The Canadian Extreme Water Level Adaptation Tool (CAN-EWLAT)

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Les établissements de l’ancien secteur des Sciences et Levés océaniques dans les régions et à l'administration centrale ont cessé de publier leurs diverses séries de rapports en décembre 1981. Vous trouverez dans l'index des publications du volume 38 du *Journal canadien des sciences halieutiques et aquatiques*, la liste de ces publications ainsi que le dernier numéro paru dans chaque catégorie. La nouvelle série a commencé avec la publication du rapport numéro 1 en janvier 1982.

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ABSTRACT

Zhai, L., Greenan, B.J.W. and Perrie, W. 2023. The Canadian Extreme Water Level Adaptation Tool (CAN-EWLAT). Can. Tech. Rep. Hydrogr. Ocean. Sci. 348: iii + 15 p.

Global sea level rise resulting from climate change will have significant impacts on the Canadian coastline in the coming century. Climate change adaptation will be necessary in order to reduce the risks for coastal communities. The Canadian Extreme Water Level Adaptation Tool (CAN-EWLAT) has been developed to provide science-based advice for climate change adaptation planning of coastal infrastructure. The tool includes two main components: 1) vertical allowance and 2) wave climate. CAN-EWLAT was developed primarily for DFO Small Craft Harbours (SCH) locations, but it should prove useful for coastal planners dealing with infrastructure along Canada's ocean coastlines. This tool provides information for more than 1000 SCH marine sites in Canada based on the two most recent assessment reports of the Intergovernmental Panel on Climate Change (IPCC).

RÉSUMÉ

Zhai, L., Greenan, B.J.W. and Perrie, W. 2023. The Canadian Extreme Water Level Adaptation Tool (CAN-EWLAT). Can. Tech. Rep. Hydrogr. Ocean. Sci. 348: iii + 15 p.

L'élévation du niveau de la mer à l'échelle mondiale résultant des changements climatiques aura des répercussions importantes sur le littoral canadien au cours du prochain siècle. L'adaptation aux changements climatiques sera nécessaire afin de réduire les risques pour les communautés côtières. L'Outil canadien d'adaptation aux niveaux d'eau extrêmes (OCANEE) a été mis au point afin de fournir des avis fondés sur les données scientifiques pour la planification de l'adaptation des infrastructures côtières aux changements climatiques. L'outil a deux composantes principales : 1) la hauteur d'élévation et 2) le régime des vagues. L'OCANEE a principalement été élaboré pour les installations de la Direction des ports pour petits bateaux (PPB) de Pêches et Océans Canada (MPO), mais il pourrait s'avérer utile pour les planificateurs côtiers chargés de l'infrastructure située le long du littoral océanique du Canada. Cet outil fournit des renseignements sur plus de 1000 sites marins de PPB au Canada selon les deux plus récents rapports d'évaluation du Groupe d'experts intergouvernemental sur l'évolution du climat (GIEC).

1 Introduction

Globally, sea level has risen, and is projected to continue to rise throughout this century and beyond. The projected amount of global sea-level rise in the 21st century is many tens of centimetres and it may exceed one metre (Fox-Kemper et al., 2021). However, sea level in different parts of Canada is projected to rise or fall, depending on local vertical land motion and the future greenhouse gas emission scenario (Greenan et al., 2019). This is referred to a relative sea level change, and is important because this is what is experienced at the local (community) level. Due to land subsidence, parts of Atlantic Canada are projected to experience relative sea-level change higher than the global average during the coming century. Where relative sea level is projected to rise (most of the Atlantic and Pacific coasts and the Beaufort coast in the Arctic), the frequency and magnitude of extreme high water-level events will increase. This will result in increased flooding, which is expected to lead to infrastructure and ecosystem damage as well as coastline erosion, putting communities at risk. Due to the regional variability of sea level change in Canada, adaptation actions need to be tailored to local projections of relative sea-level change. Extreme high water-level events are expected to become larger and occur more often in areas where, and in seasons when, there is increased open water along Canada's Arctic and Atlantic coasts, as a result of declining sea ice cover, leading to increased wave action and larger storm surges.

The Canadian Extreme Water Level Adaptation Tool (CAN-EWLAT) is a climate change adaptation planning tool developed by DFO that provides sea-level rise projections for Canada's coastline over the coming century, and advice on how much higher to build coastal infrastructure to accommodate the projected rise. The tool, developed for DFO Small Craft Harbours (SCH) locations, is also useful for planners dealing with infrastructure along Canada's ocean coastline. This tool led to the creation of the Educating Coastal Communities About Sea-level Rise Project that helps inform Canadians about sea-level rise. Through this project, Fisheries and Oceans Canada and the Ecology Action Centre worked together to create an informative website and deliver workshops for residents, harvesters and municipalities. This information will help local harbour authorities and developers incorporate sea-level rise into future community planning.

Section 2 will describe the methods and data used to develop CAN-EWLAT; Section 3 will present the results of vertical allowances for low, medium and high emission scenarios; and conclusions and limitations will be given in section 4.

2 Methods and data

2.1 Relative sea level projections

The relative sea-level (RSL) projections from the Fifth Assessment Report (AR5, Church et al., 2013) of the Intergovernmental Panel on Climate Change (IPCC) incorporated contributions from thermal expansion, Greenland and Antarctic Ice Sheet mass loss, land-based glacier melt, land-based water storage, ocean dynamics, gravitational, rotational and deformation effects, and Glacial Isostatic adjustment (GIA). In the Sixth Assessment Report of the IPCC (AR6), the RSL projections included the above contributions and the vertical land motion from sources other than GIA (Fox-Kemper et al., 2021). James et al. (2021) improved the AR5 RSL projections along the Canadian coastline by removing the GIA model estimates of vertical land motion (Peltier, 2004; Lambeck et al., 1998 and subsequent improvements) and replaced this with the Canadian NAD83v70VG vertical land motion product (Robin et al., 2020). The NAD83v70VG vertical land motion incorporated recent Global Positioning System (GPS) measurements of vertical land motion in Canada. Similar methodology is applied to improve the AR6 projections (personal communication, Thomas James 2022).

The improved AR5 and AR6 RSL projections are available at tide gauges and SCH sites on the CAN-EWLAT tool. The AR6 report has a baseline period of 1995 to 2014. The sea level change of AR6 in 2010 is calculated using a linear interpolation to allow comparison with AR5 reference period. The AR5 RSL projections are available in a gridded format at a resolution of 0.1° in latitude and longitude for the entire marine coastline of Canada on the Canadian Centre for Climate Services (CCCS, https://climatedata.ca); it is expected that the AR6 projections will also be available on CCCS in the near future.

2.2 Vertical allowances

The vertical allowance is defined as the amount by which an asset should be raised in order to maintain the same frequency of inundation events as that site has experienced in the recent past. This incorporates both the expected lifetime of the infrastructure, and the uncertainty in the future projections of global sea level rise. Vertical allowance as a key component of the CAN-EWLAT tool, has been proved to be a useful tool for coastal community to adapt to sea level rise (Isaacson, 2022). CAN-EWLAT is referenced in the Small Craft Harbours section of the DFO priorities in the Departmental Plan for 2022-2023 (https://waves-vagues.dfo-mpo.gc.ca/library-bibliotheque/41037844.pdf). DFO uses the CAN-EWLAT to address the projected sea level change when designing marine infrastructure. Hence, there is a need to keep the CAN-EWLAT up-to-date once the new sea level projections are available.

Previous publications (Zhai et al., 2013; Zhai et al., 2014; Zhai et al., 2015) focused on providing allowances at tide gauges where statistics of extreme water levels can be derived from tide gauge observations. In this section, we will document the methodology of how to compute vertical allowances for the SCH sites and in a gridded format where storm surge model results are used to derive the statistics of extreme water levels. The model grids are the same as those of the updated AR5 and AR6 projections.

Following Hunter (2012), the vertical allowance is defined as:

$$a = \Delta z + \frac{\sigma^2}{2\lambda}, \qquad (1)$$

where Δz is the mean sea level projection, σ is the standard deviation of the sea level projections and λ is the scale parameter. The standard deviation σ is computed as the half range of the 5- to 95-percentile limits multiplied by 0.608 (assuming a normal distribution).

In the northwest Atlantic, scale parameters are provided by Bernier and Thompson (2006; denoted as BT2006) and Zhang and Sheng (2013; denoted as ZS2013). BT2006 used a 2D circulation model to simulate the storm surge from 1960 to 1999 for the northwest Atlantic extending from 38°N to 60°N and

72°W to 42°W. We computed the Gumbel scale parameters by fitting the Gumbel distribution to the annual maxima of storm surges and tides provided by Bernier (personal communication, 2012). ZS2016 used a 2D circulation model to simulate the past total water levels (tides and storm surges) for the period of 1979-2010 over the eastern continental shelf of North America covering the region between 7°N and 70°N and between 100°W and 35°W. They derived the scale parameters using the generalized extreme value (GEV) distribution fitted to annual maxima of hourly total water levels. The two products were chosen depending on their availability at the time when the CAN-EWLAT was developed and their spatial coverage. We linearly interpolated ZS2016's scale parameters onto the James et al. (2021) model grid. We used the nearest neighbour method to assign the BT2006's scale parameters to the SCH sites located south of 60°N, and assigned ZS2016's scale parameters to the SCH sites located north of 60°N.

In the northeast Pacific, the procedure used to derive the scale parameters starts with the tides predicted from the (CHS) tidal constants with the seasonal cycle removed using the CHS tidal prediction software (personal communication, Anne Ballantyne 2019). The predicted tides are assigned to the James et al. (2021) model grid and SCH sites using nearest neighbour method. In the northeast Pacific, the storm surge simulated by the 2D circulation model does not capture the sea level variability on intraseasonal and interannual time scales (Zhai et al., 2019). An adjustment is made to the modelled storm surge using an ocean reanalysis product to incorporate the large-scale dynamic sea level variability, such as those arising from major El Niño and La Niña events (Zhai et al., 2019). The adjusted surge is linearly interpolated onto the James et al. (2021) model grid, and assigned to the SCH sites using nearest neighbour method. Total water level is then computed as the summation of adjusted storm surge and tidal predictions, and used to derive the Gumbel scale parameter.

Vertical allowances are estimated for the coasts of British Columbia and Atlantic Canada and eastern Arctic south of 70°N. The allowances are provided every decade from 2020 to 2100 for the AR5 Representative Concentration Pathways (RCP) scenarios of RCP2.6, RCP4.5 and RCP8.5, and from 2020 to 2150 for the AR6 Shared Social-economic Pathways (SSP) scenarios of SSP1-2.6, SSP2-4.5 and SSP5-8.5. Vertical allowances available on the CAN-EWLAT web portal are relative to conditions in 2010.

2.3 Reference water level

In addition to a recommendation for the vertical allowance required for sea level change, it is important the coastal engineers have good estimates of present day water levels referenced to a standard vertical datum. The vertical allowances provided on CAN-EWLAT are with respect to Mean Water Level (MWL) epoch 2010 (Robin et al., 2016). In addition to the MWL epoch 2010, CAN-EWLAT also provides the following water level target heights:

- Lower Low Water Large Tide (LLWLT) epoch 2010,
- Higher High Water Large Tide (HHWLT) epoch 2010.

For definitions of these targets see :https://www.tides.gc.ca/en/definitions-content-tides-and-currents. The LLWLT and HHWLT are provided for each TG and SCH site relative to the known datum/reference levels:

- North American Datum of 1983 (Canadian Spatial Referencing System) {NAD83(CSRS)epoch 2010},

- Canadian Geodetic Vertical Datum of 1928 (CGVD28),
- Canadian Gravimetric Geoid model of 2013 (CGG2013).

Values relative to these references are provided using the following terminology, for example MWL_CGVD28, defining the height of MWL with respect to CGVD28. Positive values indicate that MWL is above CGVD28.

In the absence of additional tidal effects it may be assumed that all water level targets evolve vertically with relative sea level rise. Water level targets on the CAN-EWLAT site at TG stations are derived from observations. Targets at SCH sites are determined using a combination of both water level observations and modeled tides between observation sites. Potential average inaccuracies for both TG and SCH site water level target estimates can be approximately +/- 10 to 20 cm. However, inaccuracies may be larger for areas with limited observations, or where tidal behavior is either changing over time or has not been appropriately estimated by the modeling methods employed.

2.4 Wave climate

With warming air temperatures projected over the coming century, possibly the largest change in wave climate in Atlantic Canada will result from changes in sea ice in coastal areas. For example, if the Gulf of St. Lawrence has significantly less sea ice in the future, the winter wave climate would be significantly different than at present where the waves are small, or non-existent, in the winter. In this case, waves could significantly impact coastal erosion, infrastructure, and winter marine activities. CAN-EWLAT provides estimates of the projected changes in summer and winter wave climate in Atlantic Canada (Wang et al., 2018). CAN-EWLAT provides wave estimates from the model grid point closest to the SCH facility, and this can be as much as 10 km offshore. These estimates are provided for the historical and future summer periods (CurWaveSummer [1970-1999], ProjectedWaveSum [2040-2069]), and the historical and future winter periods (CurWaveWinter [1970-1999], ProjectedWaveWin [2040-2069]).

3 Results

The allowances for the RCP scenarios show significant spatial variation (Figures 1-3). It should be noted that we are only able to estimate allowances in locations where we either have historical tide gauge data or storm surge model results; therefore, we are not able to compute vertical allowances for much of the Arctic region of Canada.

The highest allowances occurs in southern Atlantic Canada, where the land is sinking due to GIA. The negative allowance along the coast of Hudson Bay is caused by the rapid land uplift due to GIA. The allowance along the Pacific coast is lower than that on the east coast. For the period up to 2050, the allowance at a specific location is similar for the RCP2.6 (low), RCP4.5 (medium) and RCP8.5 (high) scenarios, which provides a robust basis for short-term adaptation planning. Beyond 2050, the difference in the allowance increases substantially between RCP2.6 and RCP8.5 and the adaptation depends on the risk tolerance of stakeholders. Similar conclusions can be drawn for the allowances based on the updated AR6 projections (Figures 4-6), where the sea level rise and allowances are slightly increased relative to AR5.

4 Conclusion

Vertical allowance is one tool that coastal engineers can use to incorporate sea level rise into their planning. It takes into account future mean sea level projections and associated uncertainties, and the statistics of storm tides. By definition, any coastal infrastructure raised by this allowance would experience the same frequency of flooding event under sea-level rise as it would without the allowance and without sea-level rise (Hunter, 2012). However, the following limitations should be recognized:

- The allowance only covers part of the coastline, and does not cover river estuaries where freshwater discharge is more important. In the Arctic north of 70°N, the vertical allowances cannot be computed since there is no storm surge model available.
- The allowance depends on the level of risk you assume. If there is a critical infrastructure, such as power plant or hospitals, you may need to choose an allowance based on the high end sea level scenario (Fox-Kemper et al., 2021).
- The allowance depends on the shape of the distribution of the uncertainty of the sea level projections.
- The allowance assumes the statistics of storm tides will not change in time. This is supported by the fact that the sea level rise is the primary driver of changes in extreme water levels.
- The allowance includes no contribution due to possible changes in wave setup and runup.
- The allowance includes no contribution due to changes in tides caused by sea level rise.

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Glossary of Terms:

AR5	The Fifth Assessment Report of the IPCC
AR6	The Sixth Assessment Report of the IPCC
CurWaveSummer	Maximum wave height during the summer in the current climate
CurWaveWinter	Maximum wave height during the winter in the current climate
DFO	Department of Fisheries and Oceans
GIA	Glacial Isostatic Adjustment is caused by the rebound of the Earth from the several kilometer thick ice sheets that covered much of North America and Europe around 20,000 years ago. Mantle material is still moving from under the oceans into previously glaciated regions on land.
GPS	Global Positioning System. In the CAN-EWLAT application, GPS is used to measure the vertical movement (up/down in millimetres per year) of the Earth's crust over time.
IPCC	The Intergovernmental Panel on Climate Change
MRSL projections	Relative sea level (RSL) is defined as sea level measured with respect to land. Mean RSL is defined as RSL at a given location averaged over a period of one year. A projection is a potential future evolution of a quantity or set of quantities, often computed with the aid of a model. Unlike predictions, projections are conditional on assumptions concerning, for example, future socioeconomic and technological developments that may or may not be realized.
ProjectedWaveSum	Maximum wave height during the summer in the projected future climate
ProjectedWaveWin	Maximum wave height during the winter in the projected future climate
RCPs	Representative Concentration Pathways. RCPs are concentration pathways used in the IPCC AR5. They are prescribed pathways for greenhouse gas and aerosol concentrations, together with land use change, that are consistent with a set of broad climate outcomes used by the climate modelling community. The pathways are characterized by the radiative forcing produced by the end of the 21st century. Radiative forcing is the extra heat the lower atmosphere will retain as a result of additional greenhouse gases, measured in Watts per square metre (W/m^2). Four RCPs scenarios have been designed for the AR5 and in CAN-EWLAT we are using three of these, RCP 2.6 (low), RCP 4.5 (intermediate) and RCP 8.5 (high). The RCPs were labelled by the approximate radiative forcing reached at the year 2100, going from 2.6, 4.5, to 8.5 W m^{-2}. For more details, please refer to the AR5 report directly.

SCH	Small Craft Harbours, a sector of the federal Department of Fisheries and Oceans.
SSPs	Shared Socioeconomic Pathways (SSPs) are scenarios of projected socioeconomic global changes up to 2100. They are used to derive greenhouse gas emissions scenarios with different climate policies, and serve as the basis for IPCC AR6. In the SSP labels, the first number refers to the assumed shared socio-economic pathway, and the second refers to the approximate global effective radiative forcing in 2100.
Storm Surge	The positive or negative difference in sea level from the predicted astronomical tide, due to the forces of the atmosphere. The two main atmospheric components that contribute to storm surge are air pressure and wind. Deep low-pressure systems can create a dome of water under the storm (much like the low pressure under a vacuum on a carpet). High winds along a coastline can also elevate the water levels at the shore, depending on the direction of the wind with respect to the coast. For powerful storms like hurricanes, the abnormally high water levels are due mostly to the high winds and high waves at the coast.
Storm Tide	The combined effect of storm surge and tides.
Tide	The rise and fall of sea levels caused by the combined effects of the gravitational forces exerted by the Moon and the Sun and the rotation of the Earth.
TG	Tide Gauges are installed by the Canadian Hydrographic Service to collect water levels against a vertical reference.
Vertical Allowance	Vertical distance that coastal infrastructure (I.E. a building or Wharf) needs to be raised under a rising sea level so that the present likelihood of flooding does not increase. In other words, any asset raised by this allowance would experience the same frequency of flooding events under sea level rise as it would without the allowance and without sea level rise. It is important to note that the allowances only relate to inundation, and not erosion of soft shorelines, or impacts associated with this erosion.
Wave Climate	In CAN-EWLAT, this is defined as the monthly average wave height for a specified time period.

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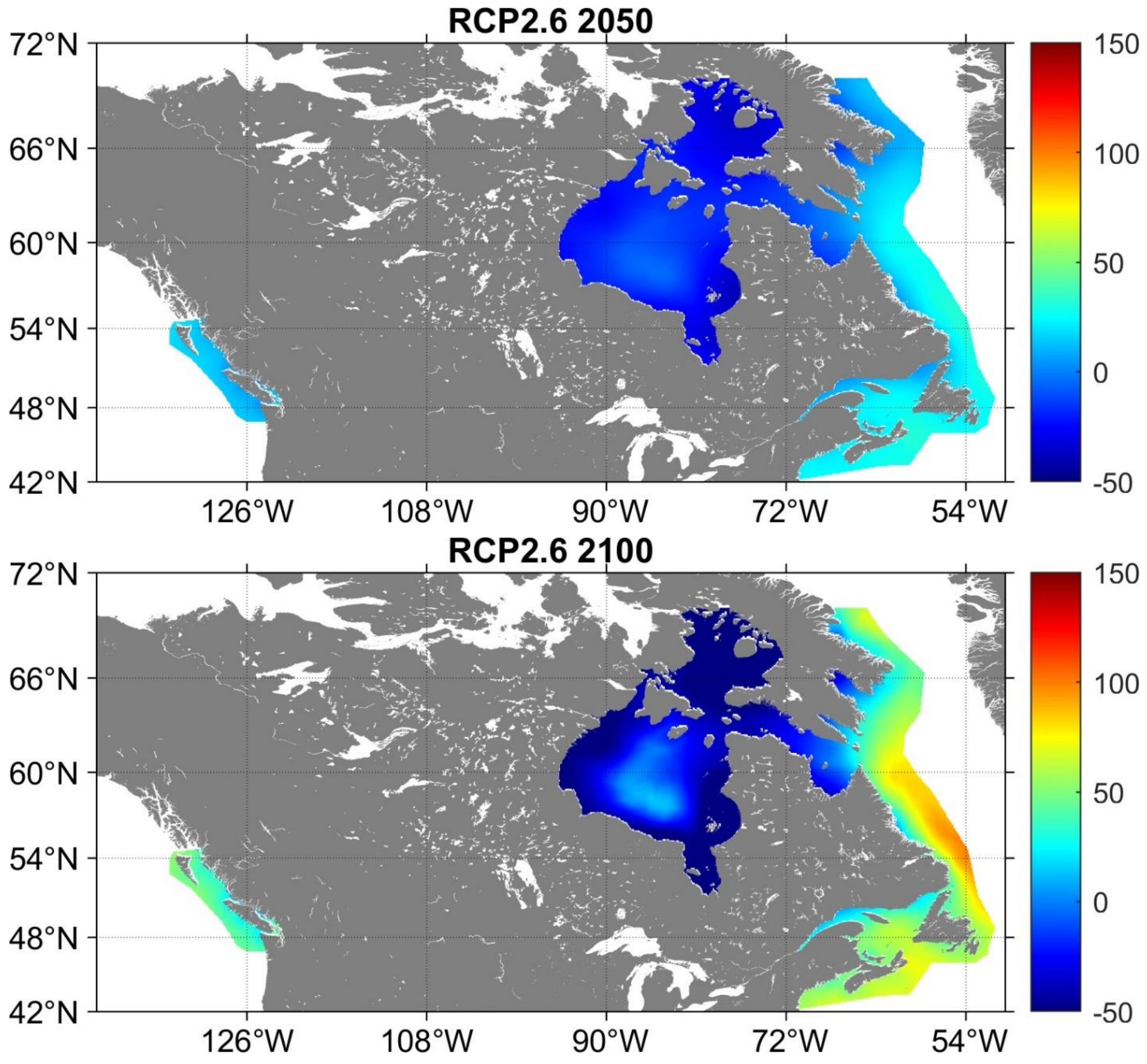

RCP2.6 2050

RCP2.6 2100

Figure 1: Vertical allowance in cm for RCP2.6 scenario in 2050 (top) and 2100 (bottom) referenced to the year 2010.

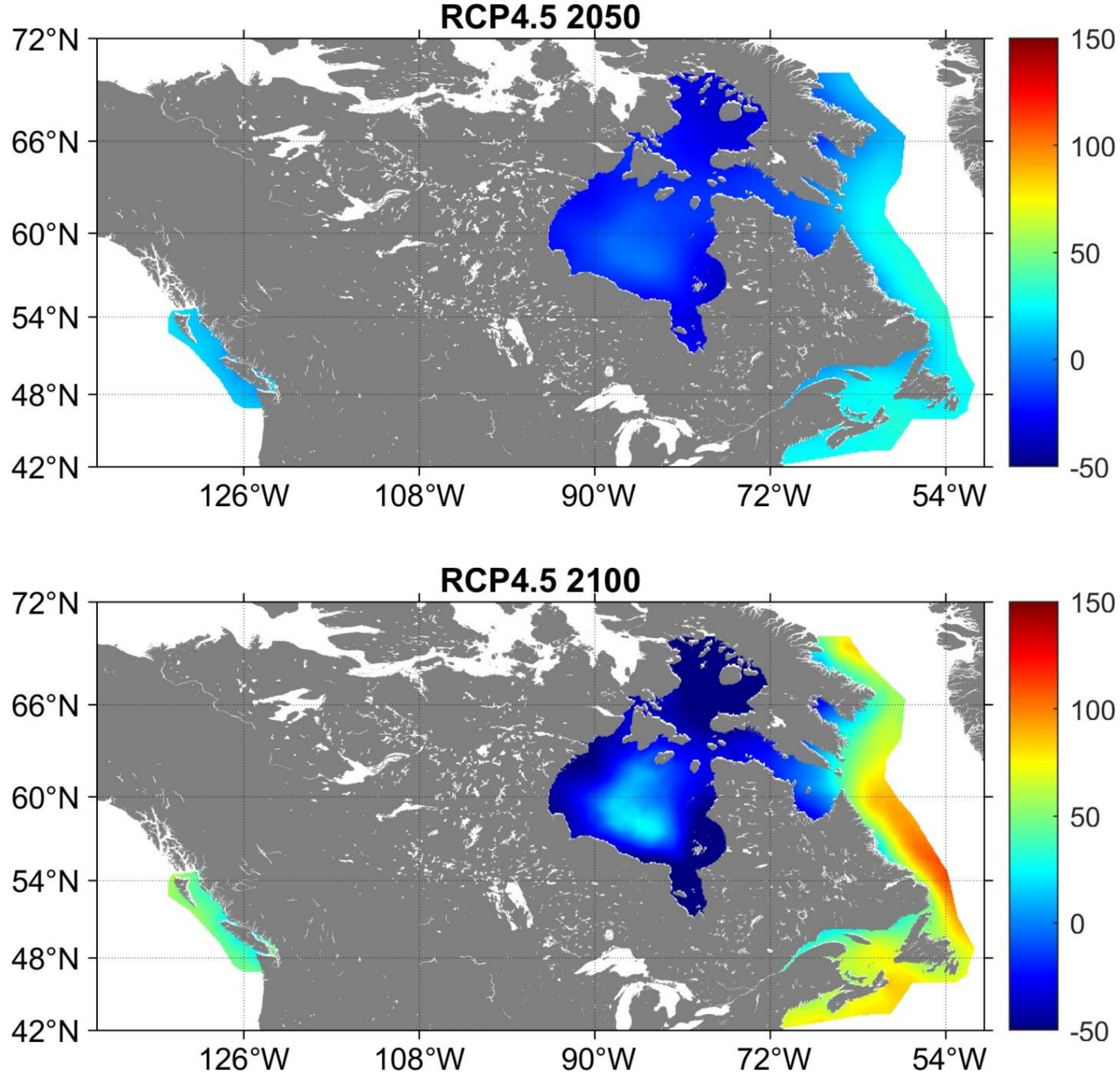

Figure 2: Vertical allowance in cm for RCP4.5 scenario in 2050 (top) and 2100 (bottom) referenced to the year 2010.

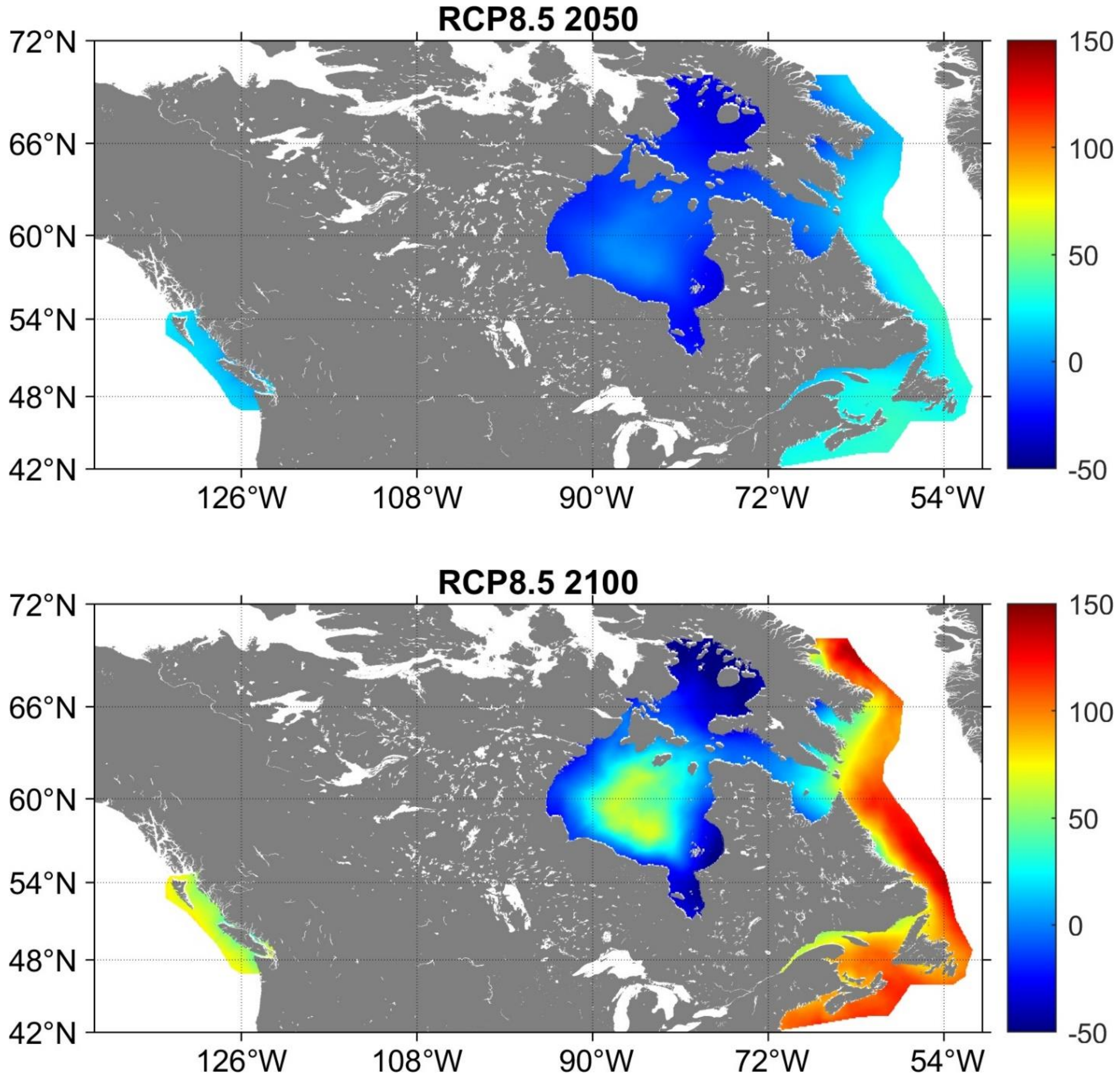

Figure 3: Vertical allowance in cm for RCP8.5 scenario in 2050 (top) and 2100 (bottom) referenced to the year 2010.

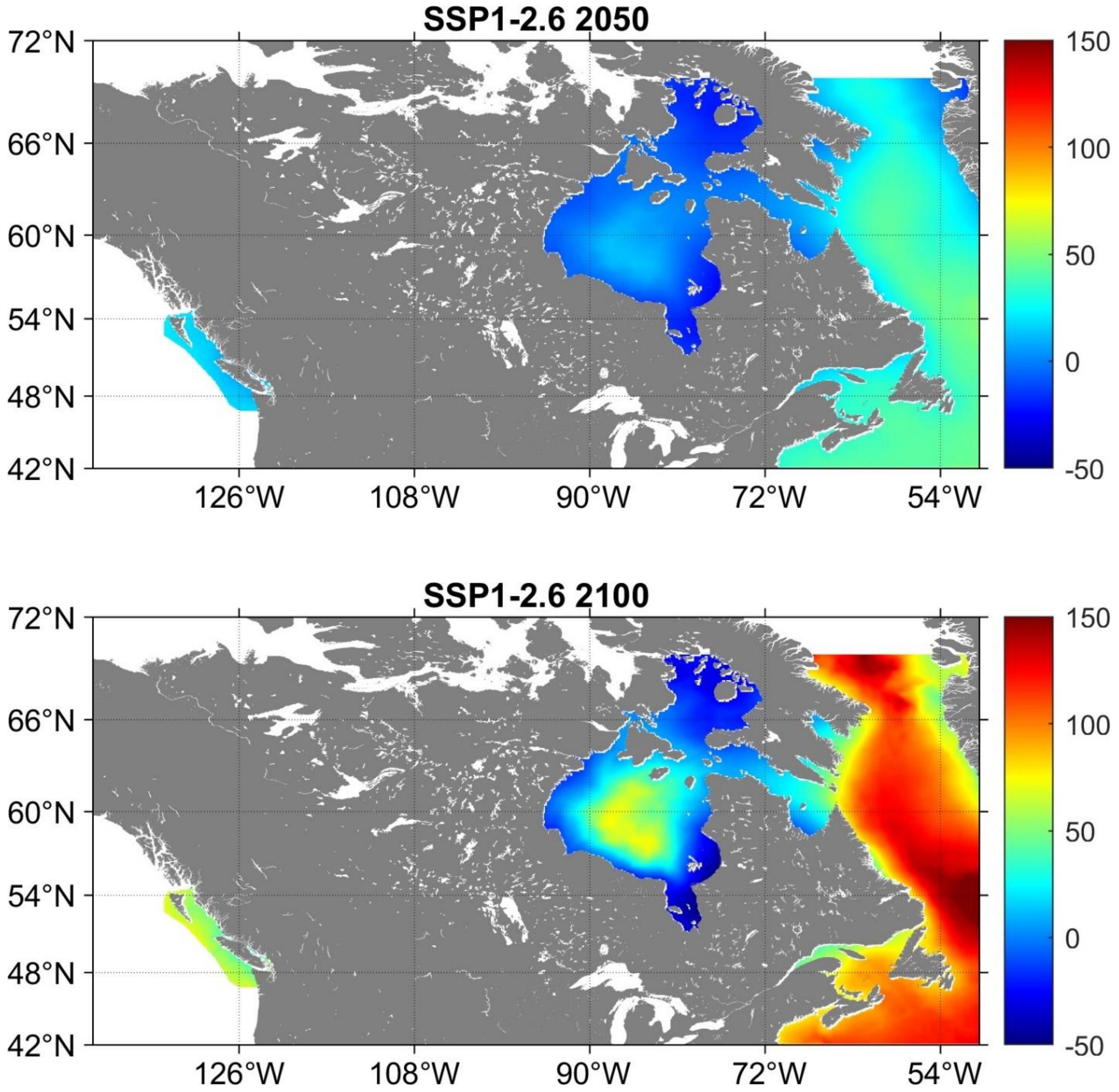

Figure 4: Vertical allowance in cm for SSP1-2.6 scenario in 2050 (top) and 2100 (bottom) referenced to the year 2010.

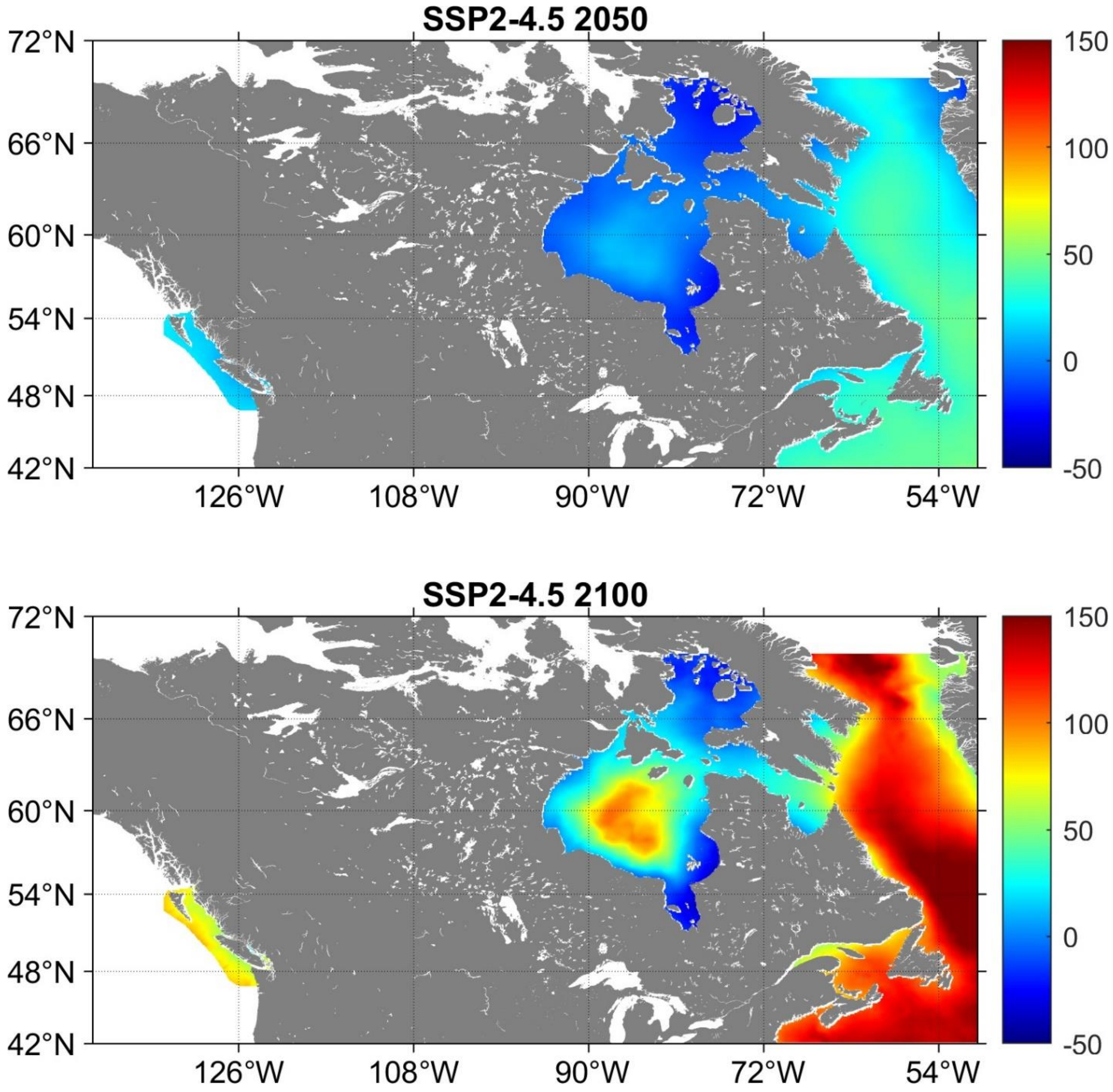

Figure 5: Vertical allowance in cm for SSP2-4.5 scenario in 2050 (top) and 2100 (bottom) referenced to the year 2010.

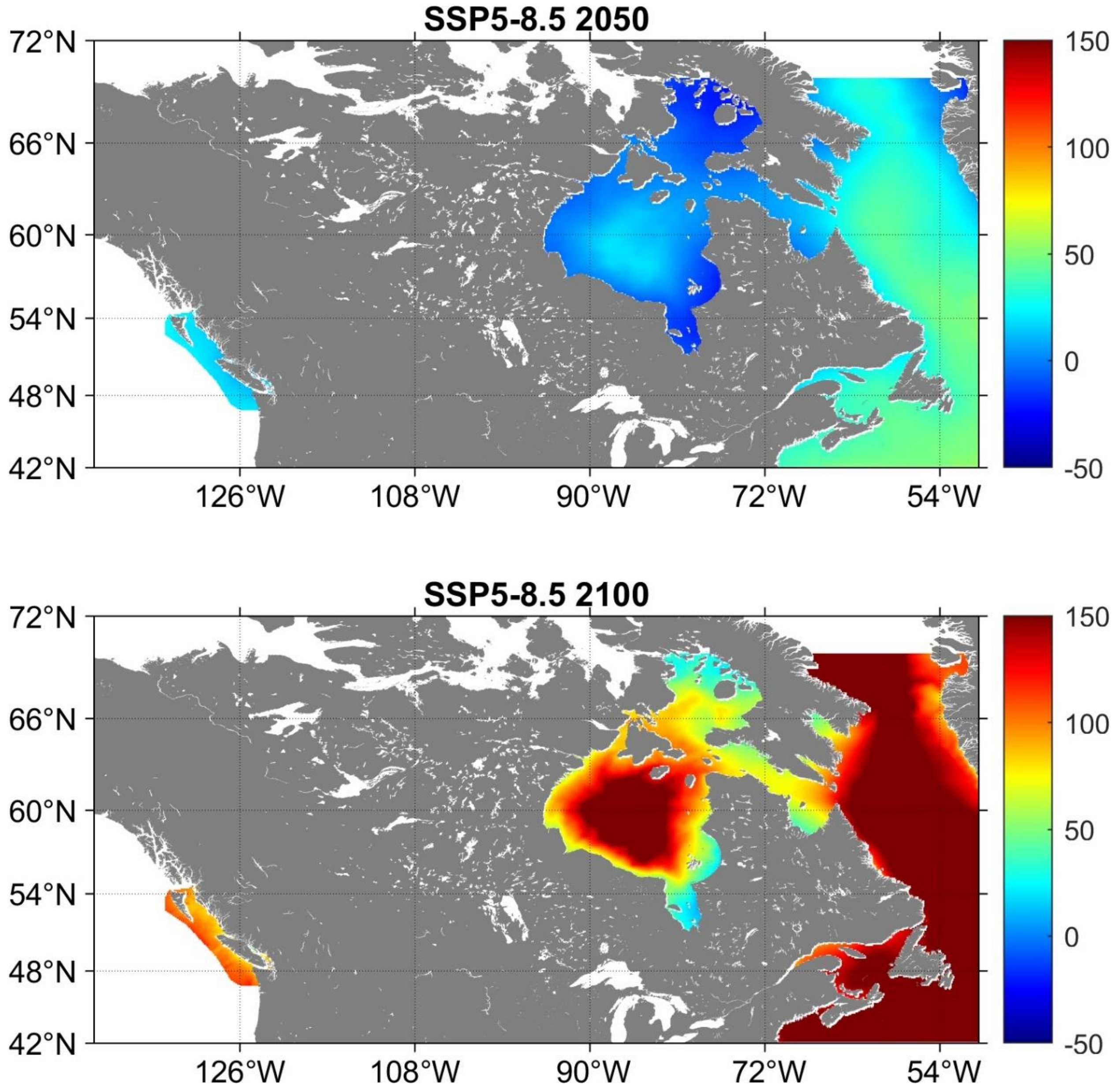

Figure 6: Vertical allowance in cm for SSP5-8.5 scenario in 2050 (top) and 2100 (bottom) referenced to the year 2010.