Application of Spatial Statistical Stream Models to Downscale Effects of Climate Change on River Network Temperatures

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Introduction

A warming climate may bring unprecedented changes to stream ecosystems, with temperature considerations of utmost importance, given that most aquatic organisms are ectothermic and confined to river networks that are easily fragmented. Previous broad-scale assessments of climate impacts to streams have relied on surrogates for stream temperature like air temperature or elevation. These approaches are often imprecise, especially when applied in complex mountain topographies, and methods for directly modeling stream temperatures across broad areas are needed for conservation and planning purposes.

Spatial Stream Models

Recently, a new class of spatial statistical model has been developed that incorporates covariance structures that account for the unique forms of spatial dependence (e.g., longitudinal connectivity, flow-volume, and flow-direction) inherent to stream networks (Ver Hoef et al. 2006; Ver Hoef and Peterson, *In press*). Moreover, the spatial models can employ a mixed model approach to residual errors, thereby allowing multiple covariance matrices to be combined in a robust and flexible covariance structure (Figure 1).

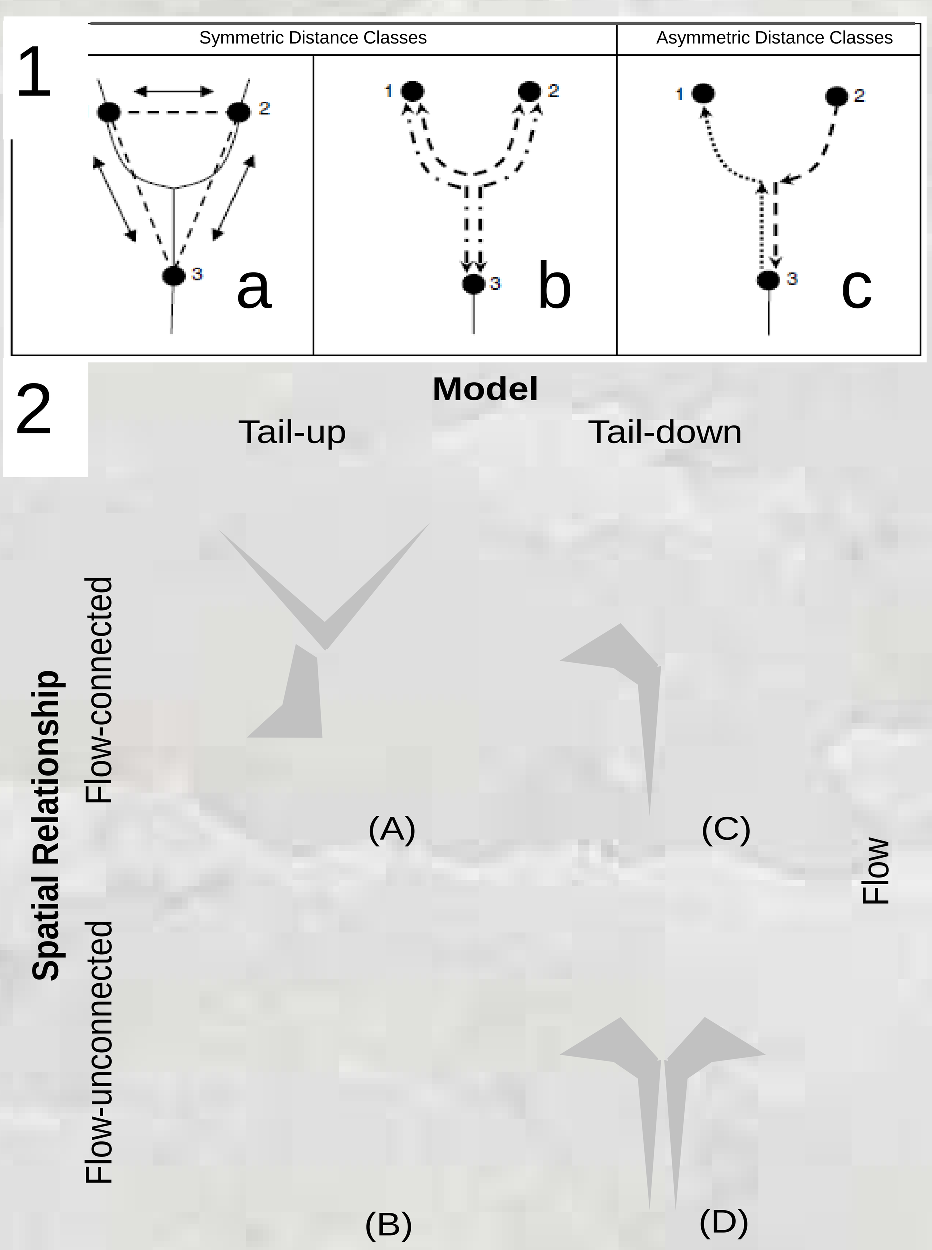


Figure 1. Distance measures relevant to stream networks include Euclidean distance (1a), symmetric instream distance (1b), and asymmetric instream distance (1c). Covariance matrices using instream distances may be calculated in "tail-up" or "tail-down" configurations (2). Tail-up covariances restrict spatial correlation to "flow-connected" sites, meaning that water must flow downstream from one site to another. Tail-down covariances allow spatial correlation between any two "flow-unconnected" sites, and require only that two sites occur on a network sharing a common outlet.

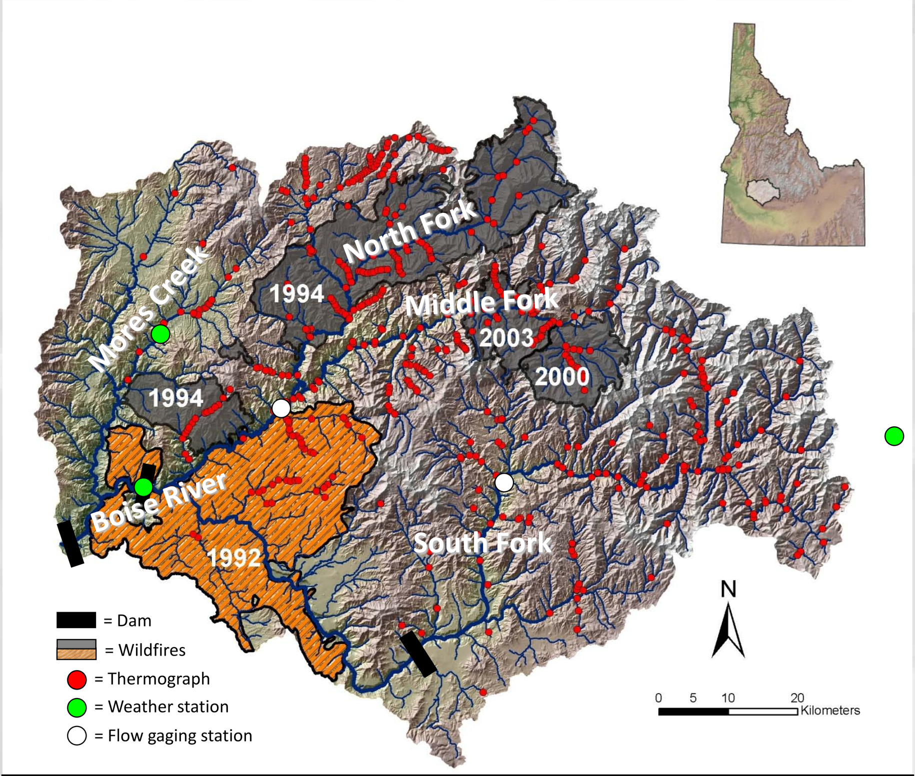


Figure 2. Boise River basin in central Idaho. Stream temperatures were recorded with digital thermographs at 518 unique sites from 1993 - 2006 to yield 780 temperature records (some sites were sampled more than once). Orange and gray polygons show perimeters of recent wildfires.

Methods

We applied the spatial stream models to an extensive, but non-random database of stream temperature measurements within the mountainous 2,500 km Boise River network of central Idaho (Figure 2). The temperature measurements were obtained by numerous resource agencies for a variety of purposes from 1993–2006. Like many watersheds in the western US, environmental trends associated with a warming climate are evident within the Boise River and wildfires have become common (Figures 2 and 3).

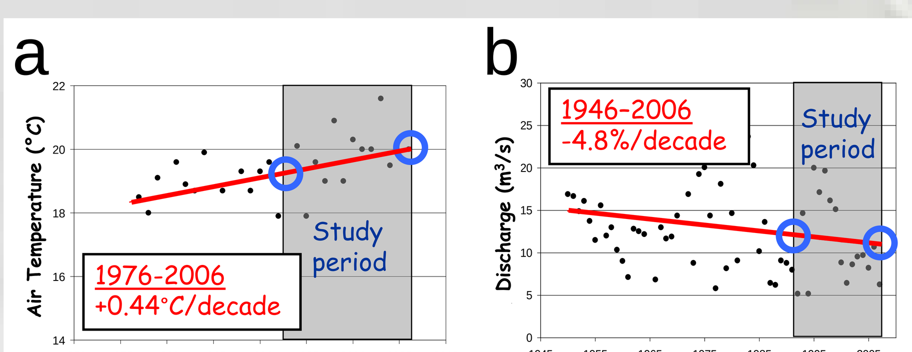


Figure 3. Long-term trends in summer air temperatures (a) and stream flows (b) in the Boise River basin. Shaded areas highlight the study period; red lines are simple linear regressions denoting long-term climate trends.

For comparative purposes, we modeled mean summer stream temperatures using both a traditional, non-spatial multiple regression model and the spatial statistical model. Four predictor variables—radiation, elevation, air temperature, and stream flow—with important effects on stream temperatures were used in each model. Values for the air temperature and stream flow predictors were derived from weather stations and flow gages in the basin, elevations were derived from a digital elevation model, and solar radiation was estimated from Thematic Mapper riparian vegetation classifications to represent wildfire effects.

Results

The non-spatial regression model accounted for approximately two-thirds of the variation in mean summer stream temperatures, but exhibited systematic prediction bias (Figure 4). Predictions from the spatial models were more accurate, with average prediction errors < 1°C. Parameter estimates for the predictor variables differed between the two models, indicating that spatial autocorrelation among temperature observations skewed the results of the non-spatial model.

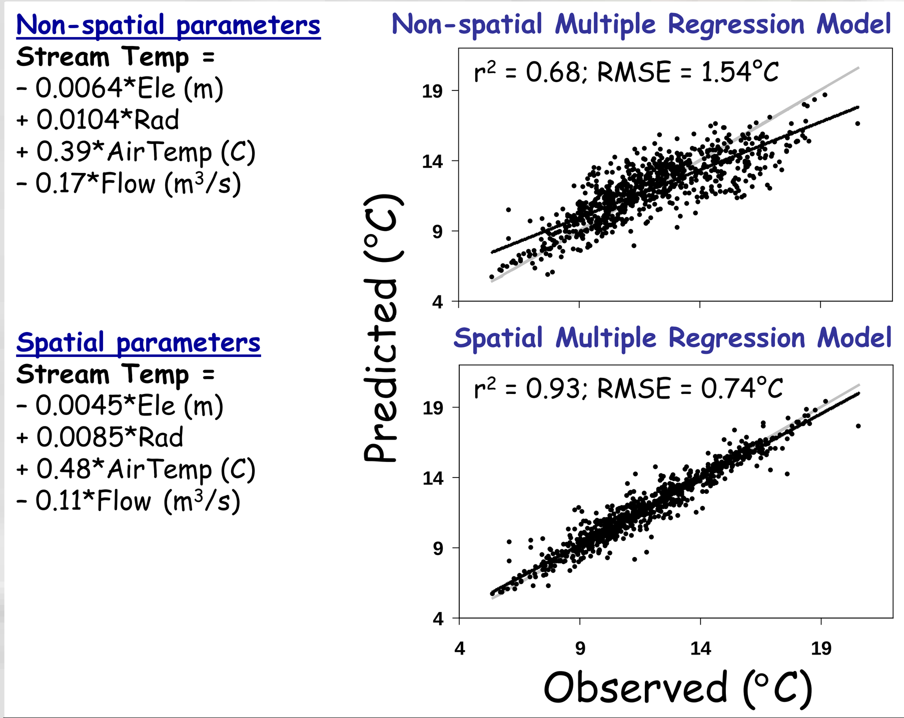
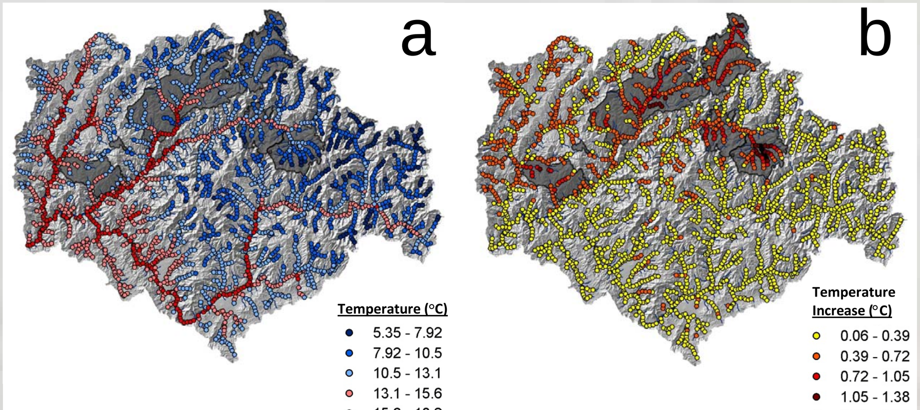


Figure 4. Scatterplots of predicted mean summer stream temperatures versus observed values for a non-spatial multiple regression model (top panel) and the spatial regression model (bottom panel). Grey line indicates 1:1 relationship; black line is simple linear regression between predicted and observed.

The spatial statistical model was used to predict stream temperatures at 1 km intervals throughout the river network using Cressie's universal kriging algorithm (Figure 5). Predictions were made for different climate scenarios by adjusting predictor variable inputs. The effects of recent climate change in this network were described by subtracting stream temperatures associated with the "average" climate conditions in 1993 from those in 2006 (values in blue circles, Figure 3). During this period, we estimate that basin-scale mean summer stream temperatures increased by 0.38°C, which equates to a warming rate of 0.27°C/decade. Within wildfire perimeters, rates of warming were greatly accelerated (Figure 5).



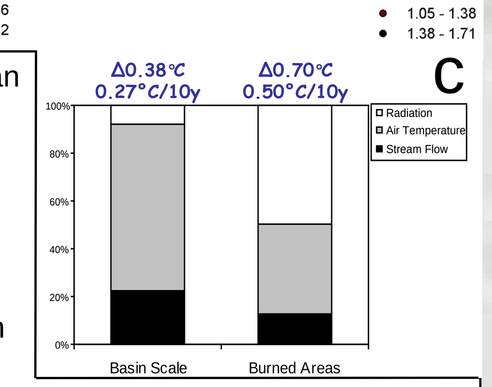


Figure 5. Map of predicted mean summer stream temperatures based on climate conditions in 2006 (a). Map of changes in summer stream temperatures between 1993 and 2006 based on climate trends and wildfires during this period (b). Attribution of stream temperature changes within wildfire perimeters and across the entire river network (c). Total temperature increases and decadal rates of change are given above bars.

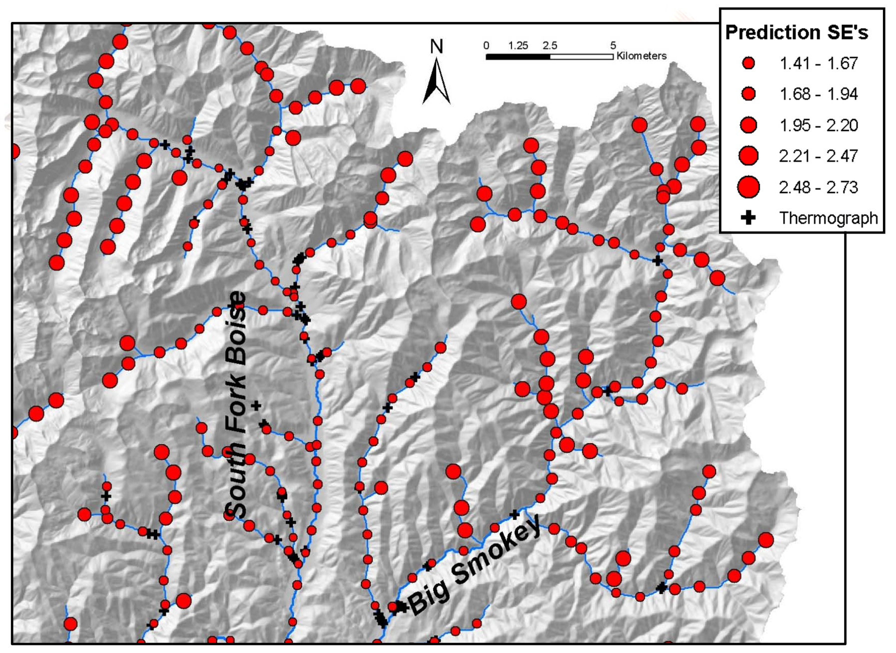


Figure 6. Precision associated with stream temperature predictions for a portion of the network in the Boise River. Size of the red circles is proportional to the standard error of the prediction; **+** denote locations of stream temperature observations.

In addition to improving overall predictive accuracy, the spatial models were useful for describing geographic variation in the precision of stream temperature predictions (Figure 6). Spatial differences in precision could help guide future data collection efforts within a particular area, and formal descriptions of patterns in spatial variation associated with a response variable could be used to optimize monitoring designs.

Conclusions

By overcoming many issues that have limited statistical analyses of stream systems in the past, the spatial models facilitated precise and accurate downscaling of climate trends in the Boise River. The spatial models are especially well-suited to "found" data like our temperature database that are often characterized by clustering and non-randomness because spatial autocorrelation among sites improves the predictive accuracy of the models. Although current applications of the spatial statistical models have been limited primarily to understanding patterns in water quality attributes, the models could also be profitably employed to address biological response variables. Numerous applications can be envisioned that would draw on large, georeferenced databases now routinely compiled by natural resource agencies. The integration of spatial stream models with ever-improving abilities to characterize important landscape features using GIS and remote sensing promises to significantly advance our understanding of streams by reducing the imprecision associated with larger-scale inquiries, improving future data acquisition, and harnessing existing databases.

Key Literature

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