North American water and energy cycles

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[1]   Closure of the water and energy cycles for North America has been improved by combining several new data sets to provide an integrated view from 1979 to 2010. We use new global atmospheric reanalyses, top-of-atmosphere radiation, surface fluxes including evaporation E and precipitation P, streamflow and river discharge, and Gravity Recovery and Climate Experiment estimates of water storage and its tendency. The atmospheric moisture budget provides more reliable estimates and reproducible time series of $E-P$ than separate estimates of E and P. The excess of P over E is greatest in winter largely because of changing evapotranspiration, whereas precipitation is largest in summer. The annual mean loss of energy to space of $33\,\mathrm{W\,m^{-2}}$ is compensated for nearly equally by transports of dry static energy and latent energy onto land. The annual cycle (amplitude of $\sim20\,\mathrm{W\,m^{-2}}$) of implied downward surface flux corresponds to changes in surface and soil temperatures and seasonal snowmelt.
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1.   Introduction

[2]   It has been a challenge to determine all aspects of the hydrological cycle and their changes over time, although they are of considerable interest to society, especially as the climate changes. The water cycle is also a key part of the energy cycle through the evaporative cooling at the surface and latent heating of the atmosphere, and conservation constraints on the energy and water budgets can be used to provide a commentary on accuracy of observational estimates. *Trenberth et al.* [2007b] provided a synthesis of the understanding of some aspects of the global hydrological cycle and its annual cycle, both globally and for continents. In this article, we take advantage of improvements in a number of data sets and attempt to synthesize them by examining the mean, annual cycle, and variability of the various components. For energy, these include top-of-atmosphere (TOA) radiation from the Clouds and the Earth's Radiant Energy System (CERES) observations, atmospheric energy quantities and transports from new reanalyses and the implied surface fluxes, which may be evaluated using alternative surface flux products and changes in subsurface storage. For the water cycle, they include atmospheric quantities and transport from reanalyses, estimates of terrestrial runoff and discharge into the ocean,

and microgravity measurements from Gravity Recovery and Climate Experiment (GRACE) that provide estimates of changes in water storage. The focus is on land on continental scales to avoid the complexity associated with individual river basins, and in this article, we consider only North America.

[3]   An evaluation of the global hydrological and energy cycles in atmospheric reanalyses [*Trenberth et al.*, 2011] reveals that energy and water are not conserved in atmospheric reanalyses, although some are better than others. The more recent reanalyses from ERA-Interim (ERA-I) [*Dee et al.*, 2011] and Modern Era Retrospective-Analysis for Research and Applications (MERRA) [*Rienecker et al.*, 2011] use 4-D variational analysis (ERA-I) or an incremental update procedure (MERRA), which largely removes spin-up of the hydrological cycle that is present in other reanalyses. Hence, recent atmospheric reanalyses have improved markedly, but residual problems that persist must be accounted for. Reanalyses have the major advantage of postprocessing all of the data that are available after considerable quality control in a consistent data assimilation system. However, in the absence of a perfect model and observations, because the model state at any time is adjusted by the available observations to produce an analysis increment, quantities such as water and energy are not conserved (but are in nature). Moreover, the sea surface temperatures are specified as boundary conditions for the reanalyses, thereby providing an infinite reservoir of heat for the overlying atmosphere. Further, large spurious changes associated with the changing observing system greatly influence precipitation and some related variables. The transports of moisture from ocean to land were found to be much more resilient to such changes and more reliable and consistent across reanalyses. *Bosilovich et al.* [2011] have also carried out a comprehensive evaluation of the current reanalyses in parallel with a focus on MERRA and the global energy and water cycles.

[4]   For energy, we make use of CERES TOA observations [*Loeb et al.*, 2009], which limits the timeframe from March 2000 to 2010. GRACE data [e.g., *Syed et al.*, 2009, 2010] are available only after March 2002 for 66°N to 66°S. The global-gridded terrestrial water storage adjusted for signal modification due to filtering and truncation from *Landerer and Swenson* [2012] is used for 2003–2010. Using individual river basins enables observations of river discharge to be used, but the complex topography that bounds a basin may contribute to errors via the GRACE data, owing to its footprint size and "leakage" across the domain borders. Here, we overcome the latter problem to a large degree. Owing to some irregularities in the data over time arising from downtime during operation of the satellites, care was taken to use the actual dates of data. We also use the synthesized river discharge data from *Dai and Trenberth* [2002] and *Dai et al.* [2009] with modeling of the missing data in space and time, for 1990 to 2004, which is not concurrent in time. We assess the mean annual cycle, and the observed variability is used to place uncertainties on the values.

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[5] *Syed et al.* [2009] made GRACE-based estimates of terrestrial freshwater discharge for the limited period of 2003–2005 using the earlier-generation reanalyses for atmospheric transports, which suffer from multiple problems [*Sturaro*, 2003; *Trenberth et al.*, 2005, 2011]. Alternative estimates of water discharge from land [*Syed et al.*, 2010] for 1994–2006 are based on changes in the ocean mass and sea-level changes plus precipitation and surface evaporation flux estimates over ocean, but these have quite large uncertainties [e.g., *Trenberth et al.*, 2007a, 2011] and they are not constrained by conservation principles. A comprehensive approach to estimating the terrestrial water cycle [*Sahoo et al.*, 2011], albeit with satellite data, used multiple satellite remote sensing and ground-based products for 2003–2006 that were reconciled and merged into a single best estimate for 10 river basins based on uncertainty estimates. With the original data, closure of the water budget was not achievable and errors were of order 5–25% of the mean annual precipitation, with the biggest errors assigned to satellite precipitation products.

[6] The atmospheric conservation of moisture equation when vertically integrated in flux form is

$$\frac{\partial w}{\partial t} + \nabla \cdot \frac{1}{g} \int_0^{p_s} \mathbf{v} q \; dp \quad = \quad E - P \qquad (1)$$

where q is the specific humidity, $w = \frac{1}{g} \int_0^{p_s} q \, dp$ is the precipitable water (total column water vapor), E is the surface evaporation, and P is the net surface precipitation rate. In addition to water vapor, atmospheric liquid water and ice components are also included, although these are mostly small. The whole equation can be expressed also in terms of energy by multiplying by L, the latent heat of vaporization. Because the tendency term is small, the primary balance is thus between the freshwater flux E-P and the moisture divergence. The surface water conservation equation is

$$\partial S / \partial t = P - E - R \qquad (2)$$

where S is the subsurface storage of water substance and R is the runoff. Hence, if the changes in atmospheric and surface storage are negligible, the balance is between atmospheric moisture convergence and runoff.

2. Transports of Energy From Ocean to Land

[7] We ensure that the area of land is the same across all reanalyses and use the same land-sea mask at T63 resolution. The area of North America is 1.94×10^{13} m^2. Accordingly 1 mm day^{-1} in rainfall converts to 7101 km^3 yr^{-1}, 0.6 Eg mo^{-1}, or 0.225 Sverdrup (10^6 m^3 s^{-1}). In the figures, the spread around the mean annual cycle is determined from the interannual variability and given as 1 standard deviation (not a standard error). Hence, the standard error of the mean (SEM) values depends on the number of years. Because the river discharge is for a different period, we make use of the full 1948–2004 record to compute the standard deviation of 8-year means in estimating a SE of the residual of the water budget. Evaluations of the reanalyses [*Trenberth et al.*, 2011] provide information on some of their errors, but structural errors are difficult to determine. They are partly revealed by comparisons among different data sets and also by how well closure of budgets is achieved—as a necessary but not sufficient constraint.

[8] For transports of energy from ocean to land, in the extratropics, strong westerlies in winter transport heat and moisture from ocean to land, highlighting the maritime versus continental influences. In summer, land is typically warmer than the ocean and sea breezes may develop that transport heat from land to ocean although compensated by moisture transport to land as part of the hydrological cycle. At lower latitudes in monsoons, there is a transport of moisture from ocean to land as latent energy (*LE*) that gives rise to diabatic heating in the monsoon rains, and the monsoon circulation itself transports dry static energy (*DSE*) from land to ocean in summer. A characteristic of these kinds of flows is a very large cancellation between *LE* and *DSE* transports [*Trenberth and Stepaniak*, 2003] with an overall net transport of energy from land to ocean, including a moisture component as part of the hydrological cycle.

[9] The annual cycle and annual means of several components of the energy quantities for North America (Figure 1) reveal the annual mean absorbed solar radiation (ASR) as ~193 W m^{-2}, whereas outgoing longwave radiation (OLR) is slightly larger at 226 W m^{-2} so that the annual mean TOA energy imbalance is -33 W m^{-2}. This has to be compensated for by transport of energy from the ocean to land. The mean annual cycle shows the ASR to be in phase with the sun, whereas OLR peaks in July, in phase with the surface temperature, and net incoming radiation at the TOA (R$_T$) peaks in early June with an amplitude of close to 100 W m^{-2}.

[10] The total atmospheric energy (*TE*) is dominated by the combination of internal and potential energy, with a very small kinetic energy component, and a modest *LE* (related to atmospheric moisture) component peaks in July in phase with temperature; therefore, the tendency is positive from January to June and drops sharply in September (Figure 1). The divergence of total energy is dominated by that of the *DSE*, with a small *LE* component that peaks in July. The annual mean total energy convergence is 31 W m^{-2} (note that the divergence is plotted and is negative) and is contributed to nearly equally by the *DSE* and *LE* components.

[11] As a result, the annual mean net surface energy imbalance, expressed as the downward surface energy flux F_s, is -2 W m^{-2}, which is composed mostly of errors arising from lack of closure of the other terms, as estimates of net heating of land are more than an order of magnitude smaller. However, there is a very distinctive annual cycle to the residual that may be largely real and associated with the annual cycle of the warming of land. We have examined the National Center for Atmospheric Research Community Climate System Model [*Gent et al.*, 2012] over North America and compared the maps of the local F_s from the residual calculation with those from a coupled model simulation. The model itself has some unrealistic features owing to poorly simulated clouds. The local agreement between F_s from our analysis and the model is not very good (not shown), although reasonable qualitative agreement is achieved. We conclude that the overall residual annual cycle likely has a major real component (Figure 1) but likely cannot be downscaled to regional scales.

3. Transports of Moisture From Ocean to Land

[12] The main components of the moisture budget on land are P, E, and the moisture transport from ocean to land (Figure 2). The displayed E and P from ERA-I are known
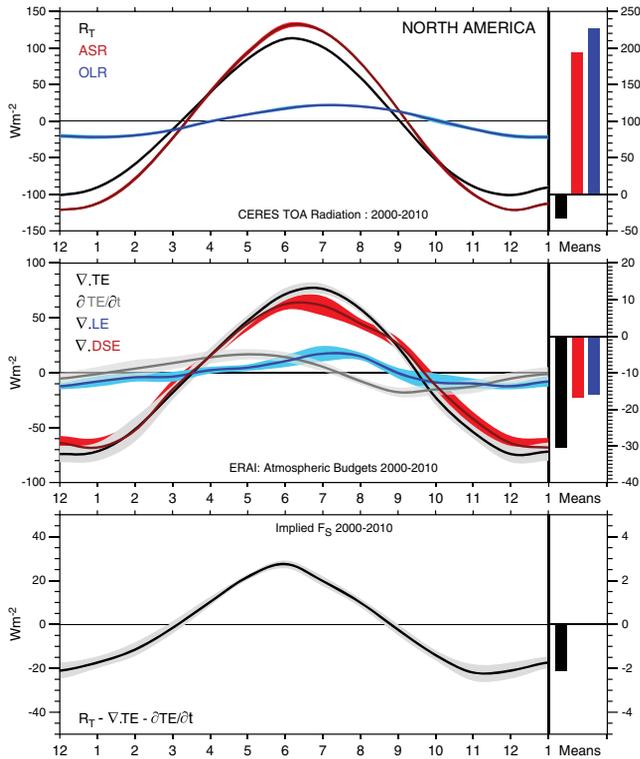
Figure 1. Regional energy budget terms for North America in W m^{-2} with the annual means as bars (right) and the departures from the annual means (left). The shading denotes 1 standard deviation spread about the mean. (top) TOA radiation for ASR (red), OLR (blue), and net (R$_T$) (black) for 2000–2010. (middle) Divergence of total energy (black), *LE* (blue), and *DSE* (red) and the rate of change in total energy (gray) for 2000–2010. (bottom) The residual computed is the implied surface energy flux into the Earth from the net downward radiation minus the divergence of total energy minus the change in energy storage.

the interannual variability, a smoother was first applied to the values before differentiating to avoid 2-month noise. It follows that the annual mean of the GRACE tendencies are zero by design, although in some regions, such as Greenland, this is far from true and the nonstationary component would have to be extracted separately.

[15] Also given in Figure 2 (bottom) is the residual as a dashed curve. The annual mean residual is -0.22 mm day^{-1}, which is equivalent to 1562 km^3 yr^{-1}. The monthly mean residual is somewhat noisy and may have a component related to the different temporal character of the various time series. The largest monthly total residual errors of -0.5 mm day^{-1} occur in July when total *P-E* is -0.1 mm day^{-1}, whereas *Trenberth et al.* [2007b] found values of 0.3 mm day^{-1}, which would reduce the residual error to <0.1 mm day^{-1}. ERA-I has been somewhat deficient in precipitation in the Midwest in summer and likely has too much evaporation [*Albergel et al.*, 2012]. The latter relates to how the soil moisture in the model is analyzed and restored, and this affects both the moisture and the energy budgets. The annual
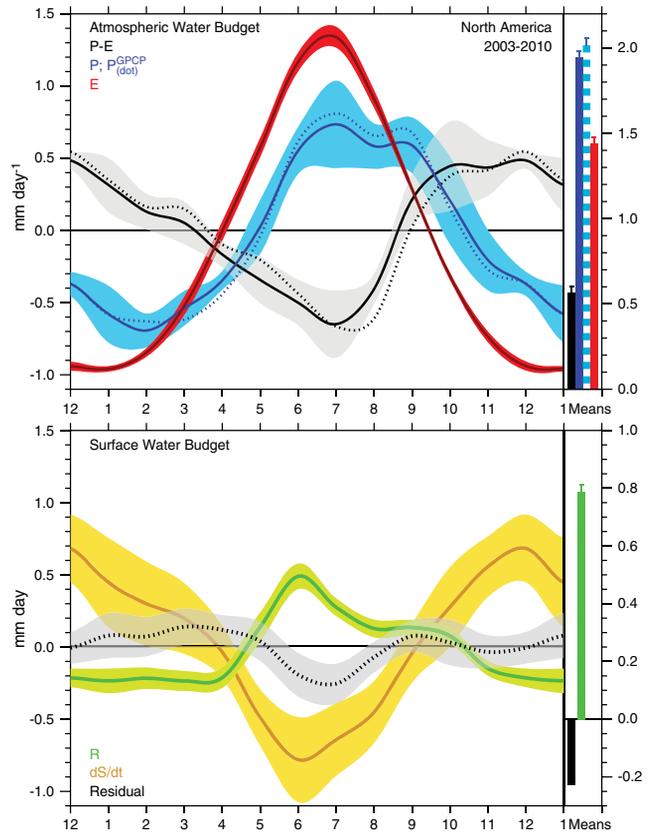
Figure 2. Moisture budget terms for North America in mm day^{-1} with the annual means as bars (right) and the departures from the annual means (left). (top) Precipitation from ERA-I (blue) and dotted from GPCP (dashed; right), evaporation from ERA-I (red), *P-E* from the moisture budget (black), and the convergence of the *LE* flux (black dotted), all for 2003–2010. (bottom) River discharge *R* into the oceans (green) for 1990–2004, change in water storage *S* on land (orange) for 2003–2010, and the residual (black dotted or solid; right) computed as *P-E – dS/dt – R*. The shading or whisker plot denotes 1 standard deviation spread about the mean, except for *R* that includes the interannual variability of 8-year means and the residual that is an estimated SEM.

to have some problems [*Trenberth et al.*, 2011]; hence, *P* from the Global Precipitation Climatology Project (GPCP) [*Huffman et al.*, 2009] is also presented (dotted). The *E-P* from the moisture budget (Eq. 1) is considered more reliable and accurate [*Trenberth et al.*, 2011] and the convergence of the vertically integrated moisture flux is also shown (dotted). The difference between *P-E* and moisture convergence is the moisture tendency term (see Eq. (1)).

[13] In *Trenberth et al.* [2011], an evaluation of the annual mean *P-E* from the ERA-I and MERRA reanalyses model revealed spurious negative values on land, which arise mainly in summer over North America. Negative values could be possible if irrigation and withdrawal of aquifer waters were large, but comparisons with GPCP reveal that the summer precipitation is too low in both reanalyses. Nevertheless, this error partly cancels when integrating over the entire continent; furthermore, neither reanalyses used herein explicitly accounted for irrigation or groundwater withdrawal.
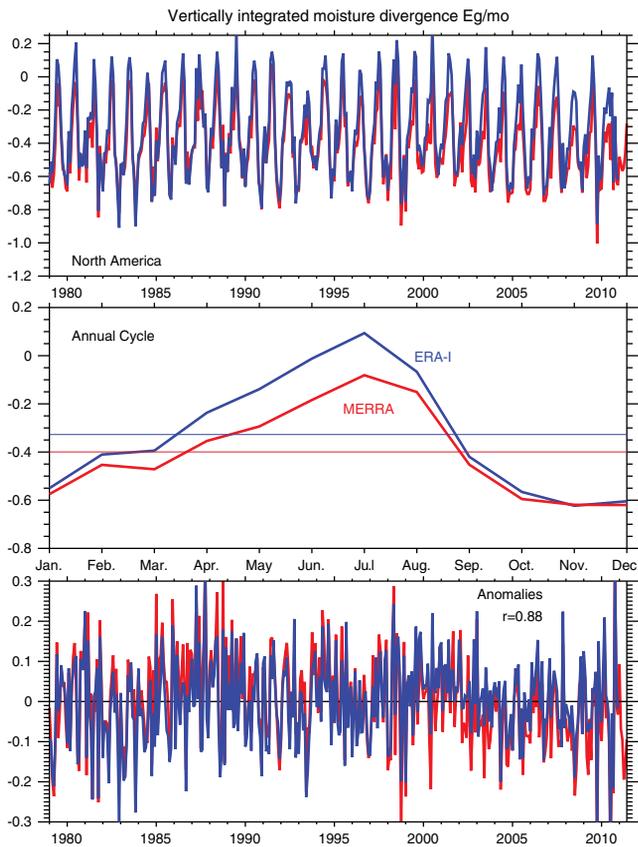
[14] In Figure 2 (bottom), the net river discharge from North America into the ocean is given along with the changes in water storage derived from GRACE. To obtain the tendencies, a harmonic fit was made to the mean annual cycle of the water storage and differentiated with the first four harmonics (12, 6, 4, and 3 months) retained. To obtain the standard deviation of

Figure 3. Vertically integrated moisture divergence for North America in Eg mo^{-1} from ERA-I (blue) and MERRA (red). (top) Monthly mean total. (middle) Mean annual cycle from 1979 to 2010. (bottom) Monthly anomalies.

cycle of river discharge is especially distorted by dams, which create storage regions, and these should be picked up by the GRACE observations, although this could be upset by the different time frame for the two sets of observations. According to this analysis, the net convergence of atmospheric moisture into North America is 0.58 mm day^{-1} (Figure 2), which is equivalent to 16 W m^{-2} (Figure 1). The *LE* transport accounts for about half of the deficit in TOA energy imbalance over North America.

4. Interannual Variability

[16] The moisture convergence over North America from recent atmospheric reanalyses has become much more reliable, owing to assimilation of moisture information from SSM/I and water vapor channels, and provides a superior estimate of *E-P* from the moisture budget compared with any estimates from *P* and *E* separately [*Trenberth et al.*, 2011]. Accordingly, Figure 3 presents the time series of the moisture divergence for North America from two reanalyses, ERA-I and MERRA. The units are Eg mo^{-1}, which correspond to 1.63 mm day^{-1} for North America. It is known that MERRA suffers from spurious changes in 1998 and 2001 as the observing system changed via new instrumentation on satellites [*Trenberth et al.*, 2011]. After 1998, MERRA values run consistently below those of ERA-I, whereas, before then, they are higher. Nevertheless, the correlation of monthly values is 0.88 and the level of agreement can readily be seen in both

the total and the departures from the annual mean. The overall annual means themselves differ somewhat at -0.33 Eg mo^{-1} for ERA-I and -0.40 Eg mo^{-1} for MERRA and these values vary over time. For the 1990s, the ERA-I value is -0.36, and for 2002–2008, the value is -0.39 Eg mo^{-1}, whereas corresponding MERRA values are -0.52 and -0.44 Eg mo^{-1}. The runoff from *Dai et al.* [2009] is 0.42 Eg mo^{-1}. *Syed et al.* [2009] have values of 0.50–0.59 Eg mo^{-1} for 2003–2005 using two earlier-generation reanalyses. Hence, the newer values are somewhat lower than previous estimates, including most earlier ones reviewed by *Syed et al.* [2009]. Their short timespan accounts for some of the differences, as can be seen in Figure 3.

[17] The variability in anomalies (Figure 3, bottom) is dominated by monthly variations. A low-pass filter has been applied (not shown) to emphasize the interannual variations, and wetter spells can be seen, such as from 1999 to 2002, whereas the driest prolonged spell is from 1982 to 1985 based on ERA-I anomalies. However, these annual variations are <0.04 Eg mo^{-1}: <10% of the annual mean, highlighting the large cancellation that often occurs when much larger regional dry or wet spells occur, indicating the dominant role of the changing atmospheric circulation. Recent standout anomalies occur in October 2009, when strong moisture convergence anomalies were present (Figure 3), and it was very wet most places across the United States. July 2010 was very wet in Texas and the Midwest. In contrast, in October 2010, it was very dry in Texas, Florida, and the Midwest, although it was wetter than normal in California, Nevada, and New England.

5. Conclusions

[18] Taking advantage of improved data sets, we have provided a new energy and water budget study of North America, showing that the overall balance is much closer to being achieved than in previous studies. For North America, there is an annual mean loss of energy to space of ~33 W m^{-2}, which is compensated for nearly equally by transports of *DSE* and *LE* onto land. The excess of *P* over *E* is greatest in winter and lowest in summer largely because of changing evapotranspiration, whereas precipitation is largest in the summer months. The total energy convergence has an annual cycle amplitude of order 75 W m^{-2} and is dominated by the *DSE* component (~60 W m^{-2}). There is an implied distinctive downward surface flux annual cycle with an amplitude of ~20 W m^{-2}, which corresponds to the changes in surface and soil temperatures and seasonal snowmelt. The moisture budget has 10% errors and further improvements are desirable and possible.

[19] The atmospheric reanalyses have improved substantially and produce quite good results for precipitation over land, but *E*, *P*, and *E-P* based on the model output disagree and are unreliable and probably should not be used without constraints [see *Trenberth et al.*, 2011]. However, as shown by *Trenberth et al.* [2011] and the reproducibility in Figure 3, *E-P* from the moisture budget is far more promising. Nevertheless, ERA-I is deficient in precipitation in summer and has too much evaporation. Analyzing both energy and moisture budgets together has advantages owing to the common *LE* component, and synthesizing with other data sets helps close the moisture budgets in physically consistent ways.

[20] The improvement in large-scale moisture convergence suggests that it can be used on regional scales. However, divergence of atmospheric flow is an inherently noisy quantity and is much less reliable locally. Whether the GRACE data can be applied regionally is still an issue owing to the need for spatial filtering and leakage issues [*Landerer and Swenson*, 2012], and streamflow records are not as complete as desirable to complete the moisture budgets alone. However, because the *E-P* from the atmospheric moisture budget is so much better than any combination of *E* and *P* estimated independently from observations or bulk surface fluxes, it may be used to constrain the other products. Good models can also be used to help downscale information in physically consistent ways, as in *Sahoo et al*. [2011]. Prospects are good for improving information and knowledge about water resources and their variations.

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Errata

In the section4, para [17] it states:

"and wetter spells can be seen, such as from 1999 to 2002,
whereas the driest prolonged spell is from 1982 to 1985"

but should read"
"and drier spells can be seen, such as from 1999 to 2002,
whereas the wettest prolonged spell is from 1982 to 1985"