An Evaluation of the Apparent Interdecadal Shift in the Tropical Divergent Circulation in the NCEP–NCAR Reanalysis

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ABSTRACT

Recent decadal regime shifts in the large-scale circulation of the tropical atmosphere are examined using analyses and independent observations of the circulation and precipitation. Comparisons between reanalysis products and independent observations suggest that the shifts that are apparent and significant in the reanalysis products may be artifacts of changes in the observing system and/or the data assimilation procedures.

1. Introduction

The National Centers for Environmental Prediction (NCEP) and the National Center for Atmospheric Research (NCAR) produced a 50-yr analysis of the global atmospheric circulation (Kalnay et al. 1996) whose length makes it an attractive database for discovering and quantifying decadal time scale climate variations. Numerous studies have made use of reanalysis products to evaluate many aspects of atmospheric variability, including several recent contributions examining the secular variations and decadal regime shifts in the atmosphere.

The object of reanalysis is to optimally combine atmospheric observations with an atmospheric general circulation model (AGCM) to produce the best estimate of the global atmospheric state (Bengtsson and Shukla 1988). By using an AGCM as the source of the background state in the data assimilation, it is possible to infer many atmospheric parameters in addition to those that were observed. For example, the divergent and rotational components of the wind may be separately analyzed, and AGCM model diagnostic quantities such as precipitation and evaporation may be calculated. In this paper, atmospheric parameters that are observed and directly assimilated will be referred to as ''reanalysis fields'' and quantities that are strictly AGCM outputs will be referred to as ''reanalysis products.''

Several studies have questioned the reliability of reanalysis fields and reanalysis products. For example, Trenberth and Guillemot (1998) performed a comprehensive evaluation of the humidity and water cycle inferred from reanalysis. In their case, they examined both reanalysis fields (specific humidity and moisture transport) and reanalysis products (precipitation and divergence), and they found that there are substantial problems with reanalysis quantities of both types, stemming from the fact that moisture is not conserved in the data assimilation process. Newman et al. (2000) compared the reanalysis product of precipitation from NCEP–NCAR, European Centre for Medium-Range Weather Forecasts (Gibson et al. 1997), and the National Aeronautics and Space Administration (NASA; Schubert et al. 1997) in the region of the western tropical Pacific, and they found serious discrepancies in the spatial structure of the time mean. They pointed out that the heating discrepancies represented by the precipitation differences lead to large differences in the divergent circulation in the Tropics, even though the rotational circulation is fairly well represented. Trenberth et al. (2001) and Trenberth and Stepaniak (2002) also evaluated aspects of reanalysis fields and products associated with the tropical circulation and the stratospheric analysis, respectively. In both cases, it was found that there are difficulties in properly assimilating satellite data and there is significant sensitivity to the choice of vertical coordinate in the AGCM used to produce the background state for data assimilation, particularly in the representation of basic atmospheric dynamics in the highest levels of the model.

Krishna Kumar et al. (1999), in attempting to explain the recent reduction in the correlation between Indian monsoon rainfall and indicators of El Niño–Southern Oscillation (ENSO), noted that the divergent tropical circulation deduced from the NCEP–NCAR reanalysis product of velocity potential was significantly different during El Niño (warm sea surface temperature) events in the 1958–80 and 1981–97 periods. They inferred that

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this change was due to a southeastward shift in the center of anomalous ascent and subsidence, because such a change would be associated with a shift in the zonal overturning circulation in the Tropics, known as the Walker circulation, which is associated with the Indian monsoon (e.g., Webster et al. 1998; Klein et al. 1999).

Chen et al. (2001) noted a secular upward trend in the rainfall in the Amazon basin of South America, based on data from several stations in that region. They pointed out that this is opposite to the trend that would be expected from ongoing deforestation in the Amazon region that would tend to reduce the efficiency of moisture recycling and therefore the rainfall. They noted that the trend in the divergent circulation, inferred from the NCEP–NCAR reanalysis, would support an increase in the precipitation in that region. The trend in velocity potential over South America was also noted by Krishna Kumar et al. (1999). Chen et al. (2001) went on to speculate that the trend in the velocity potential could be associated with regional and global changes in sea surface temperature (SST) that have been observed, and they offered a heuristic argument for how that might have taken place.

Can the secular changes in the reanalysis product of velocity potential, used by Krishna Kumar et al. (1999) and Chen et al. (2001) to explain interdecadal variations in large-scale tropical phenomena, be corroborated with independent data that extend over a similar length of time? In this paper, the velocity potential variation over the last 50 yr, as represented in reanalysis products, is examined, and the reanalysis precipitation product, which may be viewed as a proxy for the heating field that drives the divergent circulation in the Tropics, is compared with independent estimates of the decadal variations of tropical precipitation derived from observations and from climate model integrations. The following section describes the data sources and data analyses that were undertaken, and section 3 provides the results of a comparison between reanalysis and various independent observational datasets. Section 4 describes the results of the comparison between the reanalysis and several atmospheric model integrations. Some concluding remarks are given in section 5.

2. Data sources and analysis

Two principal types of data were used for this study. First, objective analyses and assimilations of large sets of observations were used. These analyses include the monthly mean atmospheric quantities from the NCEP–NCAR reanalysis (Kalnay et al. 1996) as well as monthly mean objective analyses of global precipitation including the Climate Prediction Center Merged Analysis of Precipitation (CMAP; Xie and Arkin 1997) and the Climate Research Unit (CRU) of the University of East Anglia analysis of monthly mean precipitation (Hulme 1994); objective analyses of regional precipitation, including Willmott's analysis for South America (C. Willmott 2001, personal communication; analysis method of Willmott and Robeson 1995); and station observations of river discharge (Vörösmarty et al. 1996a,b, 1998).

Second, the output of atmospheric general circulation models that have been used to estimate the variability of the global atmospheric circulation and precipitation in so-called climate-of-the-twentieth-century (C20C) integrations was used. In the C20C methodology, the lower boundary conditions are specified from several decades of monthly mean global analyses of observed SST and sea ice, and the models are integrated from an initial atmospheric state over the period of the observed boundary conditions (Folland and Kinter 2002). Each AGCM is integrated several times with different initial conditions to estimate the internal variability of the atmosphere. The C20C methodology is similar to that used for the Atmospheric Model Intercomparison Project (AMIP; Gates 1992).

The C20C data that have been analyzed were produced using three different AGCMs: the Center for Ocean–Land–Atmosphere Studies (COLA) AGCM, version 2.2, at T63 horizontal resolution with 18 vertical levels (Schneider 2002); the Max Planck Institute for Meteorology AGCM version ECHAM3 at T42 resolution with 18 vertical levels (Bengtsson et al. 1996); and the NASA Seasonal-to-Interannual Prediction Project (NSIPP) AGCM at $2° \times 2.5°$ horizontal resolution with 18 vertical levels (Takacs and Suarez 1996). In each case, an ensemble average of 9–10 model integrations was evaluated over 50 yr of monthly mean model output data.

For all the datasets examined, monthly mean data were used to compute a mean annual cycle and interannual variance of monthly means. The entire period for which data are available in each dataset were used to compute the mean and variance, except as noted below. In some cases, the seasonal mean for June–July–August (JJA) was computed, and in some cases all months were included in the analysis. Area average quantities were computed with appropriate area weights.

3. Results of comparison with independent observations

The inverse relationship between interannual variations of the Indian monsoon and ENSO has been known for nearly a century (Walker 1923, 1924). The relationship has a strong linkage to the annual cycle, primarily because the Indian monsoon is a boreal summer phenomenon while the peak ENSO amplitude is observed in boreal winter (Rasmusson and Carpenter 1983). There is also a strong decadal waxing and waning of the ENSO–monsoon relationship (e.g., Krishnamurthy and Goswami 2000). At times, the relationship has been sufficiently strong to be used as a basis for predicting the Indian monsoon (e.g., Shukla and Paolino 1983).

Over the last 20 yr, the magnitude of the negative correlation between Indian monsoon rainfall and eastern tropical Pacific SST has dropped from a value of about 0.8 to a value of about 0.2 (e.g., Kinter et al. 2002).

Krishna Kumar et al. (1999) proposed an explanation for this reduction, suggesting that the interdecadal shift toward the southeast of the Walker circulation centers of seasonal anomalous ascending and descending motion over the tropical Indian and Pacific sectors (as well as over South America), associated with the seasonal anomalous upper-tropospheric divergent and convergent flows, respectively, had altered the connection between the Indian monsoon and ENSO. To substantiate this explanation, they showed that the NCEP–NCAR reanalysis product of velocity potential at 200 hPa has centers of positive and negative anomalies in composites of El Niño events that have indeed shifted to the southeast.

The calculation of Krishna Kumar et al. (1999) was repeated, and their result was reproduced. Since the decade of the 1970s is a climatic transition period in the Tropics (Kinter et al. 2002), attention was restricted to the 21 yr preceding (1950–70) and the 21 yr following (1980–2000) that decade for our analysis. It was found that the southeastward shift noted by Krishna Kumar et al. (1999) in composites of El Niño events is not strictly associated with El Niño, but it is a ubiquitous feature of the NCEP–NCAR reanalysis product. Figure 1a shows the difference in 200-hPa velocity potential for the JJA-mean composite of El Niño events in the 1980–2000 period minus the 1950–70 period. In this case, the period 1950–2000 was used to construct a climatological mean from which the anomalies were computed that are included in the composites. Figure 1b shows the difference computed for all JJA seasons in the two periods. It is apparent from Figs. 1a and 1b that the same southeastward shift of the centers of upper-level divergence and convergence over the Indo-Pacific sector of the Tropics is found whether or not the data are composited for El Niño events. A separate calculation for a non-ENSO composite was found to be qualitatively similar to the ENSO and all-years composites (not shown). The magnitude of the mean shift is about double that of the shift in the El Niño composites, indicating that the mean shift dominates the change in the interannual variability.

The interdecadal change in the NCEP–NCAR reanalysis product is not restricted to 200 hPa, but can be seen throughout the troposphere. Figure 2 shows the 21-yr means of the vertical component of velocity in pressure coordinates near the equator for JJA seasons in the early period (1950–70; Fig. 2, top) and the recent period (1980–2000; Fig. 2, bottom). The main differences in the two periods are: 1) the center of upward motion in the upper troposphere at about 100°E is considerably stronger in the recent period than in the early period; 2) the center of upward motion near the date line is considerably weaker in the recent period than in the early period; and 3) the center of descending motion overlying ascending motion at about 55°W in the early period changes sign to become a center of upward motion throughout the troposphere in the recent period.

The dominant balance that determines large-scale motions in the Tropics is between heating and the product of the vertical component of velocity and the static stability. In the time mean, the vertical component of velocity and the associated horizontal convergence and divergence are completely determined by the distribution of heating due to condensational heating and radiative cooling. Annamalai et al. (1999) found that the divergent circulation in reanalyses is strongly influenced by the model heating, especially in the upper-tropospheric wind, in data-sparse regions such as are common in the Tropics. Thus it is reasonable to consider the reanalysis product of precipitation, which is representative of the vertically integrated heating in the Tropics, as a driver of the vertical motion and horizontally divergent wind fields, and to compare that quantity with independent estimates of tropical precipitation on seasonal time scales (Newman et al. 2000). Estimates such as the CMAP, CRU, and Willmott analyses are independent of the NCEP–NCAR reanalysis since no precipitation observations were assimilated in the latter. Furthermore, while the JJA season is of particular importance for such phenomena as the Indian monsoon, it is not unique with respect to the relationship among tropical precipitation, total heating, and the divergent circulation in the Tropics. For this reason, the remainder of this paper considers the behavior of these quantities for all months of the year.

The 21-yr means of precipitation were computed from the NCEP–NCAR reanalysis product for the two periods of 1950–70 and 1980–2000 (all months), and it was found that the two periods were considerably different (Fig. 3a). Three regions of large differences were found in the vicinity of Indonesia, the north-central tropical Pacific at about 160°W, and over the Amazon basin of South America. The time series of area averages for these three regions are shown in Figs. 3b, 3c, and 3d, respectively. The region near Indonesia has substantial interdecadal fluctuations with three periods (1950–54, 1955–83, and 1984–2000) having distinct means and interannual variability. The central tropical Pacific region undergoes a marked transition from a higher to lower precipitation rate in about 1973–74. The Amazon basin region undergoes a similar sharp transition of the opposite sign at about the same time. The decrease in precipitation in the central Pacific and the increase in precipitation over the Amazon basin are consistent with the interdecadal changes in the upper-tropospheric divergent circulation represented in the reanalysis products (Fig. 1b). The same qualitative behavior is found in the JJA season alone (not shown).

The analysis of Hulme (1994) includes the period of the reanalysis, so the interdecadal variations in the two datasets can be compared. Figure 4 shows the same interdecadal difference map and time series of area av-

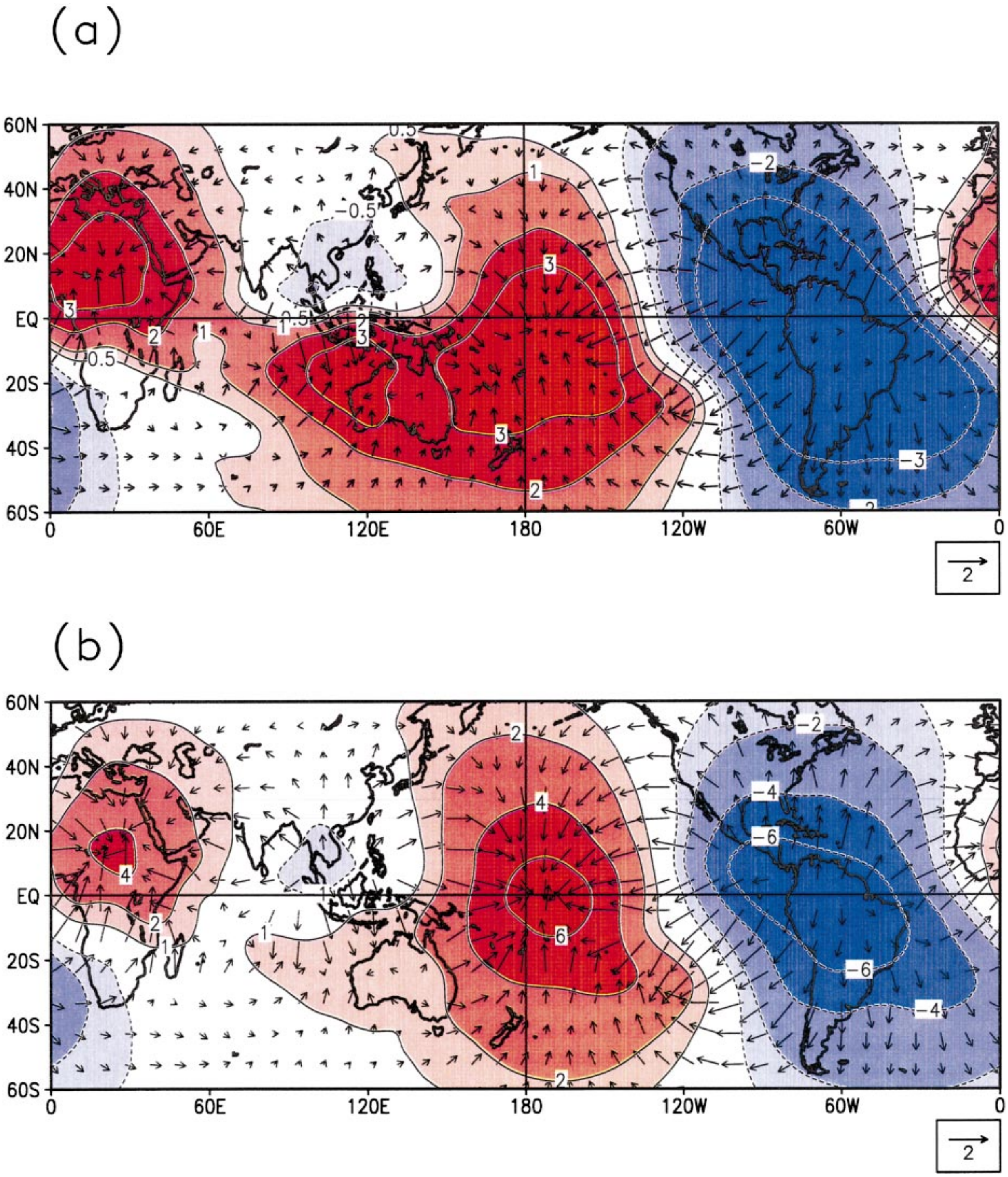

FIG. 1. (a) Difference of 21-yr-mean seasonal means of NCEP–NCAR reanalysis 200-hPa velocity potential for the JJA mean composite of El Niño events in the 1980–2000 period (1982, 1986, 1991, 1994, 1997) minus the 1950–70 period (1951, 1957, 1963, 1965, 1968, 1969). The vectors show the difference of the composite divergent wind. The scale for the vectors in m s^{-1} is shown at lower right. (b) Difference computed for all JJA seasons in the two periods.

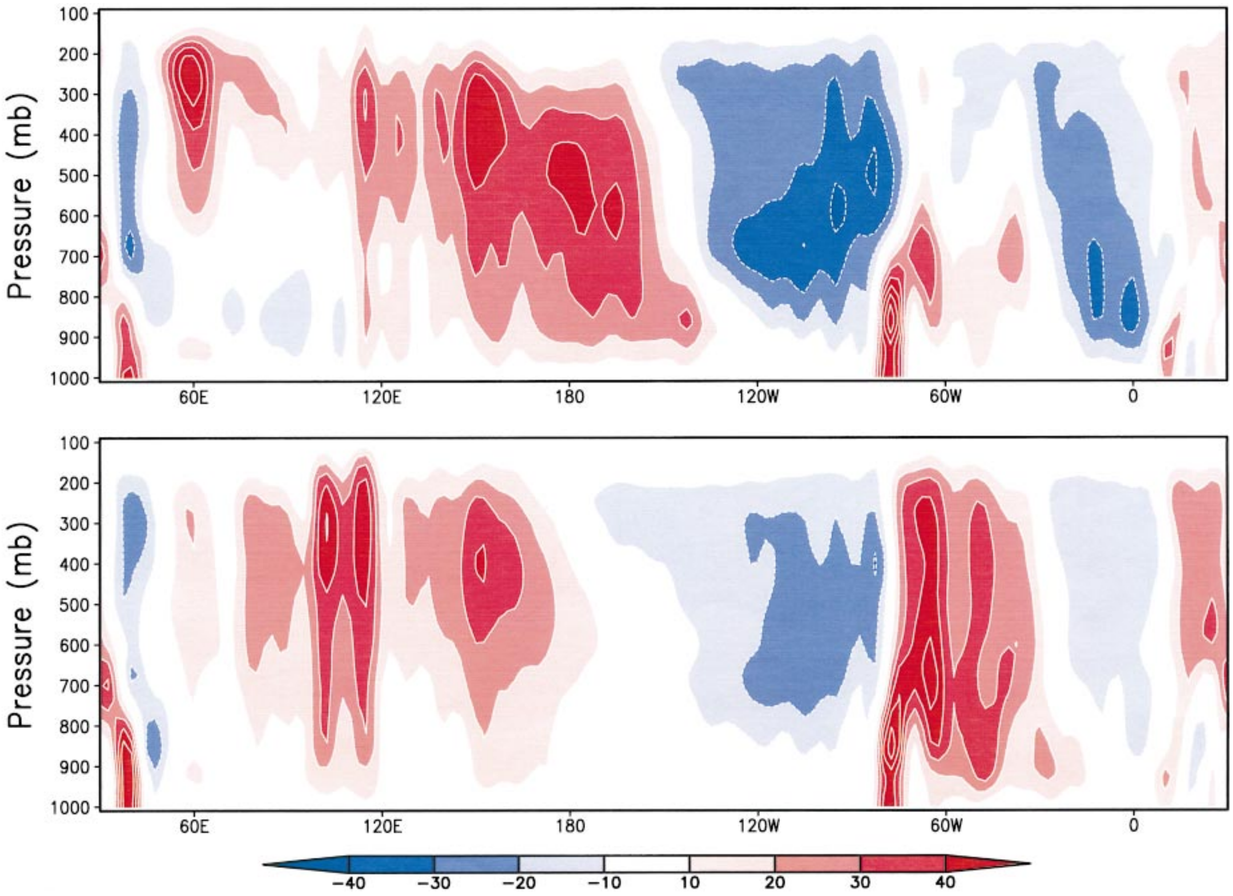

FIG. 2. The 21-yr means of NCEP–NCAR reanalysis negative vertical component of velocity averaged over 2.5°S–2.5°N for JJA seasons in the (top) early period (1950–70) and (bottom) recent period (1980–2000).

erages as shown in Fig. 3, computed for the CRU precipitation analysis. The large interdecadal differences found in the reanalysis product of precipitation are not found in the CRU analysis. In particular, the central Pacific precipitation is, if any trend may be ascribed to the time series, increasing rather than decreasing. The magnitude of precipitation anomalies in the central Pacific is considerably larger in the CRU time series than in the reanalysis product (note change of scales between Fig. 3 and Fig. 4), which may be due to the bias toward island rainfall in the latter. There is a slight increase in the precipitation over the Amazon basin, but the trend is not significant. Importantly, there is no evidence of a regime shift in the decade of the 1970s as is found at several locations in the reanalysis product of precipitation.

The CRU analysis, being an objective analysis based solely on gauge observations, suffers from the shortcoming of sparse coverage, particularly over oceanic regions where only limited island station data are available. The reanalysis product of precipitation was also compared with the CMAP analysis that merges observations based on gauge measurements and proxies for precipitation based on infrared radiation measured from satellites. While the time series is much shorter because of the shorter record of the satellite data, there is little agreement between the reanalysis product of precipitation and the CMAP analysis (not shown). During the same period, there is good agreement in the area average time series between the CRU and CMAP analyses, especially for the Indonesian and South American regions.

A very detailed objective analysis was performed by C. Willmott and S. Webber [2001, personal communication, hereinafter WW, see Willmott et al. (1996) for a description of the analysis method] for the South American gauge observations of precipitation. The time series for the area average over part of the Amazon basin is shown in Fig. 5 for the reanalysis product, the CRU analysis, the CMAP analysis, and the WW analysis. It is clear that the latter three are in good agreement in the overlapping periods, while the reanalysis product is an outlier.

The correlation coefficients among pairs of these time series (for all months) are given in Table 1. The correlation was computed for the period of overlap of all time series (upper triangle in Table 1) and for the period of overlap of each pair of time series (lower triangle in Table 1).

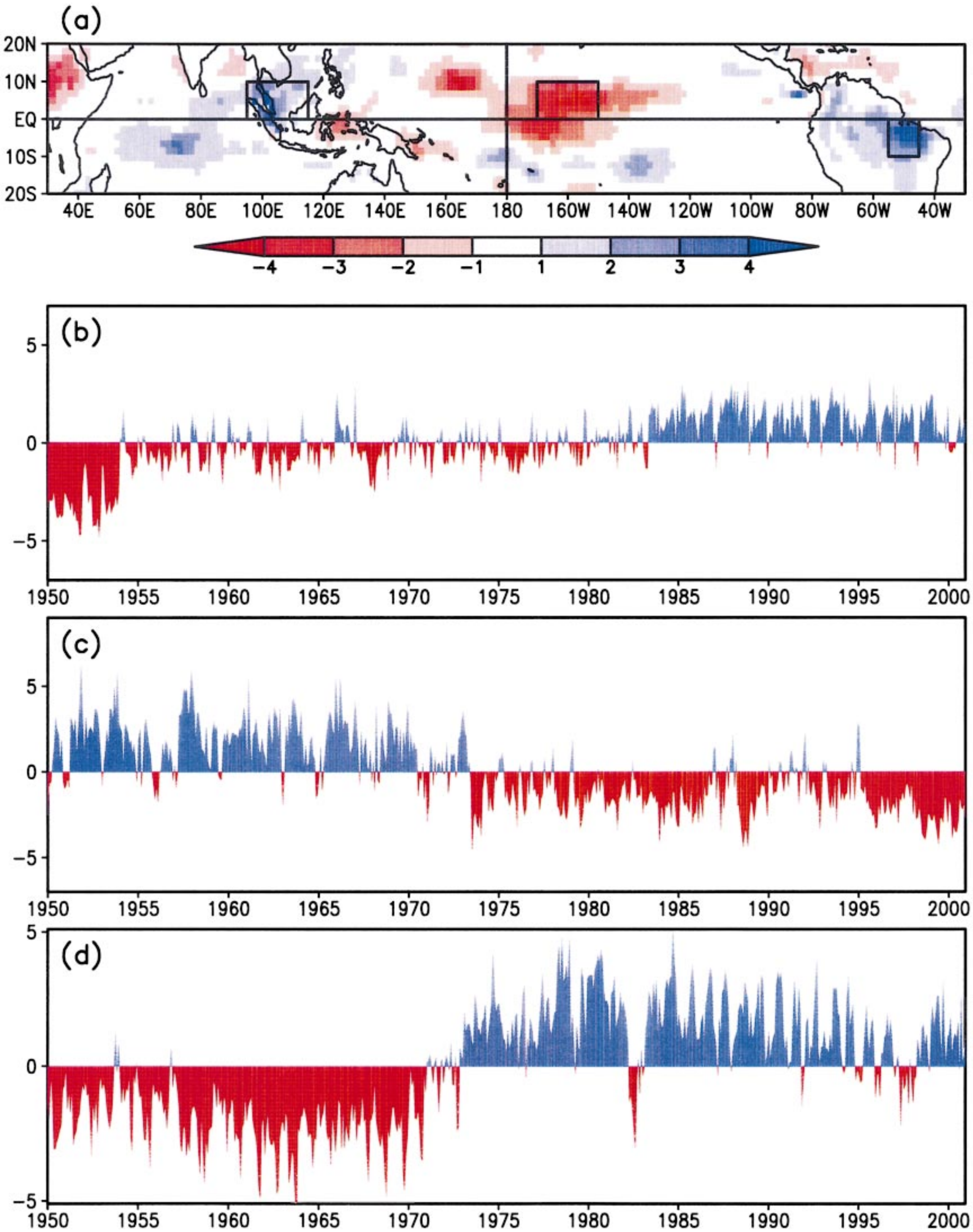

FIG. 3. (a) Difference of 21-yr-mean annual means of NCEP–NCAR reanalysis precipitation in the 1980–2000 period minus the 1950–70 period. (b) Time series of NCEP–NCAR reanalysis monthly mean precipitation averaged for the region equator–10°N, 95°–115°E. (c) As in (b) but for the region equator–10°N, 170°–150°W. (d) As in (b) but for the region 10°S–equator, 55°–45°W.

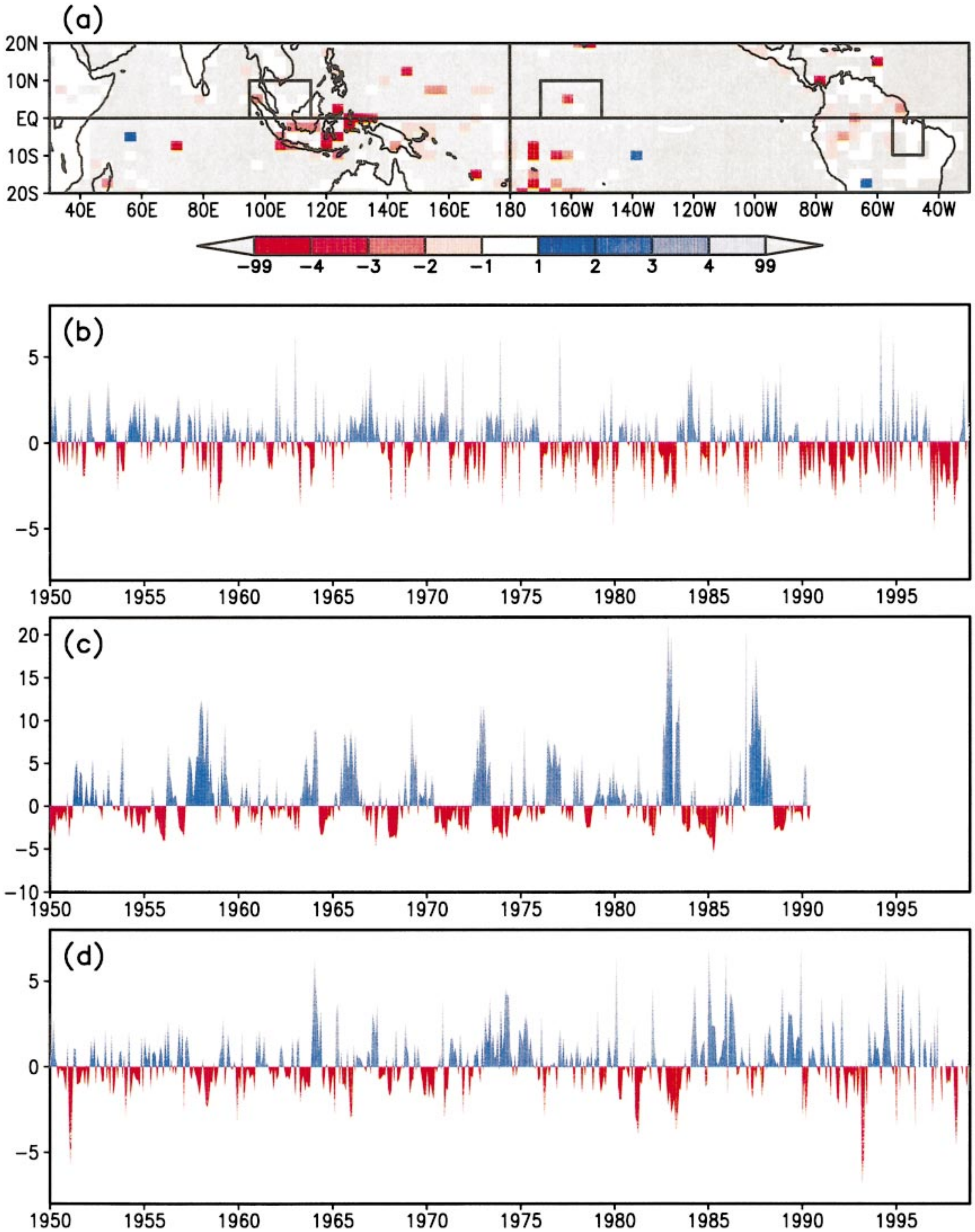

FIG. 4. As in Fig. 3 but for the CRU precipitation analysis.

There is clearly a high degree of correspondence among the three analyses of precipitation other than the reanalysis product. The correlations, computed with respect to two choices of base periods, show that the reanalysis product is an outlier. It should be noted that the low correlation between the reanalysis product and the other analyses of precipitation may be due to the bias in the latter toward land points and island stations. It should also be noted that the high degree of correlation among the analyses of precipitation, other than the re-

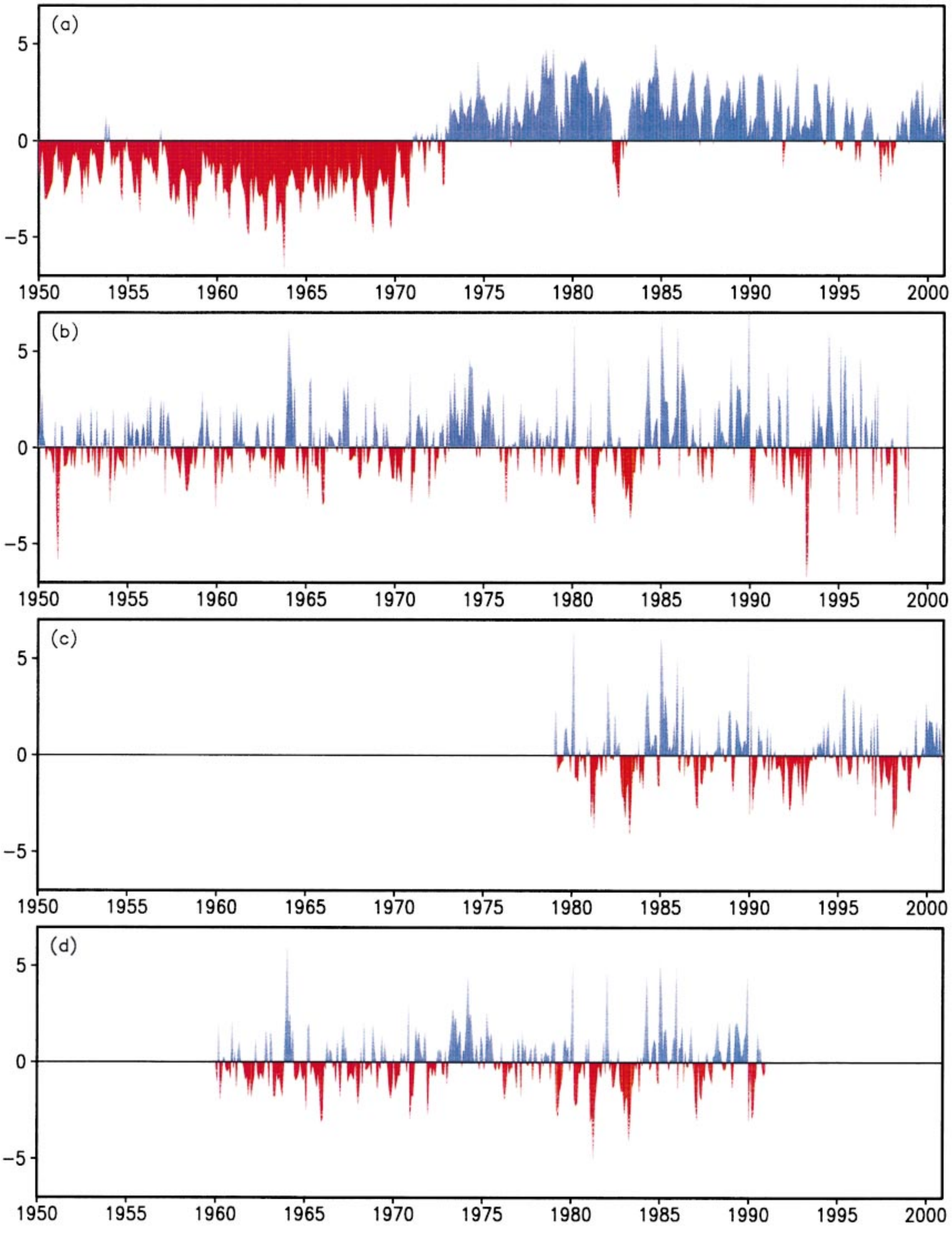

FIG. 5. Time series of precipitation analyses averaged for the region 10°S–equator, 55°–45°W: (a) NCEP–NCAR reanalysis, (b) CRU analysis, (c) CMAP analysis, and (d) WW analysis.

analysis product, is not surprising, given the fact that many of the same observations of precipitation were used in constructing those analyses. The fact that the reanalysis product is an outlier shows that the reanalysis is not sufficiently constrained to produce a precipitation analysis that adequately represents the observed precipitation.

Another way to see the differences among these rep-

TABLE 1. Lag autocorrelation and correlation coefficients of time series of monthly mean (all months) area-averaged precipitation for the region 10°S–equator, 55°–45°W. The upper triangle of correlations is based on the period 1979–90, the period of record for which all time series are available. The lower triangle of correlations is for the time periods that are common in each pair of time series: 1950–98 for reanalysis–CRU, 1979–2000 for reanalysis–CMAP, 1960–90 for reanalysis–WW, 1979–98 for CRU–CMAP; 1960–90 for CRU–WW, and 1979–90 for CMAP–WW. The main diagonal (boldface) contains the 1-month autocorrelation for each time series computed for all months over the maximal base period for each precipitation analysis.

	Reanalysis	CRU	CMAP	WW
Reanalysis	**0.88**	0.15	0.11	0.080
CRU	0.19	**0.29**	0.88	0.91
CMAP	0.11	0.78	**0.26**	0.91
WW	0.17	0.90	0.91	**0.36**

resentations of the precipitation over part of the Amazon basin is to compare the lag-1 autocorrelation of the monthly values, for all months, shown on the main diagonal of Table 1. The 1-month-lag autocorrelation for the reanalysis product is substantially larger. For the reanalysis product of precipitation, the persistence of monthly mean anomalies explains over 75% of the total variance, which is uncharacteristic of tropical rainfall. Resampling the reanalysis data to the much sparser grid of the CRU dataset does not significantly change the result. The same behavior can be found in other regions where there are large decadal shifts in the reanalysis precipitation product (not shown).

The time series of precipitation for the South American region was also compared with river discharge data available from the River Discharge Database (RivDis) dataset (Vörösmarty et al. 1996a,b, 1998). Although none of the time series of discharge data for the rivers that drain the region in question either spanned the relevant period or were continuous over the full period, no trends or regime shifts comparable to those found in the NCEP–NCAR reanalysis precipitation product were found. For example, time series of river discharge at Obidos, Brazil, are available for the 1930s, 1940s, and 1970s, and the mean annual cycle and interannual variance of the time series for the earlier decades are quite similar to those of the later decade (not shown).

4. Results of comparison with model integrations

Because the analyses of precipitation have shortcomings in terms of their spatial coverage or their temporal extent, an alternative method of evaluating the reanalysis products was employed, namely, to compare with the output of AGCMs integrated over the same period of time as the reanalysis with observed SST and sea ice as lower boundary conditions. Insofar as the models are able to reproduce the observed state of the climate, it may be presumed that features of the model climate, such as its mean precipitation and mean divergent circulation, are representative of the observed features. For example, Sperber and Palmer (1996) noted that the precipitation variability over the Nordeste region of Brazil, which is similar to the region of the Amazon basin used in this study, is fairly well simulated in AMIP integrations, similar to the C20C integrations used here.

Given that the mean annual cycle and interannual variability of the precipitation in the AGCM integrations closely resemble the observed, ensemble means of C20C integrations from different models were used for comparison with both the reanalysis products and the independent observations of precipitation. The SST datasets used to force the C20C integrations and the reanalysis were nearly identical.

As a representative C20C example, the model output from the COLA AGCM that was integrated at T63 horizontal resolution with 18 vertical levels using the Hadley Centre Global Sea Ice and SST dataset, version 1.1, (HadISST1.1) analysis of SST and sea ice as a lower boundary condition was used (Rayner et al. 2003). The same interdecadal difference and area-averaged time series as shown in Fig. 3 was computed from the ensemble mean of COLA AGCM C20C integrations. The result is shown in Fig. 6. There are regions in which the model output has large interdecadal differences, notably the increase in precipitation in the tropical western North Pacific and the decrease in the precipitation over the oceanic regions west of Central America and northeast of South America. The latter extends over the Amazon basin in the COLA AGCM model output. The COLA AGCM does not reproduce the large, systematic interdecadal differences in precipitation that were found in the reanalysis product, particularly those over the central tropical Pacific and over the Amazon basin. In fact, the model output has a slight downward trend in the precipitation over the Amazon basin. Importantly, the model does not show a regime shift in the decade of the 1970s.

To determine the extent to which this may be a model-dependent result, the same calculation was made for similar ensembles of multidecadal integrations made with the ECHAM3 and NSIPP models. All three models produce interdecadal differences that are very similar to that shown in Fig. 6a with regions of similar extent having differences of similar extent and magnitude. Figure 7 shows the time series for the Amazon basin area average from the NCEP reanalysis (repeated from Fig. 3d) and the COLA, ECHAM3, and NSIPP AGCM simulations. The time series were all normalized by their respective standard deviations. The slight downward trend in precipitation is present in all three models, although the trend is not significant in all three. Again, there is no regime shift in any of the model outputs in the decade of the 1970s.

The correlation coefficients (Table 2) among the AGCM runs and the various analyses of precipitation in the Amazon basin indicate that the models behave more like the reanalysis product in terms of their lag correlation, but they are essentially uncorrelated with it. As with reanalysis, resampling the AGCM output data

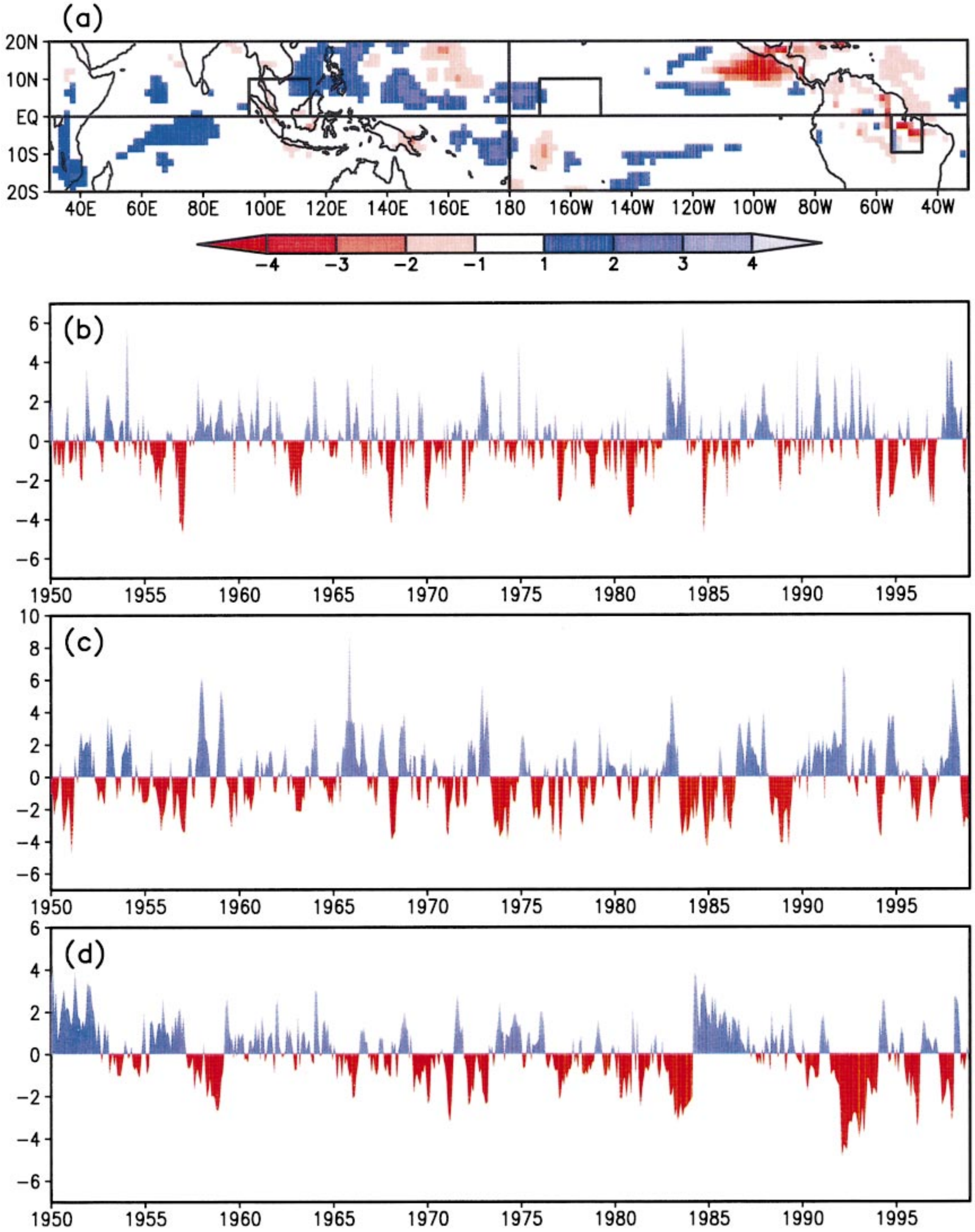

FIG. 6. As in Fig. 3 but for the COLA AGCM simulation of precipitation.

to the much sparser grid of the CRU dataset does not significantly change this result. All model simulations of interannual variability in the Amazon region are moderately well correlated with the other analyses of precipitation and each other.

5. Concluding remarks

There is ample evidence that several parameters that characterize the tropical climate underwent a regime shift in the middle of the decade of the 1970s, partic-

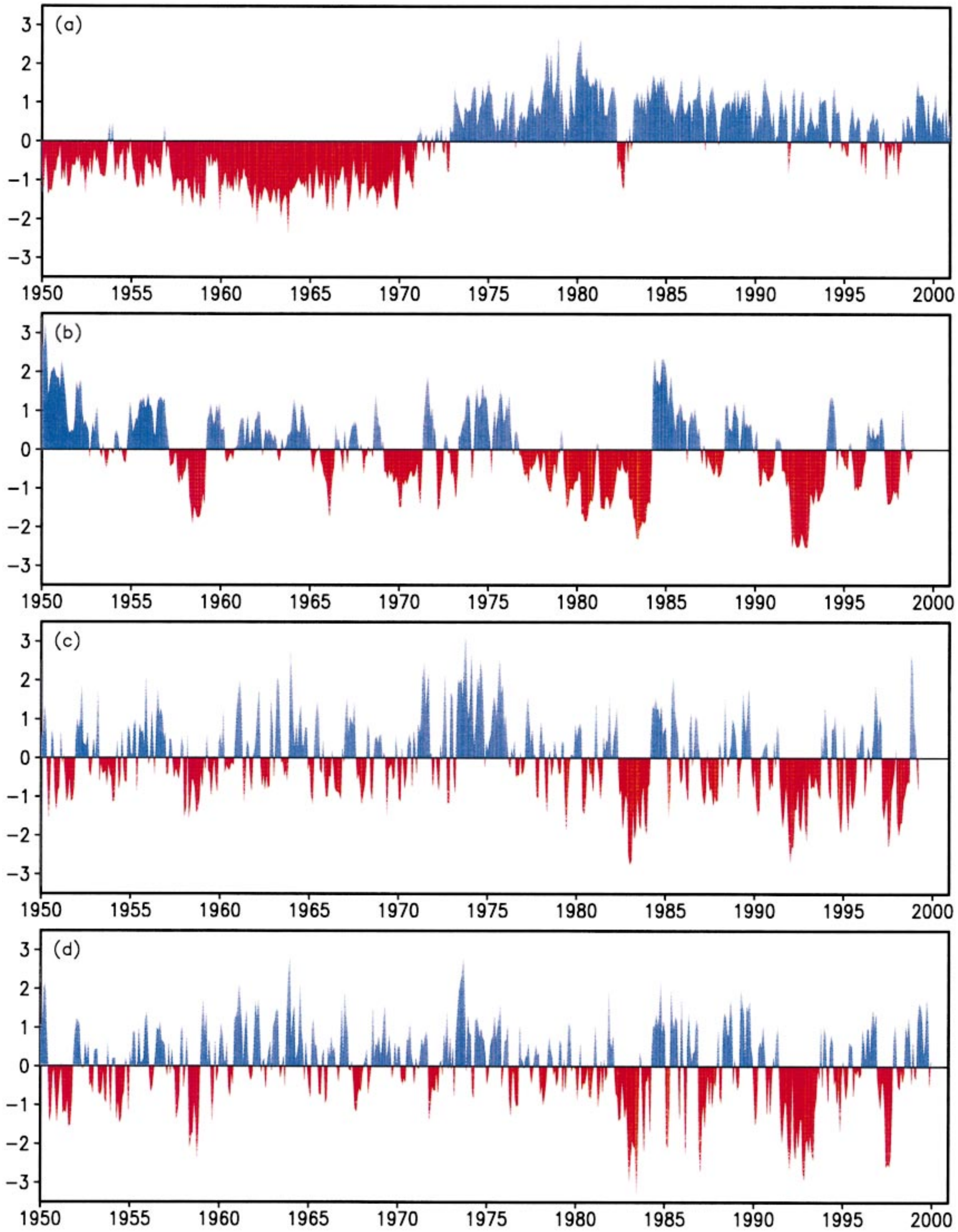

FIG. 7. The 1950–98 time series of precipitation analyses averaged for the region 10°S–equator, 55°–45°W. The 1950–98 mean annual cycle has been subtracted from each time series, which has also been normalized by its own standard deviation. (a) NCEP–NCAR reanalysis; (b) COLA AGCM simulation; (c) ECHAM AGCM simulation; (d) NSIPP AGCM simulation.

TABLE 2. Lag autocorrelation and correlation coefficients of time series of monthly mean, area-averaged precipitation for the region 10°S–equator, 55°–45°W from reanalysis, the CRU analysis, and several AGCM ensemble means. The upper triangle of correlations is based on the period 1979–90, for comparison with Table 1. The lower triangle of correlations is for the maximal time period that is common for all time series: 1950–98. The main diagonal (boldface) shows the 1-month lag autocorrelation for each time series for all months in 1950–98.

	Reanalysis	CRU	COLA	ECHAM	NSIPP
Reanalysis	**0.88**	0.15	0.049	0.029	0.16
CRU	0.19	**0.29**	0.42	0.29	0.32
COLA	−0.090	0.18	**0.78**	0.42	0.42
ECHAM	0.024	0.26	0.32	**0.62**	0.58
NSIPP	0.043	0.27	0.38	0.49	**0.66**

ularly in the Pacific (Nitta and Yamada 1989; Trenberth 1990; Gaffen et al. 1991; Graham 1994; Stephens et al. 2001). Attributing the cause of the regime shift is a difficult problem. Several studies have noted the apparent regime shift at about the same time in the divergent atmospheric circulation in the Tropics that can be inferred from the NCEP–NCAR reanalysis products. This circulation regime shift was examined in detail, and we find that, while it is consistent with the regime shift in the reanalysis product of precipitation, it is not consistent with several other precipitation analyses. In particular, it is found that the spatial structure and the abrupt nature of the regime shift in the reanalysis product of precipitation are not found in other decades-long analyses of tropical precipitation. Focusing, for example, on the Amazon basin, it was found that the reanalysis precipitation product is very poorly correlated with all other analyses of precipitation, which are well correlated among themselves. It was also found that AGCMs forced by decades of observed SST produce tropical precipitation simulations that are moderately well correlated with the independent analyses of precipitation but not with the reanalysis product of precipitation. The 1-month-lag autocorrelation of the reanalysis product is more similar to the model simulations than to the independent analyses of precipitation observations, which suggests that the reanalysis precipitation product is more like a model output than an observed quantity. Given the direct relationship between tropical precipitation and the divergent circulation in the tropical atmosphere, it is apparent that the reanalysis velocity potential product is an artifact of the reanalysis rather than a representation of the actual divergent circulation.

It may be concluded that the apparent decadal regime shift in the divergent circulation inferred from the reanalysis wind field is probably spurious insofar as the precipitation that drives the divergent circulation undergoes a decadal regime shift that is not consistent with all other indicators of tropical rainfall that were examined. This suggests that the reanalysis product of the tropospheric divergent circulation cannot be used to support the hypothesis that a decadal shift in the divergent circulation in the Tropics was responsible for the change in either the ENSO–monsoon relationship or the trends in South American rainfall as has been suggested in previous studies. We do not conclude that the divergent circulation is not involved in the decadal variations of the ENSO–monsoon relationship, but only that the reanalysis product may not be suitable to validate this hypothesis. Several other hypotheses have been advanced for the change in the ENSO–monsoon relationship, many of which involve rotational atmospheric dynamics [see, e.g., Kinter et al. (2002) for one hypothesis and a review of others].

Several open questions remain about the regime shift observed in the mid-1970s. Given the absence of an abrupt change in the independent analyses of precipitation, is there a more complex relationship between, for example, surface temperature and precipitation on decadal time scales? Is the observed change a part of a longer period fluctuation or is it an abrupt change? To what extent is the observed shift in the divergent circulation an artifact of the observing system changes and data processing methods that occurred at about the same time? Are there unambiguous indicators of the regime shift? Can a cause be attributed to the apparent regime shift? In seeking an attribution for the regime shift, it is important to isolate possible artifacts of the changes in the way observations are processed and assimilated from real climatic signals. The reanalysis efforts by several groups address the question of inhomogeneity of the assimilation system, but cannot address the question of observing system changes unless a controlled reanalysis with a fixed-in-time observing system is performed. The results described in this paper argue in favor of such an experiment.

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