Observed twentieth century land surface air temperature and precipitation covariability

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[1] Significant positive trends in surface air temperatures (SATs) and precipitation were observed over 71% and 27%, respectively, of the global land surface during the twentieth century. Although the terrestrial surface is becoming warmer and wetter, the covariability between annual SAT and precipitation is not well understood. Significant anticorrelations between annual values of SAT and precipitation exist over 24% of the global land surface. Regional-scale interannual climate variability alternates between two dominant regimes, namely relatively warm and dry or cool and wet conditions. The out-of-phase positive trends in terrestrial SATs and precipitation observed during the twentieth century provide an important climate simulation benchmark. **Citation:** Déry, S. J., and E. F. Wood (2005), Observed twentieth century land surface air temperature and precipitation covariability, *Geophys. Res. Lett.*, *32*, L21414, doi:10.1029/2005GL024234.

1. Introduction

[2] The global land surface air temperature (SAT) rose by 0.6°C and global land precipitation increased by ≈2% during the twentieth century [*Jones et al.*, 1999; *Intergovernmental Panel on Climate Change* (*IPCC*), 2001; *New et al.*, 2001]. As greenhouse gas emissions accelerate in the twenty-first century, further changes in SAT and precipitation are expected. Global climate model (GCM) simulations predict SAT increases in the range of 1.4–5.8°C by 2100 with a concomitant acceleration of the hydrologic cycle [*IPCC*, 2001; *Ziegler et al.*, 2003]. This will lead to greater risks of floods, droughts, and other climatic extremes with severe socioeconomic consequences [*IPCC*, 2001]. Rising SATs and changes in precipitation patterns, phases, and intensity will affect water resources and river runoff, ground and permafrost temperatures, vegetation morphology and species composition, and many other aspects of the global environment [*Labat et al.*, 2004; *Déry and Wood*, 2005; *Stieglitz et al.*, 2003; *Sturm et al.*, 2001].

[3] Although the observed trends in SAT and precipitation for the twentieth century over the global land surface are generally well established (Table 1) [*IPCC*, 2001], little is known on the annual covariability of these two meteorological variables. Previous work on this topic focused on the monthly and daily relationships between SAT and precipitation in North America and Europe [*Madden and Williams*, 1978; *Isaac and Stuart*, 1992; *Huang and Van den Dool*, 1993; *Zhao and Khalil*, 1993]. *Hulme* [1995] documented the weak relationship that exists between the global land SAT and precipitation but provided no spatial correlation fields of these quantities. *Trenberth and Shea* [2005] explored the seasonal covariability between surface temperature from the European Centre for Medium-Range Weather Forecasts reanalysis (ERA-40) and precipitation from the Global Precipitation Climatology Project for 1979–2002. A comparison of their statistical analyses with GCM output showed that the numerical models produced stronger than observed relationships between seasonal surface temperatures and precipitation. This highlights the fact that confidence in GCM simulations and predictions of precipitation rates and patterns remains modest at best and improved simulations of precipitation processes and of atmosphere/land surface interactions in a warming environment are still a priority for the climate modeling community [*IPCC*, 2001]. No work in the literature has investigated the observed twentieth century SAT and precipitation covariability and co-trends at annual time scales on the global land surface. The results of this study therefore provide historical information on the relationship between these two meteorological variables, yielding an important climate simulation benchmark and insights on the possible future state of the terrestrial energy and water budgets.

2. Data and Methods

[4] Annual mean SAT and total precipitation data from the Climate Research Unit (CRU, 2005, http://www.cru.uea.ac.uk/cru/data) of the University of East Anglia on a 0.5° latitude × 0.5° longitude grid for the period 1901–2000 are used in this study [*New et al.*, 2000; *Mitchell and Jones*, 2005]. The data cover the entire Earth's surface excluding Antarctica and the global oceans. Time series of SAT and precipitation are first expressed as normalized quantities, defined as the difference between the annual and mean annual values divided by their respective standard deviations (σ). Trends in the normalized SAT and precipitation and their significance are determined using the non-parametric Mann-Kendall test [*Mann*, 1945; *Kendall*, 1975]. Trends not significant at the $p < 0.05$ level are excluded from the analysis. The twentieth century trends in the normalized grid-point values of SATs and precipitation are then multiplied to reveal areas that are becoming

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Table 1. Annual Mean and Standard Deviations (σ) of SAT and Precipitation for the Global Land Surface, 1901–2000[a]

Statistic	SAT	Precipitation
Mean	13.1°C	823. mm
σ	0.262°C	18.8 mm
Trend	0.578°C $(\text{century})^{-1}$	34.8 mm $(\text{century})^{-1}$
	2.21 n. u. $(\text{century})^{-1}$	1.85 n. u. $(\text{century})^{-1}$
p	<0.001	<0.001

[a]The magnitude and probability (*p*) of the linear trends as inferred from the Mann-Kendall test are also listed.

warmer and wetter, warmer and drier, cooler and wetter, or cooler and drier.

[5] The covariability of SAT and precipitation is then determined from the correlation of grid-point values of annual normalized SAT and precipitation. The original data are used since the detrended time series of normalized SAT and precipitation yield marginal differences in the correlation fields. Only correlation coefficients with $p < 0.05$ are considered statistically-significant and are used in the analysis. The global terrestrial annual mean SAT and total precipitation are then examined to reveal years that were warm and wet (WW), warm and dry (WD), cool and wet (CW), or cool and dry (CD) relative to the 1901–2000 averages.

[6] Before proceeding, we invoke three important points of consideration in the application of the CRU climatological data to this study and in our methodology. First, interpolation was required to generate complete SAT and precipitation data over the global land surface for the entire twentieth century [*Mitchell and Jones*, 2005]. This implies that over certain remote areas and/or the developing world (e.g., northern Canada and Russia, the Middle East, and Indonesia), anomalies are relaxed to zero when data are missing, particularly during the early part of the century [*Hulme*, 1995]. Since the SAT and precipitation data are more spatially and temporally complete after 1920, we test and discuss the sensitivity of the results to an abridged study period (1921–2000). Second, the CRU precipitation data have not been corrected to minimize the large systematic biases that arise in measuring snowfall [e.g., *Groisman et al.*, 1991]. No attempt is made here to remove these precipitation biases; rather, we apply the original CRU precipitation data and assume that the biases are constant in time and do not affect the trend and covariability analyses. Third, the determination of trends in SAT and precipitation depends on the type of anomaly used in the analyses and on the different area-averaging methods [*Jones and Hulme*, 1996]. Although the use of normalized anomalies is often preferred for trend analyses of precipitation, some problems may still arise in dry areas. Details on these data and methodology issues as well as their possible impacts on the results are given by *Hulme* [1995], *Jones and Hulme* [1996], *New et al.* [2000] and *Mitchell and Jones* [2005].

3. Results

[7] Figure 1 illustrates the spatial distribution of SAT and precipitation trends, expressed in normalized units per century, over land during the twentieth century. This shows that 71% and 27% of the global land surface experienced significant increases in SATs and precipitation, respectively, over that time period. Significant positive SAT trends are greatest in eastern Brazil, South Africa, northern Africa, the Iberian Peninsula, southern Siberia, and Japan. Significant negative SAT trends are limited to Madagascar, western Oceania, central South America, and the southeastern United States. Trends in precipitation exhibit less spatial coherence than those in SAT. Figure 1b shows that significant positive precipitation trends are greatest over Canada, northern Eurasia, and Argentina. Significant negative trends in precipitation exist over western Peru, the Sahel of Africa, the Arabian Peninsula, the Tibetan Plateau, and the southern tip of Greenland. Restricting the trend analysis to 1921–2000 shows similar tendencies for both SAT and precipitation over the global land surface, with the exception of negative SAT trends over Greenland and the Tibetan Plateau and of more pronounced and expansive negative precipitation trends over the Sahel of Africa (not shown).

[8] The SAT times precipitation trend shown in Figure 2a provides a measure of the greatest concurrent changes in these quantities over land. Most prominent are the trends in South America, Canada, and Siberia. Twenty percent of the global land surface became significantly warmer and wetter during the twentieth century, whereas 6% of the global land surface became significantly warmer and drier. Figure 2b shows the covariability between the annual normalized values of mean SAT and precipitation. Negative correlation coefficients indicate WD or CW conditions whereas positive correlation coefficients signify WW or CD conditions. Significant anticorrelations encompass 24% of the global

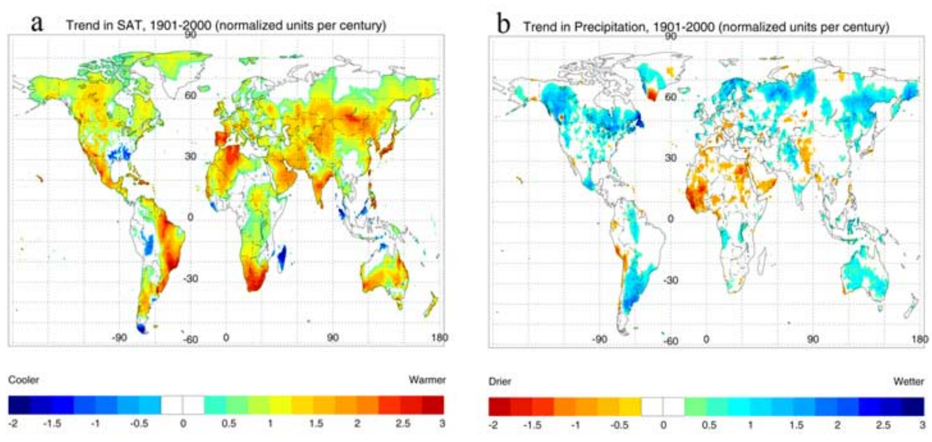

Figure 1. Trend in annual (a) mean SAT and (b) total precipitation (normalized units), 1901–2000.

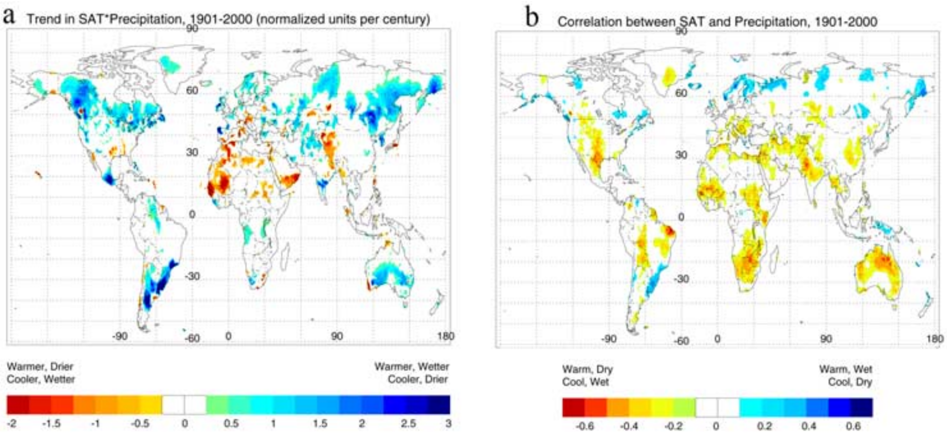

Figure 2. (a) Trend in annual mean SAT times total precipitation (normalized units), 1901–2000. (b) Correlation coefficient between the annual mean SAT and total precipitation, 1901–2000.

land surface and are generally found in the tropics, subtropics, and mid-latitudes, whereas significant positive correlations cover 5% of the global land surface and are generally restricted to high latitudes. The co-trend and covariability analyses for 1921–2000 are nearly identical to the ones for the twentieth century (not shown).

[9] Figure 3 clearly illustrates the weak correspondence that exists between the global terrestrial annual mean SAT and total precipitation, in accord with *Hulme* [1995]. There is a slight positive but significant correlation ($r = 0.21$, $p = 0.036$) between the global annual mean SAT and total precipitation over land during the twentieth century. The slope of the linear regression shown in Figure 3 is 15 mm °C^{-1} (1.8% °C^{-1}), which is four times less than the observed twentieth century trend of 60 mm °C^{-1} (7.3% °C^{-1}) (Table 1). This suggests strong non-linearities between SAT and precipitation exist within the climate system.

[10] The significant positive correlation between the globally-averaged annual SAT and precipitation values obtained in Figure 3 appear to be in conflict with the predominance of significant anticorrelations over the global land surface found in Figure 2b. In fact, this implies that the two dominant modes of interannual climate variability operating at the regional (grid-point) scale are relatively warm, dry conditions followed by relatively cool, wet conditions. It suggests that positive anomalies in globally-averaged annual SAT and precipitation occur out-of-phase over land [*Hulme*, 1995]. Figure 4 illustrates 9-year running means of the normalized SAT and precipitation anomalies over land during the twentieth century. Relatively WD conditions emerge between 1930 and 1950, followed by a period of relatively CW events between 1950 and 1980, and then a return to more prominent WD conditions from 1980 to 2000. It reveals low-frequency (20- to 30-year) cycles between relatively WD conditions and relatively CW conditions. Imposed on the low-frequency variability are positive linear trends in SAT and precipitation that have nearly identical slopes of 2 normalized units per century (see Table 1).

4. Discussion

[11] Several mechanisms may be invoked to explain the observed SAT and precipitation covariability over land during the twentieth century. These include large-scale atmospheric teleconnection patterns such as the annular modes or large-scale sea-surface temperature anomalies [*Thompson and Wallace*, 1998; *New et al.*, 2001]. Another possible mechanism involves the role of soil moisture anomalies. Interactions between the land surface and the atmosphere tend to sustain soil moisture anomalies at seasonal-to-interannual timescales [*Koster et al.*, 2003, 2004]. For instance, a negative soil moisture anomaly suppresses evapotranspiration and warms the land surface [*Huang and Van den Dool*, 1993]. In turn, the reduced availability of atmospheric moisture diminishes precipitation, creating a feedback mechanism by which the observed negative annual covariability between SAT and precipitation may arise [*Koster et al.*, 2003]. In fact, the areas with significant anticorrelations between SAT and precipitation shown in Figure 2b bear considerable resemblance to "hot spots" of strong coupling between soil moisture

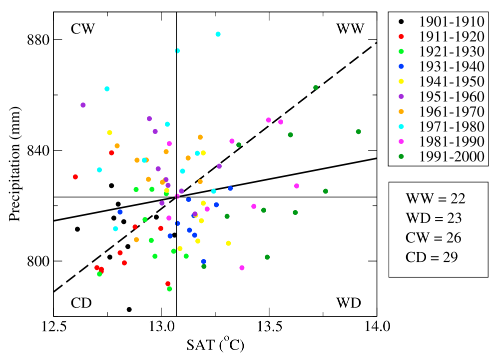

Figure 3. Relationship between the annual mean SAT and total precipitation over the global land surface during the twentieth century. The bold line indicates the linear regression and the dashed line represents a line with slope inferred from the twentieth-century trends in SAT and precipitation that intercepts the point representing the mean of these quantities. The number of years with warm and wet (WW), warm and dry (WD), cool and wet (CW), and cool and dry (CD) conditions compared to the 1901–2000 means (thin lines) are also listed.

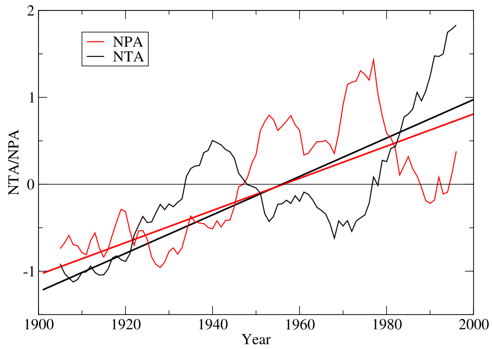

Figure 4. Nine-year running means of the global terrestrial normalized SAT and precipitation anomalies (NTA and NPA, respectively) during the twentieth century. The bold lines indicate the linear trends.

and precipitation, particularly in the Northern Hemisphere [*Koster et al.*, 2004]. The soil moisture/precipitation feedback is therefore a possible mechanism that may account for the observed terrestrial SAT/precipitation covariability during the twentieth century.

[12] The impact of rising SATs on the hydrologic cycle has been of much debate. For instance, *Hulme* [1995] and *Labat et al.* [2004] claim that a rise of 1°C in terrestrial SAT yields a 3.2% and a 4.0% increase in global land precipitation and river runoff, respectively. Although some uncertainties in these figures exist and their applicability to the future state of the hydrologic cycle remains unknown [*Lambert et al.*, 2004], the results of *Hulme* [1995] and *Labat et al.* [2004] fall within the range of 1.8% $°C^{-1}$ (linear regression analysis) to 7.3% $°C^{-1}$ (trend analysis) for precipitation (Figure 3). This suggests that the twentieth century trend in terrestrial SAT and precipitation could explain the positive trend in observed global river discharge. Interestingly, the trend analysis yields a change in precipitation that nears the 6.5% $°C^{-1}$ implied by the Clausius-Clapeyron relation [*Allen and Ingram*, 2002]. Rigorous water budget studies for all major global river basins are required to verify the covariability between SAT and precipitation as well as streamflow.

[13] One of the greatest challenges presently facing the climate modeling community remains the prediction of the future state of the hydrologic cycle, including the distribution and amounts of continental precipitation [*IPCC*, 2001]. Most GCM simulations predict a concomitant increase in global precipitation as SATs continue to rise in the twenty-first century. This study suggests that future SAT and precipitation increases may well occur out-of-phase. Relatively warm years will generally be dry whereas relatively cool years will generally be wet over most of the global land surface. Confidence in predictions of the future hydrologic cycle will improve if GCM simulations can reproduce the observed twentieth century SAT and precipitation covariability.

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