ENVIRONMENTAL RESEARCH
LETTERS

The recycling rate of atmospheric moisture over the past two decades (1988–2009)

Environ. Res. Lett. **6** (2011) 034018 (6pp) doi:10.1088/1748-9326/6/3/034018

The recycling rate of atmospheric moisture over the past two decades (1988–2009)

Liming Li[1], Xun Jiang[1], Moustafa T Chahine[2], Edward T Olsen[2], Eric J Fetzer[2], Luke Chen[2] and Yuk L Yung[3,4]

[1] Department of Earth and Atmospheric Sciences, University of Houston, USA
[2] Science Division, Jet Propulsion Laboratory, California Institute of Technology, USA
[3] Division of Geological and Planetary Sciences, California Institute of Technology, Pasadena, USA

E-mail: yly@gps.caltech.edu

Received 11 April 2011
Accepted for publication 21 July 2011
Published 17 August 2011
Online at stacks.iop.org/ERL/6/034018

Abstract

Numerical models predict that the recycling rate of atmospheric moisture decreases with time at the global scale, in response to global warming. A recent observational study (Wentz *et al* 2007 *Science* **317** 233–5) did not agree with the results from numerical models. Here, we examine the recycling rate by using the latest data sets for precipitation and water vapor, and suggest a consistent view of the global recycling rate of atmospheric moisture between numerical models and observations. Our analyses show that the recycling rate of atmospheric moisture has also decreased over the global oceans during the past two decades. In addition, we find different temporal variations of the recycling rate in different regions when exploring the spatial pattern of the recycling rate. In particular, the recycling rate has increased in the high-precipitation region around the equator (i.e., the intertropical convergence zone) and decreased in the low-precipitation region located either side of the equator over the past two decades. Further exploration suggests that the temporal variation of precipitation is stronger than that of water vapor, which results in the positive trend of the recycling rate in the high-precipitation region and the negative trend of the recycling rate in the low-precipitation region.

Keywords: precipitation, water vapor, recycling rate, hydrological cycle

1. Introduction

The hydrological cycle, which involves the atmosphere, surface and biosphere, has enormous impact on human activity. The atmospheric branch of the hydrological cycle, in which water vapor leaves the surface by evaporation and returns to the surface by precipitation, is a crucial component of weather and climate.

Besides the effects of regional meteorology (Ye and Fetzer 2009), the temporal variation of the total mass of water vapor in the global atmosphere is related to atmospheric temperature by the Clausius–Clapeyron equation under the approximation that the relative humidity in the atmosphere stays constant. Different datasets display qualitatively consistent increasing trends in the total mass of water vapor in the global atmosphere (Trenberth *et al* 2005, Wentz *et al* 2007, Santer *et al* 2007). Such increasing trends in water vapor are also simulated in the numerical models (Bosilovich *et al* 2005, Held and Soden 2006) even though the mechanism of how water vapor affects climate change is still not very clear (Held and Soden 2006, Ingram 2010).

On the other hand, precipitation, which is controlled by the atmospheric circulation and cloud microphysics, is more complicated. Consequently, there is no simple relationship between precipitation and temperature at the global scale even though surface temperature is correlated with local precipitation (Trenberth and Shea 2005, Adler *et al* 2008) and precipitation extremes (Allan and Soden 2008, Liu *et al* 2009). Large discrepancies in the linear trend of global precipitation

[4] Author to whom any correspondence should be addressed.

exist among different studies (Allen and Ingram 2002, Adler *et al* 2003, Trenberth *et al* 2003, Held and Soden 2006, Gu *et al* 2007, Stephens and Ellis 2008, Adler *et al* 2008, Liepert and Previdi 2009, Trenberth 2011, Zhou 2011). A recent letter by Wentz *et al* (2007) suggests that the increasing trend with time was roughly the same for global precipitation ($1.4 \pm 0.5\%$ per decade) and total water vapor ($1.2 \pm 0.5\%$ per decade) during the period 1987–2006.

The study by Wentz *et al* (2007) implies that the recycling rate of atmospheric moisture, which is defined as the ratio of precipitation to column water vapor, remained constant or intensified with time. From the perspective of atmospheric radiative imbalance, it is possible that global precipitation is increasing at a rate of 1.4% per decade (Liepert and Previdi 2009). However, most other observational studies (Adler *et al* 2003, Gu *et al* 2007, Adler *et al* 2008) and climate models (Allen and Ingram 2002, Held and Soden 2006, Stephens and Ellis 2008) suggest that global precipitation is increasing (∼0.2–0.7% per decade) more slowly than in the total mass of water vapor (∼1.4–1.5% per decade) in response to global warming. In this study, we revisit the temporal variation of water vapor and precipitation based on the latest version of global data sets with emphasis on the variation of the recycling rate of atmospheric moisture that accompanies global warming during the past two decades (1988–2009).

2. Methodology and data

A useful method of estimating the intensity of the hydrological cycle in the global atmosphere is to use some simple parameters, which include recycling rate (Chahine *et al* 1997), residence time (Chahine *et al* 1992, Trenberth 1998), and a non-dimensional ratio between the precipitation sensitivity and the water vapor sensitivity (Stephens and Ellis 2008). The purpose of these parameters is to compare the increasing rates between the total water vapor and precipitation. Here, we use the recycling rate of atmospheric moisture (R) (Chahine *et al* 1997) to compare the temporal variation between column water vapor (W) and precipitation (P).

$$R = P/W. \tag{1}$$

So we have

$$\begin{aligned} &\ln R = \ln(P/W) \\ \Rightarrow\quad & \mathrm{d}(\ln R)/\mathrm{d}t = \mathrm{d}[\ln P - \ln W]/\mathrm{d}t \\ \Rightarrow\quad & (\mathrm{d}R/\mathrm{d}t)/R = (\mathrm{d}P/\mathrm{d}t)/P - (\mathrm{d}W/\mathrm{d}t)/W. \end{aligned} \tag{2}$$

Therefore, during a time period we can approximate equation (2) as below

$$\Delta R/\bar{R} = \Delta P/\bar{P} - \Delta W/\bar{W} \tag{3}$$

where ΔX and $\bar{X}$ represent the change and mean value of variable X (i.e., R, P, and W) during the time period. When the varied percentage of precipitation ($\Delta P/\bar{P}$) is larger than the varied percentage of column water vapor ($\Delta W/\bar{W}$), we have the ratio $\Delta R/\bar{R} > 0$. Otherwise, we have the ratio $\Delta R/\bar{R} \leqslant 0$. In physics, the parameter $\Delta R/\bar{R}$ is the same as another non-dimensional ratio $\varepsilon = (\Delta P/\bar{P})/(\Delta W/\bar{W})$, which is developed by Stephens and Ellis (2008). It should be mentioned that the balance described in equation (3) probably does not hold except for the global mean where the flux divergence term drops out.

Equation (2) shows that the temporal variation of recycling rate is determined by the temporal variations of precipitation and column water vapor. In this study, the latest data sets from the Special Sensor Microwave Imager (SSM/I) (Wentz 1997, Wentz and Spencer 1998) and the Global Precipitation Climatology Project (GPCP) (Huffman *et al* 2009) are utilized to examine the temporal variations of precipitation, column water vapor, and recycling rate over the past two decades. The data set of SSM/I (V 6) has oceanic precipitation and water vapor from 1988 to 2009 with spatial resolution at $0.25° \times 0.25°$ (latitude by longitude) (SSM/I data are provided by Remote Sensing Systems from the website: www.ssmi.com/ssmi/ssmi_browse.html). The latest version of GPCP (V 2.1) has the global precipitation data from 1979 to 2009 with spatial resolution at $2.5° \times 2.5°$ (latitude by longitude) (GPCP V 2.1 data are provided by the Earth System Research Laboratory from the website www.esrl.noaa.gov/psd/data/gridded/data.gpcp.html). To be consistent with the length of water vapor data from SSM/I, we only use the GPCP precipitation between 1988 and 2009.

3. Results

The temporal variations of precipitation and water vapor at the global scale are shown in figure 1. Figure 1(A) shows two time series of the temporal variations of precipitation based on a combined global data from SSM/I and GPCP and the global data from GPCP. The combined global data was constructed by combining the precipitation data over ocean from the SSM/I and the precipitation data over land from GPCP. Figure 1(B) displays the temporal variation of column water vapor over the global oceans, which is based on the oceanic data from SSM/I. We calculate the linear trends and corresponding uncertainties of the time series shown in figure 1 by the least-squares method (Bevington and Robinson 2003). The linear trend of global precipitation is $0.08 \pm 0.43\%$ per decade and $0.26 \pm 0.41\%$ per decade for the combined global data and the GPCP global data, respectively. The linear trend of column water vapor is $1.01 \pm 0.39\%$ per decade, which is basically consistent with the value of $1.37 \pm 0.72\%$ per decade from a recent study (Santer *et al* 2007). We also calculate the confidence level of linear trends in figure 1 (please refer to the appendix), which shows that the confidence level of linear trend in the global precipitation is less than 90% and the confidence level of linear trend in the oceanic water vapor is more than 95%. The weak positive trend of global precipitation ($0.08 \pm 0.43\%$ per decade and $0.26 \pm 0.41\%$ per decade) is much smaller than the linear trend ($1.4 \pm 0.5\%$ per decade) in the previous study (Wentz *et al* 2007). The previous study was also based on a combined global data from SSM/I (ocean) and GPCP (land), but a relatively old version of GPCP (V 2) was used (Wentz *et al* 2007). Our study (figure 1) is based on a recent-released version of GPCP (V 2.1) (Huffman *et al* 2009).

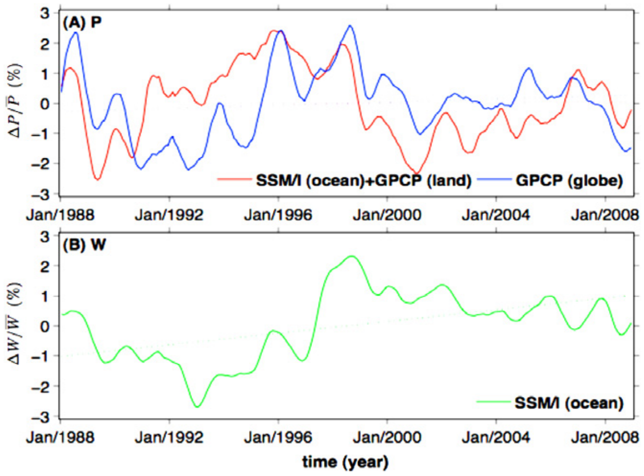

Figure 1. Temporal variations of global-mean precipitation and oceanic-mean water vapor. (A) Precipitation (P). (B) Column water vapor (W). The red line in panel (A) is based on the combined global data from the latest version of GPCP (V 2.1) (land) and SSM/I (V 6) (ocean), and the blue line in panel (A) is based on the global data from the latest version of GPCP (V 2.1). Deseasonalization and low-pass filter were applied to the time series. Seasonal cycle was removed by subtracting the monthly mean data. Low-pass filter was constructed so that only signals with periods longer than six months were kept.

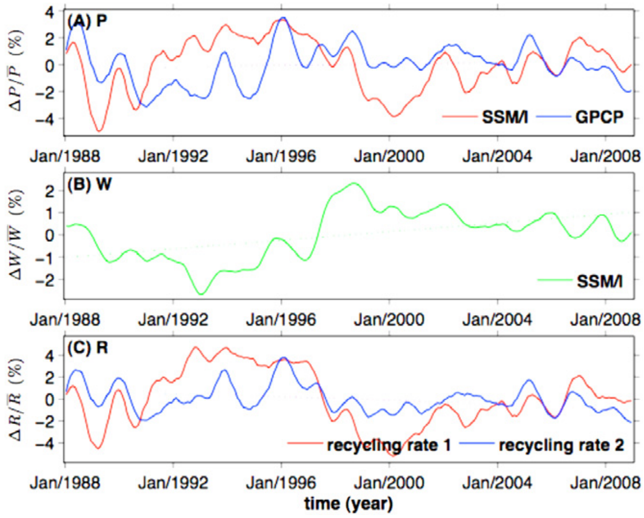

Figure 2. Temporal variations of precipitation, water vapor, and recycling rate averaged over ocean between 60°N and 60°S. (A) Precipitation (P). (B) Water vapor (W). (C) Recycling rate (R). El Niño-Southern Oscillation (ENSO) signals have been removed from time series by a regression method based on the Niño3.4 index. Note: the linear trend of time series is basically consistent between the data with the ENSO signals and the data without the ENSO signals. The recycling rate 1 is defined as the ratio of SSM/I precipitation to SSM/I water vapor, and the recycling rate 2 is defined as the ratio of GPCP precipitation to SSM/I water vapor.

The new dataset of GPCP has been improved by applying a new updated climate anomaly analysis method for gauge data (Schneider *et al* 2008) and several correction schemes (Huffman *et al* 2009). GPCP V 2.1 has better data quality and more continuous coverage than the old version (Huffman *et al* 2009). Therefore, an exploration of the temporal variation based on the latest GPCP (V 2.1) will be more robust than the analyses in the previous study based on the relatively old version. The differences of trend between this study (figure 1) and the previous study (Wentz *et al* 2007) are mainly due to the dramatic drop in the rate of increase of precipitation over land between the old version (V 2) and the new version (V 2.1) of the GPCP dataset (Huffman *et al* 2009).

The weak positive trend with larger uncertainty in the global precipitation suggests that the linear trend of global precipitation is not statistically significant, and the precipitation trend is smaller than the significant linear trend in the oceanic water vapor. The comparison of linear trends between precipitation and water vapor implies that the recycling rate of global atmospheric moisture decreased with time during the past two decades. Therefore, the linear trends of precipitation (0.08 ± 0.43% per decade or 0.26 ± 0.41% per decade) based on the latest and improved precipitation data are basically consistent with the estimated trends for precipitation (∼0.2–0.7% per decade) from the numerical simulations (Allen and Ingram 2002, Held and Soden 2006, Stephens and Ellis 2008), which reconcile the discrepancy of recycling rate of global atmospheric moisture between the study by Wentz *et al* (2007) and the other studies (Allen and Ingram 2002, Held and Soden 2006, Stephens and Ellis 2008). A consistent view—the slowing in the recycling rate of global atmospheric moisture in response to global warming—now emerges. The slowing of the recycling rate of global atmospheric moisture can be explained from the perspective of atmospheric energetics (Allen and Ingram 2002). The physics behind the slowing is complicated, which includes the modification of the tropical Walker Circulation by changing the frequency of strong/weak updrafts (Emori and Brown 2005, Vecchi and Soden 2007), suppression of the surface evaporation (Richter and Xie 2008), and reduction in the precipitation efficiency by a negative feedback through cloud radiative heating (Stephens and Ellis 2008).

Due to the lack of global long-term continuous data of water vapor, we assume that the linear trend of global water vapor is same as that of oceanic water vapor in the above comparison between precipitation and water vapor. Such an assumption was also used in the previous study (Wentz *et al* 2007). However, it is possible that the linear trend of water vapor is different between ocean and land (Simmons *et al* 2010) so that the above assumption is not valid. Here, we conduct a strict comparison of linear trends between oceanic precipitation and oceanic water vapor over the past two decades in figure 2. The retrieval of water vapor and precipitation near coasts is generally not robust due to the complicated meteorological situations there. Therefore, the data of water vapor and precipitation close to coasts (i.e., 1° latitude within coasts) are not included in this study. The data quality in the polar region is not very good either because there are very few *in situ* observations available to validate the satellite data. Therefore, only the data of precipitation and water vapor over ocean between 60°N–60°S are used to discuss the recycling

Table 1. The linear trends of ocean-mean precipitation (P), column water vapor (W), and recycle rate (R) shown in figure 2 (1988–2009).

	Precipitation (P)		Water vapor (W)	Recycling rate (R)		
	SSM/I	GPCP	SSM/I	Rate 1	Rate 2	Units
Linear trend	0.13	0.33	0.97	−0.82	−0.65	%/decade
Uncertainty	0.63	0.54	0.37	1.11	0.51	%/decade

rate of atmospheric moisture during the past two decades in figure 2.

Figure 2 displays the temporal variations of oceanic precipitation, water vapor, and recycling rate. Details for the linear trends of the time series in figure 2 are written in table 1. As shown in table 1, the positive linear trend of oceanic precipitation is very weak with large uncertainty. The linear trend of oceanic water vapor between 60°N and 60°S is roughly the same as the linear trend of oceanic water vapor from pole to pole (figures 1(B) and 2(B)). The recycling rate 1 is defined as the ratio of the SSM/I precipitation to the SSM/I water vapor, and the recycling rate 2 is defined as the ratio of the GPCP precipitation to the SSM/I water vapor. From table 1, we find that the linear trend of recycling rate roughly equates to the difference of linear trends between precipitation and water vapor, which is consistent with equation (2). The confidence level of linear trend in the recycling rate 1 is less than 90%, but the confidence level of linear trend in the recycling rate 2 is more than 90%. The qualitatively consistent oceanic recycling rate between the recycling rate 1 and recycling rate 2 confirms that the previous conclusion based on the global precipitation and oceanic water vapor (figure 1): the recycling rate of atmospheric moisture has decreased during the past two decades.

In addition to the temporal variation of recycling rate averaging over globe and ocean, we also explore the spatial patterns of recycling rate in response to global warming. Figure 3 shows the spatial pattern of temporal variation of two recycling rates (recycling rate 1 and recycling rate 2). As shown in figure 3, the two recycling rates have similar spatial patterns. The temporal variation of recycling rate is positive in a narrow band around the equator, which is roughly the intertropical convergence zone (ITCZ) identified by highly reflective clouds (Waliser and Gautier 1993). Even though the confidence level of the linear trend of precipitation in the narrow band is less than 90%, the positive temporal variation suggests that the recycling rate of atmospheric moisture has intensified in the ITCZ during the past two decades. The recycling rate displays strong negative temporal variation at the two sides of the ITCZ in the Pacific Ocean with the confidence level of the linear trend larger than 90%, which suggests that the recycling rate of atmospheric moisture has slowed down in these areas. Besides the dominant feature in the tropical region, figure 3 also shows other positive and negative centers in the relatively high latitudes. Since the global average of recycling rate is decreased, it implies that the negative recycling is stronger (or spatially larger) than the positive recycling rate.

The dominant feature of recycling rate in the tropic region shown in figure 3 is very interesting. Considering that the recycling rate of atmospheric moisture is determined

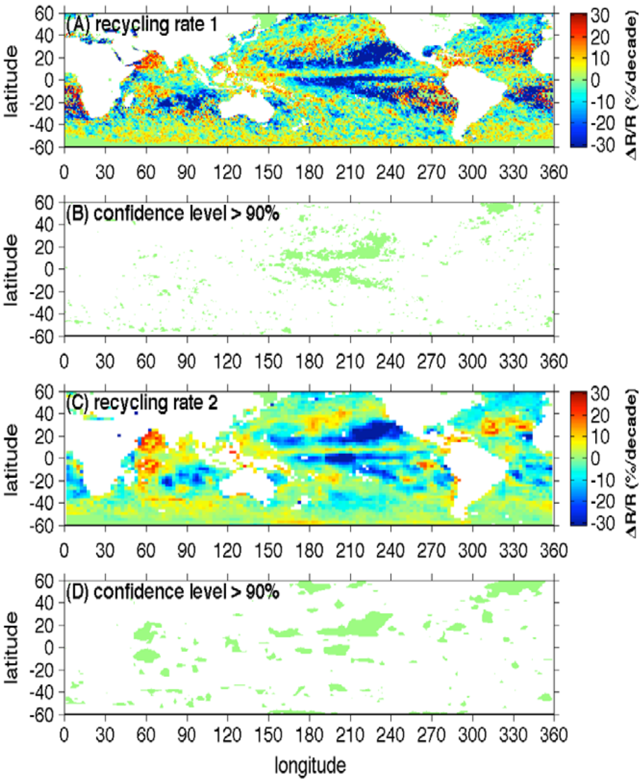

Figure 3. Spatial pattern of temporal variation of recycling rate ($\Delta R/\bar{R}$) over the time period of 1988–2009. Color represents the ratio of temporal variation to time mean during one decade. For each grid point of the global maps, the temporal variation of recycling rate (ΔR) over one decade is estimated by the production of linear trend and time span (one decade). Time mean value ($\bar{R}$) is computed for the time period of 1988–2009. (A) Recycling rate based on SSM/I precipitation and SSM/I water vapor. (B) Area with confidence level of linear trend in (A) larger than 90%. (C) and (D) are the same as (A) and (B) except for the recycling rate based on GPCP precipitation and SSM/I water vapor.

by precipitation and water vapor (equation (2)), the spatial patterns of temporal variations in precipitation and water vapor are also explored. Figure 4 displays the spatial patterns of oceanic precipitation and water vapor. Figure 4(A) shows that there are positive temporal variations of precipitation in the ITCZ, which is a high-precipitation area. In addition, negative temporal variations of precipitation occur in the two sides of the ITCZ in the tropic region, which are is a low-precipitation area. The opposite temporal variations of precipitation between the high-precipitation and low-precipitation areas are consistent with a recent study (Allan *et al* 2010). It suggests that the precipitation over high-precipitation areas has intensified during the past two decades. This intensification provides a new perspective to examine the

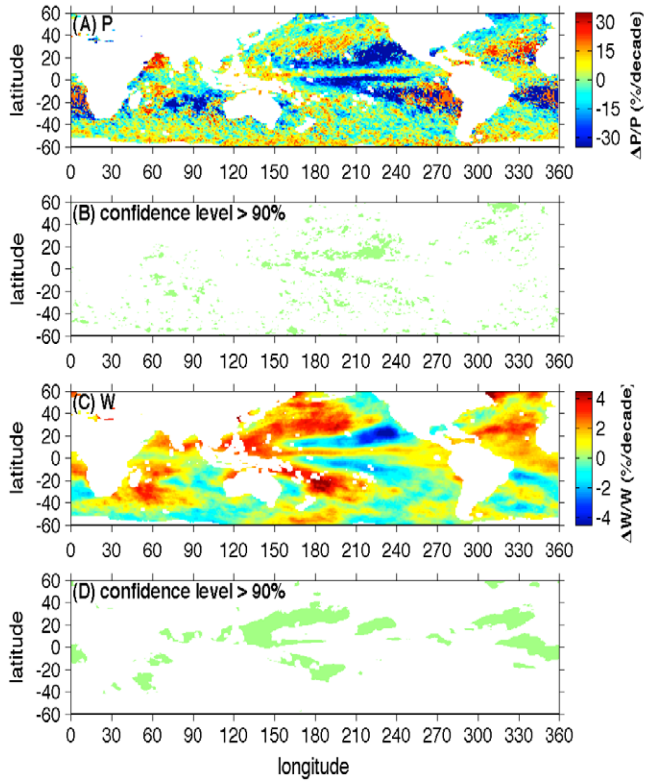

Figure 4. Same as figure 3 except for the temporal variations of precipitation and water vapor. (A) Precipitation (P). (B) Area with confidence level of linear trend in (A) larger than 90%. (C) and (D) are the same as (A) and (B) except for the column water vapor (W). The precipitation data in panel (A) is from SSM/I. The spatial pattern of precipitation from GPCP, which is basically the same as the pattern from SSM/I, is not shown.

amplification of precipitation extremes in response to global warming (Allan and Soden 2008, Liu *et al* 2009). The spatial pattern of temporal variation in precipitation also provides an observational evidence for a 'rich-get-richer' mechanism from numerical simulations (Chou and Neelin 2004, Neelin *et al* 2006), in which the tendency of precipitation increasing in the ITCZ and decreasing in the neighboring dry region was suggested. The dynamical processes responsible for the 'rich-get-richer' mechanism are probably associated with the variation of gross moist stability of the atmospheric boundary layer and the related adjusting of convection and precipitation (Held and Soden 2006, Chou *et al* 2009).

The spatial pattern of temporal variation is similar between recycling rate (figure 3) and precipitation (figure 4(A)). In addition, the magnitude of temporal variation is much stronger in precipitation than in water vapor (figure 4). Globally the trend in precipitation is smaller than that of water vapor, but regionally the trend in precipitation appears to dominate in the temporal variation of the recycling rate of atmospheric moisture (figures 4(A) and (B)). Figure 4 also shows that the spatial patterns of temporal variations are similar between precipitation and water vapor, which implies that the temporal variations of precipitation are related to the temporal variations of water vapor even though the magnitudes of their temporal variations are different.

4. Conclusions

In this study, we explore the temporal variations of global and oceanic precipitation, water vapor, and recycling rate of atmospheric moisture during the past two decades. Our analyses suggest that a consistent view between observation and numerical modeling—the global or oceanic recycling rate of atmospheric moisture has decreased over the past two decades. Considering that the linear trend of global precipitation is sensitive to different datasets and different versions of datasets, we suggest caution in interpreting the linear trends of time series at the global scale, as pointed out by some previous studies (Gu *et al* 2007, Lambert *et al* 2008, John *et al* 2009, Huffman *et al* 2009). We urge further examination of this important trend at the global and regional scales when longer and better global precipitation datasets become available.

We also explore the spatial pattern of temporal variations in the recycling rate of atmospheric moisture. Recycling rate has increased in the ITCZ and decreased in the neighboring region over the past two decades. Our exploration shows that the spatial pattern of temporal variations in the recycling rate is mainly controlled by the spatial pattern of temporal variations in precipitation whose magnitude is much stronger than the magnitude of the temporal variations in water vapor. The spatial patterns of temporal variations in precipitation, water vapor, and recycling rate enrich our knowledge of the hydrological cycle, which further provide constraints for climate models. Correct simulation of these important features by the climate models will help elucidate the physics behind the different temporal variations in the wet and dry areas, paving the way for more accurate prediction of future climate change driven by anthropogenic activities.

Acknowledgments

We thank S Newman, N Heavens, R Shia, L Kuai, M Line, X Zhang, and M Gerstell for helpful comments. This work was partly supported by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration. Precipitation data are from GPCP V 2.1 and SSM/I. Water vapor data are from SSM/I.

Appendix. Confidence level of linear trend

The confidence levels on the linear trends of the time series of the precipitation are estimated by the t-statistics. For the linear trend coefficient b calculated from the least-square fitting, the t-statistics is defined by $t = |b/\mathrm{SE}(b)|$ (Box *et al* 2005). SE(b) is the standard error of the linear trend b, which is estimated by $\mathrm{SE}(b) = (\sigma/\sqrt{N_1})/\sqrt{(1/N_2)\sum x_i^2}$ (Bevington and Robinson 2003), where σ is the standard deviation of the data, N_1 is the number of degrees of freedom of the data, N_2 is the length of the data set, and x_i is the time series corresponding to a number of measurements with $\sum x_i = 0$. The number of degrees of freedom N_1 is estimated by a formula suggested by

$N_1 = N_2[1 - r(\Delta x)^2]/[1 + r(\Delta x)^2]$ (Bretherton *et al* 1999), where $r(\Delta x)$ is the autocorrelation corresponding to a lag of time interval Δx. The linear trend is statistically significant when t is larger than a certain value t_0, which can be found from the t-distribution table (Box *et al* 2005).

References

Adler R F *et al* 2003 The version-2 global precipitation climatology project (GPCP) monthly precipitation analysis (1979-present) *J. Hydrometeorol.* **4** 1147–67

Adler R F, Gu G J, Wang J J, Huffman G J, Curtis S and Bolvin D 2008 Relationships between global precipitation and surface temperature on interannual and longer timescales (1979–2006) *J. Geophys. Res.* **113** D22104

Allan R P and Soden B J 2008 Atmospheric warming and the amplification of precipitation extremes *Science* **321** 1481–4

Allan R P, Soden B J, John V O, Ingram W and Good P 2010 Current changes in tropical precipitation *Environ. Res. Lett.* **5** 025205

Allen M R and Ingram W J 2002 Constraints on future changes in climate and the hydrological cycle *Nature* **419** 224–32

Bevington P R and Robinson D K 2003 *Data Reduction and Error Analysis for the Physical Sciences* 3rd edn (New York: McGraw-Hill)

Bosilovich M G, Schubert S D and Walker G K 2005 Global changes of the water cycle intensity *J. Clim.* **18** 1591–608

Box G E P, Hunter J S and Hunter W G 2005 *Statistical for Experiments* 2nd edn (New York: Wiley)

Bretherton C S, Widmann M, Dymnikov V P, Wallace J M and Blade I 1999 The effective number of spatial degrees of a time varying field *J. Clim.* **12** 1990–2009

Chahine M T 1992 The hydrological cycle and its influence on climate *Nature* **359** 373–80

Chahine M T, Haskins R and Fetzer E 1997 Observation of the recycling rate of moisture in the atmosphere: 1988–1994 *GEWEX* **7** 1–4

Chou C and Neelin J D 2004 Mechanisms of global warming impacts on regional tropical precipitation *J. Clim.* **17** 2688–701

Chou C, Neelin J D, Chen C A and Tu J Y 2009 Evaluating the 'rich-get-richer' mechanism in tropical precipitation change under global warming *J. Clim.* **22** 1982–2005

Emori S and Brown S J 2005 Dynamic and thermodynamic changes in mean and extreme precipitation under changed climate *Geophys. Res. Lett.* **32** L17706

Gu G J, Adler R F, Huffman G J and Curtis S 2007 Tropical rainfall variability on interannual-to-interdecadeal and longer time scales derived from the GPCP monthly product *J. Clim.* **20** 4033–46

Held I M and Soden B J 2006 Robust responses of the hydrological cycle to global warming *J. Clim.* **19** 5686–99

Huffman G J, Adler R F, Bolvin D T and Gu G J 2009 Improving the global precipitation record: GPCP version 2.1 *Geophys. Res. Lett.* **36** L17808

Ingram W 2010 A very simple model for the water vapor feedback on climate change *Q. J. R. Meteorol. Soc.* **136** 30–40

John V O, Allan R P and Soden B J 2009 How robust are observed and simulated precipitation responses to tropical ocean warming *Geophys. Res. Lett.* **36** L14702

Lambert F H, Stine A R, Krakauer N Y and Chiang J C H 2008 How much will precipitation increase with global warming *EOS* **89** 193–4

Liepert B G and Previdi M 2009 Do models and observations disagree on the rainfall response to global warming? *J. Clim.* **22** 3156–66

Liu S C, Fu C B, Shiu C J, Chen J P and Wu F T 2009 Temperature dependence of global precipitation extremes *Geophys. Res. Lett.* **36** L17702

Neelin J D, Munnich M, Su H, Meyerson J E and Holloway C E 2006 Tropical drying trends in global warming models and observations *Proc. Natl Acad. Sci.* **103** 6110–5

Richter I and Xie S P 2008 Muted precipitation increase in global warming simulations: a surface evaporation perspective *J. Geophys. Res.* **113** D24118

Santer B D *et al* 2007 Identification of human-induced changes in atmospheric moisture content *Proc. Natl Acad. Sci.* **104** 15248–53

Schneider U, Fuchs T, Meyer-Christoffer A and Rudolf B 2008 *Global Precipitation Analysis Products of the GPCC* (Deutscher Wetterdienst Offenbach am Main, Germany) (available at ftp://ftp-anon.dwd.de/pub/data/gpcc/PDF/GPCC_intro_products_2008.pdf)

Simmons A J, Willett K M, Jones P D, Thorne P W and Dee D P 2010 Low-frequency variations in surface atmospheric humidity, temperature, and precipitation: inferences from reanalyses and monthly gridded observational data sets *J. Geophys. Res.* **115** D01110

Stephens G L and Ellis T D 2008 Controls of global-mean precipitation increases in global warming GCM experiments *J. Clim.* **21** 6141–55

Trenberth K E 1998 Atmospheric moisture residence times and cycling: implications for rainfall rates and climate change *Clim. Change* **39** 667–94

Trenberth K E 2011 Changes in precipitation with climate change *Clim. Res.* **47** 123–38

Trenberth K E, Dai A, Rasmussen R M and Parsons D B 2003 The changing character of precipitation *Bull. Am. Meteorol. Soc.* **84** 1205–17

Trenberth K E, Fasullo J and Smith L 2005 Trends and variability in column-integrated atmospheric water vapor *Clim. Dyn.* **24** 741–58

Trenberth K E and Shea D J 2005 Relationships between precipitation and surface temperature *Geophys. Res. Lett.* **32** L14703

Vecchi G A and Soden B J 2007 Global warming and the weakening of the tropical circulation *J. Clim.* **20** 4316–40

Waliser D E and Gautier C 1993 A satellite-derived climatology of the ITCZ *J. Clim.* **6** 2162–74

Wentz F J 1997 A well-calibrated ocean algorithm for SSM/I *J. Geophys. Res.* **102** 8703–18

Wentz F J, Ricciardulli L and Hilburn K 2007 How much more rain will global warming bring? *Science* **317** 233–5

Wentz F J and Spencer R W 1998 SSM/I rain retrievals within a unified all-weather ocean algorithm *J. Atmos. Sci.* **55** 1613–27

Ye H and Fetzer E J 2009 Atmospheric moisture content associated with surface air temperatures over northern Eurasia *Int. J. Climatol.* **30** 1463–71

Zhou Y P, Xu K M, Sud Y C and Betts A K 2011 Recent trends of the tropical hydrological cycle inferred from Global Precipitation Climatology Project and International Satellite Cloud Climatology Project Data *J. Geophys. Res.* **116** D09101