

## Relationships between precipitation and surface temperature

Kevin E. Trenberth and Dennis J. Shea

National Center for Atmospheric Research, Boulder, Colorado, USA

Received 28 February 2005; revised 3 June 2005; accepted 8 June 2005; published 19 July 2005.

[1] The co-variability of monthly mean surface temperature and precipitation is determined globally for 1979–2002 from observationally-based analyses (ERA-40) for surface air temperature and the Global Precipitation Climatology Project (GPCP) version 2 for precipitation and compared with results from the NCAR Community Atmospheric Model version 3 (CAM3) and Community Climate System Model version 3 (CCSM3). Results are combined for the 5 months for northern winter (November to March) and summer (May to September). Over land, negative correlations dominate, as dry conditions favor more sunshine and less evaporative cooling, while wet summers are cool. At high latitudes in winter, positive correlations dominate as warm moist advection in extratropical cyclones favors precipitation and the water holding capacity of the atmosphere limits precipitation amounts in cold conditions. Where ocean conditions drive the atmosphere, higher surface air temperatures are associated with precipitation, as in El Niño, but some areas, such as the western Pacific in northern summer, feature negative correlations indicating that the atmosphere determines the surface temperatures. In the CAM driven with observed sea surface temperatures and the CCSM in fully coupled mode the latter mechanism is largely absent, and correlations are generally much stronger than observed, indicating more local control. Neither temperature nor precipitation records should be interpreted without considering the strong covariability that exists. **Citation:** Trenberth, K. E., and D. J. Shea (2005), Relationships between precipitation and surface temperature, *Geophys. Res. Lett.*, 32, L14703, doi:10.1029/2005GL022760.

### 1. Introduction

[2] There is considerable interest in variability and trends in surface temperatures and precipitation. Intuitively we expect that when it is raining in summer it is cooler, while heat waves often accompany droughts. In winter, the expression “it is too cold to snow” builds in the idea that the atmosphere cannot hold much moisture when it is very cold and, accordingly, the total precipitation amount, in terms of melted liquid water, is expected to be higher if temperatures are higher. The fact that warm advection typically also means moist advection in extratropical cyclones, fosters the idea that higher temperatures and precipitation may go hand-in-hand, although in more maritime environments, the passage of a cold front followed by showers evokes the combination of cold and wet. The heat budget is important for surface temperature change but depends a lot on the Bowen ratio of sensible to latent heat fluxes. If the ground is

wet, then more energy is likely to go into evaporation at the expense of sensible heating and there is a strong negative correlation between sensible and latent heat flux [e.g., *LeMone et al.*, 2003], so that moisture acts as an “air conditioner”. Moreover, if the ground is wet from precipitation then it is likely that associated clouds block out the sun, providing less energy in the first place, further reducing temperatures. Over the oceans, it is well understood in the tropics that higher sea surface temperatures (SSTs) are accompanied by increased convection, as in the El Niño phenomenon, for example. With all of these general ideas, it is surprising how little the covariability of temperature and precipitation has been examined.

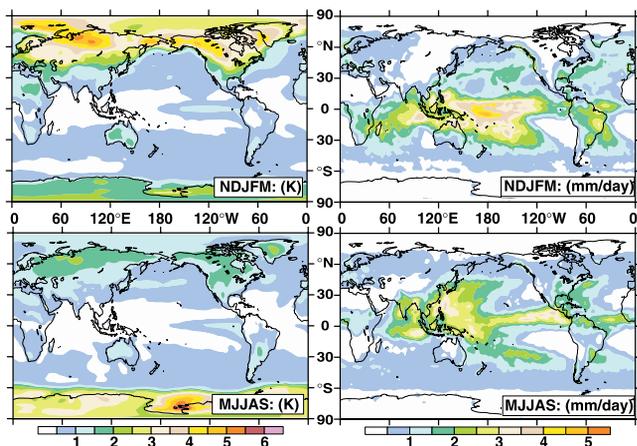
[3] Some early studies of temperature–precipitation relationships were summarized by *Madden and Williams* [1978] when they computed correlations between temperature and precipitation in the contiguous United States and Europe for 64 years from 1897 to 1960. They found that cold winters were mostly wet in the plains states, while in the eastern U.S. the relationship supported the warm–moist advection relationship in cyclonic storms. Cool summers were wet while drought went along with heat waves in both Europe and the U.S. *Madden and Williams* [1978] further noted the relationships were robust on different time scales from interannual to multi-decadal. The relationships for the U.S. stations were updated for 1905 to 1984 by *Zhao and Khalil* [1993] for each month of the year. They confirmed the strong negative correlations in summer, strongest in the central and southern Great Plains and the region of positive correlations south of the Great Lakes region.

[4] *Isaac and Stuart* [1992] computed temperature–precipitation relationships for Canadian stations using daily data. For the east and west coasts and northern Canada, more precipitation accompanies warm conditions in winter and cool conditions in summer, thereby reversing the correlation with seasons. For stations in and downwind of the Rockies, precipitation is preferred in colder conditions in all seasons.

[5] Here we explore the observed monthly mean relationships between temperatures and precipitation. We also examine the NCAR Community Atmospheric Model version 3 (CAM3) for simulations run with specified SSTs and NCAR Community Climate System Model version 3 (CCSM3) results to see how well the models match nature. We are interested in the extent to which regional increases in temperatures may have been moderated by increases in precipitation. We therefore analyze the total record of monthly anomalies, the detrended record, and the trends themselves, to separate out these aspects.

### 2. Data and Methods

[6] To obtain complete global coverage, we use the global surface analyzed air temperatures from the ERA-40



**Figure 1.** Standard deviations of anomalies for 1979–2002 for the months NDJFM (top) and MJJAS (bottom) of surface air temperature from ERA-40 in  $^{\circ}\text{C}$  (left) and GPCP precipitation in mm/day (right).

reanalyses, which have been extensively evaluated by *Simmons et al.* [2004]. In addition to very similar short-term variability when compared with station-based data, the ERA-40 trends were within 10% of station data after 1979 in the satellite era, and we use monthly anomalies for only that period. The ERA-40 temperature trends are, however, erroneous over Australia [*Simmons et al.*, 2004], where analyzed negative trends do not agree with observed positive trends, but this does not impact the anomalies much. For precipitation, we use version 2 of the Global Precipitation Climatology Project (GPCP) [*Adler et al.*, 2003], which is based on gauge data over land and satellite data over the oceans merged from several different sensors and algorithms. The large regional signals from monsoons and El Niño Southern Oscillation (ENSO) that emphasize large-scale shifts in precipitation are well captured in GPCP, although there is uncertainty about absolute values over the oceans [see also *Yin et al.*, 2004]. The anomalies appear more reliable and the biases do not affect our computations.

[7] We compute monthly anomalies on a  $2.5^{\circ}$  grid for 1979 to 2002 and, after testing for consistent relationships, we have combined the months from November, December, January, February and March (NDJFM) as northern cold season months, and May, June, July, August and September (MJJAS) as northern warm season months, so there are 24 years and a total of 120 values in each correlation computed. Values are almost identical for shorter DJF and JJA seasons. If values were independent, the 5% significance level would be 0.18, or 0.24 for the 1% significance level (2-tailed). Results are of interest even if not statistically significant.

[8] The data we use is independent of the *Madden and Williams* [1978] period entirely, and is also characterized by significant warming trends in many regions. Accordingly it is desirable to perform analyses not only with all data to establish the overall relationships, but also with detrended data to remove influence of the linear trend.

[9] Ensemble mean results from CAM3 [*Collins et al.*, 2005b] run at T42 resolution and forced by observationally-based SSTs and sea-ice concentrations for 1979 to 2000 are

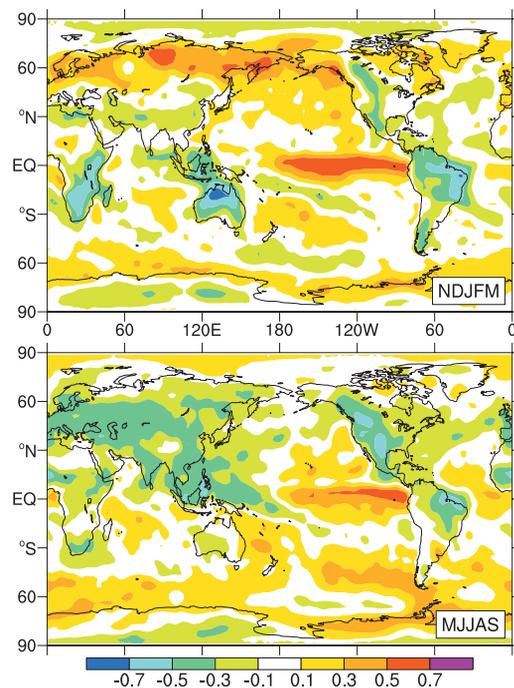
used for examining the temperature–precipitation correlations in the CAM, and a 24 year period is selected from a 1990 control climate at T42 atmospheric resolution and nominal  $1^{\circ}$  grid for ocean and sea ice from the CCSM3 [*Collins et al.*, 2005a] for similar analysis.

### 3. Results

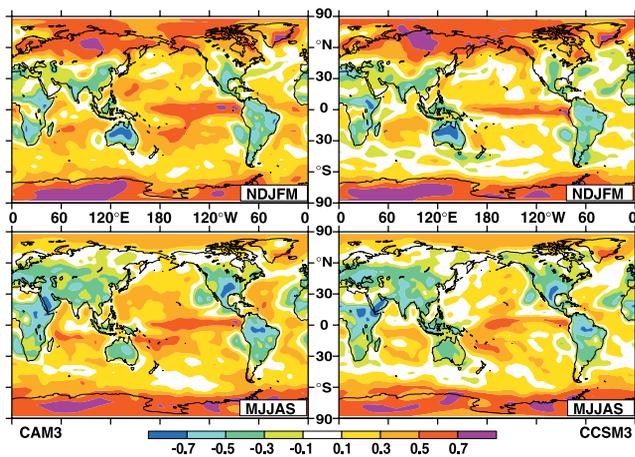
[10] A key ingredient in the correlations is the magnitude of the variability, as given by the standard deviations (Figure 1). In many respects these are reciprocals of each other, with variability high in the tropics for precipitation and low at high latitudes, while the reverse is true for temperature. Also precipitation means and variability are largest in summer over the oceans, while temperature variability is largest in winter over land. Part of this relates to the Clausius-Clapeyron relationship whereby the water holding capacity of the atmosphere increases about  $7\% \text{ K}^{-1}$  [*Trenberth et al.*, 2003]. Hence precipitation amount is inherently limited at higher latitudes by the cold, and over land by the limited water supply. However, another part relates to the air conditioning effects of moisture, discussed in the introduction.

[11] The maximum trends are only a fraction of the standard deviation for both fields. For instance over the 120 months, trends of 1 mm/day and  $\sim 0.25^{\circ}\text{C}$ , which correspond to standard deviations of 3 mm/day and  $0.5^{\circ}\text{C}$ , contribute to correlations by 0.014. As the detrended correlations differ by only such tiny amounts, we present only the full result.

[12] The correlation results (Figure 2) are strikingly large-scale and distinctive. Highest positive correlations in the tropical Pacific clearly relate to ENSO. Above normal SSTs



**Figure 2.** Correlation between observed monthly mean anomalies of surface air temperature and precipitation amount for groups of months of NDJFM and MJJAS for 1979–2002.



**Figure 3.** Correlation between CAM3 (left) and CCSM3 (right) model monthly mean anomalies of surface air temperature and precipitation amount for groups of months of NDJFM and MJJAS for 1979–2000 for CAM3 and a 24 year period for CCSM3.

are associated with increased convection and precipitation, and the relationship is driven by the SSTs forcing the atmosphere. Strong negative correlations occur over continental land in summer in both hemispheres, so that summers tend to be either hot and dry or cool and wet, but not some other combination. With the diminished role of large-scale dynamics in summer, reduced precipitation is reflected in less soil moisture and thus a higher Bowen ratio, whereby more heat raises temperatures as evaporation is reduced, as noted in the introduction. In winter over land, the relationship is reversed compared with summer at high latitudes, including evidently the Antarctic coast, although surface data are poor there. This reflects the increased moisture holding capacity of air with temperature and warm-moist advection process in extratropical storms [Isaac and Stuart, 1992]. The exception is the Rocky Mountains and the Mexican highlands, and an extensive band from northern Africa across southern Asia. In mountain areas upslope conditions are wet, cloudy and cool, while downslope conditions are more likely dry and mild, with possibly even Chinook-type foehn winds.

[13] A coherent region over oceans where the relationship is negative is the Pacific Warm Pool Indonesian maritime continent. This region is greatly influenced by ENSO, and so non-local effects may be a key factor. During El Niño, when SSTs warm in the central and eastern tropical Pacific, they frequently cool in the Warm Pool. At the same time, the skies clear with a decrease in precipitation, and strong solar radiation prevails in the tropical western Pacific and tropical Indian Ocean, so that surface temperatures warm over the next year [Trenberth *et al.*, 2002]. Rain cools the air through evaporation and is accompanied by cloud and less sunshine, and so cool and wet conditions go hand-in-hand, while dry conditions favor sunshine and warmth. In this regime the surface is more likely responding to the atmosphere, rather than the other way round.

[14] In the North Pacific the Aleutian Low is deeper during El Niño events, increasing surface fluxes of sensible and latent heat, and cooling part of the ocean, but warm

moist advection warms and increases precipitation in Alaska. The relationships in Figure 2 are consistent with those for the Pacific Decadal Oscillation [Deser *et al.*, 2004]. In winter over the North Atlantic, the North Atlantic Oscillation [Hurrell *et al.*, 2003] results in shifts in storm tracks, such that wetter conditions over Scandinavia and drier conditions over the Mediterranean and Northern Africa accompany generally warmer conditions north of 40°N, consistent with positive correlations in northern regions, while the negative correlations across southern Europe and Asia correspond to the more general summer relationship over land. Correlations are also negative, although weak, over parts of the Atlantic.

[15] The corresponding results from CAM3 and CCSM3 (Figure 3) have strong similarities to each other and also some similarities to observations, but also distinctive differences. The values are generally much higher in magnitude, especially on the positive side. Indeed the most outstanding feature of the CAM3 model results is the widespread positive correlation over the oceans, suggesting that the SST anomalies directly influence local precipitation much more than in nature. Values are only slightly reduced in CCSM3 where the SSTs can respond to the atmosphere. Over land in winter, the correlations are negative and also stronger than observed, except for the high latitudes polewards of 40° in winter, where positive correlations are evident, as observed, reflecting the effect of cold on the water-holding capacity of the atmosphere. The stratus decks in the Pacific off the coast of California (MJJAS) and South America (both seasons) exhibit negative correlations in the models much stronger than observed, indicating that cold surface conditions produce stratocumulus and precipitation, while warm SSTs are accompanied by drier air, whereas observations during El Niño-induced higher SSTs, show that the stratocumulus is likely to burn off but convective rains occur.

#### 4. Discussion and Conclusions

[16] The relationships established for the monthly means are robust during the seasons and should apply on multiple time scales, including trends [Madden and Williams, 1978]. Hence the actual observed trends are likely to have been influenced by trends in the other variable. Precipitation trends are small or mixed in many areas [e.g., Adler *et al.*, 2003] although negative trends over western parts of the U.S. are present during this period in association with the drought that began about 1999. Over the 20th Century, however, precipitation trends are more generally positive over the U.S. [Groisman *et al.*, 2004] and at higher latitudes in other areas [Groisman *et al.*, 2005], which is presumed to be associated with warming and associated increased moisture observed in the atmosphere [Trenberth *et al.*, 2005]. The relationships outlined here support this interpretation. Nicholls *et al.* [2004] find a strong negative correlation between annual rainfall and maximum temperature of  $-0.71$  for New South Wales in Australia 1910–2002 and show how changes in rainfall have similarly influenced temperatures.

[17] The trends in some areas of the ERA-40 surface temperatures are not reliable (notably Australia), but observed trends (not shown) in surface temperatures over land

for 1979–2001 are up nearly everywhere that reliable data exist [Simmons *et al.*, 2004]. The general warming may nevertheless be moderated by increased precipitation and associated increased surface wetness in some regions. It suggests that overall warming in the U.S. has likely been diminished owing to the increase in precipitation up till the 1980s [Dai *et al.*, 1999, 2004] and cloud [Liepert, 2002], with more energy going into evaporation [Milly and Dunne, 2001; Walter *et al.*, 2004] rather than sensible heating. The same may also be true elsewhere [Golubev *et al.*, 2001; Nicholls *et al.*, 2004]. Dai *et al.* [2004] find that drought has increased globally in association with increased potential evapotranspiration arising from higher temperatures. Accordingly, the covariability revealed by this study strongly suggests that the relationships and physics should be taken into account in interpreting climate anomalies.

[18] The results are consistent with the independent earlier results of Madden and Williams [1978], except that the positive correlations over the eastern U.S. in winter are not as strong. The relationships in the CAM3 driven with observed SSTs are too strong in general, and mainly positive correlations occur between SST and surface temperature over the oceans. This is partly caused by the way the model is driven, as the direction of the surface heat fluxes reverses in mid-latitudes in coupled model runs [Saravanan, 1998], but CCSM3 results are only slightly more realistic over the oceans. Hence the model results suggest stronger local relationships than in nature.

[19] **Acknowledgments.** This research is partially sponsored by the NOAA CLIVAR and CCDD programs under grants NA17GP1376 and NA04OAR4310073. NCAR is sponsored by the National Science Foundation.

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D. J. Shea and K. E. Trenberth, National Center for Atmospheric Research, P.O. Box 3000, Boulder, CO 80307, USA. (trenbert@ucar.edu)