JA, Pielke RA Sr, Kalnay E (2003) Changes in global monsoon circulations since 1950. Nat Hazards 29:229–254

Chou C, Neelin JD, Chen C-A, Tu J-Y (2009) Evaluating the rich-get-richer mechanism in tropical precipitation change under global warming. J Clim 22:1982–2005

Compo GP, Whitaker JS, Sardeshmukh PD (2006) Feasibility of a 100-year reanalysis using only surface pressure data. Bull Am Meteorol Soc 87:175–190

Dai A (2011) Drought under global warming: a review. Wiley Interdiscip Rev Clim Change 23:5–7. doi:10.1002/wcc.81

Deser C, Phillips AS, Bourdette V, Teng H (2011) Uncertainty in climate change projections: the role of internal variability. Clim Dyn. doi:10.1007/s00382-010-0977-x

Fasullo JT (2010) Robust land–ocean contrasts in energy and water cycle feedbacks. J Clim 23:4677–4693. doi:10.1175/2010JCLI3451.1

Held IM, Soden BJ (2006) Robust responses of the hydrological cycle to global warming. J Clim 19:5686–5699

Huffman GJ, Adler RF, Bolvin DT, Gu G (2009) Improving the global precipitation record: GPCP version 2.1. Geophys Res Lett 36:L17808. doi:10.1029/2009GL040000

Huntington TG (2006) Evidence for intensification of the global water cycle: review and synthesis. J Hydrol 319:83–95. doi:10.1016/j.jhydrol.2005.07.003

Joshi MM, Gregory JM, Webb MJ, Sexton DMH, Johns TC (2008) Mechanisms for the land/sea warming contrast exhibited by simulations of climate change. Clim Dyn 30:455–465

Kalnay E et al (1996) The NCEP/NCAR 40-year reanalysis project. Bull Am Meteorol Soc 77:437–472

Khain AP (2009) Notes on state-of-the-art investigations of aerosol effects on precipitation: a critical review. Environ Res Lett 4 015004. doi:10.1088/1748-9326/4/1/015004

Kim H-J, Wang B, Ding Q (2008) The global monsoon variability simulated by CMIP3 coupled climate models. J Clim 21(20):5271–5294. doi:10.1175/2008JCLI2041.1

Lau K-M, Kim K-M (2006) Observational relationships between aerosol and Asian monsoon rainfall, and circulation. Geophys Res Lett 33:L21810. doi:10.1029/2006GL027546

Ma J, Xie S-P, Kosaka Y (2011) Mechanisms for tropical tropospheric circulation change in response to global warming. J Clim (in press)

Meehl GA et al (2007) Global climate projections. In: Solomon S et al (eds) Climate change 2007: the physical science basis. Cambridge University Press, Cambridge, pp 747–845

Neelin JD (2007) Moist dynamics of tropical convection zones in monsoons, teleconnections and global warming. In: Schneider T, Sobel A (eds) The global circulation of the atmosphere. Princeton University Press, Princeton, p 385

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

O'Gorman PA, Schneider T (2009) The physical basis for increases in precipitation extremes in simulations of 21st-century climate change. Proc Natl Acad Sci 106(35):14773–14777. doi:10.107/pnas.0907610106

Onogi K et al (2007) The JRA-25 reanalysis. J Meteorol Soc Jpn 85:369–432

Ramanathan V, Crutzen PJ, Kiehl JT, Rosenfeld D (2001) Aerosols, climate, and the hydrological cycle. Science 294:2119–2124

Rienecker MM et al (2011) MERRA: NASA's modern-era retrospective analysis for research and applications. J Clim 24:3624–3648. doi:10.1175/JCLI-D-11-00015.1

Saha S et al (2010) The NCEP climate forecast system reanalysis. Bull Am Meteorol Soc 91:1015–1057

Simmons A, Uppala S, Dee D, Kobayashi S (2007) ERA-interim: new ECMWF reanalysis products from 1989 onwards. ECMWF Newsletter No. 110

Sun Y, Ding Y, Dai A (2010) Changing links between South Asian summer monsoon circulation and tropospheric land–sea thermal contrasts under a warming scenario. Geophys Res Lett 37:L02704. doi:10.1029/2009GL041662

Syed TH, Famigliettia JS, Chambers DP, Willis JK, Hilburn K (2010) Satellite-based global-ocean mass balance estimates of interannual variability and emerging trends in continental freshwater discharge. Proc Natl Acad Sci USA 107(42):17916–17921. doi:10.1073/pnas.1003292107

Trenberth KE, Fasullo JT (2009) Global warming due to increasing absorbed solar radiation. Geophys Res Lett. doi:10.1029/2009GL037527

Trenberth KE, Stepaniak DP, Caron JM (2000) The global monsoon as seen through the divergent atmospheric circulation. J Clim 13:3969–3993. doi:10.1175/1520-0442(2000)013<3969:TGMAST>2.0.CO;2

Trenberth KE, Stepaniak DP, Caron JM (2002) Accuracy of atmospheric energy budgets from analyses. J Clim 15:3343–3360

Trenberth KE, Fasullo J, Smith L (2005) Trends and variability in column-integrated water vapor. Clim Dyn 24:741–758

Trenberth KE, Fasullo JT, Mackaro J (2011) Atmospheric moisture transports from ocean to land and global energy flows in reanalyses. J Clim (in press)

Uppala SM et al (2005) The ERA-40 reanalysis. Q J R Meteorol Soc 131:2961–3012

Vecchi GA, Soden BJ, Wittenberg AT, Held IM, Leetmaa A, Harrison MJ (2006) Weakening of tropical Pacific atmospheric circulation due to anthropogenic forcing. Nature 441(7089):73–76. doi:10.1038/nature04744

Wang B, Ding Q (2006) Changes in global monsoon precipitation over the past 56 years. Geophys Res Lett 33:L06711. doi:10.1029/2005GL025347

Wang B, Ding Q (2008) Global monsoon: dominant mode of annual variation in the tropics. Dyn Atmos Ocean 44:165–183. doi:10.1016/j.dynatmoce.2007.05.002

Webster PJ, Yang S (1992) Monsoon and Enso: selectively interactive systems. Q J R Meteorol Soc 118:507, 877–926. doi:10.1002/qj.49711850705

Webster PJ, Magana VO, Palmer TN, Shukla J, Tomas RA, Yanai M, Yasunari T (1998) Monsoons: processes, predictability, and the prospects for prediction. J Geophys Res 103(c7 (TOGA special issue)):14451–14510

Xie S-P, Deser C, Vecchi GA, Ma J, Teng H, Wittenberg AT (2010) Global warming pattern formation: sea surface temperature and rainfall. J Clim 23:966–986. doi:101175/2009JCLI3329.1

Yang Song, Lau K-M, Kim K-M (2002) Variations of the East Asian jet stream and Asian–Pacific–American winter climate anomalies. J Clim 15:306–325. doi:10.1175/1520-0442(2002)015<0306:VOTEAJ>2.0.CO;2

Yin X, Gruber A, Arkin P (2004) Comparison of the GPCP and CMAP merged gauge-satellite monthly precipitation products for the period 1979–2001. J Hydrometeorol 5:1207–1222

Zhou YP, Xu K-M, Sud YC, Betts AK (2011) Recent trends of the tropical hydrological cycle inferred from Global Precipitation Climatology Project and International Satellite Cloud Climatology Project data. J Geophys Res 116:D09101. doi:10.1029/2010JD015197