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A long-term data set for hydrologic modeling in a snow-dominated mountain catchment

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[1] A modeling data set (meteorological forcing data, geographic information system data, and validation data) is presented for water years 1984 through 2008 for a snow-dominated mountain catchment. The forcing data include hourly precipitation, wind speed and direction, air and soil temperature, relative humidity, dew point temperature, and incoming solar and thermal radiation from two sites. Validation data include stream discharge, snow water equivalent, snow depth, soil moisture, and groundwater elevation. These data will improve the development, testing, and application of the next generation of hydrologic models.

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1. Introduction

[2] In snow-dominated mountain regions, comprehensive hydroclimatic measurements are exceedingly rare. We present a coherent, serially complete, long-term (25 years) modeling data set from a snow-dominated headwater mountain catchment. This modeling data set includes forcing and validation data from water years (WY) 1984 through 2008 and geographic information system (GIS) information at Reynolds Mountain East (RME), located within Reynolds Creek Experimental Watershed (RCEW) (43°11′9.6″N, 116°46′58.9″W; Figures 1a–1c). RME is a small (0.38 km^2) snow-dominated headwater catchment that ranges in elevation from 2028 to 2137 m above mean sea level. Vegetation is patchy with fir, aspen and sagebrush [*Marks et al.*, 2002].

[3] The two measurement sites used to generate this data set represent the major landscape units in the catchment. The sheltered site is located within a clearing in an aspen/fir grove near the center of the catchment (Figure 1d) and has been used extensively for snow measurement and instrument development and validation [e.g., *Marks et al.*, 2001a; *Reba et al.*, 2009; *Flerchinger et al.*, 2010]. The exposed site is located on the western catchment divide in an area dominated by mixed sagebrush (Figure 1e). The contrast between the exposed and sheltered sites offers a unique opportunity to determine gradients across the RME catchment.

[4] Forcing data include precipitation (rain and snow), wind speed and direction, air and soil temperature, relative humidity, dew point temperature, incoming solar radiation and simulated thermal radiation. These data are hourly and continuous from 1 October 1983 to 30 September 2008, which results in 219,168 values for the parameters measured at each site over the 25 year period of record. Both the sheltered and exposed sites are similarly instrumented. Over the 25 year period of record, the following hourly forcing parameters were measured at both sites: precipitation, wind speed, air temperature, humidity, and solar radiation. At the exposed site, wind direction and soil temperature were also measured for the entire period of record. Soil temperature was measured at the sheltered site beginning in 1990, and above and below canopy thermal radiation was measured at the sheltered site beginning in 2005.

[5] GIS layers are presented in ArcInfo interchange file format. Included with these data are GIS layers defining the drainage basin extent and characteristics (10 m DEM with basin outline, vegetation, soils, and geology, as well as files locating roads, stream channels and measurement sites).

[6] Validation data provided include: discharge at the outlet, snow water equivalent (SWE), snow depth, soil moisture and groundwater elevation at three locations (Figure 1f and Figure S1 in the auxiliary material).[1] Discharge measurements made at the outlet weir are hourly and continuous for the entire period of record. A snow pillow, located at the sheltered site, was used to measure hourly SWE for the entire period of record. The snow course, located at the sheltered site, provided biweekly measurement of SWE, snow depth and snow density over the period of record. Instrumentation for the continuous measurement of snow depth was added to the sheltered site in WY 1997, and to the exposed site in WY 2000. Neutron probe tubes, located near the sheltered and exposed sites, provided soil moisture data approximately every 2 weeks over the period of record. Hourly measurements of soil moisture near the sheltered site began in late 2005. Hourly groundwater ele-

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[1] Auxiliary materials are available in the HTML. doi:10.1029/2010WR010030.

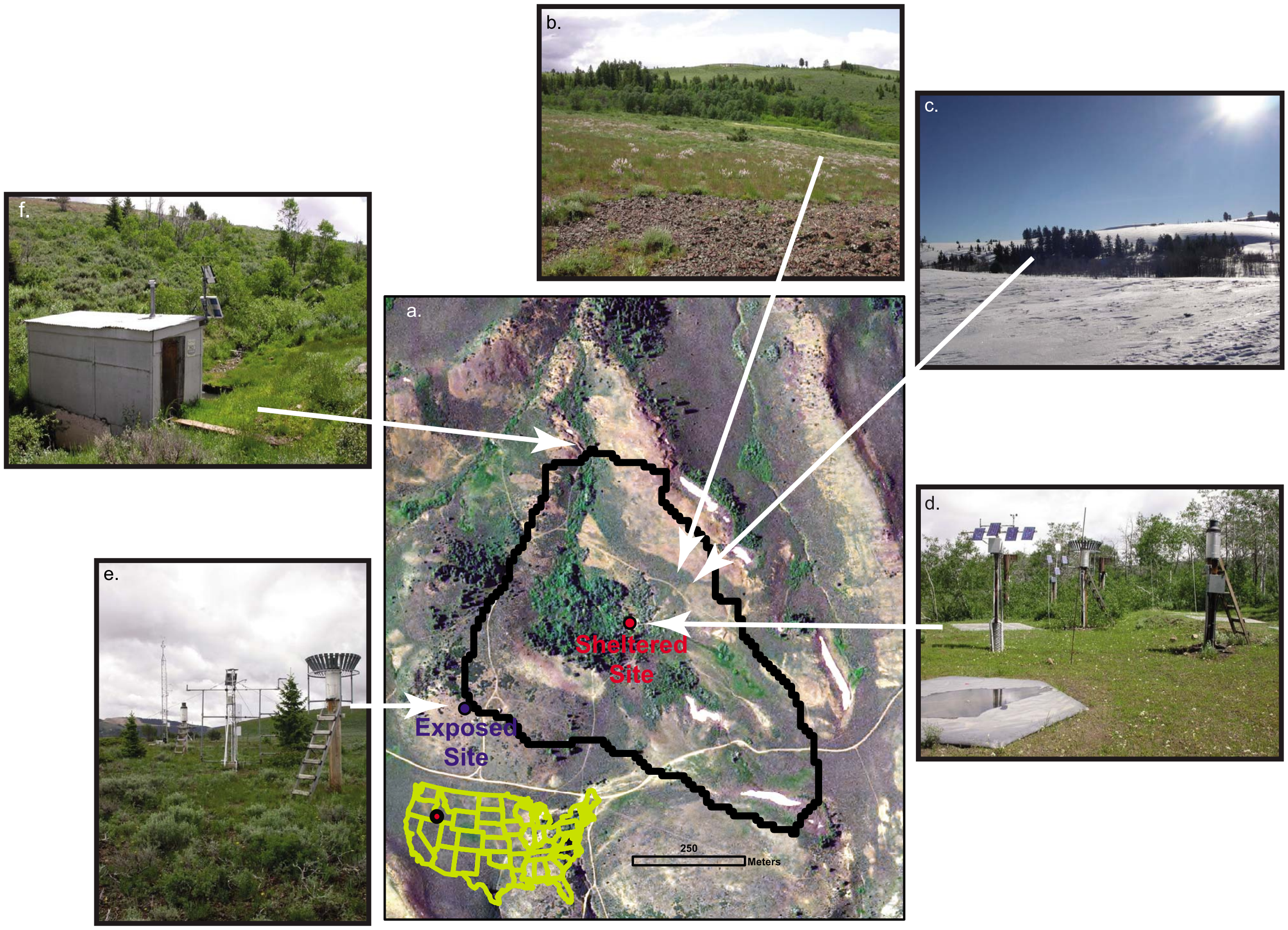

Figure 1. (a) Location map for the Reynolds Mountain East (RME) catchment with a shaded relief image of vegetation classes, roads, perennial streams, and locations of the outlet weir and sheltered and exposed sites, with (b) a view from the north in late spring, (c) a view from the north in winter, (d) sheltered site instrumentation and (e) exposed site instrumentation, and (f) the outlet weir.

vation is provided from three wells and began in late August of 2005.

2. Data Description

[7] Table 1 presents a summary of the forcing data presented, including the current sensor type and height, site, and measurement locations. Table 2 presents a summary of the validation data presented, including the current sensor type, height, and location, mean water year value, data interval, and period of record. Over the period of record, a variety of digital data recording and snow, hydrological and meteorological sensors were used at the sheltered and exposed sites. While information on these changes has been partially documented [*Marks et al.*, 2001a; *Pierson et al.*, 2001; *Seyfried et al.*, 2001; *Johnson and Marks*, 2004], only current measurement configurations are presented (Tables 1 and 2).

[8] While missing values are inevitable in a data record of this length, these represent less than one half of one percent of the record. Data gaps seldom occurred simultaneously at both sites, so the relationship between sites was used to fill gaps when they occurred. During the few occasions when both sites failed at the same time, data from other meteorological sites within RCEW were used to fill in missing values.

2.1. Meteorological Forcing Data

2.1.1. Precipitation

[9] Unshielded, shielded and wind-corrected (hereafter referred to as corrected) precipitation data are provided for both the exposed and sheltered sites. Figure S2 presents total water year corrected and shielded precipitation divided into snow and rain fractions for the entire period of record for both the sheltered and exposed sites. Differentiation between rain and snow was based on dew point temperature during the precipitation event after the analysis of *Marks et al.* [1998; 2001b]. Shielded and unshielded precipitation were measured continuously at both sites for the entire period of record, with wind corrected values computed using the dual-gage approach [e.g., *Hanson*, 1989; *Yang et al.*, 1999; *Hanson et al.*, 2004].

2.1.2. Wind

[10] Wind speed and direction were measured for the entire period of record at the exposed site, but only wind speed was measured at the sheltered site (see Table 1). The average water year wind speed at the exposed site was between 1.7 and 3.2 times that measured at the sheltered site

Table 1. Hourly Forcing Data for the Sheltered and Exposed Sites, Including the Parameters Measured, Current Sensor, Site, Measurement Height, and Mean Water Year Value[a]

Parameter	Current Sensor[b]	Site	Height[c] (m)	Mean WY Value[d]
Precipitation	Pair of modified Belfort Universal (20.3 cm) gages[e]	Sheltered	3	Unshielded: 689 mm
	Pair of modified Belfort Universal (20.3 cm) gages[e]	Sheltered	3	Shielded: 822 mm
	Pair of modified Belfort Universal (20.3 cm) gages[e]	Sheltered	3	Corrected: 964 mm
	Pair of modified Belfort Universal (20.3 cm) gages[e]	Exposed	3	Unshielded: 385 mm
	Pair of modified Belfort Universal (20.3 cm) gages[e]	Exposed	3	Shielded: 550 mm
	Pair of modified Belfort Universal (20.3 cm) gages[e]	Exposed	3	Corrected: 779 mm
Wind speed and direction	MetOne 013/023	Sheltered	3	1.9 m s^{-1}
	MetOne 013/023	Exposed	3	4.5 m s^{-1}
Air temperature and humidity	Vaisala HMP 45	Sheltered	3	T_a = 5.1°C, T_d = −3.2°C
	Vaisala HMP 45	Exposed	3	T_a = 5.2°C, T_d = −3.4°C
Soil temperature	Yellow Springs Instruments thermister	Sheltered[f]	−0.3	6.7°C
	Yellow Springs Instruments thermister	Exposed	−0.3	6.7°C
Solar radiation	Eppley precision spectral pyranometer	Sheltered	4	181 W m^{-2}, 15.6 MJ d^{-1}
	Eppley precision spectral pyranometer	Exposed	3.5	185 W m^{-2}, 16.0 MJ d^{-1}
Thermal radiation	Simulated	Sheltered	NA	274 W m^{-2}, 23.7 MJ d^{-1}
	Simulated	Exposed	NA	249 W m^{-2}, 21.5 MJ d^{-1}
	Eppley precision infrared radiometer	Near sheltered site[g]	3	260.6 W m^{-2}
	Eppley precision infrared radiometer	15 m tower near sheltered site[h]	15	272.0 W m^{-2}
	Kipp and Zonen CNR1	exposed site[i]	1.5	261.3 W m^{-2} (excluding WY 2008)

[a] The period of record is 1 October 1983 to 30 September 2008.

[b] Sensors are listed for informational purposes only and do not necessarily indicate an ARS endorsement or recommendation for use.

[c] Negative values for indicate below-ground locations.

[d] T_a and T_d indicate air and dew point temperature, respectively.

[e] One with Alter windshield and one without, using Huntley load cell.

[f] From October 1990 to 30 September 2008.

[g] From 1 October 2005 to 30 September 2008.

[h] From 1 October 2005 to 24 September 2008.

[i] From 1 October 2005 to 15 January 2008.

with larger differences during winter than summer. The water year maximum hourly measured wind speed ranged from 6.1 to 10.1 m s^{-1} and 16.1 to 26.5 m s^{-1} at the sheltered and exposed sites, respectively. A more detailed discussion of the wind characteristics at the two sites for select water years is given by *Reba et al.* [2009].

2.1.3. Temperature

2.1.3.1. Air Temperature

[11] Air temperature was measured at both the sheltered and exposed sites for the entire period of record (see Table 1). Water year maximum hourly air temperatures ranged from 26.6°C to 34.0°C while minimum hourly air temperatures ranged from −31.0°C to −13.9°C at both sites. Mean water year air temperature ranged from 3.2°C to 6.4°C and 3.6°C to 7.2°C at the sheltered and exposed sites, respectively.

2.1.3.2. Soil Temperature

[12] Soil temperature at 30 cm was measured at the exposed site for the entire period of record, and at the sheltered site beginning in October 1990 (Table 1). Because unstable electronics caused noise and spikes in early record soil temperature data from the exposed site, the data were filtered using a 3 h moving average filter based on the central hour. For the period prior to October 1990 soil temperature at the sheltered site was estimated from exposed site values and corrected for differences in snow cover duration between the sites. While the ground is snow covered, soil temperature is nearly constant or changes very slowly, with no indication of a diurnal cycle. However, once the snow cover is depleted, the soil warms rapidly during the day and cools at night, showing a strong diurnal soil temperature cycle. Snow cover duration was determined from a snow pillow located at the sheltered site. Once measurement of soil temperature began at the sheltered site, those data were also filtered with a 3 h moving average to remove spikes. Soil temperatures at both sites are quite similar. Data from both sites show that values stabilize at initiation of the seasonal snow cover, then gradually cool to values of near 0°C by peak snow accumulation, which is maintained through melt out. Water year maximum soil temperatures

Table 2. Validation Data, Including the Parameters Measured, Current Sensor, Location, Measurement Height, Mean Water Year Value, Data Interval, and Period of Record

Parameter	Current Sensor[a]	Location	Height[b] (m)	Mean WY Value	Data Interval	Period of Record[c]
Discharge	90° V notch weir	Outlet	0	505 mm	Hourly	10/1/83–9/30/08
Snow water equivalent	Snow pillow	Sheltered site	0	549 mm (peak)	Hourly	10/1/83–9/30/08
	Snow course	Sheltered site	0	531 mm (peak)	Biweekly	10/1/83–9/30/08
Snow depth	Judd ultrasonic depth sensor	Sheltered site	3	164 cm (peak)	Hourly	10/11/96–9/30/08
	Judd ultrasonic depth sensor	Exposed site	3	89 cm (peak)	Hourly	11/24/99–9/30/08
	Snow course	Sheltered site	0	154 cm (peak)	Biweekly	10/1/83–9/30/08
Soil moisture	Troxler neutron probe	Sheltered site	−0.3	0.259 m^3 m^{-3}	Biweekly	10/1/83–9/30/08
	Troxler neutron probe	Exposed site	−0.3	0.164 m^3 m^{-3}	Biweekly	10/1/83–9/30/08
	Hydra Probe	Sheltered site	−0.3	0.329 m^3 m^{-3}	Hourly	12/29/05–9/30/08
Relative water content	Troxler neutron probe	Sheltered site	−0.3	0.098 m^3 m^{-3}	Biweekly	10/1/83–9/30/08
		Exposed site	−0.3	0.078 m^3 m^{-3}	Biweekly	10/1/83–9/30/08
	Hydra Probe	Sheltered site	−0.3	0.154 m^3 m^{-3}	Hourly	12/29/5–9/30/08
Relative storage	Neutron probe	Sheltered site	−1.06	8.7 cm	Biweekly	10/1/83–9/30/08
		Exposed site	−1.06	7.4 cm	Biweekly	10/1/83–9/30/08
Groundwater	Hobo U20 water level logger	Well-RME 1	−8.99	-	Hourly	8/29/05–9/30/08
	Eppley precision infrared radiometer	Well-RME 2	−9.54	-	Hourly	8/29/05–9/30/08
	Kipp and Zonen CNR1	Well-RME 3	−9.86	-	Hourly	8/29/05–9/30/08

[a] Sensors are listed for informational purposes only and do not necessarily indicate an ARS endorsement or recommendation for use.
[b] Negative values indicate below-ground locations.
[c] Read, e.g., 10/1/83–9/30/08 as 1 October 1983 to 30 September 2008.

range from 16.6°C to roughly 24.5°C, with minimum soil temperatures from 0.0°C to −2.2°C at both sites.

2.1.4. Relative Humidity and Dew Point Temperature

[13] Humidity was measured at both sites for the entire period of record (see Table 1). During this time, sensor technology steadily improved, so numerous sensor changes occurred. The typical water year humidity condition at both sites is very low humidity during summer and fall, with variable conditions during the passage of winter storms. Because relative humidity is meaningless outside the context of air temperature, hourly air temperature and relative humidity were used to calculate a dew point temperature for both sites for the period of record. These calculations were performed using conversion equations optimized for accuracy around 0°C to ensure the greatest precision during phase change [*Marks et al.*, 1999a].

[14] Maximum dew point temperatures occur in summer and late fall with minimum values in winter. The maximum water year dew point temperature recorded was 23.4°C and 17.4°C and the minimum was −41°C at the sheltered and exposed sites, respectively. Mean water year dew point temperature ranged from −1.4°C to −5.0°C and −2.0°C to −4.7°C at the sheltered and exposed sites, respectively.

2.1.5. Radiation

2.1.5.1. Incoming Solar Radiation

[15] Solar radiation was measured at both the sheltered and exposed sites for the entire period of record. Solar radiation at the two sites is summarized in Table 1. On average, there is little difference in solar loading at the two sites, though the sheltered site is slightly more shaded in winter because of adjacent canopy and topography. Note that the sheltered site is wind sheltered, not shaded. Though there are canopy and terrain features that obstruct solar radiation at low sun angles, because the radiometers are 3–4 m above ground level, these do not affect solar irradiance during most of the day.

2.1.5.2. Incoming Thermal Radiation

[16] Thermal radiation was measured for only a few years toward the end of the 25 year period of record at three locations. The first two locations were in the area near the sheltered site at an open location 3 m above the ground approximately 10 m northeast of most of the canopy surrounding the sheltered site and from the top of a 15 m tower through the aspen canopy just adjacent to the sheltered site which is unobstructed in the winter but has a reduced field of view during the growing season because of aspen leaves. The top of the 15 m tower was near, but not quite above the aspen canopy at the tower location. Finally, measurements were made at the exposed site in a representative open area approximately 1.5 m above the ground.

[17] For the three sites, the measurement period is about 3 years (WY 2006 through 2008), which is relatively brief in comparison to the 25 year period of record. Collectively, however, they provide useful information on how thermal radiation varies seasonally and diurnally in response to different canopy and terrain exposure conditions. Clear-sky thermal radiation was simulated for the 3 year period during which thermal radiation was measured. The simulated values were based on methods described by *Brutsaert* [1975] and extended to mountain regions by *Marks and Dozier* [1979]. Using methods described by *Link and Marks* [1999b, 1999a] and *Susong et al.* [1999], factors derived from site-specific

information on temperature, humidity, terrain, and canopy structure during the model fitting period were combined with GIS-derived topographic view factor. Seasonally adjusted canopy closure index and measured cloud cover solar reduction were then used to simulate thermal radiation for both the sheltered and exposed sites for the entire 25 year period of record. These values are summarized in Table 1 for both the sheltered and exposed sites over the period of record.

2.2. GIS Watershed Descriptors

[18] Nine GIS data layers are available and include: 10 m raster grid of a digital elevation model (DEM), 10 m raster grid of vegetation, basin outline, soils, geology, primary and secondary roads, stream channels and measurement site locations over the same geographic domain (Figure S1). All GIS data are in ArcInfo interchange file format and can be accessed through the ftp site.

2.3. Validation Data

2.3.1. Stream Discharge

[19] Stream discharge from RME was measured continuously for the entire 25 year period of record using a 90° V notch weir [*Pierson et al.*, 2001] (Table 2 and Figures 1 and S1). The weir is located below a heated instrument shelter for cold season data collection of discharge. The stream at RME is perennial with spring high flows and late summer low flows. Typically, the largest hourly events are associated with rain on snow, while the largest daily events occur during spring snowmelt. Figure S3a presents mean water year streamflow for the 25 year period of record. The measured mean water year specific discharge at the weir for WY 1984 through WY 2008 was 505 mm. The range for the mean water year specific discharge was from 122 mm (WY 1992) to 1076 mm (WY 1984).

2.3.2. Snow Water Equivalent and Snow Depth

[20] The majority of snow measurements were made at the sheltered site. A snow pillow was used to measured snow water equivalent (SWE) continuously for the entire 25 year period of record. SWE, snow depth and snow density were measured biweekly during the period of record along a snow course, located at the sheltered site [*Marks et al.*, 2001a]. Though they are separated by about 5 m, snow course data closely track the snow pillow measurements in most years, with an RMSD of 43 mm and Nash-Sutcliffe model efficiency of 0.96. *Marks et al.* [2001a] discuss the details of the snow course layout and the methodology of the measurements. Table 2 summarizes snow measurements over the period of record and Figure S3b presents both snow pillow and snow course SWE for the period of record. The maximum peak snow pillow SWE recorded was 1087 mm in WY 1984. The minimum peak snow pillow SWE recorded was 186 mm in WY 1992. The five lowest SWE water years in ascending order are 1992, 2005, 2001, 1991 and 1987, and the five highest SWE water years in descending order are 1984, 1989, 1997, 2006 and 1986. SWE data from the snow pillow indicate that, over the 25 year record, the snow cover was initiated between 12 October and 23 November and melted completely between 1 April and 11 June.

[21] Ultrasonic snow depth sensors were deployed at the sheltered site at the beginning of WY 1997 and at the exposed site at the beginning of WY 2000. The maximum value recorded was 214 cm in WY 1999 and 134 cm in WY 2004 at the sheltered and exposed sites, respectively. As reported in previous studies [*Winstral and Marks*, 2002], snow redistribution and drifting is extensive in the RME catchment. Drift depths in excess of 4 m have been measured, and *Marks et al.* [2002] report that though the drift zones in the catchment represent only about 9% of the area, they generally contain 25% or more of the catchment SWE.

2.3.3. Soil Moisture

[22] Soil moisture data presented was measured at 30 cm below the surface at the sheltered and exposed sites for the entire 25 year period of record. Soil water data were obtained by neutron probe near the two sites, and via electronic measurement using a dielectric soil water sensor (Hydra Probe) since 2005 near the sheltered site. See *Seyfried et al.* [2001] for descriptions of neutron probe precision and accuracy assessment. Readings were made approximately every two weeks over the entire record at two locations (Figure S1).

[23] The soil water data from the dielectric soil water sensor were collected hourly beginning 29 December 2005. The principles of measurement and calibration relationships are described by *Seyfried et al.* [2005]. The sensor was located at the sheltered site at a depth of 30 cm (Figure S1). Because of the insulating effect of snow, soil freezing is extremely rare at a depth of 30 cm.

[24] The data are included for each measurement date as soil water content at depth, relative water content at depth, and relative storage in the soil profile. Soil water content is typical volumetric data, while the relative water content was normalized as a function of soil texture and rock content to the proportion of plant-available water in the top 30 cm of the soil layer at each site. Plant-available water, also referred to as the water content wilting point, is volumetric soil water above the seasonal dry-down limit. The relative storage is the storage of water from the surface to a given depth, in this case 106 cm.

2.3.4. Groundwater

[25] Three groundwater wells provide continuous water elevation data for water years 2006, 2007, and 2008. A summary of the well depth and instrumentation is presented in Table 2, and the locations of the wells are shown in Figure S1. These wells were recently reinstrumented and are fully screened and approximately 10 m deep. At two of the three well locations, the water table goes to the surface and the ground remains saturated for extended periods during late spring melt. The groundwater recedes during dry periods lasting from late spring through early snowmelt.

2.4. Examples of Data Use

2.4.1. Snow Water Equivalent

[26] The development and ablation of the seasonal snow cover can be captured through the simulation of the snow water equivalent. Isnobal, a distributed, physically based, two-layer snow cover mass and energy balance model [*Marks et al.*, 1999b] was used to simulated SWE for WY 2006 and 2007 at the study catchment, RME. Measurements of SWE from both the snow pillow and snow course were compared to the simulated values (Figure S4a). Nash-Sutcliffe (NS) model efficiency [*Nash and Sutcliffe*, 1970] is a test of how well the model captures the variability in the measured values. NS of 0.96 and 0.91 was calculated for the snow pillow measured SWE for WY 2006 and 2007, respectively.

2.4.2. Soil Moisture

[27] Soil moisture influences surface evaporation, plant water availability, and groundwater recharge. Measurements of soil moisture can be helpful in hydrologic modeling because of the importance of the parameter and its association with surface-atmosphere, surface-subsurface, and vegetative interactions. The Penn State University Integrated Hydrologic Model (PIHM) [*Qu and Duffy*, 2007; *Kumar et al.*, 2009] was used to simulate the soil saturation near the sheltered site at the dielectric soil water location during WY 2006 and 2007 (Figure S4b). The coefficient of determination (CD), which explains the amount of observed dispersion captured by the modeled time series [*Krause et al.*, 2005], was calculated as 0.91.

2.5. Data Availability

[28] All data presented in this paper are available from the anonymous ftp site ftp://ftp.nwrc.ars.usda.gov/publications/wrr/rme-25yr-data maintained by the USDA Agricultural Research Service, Northwest Watershed Research Center, in Boise, Idaho. Included is a readme file listing the contents of the data with contact information for additional details, a data license and disclaimer file. Within the readme file there is a description of the data files defining the contents and formats for the two precipitation data files, two meteorological data files, seven validation data files and nine GIS data files.

3. Summary and Conclusions

[29] The data presented include 25 water years (1984–2008) of hourly measurements of precipitation, wind, air and soil temperature, humidity, dew point temperature and incoming solar radiation and simulated thermal radiation for a pair of sites: one wind protected by terrain and vegetation and the other on a wind-exposed sagebrush-dominated ridge. These sites generally represent the two primary land cover types in the area. These data represent the full range of hydrometeorological conditions found in this mountain catchment, spanning both the driest (WY 1992) and wettest (WY 1984) years on record and generally represent conditions across a large region in the interior mountain western United States. GIS data provided include information on topography, catchment outline and drainage area, vegetation, soils, geology, stream channels, roads, and measurement site locations. Validation data include hourly stream discharge and snow pillow SWE for the entire period of record, biweekly snow course snow depth, SWE and snow density, and neutron probe soil moisture for both sites over the period of record. Also included for the past several years, are hourly measurements of soil moisture at the sheltered site, snow depth at both sites and groundwater elevation from three wells.

[30] This paper presents a carefully crafted model forcing data set for a snow-dominated mountain catchment to the hydrologic modeling community. They provide all of the information required for developing, testing and applying snow and hydrologic models. It is hoped, that findings from the use of this modeling data set will lead to innovation in hydrologic modeling and will improve our understanding of basin-scale snow-dominated mountain hydrology.

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