Revisiting earlier predictions of glacier retreat: The case of Langfjordjøkelen

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ABSTRACT

European glaciers constitute a part of the climate system that is bound to greatly change in the course of the 21st century. Recent length-change observations from Langfjordjøkelen in northern Norway confirm the earlier predictions of Charalampidis (2012), who identified the glacier's disequilibrium with climate and hence extensive committed ice loss in the 21st century. Simulations suggest that, over the 2026–2050 period, the glacier outlet will continue adjusting its geometry with a rate of retreat of $\sim 33\,\mathrm{m\,a^{-1}}$ for a moderate regional precipitation increase in a warming climate, and with regional climate variability in the context of a warming Arctic only augmenting the persistent retreat. The glacier outlet of Langfjordjøkelen is predicted to eventually split in two parts due to substantial retreat and thinning sometime in the 2050s.

CLIMATE TRENDS IN EUROPE

Summer 2022 in the European continent was extreme: The persistent hot and dry conditions resulted in major rivers across Central Europe being dried up by the beginning of August, when according to a combined drought indicator (CDI) map of the European Drought Observatory, 47 and 17 % of the EU territory were in "warning" and "alert" conditions, respectively (Toreti and others, 2022). Overall, August 2022 was the warmest August since 1979, with the average temperature being $\sim 1.7\,°\mathrm{C}$ above the 1991–2020 average and $\sim 95\,\%$ of Europe experiencing positive temperature anomalies (data source: copernicus.eu). Regarding glacier-ice loss, in late August 2022, Swiss glaciologist Matthias Huss reported on social media that, in the European Alps, we are "far beyond historical variability." Schneeferner, the iconic Bavarian glacier, suffered dramatic area losses, while its ice thickness dropped in most places below two meters.

With such low ice thickness—and hence ice movement—Schneeferner lost its "glacier" status in the end of September 2022 (Latzin, 2022).

Unprecedented climate extremes, such as summer 2022 in Europe, have been occurring ever so often in recent years (IPCC, 2022). According to the various recent IPCC—Intergovernmental Panel on Climate Change reports (e.g. IPCC, 2019), persistent increasing or decreasing trends that different parts of the climate system (e.g., global surface temperature, global average sea level, Arctic sea-ice cover, etc.) have been exhibiting in recent decades will likely persist for at least the next 20 years. Accordingly, summers in Europe are expected to become warmer, with more frequent, more intense, and long-lasting heatwaves (IPCC, 2022).

Regarding European glaciers, several recent studies (e.g. Charalampidis and others, 2018; Zekollari and others, 2020) have identified extensive committed ice losses due to the relatively slow glacier response times caused by the lag between climate forcing and glacier adaptation. In light of the accumulating glacier observations, revisiting earlier predictions of glacier retreat can elucidate the recent glacier responses in the context of the current climate trends, as well as different aspects of the utilised methodologies.

TWENTY-FIVE YEARS OF OBSERVED LENGTH CHANGE OF LANGFJORDJØKELEN

Langfjordjøkelen (70° 10´ N, 21° 45´ E) is a maritime plateau glacier at the Troms og Finnmark county, northern Norway; its area is $\sim 6.2\,\mathrm{km}^2$ (2018 estimate), of which $2.6\,\mathrm{km}^2$ drains eastward and is where the Norwegian Water Resources and Energy Directorate (NVE) has been conducting investigations. Langfjordjøkelen has been experiencing negative annual mass budgets (MBs) since 1996, with the mean annual MBs for 2001–2010, 2011–2020, and 1996–2020 (i.e., 25 years) being -1.25, -0.99, and $-1.07\ \mathrm{m\,w.e.\,a^{-1}}$, respectively (Kjøllmoen and others, 2021). The length change of Langfljordjøkelen has been recorded on an annual basis since 1998, while the dataset has been extended further back in time based on available maps from 1994 and 1966 (Andreassen and others, 2020; Andreassen and Elvehøy, 2021). Observations are freely available through NVE's glacier data portal (http://glacier.nve.no/glacier/viewer/ci/en/).

Charalampidis (2012) used a two-dimensional ice-flow model based on the shallow-ice approximation (SIA) involving a partially implicit/partially explicit discretisation method (i.e., alternating direction implicit method) to investigate the response of Langfjordjøkelen to various 21st century climate-change scenarios. Simulations were performed at a relatively coarse $50 \times 50\,\mathrm{m}$ spatial resolution based on a series

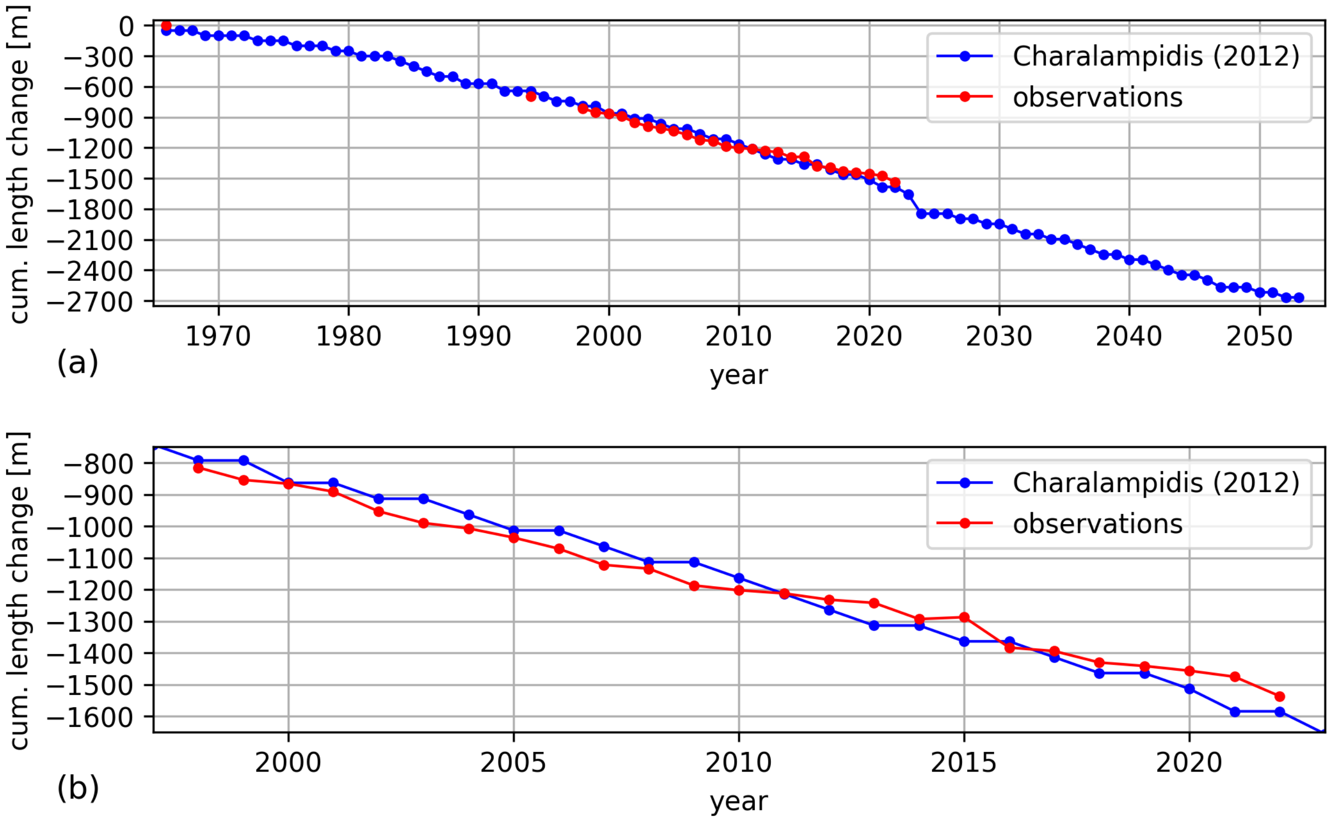

Fig. 1. (a) Predicted versus observed cumulative length change of Langfljordjøkelen since 1966. The predicted values are in response to linear mass-budget decrease until a 2071–2100 scenario of increased regional temperature and precipitation by 3.0 °C and 20 %, respectively, with respect to the 1961–1990 former normal period. (b) Same as in panel a, but for the 25-year, 1998–2022 period of continual observations, over which the average predicted and observed glacier retreats are 34.2 and 29.2 $\mathrm{m\,a^{-1}}$, respectively (both values corresponding to linear regressions with $R^2 = 0.99$), and the mean signed, mean absolute, and root-mean-square errors are 3.0, 42.2, and 49.5 m, respectively.

of assumptions/approximations regarding the climate forcing (e.g., stepwise MB changes for the historical period and linear MB decreases for the future projections). The ice-flow model was dynamically calibrated on the observed ice-thickness and length changes of the glacier outlet up until 2010, and was ultimately well able to reproduce them.

Since 2010, 12 years have passed, with continual length-change observations for Langfjordjøkelen spanning now a total of 25 years (Fig. 1). Over the 1998–2022 period, Langfjordjøkelen has been persistently retreating by $\sim 29\,\mathrm{m\,a^{-1}}$; this rate of retreat is very close to the $\sim 34\,\mathrm{m\,a^{-1}}$ of the "most probable scenario" of Charalampidis (2012) (i.e., a 2071–2100 scenario of increased regional temperature and precipitation by 3.0 °C and 20 %, respectively, with respect to the 1961–1990 former normal period), which is in accordance with the recent Arctic climate trends (Box and others, 2019). The predicted length change remains valid—within the model's limitations—with the root-mean-square error over the 1998–2022 period being approximately equal to the spatial resolution of the model (i.e., 50 m).

Sensitivity analysis showed that Langfjordjøkelen will continue adapting its geometry by retreating (also thinning), as it is far away from a steady state (Charalampidis, 2012). For the second quarter of the 21st century (i.e., 2026–2050), the model predicts a rate of retreat of $\sim 33\,\mathrm{m\,a^{-1}}$; for this period, and for a reasonable regional precipitation increase (i.e., $< 20\,\%$ with respect to the 1961–1990 average) in a warming atmosphere, this rate is relatively insensitive to the magnitude of regional temperature increase. This means that potential regional climate extremes in the context of a warming Arctic (Serreze and Barry, 2011; Box and others, 2019) will only augment the ongoing persistent retreat of Langfjordjøkelen.

The glacier outlet is predicted to split in two parts sometime in the 2050s, owing to the combined effects of reduced ice thickness and large (i.e., $\sim 50\,\%$) slope of the bedrock at a certain point along the flowline. While the exact year when this happens depends on the magnitude of the impending regional warming, a precise prediction of the timing of the split is hindered by the following two factors: First, compared to the ice-thickness measurements, the SIA underestimates the ice thickness over the large-slope area, which could mean a prediction of the split ahead of time; second, the ice-thickness measurements at this part involved increased chance of uncertainties (i.e., $\pm 20\,\mathrm{m}$), thereby compromising the precision of the comparison between predicted and measured ice thickness.

Discrepancies between the predicted and observed length changes owing to the definition of the flowline in the model have been thus far quite small, given the approximately straight line along which the glacier outlet has been retreating. They are, however, expected to increase as the glacier outlet retreats further uphill and defining the length and/or the flowline becomes more challenging, both in situ and in simulations.

An ice-flow model with increased complexity that accounts for the seasonal variations of the ice velocities and adopts distributed climate forcing should provide a more refined estimate of when Langfjordjøkelen will become restricted to the plateau area. Nevertheless, it is unlikely that the general results outlined here will considerably change.

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