UNIVERSITÉ DU QUÉBEC À TROIS-RIVIÈRES

COMPARAISON DE LA PERFORMANCE DE MODÈLES EMPIRIQUES DE BILAN DE MASSE GLACIOLOGIQUE DANS UN CONTEXTE DE CHANGEMENT CLIMATIQUE : APPLICATION AU GLACIER SASKATCHEWAN, CANADA

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CHAPITRE 1

Introduction

1.1 Mise en contexte

Le volume des glaciers à travers le monde est en diminution depuis le début du 20e siècle, avec des taux de fonte qui ont été plus rapides dans les dernières décennies et en milieu alpin (Huss *et al.*, 2017). Les prédictions indiquent que ces taux de fonte continueront à augmenter dans les décennies à venir (IPCC, 2021). En ce qui concerne les glaciers de l'ouest canadien, les prévisions de pertes de masse glaciaire en fonction du changement climatique varient peu selon les auteurs. Effectivement, Clarke *et al.* (2015) prédisent une diminution de volume moyenne de 70% entre 2005 et 2100; et Huss *et al.* (2017) prédisent une perte de volume d'environ 65%. Dans toutes les études, les prévisions indiquent que les glaciers des Rocheuses canadiennes subiraient d'importantes pertes de volume avant la fin du 21e siècle (IPCC, 2021). De plus, dans l'Ouest canadien, les glaciers des Rocheuses seraient plus sensibles au changement climatique que ceux de la chaîne côtière (Clarke *et al.*, 2015).

Ce retrait glaciaire généralisé a différents impacts sur l'environnement et sur les populations humaines à travers le monde. Durant le siècle dernier, les glaciers qui ne sont pas des inlandsis (c'est-à-dire en excluant le Groenland et l'Antarctique), ont fortement contribué à la hausse du niveau moyen de la mer (Zemp *et al.*, 2019). Ceux-ci auraient causé une augmentation de 3.7 [3.2 à 4.2] mm par année entre 2006 et 2018 (IPCC, 2021). Il est également estimé que leur fonte continuera d'avoir un impact important sur le rehaussement du niveau marin global durant le 21e siècle (Edwards, *et al.*, 2021; IPCC, 2021; Radic et Hock, 2011). D'autre part, plusieurs régions à travers le monde dépendent des glaciers pour leur approvisionnement en eau potable. La présence de glace permanente dans un bassin versant a un effet régulateur sur le débit (Fountain et Tangborn, 1985). Lors des saisons sèches, l'eau de fonte provenant de l'amont du bassin versant continue d'alimenter le cours d'eau et assure un certain débit de base, permettant ainsi aux populations en aval d'être approvisionnées en eau tout au long de l'année. Cette régulation du débit est également primordiale pour la gestion des pics de crue et pour la production d’hydroélectricité (IPCC, 2021; Jansson *et al.*, 2003; Huss *et al.*, 2017; Huss et Hock, 2018).

Malgré le fait que le Canada soit le 5^{e} pays ayant la plus grande quantité d’eau par habitant, les provinces des prairies sont situées dans la plus grande zone sèche du pays et sont particulièrement vulnérables au changement climatique. En effet, le bilan hydrique de ce secteur est fréquemment en déficit, ce qui signifie qu’il y a en moyenne davantage d’évapotranspiration que de précipitations (Schindler et Donahue, 2006). Une grande part de ce territoire est alimentée en eau par les rivières provenant des Rocheuses, dont plusieurs sont approvisionnées, entre autres choses, par la fonte de la neige et des glaciers (Schindler et Donahue, 2006; Jansson et al., 2003; Huss et al., 2017; Huss et Hock, 2018). Les prévisions indiquent que la fonte des glaciers des Rocheuses canadiennes causera une modification des pics de crues de la rivière Saskatchewan Nord et Sud, et à plus long terme, une diminution du débit total annuel. Cela aura un impact sur l’utilisation de l’eau sur le territoire, surtout en ce qui concerne les industries et l’agriculture (Comeau *et al.*, 2009; Schindler et Donahue, 2006).

En plus des impacts directs du changement climatique sur la cryosphère en milieu alpin (évolution du bilan de masse des glaciers, modification du débit des cours d’eau, changement de la saison de fonte), il y a également de nombreuses conséquences indirectes reliées à la fonte des glaciers. La modification de la saison de fonte augmente le transport de sédiments dans les cours d’eau (Huss *et al.*, 2017). La modification du cycle hydrologique des cours d’eau entraine un changement des pics de crue et augmente le risque d’occurrence d’évènements hydrologiques extrêmes tels que les inondations, les coulées de débris, les inondations dues au bris des barrages de lacs morainiques et les sècheresses (Moore *et al*., 2009). Ces évènements extrêmes modifient la disponibilité en eau pour la consommation d’eau potable, l’agriculture et l’industrie, créent des changements dans les systèmes écologiques, causent une perte de la valeur économique et touristique du territoire et font diminuer la biodiversité dans les cours d’eau (Huss, *et al.*, 2017). La diminution du volume des glaciers en amont des bassins versants des rivières de l’Ouest canadien fera augmenter le débit hivernal et diminuer le débit estival (Moore *et al.*, 2009). Cela fait en sorte que la température moyenne de l’eau va augmenter, ce qui peut être dangereux, voir mortel, pour certaines espèces de salmonidés dans la région (Grah et Beaulieu, 2013).

Pour réduire l'impact de la fonte des glaciers sur les écosystèmes et les services écosystémiques rendus à la population, il est important de connaître la sensibilité des glaciers au changement climatique. Cela permet de mieux prédire la hausse du niveau moyen de la mer, ainsi que de faire une gestion adéquate de la ressource en eau sur le territoire (Anderson *et al.*, 2010; Meier *et al.*, 2007). Pour ce faire, il est d'abord important de connaître quels sont les changements que subiront le bassin versant, et donc, d'avoir des projections d'évolution du volume des glaciers qui sont les plus précises et exactes possibles (Huss *et al.*, 2014).

1.2 Problématique

Afin de faire des projections de fonte des glaciers, des modèles de différents niveaux de complexité peuvent être utilisés (Marzeion *et al.*, 2020). Ceux-ci tentent de reproduire l'évolution du bilan de masse, qui représente les gains ou les pertes de volume d'un glacier sur une période de temps (Marzeion *et al.*, 2020). Il existe deux catégories de modèles d'évaluation du bilan de masse glaciologique, soit les modèles physiques et empiriques. Avec de nombreuses données météorologiques, les modèles physiques quantifient le taux de fonte d'un glacier en calculant son bilan d'énergie, c'est-à-dire tous les flux d'énergie entrant et sortant de la surface. Les modèles empiriques quant à eux définissent le bilan de masse d'un glacier en assumant une relation directe entre le taux de fonte et la température de l'air (Hock, 2003). Il existe plusieurs modèles intermédiaires qui ajoutent une ou plusieurs variables aux modèles empiriques pour tenter de les rendre plus précis et physiquement plus réalistes (Pellicciotti *et al.*, 2005; Pellicciotti *et al.*, 2008). Les modèles empiriques sont souvent utilisés pour faire des projections de fonte à l'échelle locale, régionale et globale pour plusieurs raisons. En effet, ils ont seulement besoin de la température de l'air et des précipitations comme donnée météorologique entrante, qui sont des variables plus fréquemment disponibles. De plus, la prévision et l'interpolation de la température de l'air en climat futur est relativement facile si on compare avec d'autres variables météorologiques, telles que la vitesse du vent. Enfin, ces modèles sont simples à utiliser et leur performance est généralement bonne (Gabbi *et al.*, 2017; Hock, 2003; Ohmura, 2001). Toutefois, les modèles empiriques ont des désavantages dont il est important de tenir compte. Ceux-ci sont habituellement efficaces pour faire des projections à court terme, mais ils le sont beaucoup moins pour le long terme. En effet, ils perdent de la précision lorsque les paramètres sont extrapolés en dehors des conditions climatiques de calibration (Carenzo *et al.*, 2009). À l'opposé, les modèles physiques sont beaucoup plus efficaces pour faire des prévisions d'évolution du bilan de masse à long terme puisqu'ils représentent beaucoup mieux la réalité physique du terrain (Carenzo, 2012; Réveillet *et al.*, 2018). Toutefois, ils sont beaucoup plus complexes à utiliser et ils nécessitent beaucoup de données météorologiques, qui ne sont pas toujours disponibles (Carenzo *et al.*, 2009; Pellicciotti *et al.*, 2008). C'est pourquoi les modèles empiriques sont, malgré tout, souvent utilisés pour la projection des impacts du changement climatique sur le bilan de masse des glaciers à des échelles locales, régionales et continentales. Il est donc important de tester la capacité de ces modèles empiriques à projeter le bilan de masse en climat futur pour avoir des estimations adéquates du taux de fonte des glaciers et assurer une meilleure gestion de la ressource en eau (Carenzo *et al.*, 2009).

Ce projet vise à évaluer la performance de différents modèles empiriques de bilan de masse afin de tester leur capacité à représenter l'impact du changement climatique sur le bilan de masse du glacier Saskatchewan dans les Rocheuses canadiennes. Plusieurs travaux comparant différents modèles de bilan de masse ont déjà été réalisés sur de nombreux glaciers à travers le monde. Ces études comparent les résultats des modèles avec des observations mesurées sur le terrain et assument que les modèles reproduisant le mieux les observations du passé seront les meilleurs pour estimer le bilan de masse futur de ce même glacier (Gabbi *et al.*, 2017; Réveillet *et al.*, 2018). Toutefois, en raison du changement climatique, les conditions dans lesquelles ces modèles ont été calibrés ne seront plus les mêmes dans les prochaines décennies. Ces conclusions peuvent donc être erronées puisque, les modèles empiriques sont moins performants lorsqu'ils sont utilisés hors de leurs conditions de calibration (Carenzo et al., 2009). Cette étude a comme objectif de comparer les performances de cinq modèles empiriques dans des conditions de changement climatique. Pour ce faire, les résultats des modèles empiriques sont comparés aux résultats du modèle physique de Hock et Holmgren (2005) modifié par Kinnard et al. (2022) pour le glacier Saskatchewan. Étant donné que ce modèle est ancré dans la physique des processus glaciologiques, il est considéré comme apte à simuler l'évolution du bilan de masse en climat futur. C'est pourquoi dans cette étude, les projections de ce modèle sont considérées comme étant les 'valeurs réelles' de bilan de masse du glacier Saskatchewan dans différents scénarios de changement climatique. Cela permet d'évaluer directement la capacité de prévision à long terme des modèles empiriques de bilan de masse en climat futur. Trois méthodes de calibration sont utilisées afin de mieux connaître l'impact du choix de la méthode de calibration sur les projections des modèles. Selon nos lectures, l'impact de la méthode de calibration sur la performance des modèles et sur leur capacité à être transférés dans différentes conditions climatiques n'a pas encore été étudié dans le domaine de la glaciologie. Trois méthodes de calibration seront testées sur les cinq modèles empiriques étudiés. La première est la méthode « géodésique », qui représente les études utilisant des modèles d'élévation numérique afin de faire le suivi de l'évolution de la surface des glaciers afin d'en faire le bilan de masse (Berthier & Brun, 2019; Denzinger et al., 2021; Mingyang et al., 2019). La deuxième est la méthode « glaciologique » qui reproduit les mesures de bilan de masse à l'aide d'un réseau de balises (Gabbi et al., 2014; Hock, 2005; Hock et Radic, 2007; Huss et al., 2014). Dans ce cas-ci, les balises sont représentées par des pixels du modèle d'élévation numérique qui sont situés au même endroit que les balises utilisées pour le suivi du glacier Saskatchewan. La dernière est la méthode « spatiale » qui fait une discrimination spatiale des valeurs de bilan de masse en comparant les balises individuellement. Cette méthode vise à inclure la variabilité spatiale du bilan de masse dans la calibration des modèles. Les projections faites avec les modèles empiriques calibrés sont ensuite validées avec différents scénarios climatiques. Il sera donc possible d'observer comment la corrélation entre les résultats des modèles empiriques et du modèle physique évolue lorsque les conditions de précipitations et de température changent.

1.3 Objectifs

L'objectif principal de cette étude est d'évaluer la capacité des modèles empiriques à reproduire le bilan de masse du glacier Saskatchewan en contexte de changement climatique, tel que simulé par un modèle physique. Afin d'atteindre cet objectif, les objectifs spécifiques suivant doivent être étudiés et réalisés :

1) Le premier objectif spécifique de cette étude est d'évaluer la capacité des modèles empiriques à reproduire le bilan de masse du glacier Saskatchewan en contexte de changement climatique, tel que simulé par un modèle physique. Cet objectif permet de répondre à la question suivante : Quel modèle empirique permet de mieux simuler le bilan de masse du glacier Saskatchewan en climat futur? L'hypothèse est qu'un modèle empirique incluant l'albédo de la surface et le rayonnement solaire net comme prédicteur (Pellicciotti *et al.*, 2005), sera le plus performant pour prévoir les effets du changement climatique sur le bilan de masse du glacier Saskatchewan. En effet, selon Pellicciotti *et al.* (2005), celui-ci serait le plus adapté à prédire les impacts du changement climatique sur les taux de fonte des glaciers. De plus, il serait particulièrement efficace pour simuler les taux de fonte dans les zones d'ablation, où les valeurs d'albédo changent beaucoup. Carenzo *et al.* (2009) affirment même que le modèle ETI serait plus apte à faire des prévisions de bilan de masse en fonction du changement climatique que les modèles physiques parce qu'il utilise moins de variables météorologiques, donc il a une moins grande incertitude par rapport à l'évolution de ces variables. Enfin, ce modèle a été identifié comme étant le plus performant entre les différents modèles empiriques à la fois dans les Alpes (Gabbi *et al.*, 2014) et dans les Andes chiliennes (Pellicciotti *et al.*, 2008), qui ont des climats très différents
2) Le second objectif spécifique est de définir l'impact du choix de la méthode de calibration sur les valeurs optimales des paramètres des modèles, donc sur les projections de bilan de masse en contexte de changement climatique. Trois méthodes de calibration sont proposées : (i) la calibration sur le bilan de masse moyen, calculé à partir de toute la surface du glacier; (ii) la calibration sur le bilan de masse moyen, estimé à partir des valeurs ponctuelles simulées à un réseau de balises; (iii) la calibration sur le bilan ponctuel simulé aux balises (calibration spatiale). Cet objectif permet de répondre à la question suivante : Quelle méthode de calibration est la plus efficace et permet de mieux filtrer les

meilleures combinaisons de paramètres pour les différents modèles? Notre hypothèse est que la méthode utilisant les valeurs de bilan de masse aux balises serait la plus efficace, car les simulations reproduiraient moins fréquemment les résultats de plusieurs valeurs de bilan de masses distinctes (pour chaque balise), plutôt qu'une seule valeur moyenne.

CHAPITRE 2

Comparison of mass balance temperature-index models performance in climate change conditions: application on Saskatchewan Glacier, Alberta, Canada

2.1. Abstract

2.1.1 Abstract

In the last decades, glaciers worldwide have been losing mass, and this process is going to accelerate according to projections. Studies compared the performances of temperature-index models by comparing their simulations with mass balance historical data. They observe that performances diminish when the climate conditions are different than the ones during calibration period, but still concluding that models which better represent past mass balance will better represent future mass balance. Predictions for the evolution of glaciers in the future are based on these assumptions. This study aims to validate five temperature-index models performances in future climate change conditions and to analyse how different calibration methods affects the performances of the temperature-index models. This is achieved by comparing projections from temperature-index models with the ones from a physically based model produced by Kinnard et al. (2022) in a calibration period and in 81 climate change scenarios. We observed that temperature-index models are very sensible to air temperature changes and that precipitation rates changes have very small impact on their performances. We observed that a spatially discriminating calibration method brings the models to have better results in climate change scenarios and to have a bigger uncertainty due to a larger equifinality. Calibration methods based on total mass balance and on mean mass balance of the stakes have very similar performances and give closer results to the physical model in calibration scenario compared to spatially discriminations methods. Impacts of calibration methods on temperature-index models performances should be further studied on glaciers in different climate and topographic contexts to confirm these conclusions.

Keywords: Mass balance, Saskatchewan glacier, Temperature-index models, Calibration, Climate change

2.1.2 Résumé

Durant les dernières décennies, le volume des glaciers est en diminution à travers le monde et cela continuera en accélérant dans les prochaines années selon les projections faites par des modèles. Plusieurs études ont fait la comparaison de la performance des modèles empiriques de bilan de masse glaciologique en comparant leurs simulations avec des données historiques et mentionnent que leur performance diminue en dehors des conditions climatiques de calibration, sans toutefois valider leurs résultats dans un contexte de changements climatiques futurs. L'objectif de cette étude est de valider la performance de cinq modèles empiriques dans différents scénarios climatiques en comparant leurs simulations avec les résultats d'un modèle physique produits par Kinnard et al. (2021). Le second objectif est d'étudier l'impact de trois différentes méthodes de calibration sur la performance de ces modèles. Nous avons observé que les modèles empiriques sont très sensibles aux changements de température de l'air et peu sensibles aux changements de taux de précipitations. La méthode 1 (qui compare le bilan de masse total de la surface du glacier) et la méthode 2 (qui compare les moyennes du bilan de masse aux balises) obtiennent des résultats similaires et ont des résultats plus près du modèle physique dans le scénario de calibration. La méthode de calibration 3, faisant une discrimination spatiale du bilan de masse, a de moins bons résultats en période de calibration mais permet de mieux représenter l'évolution du glacier dans le scénario de changement climatique le plus probable. De plus, cette méthode donne une plus grande incertitude aux prédictions des modèles, qui est due à une plus grande équifinalité des valeurs de coefficients.

Mots-clés : Bilan de masse glaciologique, modèles empiriques, calibration, changement climatique, Glacier Saskatchewan

2.2 Introduction

Modelling is essential to study changes in the cryosphere around the world. Glacier melt impact sea level (Zemp *et al.*, 2019), water availability in watersheds (IPCC, 2021; Huss & Hock, 2018), changes in the occurrence of floods, droughts, debris flows (Moore *et al.*, 2009), biodiversity (Huss *et al.*, 2017) and other things that can affect greatly the ecosystems and worldwide populations. Different types of models are used to make projections of the evolutions of glaciers (Marzeion *et al.*, 2020). These models calculate glacier ablation and accumulation to estimate glacier mass balance, i.e., the net gain or loss of mass over a period, usually a hydrological year (Oct 1 – Sept 30 in the northern hemisphere). Physically based models calculate the energy balance of the surface (Hock, 2005). They have proven to be very efficient to make long term mass balance projections (Carenzo, 2012; Réveillet *et al.*, 2018), but they require many meteorological forcing data (e.g., short and long waves radiation) and prescribing or parameterizing dynamic surface condition data (e.g., surface aerodynamic roughness and albedo) that are not always available or easy to quantify accurately (Carenzo *et al.*, 2009; Johnson & Rupper, 2020; Pellicciotti *et al.*, 2008). Because of this, temperature-index models are used more often to make local (Heynen *et al.*, 2013; Pellicciotti *et al.*, 2005), regional (Réveillet *et al.*, 2018; Shea *et al.*, 2009), and global (Hirabayashi et al., 2013; Huss & Hock, 2015) glacier mass balance projections. These models assume a direct relation between air temperature and melt. They require limited meteorological data, i.e., air temperature, precipitation, and sometimes global radiation, and their performance is generally good for short term projections (Braithwaite, 1981; Gabbi *et al.*, 2014; Hock, 2003; Ohmura, 2001). However, they do not perform as well for long term projections because their performance can decrease outside of the climate conditions in which they were calibrated (Carenzo *et al.*, 2009; Réveillet et al., 2017; Wheler *et al.*, 2014).

Several studies have compared the performance of different temperature-index models against observed mass balance observations. Gabbi *et al.* (2014) and Réveillet *et al.* (2018) both concluded that more sophisticated models had better performances and had better abilities to reproduce the mass balance evolution of the glaciers. On the other hand, Hock *et al.* (2007) concluded that an increase in model complexity did not improve their performance and that the choice of the model is an important source of uncertainty for mass balance projections. Therefore, it is important to test models with different levels of complexity to test their ability to simulate mass balance evolution of Saskatchewan glacier. It is typically assumed that the models that performed better to recreate past mass balance variations will also perform better in predicting future glacier mass balance (Gabbi *et al*., 2014; Réveillet *et al*., 2018). However, because of climate change, the conditions in which the models are calibrated will not be the same in the next decades. Since model performance can decrease outside of the calibration climate conditions (Carenzo *et al*., 2009; Gabbi *et al*., 2014; Réveillet *et al*., 2018), the assumption that models calibrated under current climate condition transfer well to future climate is questionable. Therefore, we test the ability of the models to be transferred in different climate conditions to see how their performance is affected and how they can be transferred more easily in climate change conditions. Most studies usually calibrate temperature-index models by comparing the simulated and measured mean (or 'specific') surface mass balance of a glacier (e.g. Hock, 2005; Hock et Radic, 2007; Huss *et al.*, 2014). Other studies have compared the simulated and measured mean mass balance using point mass balance measured at stakes (e.g., Gabbi *et al*., 2014; Guömundsson *et al*., 2009). In these studies, they asses the performance of their models by calculating the correlation (Guömundsson *et al*., 2009; Hock *et al*., 2007; Réveillet *et al*., 2018) or the NSE (Gabbi *et al*., 2014) between simulated and measured mass balance. NSE criterion have the advantage of considering correlation, bias and relative variability between projections and measured mass balance data (Nash & Sutcliffe, 1970). The impact of the different calibration methods on the accuracy, incertitude and transferability of the temperature-index models have not yet been investigated.

This study aims to assess the performance of five temperature-index models with different levels of complexity under climate change conditions. To do so, mass-balance projections from five temperature-index models are compared with projections made with the physically-based model from Hock and Holmgren (2005) and Hock and Tijm-Reijmer (2012) and modified by Kinnard *et al.* (2022) for Saskatchewan glacier in the Canadian Rockies. The physical model have been executed with the *Distributed Energy Balance Model* (DEBAM) program made by Hock and Tijm-Reijmer (2012). Because DEBAM rests on physical processes it is considered apt to simulate the long-term evolution of glacier mass balance under changing climate and energy balance regimes. As such, the mass balance outputs from DEBAM are used as pseudo-observations from the virtual world against which the transferability of empirical models into the future can be assessed. These 'virtual world' experiments have been used before in catchment hydrology (e.g., Troin *et al.*, 2016; Troin *et al.*, 2018), but to our knowledge, this is the first known application of this method in glaciology. Three methods of calibration were also tested in this study, to assess their influence on model transferability. One reproducing the geodetic mass balance measurement method, one reproducing the glaciological method and one making a spatial discrimination of mass balance data.

2.3 Study area

Saskatchewan glacier (52,08 ˚N, 117,32 ˚W) is in the Canadian Rockies, Alberta, close to the border of British-Columbia (Fig.1). This valley glacier is the largest outlet of the Columbia Icefield, and also the one that suffered the largest mass loss during the 20th century (Tennant & Menounos, 2013). Its elevation ranges between 2400 and 3400 m (Ednie *et al.*, 2017). The mass balance of Saskatchewan glacier is measured since 2010 by the Geological Survey of Canada with the glaciological method and has varied between -0.84 and -1.22 m w.e. a^{-1} over the period 2014-2016 (Ednie *et al.*, 2017). On the glacier, flow velocities display a strong spatial variability, increasing from zero at the front to a maximum speed of around 110 m per year at the icefall between the head and the tongue of the glacier, approximately 6.5 km from the front (Van Wychen *et al.*, 2018). Saskatchewan glacier is the source of the North Saskatchewan River that is an essential water supply for the ecosystem and for agriculture downstream (Comeau et al., 2009). Saskatchewan river has economic importance in the region because it is part of the *Icefields Parkway*, which is famous for the glacial landscape and visited by approximately 1.2 million persons per year (Parks Canada, 2019).

The glacier has a cold continental climate with dry temperate summers, according to the updated Koppen classification (Peel *et al.*, 2007). However, the presence of the Columbia Icefield creates a micro-climate. The high elevation of the icefield and its cooling effect causes large precipitation amount that mostly fall as snowfall, except in summer

(Tennant & Menounos, 2013). The mean annual precipitation on the Icefield were 1277 mm between 1919 and 2009 (Tennant & Menounos, 2013).

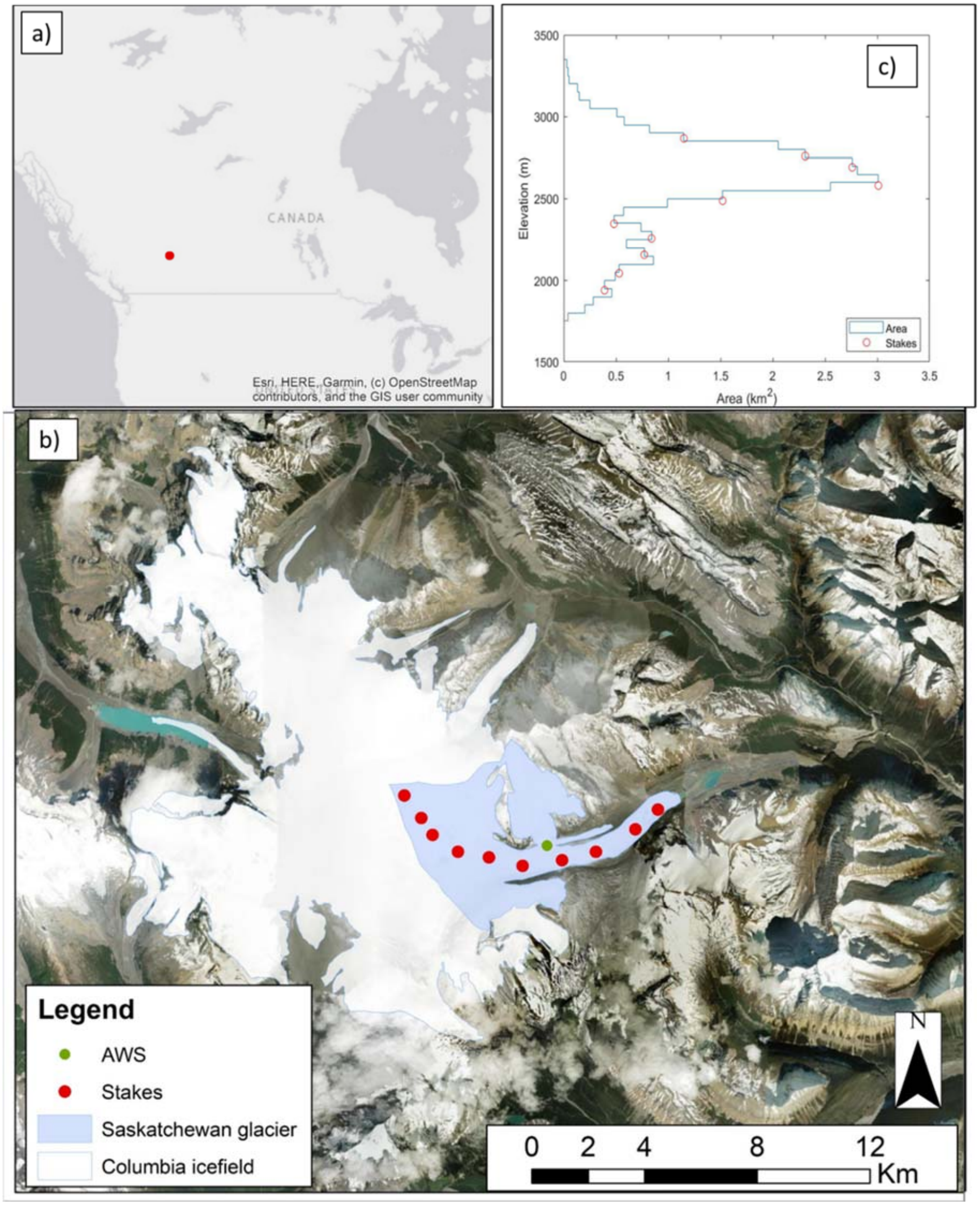


Figure 1. Study area map. (a) Location of the Columbia Icefield. (b) Map of the Saskatchewan Glacier in the Columbia Icefield and location of the ablation stakes in red (cells from Digital Elevation Model (Kinnard *et al*., 2022)). (c) Hypsometry of the glacier; ablation stakes are shown in red.

2.4 Data

The topographic and meteorological data used for this study are the same as those used in the modelling study by Kinnard *et al.* (2022). In this section a brief description of the data processing done by Kinnard *et al.* (2022) is given, and more details on data manipulations and specifications on the physical model are available in their article.

2.4.1 Topographic data

The elevation data from the glacier surface and surrounding environment must be included to apply the mass balance models and represent the meteorological variability and melt variations on the glacier. Two stereoscopic WorldView-2 (WV2) satellite images were acquired on July 31 and September 18, 2010, which respectively cover the bottom and top of Saskatchewan glacier. A digital elevation model (DEM) with a resolution of 1 m has been produced from these images (Kinnard *et al.*, 2022). To include all the topographic features that could cast shade on the glacier surface, the DEM has been extended with the *Canadian Digital Surface Model* (CDSM), that has a spatial resolution of 20 m. The merged DEM was then resampled to a 100 m spatial resolution to speed up calculations with the mass balance models (Kinnard *et al.*, 2022). The outline of Saskatchewan glacier is based on that delimited in 2009 by Tennant and Menounos (2013). The firn zone was delimited from 18 cloud-free Landsat images, all taken around the end of the hydrological season (September 30) between 1986 and 2013 (Kinnard *et al.*, 2022). The slope, direction and aspect of the glacier surface were derived from the DEM to be used within the mass balance models. Mass balance observations at ablations stakes from the observational network (Ednie et al., 2017) were used by Kinnard et al. (2022) to validate DEBAM; the same stake locations (Fig.1.b) were used as ‘virtual stakes’ in this study to calibrate the empirical models against DEBAM pseudo stake observations (see further details on calibration methods).

2.4.2 Meteorological data

The meteorological data needed to run the five temperature-index models used in this study are air temperature, precipitation, and global radiation. The same data used to drive the DEBAM model by Kinnard et al (2022) was used for the temperature-index models and are summarized here.

An automatic weather station (AWS) was operated on the central moraine of Saskatchewan glacier between august 2014 and June 2016, where air temperature and global radiation were recorded. Data gaps occurred in June 2015 due station malfunction. Air temperature *HOBO*™ sensors were installed on five stakes on Saskatchewan glacier, recording data from may to June 2015. These data were used to calculate the mean diurnal cycle of the air temperature lapse rate. A mean monthly lapse rate estimated from the permanent weather station network was combined with the mean diurnal glacier lapse rate cycle (Kinnard *et al*., 2022).

Meteorological data from seven permanent weather stations ranging in elevation from 1050 to 2025m a.s.l were used to calculate the mean monthly air temperature lapse rate and the constant precipitation lapse rate (15% 100 m^{-1}). Historical precipitation from the two stations closest to Saskatchewan glacier (Parker Ridge, 2023 m a.s.l. and Columbia Icefield, 1981 m a.s.l.) were merged (averaged) (Kinnard *et al*., 2022).

Reanalysis data were used to force the mass balance models on the 1979-2010 period. Data from the *North American Regional Reanalysis* (NARR) were used because it has a good spatial and temporal resolution, and it represents well air temperature and humidity at high altitude sites in southern British-Columbia (Trubilowicz et al., 2016). The 3-hourly NARR data was interpolated to 1 hourly values to be used by the models. For air temperature and solar radiation data, to avoid underestimation of daily peaks, a shape-preserving piecewise cubic interpolation was used for interpolation, while linear interpolation was used for other variables. NARR precipitation data were disaggregated by dividing 3-hour values in three equal (1h) quantities (Kinnard *et al.*, 2022).

The NARR data was interpolated to the reference weather stations and further bias-corrected against the AWS 2014-2016 data for all variables except precipitation (Kinnard *et al.*, 2022). Because precipitations were not measured at the on-glacier AWS, the merged historical precipitation record from Parker Ridge and Columbia stations were used to correct the NARR precipitation data. A simple scaling correction was used to correct the bias of NARR air temperature, wind speed, relative humidity and precipitation (Kinnard *et al.*, 2022). For global radiation data, a time-varying scaling method was used to correct NARR radiation data: a separate diurnal scaling function was developed for each month to account for the diurnal and seasonal variations in global solar radiation. Kinnard *et al.* (2022) assessed the performance of the bias corrections on meteorological data at hourly and daily time intervals. They found that air temperature and global radiations showed strong correlations values (r= 0.98-0.92) between NARR data and AWS values, and low to moderate correlation of precipitation on a daily scale even if the bias of NARR is low.

2.4.3 Climate scenarios

The climate scenarios used to validate the temperature-index models are the same as those used to drive DEBAM in Kinnard *et al.* (2022). Since it is yet difficult to obtain reliable projections of meteorological data other than air temperature and precipitation (e.g. wind speed, relative humidity, radiation) to drive physically based glacier models, they used a climate perturbation approach to examine the climate sensitivity of Saskatchewan glacier. These scenarios are potential changes of air temperature (ΔTa) between 0 to 8°C (with 1°C intervals) and changes of precipitation rates (ΔP) of -20 to +20% (with 5% intervals) that are imposed on the historical forcing over a 30-year reference period (1979-2010), for a total of 81 different climate scenarios (Kinnard *et al.*, 2022). These air temperature and precipitation rate changes were chosen because they encompass the climate change scenarios predicted by the IPCC (2013) for the closest point to Saskatchewan glacier's equilibrium line according to projected ensemble general circulation model (GCM) simulations for the mid (2041-2070) and late (2071-2100) 21st century (Trouet & Van Oldenborgh, 2013). These scenarios represent climate changes susceptible to happen under different Representative Concentration Pathway (RCP) scenarios (RCP2.6, RCP4.5, RCP6.0 & RCP8.5). The same perturbed climate scenarios were used in this study to drive the temperature-index models and validate their performance against DEBAM.

2.4.4 DEBAM reference simulations

The physically-based mass balance model used by Kinnard *et al.* (2022) to simulate the evolution of the Saskatchewan glacier is the grid-based distributed surface energy-balance model (DEBAM) developped by Hock and Holmgren (2005). This model computes the energy balance at the glacier surface using air temperature, humidity, wind speed and global radiation. It has been showed that this model is more transferable than temperature-index models in different climates (Braun & Hock, 2004; Hock & Holmgren, 2005; Sicart, 2002)

The historical (1979-2010) mass-balance simulated with DEBAM by Kinnard *et al.* (2022) were used as pseudo-observations to calibrate the temperature-index models, while the DEBAM projections were used to validate the tempearture-index models under the climate change scenarios. Kinnard *et al.* (2022) found that DEBAM, when forced by regional reanalysis data, can reproduce well the mass balance evolution of Saskatchewan glacier on recent and long-term scales when forcing and key model parameters are constrained with observation and ancillary data.

2.5 Temperature-Index models

This study compares the performance of five temperature-index mass balance models of different complexity levels. They have been executed with the DETIM program made by Hock and Tijm-Reijmer (2012), which was modified to include the Enhanced Temperature Index model (ETI) from Pellicciotti et al., (2005). All models were forced with the same precipitation forcing, i.e., the NARR total precipitation downscaled to the glacier by Kinnard et al. (2022). To separate liquid and solid precipitation, a linear interpolation was performed between -1°C (100% snow) to 1°C (100% rain).

2.5.1 Classical temperature-index

The classical temperature-index model (TI) of Braithwaite and Olesen (1989) makes a direct relation between melt M (mm/h w.e.) and air temperature T (K) through a degree-day factor for ice (DDF_{ice}) and for snow (DDF_{snow}) (mm d^{-1} K^{-1}) (Equation 1).

$$M = \begin{cases} DDF_{snow/ice} * T & ,T > 0 \\ 0 & ,T \leq 0 \end{cases} \tag{1}$$

Melting occurs only when the air temperature is positive, i.e., the melting threshold is 0 °C. This assumption is used for all other empirical models in this study. This model only considers air temperature and precipitation to compute snow accumulation and snow and ice melt. $DDF_{snow/ice}$ needs to be calibrated against observed data. This simple model has proven to reproduce well glacier mass balance at a relatively short temporal scale and at regional scale but has difficulties reproducing mass balance at a diurnal scale and at high spatial resolution (Hock, 1999).

2.5.2 Temperature-index with potential clear-sky solar radiations

The temperature-index model by Hock (1999) includes the potential clear-sky radiation (HTIa) which accounts for topographic and seasonality effects on melt rates (Equation 2).

$$M = \begin{cases} \left(MF + rad_{snow/ice} * I\right) * T & ,T > 0 \\ 0 & ,T \leq 0 \end{cases} \tag{2}$$

In this equation, the constant melt factor MF (mm h^{-1} K^{-1}) is modulated by the temporally and spatially variable potential solar radiation I (W/m^2), and a separate radiation parameter for snow and for ice, $rad_{snow/ice}$ (mm m^2 W^{-1} h^{-1} K^{-1}). Potential radiation is calculated with equation 3:

$$I = I_o * \left(\frac{R_m}{R}\right)^2 * \psi_a * \left(\frac{P}{P_o \, cos\theta}\right) * cos\theta \tag{3}$$

This equation considers the atmospheric pressure at the study site P and at sea level P_o (Pa), the incidence angle between the glacier surface and the sun position θ (°), the solar constant

I_o (1368 Wm^{-2}), the mean atmospheric transmissivity in clear-sky conditions ψ_a, and the instant R and mean R_m Earth-Sun distance. This allows to include the effect of diurnal melt rate variability in the model by incorporating the topography effect on potential radiations. MF, rad_{ice} and rad_{snow} are the parameters that are calibrated with data from the physical model simulations.

2.5.3 Temperature-index with potential clear-sky solar radiations and measured global radiations

The second temperature-index model modified by Hock (1999) (HTIb) includes potential clear-sky radiations and add measured global radiation measured at the glacier surface (Equation 4).

$$M = \begin{cases} \left(MF + rad_{snow/ice} * I * \frac{G_s}{I_s}\right) * T & ,T > 0 \\ 0 & ,T \leq 0 \end{cases} \tag{4}$$

This model considers the effect of variations in cloud cover and clear-sky atmospheric on solar radiation by multiplying the potential radiation with the ratio of measured global radiation G_s (W/m^2) to potential radiation at the weather station. Cloud cover can greatly affect melt, especially at sites with a lot of annual precipitation (Pellicciotti *et al.*, 2011). This allows a better estimation of diurnal melt cycles and melt variability at the glacier surface than the previous models (Hock, 1999). The parameters to calibrate in this model are the same than for the HTIa model.

2.5.4 Enhanced temperature-index

The enhanced temperature-index model (ETI) made by Pellicciotti *et al.* (2005), adds the albedo of the glacier surface as a factor influencing melt (Equation 5).

$$M = \begin{cases} MF * T + SRF * (I - \alpha) * G & ,T > 0 \\ 0 & ,T \leq 0 \end{cases} \tag{5}$$

The inclusion of albedo (α) allows to incorporate the impact of snow metamorphism on melt rate (Pellicciotti *et al*., 2005). The albedo parametrisation method from Oerlemans & Knap (1998) was used to simulate albedo values of the surface (Kinnard *et al*., 2022). This method simulates to change of albedo due to snow metamorphism using time since last snowfall (days) and snow depth (cm). Fresh snow value was set at 0.9 based on observations at the AWS. The typical ice albedo value (0.24) was mapped from Landsat images (Kinnard *et al*., 2022). The inclusion of albedo in this model means that the melt parameters do not need to be adjusted separately for snow or ice, but errors can be increased due to uncertainties associated with the albedo parameterisation, especially during snow to ice transitions (Pellicciotti *et al*., 2005). MF and SRF need to be calibrated against observations.

2.5.5 Enhanced radiation-decorrelated temperature-index

The enhanced temperature-index model with decorrelated temperature data (ETIb) is a modified version of the ETI model (Equation 6) inspired by the work of Bash and Marshall (2014).

$$M = \begin{cases} MF * T_{residual} + SRF * (I - \alpha) * G & , T > 0 \\ 0 & , T \leq 0 \end{cases} \tag{6}$$

It was suggested by Anslow (2004) to air temperature on radiations to remove the variance of air temperature that is due to radiations in the ETI model. The residual temperature $T_{residual}$ is then used as the input in the ETIb model instead of T. Bash and Marshall (2014) found that this model improved the performance of the ETI model. In this work, since albedo is parameterized by the model, air temperature was regressed against global radiation (instead of net solar radiation) and the residuals $T_{residual}$ were used in equation (6). The parameters to calibrate in this model are the same than for the ETI model.

2.6 Methods

2.6.1 Calibration

The optimal values of the parameters from the temperature-index models were determined by systematic calibration. Simulations were run for the calibration period (1979-2010) with every combination of parameter values. The minimum, maximum, and search intervals for each model parameter where set to have a manageable number of simulations (Table 1). The initial minimum and maximum parameter values were based on Gabbi et al. (2014). Then, the search range was adjusted according to initial NSE results in order to capture the optimum. The simulated mass balance from each run was then compared with the mass balance simulated by DEBAM and the parameter set that minimized the difference was retained. Three different calibration methods were used and compared. For each method the model error (ε) is indexed by the calibration method number.

Table 1. Values of parameters used for iterations of the temperature-index models

	Parameter	**Minimum**	**Maximum**	**Interval**	**Optimal value**			**Number of simulations**
					Method 1	**Method 2**	**Method 3**	
TI Model 1	DDF ice	1	13	0.1	5.3	4.9	7.3	9 801
	DDF snow	1	9	0.1	3.3	3.4	2.9	
HTIa Model 2	MF	0	4	0.1	0	0	1.5	28 413
	Rad ice	0	0.0016	0.00005	1	1	0.95	
	Rad snow	0	0.001	0.00005	0.45	0.45	0.2	
HTIb Model 3	MF	0	4	0.1	0	0	2.6	28 413
	Rad ice	0	0.0016	0.00005	1.05	1.05	0.9	
	Rad snow	0	0.001	0.00005	0.55	0.55	0.05	
ETI Model 4	MF	0	0.1	0.1	2.4	2.4	0	11 826
	SRF	0	0.015	0.0001	4.4	4.4	13.3	
ETIb Model 5	MF	0	0.1	0.1	1.4	1.4	2.2	11 826
	SRF	0	0.015	0.0001	8.9	8.9	8.8	

The first method (method 1: 'geodetic') compares the mean mass balance simulated over the entire glacier surface ($B_{a_{sim}}$) against the DEBAM reference value ($B_{a_{ref}}$) (Equation 7). This method mimics the situation where the mean mass balance simulated by a distributed model ($B_{a_{sim}}$) would be compared to geodetic mean mass balance estimates ($B_{a_{ref}}$), i.e. when mass-balance are derived from elevation changes over the entire glacier (e.g. Denzinger et al., 2021; Lv et al., 2019).

$$\varepsilon_1 = B_{a_{sim}} - B_{a_{ref}} \tag{7}$$

The second method (method 2: ‘glaciological’) compares the mean simulated mass balance ($\hat{B}_{a_{sim}}$) estimated by applying the glaciological method to the virtual stake network (Figure 1.b) against the same method applied to the reference DEBAM data ($\hat{B}_{a_{ref}}$) (Equation 8).

$$\varepsilon_2 = \hat{B}_{a_{sim}} - \hat{B}_{a_{ref}} \tag{8}$$

The mean mass balance ($\hat{B}_{a_{sim}}, \hat{B}_{a_{ref}}$) was obtained by regressing the simulated and reference point balance (b_{sim}, b_{ref}) at the stakes against elevation, using a second-order polynomial. The point balances were extrapolated to the whole glacier DEM with the derived function and then averaged to obtain $\hat{B}_{a_{sim}}$ and $\hat{B}_{a_{ref}}$. The positions of the virtual stake are selected to fit the stakes positions used on the glacier to measure mass balance using the glaciological method (Ednie et al., 2017).

The third calibration method (method 3: ‘spatial’) calculates the model errors at each individual stake, i.e., using the simulated ($b_{a_{sim}}$) and reference ($b_{a_{ref}}$) point mass balances (Equation 9).

$$\varepsilon_3 = b_{a_{sim}} - b_{a_{ref}} \tag{9}$$

This method thus includes the spatial variability of mass balance in the calibration process.

The Nash-Sutcliffe efficiency (NSE) criteria was used as the objective function to maximise during calibration. The NSE is a relative error metric that allows comparing the performance between models (Nash & Sutcliffe, 1970).

$$NSE = 1 - \frac{\sum \epsilon_n{}^2}{\sum (Ba_{ref} - \overline{Ba_{ref}})^2} \tag{10}$$

Where is the error from the nth calibration method (equation 7-9). NSE values can vary between -∞ and 1, a perfect simulation. A NSE value of 0 implies that the model is not a better predictor than using the mean of observations while NSE have no prediction skill (Gupta *et al.*, 2009).

For each calibration method, the parameter combination that gave the highest NSE value was considered as the optimal parameter set. In addition, parameter sets that yielded a NSE within 0.01 of the optimal (maximum) value were considered as equifinal and retained. The 50 combinations with the closest NSE to the optimal were selected. A limit of 50 equifinal parameter sets was used to reduce model computing time. Equifinal combinations are statistically equivalent to the optimal values according to the calculations of the NSE criterion but can have very different parameter values and thus lead to transferability issues over long periods or in different climate scenarios (Gupta *et al.,* 2009; Thirel *et al*., 2015).

In addition, the mean error or bias, equation 11) and root mean square error (RMSE, equation 12) were also reported for each optimal model and calibration period.

$$ME = \overline{\varepsilon_n} \tag{11}$$

$$RMSE = \sqrt{\overline{\varepsilon_n}^2} \tag{12}$$

2.6.2 Validation

Following model calibration, the temperature index models were validated against DEBAM pseudo-observations under climate changes scenarios, to examine model transferability outside calibration conditions. Simulations were run for the 81 climate scenarios (ΔTa of 0 to 8°C with 1°C intervals; ΔP of -20 to +20% with 5% intervals) using the optimal and equifinal parameter set from the five temperature-index model. The model transferability was assessed by the absolute (Bias) and relative (rBias) errors (equation 13-14), which express the systematic deviations of the model relative to the DEBAM reference values under climate change. These will be referred to as 'projection bias' hereafter:

$$Bias_{projection} = \frac{1}{n}\sum_{t=1}^{t=n}(B_{sim} - B_{ref}) \quad (13$$

$$rBias_{projection} = \frac{\sum_{t=1}^{t=n}(B_{sim} - B_{ref})}{\sum_{t=1}^{t=n} B_{ref}} \times 100 \tag{14}$$

Where B_{sim} and B_{ref} are the annual simulated and reference specific simulated balance, respectively. The biases were calculated over a 3-year (n = 31) period corresponding to the historical 1979-2010 period perturbed by the climate change scenario.

We also examined in more details the model performances by observing their cumulated mass balance over 30 years for the calibration scenario (ΔTa = 0°C; ΔP = 0%) and in the most probable climate change scenario (ΔTa +2°C; ΔP +5%) for the region in the 2041-2070 period for the RCP4.5 "intermediate" scenario according to IPCC (2013). This allows portraying the cumulative impact of a systematic model bias when it is accumulated over a long-term projection and to contrast the impact of model structure and calibration method on this cumulative bias.

2.7 Results

2.7.1 Calibration

Calibration method 1 and 2 gave the same optimal parameter sets for the HTIa, HTIb, ETI and ETIb models (Table 1, Fig 2). For the HTIa and HTIb, the melt factor parameter has an optimal value of 0 with calibration methods 1 and 2. The ETI model has an optimal value of 0 for the melt factor parameter with method 3.

The calibration statistics for the optimal parameter sets presented in Table 2 were recalculated using the mean mass balance over the entire glacier surface, i.e., using equation 7 and equation 10-12. This allows to compare the model performance from the different calibration methods relative to the same prediction target (B_{ref}). The spatial method 3 has a larger bias compared to the other methods, for all the models. The performance metrics are equal between method 1 and 2 for all the enhanced models and almost equal for TI. The RMSE is lower for the calibration method 1 and 2 for all the temperature-index models. The bias is also closer to zero for these two methods, while it is consistently negative for method 3. This indicates that the spatial calibration method 3 results in less accurate mean mass balance prediction compared to the other two methods which are calibrated directly on the mean mass balance, either calculated from the whole surface (geodetic method 1) or from the glaciological method 2. Hence for all models, the NSE is closer to 1 for method 1 and 2 but decreases somewhat for method 3, implying that the 'global' calibration method 1 and 2 give parameter values that are better predictor of the true mean mass balance in the calibration period.

Statistics from Table 2 shows that model HTIa globally shows the best performance, and ETIb the worst performance, during the calibration period (1979-2010) regardless of the method. The models that included solar radiation (exept ETIb) performed better than TI in reproducing the glacier mass balance evolution as simulated by DEBAM, when calibrated globally (ETI), or using any method (HTIa,b). However, the performance of the enhanced models seem to diminish with the increase in model complexity.

Table 2. Bias (m w.e.), RMSE (m w.e.) and NSE (unitless) for the optimal parameter set for each calibration methods and model. All metrics were calculated for the surface-wide mean mass balance, B_{ref}. A positive bias indicates that the model underestimate melt, and a negative bias indicates that it overestimates melt.

	Calibration method	**BIAS (m w.e.)**	**RMSE**	**NSE**
TI Model 1	Method 1	0.0026	0.1695	0.9084
	Method 2	0.0165	0.1698	0.9081
	Method 3	-0.0838	0.2031	0.8685
HTIa Model 2	Method 1	-0.0006	0.1225	0.9521
	Method 2	-0.0006	0.1225	0.9521
	Method 3	-0.0511	0.1559	0.9225
HTIb Model 3	Method 1	0.0161	0.1400	0.9375
	Method 2	0.0161	0.1400	0.9375
	Method 3	-0.0573	0.1788	0.8981
ETI Model 4	Method 1	0.0025	0.1488	0.9294
	Method 2	0.0025	0.1488	0.9294
	Method 3	-0.0573	0.3537	0.6012
ETIb Model 5	Method 1	0.0194	0.1907	0.8841
	Method 2	0.0194	0.1907	0.8841
	Method 3	-0.3485	0.4192	0.4400

Fig 2 shows strong equifinality for all models, especially for those enhanced with radiation. The shape of the NSE distribution indicates the level of parameter identifiability: a rounded distribution better outlines the best parameter values while more elongated patterns imply equifinality and thus reduced parameter identifiability. The spatial calibration method 3 seems to better encompass the optimal values than the other methods, for the TI, HTIa and HTIb models at least. On the opposite, the more linear distributions of the best NSE values and equifinal combinations shows uncertainty on the best values for the parameters. All of the equifinal combinations are statistically equally good even if their values vary a lot. The parameter equifinality seen on Fig. 2 raises question on the resulting parameter incertitude and its impact on projections made in different climate conditions. This is particularly the case for calibration methods 1 and 2 for all five temperature-index models, and method 3 for the ETI and ETIb models (Fig. 2). The equifinality space is wider for ETI than for ETIb, suggesting a smaller parameter uncertainty for the optimal parameter values for ETIb. The HTIa and HTIb models show the widest distributions of equifinal parameter values, suggesting a bigger uncertainty of the optimal values of their parameters.

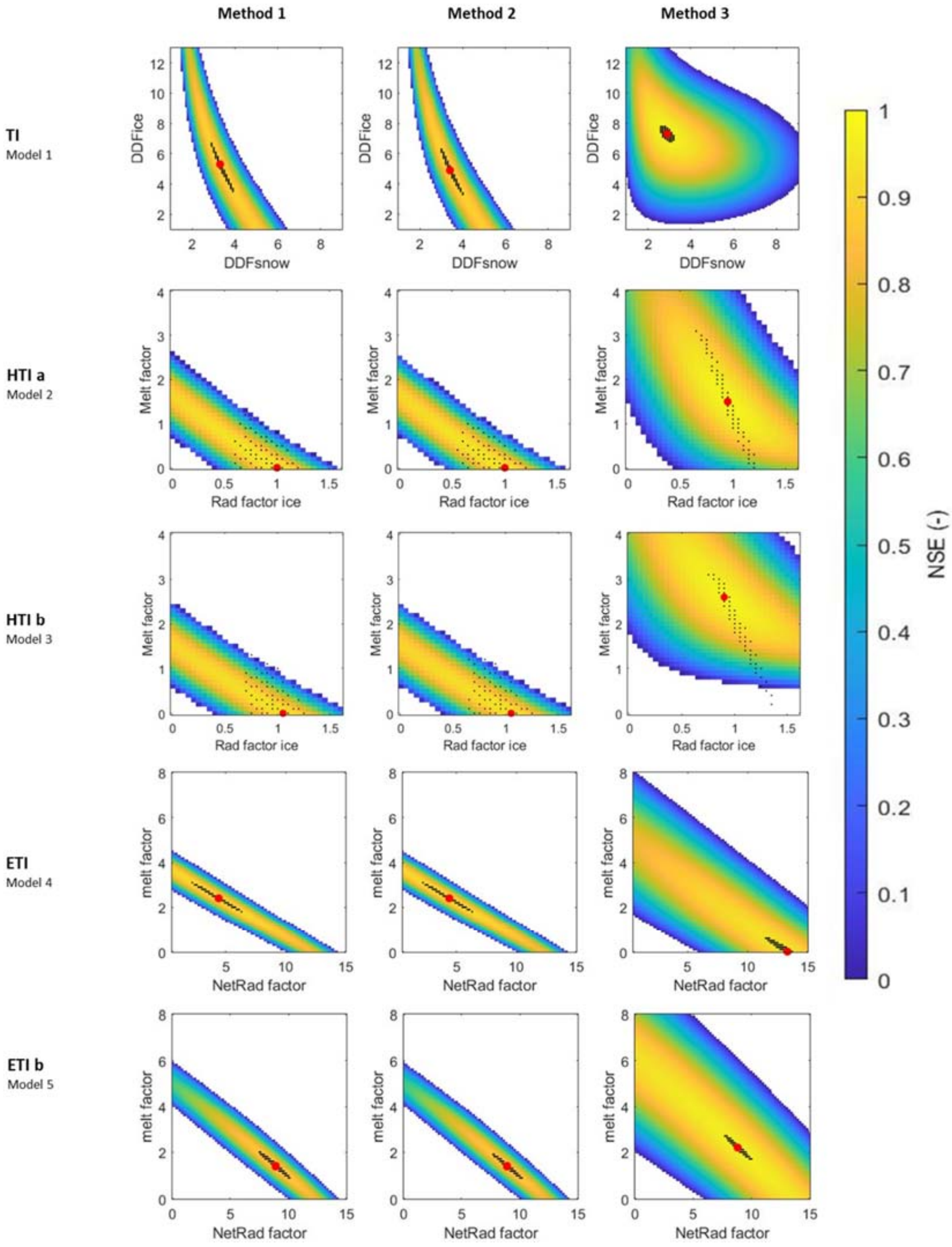


Figure 2. NSE values (colors), optimal combinations (red dots) and equifinal combinations (black dots) of the parameters from the five temperature-index models for the three calibration methods. Negative values are plotted white to emphasize skillful predictions only

2.7.2 Projection biases

All temperature index models are found to under-estimate melt, leading to over-estimated mass balance projections under climate change conditions (Fig. 3). This positive projection bias ($Bias_{projection}$: equation 13) generally increases with the warming level (Fig. 3). Exceptions are situated around ΔTa of 0 to 1°C, and in the method 3 distribution of ETIb were we see more negative values.

As found in calibration, the pattern of projection bias under climate change scenarios is similar among the two global calibration methods, i.e. the geodetic method 1 and the glaciological method 2. We observe however, that the projection bias is generally lower and less sensitive to warming when models are calibrated spatially with method 3, than when calibrated globally via methods 1 or 2. The ETI model is the only notable exception, for which the projection bias is more sensitive to warming when calibrated with method 3.

The projection bias for all the temperature-index models is much more sensitive to warming than to changes in the precipitation rate, which only have a minor effect on the projection bias.

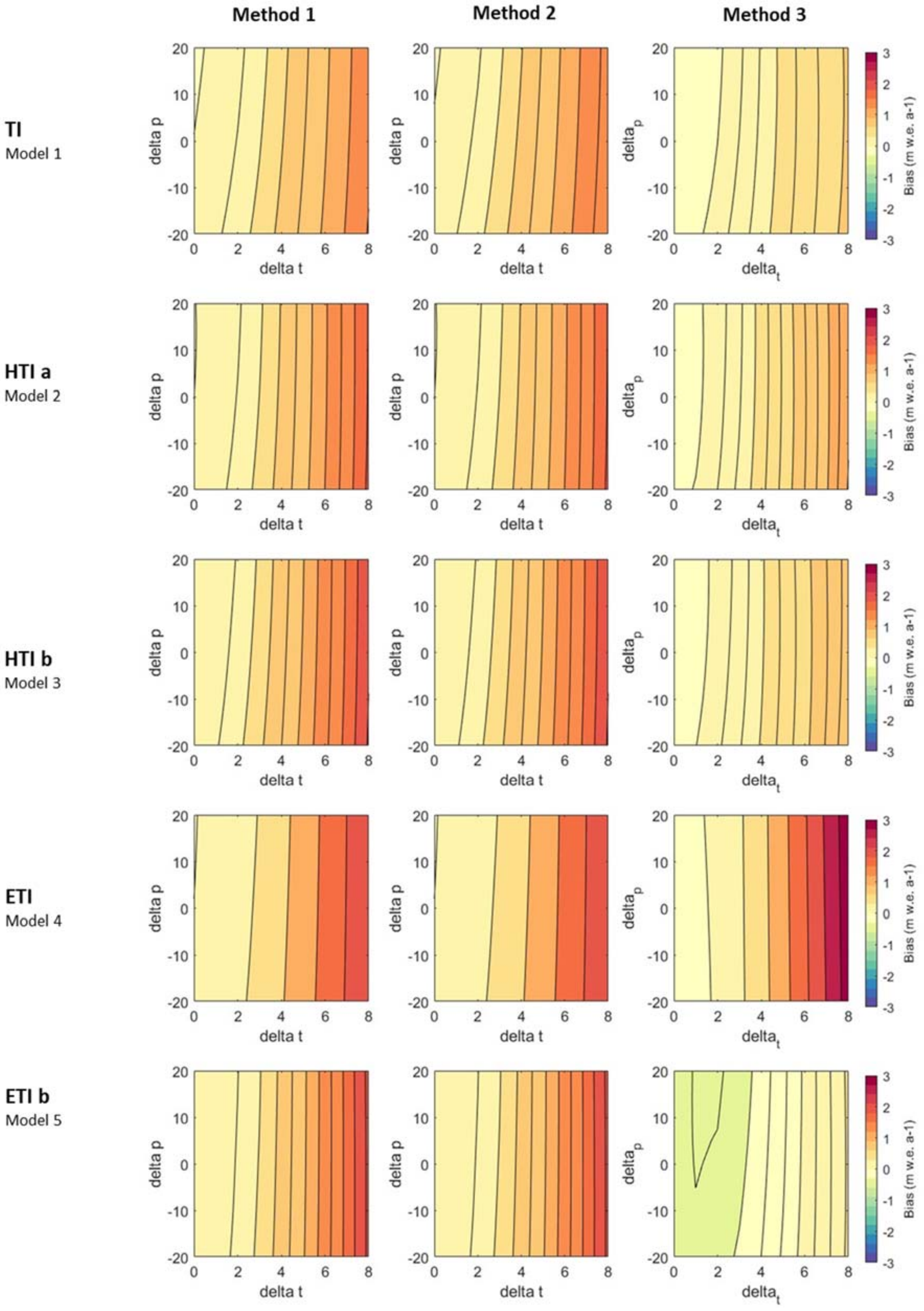


Figure 3. Projection bias (m w.e.) for five temperature index models and three calibration methods under different climate scenarios (delta p: changes in precipitation (%); delta t: changes in air temperature (°C)).

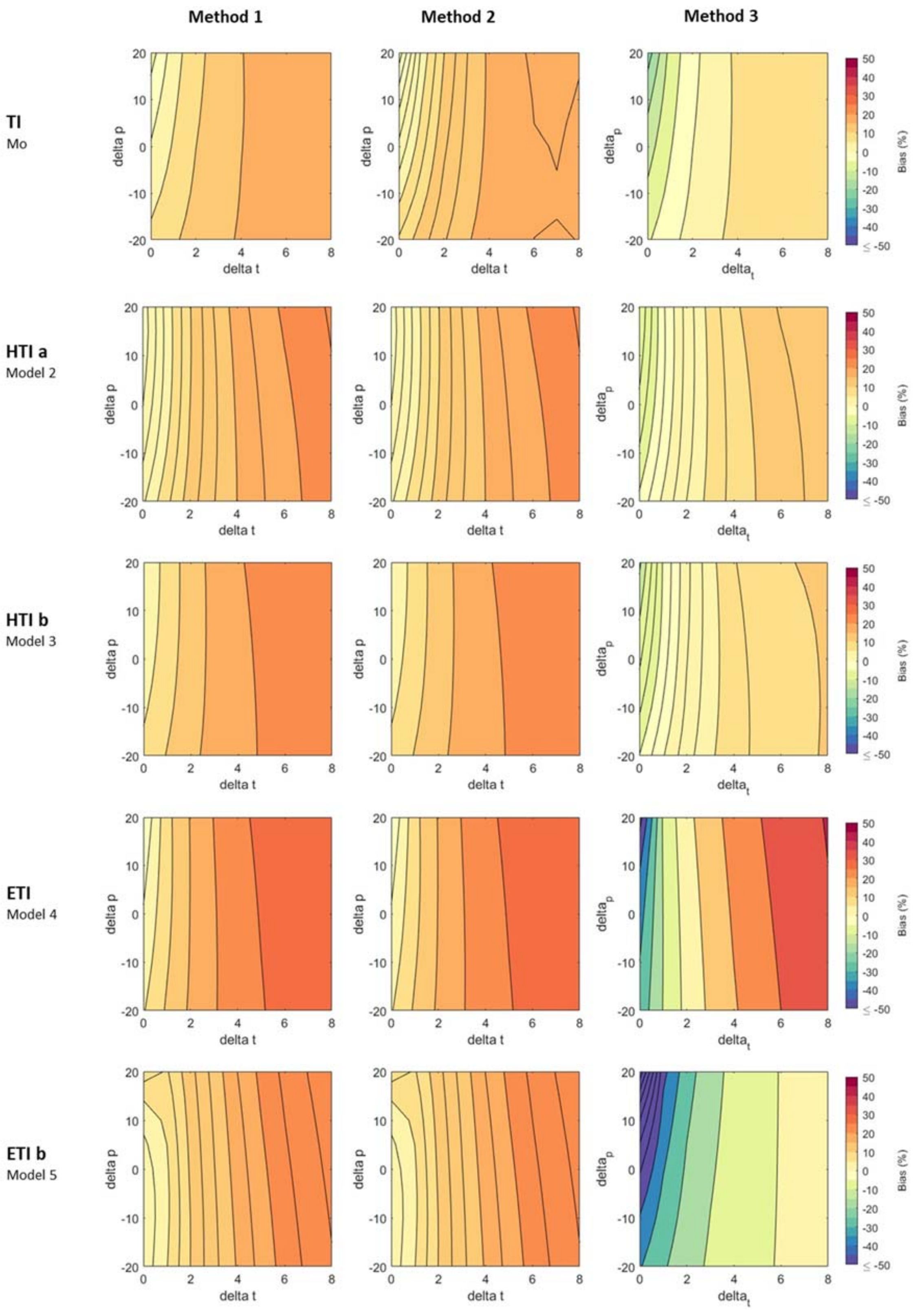


Figure 4. Relative projection bias (rBias, %) for five temperature index models and three calibration methods under different climate scenarios (delta p: changes in precipitation (%); delta t: changes in air temperature (°C)).

The relative projection bias (rBias) allows to compare the relative importance of the bias between models and calibration methods (Fig. 4). We see that the relative projection bias is again similar for method 1 and 2, i.e., increasing with the warming level. For all the models, the relative projection bias is close to zero between ΔTa0°C and ΔTa1°C for method 1 and 2. For method 3, all the models but HTIb show the same pattern, where the relative projection bias is farther from zero with negative values around the calibration scenario (ΔTa 0°C; ΔP 0%), increasing to values close to zero between ΔTa of 0 to +3°C depending on the model, and then increasing thereafter. This shows that the global calibration methods 1 and 2 gave optimal parameter values that performed better during calibration, while method 3 gave parameter values that performed less well in calibration but comparatively better under the most probable climate change scenario (ΔTa +2°C; ΔP +5%) for the region according to IPCC (2013). The distribution of rBias for ETIb with method 3 shows that the relative bias increases when ΔTa increases with rBias values of -107% at ΔTa 0°C; ΔP +20% scenario and minimal rBias values at extreme ΔTa scenarios (ΔTa +6°C to +8°C). We can also see that all five models are more impacted by changes in precipitation than what we could observe in Fig.3, especially when ΔTa is closer to zero. Globally, the maximum rBias of the models in climate scenarios increases along with the complexity of the models.

During the calibration phase, many equifinal combinations were found (Fig. 2). These all have approximately the same NSE value (within a range of 0.01 of the optimal NSE value), but they all give different mass balance projections. To calculate the uncertainty in mass balance projections due to parameter equifinality, the standard deviation of the bias for each equifinal set was calculated and plotted in Fig. 5. A higher value means that the incertitude of the model due to parameter equifinality is more significant. We observe that for all models and calibration methods, the uncertainty due to equifinality increases with the warming level, in line with the increasing bias itself (Fig. 3). The impact of equifinality on the projection accuracy is somewhat larger for the TI, HTIa and HTIb models, especially for larger warming and for calibration method 3. ETI and ETIb do not show significant differences between calibration methods. For the three calibration methods, ETIb shows the highest uncertainity values, especially for the most extreme warming.

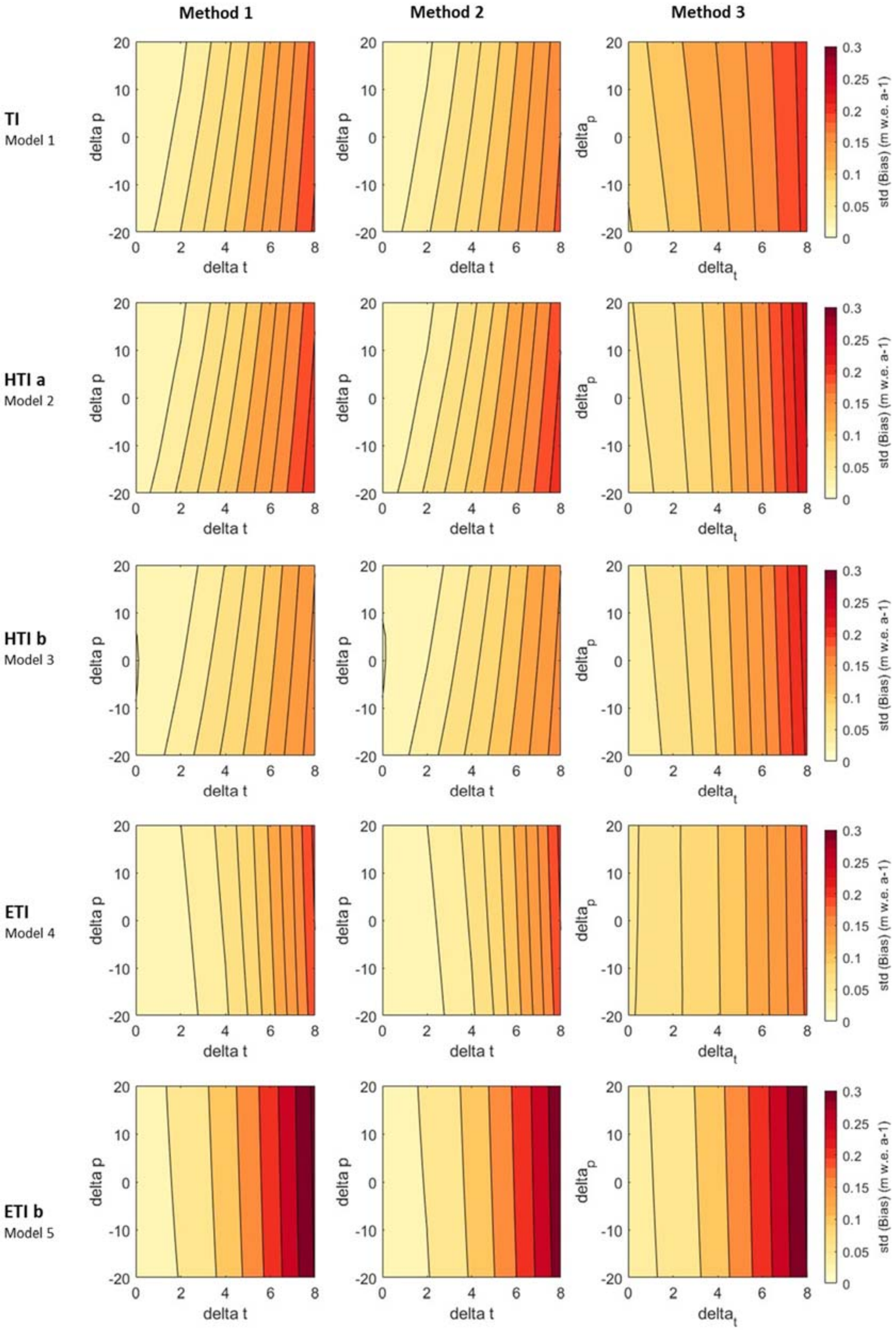
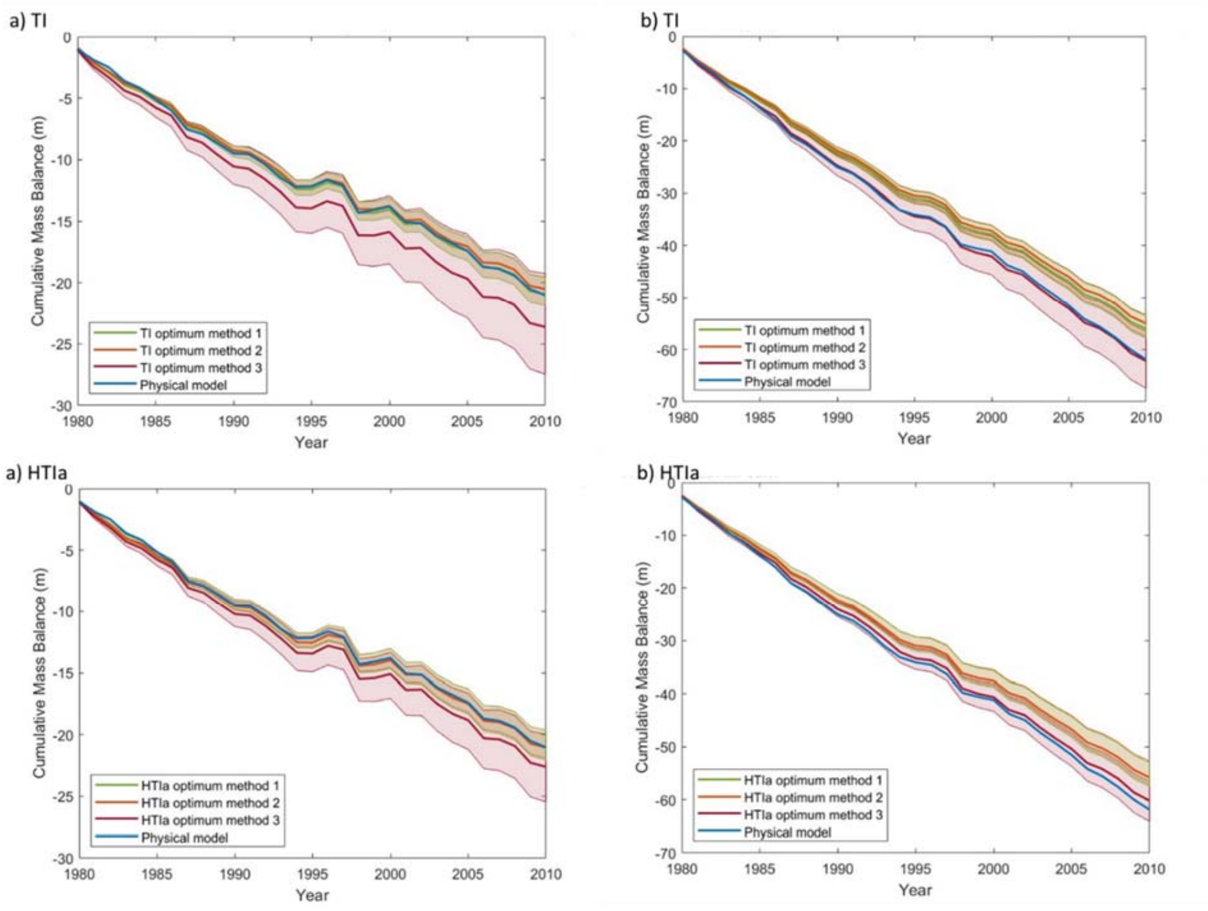


Figure 5. Standard deviation of equifinal combinations simulations bias with the reference mass balance in different climate scenarios (delta p: changes in precipitation (%); delta t: changes in air temperature (°C)) from simulations of five temperature-index models.

Accumulated over a long period of time, a small projection bias in simulated annual mass balance can affect greatly the cumulated mass balance over that period. To investigate this effect, the cumulated mass balance simulated by the optimal and equifinal parameter sets is illustrated in Fig. 6 for the calibration climate as well as for the calibration climate perturbed by the most probable climate scenario ΔTa = 0°C; ΔP = 0%) (IPCC, 2013).

Fig. 6 shows that simulations from method 1 and 2 are closer to the DEBAM reference simulation for the calibration interval. Under the perturbed climate, method 3 results in projections that are closer to the reference for TI, HTIa, HTIb, and ETI. In both climate scenarios (calibration and future), these four models show that using the calibration method 3 also results in a wider uncertainity to parameter equifinality.



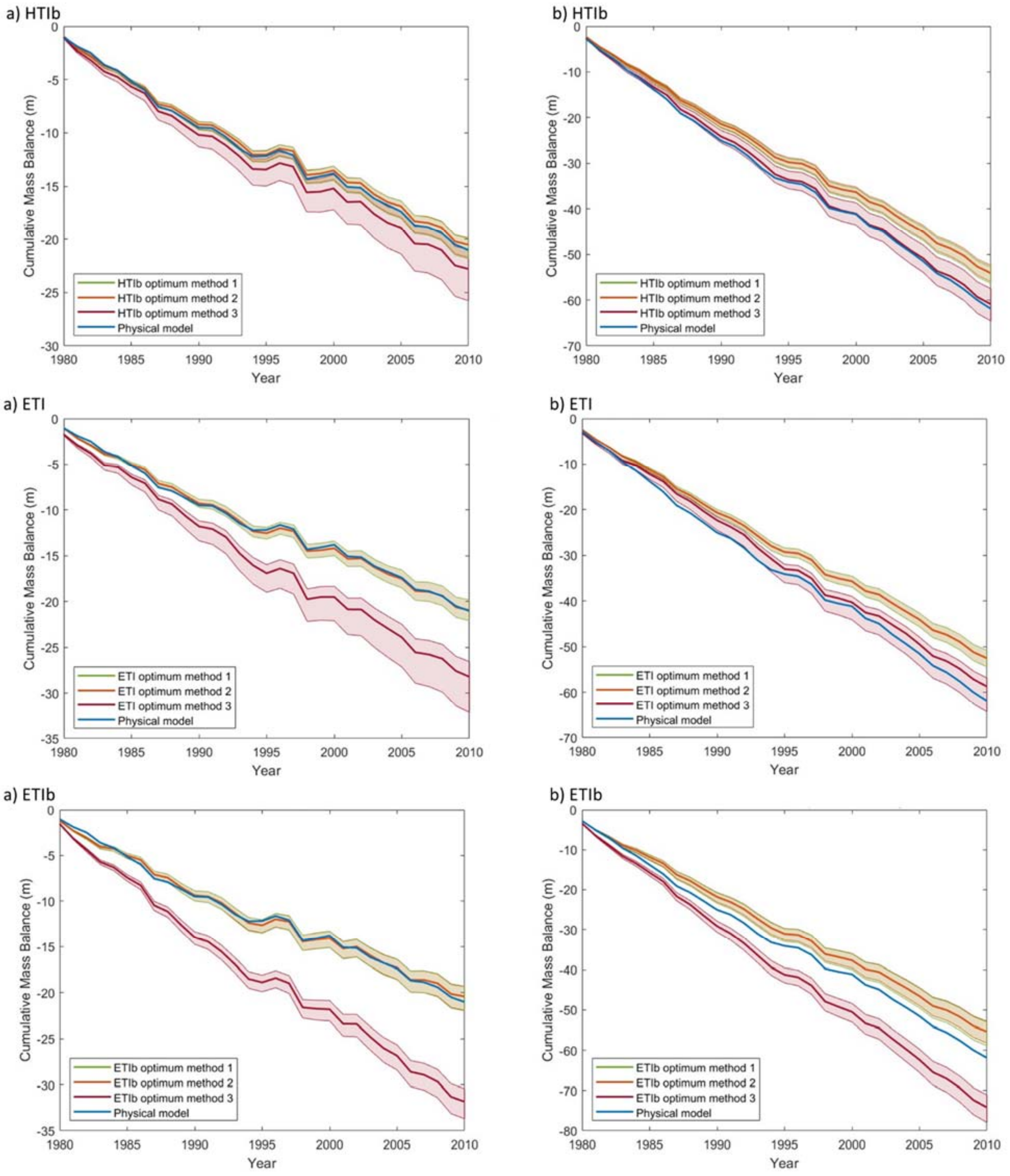


Figure 6. Cumulative mass balance simulated by the optimal parameter set (bold coloured lines) and 90 percentile uncertainty envelopes due to parameter equifinality (transparent envelopes) for calibration method 1 (Green), method 2 (orange) and method 3 (red). The reference (DEBAM) cumulative mass balance is shown by the bold blue line. a) the graphs on the left column are for the 1979-2010 calibration period (*ΔTa = 0°C; ΔP = 0%*). b) The graphs on the right column are for 1979-2010 perturbed by the most probable climate change scenario for the study area (*ΔTa = 2°C; ΔP = 5%*) according to IPCC (2013).

2.8 Discussion

2.8.1 Impact of model complexity on performance and transferability

This study aimed to assess the performance of five temperature-index model in climate change conditions by comparing their results with projections from a physical model. This study also aimed to examine the impact of using different calibration methods on the mass balance projections in different climate scenarios. We have observed that simpler models (TI, HTIa, and HTIb) globally performed better than more complex models (ETI and ETIb), especially in climate change conditions. Several previous studies have reported that more complex models, like ETI and ETIb perform better than simpler temperature-index models (Anslow, 2004; Bash & Marshall, 2014; Bouamri *et al.*, 2018; Gabbi *et al.,* 2014; Pellicciotti *et al*., 2005). In this study, we found the opposite observation. There could be two main reason to explain this unexpected result.

First, it has been shown by Pellicciotti *et al*. (2005) that the parametrization of albedo has an important impact on the performance of the models using this variable (ETI and ETIb). Since fresh snow, ice and firn albedo values are the same for ETI, ETIb and the physically-based model, there is no error caused by the albedo parameterisation itself. The uncertainty would therefore be caused by spatio-temporal differences in simulated snow cover between the models, that results in different albedo values and causes errors.

Second, the correlation between air temperature and solar radiation in ETI model can have an important impact on the results as shown by Anslow (2004). Air temperature can be highly correlated to solar radiation; this impact does not affect TI because only air temperature is considered. The multicollinearity of air temperature and solar radiation could exacerbate equifinality problems and complicates the identification of parameters (Bouamri and Kinnard, 2018), explaining why the ETI model had a worst performance than TI, HTIa and HTIb. The overlapping influence of the effect of radiation on air temperature is less of a problem for the HTIa and HTIb models because the radiation terms are included in the melt coefficient instead of being an independent variable like in the ETI model as suggested by Bash & Marshall (2014). The ETI model indeed showed more equifinality during calibration (Fig. 2). In the ETIb model, the residual air temperature was used to try alleviating the collinearity problem (e.g., Bash & Marshall, 2014). However, this approach did not improve the performance of the model as we expected. In their study, Bash and Marshall (2014) regressed air temperature against daily absorbed radiation data measured by an AWS and obtained better results than the ETI model. In our study, air temperature was regressed against global radiation since albedo is modelled internally as a function of snowpack age and thickness. This different approach to decorrelate temperature from solar radiation could explain why the ETIb model performed less well than the other models, especially in climate changes scenarios and when using calibration method 3.

2.8.2 Impact of calibration method on performance and transferability

The calibration method was found to have an impact on the transferability of the models. The choice of calibration method also had an impact on the uncertainty of the TI, HTIa, and HTIb models. For these models, the use of method 3 caused a larger uncertainty on mass balance projection due to the distribution of equifinal combinations. When using the 'geodetic' method 1 and 'glaciological' method 2, all models had a better performance in the calibration period. In future climate conditions the opposite was observed; all models but HTIb transferred better when using the 'spatial' calibration method 3. This could be explained by an overadjustment of the model parameters during calibration. The parameter values are adjusted to the calibration period to obtain good results. Changes in climate conditions can change the relative impact of variables used in the model, causing the adjusted parameter value to be ill fitted in these different conditions. In these conditions, the adjustment of the parameters increase rather than decreases the projection bias or it can decrease the precision without affecting bias (Schisterman *et al.*, 2009). The model parameters seem to be overadjusted when using 'geodetic' method 1 and 'glaciological' method 2 because they have a good performance in calibration period but a poor transferability of all models in climate change conditions. When using the 'spatial' method 3, TI, HTIa and HTIb seem to have better adjusted parameters because they have a good transferability even if their performances is less good than methods 1 and 2 in the calibration period.

We observed that for most of the models, calibration methods 1 and 2 have similar, if not the same results. This could be explained by the fact that we can reliably estimate the mass balance over the entire surface of the glacier using only a few stakes. Indeed, it has been showed by Fountain and Vecchia (1999) that a minimum of five well spatially distributed stakes can give a result close to the real mass balance value. This is typically due to the strong influence of altitude on mass balance and the comparatively small transverse variations of mass balance on mountain glaciers (Fountain & Vecchia, 1999). For our study, we used 10 well spatially distributed stakes. This can explain why the method using the mean mass balance of the surface (method 1) and the method using the mean mass balance of the stakes (method 2) gave very similar results.

2.8.3 Impact of equifinality on performance and transferability

A large number of equifinal parameter combinations indicate that the optimum values of these parameters are not clearly defined (Bouamri *et al*., 2018). As underlined by Triana *et al*. (2019), different equifinal parameter combinations will not represent the same response to meteorological factors of the glacier system. Large equifinality means that the model can be badly calibrated and less accurate, and therefore it is important to evaluate the impact of equifinality on models (Triana *et al.*, 2019).

In this study, there was no clear correlation between the uncertainty in simulated mass balance due to parameter equifinality (Fig.5) and the performance of the models. In Figure 6, we can see that models with a larger variation of equifinal projections (TI, HTIa and HTIb) did not have weaker performances than models with a smaller variation from equifinal combinations (ETI and ETIb), on the contrary.

Equifinality does not seem to affect the transferability of the tested models. Higher values of the standard deviation of equifinal combinations projection bias do not necessarily correspond to higher relative projection bias in the same scenarios.

2.8.4 Impact of the objective function on performance and transferability

Another important factor regarding the potential errors or limits of the study is the use of NSE as the calibration criterion. NSE integrates the effect of bias, the correlation, and relative variability between the temperature-index simulations and the DEBAM pseudo-observations (Nash & Sutcliffe, 1970). Different values of these three components can give the same NSE value, even if their performance is not the same. It has been shown that the variability of the models must be underestimated to maximise the NSE value (Gupta et al., 2009). Nevertheless, NSE is commonly used to compare model performance and usually gives good results despite its disadvantages (Gupta et al., 2009). It has been shown by Gupta *et al*. (2009) that the correlation component of the NSE has a larger impact on the NSE. Therefore, the bias and variability tend to be underestimated when maximizing the NSE value (Gupta *et al.*, 2009). Kling *et al.* (2012) proposed to use a modified version of the KGE as a solution to the disadvantages of the NSE. According to their study, the KGE criterion would ensure that the bias, the variability ratio, and the correlation coefficient are equally considered by the equation. This would ensure that the variability of the models is accounted for. We tested the KGE on the TI model to see the differences with the NSE that was used for this study. Using the same steps, we calibrated the model using the KGE as the objective function for the optimal and equifinal combinations (Fig. 7).

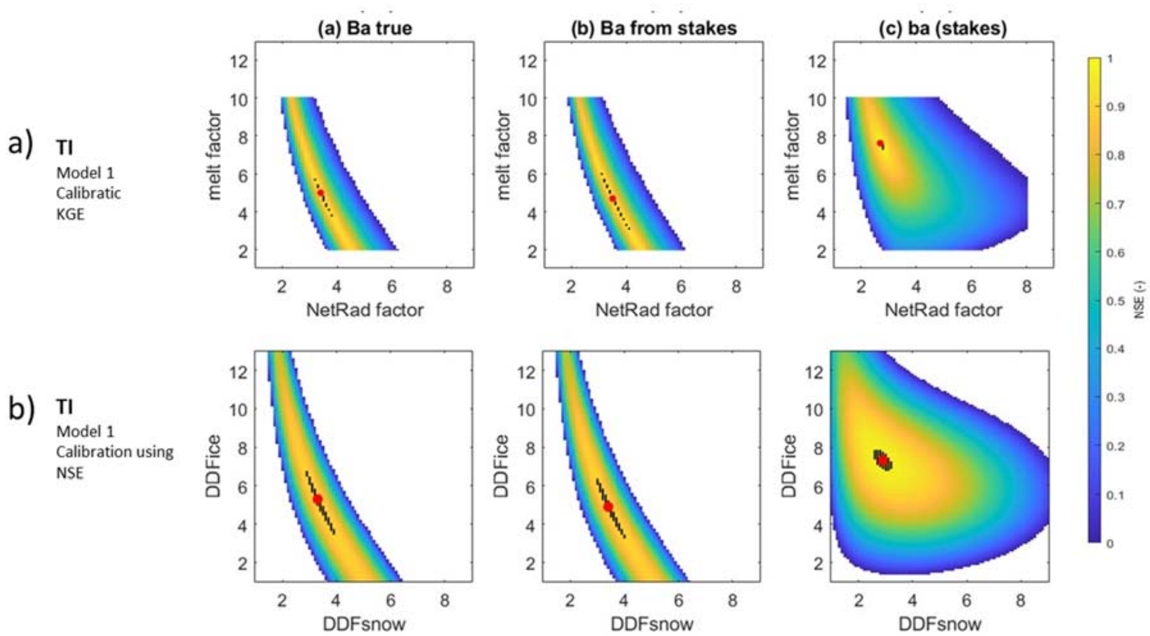


Figure 7. Calibration of TI model using KGE as the criterion (a) and using NSE as the criterion (b). KGE and NSE values (colors), optimal combinations (red dots) and equifinal combinations (black dots).

The major difference that can be observed is the difference in the number of equifinal combinations. It seems that using the KGE instead of the NSE criterion diminishes considerably the uncertainty of the model for the three calibration methods. Indeed, for the three calibration methods we have respectively eleven, eighteen and five combinations. In comparison, we had to put a limit of 50 equifinal combinations when using the NSE to restrain the number of simulations during the validation step. We compared the projections from the optimal and equifinal combinations obtained with the KGE with the physical model in different climate scenarios to see if there are conclusive differences with the results of the study (Fig. 8).

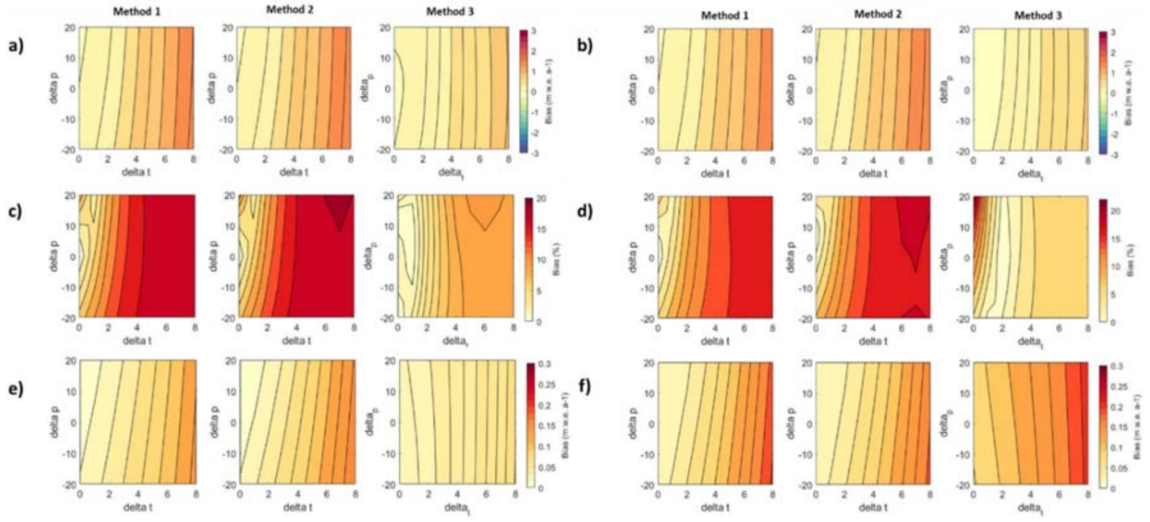


Figure 8. Validation of TI model for optimal and equifinal parameter sets obtained with the KGE criterion (a-c-e) and the NSE criterion (b-d-f). (a-b) Bias (m w.e.) from the optimal parameters set in different climate scenarios (delta p: changes in precipitation (%); delta t: changes in air temperature (°C)). (c-d) rBias (% of total mass balance of reference) from the optimal parameter set in different climate scenarios. (e-f) Standard deviation of the bias from equifinal parameter sets.

There are no major differences concerning the bias (m w.e.) of the optimal combinations from KGE and NSE criterion (Fig. 8-a-b). For the relative bias, we observe a major change in the distribution of the optimal combination of method 3 (Fig. 8-c-d). Using the optimal parameter set determined by the KGE, the maximum relative bias decreases, but the relative bias becomes higher under extreme climate change conditions. It can also be observed in the cumulative mass balance graphs (Fig. 9) that calibration method 3 yields simulations that are closer to the reference DEBAM model in the calibration scenario using the KGE (Fig. 9-a) than when using the NSE (Fig. 9-c) criterion. But there is no major differences in the climate change scenario of ΔTa 2°C; ΔP 5% (Fig. 9-b-d).

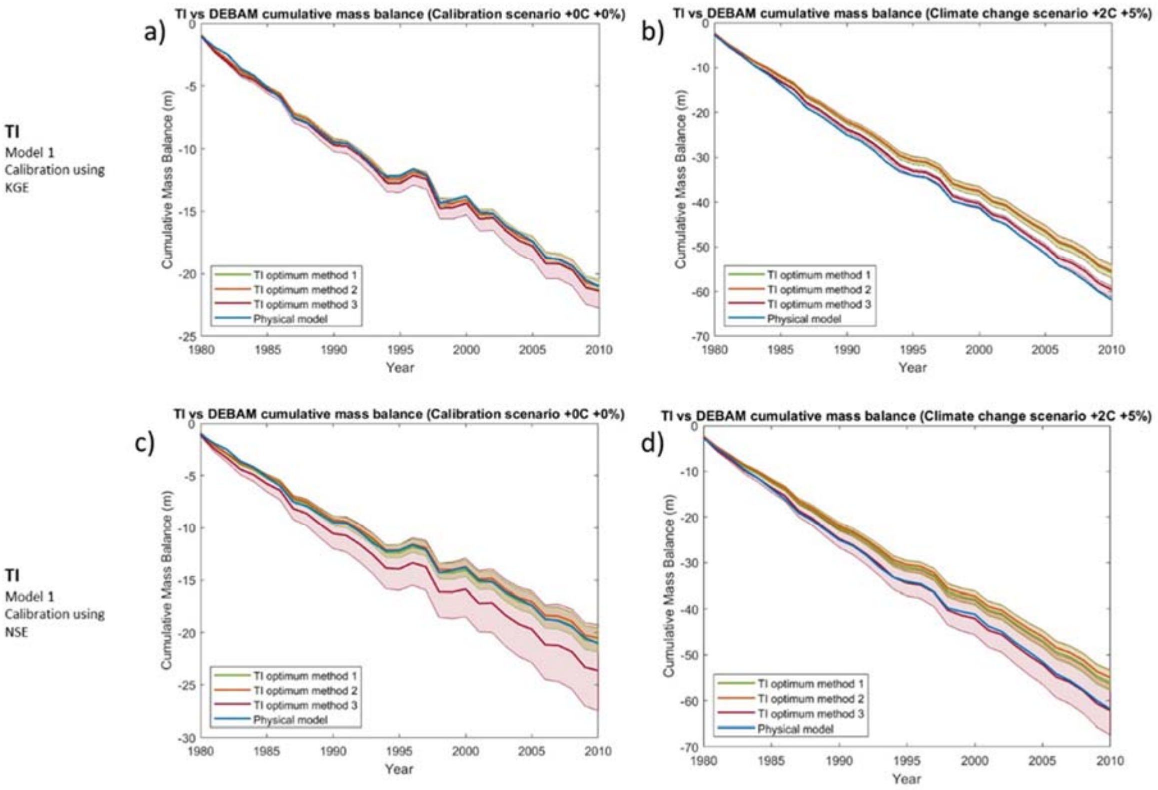


Figure 9. Cumulative mass balance for the optimal parameter sets (bold) and 90 percentiles uncertainly due to parameter equifinality (transparent envelopes) for calibration method 1 (green), method 2 (orange) and method 3 (red). Cumulative mass balance of the physical model is represented by the bold blue line. Graphs on the left side are the cumulative mass balance of the 1979-2010 period in calibration scenario (*ΔTa = 0°C; ΔP = 0%*). Graphs on the right side are the cumulative mass balance of the 1979-2010 perturbed by the most probable climate change scenario for the study area (*ΔTa = 2°C; ΔP = 5%*) according to IPCC (2013). (a-b) Calibration with the KGE criterion. (c-d) Calibration with the NSE criterion.

Finally, the standard deviation of the equifinal bias values (Fig. 8-e-f) show that for the three methods, the uncertainty of the TI model is smaller when calibrated with the KGE. This preliminary test show that the major difference we can observe in our results when using the KGE instead of the NSE as the calibration criterion is that we have less equifinal combinations and a smaller uncertainty of the TI model. A smaller uncertainty on the optimal values of the parameters could help improve the performance of the models. We can also observe that 'spatial' calibration method 3 have a better performance in calibration scenario when using KGE as the calibration criterion. Differences of temperature-index model long term performances using optimal values determined by KGE and NSE should be analysed to better represent mass balance variability and calibrate models more accurately.

2.8.5 Possible causes for poor model transferability

Gabbi *et al.* (2014) and Pellicciotti *et al.* (2005) observed that temperature-index models are particularly sensitive to air temperature changes and analyses from Kinnard *et al.* (2022) on the physical model projections, showed that the model is much more sensitive to air temperature changes than to precipitation rate changes. During the validation process, we observed that the projection bias of empirical models is a lot more sensitive to warming than to precipitation rate changes. Positive projection biases in climate change scenarios indicates that the models underestimate melt in these conditions. Therefore, a positive bias indicates that the temperature-index models are less sensitive to climate warming than the physically-based model. When using the 'geodetic' method 1 and the 'glaciological' method 2, all the models were found to be less sensitive to climate warming than the physically-based model. When using the 'spatial' method 3, all the models showed a larger sensitivity to warming than the physically-based model for scenarios closer to calibration (ΔTa 0°C to 1°C except ETIb) and a lesser sensitivity under extreme air temperature change (ΔTa 3°C to 8°C except ETIb).

Kinnard et al. (2022) showed that 44% of the mass balance response to warming on Saskatchewan Glacier was due to albedo reduction, 24% to atmospheric warming and the rest driven by a positive humidity feedback and the conversion of snowfall to rainfall. In all five models, atmospheric warming is represented by air temperature and conversion of snow to rain fall are accounted for by precipitation data. Temperature-index models are considering albedo either by differentiating snow and ice parameter (TI, HTIa and HTIb), representing changes in snow cover, or by including an albedo parameter (ETI and ETIb) representing changes in snow cover and snow metamorphism through time. However, humidity feedbacks are not represented by the temperature-index models. This could explain the growing projection bias with the warming level and the fact that the models are less sensitive to climate changes than the physically-based model in most situations.

2.9 Conclusion

In this study, we tested the capacities of five temperature index models to reproduce similar results in different climate scenarios than the projections of a physical model run by Kinnard *et al.* (2022) on the Saskatchewan glacier. Three calibration methods were tested to study their impact on the bias of projections and on the uncertainty of the models. The main conclusions of this work are:

1. The global calibration methods ('geodetic' method 1: using the total mass balance of the glacier surface; 'glaciological' method 2: mean mass balance extrapolated from the stakes) have very similar or equal results, for all five temperature-index models that we tested.
2. Calibration methods 1 and 2 have results closer to the physical model during the calibration period, but the spatial calibration method 3 (calibration on point balance at stakes) yields closer results to the physical model in the most probable climate change scenario for the study area (ΔTa 2°C; ΔP 5%).
3. Simpler models (TI, HTIa and HTIb) were more able to reproduce mass balance variations as simulated by the physical model than more complex models (ETI and ETIb) in calibration period and in climate change scenarios.
4. The projection biases of the models were a lot more sensitive to air temperature changes than to precipitation rates changes.
5. Impact of objective function (NSE vs KGE)

This study shows the importance of choosing the appropriate calibration method for the goals of a study. As seen by our results, different methods can give more or less accurate results in calibration and climate change scenarios. The difference between methods should be tested on more glaciers in different climate. We also observed briefly that the statistic criterion used to select the optimal and equifinal combinations affects the performance of the models and their transferability into different climate scenarios.

In future studies, the impact of the calibration method on model's projections and uncertainty should be studied more. A more profonde knowledge of the impacts of different calibration methods in different contexts and climates could help improve mass balance projections on glaciers that don't have the necessary data to use physically based models. The impact of the calibration criterion on projections should also be studied more to have a better idea of the behaviour of temperature-index models when they are calibrated with different criterion. This could help reduce the uncertainty of the models due to equifinality.

2.10 Code availability

The glacier mass balance model code is available at https://regine.github.io/meltmodel/ . Modifications have been made on this code to insert models ETI and ETIb. For more information on the subject, contact the corresponding author.

2.11 Author contribution

Conceptualisation: CK, Data analysis: CK & LM, Supervision: CK, Composition, revision & editing: CK & LM.

2.12 Competing interests

The authors declare that they have no conflict of interest.

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CHAPITRE 3

CONCLUSION GÉNÉRALE

Ce projet de recherche visait à comparer la performance de cinq modèles empiriques de bilan de masse dans différents scénarios de changement climatique. Les projections des modèles ont été comparées avec les simulations d'un modèle à base physique qui ont été réalisées par Kinnard *et al.* (2022) pour le glacier Saskatchewan. L'étude visait également à tester l'impact de trois différentes méthodes de calibration sur les performances des modèles. Les hypothèses émises précédemment se sont vues partiellement réfutées par les observations suivantes :

1. La comparaison de la performance des modèles nous a montré que les modèles les plus complexes (ETI et ETIb) ne sont pas ceux qui ont eu les résultats les plus proches du modèle physique, contrairement à l'hypothèse que l'on avait émise. Ce sont plutôt les trois modèles les plus simples qui ont eu les meilleures performances (TI, HTIa et HTIb). Ces résultats montrent l'importance de tester différents modèles pour représenter le mieux possible l'évolution du bilan de masse d'un glacier plutôt que de se fier sur les résultats d'autres études sur d'autres glaciers pour la sélection du modèle.
2. Le biais des projections des modèles était plus sensible aux changements de température de l'air qu'aux changements de taux de précipitations.
3. Les méthodes de calibration 1 (comparant le bilan de masse de toute la surface du glacier) et 2 (comparant la moyenne du bilan de masse des balises) ont des résultats similaire ou identiques pour tous les modèles testés. L'utilisation de l'une ou l'autre de ces méthodes ne semble pas affecter la performance des modèles.
4. Les méthodes de calibration 1 et 2 ont obtenus des résultats plus près du modèle physique dans la période de calibration. La méthode de calibration 3 (qui fait la moyenne des différences de bilan de masse de chacune des balises) a des résultats plus près du modèle physique dans les scénarios de changement climatique, particulièrement dans le scénario le plus probable pour la région d'étude (ΔTa 2°C;

ΔP 5%). Ces résultats montrent que la méthode 3 permet une meilleure transfert du modèle dans des conditions climatiques différentes.

3.1 Perspectives de recherche

Les résultats énoncés ci-haut démontrent l'importance de choix du modèle et de la méthode de calibration sur les projections de bilan de masse obtenus. Il serait donc pertinent que l'évaluation des différentes méthodes de calibration soit incorporées dans les futures études sur la modélisation glaciologique afin de sélectionner la méthode qui convient le mieux au site à l'étude et ainsi améliorer les projections des modèles. Une connaissance plus approfondie de l'impact des méthodes de calibration sur la performance des modèles dans différents contextes et climats permettrait d'améliorer les projections de bilan de masse, donc de mieux prévoir l'évolution des glaciers pour lesquels il n'y a pas les données nécessaires à l'utilisation des modèles à base physique. Il serait également intéressant d'approfondir les connaissances sur l'impact du choix de la métrique utilisée pour sélectionner les valeurs optimales des paramètres sur la performance des modèles. Ces connaissances permettraient de réduire l'incertitude des modèles et d'améliorer les projections hydrologiques et climatiques liées à l'évolution des glaciers dans le temps.

Cette étude permet de poser des premières conclusions sur ces problématiques peu étudiées dans le domaine de la glaciologie. Cela souligne la pertinence de faire d'autres études du même type sur des glaciers ayant des climats similaires et différents afin de confirmer ou d'infirmer ces hypothèses. Il serait donc recommandé de faire des études similaires sur les glaciers pour lesquels les données météorologiques nécessaires sont disponibles. Cela permettrait d'améliorer la modélisation de l'évolution des glaciers dans les décennies à venir.

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