Developments in statistical downscaling since TAR (2001): North America

11.3.5.2.3 Statistical downscaling

Since the TAR there have been numerous statistical downscaling (SD) studies but several important challenges remain largely unresolved (Leung et al., 2003). Foremost are questions surrounding the characterisation of predictor-predictand relationships, and the extent to which more sophisticated techniques can extract greater regional predictability. A significant fraction of articles were devoted to model inter-comparison (principally statistical versus statistical methods); others highlighted the synergy between techniques used for statistical downscaling and those used for seasonal prediction. Although a few novel applications have emerged, regional climate change projections by SD methods continue to be most widely applied to the water resource, agricultural and conservation sectors. However, a handful of integrated assessments have begun to appear.

Modelling developments

In common with other regions, there has been a proliferation of SD studies since the TAR. More sophisticated procedures are being used to classify primary features of synoptic scale circulation patterns and/or to develop transfer functions to local-scale predictands. For example, Hewitson and Crane (2002) employed self-organizing maps (SOMs) to investigate changes in January precipitation over Pennsylvania related to the frequency and characteristics of circulation patterns. Others have applied genetic programming (Coulibay, 2004), neural networks (Schoof and Pryor, 2001) or nearest-neighbour analogs (Gangopadhyay et al., 2005) to capture the non-linear behaviour of local-scale temperature and precipitation. These methods typically out-perform step-wise linear-regression models, and consistently show greater skill for temperature than precipitation (Cannon and Whitfield, 2002; Schoof and Pryor, 2001).

Choice of predictor variable(s) is a critical step affecting the outcome of downscaling assessments. Therefore, much effort has been invested in evaluating the range of variables typically used for model calibration, and in maximising predictability for particular locations. Cavazos and Hewitson (2005) undertook a systematic analysis of the relative skill of different NCEP-NCAR reanalysis variables as predictors of precipitation and found that mid-tropospheric geopotential heights and mid-tropospheric humidity emerged as the preferred predictors for all locations and seasons. A growing number of studies have also employed GCM-simulated precipitation as a predictor for local precipitation, noting that the improved skill relative to conventional predictors (e.g., geopotential height, temperature, humidity) and ease of use make it particularly appealing (Salathé, 2003; Widmann et al., 2003).

Resolving fine scale structures of daily precipitation is especially challenging in complex terrain. The task was addressed for daily winter precipitation across the Sierra Nevada by introducing the additional step of a simplified orographic precipitation model (Pandey et al., 2000). An alternative approach to resolving local-scale variability is to apply spatial and/or temporal averaging of the precipitation. For example, Gangopadhyay et al. (2004) showed that the skill of downscaling daily precipitation forecasts in the upper Colorado River basin was generally higher at spatial scales greater than 50km than at individual stations. Similarly, the maximum forecast skill of 6-hourly precipitation totals was approximately half that of daily totals. Even lower frequency variations in (seasonal) precipitation totals across the southeastern US may be conditioned by slowly varying predictors such as the El Nino-Southern Oscillation Index or Bermuda High index (Katz et al., 2003). This is consistent with Brinkmann's (2002) finding that the optimum domain for the predictor variable may be geographically remote from the downscaling target.

Model inter-comparisons

The classic approach involves straightforward comparison of skill from linear and non-linear transfer functions given a common set of synoptic scale predictors (Schoof and Pryor, 2001). Another reason for applying a range of techniques is because differences amongst downscaling methods can translate into quite different adaptation responses, particularly when projected climate changes are of opposite sign (Payne et al., 2004). Other studies focus on the uncertainty due to the choice of GCM or emission scenario used for the downscaling. Using a scaling approach for present day meteorology, Salathé (2005) showed that ECHAM4 captures the timing of precipitation, links to temperature variability and streamflow in the Yakima River Basin better than HadCM3 or NCAR-PCM.

Weather generators continue to be the method of choice for agricultural applications and have been the subject of several comparisons (Mavromatis and Hansen, 2001; Qian et al., 2004). These studies show that crop responses based on weather generators can be sensitive to assumptions about the extent and nature of variability of the derived weather sequences under climate change. For example, stochastic weather generators tend to underestimate interannual variability of generated climate, unless a low-frequency component is applied to model parameters (Hansen and Mavromatis, 2001; Katz et al., 2003).

Comparisons are performed using a range of diagnostics including primary variables such as daily maximum temperature (Qian et al., 2004), or derived quantities such as agroclimatic indices (Mavromatis and Hansen, 2001) and river flow (Hay and Clark, 2003). One major study evaluated six approaches for downscaling climate model outputs for use in hydrologic simulations of the Columbia River Basin (Wood et al., 2004). Downscaled precipitation and other variables were used to drive a macroscale hydrology model for a 20-year retrospective (1975-1995) and future (2040-2060) climate conditions. The study showed that neither PCM nor RCM output yields plausible hydrologic simulations without a bias-correction step. Furthermore, one way coupling of the coarse scale climate models with the high-resolution hydrologic models does not recover important regional scale processes such as snow-albedo feedbacks at higher elevations. This highlights an important limitation of SD methods.

A major question hangs over the findings of most inter-comparison studies: to what extent are findings transferable between locations and time periods? For example, Hay and Clark (2003) recommend the use of SD-based simulations of runoff in preference to dynamically derived runoff. However, this reflects the fact that in the three mountainous basins used, SD provided more accurate estimates of daily maximum temperatures than the RCM, and hence better timing of snowmelt. Hence, spatial variations in the relative preponderance of rainfall runoff as opposed to rapid-snowmelt runoff (see Dettinger et al., 2004) can differentially affect the sensitivity of downscaled river flows to SD and RCM biases.

Statistical downscaling model applications

Practical applications of statistical downscaling continue to be closely aligned with developments in seasonal forecasting for regions in North America. This is because experimental systems used for long-range weather and hydrologic forecasting employ outputs from ensemble climate model forecasts as downscaling predictors for local precipitation and temperature (Clark et al., 2004) that, in turn, drive high resolution hydrologic models (Cannon and Whitfield, 2002; Wood et al., 2005). Thus, use of ensembles of reanalysis products for seasonal forecasting directly parallels use of multi-model ensembles for future climate downscaling. For example, Wood et al. (2002) demonstrated that six monthly forecasts of runoff for the East Coast and Ohio River basin downscaled from ensemble forecasts of monthly total precipitation and average temperature were superior to those based on climatology. This confirms the view of Leung et al. (2003) that seasonal prediction is a useful framework for assessing the added value of downscaling because results from different schemes can be evaluated *now* using observed climatology.

Statistical downscaling methods have also been used to enhance representations of subgrid surface energy and moisture fluxes. Given large-scale forcing fields, these techniques can be used for infilling or extending sparse data sets. For example, Hember et al. (2005) applied principal component analysis and *K*-means clustering to produce discrete patterns of 500 hPa geopotential height fields. The resulting cluster scheme was used to condition daily hydrometeorological anomalies and monthly evapotranspiration and potential evapotranspiration above a peat bog near Ottawa, Ontario. Crow and Wood (2002) demonstrated a power-law relationship for downscaling coarse-resolution soil moisture imagery (32-64 km) to the high-resolution (1 km) needed for hydrologic modelling of the Red-Arkansas River basin.

Finally, the close attention to climate model outputs needed for statistical downscaling often provides opportunities for verification of GCM skill against historic data. For instance, during the course of developing a SD model for winter precipitation in western North America, Lapp et al. (2002) showed that the synoptic pattern frequencies of the CCCma CGCM1 2000 output were a substantial improvement on the 1992 model version.

11.3.5.3 Climate change projections

Statistical downscaling

Since the TAR there have been a large number of SD climate change projections applied to various impact sectors and sub-regions across North America. As with RCMs, much research activity has focused on resolving future water resources in the complex terrain of the western US. Studies typically point to a decline in winter snowpack and hastening of the onset of snowmelt caused by regional warming (Dettinger et al., 2004; Hayhoe et al., 2004; Salathé, 2005). Comparable trends towards increased mean annual river flows and earlier spring peak flows have also been projected by two SD techniques for the Saguenay watershed in northern Quebec, Canada (Dibike and Coulibaly, 2005). Such changes in the flow regime also favour increased risk of winter flooding, lower summer soil moisture and river flows. However, differences in snowpack behaviour derived from HadCM3, ECHAM4 and NCAR-PCM depend critically on the realism of GCM-downscaled wintertime temperature variability and its interplay with precipitation and snowpack accumulation/ melt (Salathé, 2005).

Several articles focus on the effect of downscaled precipitation and temperature changes on agricultural potential and land quality. Bootsma et al. (2005) interpolated climate change scenarios for the Atlantic region of Canada from CGCM1 to a 10-15 km grid and computed a range of agroclimatic indices (e.g., crop heat units, effective growing degree-days, and water deficits) for 2010-2039 and 2040-2069. The interpolation procedure yielded smaller winter and summer temperature increases, and summer and autumn precipitation increases than the statistical downscaling tool (SDSM) (Wilby et al., 2002). Uncertainty due to multiple GCMs also increased the range of the indices. Work by Georgakakos and Smith (2001) further highlights the risks of drier than present soil moisture conditions in the southeastern US, whereas Zhang et al. (2004) project increased soil loss and reduced wheat yield for the Oklahoma region. However, the latter study also showed that adoption of conservation tillage and no-till measures would be effective in controlling soil erosion under the climate change scenario downscaled from HadCM3.

A key advantage of SD techniques is their potential for generating site-specific and/or exotic scenarios for specific impact sectors. For example, local wind speeds are notoriously difficult to downscale using RCMs because of highly localised controls on vertical and horizontal airflows. Nonetheless, Sailor et al. (2000) applied a neural network approach to estimate wind power from GCM output. Other challenging applications of downscaling include projections of changes in average ski seasons for southern Ontario (Scott et al., 2003), and estimates of extreme heat-related mortality in California (Hayhoe et al., 2004). Construction of land use change scenarios for the New York Metropolitan Region involved ‘downscaling’ the SRES A2 and B2 scenarios into a local narrative of alternative rural-to-urban land conversions (Solecki and Oliveri, 2004).

There have been a small, but growing number of downscaling studies that seek to integrate regional climate change impacts and/or explore adaptation options. For example, Vanrheenen et al. (2004) showed that projected reduction in winter, spring and summer streamflow in the Sacramento-San Joaquin River basin can not be fully mitigated without demand modification and investment in water infrastructure improvements. Similarly, Payne et al. (2004) found that changes in the regime of the Columbia River could be accommodated by earlier reservoir refill and greater storage allocated for compensation flows, but at the expense of less reliable hydropower production. Quinn et al. (2001) adopted a broader perspective to assess vulnerability of other water dependent activities such as water quality, ecosystem health and socioeconomic welfare within the San Joaquin River basin. Finally, Hayhoe et al. (2004) produced a standard set of downscaled temperature and precipitation scenarios to underpin a multi-sector impact assessment for California. Large increases in temperature and extreme heat were found to drive significant impacts on temperature-sensitive sectors. For example, under both the A1F1 and B1 emission scenarios there are overall declines in snowpack and loss of alpine and subalpine forests, as well as reduced dairy production and degraded wine quality.

References

Bootsma, A., Gameda, S. and McKenney, D.W. 2005. Impacts of potential climate change on selected agroclimatic indices in Atlantic Canada. *Canadian Journal of Soil Science*, **85**, 329-343.

Brinkmann, W.A.R. 2002. Local versus remote grid points in climate downscaling. *Climate Research*, **21**, 27-42.

Cannon, A.J. and Whitfield, P.H. 2002. Downscaling recent streamflow conditions in British Columbia, Canada using ensemble neural network models. *Journal of Hydrology,* **259,** pp.136-151.

Cavazos, T. and Hewitson, B.C. 2005. Performance of NCEP-NCAR reanalysis variables in statistical downscaling of daily precipitation. *Climate Research*, **28**, 95-107.

Clark, M., Gangopadhyay, S., Hay, L.E., Rajagopalan, B and Wilby, R.L. 2004. The Schaake Shuffle: A method for reconstructing space-time variability in forecasted precipitation and temperature fields. *Journal of Hydrometeorology*, **5**, 243-262.

Coulibay, P. 2004. Downscaling daily extreme temperatures with genetic programming. *Geophysical Research Letters*, **31**, L16203.

Crow, W.T. and Wood, E.F. 2002. The value of coarse-scale soil moisture observations for regional surface energy balance modeling. *Journal of Hydrometeorology*, **3**, 467-482.

Dettinger, M.D., Cayan, D.R., Meyer, M.K. and Jeton, A.E. 2004. Simulated hydrologic responses to climate variations and change in the Merced, Carson and American River basins, Sierra Nevada, California, 1900-2099. *Climatic Change*, **62**, 283-317.

Dibike, Y.B and Coulibaly, P. 2005. Hydrologic impact of climate change in the Saguenay watershed: comparison of downscaling methods and hydrologic models. *Journal of Hydrology*, **307**, 145-163.

Gangopadhyay, S., Clark, M. and Rajagopalan, B. 2005. Statistical downscaling using K-nearest neighbours. *Water Resources Research*, **41**, W02024.

Gangopadhyay, S., Clark, M., Werner, K., Brandon, D. and Rajagopalan, B. 2004. Effects of spatial and temporal aggregation on the accuracy of statistically downscaled precipitation estimates in the upper Colorado River basin. *Journal of Hydrometeorology*, **5**, 1192-1206.

Georgakakos, K.P. and Smith, D.E. 2001. Soil moisture tendencies into the next century for the conterminous United States. *Journal of Geophysical Research – Atmospheres*, **106**, 27367-27382.

Hansen, J.W. and Mavromatis, T. 2001. Correcting low-frequency variability bias in stochastic weather generators. *Agricultural and Forest Meterorology*, **109**, 297-310.

Hay, L.E. and Clark, M.P. 2003. Use of statistically and dynamically downscaled atmospheric model output for hydrologic simulations in three mountainous basins in the western United States. *Journal of Hydrology*, **282**, 56-75.

Hayhoe, K., Cayan, D., Field, C.B. et al. 2004. Emissions pathways, climate change, and impacts on California. *PNAS*, **101**, 12422-12427.

Hember, R.A., Lafleur, P.M. and Cogley, J.G. 2005. Synoptic controls on summer evapotranspiration from a bog peatland in southern Canada. *International Journal of Climatology*, **25**, 793-809.

Hewitson, B.C. and Crane, R.G. 2002. Self-organizing maps: applications to synoptic climatology. *Climate Research*, **22**, 13-26.

Katz, R.W., Parlange, M.B. and Tebaldi, C. 2003. Stochastic modeling of the effects of large-scale circulation on daily weather in the southeastern US. *Climatic Change,* **60**, 189-216.

Lapp, S., Byrne, J., Kienzle, S. and Townsend, I. 2002. Linking global circulation model synoptics and precipitation for western North America. *International Journal of Climatology*, **2002**, 1807-1817.

Leung, L.R., Mearns, L.O., Giorgi, F. and Wilby, R.L. 2003. Regional climate research: needs and opportunities. *Bulletin of the American Meteorological Society*, **84**, 89-95.

Mavromatis, T. and Hansen, J.W. 2001. Interannual variability characteristics and simulated crop response of four stochastic weather generators. *Agricultural and Forest Meteorology*, **109**, 283-296.

Pandey, G.R., Cayan, D.R., Dettinger, M.D. and Georgakakos, K.P. 2000. A hybrid orographic plus statistical model for downscaling daily precipitation in northern California. *Journal of Hydrometeorology*, **1**, 491-506.

Payne, J.T., Wood, A.W., Hamlet, A.F., Palmer, R.N. and Letternmaier, D.P. 2004. Mitigating the effects of climate change on the water resources of the Columbia River Basin. *Climatic Change*, **62**, 233-256.

Qian, B., Gameda, S., Hayhoe, H. De Jong, R. and Bootsma, A. 2004. Comparison of LARS-WG and AAFC-WG stochastic weather generators for diverse Canadian climates. *Climate Research*, **26**, 175-191.

Quinn, N.W.T., Miller, N.L., Dracup, J.A., Brekke, L. and Grober, L.F. 2001. An integrated modeling system for environmental impact analysis of climate variability and extreme weather events in the San Joaquin Basin, California. *Advances in Environmental Research*, **5**, 309-317.

Sailor, D.J., T. Hu, Li, X. and. Rosen, J.N. 2000, A neural network approach to local downscaling of GCM output for assessing wind power implications of climate change. *Renewable Energy*, **19**, 359-378.

Salathé, E.P. 2003. Comparison of various precipitation downscaling methods for the simulation of streamflow in a rainshadow river basin. *International Journal of Climatology*, **23**, 887-901.

Salathé, E.P. 2005. Downscaling simulations of future global climate with application to hydrologic modelling. *International Journal of Climatology*, **25**, 419-436.

Schoof, J.T. and Pryor, S.C. 2001. Downscaling temperature and precipitation: A comparison of regression-based methods and artificial neural networks. *International Journal of Climatology,* **21,** 773-790.

Scott, D., McBoyle, G. and Mills, B. 2003. Climate change and the skiing industry in southern Ontario (Canada): exploring the importance of snowmaking as a technical adaptation. *Climate Research*, **23**, 171-181.

Solecki, W.D. and Oliveri, C. 2004. Downscaling climate change scenarios in an urban land use change model. *Journal of Environmental Management*, **72**, 105-115.

Vanrheenen, N.T., Wood, A.W., Palmer, R.N. and Lettenmaier, D.P. 2004. Potential implications of PCM climate change scenarios for Sacramento-San Joaquin River Basin hydrology and water resources. *Climatic Change*, **62**, 257-281.

Widmann, M., Bretherton, C.S. and Salathe Jr., E.P. 2003. Statistical precipitation downscaling over the Northwestern United States using numerically simulated precipitation as a predictor. *Journal of Climate*, **16**, 799-816.

Wilby, R.L., Dawson, C.W. and Barrow, E.M. 2002. SDSM – a decision support tool for the assessment of regional climate change impacts. *Environmental Modelliing and Software,* **17,** 147-159.

Wood, A.W., Kumar, A. and Lettenmaier, D.P. 2005. A retrospective assessment of National Centers for Environmental Prediction climate model-based ensemble hydrologic forecasting in the Western United States. *Journal of Geophysical Research,* **110**, D04105, 10.1029/2004JD004508.

Wood, A.W., Leung, L.R., Sridhar, V. and Lettenmaier, D.P.2004. Hydrologic implications of dynamical and statistical approaches to downscaling climate model outputs. *Climatic Change*, **62**, 189-216.

Wood, A.W., Maurer, E.P., Kumar, A. and Lettenmaier, D.P. 2002. Long-range experimental hydrologic forecasting for the eastern United States. *Journal of Geophysical Research,* **107**, D20, 4429, 10.1029/2001JD000659.

Zhang, X.C., Nearing, M.A., Garbrecht, J.D. and Steiner, J.L. 2004. Downscaling monthly forecasts to simulate impacts of climate change on soil erosion and wheat production. *Soil Science Society of America Journal*, **68**, 1376-1385.