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A small ensemble of bias-adjusted CMIP6 climate simulations over North America extending to 2300

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Abstract. ESPO-G6-post2100 is a bias-adjusted dataset covering North America featuring CMIP6 climate projections extending from 1950 up to 2300. It is meant to support climate change impact and adaptation studies for long-lived infrastructure and long-term planning decisions. It includes 17 simulations from eight different Earth System Models driven by five ScenarioMIP scenarios. The small ensemble size and the fact that most simulations are driven by either extremely low or extremely high greenhouse gas concentration pathways raises challenges for the delivery of robust and actionable climate products post-2100. The dataset is registered at https://doi.org/10.5281/zenodo.22132713 (Lavoie et al., 2026).

1 Introduction

The evaluation of climate impacts by a diverse community of scientists and professionals is greatly facilitated by the availability of bias-adjusted climate simulation ensembles. These ensembles provide simulations from multiple Earth System Models (ESMs) on the same spatial grid, often at higher spatial resolution than the original simulations. They also correct for systematic model biases relative to a reference dataset, facilitating the use of impact models calibrated on historical observations. Publicly available bias-adjusted datasets based on the Coupled Model Intercomparison Project 6 (CMIP6) however only extend to the end of the 21st century (Lavoie et al., 2024; Sobie et al., 2024; Thrasher et al., 2022). This paper describes a new bias-adjusted dataset over North America, ESPO-G6-post2100, that provides minimum daily temperature, maximum daily temperature and precipitation for an ensemble of CMIP6 ESMs from 1950 to 2300. This ensemble aims to facilitate the evaluation of long-term climate impacts and assess possible adaptation options.

Compared to other similar ensembles (e.g., Lavoie et al., 2024; Sobie et al., 2024), ESPO-G6-post2100 is relatively small and sparse, with only 17 CMIP6 simulations in total, spread over eight different models and five scenarios from the Scenario Model Intercomparison Project (ScenarioMIP, Tebaldi et al., 2021). This is due to the severely limited availability of ESM simulations post-2100 (Lee et al., 2021; Huard et al., 2026), an impediment to the development of robust and credible climate services for the time beyond 2100.

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2 Methods

The approach used to create ESPO-G6-post2100 is very similar to that for ESPO-G6-R2, and readers are referred to Lavoie et al. (2024) for a complete description. ESPO-G6-R2 is the bias-adjusted climate projection ensemble developed by Ouranos, a regional climate service, to support climate change impact and adaptation studies. The main differences described below regard the composition of the ESM ensemble and the reference dataset used as the bias-correction target.

Another conceptual distinction is that pre-2100, greenhouse gas (GHG) and aerosol emissions are simulated by Integrated Assessment Models (IAMs). These models describe interactions between demography, economy, technology and policies to project long-term GHG emissions consistent with Shared Socioeconomic Pathways (SSPs) (Meinshausen et al., 2020). Post-2100, GHG emissions switch to *stylized pathways* based on simplifying hypotheses such as a linear return of emissions from their 2100 values to zero by a given year (Meinshausen et al., 2020).

2.1 Scenario and Model Composition

The ESMs and scenarios composing the ensemble are presented in Table 1. ESM simulations were downloaded from the Earth System Grid Federation (ESGF; Petrie et al., 2021). These simulations are part of CMIP6's ScenarioMIP (Tebaldi et al., 2021), which counts over 2,000 simulations with daily surface temperature and precipitation time series, that is, up to the end of the 21st century. Beyond 2100, fewer than 100 runs are available (Huard et al., 2026). This drop is likely due to the fact that long-term extensions are optional components of the ScenarioMIP experimental design (O'Neill et al., 2016), and computational and storage costs are proportional to the number of simulated years, making long-term simulations a costly proposition for modelling centres.

Ouranos' bias-adjusted climate projection ensembles, like ESPO-G6-R2, usually focus their efforts on medium to high range scenarios typically used in impact and risk assessments, i.e., SSP2-4.5 and SSP3-7.0 (Lavoie et al., 2024). In this case, only one model, EC-Earth3-Veg, had post-2100 simulations available for variables of interest for those two scenarios. More scenarios were thus considered, according to the priorities set by the ScenarioMIP experimental design (O'Neill et al., 2016): tier 1 21st century scenarios include SSP1-2.6, SSP2-4.5, SSP3-7.0 and SSP5-8.5, and tier 2 long-term extensions prioritize SSP1-2.6-Ext, SSP5-3.4-OS-Ext and SSP5-8.5-Ext (hereafter referred to without the extension suffix). These two sets were combined to yield a subset of five scenarios.

For all available models driven by SSP1-2.6, SSP2-4.5, SSP3-7.0, SSP5-3.4-OS and SSP5-8.5, the first ensemble member with data extending beyond 2100 was selected (see Table 1). A simulation is included only if daily time series for precipitation, minimum daily temperature and maximum daily temperature are available for both the historical period and the future projection. These variables are chosen as they are often needed as input of impact models. One climate model was excluded, IPSL-CM6A-LR, after noting that temperature instabilities led to unrealistic spikes post-2100 in daily maximum temperatures. In total, eight different ESMs with simulations meeting criteria make up the ensemble (see Figure 1). We note that these models display a disproportionately high equilibrium climate sensitivity (ECS) compared to 2.5–4°C likely range assessed by

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Table 1. Composition of ESPO-G6-post2100 ensemble, including the data citation and the end year of the simulation. All time series begin in 1950.

ESM	Scenario	Member	Reference	End
ACCESS-CM2	SSP5-8.5	r1i1p1f1	Dix et al. (2019)	2300
ACCESS-ESM1.5	SSP1-2.6	r1i1p1f1	Ziehn et al. (2019b)	2300
	SSP5-8.5	r1i1p1f1	Ziehn et al. (2019a)	2300
CanESM5	SSP1-2.6	r1i1p1f1	Swart et al. (2019a)	2300
	SSP5-3.4-OS	r1i1p1f1	Swart et al. (2019b)	2300
	SSP5-8.5	r1i1p1f1	Swart et al. (2019c)	2180
CNRM-ESM2.1	SSP5-3.4-OS	r1i1p1f2	Voldoire (2019)	2300
EC-Earth3-Veg	SSP1-2.6	r1i1p1f1	EC-Earth Consortium (2019a)	2300
	SSP2-4.5	r1i1p1f1	EC-Earth Consortium (2019b)	2300
	SSP3-7.0	r1i1p1f1	EC-Earth Consortium (2019c)	2300
	SSP5-8.5	r1i1p1f1	EC-Earth Consortium (2019d)	2300
MRI-ESM2.0	SSP1-2.6	r1i1p1f1	Yukimoto et al. (2019a)	2300
	SSP5-3.4-OS	r1i1p1f1	Yukimoto et al. (2019b)	2300
	SSP5-8.5	r1i1p1f1	Yukimoto et al. (2019c)	2300
NorESM2-MM	SSP5-8.5	r1i1p1f1	Bentsen et al. (2019)	2298
UKESM1.0-LL	SSP1-2.6	r4i1p1f2	Good et al. (2019a)	2300
	SSP5-8.5	r4i1p1f2	Good et al. (2019b)	2300

the IPCC Sixth Assessment Report (Forster et al., 2021); among the eight ESMs, only two are within the ECS likely range (ACCESS-ESM1.5, MRI-ESM2.0), five are above, and one is below (NorESM2-MM) (Zelinka, 2022).

2.2 Reference dataset

As with ESPO-G6-R2, bias-adjustment is performed with the detrended quantile mapping approach (Cannon et al., 2015) using the `xclim` library (Bourgault et al., 2023). The main difference is the reference dataset, the Canadian Surface Reanalysis (CaSR) version 3.2 from Environment and Climate Change Canada, an upgrade from CaSR v2.1 used for ESPO-G6-R2. Major changes between CaSR v2.1 and v3.2 include a switch from ERA-Interim to ERA5 reanalysis for the initialization, an upgrade of the global atmospheric model from GEM4.8 at 39 km resolution to GEM5.2 at 25 km, and an extended period covering 1968–2024 instead of 1980–2018. A detailed description of CaSR v3.2 and its differences with previous versions is given in Khedhaouiria et al. (2026). Note that although the regional spatial resolution has not changed and remains at 10 km over North

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America (see Figure 1 a), the grids are not exactly the same. The reference period used to train the bias-adjustment factors also changed from 1989–2018 to 1991–2020.

3 Data Records

The 4.1 Tb dataset is hosted at https://pavics.ouranos.ca/twitcher/ows/proxy/thredds/catalog/birdhouse/disk3/ouranos/ESPO-G/ESPO-G6-post2100_v1.0/catalog.html in netCDF format on a Thematic Real-time Environmental Distributed Data Services (THREDDS). Each of the 5864 file stores four years of the time series of one variable from one model and one scenario. File names and directory structure follow a similar pattern as the CMIP6 data reference syntax. The citation record storing the link to the ESPO-G6-post2100 ensemble is archived on Zenodo (Lavoie et al., 2026).

To facilitate access, individual files from the same model and scenario are aggregated virtually using NcML, yielding a catalog of just 17 access URLs. We recommend using this catalog for most applications.

Each aggregated dataset contains time series from 1950 to 2300 for three variables: minimum daily temperature (`tasmin`), maximum daily temperature (`tasmax`) and total daily precipitation (`pr`). The diurnal temperature range (`dtr`) is also included for reference, as well as fixed orography and land-sea fractions. The dataset covers North America at a 0.09 ° resolution on a rotated uniform latitude-longitude grid. Information about the grid can be found in the attributes of the `rotated_pole` coordinate of each file. Dataset variables, units, metadata and dimensions adhere to the CF-Convention (Eaton et al., 2025). Note that the CanESM5 simulation driven by SSP5-8.5 is only available until 2180.

The dataset domain is shown in Figure 1 (a), along with the 20-year rolling average of daily maximum temperature over the Great Lakes region (b). Climatological changes between 1971–2000 and 2271–2300 simulated by MRI-ESM2.0 are shown in Figure 2 for SSP1-2.6 and SSP5-8.5.

4 Technical Validation

It is worth noting that the literature on post-2100 climate change is extremely limited compared to the 21st century (Huard et al., 2026). As a result, simulations beyond 2100 have received much less attention, and there are likely more unresolved bugs and issues with archived simulation datasets. For instance, numerical instabilities affecting temperature and relative humidity values in simulations from IPSL-CM6A-LR seem to have been fixed before 2100, but not after (see errata).

The method used for the bias-adjustment of ESPO-G6-post2100 is very similar to that of ESPO-G6-R2 v1 (Lavoie et al., 2024), as is the validation and its results (not shown to avoid duplication). In general, the marginal properties of the adjusted simulations are very close to the marginal and multivariate properties of the reference. Though, high quantiles of `tasmin` are performing less well as it is not adjusted directly, but indirectly through `tasmax` and `dtr`, the diurnal temperature range. The annual cycles of all variables are well represented. However, the maximum length of dry/warm spells are less well represented as sequences are not directly corrected for. It should be noted that this bias-adjustment method assumes future model biases

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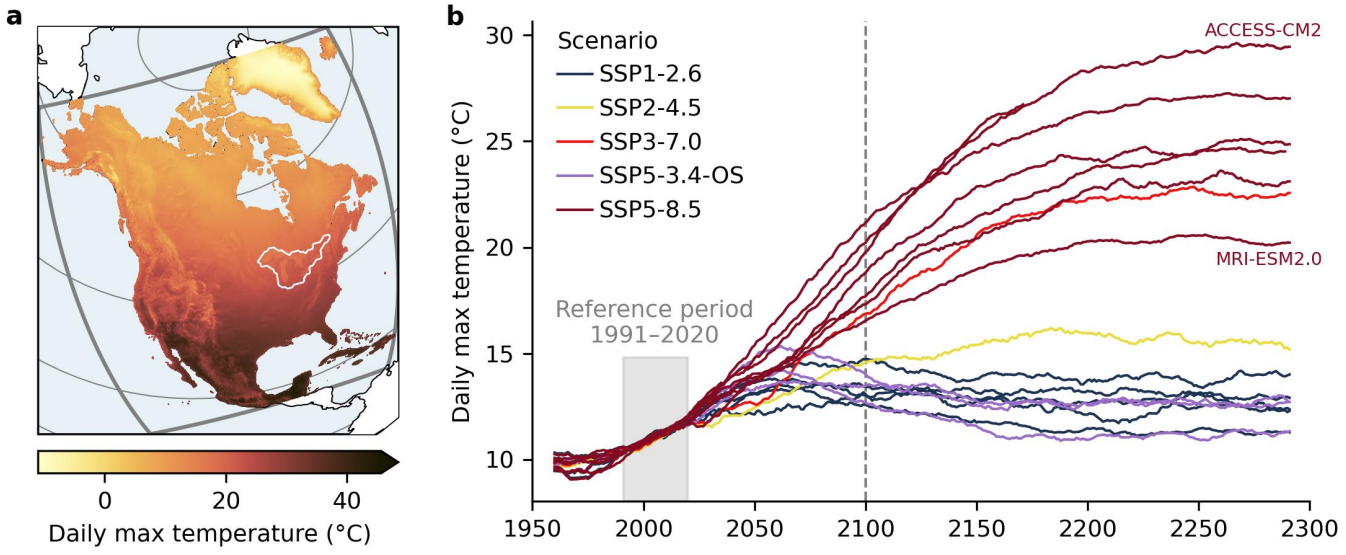


Figure 1. a) Mean daily maximum temperature (2271–2300) for the MRI-ESM2.0 simulation under scenario SSP5-8.5. The grey outline shows the dataset's area. b) Time series of the 20-year rolling average of daily maximum temperature over the Great Lakes region (white polygon in a) for all simulations of the ensemble. The reference period used for the bias-adjustment is shown to explain why all simulations have similar values around 1991–2020.

(whether they are additive or multiplicative) are identical to historical biases. This approximation is likely to fail as simulations extend farther into the future, especially in scenarios where conditions are extremely different from present day (see Figure 2).

As further validation, we perform a series of health checks on the data to make sure the values are physically plausible. The health checks are as follows:

1. No negative `pr`
2. No `tasmin` above `tasmax`
3. No `tasmax` above 80 °C
4. No `tasmin` below -90 °C
5. No `pr` above 1650 mm/d

All simulations pass the first three tests. For the `tasmin` test, only ACCESS-ESM1-5 fails the test. The only problematic points are in 1984 above Greenland. For the `pr` test, the threshold is exceeded for ACCESS-CM2, EC-Earth3-Veg and UKESM1-0-LL, but only for on average less than 1×10^{-7}% of the data. Still, users should be careful with extreme precipitations.

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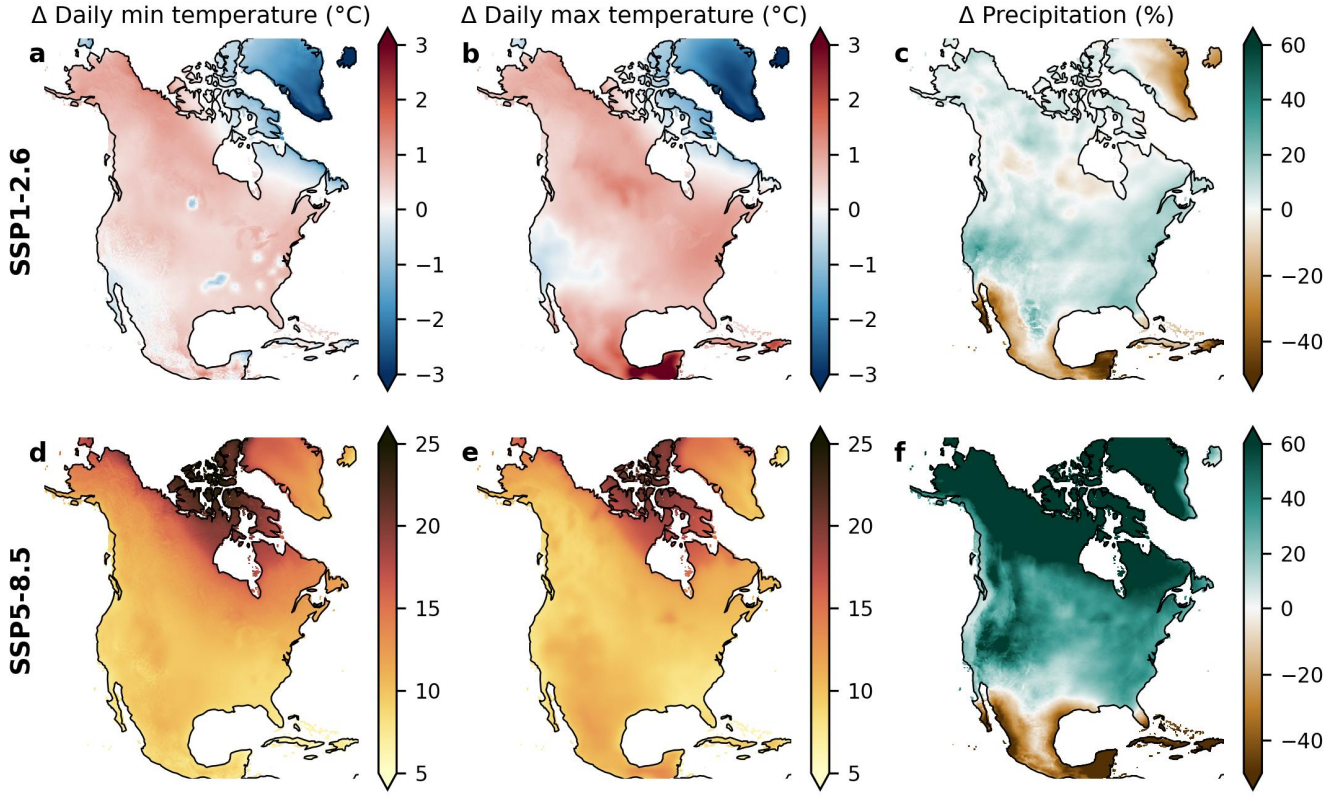


Figure 2. Climatological changes (2271–2300 vs 1971–2000) simulated by MRI-ESM2.0 under scenarios SSP1-2.6 and SSP5-8.5 for minimum and maximum daily temperature and precipitation.

Note that the thresholds for the health checks and rare exceedances in this article are more permissive than other similar tests (e.g., Lavoie et al. (2024); Thrasher et al. (2022)) because this dataset goes much farther into the future and reaches never-before-seen climates.

5 Usage Notes

We recommend accessing the ESPO-G6-post2100 data through the virtual aggregations hosted on THREDDS. The THREDDS server is part of the Ouranos PAVICS platform, which offers to registered users a JupyterLab Python programming environment to facilitate remote data analysis and avoid large data transfers (Arsenault et al., 2023).

Each link in the THREDDS catalog contains different access URLs, including OPeNDAP, a streaming protocol that lets users download only subsets of interests instead of entire datasets. Using the OPeNDAP URL, a virtual dataset holding all variables at all time steps for a given model and scenario can be accessed using the Python `xarray` library (Hoyer and Hamman, 2017):

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```
import xarray as xr
time_coder = xr.coders.CFDatetimeCoder(use_cftime=True)
url = "https://pavics.ouranos.ca/twitcher/ows/proxy/thredds/dodsC/datasets/
        simulations/bias_adjusted/cmip6/ouranos/ESPO-G/ESPO-G6-post2100v1.0/
        day_ESPO-G6-post2100_v1.0_CMIP6_ScenarioMIP_NAM-C3_CCCma_CanESM5
        _ssp126_r1i1p1f1_1950-2300.ncml"
xr.open_dataset(url,
                chunks=dict(time=1460, rlat=50, rlon=50),
                decode_times=time_coder
                )
```

Note that because simulations extend beyond year 2262, special date handling is necessary. For additional tips on climate analysis and data handling, including how to regrid the rotated pole grid to a rectilinear grid, please consult on-line tutorials hosted on PAVICS.

6 Conclusions

This paper introduces ESPO-G6-post2100, a small ensemble of bias-adjusted CMIP6 climate simulations over North America. The dataset is composed of daily timeseries for minimum daily temperature (tasmin), maximum daily temperature (tasmax) and total daily precipitation (pr) from 1950 up to 2300.

The composition of this ensemble raises multiple challenges. Users will have to account for the “hot model” problem to avoid biasing results (Cannon, 2024). Ensemble statistics under SSP5-8.5 may be influenced by the CanESM5 run terminating in 2180. Furthermore, most simulations are driven by SSP1-2.6, SSP5-8.5 and SSP5-3.4-OS, none of which represent *medium range* scenarios. While SSP1-2.6 can be considered an optimistic lower bound, SSP5-8.5 is usually framed as an unlikely high-end scenario (Riahi, K. et al., 2022), incompatible with current policies, observed trends in emissions and probabilistic IAM ensemble projections (Hausfather, 2025; Venmans and Carr, 2024; Huard et al., 2022). SSP5-3.4-OS is an overshoot scenario, initialized in 2040 from SSP5-8.5 and then implementing sudden drastic cuts in emissions, leading to a radiative forcing analog to SSP1-2.6 during the first half of the 22nd century (Lee et al., 2021). While SSP1-2.6 and SSP5-8.5 may provide lower and upper bounds in terms of climate impacts, it’s still unclear how overshoot scenarios should be framed for adaptation decision-making.

7 Code and data availability

ESPO-G6-post2100 data can be downloaded as netCDF files or streamed through the OPeNDAP protocol from this THREDDS catalog. Eventual future changes to this URL will be propagated to https://doi.org/10.5281/zenodo.22132713 (Lavoie et al., 2026). Users might also consider virtual aggregations for easier access.

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The code to reproduce the dataset ESPO-G6-post2100 dataset are available in the ESPO-G6-post2100v1.0.0 release of the ESPO-G GitHub repository.

Author contributions. EB worked on the conceptualization, supervision, methodology and original draft preparation. JL worked on the software, validation and editing of the manuscript. AB worked on the initial data acquisition and curation. ASF worked on the software and validation. DH worked on the conceptualization, supervision, methodology and original draft preparation. TL worked on data curation and publication. MB worked on supervision.

Competing interests. Authors declare no competing interest.

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