SUPPLEMENTING SPARSE OBSERVATIONS OF TEMPERATURE AND PRECIPITAION WITH A HIGH RESOLUTION ATMOSPHERIC MODEL

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ABSTRACT

The spatial scarcity of meteorological observations represents a significant challenge for distributed hydrological modelers. Mesoscale models can provide a physically-based approach to supplement surface observations over high-elevation terrain. The heavily instrumented North Fork American River basin in California offers an optimal study location to verify mesoscale model output. Gridded 6km surface temperature and precipitation were obtained from the Weather and Research Forecasting (WRF) model, which uses lateral boundary conditions from the North American Regional Reanalysis. Results indicate that during the wet season, the WRF model was shown to well represent the inter-annual variability of the large scale temperature lapse rate and the orographic gradient of precipitation. Errors in the WRF model's temperature and precipitation were of a similar magnitude to those errors using a low-elevations station coupled to a standard lapse rate and Precipitation Regression on Independent Slopes Method (PRISM). A distributed hydrological study to evaluate if the WRF based forcing improves simulated snowpack and streamflow remains as future work. (KEYWORDS: Mesoscale, distributed, hydrology, lapse rate, orographic precipitation gradient, PRISM)

INTRODUCTION

Forecasted surface warming over the next century will drastically reduce the global seasonal snowpack that provides over 40% of the world's drinking water (Meehl et al., 2007). On a seasonal basis, the accurate prediction of peak snow water equivalent (SWE), as well as significant melt events, would allow watershed managers to more efficiently manage their watershed networks. Distributed energy balance models can realistically simulate internal basin dynamics, as long as accurate input data are available (Reed et al., 2004). However, reliable meteorological input that is distributed across the basin is one of the most difficult requirements of distributed models. First, few observational stations typically exist within mountainous basins. Second, where stations do exist, temperature and precipitation are most often the only variables measured; requiring relative humidity and incoming radiation to be estimated via empirical relationships that are dependent on temperature and precipitation. Finally, the extrapolation from point measurements to a distributed grid can introduce additional errors when insufficient observational stations exist to resolve spatial patterns.

An alternative option to generating temperature and precipitation driving data is to use a physically based numerical weather prediction model. The development of these models to represent surface conditions has been motivated by the demand for short-term (< 7 days) weather prediction. Numerical weather prediction models that have grid cells on the order of 1-36 km are commonly referred to as mesoscale models (Maraun et al. 2010). Within many hydrologic basins, the density of mesoscale model grid cells has surpassed the density of available surface observations, especially at high elevations. Increased spatial resolution has allowed numerical weather prediction models to resolve the topography that drives orographic precipitation gradients. In addition, when mesoscale models are forced by synoptic scale observations of circulation they have been shown to capture the correct timing of storms (Colle and Mass, 2000; Westrick and Mass, 2002; Wang and Georgakakos, 2005).

This paper examines the ability of the mesoscale model, the Weather and Research Forecasting (WRF) model to capture the elevational gradients of temperature and precipitation over the North Fork of the American River Basin (850 km^2), located on the western slopes of the Sierra Nevada mountain range in California (Figure 1). This basin was chosen because of its unusually dense network of observational stations, which range from near sea level to 2300 meters in elevation. This unique observational network allows us to validate WRF model's performance across the 0°C isotherm zone (~1400-2000 m), where rain transitions into snow and hydrologic modeling is the most sensitive to meteorological errors (Lundquist et al., 2008b). Because most basins do not contain as many observations as the North Fork Basin, we create a gridded forcing set (temperature and

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Paper presented Western Snow Conference 2011

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precipitation) based on the observations from one low-elevation station in order to provide a control forcing set. The two forcing sets derived from the WRF model output and the one low-elevation station are compared to all observations over the North Fork Basin and we ask the question: **“On what temporal scales can the WRF model resolve the observed elevational gradients in temperature and precipitation**?”

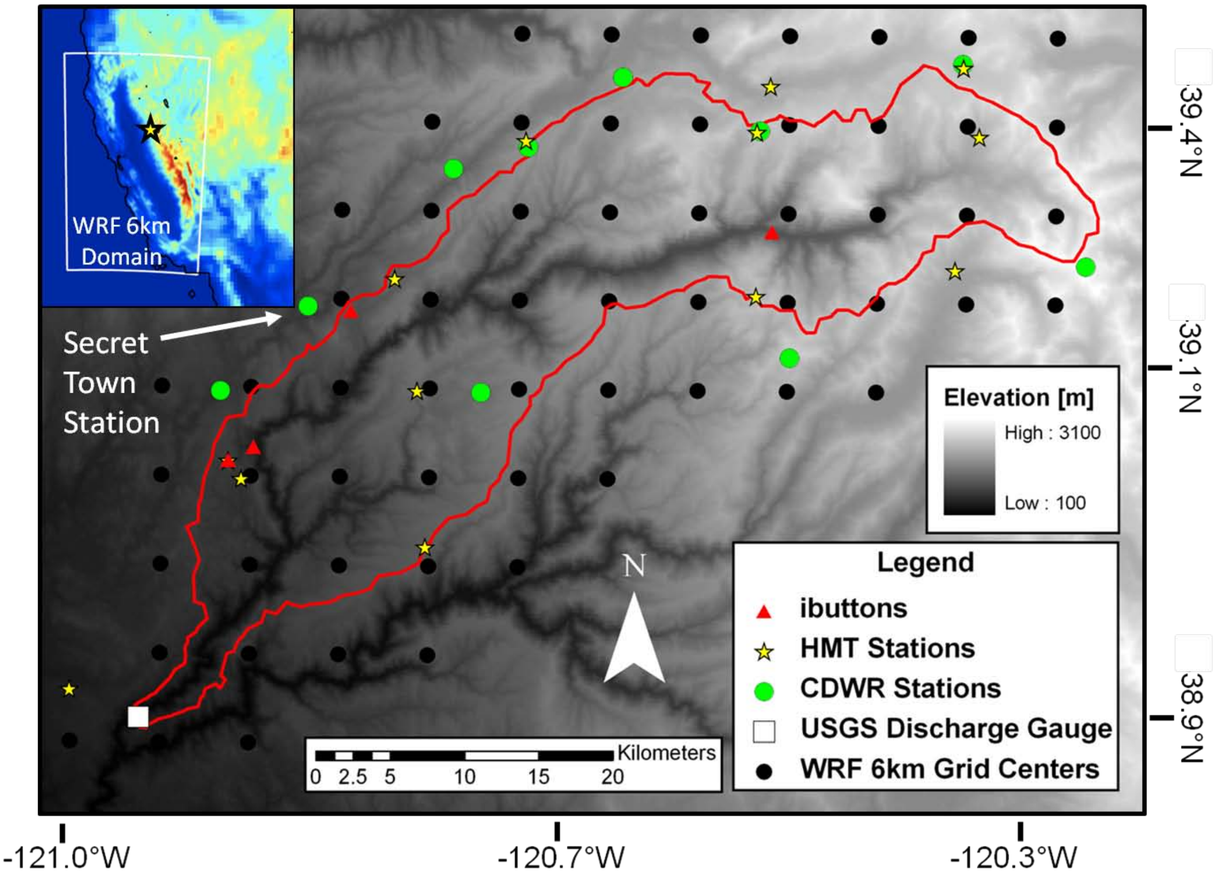

Figure 1. Map of the North Fork American River Basin located on the western slopes of the Sierra Nevada, and locations of the observational stations and WRF 6km grid cell centers used. Insert shows the 6km domain of the WRF model over California and location of the North Fork Basin. The location of the Secret Town station, which was used as the base station to extrapolate temperature and precipitation, is also shown.

OBSERVATIONAL DATA

Hourly observations of temperature and precipitation for water years 2001-2010 were obtained from 10 weather stations operated by the California Department of Water Resources (data available through the California Data Exchange Center, http://cdec.water.ca.gov/). In 2005, the National Oceanic and Atmospheric Administration’s Hydrometeorological Test Bed (NOAA/HMT) program installed meteorological stations spanning the elevation range of the American River Basin (Ralph et al., 2005). Two minute measurements of temperature and precipitation were obtained at 13 HMT stations in or near the study basin. In addition, 4 self-recording temperature sensors distributed in trees across the basin (following methods in Lundquist and Huggett, 2008) provided temperature data from 2006-2010.

All observational data were closely quality controlled. Unrealistic outliers and extreme jumps in data were removed following Meek and Hatfield (1994). The 2 min precipitation and temperature measurements from HMT were aggregated to hourly if at least 75% of that hour was available; otherwise it was flagged as missing. Due to the limited measurement of wind speed at all stations, no correction for precipitation gauge undercatch was attempted.

The Secret Town station (Figure 1) was selected as the base station for the control forcing. This choice was made because Secret Town is below 1000 m, where the majority of stations are placed, as well as having minimal missing data over the 2001 to 2010 period. However, energy balance hydrological models require continuous input data as they step through time. Therefore, missing periods of data at Secret Town were filled following Liston and Elden (2006). Temperature data with less than one hour missing were interpolated between adjacent hours. For missing data greater than one hour but less than 24 hours, each missing hour was estimated as the mean temperature from the same hour on the previous and following day. Missing data greater than 24 hours was repaired by interpolating temperature from nearby stations using monthly lapse rates between stations. Missing precipitation (0.5% of 10 years) was assumed to be zero.

ATMOSPHERIC MODELS

This paper attempts to isolate the periods when a mesoscale mode can provide improved driving data to a hydrological model. The output from a given mesoscale model may differ depending on the large scale (>36km) forcing it receives at its boundary. In order to remove possible biases in the mesoscale model caused by its lateral boundary conditions, a reanalysis product was used as the large scale driver.

North American Regional Reanalysis (NARR)

The NARR reanalysis is a 32km/45 layer product created by ingesting surface and upper air observations over the continental U.S. by the Regional Data Assimilation System into the NCEP Eta Model to produce a spatial and temporal consistent data set (Mesinger et. al. 2006). NARR's lateral boundary conditions are provided by the NCEP-DOE Global Reanalysis, and NARR data exists for the time period 1979-present. NARR can be considered one of the best representations of the meteorological record at this resolution.

Weather Research and Forecasting Model (WRF)

The 32km NARR reanalysis provided initial and lateral boundary conditions for a high resolution dynamical downscaling generated by the Weather Research and Forecast model (WRF, Skamarock et. al., 2007). The downscaling simulation contained two domains: an 18km horizontal resolution domain that covered California and extends west over the Pacific Ocean, and a 6km domain over California (Figure 1). At 6km horizontal resolution, all the major mountain complexes in California are resolved, but the fine-scale topography surrounding the river basin is not resolved. Two-directional nesting was employed between the 18- and 6-km domains. Each domain contained 27 vertical levels, with the vertical grid stretched to place the highest resolution in the lower troposphere. In the 18-km domain, the Kain-Fritsch cumulus parameterization was used (Kain, 2004); in the 6-km domain only explicitly resolved convection could occur. Both domains used the YSU boundary layer scheme (Hong, Noh and Dudhia, 2006), the Morrison 2-moment microphysics scheme (Morrison, Thompson and Tatarskii, 2009), the rapid radiative transfer model longwave radiation scheme (Mlawer et al., 1997), the Dudhia shortwave radiation scheme (Dudhia, 1989), and the Noah land surface model with 4 ground layers (Chen and Dudhia, 2000).

The downscaled data was generated for 10 partial water years (Oct.-June water years 2001-2010). Throughout this period, WRF was reinitialized three hours prior to the first of each month and every 5 days, 3 hours, thereafter. The first three hours of each run were discarded for model spin-up, resulting in a temporally continuous run, with slight meteorological discontinuities between the full model initializations. The interior conditions are updated from NARR at each initialization, and the lateral boundary conditions are updated continuously throughout the run from the NARR boundary conditions (which have 3-hourly temporal resolution). The dynamical downscaling technique used here has been shown to well-capture the variability in meteorological conditions over an 11-year period in Southern California when generated with the Penn State/NCAR mesoscale model, version 5, WRF's predecessor (Hughes and Hall, 2010; Hughes et al., 2009).

METEOROLOGICAL FORCING SETS

A) WRF Model Based

Surface output from 61 of WRF model's 6km grid cells located inside or within a boundary of one grid cell from the North Fork Basin were extracted (Figure 1). The boundary width was chosen to allow optimal interpolation along the basin edges. Because 98% of North Fork Basin precipitation occurs Oct through June (National Climatic Data Center [http://www.ncdc.noaa.gov/oa/ncdc.html]), we restrict our analysis to these months. At each grid cell, hourly 2 meter temperature and precipitation were extracted from the WRF model for water years 2001-2010.

B) Observational Based

It is common for basins within complex and inaccessible terrain to only have one available observational station at low to middle elevations. The gridded input required by distributed hydrological models, must then be created by extrapolating temperature and precipitation from this base station to rest of the basin. We simulate this type of observationally based forcing set by using the Secret Town station (Figure 1) as our base station. This choice was made because Secret Town is below 1000 m, where the majority of stations are placed, as well as having minimal missing data over the 2001 to 2010 period of interest (1% temperature, 0.5% precipitation). The continuous temperature record from the Secret Town station was extrapolated using an annual lapse rate of -6.5 °C/km, based on Californian climatology (Daley et al. 2004). Precipitation was extrapolated using the spatial weighting from the 30 arc second (800 m) 1971-2000 climatological normals product, derived using the Parameter Regression on Independent Slopes Method (PRISM) (Daley et al. 2004).

RESULTS

Temperature

Estimated gradients of mean temperature within the North Fork Basin were compared to fifteen temperature observations across the basin (Figure 1). Figure 3 shows the mean October through April temperature versus elevation for each water year between 2001 and 2010. The Secret Town station and -6.5 (degree) C/km forcing set unsurprisingly matches observations, as this lapse rate is based on northern Sierra Nevada stations . However, this method can result in biases at all elevations if the base station does not represent the mean temperature of its elevational band.

The WRF model does very well at capturing the observed large scale lapse rate. Yet, its temperature gradient does not capture the full variability that is observed during water years 2006 to 2010, when additional stations are available. The linear gradient of the WRF model is most likely a result of its inability to resolve small scale topographic variations can have a large effect on local temperature (Lundquist et al. 2008). Further downscaling that incorporates higher resolution elevation maps may improve the realistic nature of the WRF model's temperature. Nevertheless, the temperature gradients from the WRF model capture the large scale observered lapse rates and perform as well as those based off of the Secret Town station and an annual linear lapse rate.

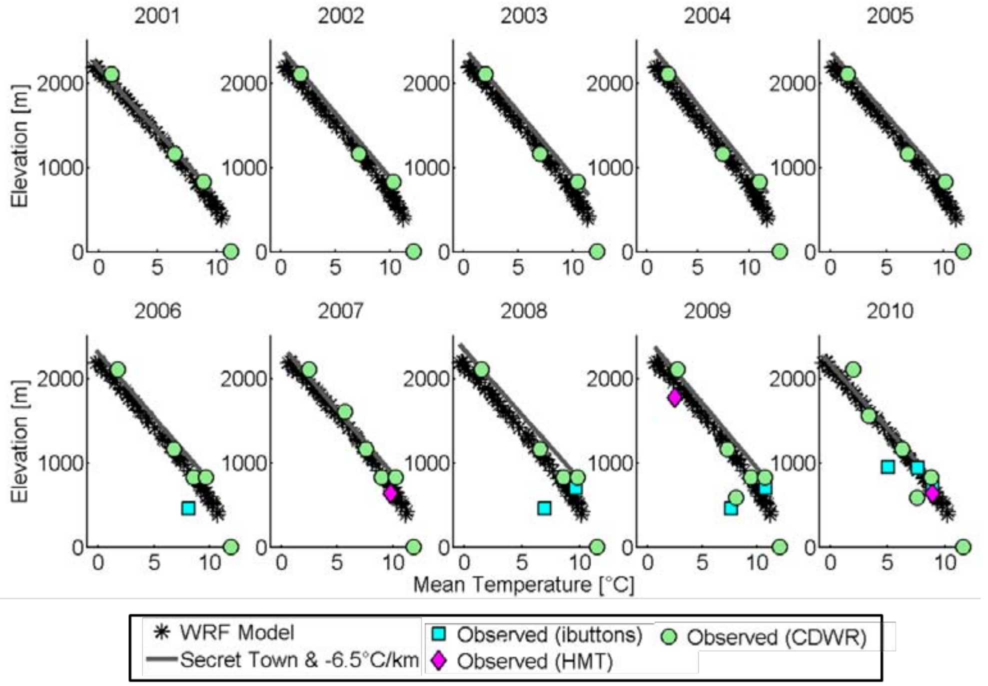

Figure 2. Mean Oct-April temperature versus elevation for water years 2001 through 2010. Black stars show the WRF model mean temperature for each of the (61) 6km grid cells. The grey line represents the mean temperature extrapolated from the Secret Town station using a -6.5 °C/km lapse rate. Observations from ibutton, HMT and CDWR stations are shown.

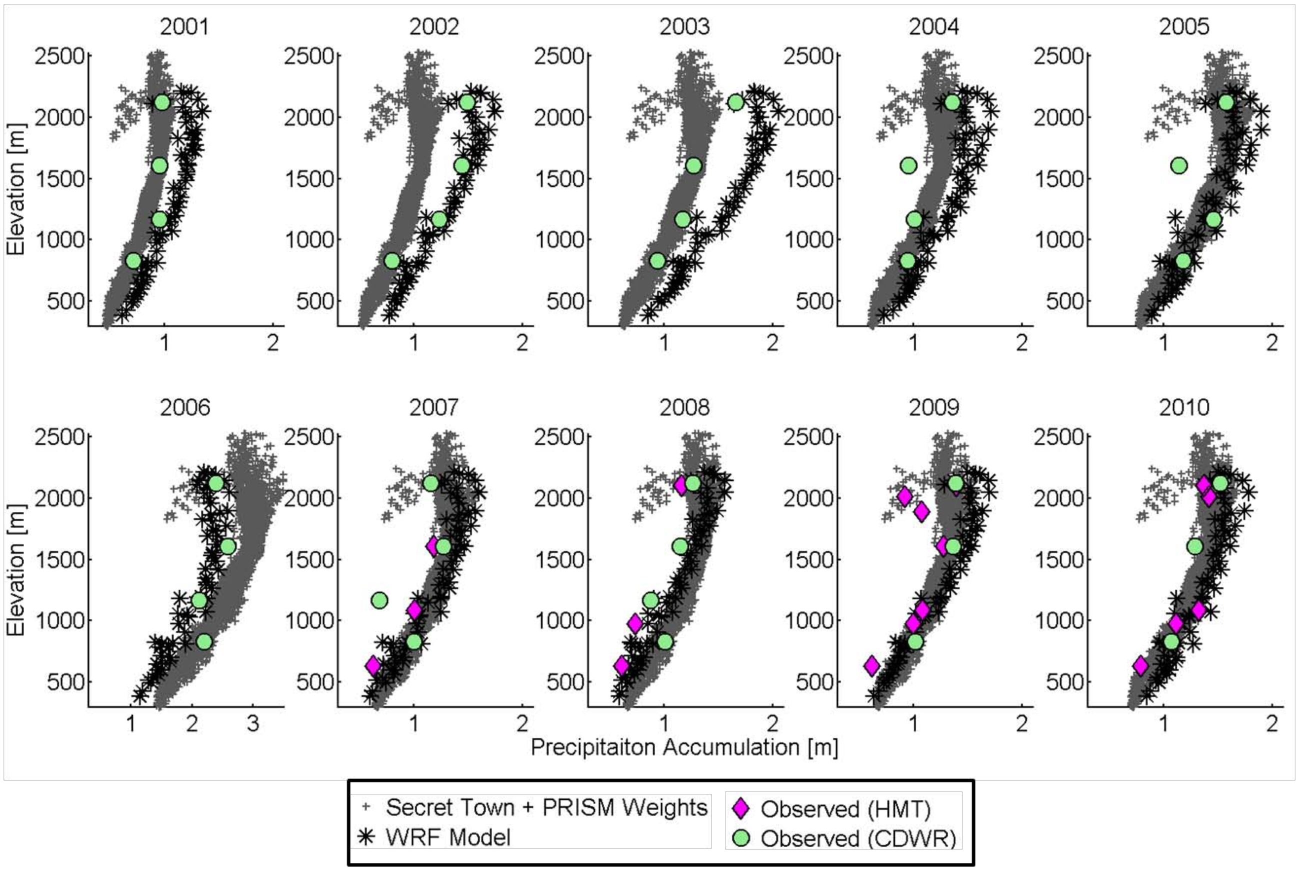

Figure 3. Total Oct-April accumulated precipitation versus elevation for water years 2001 through 2010. Black stars show the WRF model precipitation for each of the (61) 6km grid cells. The grey crosses represent the observed precipitation at the Secret Town station extrapolated using weights from PRISM climatology (see text for details). Observations from HMT and CDWR stations are shown. Note: water year 2006 required a different x-axis scaling.

Precipitation

The orographic precipitation gradient (OPG) dominates the distribution of rain and snow over the Sierra Nevada. Figure 4 shows the total accumulation of precipitation versus elevation between October and April for water years 2001 through 2010. Observed precipitation shows large inter-annual variability; water year 2006 received over 2.5 meters at high elevations whereas in the 2007 water year only accumulated 1.2 meters. The PRISM based data set has the same OPG because the same climatological weights were used for each year. As the PRISM product includes as many stations as possible into its weighting, it is expected to perform well over the highly instrumented North Fork Basin. Differences between each year are due to variations in observed precipitation at Secret Town, which effectively shifts the OPG. One of the limitations of using this method of extrapolation is that biases in the base station create biases at all other elevations. Such as is the case during water year 2006, where the PRISM based data set would have resulted in a ~500 mm wet bias in precipitation. In contrast, the WRF model precipitation captures the variability of the OPG for all years, yet shows a wet bias during 2001 and 2003. Although these results are for one basin, it is significant that the WRF model can simulate the variability of the OPG as well as PRISM within a basin with so many observations.

CONCLUSION

The lack of temperature and precipitation observations within complex terrain creates a significant obstacle for distributed hydrological modeling. Methods of extrapolating those observations are vulnerable to biases when these base stations do not represent the basin wide conditions, and are not even feasible when no observations exist. The WRF model's 6km grid cells were shown to well represent the inter-annual variability of the large scale temperature lapse rate and the orographic gradient of precipitation. In general, the WRF model's temperature and precipitation have comparable skill to traditional extrapolation methods. This study basin is unique in that the North Fork Basin has a far greater number of observations than average, which would favor the use of fitted temperature lapse rates and PRISM weighted precipitation maps. Although this remains to be shown, we hypothesize that over basins with few to none observations, the WRF model will show a larger improvement over traditional methods of generating distributed temperature and precipitation input for hydrological models.

ACKNOWLEDGEMENTS

Funding was provided in part by the National Science Foundation and the University of Washington's Program on Climate Change

Thanks the University of Washington Mountain Hydrology Research Group.

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