USING GIS TO PREDICT THE SPATIAL DISTRIBUTION OF PERENNIAL SNOW UNDER MODERN AND LATE PLEISTOCENE CONDITIONS IN THE SNAKE RANGE, NEVADA

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ABSTRACT

ELApse is a climate-driven snow and ice model developed to estimate the spatial distribution of perennial snow and ice in alpine systems. The snow model computes monthly snowfall, snowmelt, and resulting snowpack at each grid cell, and it estimates the densification of perennial snowpack and its transformation into glacial ice when appropriate. The model proceeds year-by-year until monthly snow and ice totals equilibrate. ELApse is sensitive to latitudinal and elevational controls on climate, but it is insensitive to subtle variations in the land surface that create microclimates that tend to preserve snow and ice. We use ArcView GIS to identify terrain characteristics (such as shading, slope, and curvature) that enhance accumulation and preservation of snow and ice. ELApse estimates of modern perennial snow extent in the high peaks of the southern Snake Range, NV are greatly improved by GIS postprocessing. In addition to modern solutions, we estimate the spatial distribution of perennial snow for temperature perturbations of -2°C, -4°C, and -6°C.

INTRODUCTION

An accurate representation of snowfall and snowmelt is integral to the accurate representation of surface hydrology in the west because much of the surface water in this region has its provenance in upland snowmelt. Rango and Martinec (1995) state that snowmelt makes up more than 95% of total streamflow in some mountainous regions of the world. The goal of this study is the development of a model that will allow the exploration of the effects of hypothetical future or past long-term climate change on alpine snow and ice. This necessitates creating a model that does not rely on field observations of climate or snowfall as these observations are nonexistent for hypothetical future climate or paleoclimate scenarios. ELApse, the snow model described here, is therefore constrained to make solutions solely from temperature, precipitation, and terrain boundary conditions. The snow model calculates snowfall, snowmelt, snowpack, formation of glacial ice, icemelt, and ice movement from imposed boundary conditions. No ground-based or satellite observations are input at any time during model runs. Solutions are made for gridded domains, readily allowing GIS-based spatial analyses of model results.

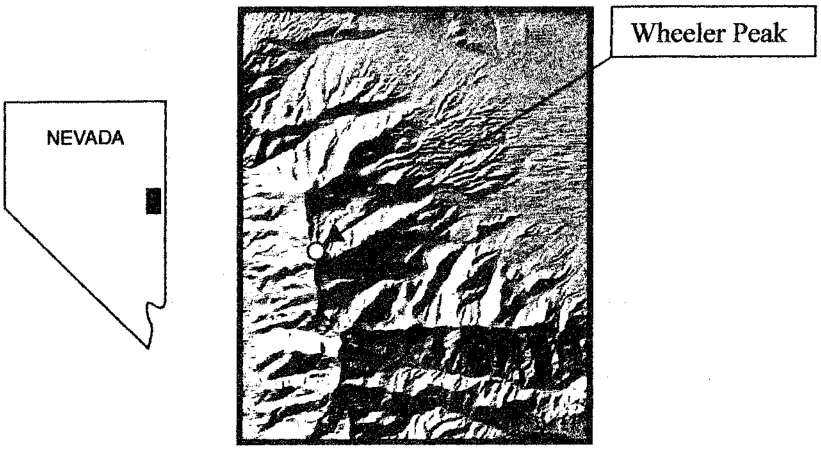

Figure 1. A digital elevation model of the southern Snake Range, Nevada.

We applied ELApse to the southern Snake Range in east-central Nevada (Figure 1). Wheeler Peak, which sits over Nevada's only modern glacier, rises to an elevation of 3,982 meters above sea level (13,063 feet). Terrain is represented as a digital elevation model (DEM) with 947 rows, 750 columns, and a 30-meter grid cell spacing; we constructed this DEM by mosaicing four USGS 7½ topographic quadrangles into a single grid. We then ran the snow

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Paper presented at the 69th Annual Meeting of the Western Snow Conference, 2001.

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model on a subset of this domain that includes both Wheeler Peak and Jeff Davis Peak. Wheeler Peak sits over a northeast facing headwall that harbors perennial snow and protects Nevada's only extant rock glacier from the sun.

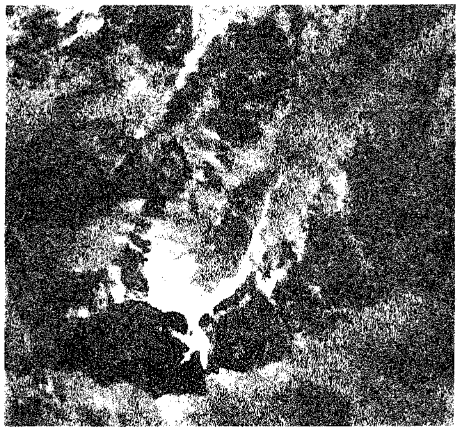

Figure 2. Perennial snow below Wheeler Peak feeds into Nevada's only active rock glacier.

SNOW MODEL STRUCTURE

The ELApse model discussed here is an updated version of the snow model discussed by Jones and Orndorff (1999, 1997) and Orndorff (1994). The model estimates monthly snowfall, snow ablation, and resulting snowpack from temperature, precipitation, and terrain boundary conditions. In addition it calculates the transformation of snow to glacial ice in grid cells where perennial snowpack exceeds the firn-ice limit. Monthly ice ablation is computed as well as the transfer of ice between grid cells when ice thickness exceeds a threshold based on terrain slope and an assumed yield stress for ice. Boundary conditions include regional climate station data and a grid of elevation values for the study area.

A linear regression of monthly maximum temperature, minimum temperature, and precipitation from climate station data (supplied by the National Geophysical Data Center) on either (1) elevation or (2) elevation and latitude supplies regression coeficients that are input to ELApse, which uses them to estimate modern climate from the base DEM. The user is offered the option of perturbing either temperature, precipitation, or both to model snow and ice for paleoclimate conditions. Monthly snowfall is assumed to be precipitation that occurs below a near-zero critical temperature, hence the fraction of precipitation that falls as snow is estimated as the integral of the monthly distribution of temperature from $-\infty$ to the critical temperature. Snowmelt is calculated using the degree-day methodology, wherein snowmelt depth is proportional to degree-days. There are two broad categories of snowmelt models used today, degree-day models and physically-based energy balance models. The disadvantage with using energy balance models is the need for large quantities of measured data, something that is simply not available for most study areas (Rango and Martinec 1995) and is certainly not availale for paleoclimate scenarios. Ease of use and accuracy comparable to that of the more sophisticated energy balance techniques (provided the operator considers the effects of changing snow cover and degree-day factor over the snowmelt season) has made the degree-day method much more popular, and it has been used successfully for 60 years. Given the agreement in accuracy between the two methodologies, it seems parsimonious to use the simpler degree-day methodology when looking at effects of long-term climate change.

In modeling snowpack, the possibility exists that annual snow accumulation will exceed annual snow ablation, resulting in a perennial snowpack. Over time, a perennial snowpack may deepen enough that it produces glacial ice. This scenario must be accounted for in the snow model, as areas to which this model has been applied (such as the Snake Range, NV) were recently heavily glaciated. Snow density increases with depth, as basal layers are compressed by the column of snow above. In ELApse variations in snowpack density are assumed to be linear, with a firn-ice transition depth of 30 meters (Paterson 1983). If the snow model predicts a perennial snowpack for a particular grid cell, the water equivalent of the snow column is compared to the firn-ice transition water equivalent. If the snow column water equivalent exceeds the transition water equivalent, then the excess is assumed to be ice at a constant density of 0.9 g/cm^3. Ice ablation is computed using a degree-day methodology similar to that used in computing snow ablation. Johannesson and others (1993) demonstrate that the degree-day factor for ice is very stable. Ice melts only when it is not covered by snow, thus ice forming under a perennial snowpack ablates only if routed elsewhere. If one assumes that glacial ice is a perfectly plastic medium, a simple relationship exists between limiting ice thickness and terrain slope (Paterson, 1983), thus maximum stable ice thickness may be determined from the DEM. If ice thickness exceeds the limiting value, the excess is routed to a downslope grid cell.

ELApse has been applied to a number of different solution domains for both modern and paleoclimatic conditions. For example, Jones and Orndorff (1999, 1997) applied an earlier version of ELApse to a solution domain (36° to 39° north latitude, 118° to 121° west longitude, with a grid cell spacing of 30 arc seconds) within the Sierra Nevada, California to estimate the temperature perturbation required to produce alpine glaciers that existed there at the last glacial maximum (LGM). Gridded modern monthly temperature and precipitation values were calculated from regional climate station data using elevation and latitude-weighted interpolation. These climate boundary conditions were then progressively perturbed and input to the snow and ice model. Under the assumption that there was no change in accumulation season precipitation at the LGM, the snow model predicted latitude-controlled equilibrium line altitudes (lowest limit of ice accumulation) and nivation threshold altitudes (lowest limit of perennial snow) that agreed with observed relict features at an average annual temperature perturbation of –7.5°C.

GIS ANALYSIS

ELApse predicts the presence of perennial snow on Wheeler Peak, Jeff Davis Peak, and along the ridge separating the two peaks (Figure 3A). The model is sensitive to orographic controls on temperature and precipitation, hence it places perennial snow on what it considers to be the coldest, snowiest locations within the southern Snake Range. The model is not sensitive to more subtle characteristics of the land surface that play an important role in preserving snow and ice. Winds are very high on exposed landforms, and the tendency is for snow to blow from high ridges into protected hollows. Shading, a function of slope aspect and intervening landforms, acts to reduce solor radiation and prevent both melting and sublimation of snow. Slope is also important, as snow avalanches down very steep slopes to collect in valleys below.

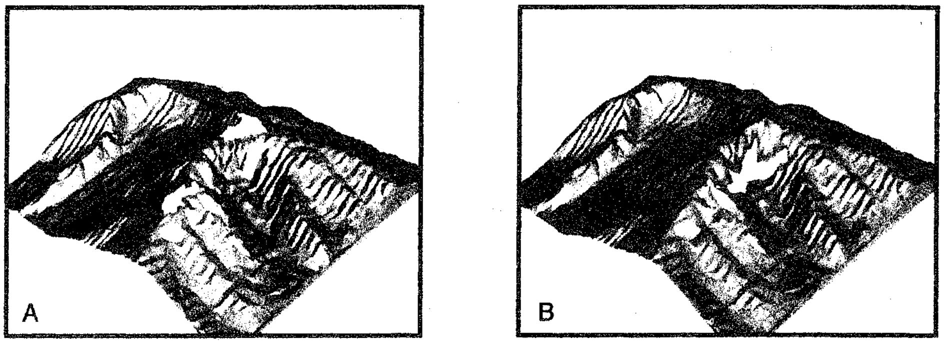

Figure 3. (A) Spatial distribution of perennial snow predicted by ELApse and (B) ELApse output after GIS postprocessing (as seen from the northeast).

We used ArcView GIS to postprocess snow model output and produce solutions that are more sensitive to terrain. We first determined the curvature of the land surface; curvature is the second derivative of surface elevation. Positive curvature values define convex features while negative curvature values delineate concave features. This allowed us to identify convex peaks and ridges from which snow will blow and the concave hollows in which it will collect. Under the assumption that accumulation season insolation is more important in controlling the location of perennial snow than ablation season insolation, we computed the azimuth and altitude of the sun for the Snake Range throughout the day for the winter solstice. We ranked cumulative shading values into three classes and determined that perennial snow was most likely to be found in areas that received the least insolation (the highest shading class). Finally we ranked slope values within the DEM into three classes: (1) 0-25°, (2) 25-50°, and (3) 50-75°. We hypothesized that it was highly unlikely that perennial or even seasonal snow would remain for long on slopes in the steepest class. We determined the distance from predicted perennial snow in the high peaks and used ArcView to pose the following question: What land surface is less than 300 meters from predicted snow (a qualitative assessment of how far snow might be blown by winter wind in this location), is concave, has slopes less than 50°, and has strong winter shade? The result is shown in Figure 3B, where we now see perennial snow collecting on the lower cirque wall beneath Wheeler Peak. This is, in fact, where we find the largest accumulation of perennial snow in the southern Snake Range, an accumulation that feeds ice into the extant rock glacier.

We used ELApse to predict the location of perennial snow under paleoclimate conditions as well. We maintained precipitation at its modern level and perturbed modern temperature by -2°C, -4°C, and -6°C. We then processed model solutions in ArcView using the criteria discussed above. Modified solutions are shown in Figure 4. With progressively cooler temperatures we see perennial snow moving downward into the deep valleys on both sides of Wheeler and Jeff Davis Peaks.

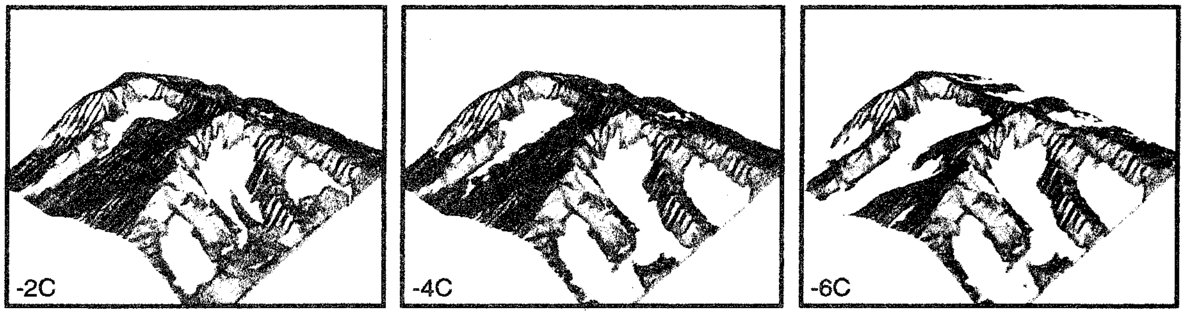

Figure 4. ELApse model output for temperature perturbations of -2°C, -4°C, and -6°C after GIS postprocessing (as seen from the northeast).

CONCLUSIONS

Representation of snowfall and snowmelt processes is critical to the characterization of surface hydrology in much of the southwestern United States because runoff there is sensitive to, and often dominated by, upland snowmelt (Kattelmann 1991; Rango and Martinec 1995). The ELApse model was developed for this purpose. It is sensitive to orographic controls on temperature and precipitation, but insensitive to more subtle characteristics of the land surface that create microclimates that tend to preserve snow and ice. We used ArcView GIS to postprocess model output to account for slope, shading, and curvature. Modified estimates of perennial snow represent the modern system much better than did the original prediction. We hypothesize that this type of postprocessing will be very useful in predicting the extent of late Pleistocene snow and ice and establishing a relationship between observed landforms and paleoclimate.

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