NEWs Water and Energy Cycle Climatology Project Status Update

Matthew Rodell, Tristan L'Ecuyer, and the NEWs Water and Energy Cycle Climatology Team
The State of the Global Water and Energy Cycles

**Premise:** In order to evaluate water and energy cycle consequences of climate change, we must establish the current "state of the global water/energy cycle".

**Methods:** Use modern, observation-integrating products and associated error-analyses to develop a monthly climatology of W&E cycle components for each continental/oceanic to global scale region.

**Outcomes:** (1) A benchmark for W&E cycle / climate change studies and model assessments. (2) Quantitative graphical depictions of the water and energy cycles.
Global Precipitation Climatology Project (GPCP)

A global data set project under WCRP/GEWEX
Adler, Huffman, Gu, Chiu, Xie, Ferraro, Schneider

Monthly Analysis of Global Precipitation Using Satellite and Gauge Information (1979-present)

GPCP data used in > 1200 journal articles

Monthly 2.5° resolution; pentad and daily products also

Low-orbit microwave over ocean and land adjusting geo-IR and merged with gauges over land with sounder estimates at high latitudes

Huffman et al. (2009) GRL

http://www.ncdc.noaa.gov/oa/wmo/wdcamet-ncdc.html
http://precip.gsfc.nasa.gov

Matt Rodell
NASA GSFC
Development and diagnostic analysis of a multi-decadal global evaporation product for NEWS

Eric F Wood

Panel a: Annual terrestrial ET using the ISCCP data and a Penman-Monteith RS model
Panel b: 1984-2007 terrestrial and global ET estimates using PM/ISCCP. Note comparison to VIC LSM and global P~2.8 mm/day
Panel c: Comparing remote sensing to operational models being assessed by NEWS
• Near-surface air temperature and humidity
  – Roberts et al. (2010) neural net technique
  – SSM/I only from CSU brightness temperatures
    (thus only covers 1997 - 2006)
  – Gap-filling uses MERRA variability – 3 hour

• Winds
  – Uses CCMP winds (cross-calibrated SSM/I, AMSR-E, TMI, QuikSCAT, SeaWinds)
  – Gap-filling uses MERRA variability – 3 hour

• SST
  – Pre-dawn based on Reynolds OISST
  – Diurnal curve from newly developed parameterization (Clayson and Bogdanoff, 2010)

• Uses neural net version of COARE 3.0 flux model to compute fluxes
NASA’s Modern Era Retrospective-analysis for Research and Applications (MERRA)
Mike Bosilovich and Pete Robertson

- 1979-present (continuing as it is feasible)
- $\frac{1}{2}^\circ$ horizontal resolution (72 model levels, sfc-strat)
- 1 hourly surface and 2D diagnostic data
  - Including complete budgets and extensive meteorology, lowest model level states
- 6 hourly 3-Dimensional atmospheric analysis
- 3 hourly 3-D model background diagnostics, coarse resolution
- >70 Tbs online storage, many portals (incl. subsetter) up to real time processing; 32 years of data
- NEW! Gridded observations and innovations from the data assimilation
**GOAL:** Integrate ground and satellite observations within sophisticated numerical models to produce physically consistent, high resolution fields of land surface states and fluxes.

**USES:** Weather and climate forecast initialization studies, water resources applications, hydrometeorological investigations.

**AVAILABILITY:** Output from 1979-present simulations of Noah (1/4°; 1°), CLM (1°), and Mosaic (1°), and VIC (1°), at http://disc.gsfc.nasa.gov/hydrology/index.shtml.
Global Continental Runoff
Dennis Lettenmaier and Liz Clark

Following Dai et al. 2009:
- Runoff estimated from 920 streamflow gages.
- Gaps in record filled in based on regression with VIC modeled runoff.
- Unmonitored areas filled in based on ratio of gaged flow and VIC modeled runoff.

Monitored basins
Terrestrial water balance
\[ \Delta S_{\text{LAND}} = P - E - R \]

Atmospheric water balance
\[ \Delta W = E - P - \text{div}Q \]

Coupled land-atmosphere water balance
\[ R = \Delta S_{\text{LAND}} - \Delta W - \text{div}Q \]

- Previously had to assume that \( \Delta S_{\text{LAND}} = 0 \) and apply at annual time scales
- Now we have \( \Delta S_{\text{LAND}} \) from GRACE so we can compute monthly time series
- \text{div}Q and \( \Delta W \) from atmospheric analyses
- Implicitly includes all surface and subsurface outflows, including water management

[Syed et al., 2005, 2007, 2009]
Atmospheric Vapor Flux
Kyle Hilburn and Frank Wentz; Tim Liu

- **PMWC**
  - “Passive Microwave Water Cycle” (Version-01b)
  - Resolution: 0.25-deg, monthly maps, global
  - Date Range: 1987-2009 (SSM/I)
  - Parameters: WVT spd, dir, div; evap, precip, vapor
  - Technique: adjust WVT to match E-P, uses CCMP winds (derived from RSS winds)
  - Note: update planned to PMWC using all new RSS Version-7 geophysical retrievals (from SSM/I, SSMIS, TMI, AMSR-E, and WindSat)

- **Liu**
  - Tim Liu (Version 3)
  - Resolution: 0.5-deg, daily maps, global (+/- 75 deg)
  - Date Range: 1999-2008 (QuikSCAT)
  - Parameters: WVT u,v, div
  - Technique: Support Vector Regression, uses 850 mb winds
GRACE Derived Terrestrial Water Storage Variations
Don Chambers, Jay Famiglietti, et al.

GRACE Science Goal: High resolution, mean and time variable gravity field mapping for Earth System Science applications

Instruments: Two identical satellites flying in tandem orbit, ~200 km apart, 500 km initial altitude

Key Measurement: Distance between two satellites tracked by K-band microwave ranging system

Key Result: Information on water stored at all depths on and within the land surface

GRACE measures changes in total terrestrial water storage, including groundwater, soil moisture, snow, and surface water. (credit: Rodell/NASA)
**Atmospheric Total Water Vapor**
Xiang Gao, Eric Fetzer, Adam Schlosser, and Van Dang

**Instruments:**
The Atmospheric Infrared Sounder (AIRS) and the Advanced Microwave Scanning Radiometer for EOS (AMSR-E) are two of six instruments on board the NASA Aqua satellite. AIRS’ spectral resolution is 100 times greater than previous infrared sounders and can create three-dimensional global distribution of water vapor. AMSR-E is a twelve channel, six frequency, passive microwave radiometer system to measure geophysical parameters, including total precipitable water vapor (TPWV) over ocean.

**Data/Processing:**
✧ 3-hourly Version 5 Level 2 (vector) total precipitable water vapor at 1-degree from AIRS and AMSR-E have been binned into 1x1 degree grids, and averaged to monthly for estimates of the annual amplitude of atmospheric moisture storage over various continents and ocean basins.
✧ Due to data gaps in the Level 2, 3-hourly AIRS/AMSR-E data, time series of the 5-day average centered on the first day of each month has been generated to estimate the monthly atmospheric moisture storage change.

**Accuracy/Error:**
✧ AIRS: Comparisons with radiosondes show AIRS TPWV uncertainties are $\leq 5\% \pm 10\%$ globally.
✧ AMSR-E: AMSR-E TPWV uncertainties, also from radiosondes comparisons, are $\leq 5\% \pm 20\%$.
✧ Smaller RMS uncertainties are expected for the averaged data used in this analysis.
A fundamental question in global climate research is: “do our current estimates of the different processes in the earth’s water and energy cycles indicate a consistent, balanced state?” For example, based upon observations over a given region, does the import of moisture in the atmosphere by horizontal wind motions and by evaporation from the earth’s surface, less export by precipitation, balance the change in atmospheric moisture storage? Similarly, at the earth’s surface, does the flux of precipitation into the ground over a given region, less evaporation from the surface and runoff of water out of the region, balance the change in ground water storage? Using a combination of satellite and earth-based observations, the NEWS Climatology working group has evaluated these water cycle processes, but generally the component fluxes/storages do not balance exactly because of uncertainties in measurement techniques. The analysis method presented here is one approach for optimally adjusting the fluxes/storages within their uncertainties to obtain expected balance.

**Analysis Method:** the method of Lagrange multipliers is used to adjust water flux/storage terms to achieve regional balance in the atmosphere and at the earth’s surface simultaneously. If the observed fluxes/storages are represented by a vector $F_{\text{obs}}$ and the “balanced” fluxes/storages are represented by $F$, and if the balance conditions are expressed $KF = 0$, where $K$ is a matrix operator representing expected balance conditions for $F$, then

$$
\Lambda = 0.5(F - F_{\text{obs}})^T S_{\text{obs}}^{-1} (F - F_{\text{obs}}) + \lambda^T K F
$$

is the Lagrangian that can be minimized (analytically) to obtain the “balanced” $F$ and the Lagrange multipliers $\lambda$. The uncertainties in $F_{\text{obs}}$ are included in the error covariance matrix $S_{\text{obs}}$. A general IDL code (with documentation) has been written to find $F$ and $\lambda$ for any number of input flux/storage terms and balance conditions.

**Application:** Jan.10-Year Mean North American Water Budget

**initial:**  
Precip. = $4.78 \pm 0.32$ cm/mo.; Evap. = $1.13 \pm 0.36$ cm/mo.;  
Atmos. import = $2.02 \pm 1.82$ cm/mo.;  
Atmos. storage = $-0.10 \pm 0.02$ cm/mo.;  
Runoff = $1.03 \pm 0.28$ cm/mo.; Ground store. = $2.05 \pm 0.20$ cm/mo.

**balanced, in cm/month:**

**Atmosphere**

Atm. Store: -0.10  
Atm. Import: 3.15

**Earth**

Precip: 4.60  
Evap: 1.36  
Grnd. Store: 2.11  
Runoff 1.14

**Results and Implications:**

- analyzed (balanced) fluxes/storages are within estimated uncertainties.
- results are consistent with OA framework implemented by T. L’Ecuyer.
- water and energy cycles can be coupled in this solution framework.
- regional (2D) and 3D budgets can also be coupled.
- budget-constrained analyses could optimally combine both observations and reanalysis estimates.
### Water Budget Example: North America, January

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<tr>
<th>Continent</th>
<th>P</th>
<th>E</th>
<th>R</th>
<th>dS</th>
<th>Residual</th>
<th>Expected Error</th>
<th>Convergence</th>
<th>dW</th>
<th>Residual</th>
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<td>4.82</td>
<td>1.54</td>
<td>1.19</td>
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<td>4.78</td>
<td>0.32</td>
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<td>0.12</td>
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<td>2.28%</td>
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**Key to Source**

- GLDAS, 4 models: Beaudoin and Rodell
- Dai and Trenberth: Gao and Schlösser
- GRACE: Chambers and Famiglietti
- MERRA: Bosilovich, Mocko, and Beaudoin
- GPCP: Gu, Huffman, and Adler
- PMWC: Hiburn and Wentz
- AIRS: Gao and Schlösser
- AMSR-E: Gao and Schlösser
- QSCAT: Liu
- Liu
- Gauge/VIC: Clark and Lettenmaier
- Princeton: Sheffield and Wood
- SeaFlux: Clayson
- Water Budget: Famiglietti

**Contributors**

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NASA GSFC
Global mean water fluxes (1,000 km$^3$/yr) at the start of the 21st century. Best guesses based on observational products and data integrating models with error estimates. When water balance is enforced, uncertainty decreases. Trenberth et al. (2006) for comparison.
Precipitation (downward arrows), evapotranspiration (upward arrows), runoff (outward arrows), and annual amplitude of terrestrial water storage (white boxes) in km$^3$/yr. Background shows GRACE-based amplitude of the annual cycle of terrestrial water storage (cm/yr). Antarctica: $P=2.8 \pm 0.4$ $E=0.1 \pm 0.0$ $Q=2.7 \pm 0.6$ AmpS=$0.6 \pm 0.3$
Precipitation (black), evapotranspiration (red), runoff (blue), and anomaly of terrestrial water storage (green) in km$^3$. 

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Oceanic Mean Annual Water Fluxes

Precipitation (downward arrows) and evaporation (upward arrows) in km$^3$/yr.

Matt Rodell
NASA GSFC
Global LH ~ 13 Wm\(^{-2}\) smaller than Trenberth et al.
Global SH ~ 9 Wm$^{-2}$ larger than Trenberth et al.
Downwelling longwave and shortwave radiation are ~ 10 Wm\(^{-2}\) and 6 Wm\(^{-2}\) larger than Trenberth et al. (2009) estimates, respectively.
Relative to Trenberth et al:

- DLR ~ 10 Wm\(^{-2}\) larger.
- SSR ~ 6 Wm\(^{-2}\) larger.
- LH ~ 13 Wm\(^{-2}\) smaller.
- SH ~ 9 Wm\(^{-2}\) larger.

⇒ Surface energy imbalance of ~19 Wm\(^{-2}\)
Uncertainties

- Simple error estimates based on standard deviation of multiple products

- In some cases dataset variability is smaller than imbalances.

- Error modeling is important and is now being done for several products
Energy Budget revisited

Trenberth et al. (BAMS 2009)
Balance Constraint

General budget equation:

\[ R = \sum_{i=1}^{M} F_i - \sum_{o=1}^{N} F_o \]

"Optimal" solution minimizes the cost function:

\[ J = (F - F_{\text{obs}})^T S_{\text{obs}}^{-1} (F - F_{\text{obs}}) + \frac{(R - R_{\text{obs}})^2}{\sigma_R^2} \]

Minimum occurs when:

\[
F = F_{\text{obs}} - S_F K^T S_y^{-1} (R_{\text{obs}} - KF_{\text{obs}}) \\
S_F = \left(K^T S_y^{-1} K + S_{\text{obs}}^{-1}\right)^{-1}
\]

Example: Surface energy budget

\[ S = F_{\text{LW}}^{\downarrow} + F_{\text{SW}}^{\downarrow} - F_{\text{LW}}^{\uparrow} - LH - SH \]

<table>
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<tr>
<th>Flux</th>
<th>Original Observation</th>
<th>Optimized Value</th>
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<tr>
<td>$F_{\text{LW}}^{\downarrow}$</td>
<td>344 ± 9</td>
<td>338.6 ± 7.8</td>
</tr>
<tr>
<td>$F_{\text{SW}}^{\downarrow}$</td>
<td>167 ± 10</td>
<td>160.3 ± 8.3</td>
</tr>
<tr>
<td>$F_{\text{LW}}^{\uparrow}$</td>
<td>397 ± 4</td>
<td>398.1 ± 3.9</td>
</tr>
<tr>
<td>LH</td>
<td>74 ± 8</td>
<td>79.4 ± 7.8</td>
</tr>
<tr>
<td>SH</td>
<td>18 ± 6</td>
<td>20.4 ± 5.6</td>
</tr>
<tr>
<td>S</td>
<td>1 ± 1</td>
<td>1.06</td>
</tr>
</tbody>
</table>
“Optimized” Estimates

Trenberth et al. (BAMS 2009)

Surface Budget: Original = 22 Wm$^{-2}$ Final = 1.07 Wm$^{-2}$
Preliminary Conclusions

• Over most regions and time periods, the “best guess” (not balanced) water budget residual is within the uncertainty range expected based on individual error estimates.

• By forcing closure of the terrestrial, atmospheric, and oceanic water budgets, uncertainty in the flux estimates are reduced.

• Our estimates compare favorably with Dai and Trenberth estimates.
Objectives for This Meeting

• Agree on Best Guess estimates
• Agree on error estimates
• Set deadline for updating datasets
• Review optimization method for forcing water/energy balance
• Determine how to present results in manuscripts (esp. figures and tables) and ensure consistency between EB and WB
• Review manuscript outlines and distribute writing assignments
• Discuss future directions
  - interannual variability and mechanisms
  - smaller scales
  - feedback of first analysis to dataset providers leading to dataset refinements and updated analysis