INTERPOLATING SURFACE AIR TEMPERATURE FOR USE IN SEMI-DISTRIBUTED SNOWMELT RUNOFF MODELS

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ABSTRACT

Surface air temperature is an important meteorological input variable for snowmelt runoff models, as well as for models of other hydrologic processes. Methods for incorporating this variable into models range in complexity from simply calculating average values from available weather station measurements and then applying a constant lapse rate, to more spatially-explicit methods, such as ordinary kriging. In complex terrain, such as that found throughout much of Idaho, it is necessary for the method of spatial interpolation to specifically account for orographic effects. Apart from most other past studies that compare spatial interpolation, this research examines techniques at a relatively fine spatial scale (basin size of ~1600 km^2) and at a daily temporal scale. This research compares the performance of various temperature spatial interpolation techniques, including the lapse rate method, ordinary kriging of elevationally-detrended data, and the use of climate interpolation models (PRISM).

INTRODUCTION

Importance of Air Temperature to Snowmelt Models

Previous studies have shown that air temperature is the most important predictor for snowmelt modeling (Zuzel and Cox, 1975). Therefore, most snowmelt models use air temperature as a surrogate for the energy that drives melt and also for differentiating rainfall from snowfall through the use of a critical temperature (usually 0°C). An empirical sensitivity analysis of the Snowmelt Runoff Model (SRM) has shown that a temperature bias of 1°C results in a 15% change in its ability to simulate seasonal streamflow volume. This research argues that, since temperature is an important variable in snowmelt runoff models, it should be estimated as precisely as possible.

Caveat Regarding the Environmental Lapse Rate

The environmental lapse rate (-0.65°C/100m) is commonly used to estimate the air temperature at unmeasured locations from available weather stations. It is a simple method that effectively captures the general temperature-elevation (T-E) trend. However, it may not effectively describe localized T-E trends. Instead, lapse rates may vary with latitude, topographic slope, and also have a significant seasonal trend (Rolland, 2003; Bolstad et al., 1998; De Scally, 1997). The error in using the environmental lapse rate increases as the temporal or spatial scale is shortened. Too often the environmental lapse rate is treated as spatially and temporally constant.

Since the research presented here is ultimately being applied to operational streamflow prediction in small basins (~1600 km^2) on a daily time scale (see Harshburger et al., current issue), alternatives to a constant environmental lapse rate were sought. These include: 1) lapse rate adjustment based on synoptic weather type, 2) ordinary kriging of elevationally-detrended temperature data, and 3) climatologically-aided interpolation (CAI) using the Parameter-Elevation Regressions on Independent Slopes Model (PRISM) as the knowledge-base.

STUDY WATERSHED: THE BIG WOOD RIVER BASIN, ID

A circular search ellipse with a ½° radius was centered over the Big Wood River Basin, located in south-central Idaho (Figure 1). All useable (11-year period of record, satisfactory data quality) meteorological stations from within this domain were selected for spatial interpolation. The ½-degree search radius was chosen based on speculations from Roland (2003) that spatial interpolation of temperature performs best when weather stations are aggregated within 1-degree of latitude. Figure 1 shows the fourteen stations used in the analysis (12 SNOwpack TELemetry (SNOTEL) sites and 2 Cooperative Observer Program (COOP) stations). Stations range in elevation from 1472 to 2731 meters. The basin itself has an elevation range of ~250 to 3500 meters.

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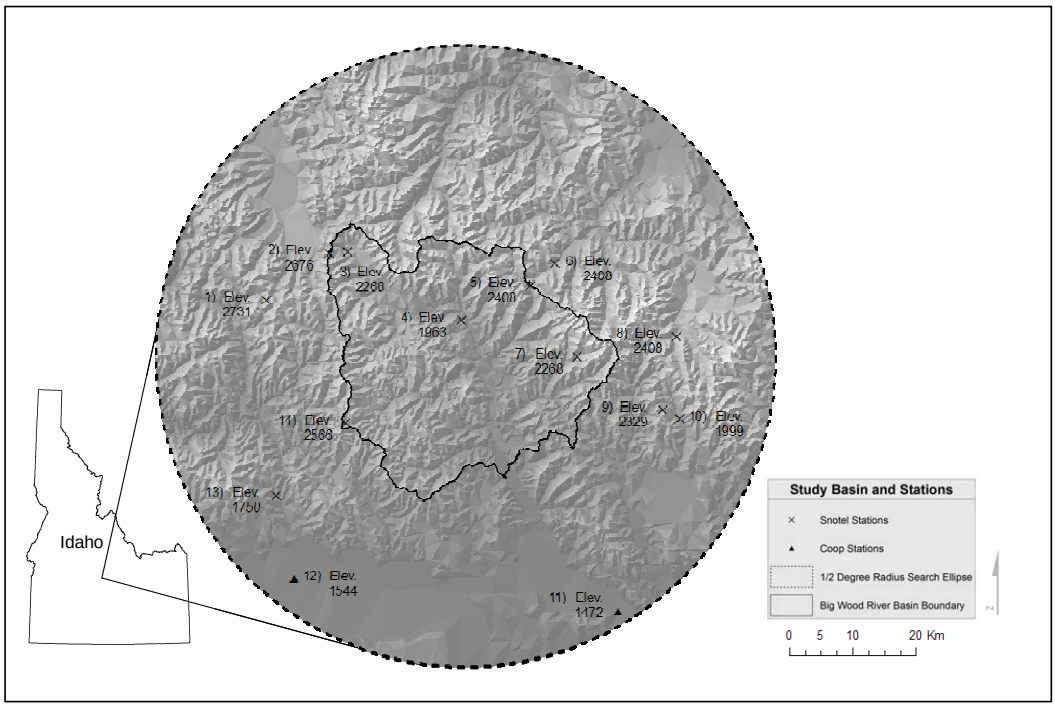

Figure 1. The Big Wood River Basin boundary surrounded by a 1/2º radius search ellipse. Also shown are the fourteen stations selected for analysis: 1) Vienna Mine, 2) Galena Summit, 3) Galena Pillow, 4) Chocolate Gulch, 5) Lost-Wood Divide, 6) Stickney Mill, 7) Hyndman, 8) Bear Canyon, 9) Swede Peak, 10) Garfield Ranger Station, 11) Picabo, 12) Fairfield Ranger Station, 13) Soldier Ranger Station, and 14) Dollarhide Summit.

METHODS AND DATA

Approach 1: Adjusting the Lapse Rate Based on Synoptic Weather Type

Surface air temperature data were obtained from the Western Regional Climate Center and the Natural Resources Conservation Service's SNOTEL Data Network. Daily air temperature maxima and minima lapse rates throughout the water year (Oct. 1, 1993 to Sept. 31, 2003) for 11 years were computed using linear regression between surface air temperature measurements and station elevations. The slope of the regression line represents the surface air temperature lapse rate.

Daily temperature lapse rates show high variability (Figure 2), and confirm the need to account for temporal variability rather than use a constant environmental lapse rate. As other papers have noted (De Scally, 1997; Rolland, 2003), a distinct seasonal trend exists with shallower lapse rates during cold periods and steeper lapse rates during warm periods. One possible method of accounting for this variability is to use a different lapse rate for each season. However, we hypothesize that the temporal variability is better explained by synoptic weather conditions. This method should allow the forecaster to determine the lapse rate on a daily rather than on a seasonal basis.

The Spatial Synoptic Classification (SSC) system categorizes ambient weather conditions. Details on how the classifications are performed can be found in Sheridan (2002) and Kalkstein et al. (1996). A day-by-day calendar of historical synoptic weather types for select stations is available on the World Wide Web (http://sheridan.geog.kent.edu/ssc.html). The calendar was used to obtain daily synoptic weather types for each of the 11 years for which the lapse rates were computed. The lapse rates were then grouped by their respective synoptic type. One-way ANOVA with a Dunnett post-hoc test was used to determine if lapse rate groups had significantly different means. Then, on days when the synoptic weather type is known, the lapse rate could be adjusted accordingly and used in place of the environmental lapse rate during air temperature extrapolation.

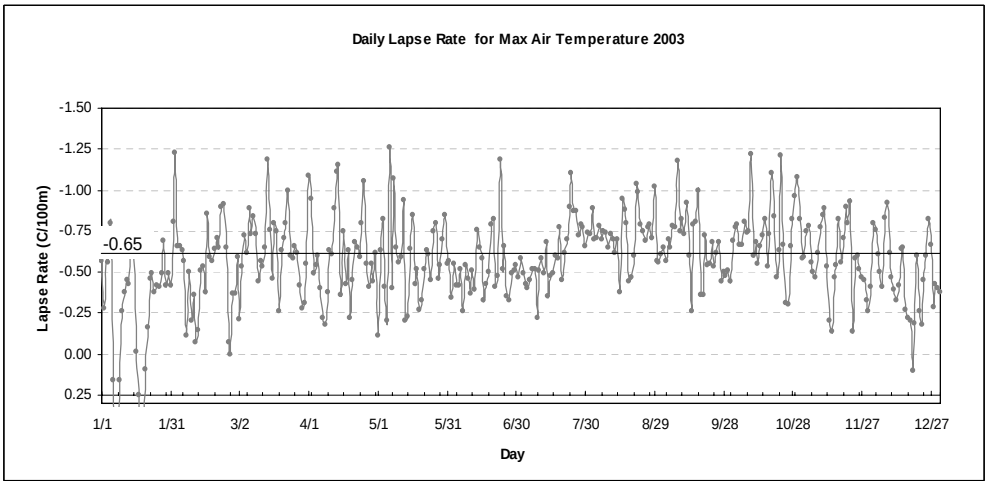

Figure 2. Air temperature lapse rates show high temporal variability. The use of the environmental lapse rate constant (solid line) on such days would be particularly erroneous.

Approach 2: Ordinary Kriging of Detrended Data

Ordinary kriging of detrended temperature data has been effectively used before, but it has typically not been used for daily interpolation at a fine spatial scale (exception, Garen et al. 1994). In general it also has not been applied to semi-distributed models, such as the Snowmelt Runoff Model, because an average (mean areal temperature) has to be computed from the interpolated values in order to obtain a single input for each zone. A single input value per variable per zone is a restriction of semi-distributed models that challenges the use of interpolated fields. However, we believe mean areal temperature derived from kriging can provide more precise zonal estimates then the traditional lapse rate extrapolation approach, despite the smoothing effect caused by averaging.

Detrended kriging has five primary steps. First, a daily temperature-elevation (T-E) regression relationship is computed using observations from the meteorological stations in the study area. Second, the elevation trend is removed from the observed temperature values by using the following equation:

$$T_{detrended} = T_{obs} - (Elev_{obs} * m_{te}) \quad (1)$$

where $T_{detrended}$ is the new temperature value with the elevation trend removed, T_{obs} is the temperature at the observation station, $Elev_{obs}$ is the elevation of the observation station, and m_{te} is the slope of the T-E trendline (i.e. the lapse rate in -°C/m).

The first two steps account for the vertical variability of temperature because the slope of the regression line represents the elevation trend. When the trend is removed the influence of elevation is no longer present in the data, which under normal temperature behavior means $T_{detrended}$ is warmer than T_{obs}. Thirdly, the residuals ($T_{detrended}$) are interpolated using ordinary kriging. This step incorporates the horizontal variability of temperature or the influence of distance, where close locations are more likely to have similar temperatures than distant locations. Next, a Digital Elevation Model (DEM) and the T-E relationship (Step 1) are used to account for the influence of elevation at all other locations throughout the basin. Lastly, the temperature at any location can be estimated by adding the influence of elevation (Step 4) back into the interpolated $T_{detrended}$ values (Step 3).

Approach 3: Climatologically-Aided Interpolation (CAI) Using PRISM as the Knowledge-Base

Climatologically-aided interpolation (CAI) uses long-term average climatological grids to essentially "train" the mapping of daily grids. We used products from the Parameter Regressions on Independent Slopes Model (PRISM) as our long-term climate grids, available from the Spatial Climate Analysis Service at Oregon State University, http://www.ocs.orst.edu/prism/products, (see Daly et al., 1994 for detailed information on PRISM). Our method to obtain daily meteorological grids using CAI is outlined in Figure 3.

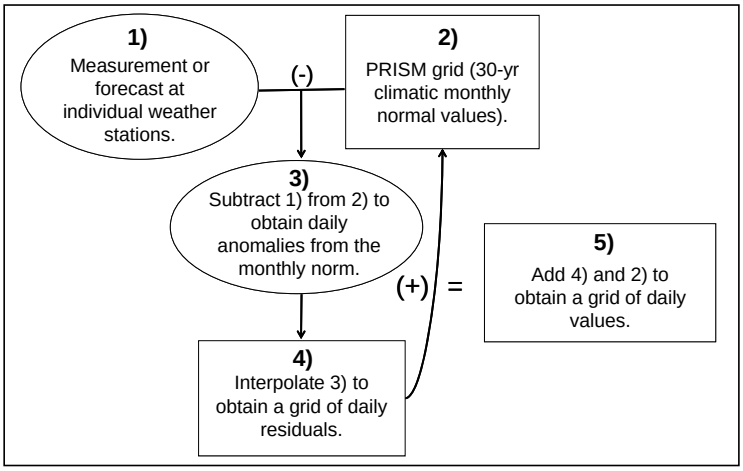

Figure 3. A method to obtain daily meteorological grids from PRISM.

RESULTS AND DISCUSSION

Figure 4 indicates that some synoptic weather types do have significantly different mean lapse rates. Air temperature maxima show significantly shallower lapse rates during dry polar conditions. This may be due to decreased convection and uplifting of warm air. During transitional weather types the mean lapse rate approximates the environmental lapse rate. Air temperature minima show a slightly positive mean lapse rate (inversion conditions) during dry tropical conditions, which is typical in the early morning hours. Overall, the synoptic weather type may be useful in predicting the daily lapse rate.

Cross-validation was used to assess the performance of detrended kriging and CAI. Both approaches performed similarly. Detrended kriging had an average RMSE of 1.7 ºC and CAI had an average RMSE of 1.9ºC. Detrended kriging consistently provides results that reflect the daily temperature-elevation trend, while CAI tends to show less extreme temperature differences between elevations when steep lapse rates are expected. This may be a result of the smoothing effect from using long-term mean climatology as the knowledge base, especially since the climate grids represent monthly norms rather than short-term weather conditions.

The three spatial interpolation approaches are being evaluated for use in a semi-distributed snowmelt runoff model. The tradeoff between the increased computational complexities of the interpolation techniques versus increased precision in their estimates of temperature needs to be further clarified. For example, in terms of zonal melted depth from the Snowmelt Runoff Model, all three methods provide similar results (Table 1).

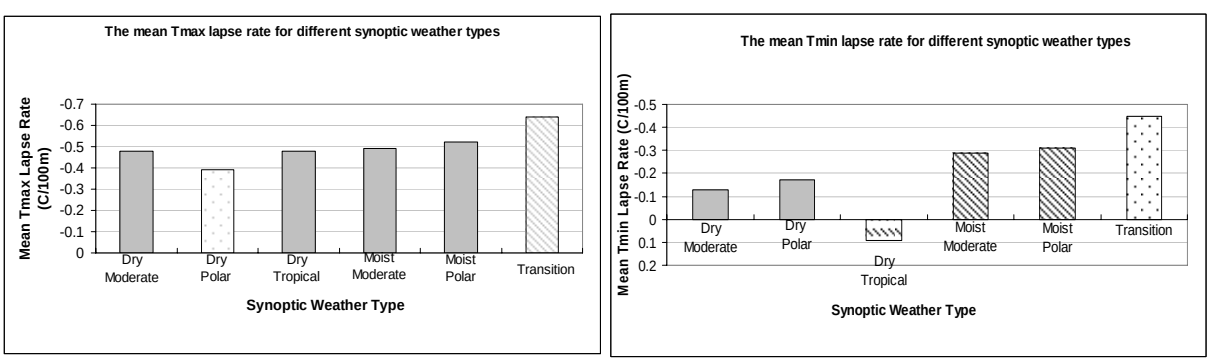

Figure 4. The relationship between mean lapse rate and the synoptic weather type (temperature max, left; temperature min, right). Bars with different shading patterns have statistically different mean lapse rates.

Table 1. Zonal melted depth (cm) computed using the Snowmelt Runoff Model and air temperature input from each of the three spatial interpolation approaches. (Assumed 100% snow-covered area, 0°C critical temperature, and a degree-day factor of 0.3 cm °C^{-1} day^{-1}).

April 3, 2005	Approach 1 (Adjusted Lapse Rate)	Approach 2 (Detrended Kriging)	Approach 3 (CAI using PRISM)
Zone 1	2.1	2.1	2.3
Zone 2	1.6	1.5	1.6
Zone 3	1.2	1.1	1.3
Zone 4	0.7	0.6	0.9
Zone 5	0.1	0	0.2

CONCLUSION

Correlation between daily lapse rates and synoptic weather types (Approach 1) shows promise in being able to better predict the daily T-E trend, as opposed to simply using a constant environmental lapse rate. Approach 1 is also the least computationally-intensive method described here, which is an important consideration for operational streamflow forecasting. Ordinary kriging of elevationally-detrended data (Approach 2) was effectively used to derive zonal temperature for the Snowmelt Runoff Model. Climatologically-aided interpolation (Approach 3) produced the most smooth daily temperature grids and seems least likely to capture short-range anomalous temperature behavior. Surprisingly, in terms of value-added to a semi-distributed snowmelt runoff model, each of the approaches provides similar results, despite large differences in the complexity in how they account for the spatial variability of surface air temperature.

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