Multifaceted Geocomputation to Support Ecological Modelling in Yellowstone

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1. Introduction

Yellowstone National Park (YNP), USA, provides a location to explore complex adaptive systems when looking at the ecology of elk. Elk cross the park border and enter other federally managed land, state managed land, and privately held land. Incumbent to elk survival is the ability to survive harsh winter conditions, human hunting pressure, and natural predation. This paper describes the geocomputation efforts developed to support an agent-based model (Bennett and Tang, 2006) that simulates the elk population dynamics and movement along Yellowstone's northern border (Figure 1). The overall project goal is to explore the coupled natural-human systems near YNP and to synthesize findings into the agent-based model.

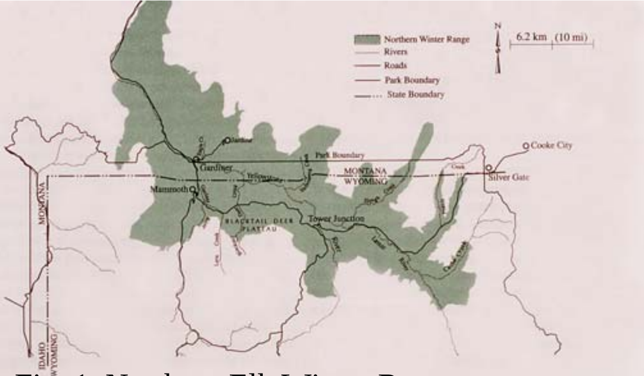

Fig. 1. Northern Elk Winter Range

Ecoysystems are an aggregate of multiple actors, and the interaction and feedbacks among system components are crucial to fully understanding the coupled natural-human system. We chose elk as a common "currency" within the system, as they cross human created boundaries and are highly valued by various human constituents. While our full project included both physical and social sciences, the purpose of this paper is to describe two primary computational components necessary for a robust agent-based elk model simulated within a physically correct landscape during the critical winter months.

Our computational model uses synoptic climate scales to produce the local-level estimates of snow pattern needed to drive our agent-based models of elk herd migration.

2. Synoptic Climatology using Self-Organizing Maps (SOMs)

Daily winter weather conditions are monitored in only a few local sites, none of which fit the elk herd range well. Thus, we use daily synoptic climate data from global scale analyses to downscale daily data to specific locations in the Yellowstone region. The downscaling targets are snow telemetry (SNOTEL) stations where daily snow water equivalence (SWE) measurements are recorded. Synoptic climatology typically defines a spatial domain that covers approximately three days of atmospheric movement over the area of interest. Daily geopotential height (or other) data are clustered into "synoptic types" (Barry and Perry, 1973; Yarnal, 1993). For this study, 700 hectopascal (hPa) geopotential heights are chosen because this height is generally the first standard level above the surface friction boundary at the elevations found in the study region. The procedure uses Kohonen Self-Organizing Map neural networks (Hewitson and Crane, 2002) to determine the relevant synoptic patterns. The basic process is:

1. Self-Organizing Map (SOM) neural networks are used to classify 700 hPa height anomaly patterns for the western U.S. into a set of 35 defined patterns (figure 2).
2. 2-day sequences of the 35 patterns are related to SWE accumulations at SNOTEL sites in the Greater Yellowstone region.
3. The probability of a snowfall event is calculated for each 2-day synoptic class sequence, and the mean SWE accumulation for the 2-day sequence is determined for each SNOTEL location.
4. 100 Monte Carlo simulations are performed to generate daily time series of snowfall at sites in the GY region. The probability of a snowfall event at each SNOTEL site is used with the 2-day SOM sequences to determine if a snowfall event occurs. If a snowfall event occurs, the mean SWE accumulation for that 2-day SOM sequence is used as the snowfall for the specific site and 2-day SOM sequence.
5. The daily snowfall values are used to compute time series of monthly snowfall. The values from the 100 simulations are averaged to produce a mean simulated time series of monthly SWE for each SNOTEL site.

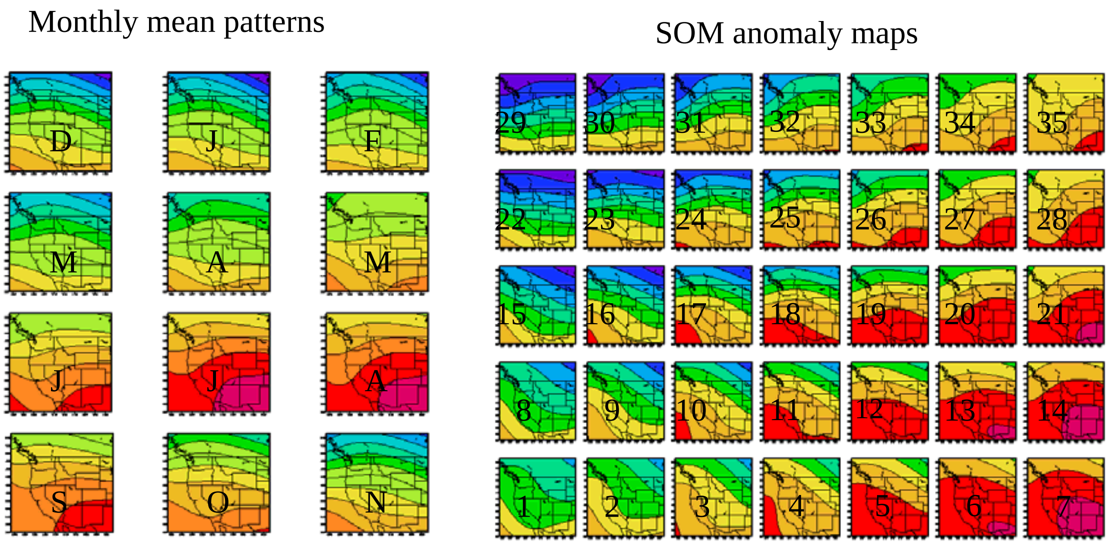

Figure 2. 700 hPa geopotential heights (left) and SOM-based anomaly classification patterns (right).

The SWE prediction is validated against observed data (figure 3). SNOTEL records only extend back to the early 1970s, but the atmospheric data extend back to 1948. Thus, using the synoptic typing methodology to predict snowfall at each SNOTEL site, we can reconstruct daily snowfall back approximately 60 years (figure 4). These data can then be related to the snow model developed described below to cover the entire elk winter range.

2. Snow Model

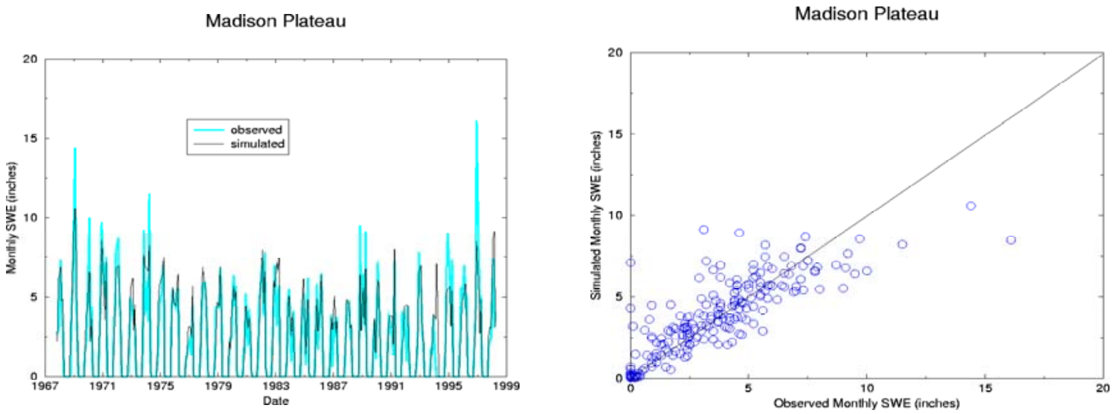

Figure 3. Madison Plateau SNOTEL daily SWE modeled vs. observed comparison

Modeling snowpack properties across space and time presents significant challenges. Accurate estimation of the spatial distribution of snowpack properties is complicated by the interrelated and multiscale nature of the processes involved (Tarboton et al., 2000). Understanding the linkages between the physical processes controlling accumulation, redistribution and ablation is critical to developing a predictive ability to describe the development of a snowpack over time (Kirnbauer et al., 1994; Bales and Harrington, 1995; Tarboton et al., 2000).

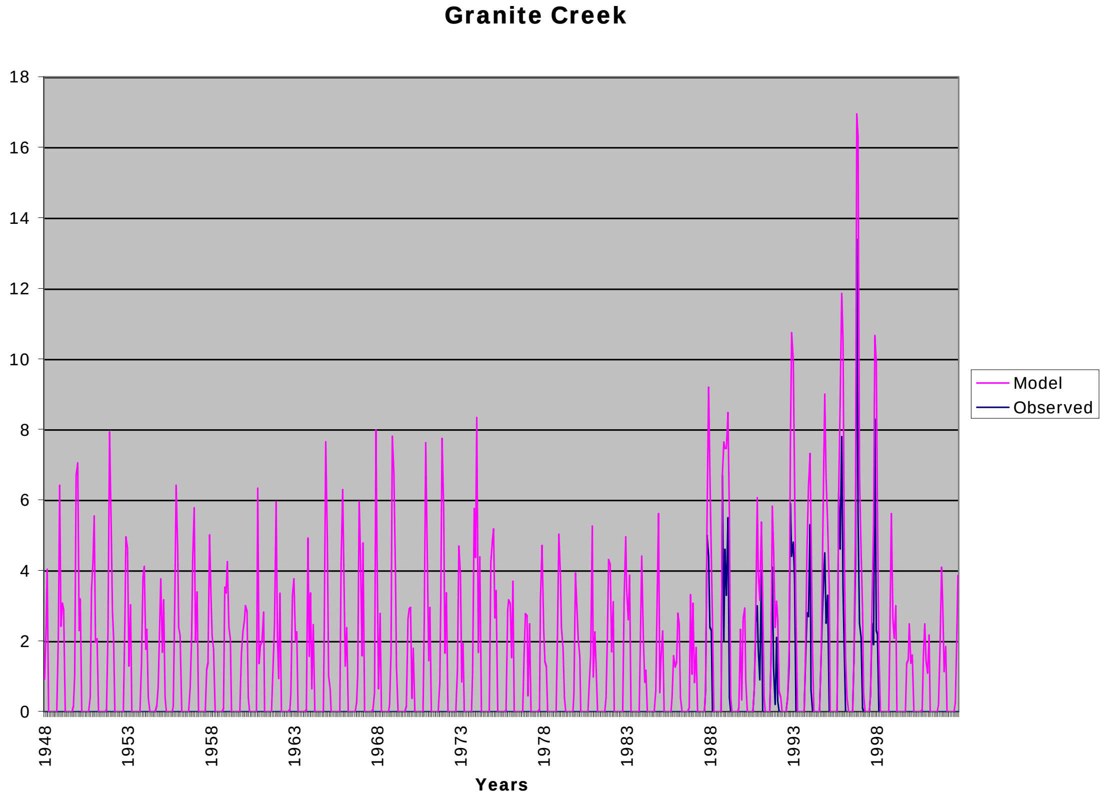

Figure 4. Granite Creek SNOTEL daily SWE reconstruction to 1948.

Our general aim is to develop a spatially distributed snowpack model for the Yellowstone study region to help identify elk distribution patterns. The model of choice was the spatially distributed, physically-based SNTHERM (Jordan, 1991). The only other snow model for the region was the Natural Resources and Ecology Laboratory (NREL) snow model for YNP (Wockner et al., 2002), which we compare to our findings.

SNTHERM is a well accepted and widely validated 1-D, mass and energy balance model that simulates physical and hydrological processes within a snowpack including snow accumulation and ablation, grain growth, compaction, and melt waterflow through the snowpack (Koivusalo and Heikinheimo, 1999; Fox, 2003). The model accomplishes this simulation by treating the snowpack as a series of horizontally infinite homogeneous layers that increase with snow depth. Energy, mass and momentum are distributed through the snowpack as a function of meteorological driving variables. The NREL snow model is a GIS-based operational snow model that simulates SWE only. The model uses SWE data from SNOTEL sites and climate stations in and around YNP to create an initial

SWE grid using inverse distance weighted interpolation and linear regression (Wockner et al., 2002). This grid is adjusted for the effects of slope, aspect and forest cover type. SWE values for each cell are adjusted for the effects of elevation using a regression equation relating SWE to elevation. The regression line slope provides a correction of millimeters of water per meter elevation difference between sites and observation stations. After the elevation adjusted SWE interpolation map is created, the model further adjusts the SWE estimate for each grid cell based upon slope and aspect derived from a 100-m DEM.

This model has been used in several studies specifically examining elk and snow interactions in the Greater Yellowstone Ecosystem (Coughenour, 1994; Coughenour and Singer, 1996; Farnes et al., 1999; Farnes et al., 2002; Hobbs et al., 2003). While the NREL model has been the standard in the literature for many years, we suspected that the model output did not encompass the full complexity of the snowpack needed in our agent-based model. Thus, we chose to focus on the SNTHERM model. A full description of SNTHERM is beyond the scope of this abstract but the model requires two sets of input variables were necessary to drive the SNTHERM model. The first set consists of user-defined parameters and initial snowpack conditions. User defined model parameters consist of general parameters, measurement heights above ground surface, characteristics for each layer type, and convergence related input. The second set of input variables includes meteorological fields that describe the components of the surface energy exchange. All of the necessary variables except for incoming longwave radiation were measured at the Crystal Creek meteorological tower that we established. Data needs that were not measurable were developed using the MTCLIM model (Hungerford et al, 1989) and various other data manipulation methods.

The NREL and distributed SNTHERM model performances were compared using measured vs. modeled SWE at two levels: (1) the test basins and (2) the extended spatial domain. Within the test basins, the distributed SNTHERM model had more predictive accuracy than the NREL model as indicated by the lower MAE and goodness-of-fit measures (Table 1). The MAE for SNTHERM was 52.2% of that for NREL, with the percent error lower by 46.4%. NREL results had a moderate R^2 of 0.33. In contrast, SNTHERM model results showed a much stronger degree of correlation with an R^2 of 0.91. Overall, the distributed SNTHERM model estimated SWE values with more accuracy than the NREL model at both scales. Temporal snapshots demonstrate the added complexity of the snow surface using the SNTHERM model (figure 5).

Table 1. Comparison of NREL and distributed SNTHERM model performances at the test basins and at the extended model domain for the winter of 2004.

Site	NREL SWE	Distributed SNTHERM SWE
Test Basins (n = 90+)		
MAE (mm)	41.9	21.9
MAE (%)	68.1	21.7
R^2	0.33	0.91
Extended Domain (n = 144)		
MAE (mm)	46.1	32.6
MAE (%)	74.2	28.5
R^2	0.25	0.71

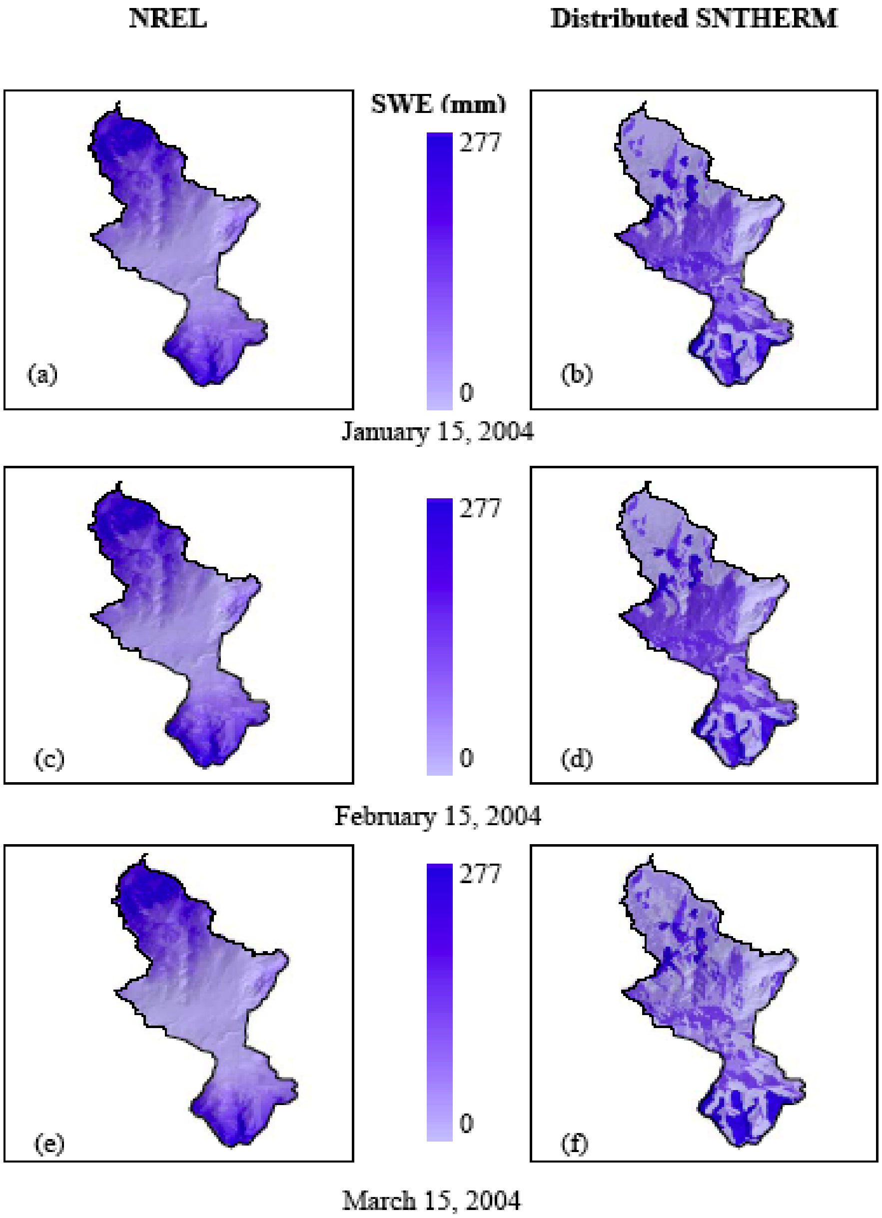

Figure 5. SWE output maps for the NREL model (a, c, and e) on the left and the distributed SNTHERM model (b, d, and f) on the right for January 15, February 15, and March 15, 2004 at the test basins.

3. Summary

This paper has demonstrated the geocomputation needs to create data layers for an agent-based model for elk in the Yellowstone northern range. While older snow models were the readily accepted and used in previous studies, this project incorporates daily climatology and downscaling methods to an energy-balance distributed snow model to significantly improve calculations for snow characteristics in our spatial domain. This combined modeling methodology crosses multiple geographic scales and provide a robust snow surface for the agent-based elk model.

4. Acknowledgements

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