Historical Meteorological Driving Data Set

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1. Introduction

Spatially distributed and temporally complete precipitation, temperature, and wind datasets are needed to drive hydrologic models used in investigations of the impacts of observed, and projected future, climatic change in the Pacific Northwest. Prior observation and modeling efforts, for example, have demonstrated regional temperature shifts of about 0.8°C over the 20th century, with projected temperature increases of 1.5-3.2°C by mid 21st century (Mote *et al.* 2003). Although not attributable to a change in greenhouse forcing, precipitation has also changed markedly in the 20th century, and future projections point to wetter winters and drier summers (Mote and Salathé 2009). These kinds of changes have important hydrologic and water management implications in the PNW (Hamlet and Lettenmaier 1999; Snover *et al.* 2003; Payne *et al.* 2004; Elsner *et al.* 2010; Hamlet *et al.* 2010; Vano *et al.* 2010).

The importance of large-scale studies not withstanding, increasingly, policy makers and water management professionals require local, or basin-specific assessments and forecasts for development of climate impact adaptation strategies. In general these needs can be met using existing modeling approaches, but require hydrologic models and meteorological driving data sets at higher spatial resolution. For the CBCCSP described in this report, the spatial resolution of the macro-scale VIC hydrologic model has been increased to 1/16th degree latitude/longitude resolution to help better resolve smaller basins included in the study (Elsner *et al*. 2010; Chapters 1,5,6, this report).

Starting with methods developed by Maurer *et al*. (2002), Hamlet and Lettenmaier (2005) developed methods to re-grid National Climatic Data Center (NDDC) Cooperative Observer (COOP) network and Environment Canada (EC) station data to produce daily time-step hydrologic forcings covering the time period of 1915 - 2003 at a spatial resolution of 1/8th degree. Their methods incorporate U.S. Historical Climatology Network (HCN) and Historical Canadian Climate Database (HCCD) data to correct for temporal biases caused by inhomogeneities in the COOP station assemblages through time, and use the Precipitation Regression on Independent Slopes (PRISM; Daly *et al.*, 1994; 2002) monthly normals to scale precipitation for orographic influences.

These driving datasets have been used as driving data for the Variable Infiltration Capacity (VIC) hydrologic model over the western U.S. Results from these studies have been used to describe regional climatic trends and their hydrologic implications (see Mote *et al*. 2005; Hamlet *et al.* 2005; Hamlet *et al.* 2007; Hamlet and Lettenmaier 2007),

For the Columbia Basin Climate Change Scenarios Project, the methods of Hamlet and Lettenmaier (2005) have been extended and improved to:

- double the spatial resolution to 1/16th degree,
- implement temperature rescaling via PRISM monthly normals,
- cover the time period 1915-2006

Several other minor improvements in the methods have also been implemented as discussed below. This paper describes the methods used in constructing the meteorological data sets used in the study.

2. Approach and Methods

2.1. Sources of data

NCDC COOP and EC daily time step station data are the primary sources for precipitation and temperature observations used in creating the daily time-step forcing series for the Pacific Northwest (PNW) domain, which encompasses the entire Columbia River drainage system, along with the basins west of the Cascade Range (Figure 1). HCN and HCCD data are used as monthly time step benchmarks to maintain temporal consistency and remove biases generated from the re-gridding of the daily station data. In contrast to primary data resources used by Hamlet and Lettenmaier (2005), the Adjusted Historical Canadian Climate Database (AHCCD) network is used instead of the HCCD. The AHCCD data has been subjected to greater quality control and homogenization than the original HCCD dataset. Precipitation has been adjusted for gauge type and undercatch (Mekis and Hogg 1999), and temperatures have been adjusted for station relocations and changes in measurement procedures (Vincent *et al.* 2002).

Maps of PRISM monthly precipitation and temperature climate normals (Daly *et al.* 1994; 2002) allow topographic adjustment of precipitation and temperature values.

Figure 1. Map of Co-Op station locations used in creating gridded meteorological records for the Pacific Northwest. Outline in red show the study domain encompassing the Columbia River basin and coastal drainages in Washington and Oregon.

2.2. Preprocessing, quality control, and gridding

The raw COOP station data were first checked for outlier values and minimum continuity requirements. As per Hamlet and Lettenmaier (2005), any PRCP values greater than 350 mm/day were deemed higher than the climatological limit and assigned the missing data value. TMAX values higher than 55°C and TMIN values lower than -55°C were also assigned the missing data value. Stations with less than 5 years total data record, or without at least 365 continuous days of data were also removed from the dataset.

The raw COOP data records also contain quality control flags for each recorded value. Individual observations were included only if the corresponding flags indicated valid data, otherwise the observation was changed to a missing data value. Some PRCP records have several days of missing data, followed by a day flagged as an "accumulated" value. In these instances, the accumulated precipitation value was evenly redistributed over all of the preceding days with missing data. Though this method may underestimate the temporal variability of precipitation over the missing data period, it was felt to be superior to simply removing the accumulated value or allowing it to remain in the dataset as-is.

Following the quality control steps, the raw COOP station data were interpolated to a 1/16th degree grid using the Symap algorithm (Sheppard 1984, as per Maurer *et al.* 2002; Hamlet and Lettenmaier 2005) with four nearest neighbors. TMAX and TMIN were adjusted for the elevation difference between the nearest neighbor stations and the target cell using the standard atmospheric pseudoadiabatic lapse rate of 6.1°C/km (Barry 1992). The HCN and AHCCD data were also interpolated using the same scheme, but with 15 nearest neighbors for PRCP to avoid sharp spatial discontinuities induced by the lower station density in these networks.

One potential side effect of the re-gridding scheme is the occasional inversion of daily TMAX and TMIN values. This situation can occur when TMAX exhibits greater spatial or temporal variability than does TMIN or when a station is missing a TMAX or TMIN value at a particular time step and the two variables are interpolated from different station patterns (Figure 2). These daily inversions were addressed during the topographic adjustment steps, as described below.

2.3. Temporal adjustments

After the initial spatial interpolation, the methods of Hamlet and Lettenmaier (2005) were followed to correct the COOP data for temporal inhomogeneities created by changes in the station assemblages used for interpolation. The roster of active stations at each time step varies due to incomplete station records and/or the period of operation for individual stations. The interpolation scheme uses a minimum number of nearest neighbors for each interpolated value, and therefore will occasionally include information from stations that exhibit statistics substantially different from the other neighbors. This process can potentially introduce bias to the resulting time series, especially in time periods or areas with a sparse COOP station network.

In order to correct for these temporal inhomogeneities, the daily COOP values were adjusted such that the monthly average matches the gridded monthly HCN/HCCD values, following the basic approach outlined by Hamlet and Lettenmaier (2005). A minor change to the methods was implemented, however, by forcing the monthly COOP values to exactly match the monthly HCN/HCCD values without temporal filtering. This change was made to avoid the introduction of bias in isolated cases when station dropouts of one month or less occurred in the time series. Thus the final product is a hybrid derived from two different data sets. The methods preserve the low frequency (monthly) fluctuations derived from the HCN and HCCD gridded data sets, while retaining important elements of the high frequency (daily) variability derived from the COOP data.

To perform the temporal adjustment, monthly averages of the daily COOP values were corrected as follows:

For TMAX and TMIN:

$$Coop_{raw}(t) = Coop_{raw}(t) + (HCN(T) - Coop_m(T)) \tag{1}$$

For PRCP:

$$Coop_{adj}(t) = Coop_{raw}(t) * (HCN(T) / Coop_m(T)) \quad (2)$$

where $COOP_{adj}(t)$ is the adjusted daily COOP data value at time step t, $COOP_{raw}(t)$ is the unadjusted daily COOP data value at time t, $HCN(T)$ is the HCN/AHCCD monthly value at monthly time step T (the month within which t occurs), and $COOP_m(T)$ is the monthly averaged COOP value at time T. Note that a multiplicative approach is used in the case of precipitation to avoid introduction of negative precipitation values.

2.4. Topographic Adjustments to Temperature and Precipitation

Following Maurer *et al.* (2002) and Hamlet and Lettenmaier (2005), the temporally adjusted daily precipitation values were then rescaled by forcing the long-term mean values to match the monthly PRISM normals. The prior 1/8th degree datasets used the 4km resolution PRISM normals based on the 1961-1990 climatology. The current data set instead uses the 30-arcsecond PRISM normals based on the 1971-2000 climatology (Daly *et al.* 2002). In Canada, only a 4km PRISM product reporting means for the 1961-2000 period was available. A quasi-30-arcsecond product for the 1971-2000 normals was developed by first estimating the 1971-2000 means from the available 1961-1990 product (via regression equations), and then interpolating from the 4km product to the 30-arcsecond resolution using an inverse square weighting with four nearest neighbors.

Additionally, a similar adjustment scheme was applied to daily maximum and minimum temperatures using the PRISM temperature normals. Temperature lapse rates vary strongly throughout the region and on daily time scales, and the typical approach of applying a constant standard atmospheric lapse rate of 6.1°C/km may cause a substantial temperature bias at higher elevations as well as introduce seasonal biases.

Topographic adjustment of precipitation on a monthly time scale is relatively straightforward: the ratio of monthly observed precipitation to monthly PRISM normals is calculated for each calendar month in the full time series (1971-2000), and this ratio is applied as a scaling factor to the entire daily time series. With temperatures, however, care must be taken to avoid introducing bias in the daily mean or daily range by adjusting maximum and minimum temperatures separately. Several important model-derived environmental variables (such as incoming solar radiation) depend on the range of daily temperatures, therefore the adjustment scheme used here was designed to explicitly preserve the range during the topographic adjustment. The daily temperature range was explicitly preserved by averaging each of the monthly PRISM and monthly mean COOP *Tmax* and *Tmin* values, and adding the offset to the *Tmax/Tmin* average at each daily time-step.

PRISM rescaling for PRCP:

$$PRCP_{adj}(t) = PRCP_{raw}(t) * [PRISM(T) / PRCP_m(T)] \tag{3}$$

PRISM rescaling for TMAX and TMIN:

$$\begin{gathered} TMAX_{adj}(t) = TMAX_{obs}(t) + \\ \left[\left(TMAX_{PRISM}(T) + TMIN_{PRISM}(T)\right)/2 - \left(TMAX_m(T) + TMIN_m(T)\right)/2\right] \end{gathered} \tag{4}$$

$$\begin{gathered} TMIN_{adj}(t) = TMIN_{obs}(t) + \\ \left[\left(TMAX_{PRISM}(T) + TMIN_{PRISM}(T)\right)/2 - \left(TMAX_m(T) + TMIN_m(T)\right)/2\right] \end{gathered} \tag{5}$$

where $TMAX_{obs}(t)$ and $TMIN_{obs}(t)$ are the temporally adjusted TMAX and TMIN values at daily time step t, $TMAX_{PRISM}(T)$ and $TMIN_{PRISM}(T)$ are the PRISM TMAX and TMIN values for monthly time step T (the month within which t occurs), and $TMAX_m(T)$ and $TMIN_m(T)$ are the monthly averaged (and temporally adjusted) TMAX and TMIN values for month T.

An additional corrective step was performed at this stage. For time steps where TMIN is greater than TMAX due to interpolation errors in the initial regridding step, the pseudo-mean of the inverted TMAX and TMIN values is offset by the difference in monthly PRISM and observed pseudo-means, and then a climatological daily range (from PRISM TMAX and TMIN) is applied:

$$\begin{gathered} TMAX_{adj}(t) = \left\lfloor \left(TMAX_{obs}(t) + TMIN_{obs}(t) \right) / 2 \right\rfloor + \\ \left[\left(TMAX_{PRISM}(T) + TMIN_{PRISM}(T) \right) / 2 - \left(TMAX_{m}(T) + TMIN_{m}(T) \right) / 2 \right] + \\ \left[\left(TMAX_{PRISM}(T) - TMIN_{PRISM}(T) \right) / 2 \right] \end{gathered} \tag{6}$$

$$\begin{gathered} TMIN_{adj}(t) = \left\lfloor \left(TMAX_{obs}(t) + TMIN_{obs}(t) \right) / 2 \right\rfloor + \\ \left[\left(TMAX_{PRISM}(T) + TMIN_{PRISM}(T) \right) / 2 - \left(TMAX_{m}(T) + TMIN_{m}(T) \right) / 2 \right] - \\ \left[\left(TMAX_{PRISM}(T) - TMIN_{PRISM}(T) \right) / 2 \right] \end{gathered} \tag{7}$$

Though this method cannot reconstruct the actual daily values, the climatological mean range is certainly preferred over the erroneous inverted values.

2.5. Wind data

Daily wind speed values for 1949-2006 were downscaled from National Centers for Environmental Prediction-National Center for Atmospheric Research (NCEP-NCAR) reanalysis products (Kalanay *et al.* 1996). For the years prior to 1949, a daily wind speed climatology (same value for each day of the year) was derived from the 1949-2006 reanalysis (Hamlet and Lettenmaier 2005).

2.6. Description of final data set and applications

The final daily meteorological data set covers the period from Jan 1, 1915 to Dec 31, 2006 for the entire Columbia River basin and coastal drainages in the PNW. The data set is available on the study web site both as a daily and monthly summary product. The historical meteorological data set is an important input to the downscaling process described in Chapter 4 of this report. The downscaling process results in alternative daily meteorological data sets that reflect the changes in PNW climate simulated by specific global climate models. These data sets are the fundamental inputs to the hydrologic models described in Chapter 5 and 6 of this report that ultimately generate the hydrologic products described in Chapter 8. The meteorological driving data sets are also pre-processed by the hydrologic models to produce additional meteorological data for solar radiation at the surface, outgoing longwave radiation, dewpoint, relative humidity, and vapor pressure deficit. These supplementary data are available on the study web site.

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