

Spatial fields of meteorological input data including forest canopy corrections for an energy budget snow simulation model

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Abstract Methods of computing spatial fields of meteorological inputs for a spatially distributed energy budget snow simulation model have been developed and applied to the Boise River catchment in Idaho, USA. Fields at a 250 m resolution and a 3-h time step have been computed for precipitation, air temperature, dew point temperature, wind speed and solar and thermal radiation using observations at up to eight meteorological stations in and near the catchment. Various methods of interpolating or distributing the values are used depending on the variable and the data available. In addition, corrections to solar and thermal radiation fields are made to account for the effects of the forest canopy.

Key words snow modelling; energy budget; spatial fields; meteorological data; solar radiation; forest canopy

INTRODUCTION

Spatially distributed energy budget snow modelling requires input data on all major meteorological variables, including precipitation, air temperature, dew point temperature, wind speed, solar radiation and thermal radiation. Each of these variables has its own characteristics and its own level of data availability, making it necessary to use a variety of procedures to develop spatial fields of each one. It is also essential to consider the effects of the forest canopy on the solar and thermal radiation reaching the snow surface, as these can be substantial. Procedures have been developed to estimate 3-h spatial field time series of these variables from the available ground measurements at a 250 m grid cell resolution. These are then used as input to the ISNOBAL snow simulation model (Marks *et al.*, 1999), which is part of the Image Processing Workbench (IPW) software package (see <http://cirque.ars.pn.usbr.gov/~ipw>).

DESCRIPTION OF AREA AND AVAILABLE METEOROLOGICAL DATA

The area modelled is a 2150 km² portion of the Boise River catchment in the state of Idaho in the USA. The elevation range is 1000–3200 m, with most of the area either sparse to moderately dense coniferous forest (55%) or shrubland (20%). Average

annual precipitation ranges from about 500 mm in the lower elevations to over 1500 mm in the highest mountains, most of which occurs as snow. The catchment is a major part of a large system of reservoirs and canals providing water for irrigated agriculture.

There are eight meteorological stations in and near the catchment that are available to provide input data. Three of these stations have precipitation and temperature data at a 15-min resolution; five stations (part of the Natural Resources Conservation Service (NRCS) SNOTEL network) have precipitation, temperature, and snow water equivalent at a 3-h resolution; three of these five also have solar radiation, wind speed, relative humidity, and snow depth sensors.

PRECIPITATION AND TEMPERATURE

A detrended kriging algorithm (Garen *et al.*, 1994; Garen, 1995) was used to interpolate daily precipitation and 3-h temperature fields. This algorithm basically divides the spatial variability into a vertical and a horizontal component. The vertical component is modelled by linear regressions of precipitation or temperature with elevation, which are computed separately for each day or 3-h period, respectively. The horizontal component is then handled by ordinary kriging, in which the residuals from this regression are interpolated over the gridded domain. The trend based on elevation is then added to the estimated residual to arrive at the final estimate at each grid cell.

Because precipitation data in mountainous areas often tend to be rather noisy, the 3-h values were not interpolated directly. The daily data are reasonably reliable, so these could be interpolated with confidence. To obtain the 3-h precipitation fields, a simple disaggregation by a fractioning approach was used. A single set of fractions, representing the portion of the daily precipitation occurring in each 3-h period of the day, was used for the entire catchment. The set of fractions for each day were obtained by subjective averaging/editing of the computed 3-h fractions at each meteorological station.

DEW POINT TEMPERATURE/VAPOUR PRESSURE

Observed relative humidity and air temperature were used with IPW utilities to calculate 3-h dew point temperature and vapour pressure at the three SNOTEL sites equipped with humidity sensors. Because these three stations are clustered near the middle of the elevation range of the catchment (1734–2310 m), vertical gradients could not be reliably identified. The values were therefore simply averaged and considered to be valid at an elevation of 2100 m. To define the elevational trend, dew point profiles from the upper air soundings at Boise Airport (approximately 90 km from the centre of the catchment) were used. These upper air soundings are available twice per day and were taken to represent the 03:00–06:00 h and the 15:00–18:00 h time periods. They were interpolated to obtain profiles for the other 3-h periods and to obtain values at 100 m elevation intervals.

The dew point profiles developed for each 3-h period were based on two main ideas. The first is that the observed averaged dew point, considered to be applicable at an elevation of 2100 m, and the surface dew point from the upper air sounding (at an

elevation of approximately 900 m) can be used reliably to represent the variation of dew point with elevation from the lowest elevation in the catchment up to 2100 m. The second idea is that above this elevation up into the mountain peaks, the dew point should gradually become that of the free atmosphere.

The adjusted dew point profile for a given time period is then composed of three segments. The first is a linear trend between the upper air profile dew point at the surface (900 m) and the observed averaged dew point at 2100 m. The second segment is a transition zone between 2100 and 2800 m in which an offset is added to the upper air profile. This offset is initially calculated as the difference between the observed value and the upper air profile at 2100 m; this is then linearly decreased to zero at 2800 m. In the third segment, above 2800 m, the upper air profile dew point temperature is used. This dew point profile is then applied to the digital elevation model (DEM) to obtain the spatial fields. These are subsequently checked to ensure that the dew point temperature is always less than or equal to the air temperature at every grid cell and for every time step. Vapour pressure fields are created directly from the dew point images using an IPW utility.

WIND SPEED

Wind speed data are available at these same three enhanced SNOTEL sites. It is believed that these values represent the lower and middle elevations, but physical reasoning suggests that wind speeds should be greater in the higher elevations. For wind, however, upper air profiles are not as useful as for dew point, as the wind speeds in the free atmosphere are usually much greater than those near the ground, even at the same elevation. The upper air data were therefore not used directly but rather used as a guide in determining the magnitude of a factor to increase wind speeds in the higher elevations.

An examination of upper air profiles for water years 1997 and 1998 indicated that the wind speed at 3300 m (just above the highest elevation in the catchment) was greater than that at 2100 m by a factor of approximately 1.5. This value agreed well with physical reasoning, so it was adopted in developing wind-elevation profiles. These were obtained by simply averaging the wind speeds at the three SNOTEL sites for each 3-h period and using this for elevations up to 2100 m. Above this, the wind speed was linearly increased up to a maximum of 1.5 times this value at 3300 m. Spatial fields of wind speed were calculated, as with dew point, by applying the derived profile for each time period to the DEM.

SNOW ALBEDO

The albedo of the snow surface determines the amount of incoming solar radiation that is reflected and is therefore a crucial factor in the net energy balance of a snowpack. It depends on the initial grain size of the snowflakes, the maximum grain size to which the snow metamorphoses, the amount of foreign particles (contamination) in the snow, the time since the snow was deposited, and the sun angle. In addition, the albedo of snow is significantly different between the visible and infrared wavebands (0.7–2.8 and 0.28–0.7 μm , respectively).

Albedo is modelled with the IPW program IALBEDO. As input, snow events and albedo parameters had to be defined. This was done with a set of heuristic rules using data from the five SNOTEL sites in the Boise River catchment. These rules were defined quantitatively, based on the precipitation, temperature and humidity characteristics of each day.

An additional albedo reduction was applied during the active melt season to account for the re-exposure of needles and other debris that had fallen during the winter and had become incorporated into the snowpack. This debris accumulates on the snow surface and reduces the albedo from what it otherwise would be if the surface were clean. This can have a significant effect on the net radiation and therefore the snowmelt. This additional albedo reduction was done in a simple manner by subtracting an increasing amount described by a square root function from the modelled albedo, beginning at the onset of the primary spring melt season (as defined by the day of maximum snow water equivalent) until melt out. The amount of this additional reduction starts at zero and ends with an adjustment of 0.4 albedo units. This results in a final albedo at the end of snowmelt of approximately 0.5 for visible and 0.3 for infrared.

SOLAR RADIATION

The computation of net solar radiation fields was done by a four-step procedure:

- (a) Calculate clear-sky incoming solar radiation for visible and infrared wavebands using the IPW program TOPORAD, which accounts for topographic effects such as slope, aspect and shading from nearby hills.
- (b) Correct for cloud cover by multiplying the clear-sky fields by a catchment-wide reduction factor estimated from a comparison of measured data with modelled values at the three SNOTEL sites with radiometers.
- (c) Apply a forest canopy correction (from Link & Marks, 1999), which reduces the amount of radiation reaching the snow surface due to attenuation through the trees. The amount of attenuation depends on the canopy density. Different functions are used for the corrections to beam and diffuse radiation, that for beam being an exponential extinction, and that for diffuse being a simple multiplicative fraction reduction.
- (d) Subtract reflected radiation due to the snow albedo (including any additional albedo reduction due to debris on the snow surface). This is done separately for the visible and infrared wavebands.

THERMAL RADIATION

Incoming thermal radiation fields were computed using a three-step procedure:

- (a) Compute clear-sky thermal radiation using the IPW program TOPOTHERM.
- (b) Correct for cloud cover by multiplying the clear-sky fields by a catchment-wide enhancement factor estimated from a relationship with the solar radiation reduction factor. This relationship was obtained using measured thermal radiation data at one SNOTEL site for a several month period.

- (c) Apply a forest canopy correction (from Link & Marks, 1999), which reduces the amount of thermal radiation from the atmosphere reaching the snow surface due to attenuation through the trees but also adds a contribution from the trees themselves. The trees are assumed to emit black body radiation at the air temperature, according to the Stefan-Boltzmann law. The relative contributions from the atmosphere and the trees depend on the canopy density. In most cases, this canopy correction results in a net increase of thermal radiation into the snowpack.

DISCUSSION AND CONCLUSION

The preparation of all the meteorological input fields needed for a spatially distributed energy budget snow simulation model involves a considerable amount of data processing and development of procedures tailored to the availability and characteristics of each variable. To some extent, the procedures used may have to be different for each catchment, depending on how many measurement sites are available and the quality of the data. The procedures described here for the Boise River may or may not be totally transferable to other catchments, but the concepts and processing steps should, for the most part, be generally applicable.

The use of this type of model does require at least one representative station in the catchment with solar and thermal radiation, wind speed, and humidity data. These data are generally not available in most areas. One of the goals of this modelling study has been to demonstrate the feasibility of installing and operating these sensors in a mountain environment. The thought is that perhaps they could be installed more widely as part of the SNOTEL system in the western USA, thus making energy balance snow modelling feasible in a number of key areas. As snowmelt is the major source of water supply in this region, and rain on snow is an important cause of major flooding, detailed process-oriented modelling can be very helpful in a careful monitoring of snowmelt, particularly when the dynamics are complex and cannot be adequately described by simpler temperature-based models.

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