Mapping of historical design values and their future-projected changes over Canada

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Abstract:
Climate change has the potential to affect buildings and infrastructure by changing the conditions to which they are exposed. To better quantify and prepare for these changes, Infrastructure Canada and the National Research Council (NRC) recently supported a collaboration between the Pacific Climate Impacts Consortium (PCIC) and Environment and Climate Change Canada (ECCC) to develop updated guidance to the engineering community. One facet of this work was the provision of standard climatic design values based on up-to-date historical observations at meteorological stations. Climatic data for infrastructure design are often required at locations not co-located with stations, necessitating some sort of interpolation. Purely mathematical or statistical interpolation tends to oversmooth spatial structure in station-poor areas and, depending on the technique, can exaggerate station measurement error in station-rich areas. Nor is physical consistency of the underlying climatic field in space guaranteed.

We developed an approach that uses historical regional climate model (RCM) simulations as a spatial interpolator of station observations. RCMs can adequately reproduce the observed spatial patterns and probability distributions of many climate variables, with the benefit of spatiotemporal consistency—albeit in a "model world" and at spatial scales resolved by the RCM. The mapping method has been implemented as an online tool (the Design Value Explorer, or DVE) for general users to explore design value variations across Canada. The seamless transition from historical to future climate states in the RCM further allows the tool to provide projected changes to design values indexed to different levels of global warming.

In this short paper, we review the development of the Design Value Explorer online tool, and showcase its main features.

Keywords:
Climate, climate change, design values

1. Introduction

The influence of climate upon built structures in Canada is codified in the Appendix C of the National Building Code of Canada (NBCC) [1] (NBCC, 2015), the Canadian Highway and Bridge Design Code [2] (CHBDC, 2014), and in corresponding provincial Codes (e.g., [3] the British Columbia Building Code, 2018).

Specifically, Table C-2 of the NBCC presents point-scale results for 15 climatic design values (DVs) at 680 locations across the country, mostly town and city centres. These data are used by planners, engineers and builders in many areas of infrastructure design, and hence are updated on a regular basis. From 2018-2020, PCIC and ECCC collaborated on the latest analysis of station data informing the Code, which are updated to 2018 for some variables. Two additional objectives of this project were: 1) to develop an objective mapping procedure to estimate DVs at locations not coincident with stations (including many in Table C-2), and; 2) to provide guidance on, and quantitative estimates of, the likely effects of climate change upon DVs, in the form of maps and tables as appropriate. The development of the Design Value Explorer (DVE), an online tool for presenting the results of the updated analysis, is the outcome of the first objective, while also serving as an appropriate platform for exploring future-projected changes in DVs. This short paper provides the background information and methods underlying the tool and also displays some example results from the development version of DVE.

2. Station data and climate model information

PCIC obtained Canada-wide observational data from the Meteorological Service of Canada (MSC), comprising more than 150 variables, some measured since the early 20th century, and created a dedicated database for use in this project. Additional snow observations from provincial snow monitoring networks collected by the MSC in Quebec and British Columbia were also obtained. These data include snow depth, density and water equivalent observations essential to providing adequate estimates of both snow and rain-on-snow loading. Quality control and analysis procedures varied by the climatic design element. While some methodological changes were made to improve the robustness of certain DV estimates (as described in the online DVE documentation), the station-based analysis largely followed that described in Appendix C of NBCC [1].

The sparse distribution of meteorological stations over most of Canada, allied with the fact that many of these stations cover periods that are too short to allow reliable estimates of DVs, creates challenges for traditional interpolation methods. We respond to these challenges by developing a mapping method based on a regional climate model, here the Canadian Regional Climate Model, Version 4 (CanRCM4), to simulate the spatial variation in design values. A full description of the model, including its merits and limitations in simulating DVs, is given in [4].

The DVs were calculated on the native CanRCM4 grid (0.44° x 0.44°, true at 60 °N), masked to Canada-only, from outputs at hourly to daily time resolution. Each gridded DV field is then downscaled by bilinear interpolation to a 10x finer "target" resolution (0.044° x 0.044°, or ~4.5 km x 4.5 km, true at 60 °N).

3. Mapping method

The main goal is to use the spatially complete, two-dimensional DV fields from CanRCM4 to guide interpolation between observationally-derived DVs at stations. Hence the principal utility of the model is in the spatial pattern, and only secondarily in the magnitude, of the DV field it simulates. The key steps of the method, which we refer to as hybrid spatial mapping (HSM), are outlined in Fig. 1. RCM values M_i are generally biased relative to observations, and thus station values S_i are often used to bias-adjust the models in some fashion. As a first step, the mean model bias over a region of interest (comprising $i = 1,\dots, N_S$ stations) is removed by the simple rescaling

$$M_j' = (\langle S_i \rangle / \langle M_i \rangle) M_j \ ,$$

where ⟨ • ⟩ denotes the arithmetic average over the station locations i and the index j ranges over all model grid cells (at the target resolution) in the region of interest. Next, we define the bias ratio, $B_i = S_i/M_j'$. and aim to find a method that, first, interpolates this quantity to all j locations on the target grid, B_j, and second, brings B_j as close to unity as possible at each point in the region (since $B_j = 1$, $j = i$, indicates no bias). Given such a method, the final step is to estimate the local DV field through multiplication of the interpolated bias B_j' by the rescaled model field, M_j', the adjusted model DV field at the target resolution. That is, we "reconstruct" the DV field as:

$$R_j = M_j' B_j'.$$

If, for example, the chosen interpolation method happens to be exact at the station grid cells, then $B_i' = B_i$ and $R_i = M_j' (S_i/ M_j') = S_i$; i.e., the reconstruction matches the station value exactly at these grid locations. At grid cells away from stations, i.e. over the majority of the domain, R_j incorporates both station and model information in a manner that automatically applies a weighting between the two according to station proximity.

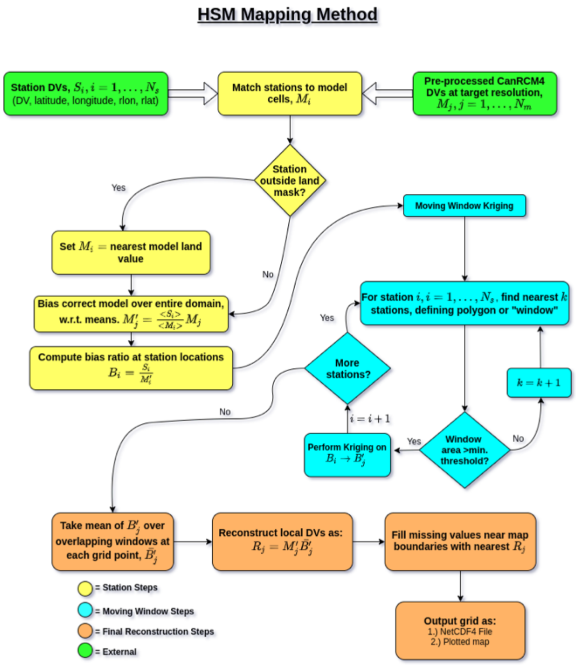

Figure 1: Flowchart illustrating various steps in the hybrid spatial mapping (HSM) method.

For the interpolation we use ordinary kriging (ORKG), which is designed to construct the best linear unbiased estimator of predicted field values [5]. The spatial structure of the DV field surrounding each station is approximated by an isotropic, exponential covariance function with three parameters (nugget, sill and range). We allow for a positive, non-zero nugget, indicating a discontinuous variogram at zero separation. Hence, while the interpolation does not exactly match the station values, it does account for unknown measurement errors, resulting in a smoother field. ORKG is applied at the regional scale to the discrete bias field B_i, with parameters estimated by maximum likelihood estimation (MLE). The ORKG-MLE method converges to parameter estimates that minimize the error variance of the set of j estimated values B_j' across the entire domain of interest. This makes the method preferable to purely mathematical interpolation or curve-fitting techniques that do not explicitly account for the local spatial covariance structure that is a feature of most physical fields.

In order to apply HSM over the entirety of Canada, we implemented ORKG-MLE in a moving polygon mode, with each polygon defined by the k nearest stations to a target station (we chose k = 30; see, e.g., [6]). This allows for regionally varying covariance parameters since, although the form of the covariance function is kept fixed in each polygon, the anisotropic station distribution is reflected in the varying size and location of the polygons. Significant overlap was allowed to avoid edge discontinuities. Once every station has acted as a target, the mean value of B_j' over all overlapping polygons is computed at each target grid cell *j*. In station-rich areas, more windows are averaged than in station-poor areas, reducing measurement error in the former regions.

ECCC and PCIC also used CanRCM4 to derive future DV fields under a high-emissions greenhouse gas scenario (RCP8.5), as detailed in the aforementioned report [4]. In DVE, model projections are presented at specified levels of annual mean global surface air temperature (GSAT) change rather than during fixed time periods. Results are provided for GSAT changes of 0.5°C, 1.0°C,…, 3.5°C, from a historical baseline of 1986-2016. Future-projected changes are provided in the form of either increments (for temperature-related DVs) or multiplicative factors (for all other DVs) to be applied to baseline values of the designated DV.

4. Results

We now present a few examples from the mapping method as implemented in DVE. Figure 2 shows an example map of the 50-year return level of maximum 1-day rainfall, highlighting the wettest part of Canada (southwestern British Columbia). Comparing the station and mapped values, it is evident that HSM adequately estimates the DV magnitude near the stations, while smoothly interpolating between stations, and providing plausible estimates in station-poor regions.

DVE allows users to interact with the tool in a host of ways to produce customized results. For example, the maps shown here were generated by the zoom feature applied to the larger, default map that covers all of Canada.

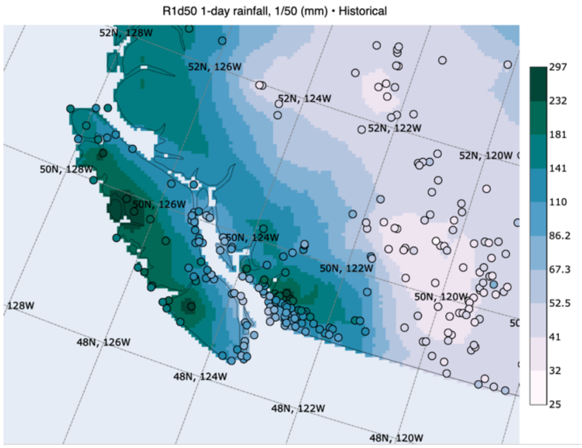

Figure 2: Map of 50-year return level of 1-day rainfall over southwestern BC from the DVE tool. Stations are indicated by filled circles.

Arbitrary domains can be examined by rectangular selection, down to the limiting resolution of the tool. Second, a mouse hover, point-and-click capability allows DVs at a single point to be examined and downloaded. This can be seen in Fig. 3, a map of the upper 2.5th percentile of hourly July wet bulb temperature, centred on southwestern Ontario, a region known for its warm and humid summers.

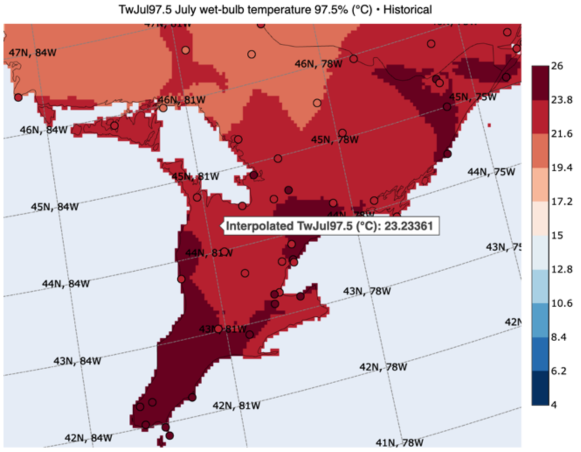

Figure 3: Upper 2.5th percentile of hourly July wet-bulb temperature over southern ON from DVE. Stations are indicated by filled circles. The DV at a single point, using the mouse hover feature, is also shown.

The impact of ongoing global warming on design values can also be assessed in DVE. Fig. 4 (*upper*) is a map of annual total precipitation (PAnn) across Canada as based by data over the last half-century. Fig. 4 (*lower*) shows the projected change in PAnn, based on CanRCM4, at a time when global temperature change reaches 2ºC above recent historical (1986-2016) levels (roughly the year 2060 in a high-emissions scenario). At the indicated point in the Northwest Territories (65 N, -125.8 W), PAnn is projected to be about 18% larger than its historical value of 254 mm.

In addition to the mapping capabilities of DVE, the tool also provides tabulated DVs at all locations listed in Table C-2 of the NBCC, extracted from the mapped fields. Future change increments and factors are also provided for each location, at the same global warming levels available for the maps. Maps and tables for each DV can be downloaded from the tool.

5. Conclusions and caveats

The HSM method is an objective mapping procedure that uses RCM gridded fields to interpolate DVs between stations. Maps and tables of projected increments or change factors to DVs at different global warming levels are also available. Online documentation and background information provides guidance on the appropriate use of the DVE tool.

Users are cautioned that the DVs provided by DVE have not yet been reviewed and accepted for inclusion into updates of the national Codes, and thus should only be considered as advisory information. Future-looking results, in particular, come with an associated uncertainty, as fully described for each design value element in [4], which should be consulted for guidance. Further development and refinement of the tool is ongoing, particularly with respect to making these uncertainties explicit.

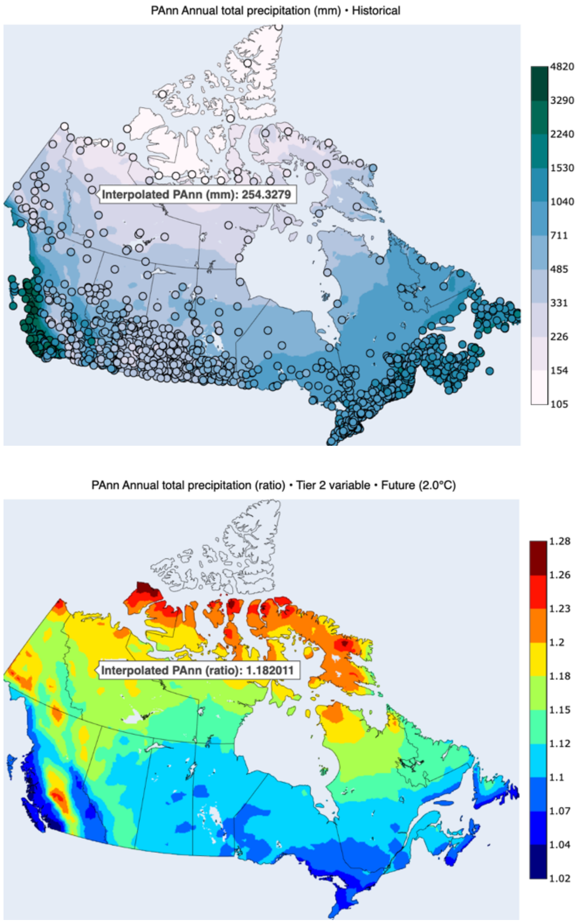

Figure 4: *Upper:* Annual total precipitation (PAnn) over Canada from the DVE tool. Stations are indicated by filled circles. PAnn at a single point is also shown. *Lower:* Projected change in PAnn under a future emissions scenario at a global warming of 2 ºC above historical levels. The relative change in PAnn at the same location is indicated.

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