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Changes in Annual Land-Surface Precipitation Over the Twentieth and Early Twenty-First Century

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Time trends in annual land-surface precipitation during the twentieth and early twenty-first centuries and their spatial patterns are estimated from gridded (at a 0.5° × 0.5° spatial resolution) rain-gauge-based precipitation data sets available from the Climatic Research Unit (CRU), the Global Precipitation Climatology Centre (GPCC), and at the University of Delaware (UDel). Our analyses of these precipitation data sets make use of spatially weighted (geographic) percentiles as well as of join-point and simple linear regression. A consistent increase in annual land-surface-average precipitation (of approximately 0.2 and 0.5 mm/year) occurred during the first half of the twentieth century. This increase was followed by nearly a half-century (approximately forty-four years, from 1949 through 1993) of decreases in annual land-surface-average precipitation (on the order of 0.3 to 0.6 mm/year). Trends, once again, reversed themselves in the early 1990s and increased (at rates of approximately 0.75 to 2.1 mm/year) over the decade from 1992 through 2002. Maps of precipitation change during these alternating periods of increasing and decreasing precipitation show considerable spatial variability. Key Words: climate change, precipitation, rain gauge data.

Las tendencias temporales en precipitación anual sobre el terreno durante el siglo XX y comienzos del XI y sus patrones espaciales están calculados a partir de conjuntos de datos de precipitación basados en registros pluviométricos distribuidos en cuadrícula (a 0.5° x 0.5° de resolución espacial), disponibles en la Unidad de Investigación Climática (CRU, sigla en inglés), el Centro de Climatología para la Precipitación Global (GPCC) y la Universidad de Delaware (UDel). Nuestros análisis de estos conjuntos de datos de precipitación utilizan percentiles espacialmente ponderados (geográficos), lo mismo que regresiones join-point y lineal simple. Se presentó un consistente incremento de la precipitación promedio anual sobre el terreno (de aproximadamente 0.2 y 0.5 mm/año) durante la primera mitad del siglo XX. A tal incremento siguió un período de cerca de medio siglo (aproximadamente cuarenta y cuatro años, de 1949 a 1993) de disminución de la precipitación promedio anual sobre el terreno (del orden de 0.3 a 0.6 mm/año). Nuevamente las tendencias se reversaron a sí mismas a principios de los 1990 y se incrementaron (a tasas de aproximadamente 0.75 a 2.1 mm/año) en la década que se extendió de 1992 a 2002. Los mapas del cambio de la precipitación durante estos períodos alternantes de incremento y disminución de la precipitación muestran considerable variabilidad espacial. Palabras clave: cambio climático, precipitación, datos pluviométricos.

A better understanding of the spatial and temporal variability of land-surface precipitation is indispensable for advancing climate change research, as well as for assessing the potential impacts of climate change on water resources. In addition to climate-model estimates of precipitation, measurement-based fields of precipitation and precipitation change are critical for evaluating the vicissitudes of Earth’s climate. Our current measurement-based knowledge of land-surface precipitation variability and change over the last 100-plus years, however, is uncertain, as is evident in the differences between available gridded land-surface precipitation data sets. The Intergovernmental Panel on Climate Change (IPCC 2007), for example, reports substantial discrepancies among trend estimates derived from different data sets. According to the IPCC (2007) report, trends vary by regions and over time, although land-surface
precipitation has generally increased north of 30°N over the past century and decreased over much of the tropics since the 1970s. Our purpose within this article is to explore, describe, and compare the patterns and historical trends in land-surface precipitation using three available high-resolution rain-gauge-based precipitation data sets.

Available Land-Surface Precipitation Data Sets

Estimated land-surface precipitation fields have tended to be of relatively coarse spatial resolution (≥ 2.5°), although efforts to develop higher resolution spatial and temporal (e.g., monthly or daily) data sets are increasing. Our analyses of the patterns and trends in annual land-surface precipitation make use of three recently available higher resolution land-surface precipitation data sets. Each of these data sets is derived primarily from in situ (rain-gauge) observations, has a monthly time step, and is gridded at (spatially interpolated to) a relatively high (0.5°) spatial resolution. The data sets are the Climatic Research Unit (CRU) archive (Mitchell and Jones 2005), the Global Precipitation Climatology Centre (GPCC) archive (Rudolf and Schneider 2005), and the recent University of Delaware (UDel) data set (Matsuura and Willmott 2009). Many of the same observational (rain-gauge) records inform all three of these data sets; however, each data set is not based on exactly the same set of rain-gauge records. It also should be noted that the CRU and GPCC archives do not contain estimates of precipitation over Antarctica; in turn, Antarctica is not included in our analyses of “land-surface” precipitation.

Each of the three precipitation data sets is based on a different method of spatial interpolation from the rain-gauge station locations to the nodes of the 0.5° grid. The CRU database is based on an angular-distance weighted (ADW) interpolation method (which bears conceptual similarity to the Shepard 1968 and Willmott, Rowe, and Philpot 1985 approaches). For each grid-node estimate, the ADW method weights each of the eight rain-gauge station precipitation observations that are nearest to the grid node by taking into account the distance from the grid node (using a correlation-decay distance [CDD]) and the directional (angular) isolation of each station. Interpolated fields are forced to a climatological mean value at grid points where there is no station within the CDD (New, Hulme, and Jones 2000; Mitchell and Jones 2005). As a consequence of this, estimated time series over some areas can be invariant for a number of years.

The GPCC data set (Rudolf and Schneider 2005) was spatially interpolated with the “SPHEREMAP” interpolation tool, which was developed at the University of Delaware. It is a spherical adaptation of Shepard’s (1968) empirical weighting scheme, which takes into account the spherical distances from the nearby rain-gauge locations to the grid node (for a limited number of the nearest stations), the directional distribution of nearby rain gauges relative to the grid node (to avoid overweighting of clusters of stations), and spatial gradients within the rain-gauge data field (Willmott, Rowe, and Philpot 1985).

The UDel data set also is based on the Willmott, Rowe, and Philpot (1985) traditional-interpolation procedure as well as on Climatologically Aided Interpolation (CAI; Willmott and Robeson 1995; Matsuura and Willmott 2009), which employs a spatially high-resolution climatology to obtain a monthly precipitation difference at each station. These station differences then are interpolated to obtain a gridded field using a version of Shepard’s algorithm (Willmott, Rowe, and Philpot 1985); finally, each gridded monthly difference field is added back onto the corresponding monthly climatology field to obtain monthly land-surface precipitation (Matsuura and Willmott 2009). These gridded monthly values then were integrated over the year to obtain an annual average for each year of interest.

The gridded monthly precipitation values contained within the three data sets analyzed here are not adjusted up for possible rain-gauge undercatch (Legates and Willmott 1990); therefore, our (and most other) estimates of annual precipitation are likely to be a little lower than actual precipitation. It is important to note, however, that this should have little or no effect on our estimates of time trends, as long as there was no meaningful time trend in rain-gauge undercatch.

Geographic Analyses of Annual Land-Surface Precipitation

Land-surface precipitation change since the beginning of the twentieth century is evaluated using spatially weighted (geographic) percentiles (Willmott, Robeson, and Matsuura 2007) and simple linear and join-point regression (Rawlins et al. 2006)—the latter is a type of change-point regression (Draper and Smith 1998)—of annual land-surface-average precipitation. An overall assessment of the longer term trends and
variability apparent within the entire 100-plus years of record—contained in the CRU, GPCC, and UDel data sets—is made first. More detailed analyses of each of three major subperiods follow. The subperiods are the first half of the twentieth century (1902–1949 herein, for reasons explained later), 1950 through 1993, and 1993 through 2002. The year 1993 is a join-point estimate of the boundary between a long period of drying and more recent increases in land-surface precipitation (discussed later). Maps of change rates for each subperiod are presented and evaluated.

Because annual land-surface precipitation is intrinsically a geographic or spatial variable, we take explicit account of the sizes (areas) of the grid cells when performing our spatial analyses (Willmott, Robeson, and Matsuura 2007). As a consequence, each of our spatial percentiles has a fundamentally geographic interpretation. Our 75th spatial percentile, for instance, bounds that 25 percent of the land surface that contains annual precipitation values that are greater than the value of the 75th spatial percentile. Our join-point regression of land-surface-average precipitation is used to identify those year(s) when major precipitation change occurred; that is, since the beginning of the second half of the twentieth century. Join-point regression finds one or more “optimal” join-points in a time series by minimizing the sum-of-squared residuals of all possible join-point regressions. It helped us locate a

Figure 1. Time series (1901–2008) of annual land-surface precipitation (mm) estimated from the Climatic Research Unit (CRU), Global Precipitation Climatology Centre (GPCC), and University of Delaware (UDel) data sets. Annual spatial means as well as the 5th, 25th, 75th, and 95th spatial percentiles are plotted for each of the three data sets. Open triangles are used to represent CRU data, open squares indicate values derived from GPCC data, and blackened circles show estimates made from the UDel data set. There are five clusters of three curves each. The top set of three curves contains the estimates of the 95th spatial percentile of annual precipitation, the next set (moving down the graph) represents the 75th spatial percentiles, then comes the spatial means, then the 25th spatial percentiles, and the last (bottom) set indicates the 5th spatial percentiles.
and among the three traces, tends to increase after the 1970s. This appears to arise from increasing variability in the maxima, as suggested in the traces of the 95th spatial percentile.

There are several reasons why the UDel annual average precipitation measures fall increasingly below the comparable CRU and GPCC measures, as the present is approached (Figure 1). The UDel data set contains records from the Global Surface Summary of the Day (GSOD) archive, which improves the station-network coverage of the land surface, especially during the recent past and over the more harsh (drier and rugged regions) of the land surface. It follows that improved representation of drier regions would lessen (relatively speaking) the UDel estimates of land-surface-average precipitation. It also is true, however, that the GSOD archive contains a variety of unrealistic extreme values, including unbelievably long strings of zeros and a limited number of unusually high values. Although Matsuura and Willmott (2009) attempted to filter out only the truly unrealistic daily and monthly precipitation values from the GSOD station records, any erroneous zero value that was missed or an incorrectly removed maximum would tend to produce an underestimate.

**Land-Surface Precipitation over the First Half of the Twentieth Century**

It is clear that there was a general increase in land-surface-average precipitation during the first half of the twentieth century (1902–1949; Figure 2). Ignoring the estimated precipitation values for the year 1901, owing to probable station-network biases (Willmott, Robeson, and Feddema 1994), all three traces indicate an increase in the spatial mean, at estimated rates of between 0.2 and 0.5 mm/year. The spatial distribution of change over this period, however, is quite variable (Figure 3). Although there are many areas over which relatively small decreases in annual precipitation can be seen (e.g., over large areas of North America, North Africa, and Australia), these are outweighed by increases elsewhere. Large increases are evident over portions of the Amazon basin (especially within the GPCC and UDel fields), over the Maritime Continent (especially within the CRU and GPCC data sets), and, to a lesser extent, over northern India (within all three data sets). Spatially extensive but relatively small increases also appear over

![Figure 2](image-url)
Figure 3. Spatial distribution of time trends (mm/year) in annual land-surface precipitation (1902–1949) apparent within the Climatic Research Unit (CRU), Global Precipitation Climatology Centre (GPCC), and University of Delaware (UDel) data sets.
much of the Arctic land surface and subtropical Africa. Annual land-surface-average precipitation during the first half of the twentieth century and into the 1950s was relatively stable (exhibiting limited variability) but increasing consistently.

Land-Surface Precipitation Since the Middle of the Twentieth Century

Graphs of the spatial means of annual land-surface precipitation from 1949 forward (especially in Figure 4)
Figure 5. Spatial distribution of time trends (mm/year) in annual land-surface precipitation (1950–1993) apparent within the Climatic Research Unit (CRU), Global Precipitation Climatology Centre (GPCC), and University of Delaware (UDel) data sets.
Figure 6. Spatial distribution of time trends (mm/year) in annual land-surface precipitation (1993–2002) apparent within the Climatic Research Unit (CRU), Global Precipitation Climatology Centre (GPCC), and University of Delaware (UDel) data sets.
indicate a dramatic decrease in land-surface precipitation as well as gradually increasing divergence among the three data sets. It is not entirely clear when the drying began but, on inspection (Figure 4), probably during the mid- to late 1950s. It is less clear exactly when it ended; therefore, we use join-point regression to help us make a determination. A single-point, join-point linear regression was fit to each of the three traces of the annual land-surface means over the period from 1949 through 2002 (Figure 4), and each suggests that the decrease ended during the early 1990s, most likely in 1993. Our regressions were applied only through 2002 because that is the last year for which CRU data were available. For comparison purposes, we also estimate and plot (Figure 4) a simple linear regression over the entire period from 1949 through 2002. It describes a general drying over the entire fifty-three-year period.

The reduction in land-surface-average precipitation from 1949 through 1993 was substantial, on the order of 0.3 to 0.6 mm/year or about 14 to 26 mm over the entire forty-four-year period. The steepest decline was estimated from the UDel data (Figure 4). To assess the spatial distribution of this land-surface drying, we estimate the linear time trend over the period from 1950 through 1993 at each land-surface grid node, and we map the rates of change (mm/year) obtained from each of the three data sets (Figure 5). Drying dominates Africa, especially over sub-Saharan Africa, as well as over the Maritime Continent, Southeast Asia, and the northwest Amazon basin. The strongest drying over sub-Saharan Africa and the northwest Amazon basin is estimated from the CRU data set. Areas wherein slight increases appear include North America, southeastern South America, western Australia, eastern Europe, and central Asia, although the signal over eastern Europe and central Asia is weaker within the UDel data set.

Reasons for the persistent, forty-four-year drying that occurred over extensive reaches of Earth’s land surface, and especially over the lower latitudes, are not completely understood, but several contributing factors have been identified for the years after 1949 (e.g., see Marengo 2004; Hoerling et al. 2006). Marengo (2004), for example, associated circulation features typical of strong El Niño years with drier conditions over the northern Amazon basin region, while Aldrian and Djamil (2008) attributed decreases in precipitation over parts of the Maritime Continent (during the period from 1955–2005) to a waning of monsoonal dominance. Droughts also tend to develop over the Maritime Continent during strong El Niño years. The drying over much of Africa has been tied to relatively warm sea-surface temperatures atop the tropical oceans, including the Indian Ocean (Hoerling et al. 2006). Our sense is that these and perhaps other factors, such as deforestation—especially within the Amazon region—and global dimming, contributed to the drying.

Land-surface-average precipitation trends then reversed themselves, ostensibly beginning in 1993, and marked increases ensued over the decade from 1992 through 2002. Our second set of join-point regression lines (fit to the 1993–2002 land-surface-average precipitation values but constrained by the 1993 join point) suggest increases that are even more dramatic than the forty-four years of drying that occurred previously (Figure 4). These increases are on the order of 0.75 to 2.1 mm/year but, of course, the reduced length of record (ten years) and nontrivial year-to-year variability argue for cautious interpretation of these increases.

Once again, to assess the spatial distribution of these increases in yearly average precipitation, we estimate the linear time trend over the period from 1993 through 2002 at each land-surface grid node, and we map the rates of change (mm/year; Figure 6). All three data sets show significant drying over much of North America and south Asia as well as over much of North Africa and parts of South America. In contrast, substantial increases in annual average precipitation can be seen over parts of South America (especially over southern South America), southern Africa, northern Australia, the Maritime Continent, and parts of Southeast Asia. Regional dissimilarities in these recent trends emerge from the three data sets (compare the three geographies of trend estimates for South America, for example) and they underscore the need for more research into the finer scale nature of land-surface precipitation variability and change. Nonetheless, judging from the most recent values of estimated land-surface-average precipitation (2003–2008) obtained from the GPCC and UDel data (Figures 1 and 4), it seems likely that land-surface-average precipitation has continued to increase.

**Summary and Conclusions**

Our assessment of the changing patterns and trends in annual land-surface precipitation is based on three recently available monthly land-surface precipitation (rain-gauge-based) data sets. The data sets were assembled at the CRU, the GPCC, and UDel. Each of these data sets was gridded at (spatially interpolated to) a $0.5° \times 0.5°$ spatial resolution and we temporally...
integrated the monthly grid-node values to obtain the annual grid-node totals.

Our analyses of land-surface precipitation change made use of spatially weighted (geographic) percentiles, simple linear regression, and join-point regression. All of the precipitation data suggest that long-term average land-surface precipitation (rain-gauge-caught) is about 716 mm/year. There appears to have been a modest but consistent increase in land-surface-average precipitation (between 0.2 and 0.5 mm/year, approximately) during the first half of the twentieth century. This was followed by nontrivial reductions in annual land-surface-average precipitation (on the order of 0.3 to 0.6 mm/year), which were estimated over the period from 1949 through 1993. Trends in land-surface-average precipitation then reversed themselves again in the early 1990s and increased (at rates of approximately 0.75 to 2.1 mm/year) over the decade from 1992 through 2002. Recent data also suggest that land-surface-average precipitation has continued to increase until the present day.

The spatial distribution of the time trends in precipitation during these alternating periods of increasing and decreasing precipitation was explored with maps of the estimated trends, which showed considerable spatial variability. Over the ten years from 1992 through 2002, for instance, there was marked drying over much of North America and south Asia as well as over much of North Africa and parts of South America; at the same time, sizable increases in annual average precipitation occurred over parts of South America, southern Africa, northern Australia, the Maritime Continent, and Southeast Asia. A number of regional differences in trends estimated from the three data sets were apparent as well, especially in recent years.

Our findings argue for additional research into assessing the regional differences among the three sets of estimated trends that emerged from the three data sets; that is, into the finer scale spatial variability of land-surface precipitation. There also is a need to resolve the intra-annual variability of precipitation change. Our hope is that in situ–based precipitation fields, such as these, also will be used to evaluate and improve climate-model estimates of precipitation.

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References


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