Evidence for trends in the Northern Hemisphere water cycle

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[1] We have applied a unique water vapor tracing algorithm using observed precipitation and atmospheric analyses for the period 1979–2003 to estimate water budgets and recycling ratio (the fraction of precipitation over a region that originated as evaporation from the same region) over land areas across the globe. Over most mid- and high-latitude areas, a strong annual cycle of recycling ratio exists; low during winter when storm tracks are active, tropospheric circulation strong, and surface evaporation rates low, high during summer when winds are light and evaporation is greater. Trends in recycling ratio have been found over large areas at high-latitudes that are consistent with an expansion into spring of the warm-season regime of water vapor recycling. These trends are consistent with observed vegetation-related changes often attributed to global climate change, and are most evident over northern Europe and North America where the density of meteorological data influencing the atmospheric analyses is high. Less extensive trends are found in other seasons. Citation: Dirmeyer, P. A., and K. L. Brubaker (2006), Evidence for trends in the Northern Hemisphere water cycle, Geophys. Res. Lett., 33, L14712, doi:10.1029/2006GL026359.

1. Introduction

[2] A key question regarding climate change is whether the hydrologic cycle is accelerating [U.S. Global Change Research Program (USGCRP), 2001]. Numerous indicators of potential climate change have been found in the observational record over the past several decades, especially over high northern latitudes. These indicators have all been a reflection of a general warming trend expressed directly in the air temperature record [Jones and Moberg, 2003], or indirectly though increases in vegetation greenness [Tucker et al., 2001], productivity [Nemani et al., 2003], the lengthening of the growing season [Sparks and Menzel, 2002], or trends in the annual freeze and thaw cycles [McDonald et al., 2004]. Changes in the climate need not be limited to changes in the energy balance, but may also extend to the water cycle. The water cycle is inexorably linked with the cycles of carbon, nitrogen and other nutrients, with agriculture and the sustainability of ecosystems and human society. Any variations in the water cycle on time scales of one season to many years can have far-reaching consequences, and trends like those observed in atmospheric composition, temperature and vegetation may be especially significant.

[3] The recycling ratio, the fraction of precipitation over a defined area that originated as evapotranspiration from that same area, is a measure of the importance of local and regional feedbacks to the water cycle in that area. Regions with a high recycling ratio may be particularly sensitive to changes in soil moisture or evapotranspiration pathways. Recycling ratio has been calculated using bulk formulations based on monthly mean data and strong assumptions about horizontal and vertical mixing and the unimportance of nonlinear terms in the time mean moisture advection [e.g., Brubaker et al., 1993; Burde et al., 1996; Trenberth, 1999]. Tracer modeling provides a means to follow exactly the path of water within an atmospheric model during integration [Dryan and Koster, 1989]. It has been used in both regional [Giorgi et al., 1996] and global atmospheric models [Bosilovich and Schubert, 2001], but results are strongly affected by systematic errors and biases in the models. Isotopic analysis of precipitation samples can differentiate moisture that has evaporated from open water from that which has passed through the vascular systems of plants [Henderson-Sellers et al., 2002], but generally cannot provide information on specific points of origin of those isotopes.

[4] To investigate seasonal to inter-annual variations in the atmospheric branch of the global hydrologic cycle, we have developed a quasi-isentropic back-trajectory (QIBT) scheme as a means to estimate the location and magnitude of sources (evaporation) and sinks (precipitation) of water vapor [Dirmeyer and Brubaker, 1999; Brubaker et al., 2001]. Using over 25 years of global atmospheric reanalyses and observed precipitation data, we can examine trends in recycling ratio for each season and locate regions with significant changes.

2. Method and Data

[5] The QIBT approach is like that used to track air pollution [Merrill et al., 1986]. Water vapor is assumed to be a passive tracer between the locations of evaporation and condensation (precipitation), and is tracked backward in time from observed locations and times of precipitation events [Xie and Arkin, 1997].

[6] Data from the National Centers for Environmental Prediction (NCEP)/Department of Energy (DOE) reanalysis [Kanamitsu et al., 2002] are used to determine the paths of multiple sample parcels, and to estimate how much moisture was contributed by surface evaporation at each point along each parcel’s trajectory. These data cover the period from 1979 to 2004 at a spatial resolution of slightly under 2°. We make use of the sigma-level atmospheric state variables, surface pressure and latent heat flux fields at 6-hour intervals. These data are used to calculate precipitable water, potential temperature, and the advection of water vapor. Reanalysis precipitation is used to downscale the observed
monthly precipitation in time, and satellite-based CMORPH precipitation estimates [Joyce et al., 2004] are used to correct the diurnal cycle of reanalysis precipitation at low latitudes.

[7] This approach can provide estimates of the recycling ratio (the fraction of precipitation falling over a given area that originated as evaporation within the same area) [Dirmeyer and Brubaker, 2006] as well as the origins of moisture falling as rain over specific regions [Reale et al., 2001]. The QIBT method avoids drawbacks of bulk recycling calculations based on monthly mean data [Burde and Zangvil, 2001] because the meteorological fields are reported at a time interval that is fine enough to resolve the diurnal cycle and synoptic-scale weather events, and the QIBT method assumes evaporated and advected moisture are well mixed over large volumes. Unlike moisture tracers within free-running atmospheric circulation models [Bosilovich and Schubert, 2002], QIBT is constrained by observations.

3. Results

[8] Both QIBT and bulk approaches show that the high latitude land areas of the Northern Hemisphere are characterized by a strong annual cycle of the recycling ratio, with high values during summer and low in winter [Trenberth, 1999]. Winter in this region is dominated by low evaporation rates over the cold land, and frequent storms deriving their moisture from oceanic sources. During summer the winds weaken, land evaporation rates increase, and more locally evaporated moisture rains out within the region.

[9] To estimate seasonal values of recycling ratio, we calculate moisture sources for each land surface grid box at the resolution of the atmospheric reanalysis (approx 1.9° in latitude and longitude) over consecutive five-day periods for 25 years beginning in January 1979, and then total the source regions for the appropriate months. The portion recycled is the fraction of the total moisture source that is attributed to the given grid box itself. These values are then scaled to a common area to remove the latitude dependence of recycling ratio on the area of the grid box [Dirmeyer and Brubaker, 2006].

[10] The signs of warming that have been observed in vegetation at high latitudes are tantamount to an earlier onset of spring and/or a later onset of autumn — in other words, an elongation of the summer season. Given the strong annual cycle of recycling, with its maximum in summer, we might expect a similar signal in the atmospheric branch of the water cycle to be manifested as an increase in the recycling ratio, particularly during spring and fall. Figure 1 shows the trends in recycling ratio over the high latitudes of the Northern Hemisphere. Red and blue shades are used to indicate regions of statistically significant trends based on a Cox-Stuart test [McCuen, 2003] with a confidence level of 98%, yellow and green are at 93% (the stepwise nature of the Cox-Stuart test leads to discrete intervals of significance). Positive trends dominate over North America during every season, with especially strong and widespread trends over Canada and Alaska during spring. There are also strong positive trends over Scandinavia during spring and over Britain and much of North-Central Europe during fall. Trends are generally weaker and not as widespread over Asia, with negative trends predominant during winter and summer. It is worth noting that Europe and North America are much richer in dense high-quality meteorological observations than is Asia, so it is possible the overall lack of coherent signals over Asia could be data related.

[11] Table 1 shows the percentage of continental land area in three broad regions that show a statistically significant trend in recycling. The cutoff at 50°N maximizes the percentages in Table 1 across all regions. Trends are generally weak south of about 40°N. In North America, positive trends dominate in every season, and are especially prevalent during spring. Over Europe, the area of positive trend is at least twice as large as the region of negative trend in every season except during summer, when the negative trend dominates. In fact, there is a widespread area of negative trend over the Iberian Peninsula, just south of the region considered here. Negative trends are dominant over Asia during winter and summer. The predominance of positive trends over North America and Europe during spring and fall is consistent with the pattern expected from global warming. However, the back-trajectory approach is susceptible to non-random errors in the estimates of evap-

![Figure 1](image-url). Trend in the recycling ratio (percent per year during 1979–2003) scaled to a common reference area of 10^5 km^2. Trends significant at the 98% confidence limit are shown in shades of red (positive) and blue (negative), 93% in yellow (positive) and green (negative).
oration [Sudradjat et al., 2003], and evaporation is a rather unreliable variable in atmospheric reanalyses [Kalnay et al., 1996]. If the trends in recycling ratio are due solely to trends in the evaporation data, the results are less trustworthy than if the modifications in the water cycle are the result of changes in the advection of water vapor caused by shifts in the circulation of the atmosphere, a feature that is directly observable.

[12] The variance in the time series of seasonal mean recycling ratios explained by the variations in total surface evaporation and rate of moisture transport (the atmospheric circulation) can be estimated through correlations. Figure 2 shows the difference of explained variance (square of the correlation) between the moisture transport and surface evaporation contributions. Interannual variations in the recycling ratio are more strongly associated with changes in the atmospheric circulation in the red areas, while blue regions appear to be where evaporation variation is dominant. Over Asia there is a clear zonal banding: circulation effects dominate poleward of a mid-latitude band where evaporation predominantly controls recycling ratio. The evaporation-dominant band shifts northward in summer, but retreats from the Pacific coast. Patterns of evaporation and moisture transport are largely uncorrelated, suggesting that these two components are independent of one another.

[13] Comparison of Figure 2 to Figure 1 suggests that the trends over Canada during spring may have their origins in evaporation trends, but over Alaska, and for most of the regions of positive trends during summer and fall, it is the circulation that is contributing more of the signal. Examination of area-averaged time series of evaporation and moisture advection (not shown) show trends that corroborate this assessment. The negative trends in recycling over France and Spain during summer appear to be connected with reduced evaporation, consistent with an increasing tendency toward warm-season drought.

4. Discussion and Conclusions

[14] We have found positive trends in recycling ratio over much of the Northern Hemisphere high latitudes during the last 25 years. The positive trends in recycling ratio during spring and fall over North America and Europe are consistent with global warming trends. The positive recycling trends in spring over Canada correlate strongly with the evaporation from reanalysis, so the confidence in this signal is lower than for the other regions and seasons where the better observed atmospheric circulation appears to play a greater role. However, this region also corresponds well to an area of late 20th century drying found by Dai et al. [2004] based on precipitation and temperature trends, so there may be a real correspondence between the surface water balance and trends in recycling ratio over Canada.

[15] The trends are strongest during spring when snowmelt is significant. The evaporation fields used from reanalysis are undifferentiated between snow sublimation and other components of evapotranspiration. Likewise, precipitation data are used without differentiation between rain and snow. Although snow and snowmelt processes are not treated explicitly in this study, they are certainly relevant and worthy of further scrutiny. A positive feedback may exist between warming temperatures, earlier green-up and snowmelt at high-latitudes, augmenting the shift of recycling to a more summertime pattern earlier in the spring.

[16] Why are the trends in recycling ratio so strong and positive over North America, but not over Asia where observed vegetation trends are strongest [USGCRP, 2001]? The global atmospheric reanalyses do not represent directly interannual changes in vegetation. The atmospheric models used for reanalyses include simple land surface parameterizations with a mean annual cycle proxy of plant canopy resistance to transpiration. In high-latitude forests, transpiration begins for conifers when the soil thaws and for deciduous plants once they leaf out. Relative humidity can be very low in the preceding weeks, but substantially higher thereafter [Betts et al., 1999]. It may be that there is a shift in the timing of evapotranspiration onset and moistening of the lower troposphere concomitant with the trends in vegetation green-up. However, over Asia, there are few surface observations of this phenomenon supplying the reanalysis (for an example of the uneven coverage of surface meteorological stations reporting long-term climate observations, see New et al. [1999]). Over North America and Europe, on the other hand, the reanalysis assimilates many temperature and humidity observations that would reflect the warming and moistening accompanying increasing springtime evapotranspiration. The reanalysis also uses a simple rainfall assimilation to constrain soil wetness [Kanamitsu et al., 2002], which also has a stronger impact where precipitation observations are denser and of high quality. The sparseness of assimilated observations over northern Asia may prevent signals from appearing there.

[17] Unlike other observed trends, which can all be explained by a change in the thermal-radiative balance, this
result also suggests evidence of high-latitude changes in the
tropospheric circulation that affect the hydrologic cycle. Although global in coverage, this analysis is dependent on
the quality of the input data, including the gridded atmos-
pheric reanalysis, which is itself affected by the uneven
distribution of high-quality observations across the globe.
Therefore, the veracity of this assessment should be greatest
where the coverage of meteorological stations is greatest—
namely over Europe and North America. Given the sensitiv-
ty of high-latitude regions to projected impacts of global
warming, improved monitoring over the vast expanse of
northern Asia is desirable.

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