GCIP Water and Energy Budget Synthesis (WEBS)

J. Roads[1], R. Lawford[2], E. Bainto[1], E. Berbery[5], S. Chen[1], B. Fekete[10], K. Gallo[8], A. Grundstein[12], W. Higgins[6], M. Kanamitsu[1], W. Krajewski[18], V. Lakshmi[9], D. Leathers[13], D. Lettenmaier[3], L. Luo[4], E. Maurer[3], T. Meyers[15], D. Miller[7], K. Mitchell[6], T. Mote[12], R. Pinker[5], T. Reichler[1], D. Robinson[4], A. Robock[4], J. Smith[11], G. Srinivasan[17], K. Vinnikov[5], T. Vonder Haar[14], C. Vorosmarty[10], S. Williams[16], E. Yarosh[6]
jroads@ucsd.edu
http://ecpc.ucsd.edu/gcip/webs.htm/

[1]Scripps Institution of Oceanography
UCSD, 0224
La Jolla, CA 92023

[2]NOAA Office of Global Programs
Suite 1210, 1100 Wayne Ave.
Silver Spring, MD 20910

[3]University of Washington
Dept. of Civil and Env. Engineering
Seattle, WA 98195-2700

[4] Dept. of Env. Sciences
Rutgers University
New Brunswick, NJ 08901-8551

[5]Department of Meteorology
University of Maryland
College Park, MD 20742

[6] NCEP/EMC/CPC
NOAA Science Center
Camp Springs, MD 20746-4304

[7]Penn State
EMS Environment Institute
University Park, PA 16802

[8] NOAA/NESDIS
USGS EROS Data Center
Sioux Falls, SD 57198

[9]Dept. Geol. Sciences
Univ. South Carolina
Columbia, SC 29208

[10]Complex Systems Research Center
University of New Hampshire
Durham, NH 03824

[11]Dept. of Civil and Env. Eng.
Princeton University
Princeton, NJ 08544

[12] Department of Geography
University of Georgia
Athens, GA 30602-2502

[13]Department of Geography
University of Delaware
Newark, DE 19716

[14]Department of Atmospheric Science
Colorado State University
Fort Collins, CO 80523

[15]NOAA/ATDD
P.O. Box 2456
Oak Ridge, TN 37830

[16]UCAR
P.O. Box 3000
Boulder, Colorado, USA 80307

[17]Earth System Science Division
Department of Science & Technology
New Delhi 110016, India

[18]IIHR-Hydroscience & Engineering
The University of Iowa
Iowa City, Iowa 52242

1. Introduction

The World Climate Research Program (WCRP) Global Energy and Water-Cycle Experiment (GEWEX) Continental-scale International Project (GCIP) was originally developed in the early 1990's for the purpose of assessing the accuracy to which water and energy budgets could be characterized and "closed" on a continental scale. GEWEX chose the Mississippi River Basin as the first Continental Scale Experiment (CSE), in part because the Mississippi River Basin is one of the major river systems of the world. It drains 41 percent of the Conterminous United States with a 3.2 million square kilometer basin, second largest river basin area in the world. At 3,705 km, the Mississippi is the longest river in North America and the third largest in the world. Its discharge of 17,300 cubic meters per second into the Gulf of Mexico ranks the Mississippi as the fifth largest in the world in this category. Elevations within the Mississippi River Basin range from sea level at the mouth of the Mississippi to some of the highest peaks in North America. The topography varies from low-lying swampland to undulating hills to craggy mountain peaks. Perhaps more importantly, however, no other identified basin at the time had its observational infrastructure and data richness as well as promise of future observing system development.

The goal of this GCIP community effort was to begin what might be vaguely thought of as the "best available" water and energy budget synthesis (WEBS) at the end of GCIP and start of the follow-on GEWEX Americas Prediction Project (GAPP). By necessity, WEBS must include models as well as observations and as part of this synthesis, some representative global and regional analyses, global and regional simulations, were compared with a macroscale hydrologic model and available observations.

This WEBS focused for the most part on developing a seasonal climatology for the 1996-1999 period, when GCIP was fully active. Interannual variations during this time period were minimal so the GCIP time period has been somewhat extended, mainly with the help of models, to also cover the 1988-1999 time period. Although long-term trends need to be better understood, only by studying interannual variations on much longer time scales will the confidence be gained to adequately describe these more subtle variations. In that regard, this WEBS could be the start of a longer-term effort in collaboration with WEBS activities in other CSEs to an eventual global synthesis. This GCIP WEBS also ignores diurnal variations, despite their potential importance to the moisture budgets. For example, there is a nocturnal jet in the Mississippi River Basin that appears to be related to nighttime precipitation maximum on the Rocky Mountain Front Range. Understanding better the character of the diurnal variations here as well as in other US geographic regions will be one of the focuses of the new GEWEX Americas Prediction Project (GAPP).

2. Observations

As described by Higgins et al. (2000) available meteorological observation networks have included the World Meteorological Organization (WMO) Global Telecommunication (GTS) sites, 24 hour reports from the River Forecast Centers (OH 1994), and NCDC cooperative stations, as well as many potential sites from SNOTEL and remote automated weather stations (RAWS), In addition, standard observations include the US Geological Survey (USGS) streamflow measurements the upper air radiosonde network and aircraft measurements of temperature and wind. New measurements begun during GCIP include the NEXRAD (NRC

1999) radar network for precipitation (Smith et al. 1996), various soil moisture measurements to complement the existing meager networks (Robock et al. 2000), and flux tower measurements (Meyers et al. 2001).

Satellite measurements include the GEWEX NVAP water vapor (Randel et al. 1996), the Pinker solar radiation, and various other satellite products of standard variables derived from TOV (Lakshmi and Susskind, 2000) such as outgoing longwave radiation and surface skin temperature. Although GEWEX precipitation products such as the Tropical Rainfall Measuring Mission (TRMM, see Adler et al. 2000) could have been utilized, standard products (2.5x2.5) are still relatively coarse in comparison to the standard higher resolution gauge (Higgins et al. 2000) and NEXRAD (Smith et al. 1996) products available to us.

It should also be noted here that there are numerous plans for future satellite measurements, including: a cold seasons mission, which will attempt to develop algorithms for measuring snow equivalent water, a soil moisture mission, which will attempt to measure soil moisture in the upper few centimeters, a gravimetric mission, which will attempt to measure groundwater, and a satellite altimetry mission, which will measure river and lake levels. There are also plans to develop GEWEX radiation data sets. From our experience with this WEBS, it is recommended satellite products be transitioned into operational streams as soon as possible so that GAPP and other field measurement programs can take advantage of them.

3. GCIP Models

Modern global and regional atmospheric and macroscale hydrologic models provide comprehensive hydroclimatological output and a means to supplement meager observations. There have been a number of different types of models used for GCIP studies, which are constrained in different ways to available observations. Global models are typically only constrained by observed sea surface temperatures (SSTs; Reichler and Roads 2002). However, they can be further constrained by global atmospheric observations in atmospheric analysis (Kanamitsu et al. 2002). Regional models (Roads and Chen 2000) are also constrained by global atmospheric analyses and can be even further constrained through additional regional atmospheric observations in a regional analysis. Hydrologic models (Maurer et al. 2002) are constrained by the need to balance observed runoff using observed precipitation (and other forcings) as input. Some of these constraints, or lack thereof, are critically dependent upon their use. For example, to make long-range predictions, only global SSTs and other boundary conditions, including perhaps land surface boundary conditions, can be specified initially and then the boundary conditions can either be assumed to persist or a coupled model can be developed that predicts the behavior of the slowly varying boundary conditions.

4. Results

Table 1 summarizes the annual areal (Mississippi River basin) means of the various budget terms. Precipitable water ranges from 16-18 mm in the models, with the NVAP observations indicating a value of 16. 8 mm. Surface water in the upper two meters, including snow liquid water, ranges from 400-500 mm in the available models with the VIC model having 413 mm. Snow contributes from 2-10 mm of this surface water in the models, with the VIC model having 5.1 mm. Surface skin temperature ranges from 8 to 11 ^{o}C, with the satellite observations indicating 9.4 ^{o}C and the average of Tmax and Tmin providing 7.9 ^{o}C. Precipitation ranges from 2.1 to 3.0 mm/day in the models with the Higgins et al. (2000) observations indicating 2.1 mm/day. The evaporation is almost as large, with the models ranging from 1.6 to 2.4 mm/day and the VIC model having 1.6 mm/day, which is comparable to the difference between the Higgins et al. (2000) precipitation and the estimate of streamflow from the USGS gauges. Runoff ranges from 0.2 to 0.6 mm/day with observations estimated to be .6 mm/day (the runoff is slightly lower at .46mm/day). Moisture convergence ranges from 0.2 to 0.6 mm/day in the models; in order to balance the observed runoff, moisture convergence should be about .6 mm/day. Sensible heating ranges from 0.01 to 0.19 K/day in the available models, which is much smaller than the associated latent heating (0.4 to 0.6 K/day) and the surface radiative heating (0.6 to 0.7 K/day). The ground heating, including energy needed for snowmelt) is much smaller but ranges from -0.1 to 0.1 K/day. Atmospheric radiative cooling ranges from -0. 72 to -0.94 K/day from the available models, which is balanced by the latent heat of condensation (0.5 to 0.75 K/day) and atmospheric heat convergence ranging from 0.05 to 0.19 K/day in the available models. Net solar radiation ranges from 134 to 172 W/m^2 with observations indicating 155 W/m^2 and the low value being provided by the VIC model and the high value provided by the Eta model. Note that we have also provided the energy variables in W/m^2. Although the general character of the water and energy budgets seems clear, there are also problems. In the VIC model the solar and infrared radiative terms as well as the surface radiative heating appear to be too low. Also, moisture convergence appears to be too low whereas precipitation and evaporation appear to be too high in the atmospheric models.

Fig. 1 shows all models have strong evaporation in the east and weaker evaporation in the west, although the GSM again has a more zonal north south gradient, as does the REAN2. The strong amounts at the outlet suggest that the large-scale models may have ocean points instead of land points here and the boundaries for the large-scale models' diagnostics may need to be better defined. Except for the VIC, none of the models shows the relatively small evaporation in the North Central and North East. Seasonally, the RSM has the strongest summertime evaporation in the East although the other models are also strong in comparison to the VIC model. Since the VIC model is forced by observed precipitation and runoff is in fairly good agreement with independent observations, this suggests that its seasonal evaporation may be well modeled, although there are certainly major evaporation differences with the other models, especially during the spring to summer. It is thus still uncertain if the soil moisture tendencies have been adequately modeled everywhere by the VIC model. Observed evaporation at the available tower sites (Little Washita and Champaign for 1997 - 1999) had much weaker seasonal variations than the models, and the values are especially lower during the summer. Still, there were some similarities. Evaporation increased during the summer and decreased during the winter. Again, there is much work needed for models as well as developing observations of this inadequately observed variable.

The interested reader should consult the Roads et al. (2002b) CD-ROM (an updated version can be found at http://ecpc.ucsd.edu/gcip/webs.htm) or paper (Roads et al. 2002c) for a more detailed discussion about other variables and processes.

5. Summary

GCIP has provided new understanding of how water and energy processes interact on a continental scale by analysis of traditional measurements, development of new measurements, new models and analyses. It is now clearer than ever that on a continental scale many of the observations needed to close the budgets cannot be obtained. There are currently inadequate soil moisture, snow equivalent water, evaporation, atmospheric moisture and dry static energy convergence, surface longwave radiation, and sensible heating observations. This inadequacy of comprehensive hydroclimatic measurements needs to be addressed in the future.

Instead continental-scale depictions of these variables and processes have to be obtained from various coupled atmosphere and land surface models and their associated global, regional, and land surface analyses. Even some of these variables were not readily available from all of the models and analyses. For example, soil moisture, radiative cooling and dry static energy convergence apparently could not be easily obtained from the Eta model operational archives. Moisture convergence was only readily available from the NCEP/NCAR analysis.

Clearly models and analyses have errors but at the same time they provide qualitative features that emulate many aspects of the observations and so one might expect that for those variables for which there are inadequate observations that these modeled processes may at least be qualitatively correct. However, there is still much uncertainty. Seasonal precipitation variations show large scatter among the models, especially during the spring to summer transition. This large scatter translates into large variations in runoff, as well as surface water tendencies. Interestingly, the atmospheric models with the best precipitation (Eta) tend to have the worst runoff. The atmospheric models also tend to produce too small a moisture convergence; although this is consistent with the subsequent model runoff, it is still too small to balance observed runoff. At the surface, the VIC hydrologic model produces a much better correspondence to mean observations (in part because it is tuned to observable surface parameters) suggesting that its surface water, evaporation and energy products might be superior. However, some of the surface energetics from the VIC are at odds with the other models as well as available observations (net solar radiation), suggesting that further examination is still needed.

Interannually, there were many problems. The GSM interannual variations could not be included in the comparison, since the GSM was driven only by SSTs and the resulting forced simulations did not provide representative (at least in time) interannual variations. The Eta analysis has overly large interannual variations, which are presumably more reflective of analysis changes than natural variations. In this regard, the Eta reanalysis is likely to eventually provide a superior product. Runoff is obviously a problem for the atmospheric models and improvements in their land surface schemes are needed before using this product to drive hydrologic and water resource models. There seem to be some relatively small variations in the VIC energy parameterizations, which may be related in part to the smaller surface water variations in that model. Finally, the satellite temperature and solar radiation observations, while certainly highly correlated with the models, seem to have some spurious variations, indicating that further work may still be needed for those products.

The VIC model appears to provide the best simulation of the mean surface water budget, suggesting, for example, that its evaporation provides a benchmark for comparison. However the

VIC surface radiation fluxes are noticeably different from other models and also observations of net solar radiation, and the VIC interannual variations are noticeably smaller than those from the other models. The Eta analysis provides the best precipitation of all the atmospheric models, although the RSM also has many realistic features, including a better agreement with the net solar radiation and various interannual variations that are clearly affected by various operational changes in the Eta output. Again, the pending Eta reanalysis should eventually provide the atmospheric model benchmark for interannual variations in the Mississippi River Basin. The global analysis and especially the GSM, do not always capture some of the regional characteristics of the Mississippi River basin, which suggests that current regional atmospheric models combined with macroscale hydrologic models might currently provide the best possible regional predictions of water and energy processes.

So, have the water and energy budgets been closed? All models have means and seasonal variations that resemble available observations and each other, meaning that qualitatively one can probably understand the annual mean and seasonal and perhaps some of the major interannual variations in the water and energy budgets for the Mississippi River Basin. However, there are large quantitative differences. A number of errors are probably canceling, giving rise to overall errors that are comparable to the residual errors calculated for the global and regional analyses. Unfortunately, these errors are not small and can swamp interannual variations. In short, despite our best effort, it is clear that this current effort should still be thought of as a preliminary synthesis and as new measurement systems and new models are developed it would be useful to once again examine just how well we can adequately characterize and close the water and energy budgets.

References

Adler, R. F., G. J. Huffman, D. T. Bolvin, S. Curtis, E. J. Nelkin, Tropical Rainfall Distributions Determined Using TRMM Combined with other Satellite and Raingauge Information, *J. Appl. Meteor., 39*, 2007-2023, 2000.

Higgins, R., W. Shi, E. Yarosh, R. Joyce, Improved US Precipitation quality control system and analysis. *NCEP/CPC Atlas*, *7*, US Department of Commerce, NOAA, NWS, 2000.

Kanamitsu, M., W. Ebisuzaki, J. Woollen, S.-K. Yang, J. Hnilo, M. Fiorino, and J. Potter, NCEP/DOE AMIP-II REANALYSIS (R-2). *Bull. Amer. Meteor. Soc.*, 2002. (In press).

Lakshmi, V. and J. Susskind, Comparison of TOVS derived land surface variables with ground observations, *J. Geophys. Res.*, *105*(D2), 2001-2004, 2000.

Maurer, E. P., A. W. Wood, J. C. Adam, D. P. Lettenmaier, and B. Nijssen, A Long-Term Hydrologically-Based Data Set of Land Surface Fluxes and States for the Continental United States, *J. Climate*, 2002. (in press).

Meyers, T. P., A comparison of summertime water and CO2 fluxes over rangeland for well watered and drought conditions, *Agricultural and Forest Meteorology, 106*, 205-214, 2001.

Reichler, T. J. and J. O. Roads, The Role of Boundary and Initial Conditions for Dynamical Seasonal Predictability, *Nonlinear Processes in Geophysics*, 2002. (in press).

Randel, D. L., T. H. Vonder Haar, M. A. Ringerud, G. L. Stephens, T. J. Greenwald, and C. L. Combs, A new global water vapor dataset, *Bull. Amer. Meteor. Soc.*, *77*, 1233-1246, 1996.

Roads, J. O. and S.-C. Chen, Surface Water and Energy Budgets in the NCEP Regional Spectral Model, *JGR-Atmospheres*, *105*(D24), 29, 539, 2000.

Roads, J., R. Lawford, E. Bainto, H. Berbery, B. Fekete, K. Gallo, A. Grundstein, W. Higgins, J. Janowiak, M. Kanamitsu, V. Lakshmi, D. Leathers, D. Lettenmaier, Q. Li, L. Luo, E. Maurer, T. Meyers, D. Miller, K. Mitchell, T. Mote, R. Pinker, T. Reichler, D. Robinson, A. Robock, J. Smith, G. Srinivasan, K. Vinnikov, T. von der Haar, C. Vorosmarty, S. Williams, E. Yarosh, GCIP Water and Energy Budget Synthesis (WEBS), 2002a, [CD-ROM] (available from GAPP program office).

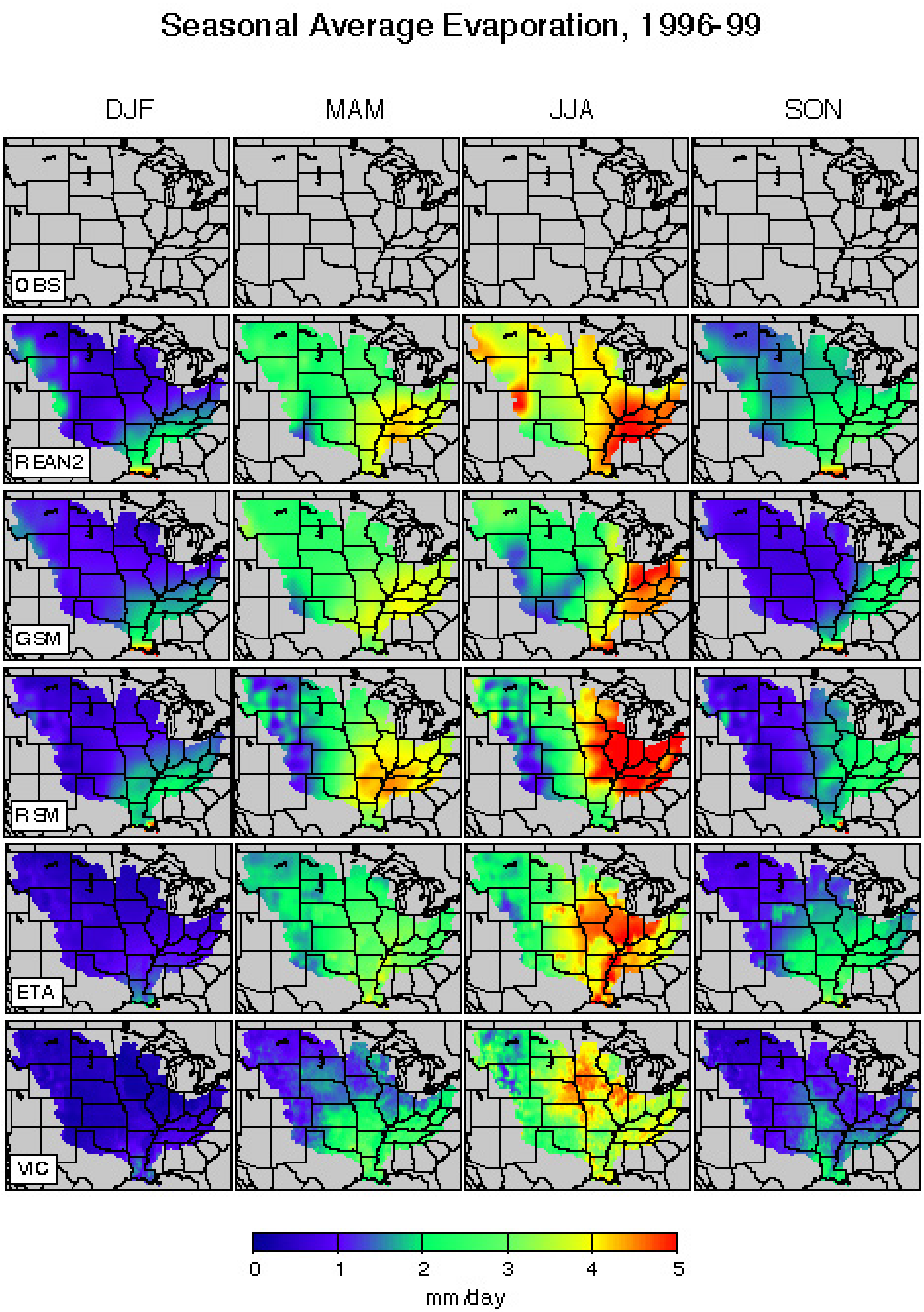
Roads, J., R. Lawford, E. Bainto, H. Berbery, B. Fekete, K. Gallo, A. Grundstein, W. Higgins, J. Janowiak, M. Kanamitsu, V. Lakshmi, D. Leathers, D. Lettenmaier, Q. Li, L. Luo, E. Maurer, T. Meyers, D. Miller, K. Mitchell, T. Mote, R. Pinker, T. Reichler, D. Robinson, A. Robock, J. Smith, G. Srinivasan, K. Vinnikov, T. von der Haar, C. Vorosmarty, S. Williams, E. Yarosh, GCIP Water and Energy Budget Synthesis (WEBS). J. Geophys. Res. (in press) 2002b.

Robock, A., K. Y. Vinnikov, G. Srinivasan, J. K. Entin, S. E. Hollinger, N. A. Speranskaya, S. Liu, and A. Namkhai, The Global Soil Moisture Data Bank, *Bull. Amer. Meteor. Soc.*, *81*, 1281-1299, 2000.

Smith, J. A., D.-J. Seo, M. L. Baeck and M. D. Hudlow, An intercomparison study of NEXRAD precipitation estimates, Water Resources Research, 32(7), 2035 - 2045, 1996.

Table 1. Mississippi River Basin annual averages (1996-1999) of the water and energy budget variables for observations and models and analyses (REAN1, REAN2, GSM, RSM, Eta, VIC). NA either means not available or not applicable. Note that the VIC precipitation and temperature come from gridded observations. Observed runoff estimates come from the Maurer and Lettenmaier (2001), naturalized USGS streamflow observations, as well as the gridded climatological estimate from Fekete et al. (2000). For temperature, observations come from the Lakshmi, and Susskind, (2000) TOVS estimate as well as from the Janowiak et al. (1999) mean of Tmax and Tmin. Moisture convergence comes from REAN1.

	OBS	REAN1	REAN2	GSM	RSM	ETA	VIC
Q (mm)	16.847	16.523	16.836	18.845	16.776	16.139	NA
W (mm)	NA	538.877	448.551	328.244	406.275	NA	413.131
Snow (mm)	NA	NA	11.378	2.237	1.716	2.957	5.084
Ts (C)	10.455(J) 9.422(L)	9.575	10.365	12.238	11.136	NA	11.129
P (mm/day)	2.153	2.319	2.316	2.172	2.318	2.096	2.255
E (mm/day)	NA	2.372	2.423	1.941	2.039	1.980	1.612
MC (mm/day)	-0.065	0.510	0.510	0.231	0.280	0.232	NA
N (mm/day)	0.626(M) 0.457 (F)	0.539	0.148	0.052	0.212	0.355	0.664
HC (K/day)	NA	0.165	0.188	0.352	0.152	NA	NA
LP (K/day)	NA	0.577	0.598	0.561	0.596	0.524	NA
LE (K/day)	NA	0.590	0.632	0.503	0.524	0.530	0.389
SH (K/day)	NA	0.099	0.077	0.113	0.194	0.285	0.206
QR (K/day)	NA	-0.960	-0.827	-0.800	-0.903	NA	NA
QRS (K/day)	NA	0.762	0.740	0.671	0.700	0.865	0.621
NSWSfc W/m^2	155.353	157.180	156.953	152.896	145.371	171.607	134.028
NSWTOA W/m^2	226.115	213.486	223.266	225.581	201.966	NA	NA
NLW Sfc W/m^2	NA	72.515	74.755	78.278	67.692	75.555	62.153
NLWTOA W/m^2	232.970	235.479	232.930	239.786	224.493	NA	NA
RESQ mm/day	NA	-0.563	-0.617	NA	NA	-0.116	NA
RESW mm/day	NA	0.592	0.255	-0.179	-0.067	NA	NA
G (K/day)	NA	-0.073	-0.031	-0.055	0.018	-0.050	-0.030
REST (K/day)	NA	0.119	-0.036	NA	NA	NA	NA
LP W/m**2	62.297	67.100	67.013	62.847	67.072	60.648	65.249
LE W/m**2	NA	65.536	70.201	55.872	58.148	61.343	45.023
LMC W/m**2	-1.881	14.757	14.757	6.684	8.102	6.713	NA
HC W/m**2	NA	18.328	20.883	39.100	16.868	NA	NA
SH W/m**2	NA	10.997	8.553	12.552	21.528	32.986	23.843
QR W/m**2	NA	-106.658	-91.862	-88.862	-100.206	NA	NA
QRS W/m**2	NA	84.665	82.198	74.533	77.679	96.052	71.875
LRESQ	NA	-16.291	-17.853	NA	NA	-3.356	NA
LRESW	NA	17.130	7.378	-5.179	-1.939	NA	NA
GG W/m**2)	NA	-8.132	-3.444	-6.109	1.997	-1.723	-3.009
RESTT W/m**2	NA	10.233	-4.587	NA	NA	NA	NA
Ps/g	NA	9553.169	9553.169	9553.169	9543.942	NA	NA


Seasonal Average Evaporation, 1996-99
DJF
MAM
JJA
SON
OBS
REAN2
GSM
RSM
ETA
VIC
0
1
2
3
4
5
mm/day