A Long-term hydrologically based dataset of land surface fluxes and states for the conterminous U.S.: Update and extensions

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ABSTRACT

We describe a publicly available, long-term (1915 – 2011), hydrologically consistent data set for the conterminous United States, intended to aid in studies of water and energy exchanges at the land surface. These data are gridded at a spatial resolution of 1/16 degree latitude-longitude and are derived from daily temperature and precipitation observations from approximately 20,000 NOAA Cooperative Observer (Co-op) stations. The available meteorological data include temperature, precipitation, and wind, as well as derived humidity and downwelling solar and infrared radiation estimated via algorithms that index these quantities to the daily mean temperature, temperature range, and precipitation, and disaggregate them to three-hourly time steps. Furthermore, we employ the Variable Infiltration Capacity (VIC) model to produce three-hourly estimates of soil moisture, snow water equivalent, discharge, and surface heat fluxes. Relative to an earlier similar data set by Maurer and others, we have: a) extended the period of analysis (1915-2011 versus 1950-2000), b) increased the spatial resolution from 1/8° to 1/16°, and c) used an updated version of VIC. The previous data set has been widely used in water and energy budget studies, climate change assessments, drought reconstructions, and for many other purposes. We anticipate that the spatial refinement and temporal extension will be of interest to a wide cross-section of the scientific community.
1.0 Introduction

Increased computational capabilities, the availability of new data sources such as remote sensing, and better understanding of the Earth system have resulted in considerable improvements in the ability to represent long-term variations in land surface water and energy fluxes and state variables. Earth system models require, among other things, consistent observational data sets for model testing and diagnosis. Furthermore, predictions of alternative future scenarios of land surface conditions resulting from changes in climate and/or land cover require benchmark historical data against which to evaluate.

We describe an observational data set (herein L13) that provides a means to analyze and verify hydroclimatic predictions as well as to drive land surface models, along with fluxes and state variables from the Variable Infiltration Capacity (VIC) model. The L13 data set is based on the methods of Maurer et al. (2002 – herein M02), who developed a set of publicly available gridded meteorological data from ground-based measurements, together with model-derived hydrologically consistent surface fluxes and states. M02 spanned the period 1/1/1949 – 7/31/2000 (~51.5 years) at a 1/8° latitude-longitude spatial resolution. The L13 data set described here refines the spatial resolution to 1/16°, extends the period of record backwards to 1/1/1915 and forward to 12/31/2011 (97 years), and provides fluxes and states from an updated version of the VIC land surface model. The significance of each of these aspects is described below, followed by a summary of evaluations of the new dataset relative to M02.

An examination of the most widely cited studies that reference and/or use the M02 data (in total, over 300 Web of Science citations) suggests that the applications can be grouped into three general areas: (i) studies that use the meteorological and hydrological data directly to characterize the state or variability of a specific hydroclimatic variable (e.g. temperature,
precipitation, snowpack), (ii) studies that use the data as a spatially and temporally complete observational baseline for downscaling climate model output (especially for bias correction) to generate future climate scenarios, and (iii) water and energy balance studies, for which the model forcings and derived fluxes are of particular interest because the derived surface water and energy budgets close at all grid cells at each time step by construct. Examples of each of these applications are discussed below.

Westerling et al. (2006) used the M02 gridded meteorological data along with other sources to isolate the signal of climatic variability on wildfire frequency in the western U.S. Hayhoe et al. (2007) used the archived hydrological fluxes and states to represent historical hydrologic conditions from which future meteorological scenarios were assessed via hydrologic simulations in the Northeastern U.S. Soil moisture data were used by Castro et al. (2007) to initialize a regional climate model to simulate U.S. climatology. Sheffield et al. (2004), used M02 soil moisture to derive a hydrologically based drought index, which showed good agreement with time series of U.S. drought from two Palmer Drought Severity Index (PDSI) data sets.

The second group of studies typically follow procedures that include correcting downscaled climate model output with the M02 forcing data, and then using the bias corrected model to produce future climatic scenarios. Cayan et al. (2008) and Hayhoe et al. (2004) both exploited the downscaled climate model outputs to assess climatic implications of future greenhouse gas emission scenarios in California using this general approach. Loarie et al. (2008) used downscaled outputs to examine impacts on the diversity of flora in California. Salathe (2005) downscaled climate model outputs to simulate streamflow over a river basin in Washington State and also evaluated performance of several climate models after bias
correction. Wood et al. (2004) used the forcing and hydrological datasets to evaluate six bias correction methods for downscaling climate model outputs over the continental U.S.

Among the third type of application, Stewart et al. (2004) utilized the forcing data to simulate streamflow over large river basins in the Pacific Northwest. Smith et al. (2004) used the meteorological data to force a suite of land surface models and compared their performance. Christensen et al. (2004) applied the forcing data over the Colorado R. basin to search for robust VIC model parameters over small river basins that were then used to assess climatic impacts under future forcing scenarios. Carpenter et al. (2004) utilized the energy forcing data to compute potential evapotranspiration in a radar-rainfall uncertainty study. Maurer et al. (2004) used climate data and the archived VIC-derived soil moisture, snow, and runoff data to examine predictability of runoff across the U.S. Andreadis et al. (2006) used the forcing data to evaluate a data assimilation scheme using satellite-based snow water equivalent information.

Climate model outputs, remote sensing and land cover data continue to become available at finer spatial resolutions, making the spatial refinement of L13 a significant improvement (from 1/8° to 1/16°). The extended period of record (from 50 to 97 years) will help to improve the statistical strength of computed trends from hydroclimatic analyses and model corrections for downscaled climate model outputs, and captures important historic extremes such as the 1930s drought that were outside the period of M02. Also, the climate model simulations for historic periods conducted as part of the fifth Coupled Model Intercomparison Project (CMIP5, Taylor et al., 2012) extend through 2005, for which an extended observational data set is useful for various purposes discussed below. Lastly, an updated VIC model version (described below) includes refinements that will be of interest for some applications of the model-derived variables.
As in the original M02 data set, we produced three types of data, all of which are publicly available (http://www.hydro.washington.edu/SurfaceWaterGroup/Data/gridded/index.html): (i) station-based daily precipitation and temperature data, and wind fields from the NCEP–NCAR reanalysis (Kalnay et al. 1996), (ii) derived sub-daily (3-hourly) land surface model forcing data, including precipitation and temperature, as well as downwelling solar and longwave radiation, humidity, and surface air pressure, and (iii) model-based hydrological states and fluxes. We attempted as much as possible to follow the methods of M02, so that studies using those data can apply L13 to extend or refine their previous analyses. Below we briefly describe the spatial gridding methodology and updates to the hydrologic model, and provide comparisons between M02 and L13. We also compare model-based hydrologic outputs with observations of streamflow, soil moisture, and surface heat and radiative fluxes, presented here in a format consistent with M02.

2.0 Gridding Methodology

The gridding methods of M02 were closely followed in L13, and the reader may find complete details in that publication. The L13 data set is derived from observations of precipitation and minimum and maximum daily temperature at National Climatic Data Center (NCDC) Cooperative Observer (Co-op) stations across the conterminous U.S. (DSI-3200). Although the cumulative total number of stations used is about 20,000, the number at any time varies, with a peak of approximately 12,000 stations in 1970. As in M02, we used only stations with at least 20 years of valid data. L13 uses the same relationships as in M02 to estimate those variables (downward solar and longwave radiation and humidity) that are not observed directly using algorithms described in the next paragraph. Both temperature and precipitation were
gridded to 1/16° using the SYMAP algorithm. Precipitation was linearly apportioned among
days based on the time of observation. Daily maximum and minimum temperature were assumed
to occur in the day of record. Station meta-data were incorporated into the gridding process
through use of the QC flags, however, issues beyond those that qualified for flagging (e.g.
instrument error or upgrade) were not explicitly accounted for given the lack of documentation,
aside from a few obvious inconsistencies in precipitation data noted in the Supplemental
Material. Gridded precipitation values were subsequently scaled on a monthly basis so as to
match the long-term mean from the parameter-elevation regressions on independent slopes
model (PRISM – Daly, 1994); for consistency with M02, a 1961-1990 PRISM climatology was
used. Wind data were linearly interpolated from a larger (approximately 1.9° grid) NCEP–NCAR
reanalysis grid (Kalnay et al. 1996). Since the reanalysis data are only available from 1948
onward, a daily wind climatology for 1948-2011 was used for years prior to 1948.

Vapor pressure, humidity, and incoming shortwave and long wave radiation were derived
using algorithms from MTCLIM (Kimball et al., 1997; Thornton and Running, 1999, Thornton
et al., 2001) as described in M02, with several updates outlined in Bohn et al. (2013) The major
difference between the version of MTCLIM used in L13 and M02 is a change in the estimate of
longwave radiation from Tennessee Valley Authority (1972) to Prata (1996). To provide sub-
daily (3-hourly) temperature, a spline was applied to daily minimum and maximum temperatures
to estimate the diurnal cycle (see Bohn et al., 2013).

2.1 Hydrologic Model

As in M02, hydrologic states and fluxes were simulated using the VIC model (Liang et
al., 1994). VIC is a grid-based hydrologic model that balances surface energy and water budgets
at typical spatial resolutions ranging from a few to hundreds of km. VIC represents sub-grid
variability of vegetation and runoff generation, while also accounting for sub-grid topography through elevation-bands. Land-cover input data are the same as in M02, with static vegetation (Hansen et al., 2000), and soils information (Miller and White 1998) aggregated from a 1-km database for the effective years of 2000 and 1998, respectively. The VIC model version used in L13, v.4.1.2, was run in energy balance mode, and has undergone a number of upgrades since the M02 data were published (using v.4.0.3). Readers are referred to the VIC website (http://www.hydro.washington.edu/Lettenmaier/Models/VIC/) for a complete description of these upgrades, the most important of which are related to the snow accumulation and ablation model, which now performs a separate energy balance for canopy snowpack and snow on the ground (Andreadis et al., 2009).

3.0 Evaluation

We first compared gridded station data from L13 and M02 (Figure 1) for summer and winter over the concurrent period 1/1/1950-7/31/2000. The two data sets are largely consistent, with differences mainly over topographically complex regions in the western U.S. The major source of discrepancies are (i) intra-grid variability from the four 1/16° L13 grid cells that weight the station data slightly differently than the single 1/8° M02 cell, and (ii) the 20-year constraint on valid stations, which leads to L13 having slightly more valid stations at the beginning and end of the concurrent period (i.e., 1950s and 1990s) than in M02.

Figure 2 compares derived surface energy budget components with observations from four Ameriflux towers during summer (see Table 1). Simulated fluxes track observations fairly well at each site with several exceptions. First, derived fluxes tend to under-predict sensible heat fluxes and over-predict latent heat fluxes. The average difference in latent heat flux across sites
and time intervals is -19.5 W/m², or 17%, which is equivalent to an overestimation of 0.69 mm/day of evaporation during summer. Second, at Niwot Ridge (a high-alpine site), there is a timing lag in the simulated peak radiation. Downward solar radiation is a derived quantity based on minimum and maximum daily air temperatures, which suggests that the assigned timing for the 1/16° grid cell is not representative of the Ameriflux site, which is situated on a ridge. The reader is referred to Bohn et al. (2013) for further explanation of the radiation algorithm. For details on model-derived cold-season fluxes and their evaluation, the reader is referred to Andreadis et al. (2010) and Cherkauer et al. (2003).

Soil moisture plays a central role in hydrologic processes such as runoff generation and ET, and is a key indicator of drought. Simulated soil moisture from VIC, driven as described above, was compared with observations from 19 sensors in Illinois retrieved from the Global Soil Moisture Data Bank (Robock et al. 2000) summarized in Table 1. Figure 3 shows mean monthly soil moisture values as well as the autocorrelations. VIC’s climatological soil moisture values are consistently lower than the observations for the 19 sensor average. However, the VIC-simulated inter-monthly variability tracks very closely with observations, indicating that the model realistically simulates moisture storage changes and water budget dynamics for this part of the domain. The monthly autocorrelation is a measure of persistence of soil moisture anomalies in time, important for seasonal runoff forecasting and characterizing drought evolution. The lower panel in Figure 3 demonstrates that the temporal structure of model response effectively captures observed persistence for the first 3 months, becoming slightly less persistent thereafter, while autocorrelations become almost negligible beyond 5 months. The L13 magnitude and autocorrelations track those from observed soil moisture comparably to the original M02 data.
In addition to soil moisture, snow water equivalent (SWE) is a key hydrologic state variable. Figure 4 shows histograms of the dynamic soil moisture range, mean and maximum SWE, and precipitation for M02 and L13 over the concurrent time period, as well as L13 for the extended period (1/1/1915-8/31/2010). SWE values were frequently larger for the finer spatial domain (1/16°) than the coarser (1/8°) during the concurrent period, corresponding to an increased meteorological variability, while the extended period had maximum values that were still larger. The dynamic soil moisture range was accordingly greatest for the extended period (at 1/16°). Maximum daily precipitation was comparable between the two data sets over the concurrent period; however, larger daily values were frequently recorded for the extended period corresponding to a wet period before 1925, as well as over topographically complex regions. Conversely, the mean daily precipitation values were stable across both periods and resolutions.

Simulated streamflows are compared with observations in Figure 5 from major river basins covering large portions of the domain. For several basins, particularly in the western U.S., naturalized streamflow data were obtained that have been adjusted for anthropogenic impacts, including upstream regulation, water withdrawals and evaporation from upstream reservoirs (see Table 1). Limited VIC parameter estimation was performed to match surface and subsurface runoff from the previously calibrated VIC version (v.4.0.3) used in M02. We employed a technique similar to Troy (2008) with the objective of matching the runoff ratio (in this case between model versions 4.0.3 and 4.1.2) at regularly-spaced intervals of 1°. A Monte-Carlo search consisting of 200 iterations was applied, which varied 3 VIC soil parameters, the variable infiltration curve parameter, b, the maximum velocity of baseflow parameter, $D_{\text{max}}$, and the depth of the bottom soil layer, $D_3$, within a narrow range ($\pm 10\%$) of their previous values.
Offline simulations were conducted to evaluate the impact of using climatological winds prior to 1948 (see supplemental materials). These comparison showed that with few exceptions use of the climatological winds slightly reduce the temporal and spatial variability of hydrologic fluxes but have small relative impacts on long-term mean values. Relative impacts on short-term (three-hourly and daily) values are greatest, and are less at monthly time steps. Given the uncertainty in using static vegetation and soil (from 2000 and 1998, respectively), the derived model outputs for the earlier part of the simulation period serve as a reference scenario (rather than a reconstruction), while providing the necessary meteorological inputs for users who might desire to produce more detailed, dynamic reconstructions (as a point of reference, Matheuson et al. (2001) found maximum changes in runoff and ET of less than 10% for reconstructed 1900 vs. 1990 vegetation in the Columbia River basin). Additional uncertainty arises from using a constant lapse rate in regions of topographical complexity (i.e. western U.S.), with the potential to bias daily temperature range in certain cases, which may impact derived downwelling shortwave radiation based on the MTCLIM algorithm. Lastly, it follows that undocumented or incomplete QC of instrument change error may hinder the robustness of trends in these data, as pointed out by Menne et al. (2009).

4.0 Data format and availability

The data are available in netCDF format, conforming to the ALMA convention of Polcher et al. (2000). This means that moisture fluxes are expressed as kg m$^{-2}$ s$^{-1}$, energy fluxes are expressed in W m$^{-2}$ and moisture states as kg m$^{-2}$. The data are freely accessible from ftp://ftp.hydro.washington.edu/pub/blivneh/CONUS/, where we also provide plots comparing a range of other states and fluxes between M02 and L13.

5.0 Conclusions
We have described an observation-based hydrologically consistent dataset for the period 1915-2011 at a 1/16 degree spatial resolution. Gridded station data for precipitation and temperature, surface wind from an atmospheric reanalysis, and derived downward solar and longwave radiation and vapor pressure were used to force a hydrologic model that was shown to reproduce, on average, observed surface heat fluxes, soil moisture, and runoff. These data have potential uses for model evaluation and diagnosis in energy and water balance studies and climate change impact studies. We expect that these data will complement studies that have used the M02 dataset, given the wider range of conditions that are included in a longer time period and at finer spatial resolution.
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Table 1: Details of observational data used for comparison with simulated fluxes and states

### Streamflow data

<table>
<thead>
<tr>
<th>River name</th>
<th>Station name</th>
<th>Area (km²)</th>
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<tr>
<td>Alabama</td>
<td>Clairborne</td>
<td>56,900</td>
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<tr>
<td>Arkansas*</td>
<td>Ralston</td>
<td>121,340</td>
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<td>Colorado*</td>
<td>Lees Ferry</td>
<td>278,070</td>
</tr>
<tr>
<td>Columbia*</td>
<td>Dalles</td>
<td>613,280</td>
</tr>
<tr>
<td>Delaware</td>
<td>Memorial Bridge</td>
<td>28,500</td>
</tr>
<tr>
<td>Missouri*</td>
<td>Hermann</td>
<td>1,357,670</td>
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<tr>
<td>Ohio</td>
<td>Metropolis</td>
<td>525,760</td>
</tr>
<tr>
<td>Potomac</td>
<td>Point of Rocks</td>
<td>25,000</td>
</tr>
<tr>
<td>Red*</td>
<td>Index</td>
<td>124,390</td>
</tr>
<tr>
<td>Sacramento*</td>
<td>Bend Bridge</td>
<td>23,050</td>
</tr>
<tr>
<td>San Joaquin*</td>
<td>Mokelumne Hill</td>
<td>1,860</td>
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<td>Upper Mississippi</td>
<td>Grafton</td>
<td>443,660</td>
</tr>
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</table>

### Ameriflux data

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<tr>
<th>Tower name</th>
<th>Climate</th>
<th>Elevation (m)</th>
<th>Latitude (°N)</th>
<th>Longitude (°W)</th>
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<tbody>
<tr>
<td>Blodgett Forest</td>
<td>Mediterranean</td>
<td>1315</td>
<td>38.89</td>
<td>120.63</td>
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<tr>
<td>Niwot Ridge</td>
<td>Sub-alpine mixed coniferous</td>
<td>3050</td>
<td>40.03</td>
<td>105.55</td>
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<td>Brookings</td>
<td>Temperate grassland</td>
<td>510</td>
<td>44.35</td>
<td>96.84</td>
</tr>
<tr>
<td>Howland Forest</td>
<td>Temperate continental</td>
<td>60</td>
<td>45.20</td>
<td>68.74</td>
</tr>
</tbody>
</table>

### Global Soil Moisture Data Bank

<table>
<thead>
<tr>
<th>Number of stations</th>
<th>Elevation range (m)</th>
<th>Latitudinal range (°N)</th>
<th>Longitudinal range (°W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>19</td>
<td>130 - 265</td>
<td>38.13 – 42.28</td>
<td>88.10 – 90.83</td>
</tr>
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</table>

*Naturalized streamflow were obtained.
Figure 1: Seasonal differences between L13 and M02 for the concurrent period (1/1/1950 – 7/31/2000) shown is L13 minus M02 for summer (JJA) and winter (DJF).
Figure 2: L13 (dashed lines) modeled energy budget components compared with observations (solid lines) for a single summer for each Ameriflux site, specifically Blodgett Forest, CA (2004), Niwot Ridge, CO (2006), Brookings, SD (2005), and Howland Forest, ME (2001).
Figure 3: Comparison of L13 (a) mean monthly soil moisture and (b) autocorrelations with 19 sensors in Illinois retrieved from the Global Soil Moisture Data Bank (1981-2004). Note: bars in (a) indicate monthly standard deviations.
Figure 4: Cumulative density functions (CDFs) of inputs (daily precipitation) and state variables (soil moisture, snow water equivalent), comparing the historic M02 data set (solid lines) with the L13 data set over the concurrent period (1/1/1950-7/31/2000; dashed lines) and the entire L13 record (1/1/1916-8/31/2010; dotted lines). Ordinate values are in millimeters; mean and maximum precipitation are separated for ease of viewing.
Figure 5: L13 mean monthly hydrographs over the period 1961-1990. Ordinate values are in units of m³/s; simulated flows are denoted by dashed lines, while observed or naturalized flows are solid lines.