



Examining Glacier Mass Balances with a Hierarchical Modeling Approach

The results of simulating past and future mass balances suggest that the Bering Glacier will lose significant ice mass and that the Hubbard Glacier will grow more slowly in the near future than in the recent past.

Much has been written and discussed about the effects of recent changes in the Arctic due to dramatic over-all climate changes (www.acia.uaf.edu). Melting land ice, for example, has direct and far-reaching consequences because the resulting water enters the ocean and changes the global mean sea level. In contrast, melting sea ice influences the climate by changing vertical ocean density profiles—the results don't directly change the global sea level, but they contribute to thermal expansion due to warmer ocean water, which also raises sea level.

Mark Meier was the first to estimate that glaciers in Alaska and NW Canada contribute more to the rising mean sea level than all other melting glaciers worldwide (excluding the Greenland and Antarctic ice sheets).¹ Airborne laser altimetry² measurements of the region confirmed this by showing that these glaciers have been suffering

rapid ice loss. From the mid 1950s to the mid 1990s, glaciers in Alaska and NW Canada accounted for approximately 5 to 9 percent of the observed global mean sea-level rise. From the mid 1990s to 2001, these glaciers lost mass almost twice as rapidly, accounting for roughly 6 to 12 percent of the increased rate of global mean sea level during this time period.³ This accelerated ice loss is most likely the result of a strong warming trend observed at northern high latitudes over the past 20 years,⁴ which is due partly to multidecadal climate variability⁵ and partly to warming resulting from increased greenhouse gases from human activities. If global warming continues as most climate model simulations project, the retreat of glaciers worldwide is likely to accelerate, which provides a strong motivation for developing computer tools to quantify estimates of future changes.

This article focuses on estimating a changing climate's influence on the mass balance of the Bering and Hubbard glaciers. Our research's overall goal is to estimate how these glaciers will contribute to rising sea levels by using an arctic regional model forced with global climate model (GCM) boundary conditions and a glacier mass balance model calibrated to altimetry measurements.

The International Polar Year

Our project is connected with two of the International Polar Year's (IPY's) six working themes (www.

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FURTHER INFORMATION ON GLACIERS

This article focuses on changes in land glaciers, but the ice sheets in Greenland and Antarctica will play an increasingly dominant role in how high the sea level rises. If melted completely, the Greenland Ice Sheet would lead to a 7-meter increase in sea level, and the West and East Antarctic Ice Sheets would add an additional 5 and 65 meters to the sea level, respectively.

The following Web sites document dramatic changes in ice sheets, their impacts, and some of the tools used to research their evolution:

- The NASA Earth Observatory (<http://earthobservatory.nasa.gov/Study/vanishing/>) presents a summary of the melting of ice on Greenland. You can find a discussion about the recent acceleration of Greenland's Jakobshavn glacier at NASA's "Looking at Earth" Web site (www.nasa.gov/vision/earth/lookingatearth/jakobshavn.html).
- The West Antarctic Ice Sheet Initiative (igloo.gsfc.nasa.gov/wais) provides information about an interdisciplinary project dedicated to WAIS. Visit the link, "What's Cool about WAIS?" (<http://igloo.gsfc.nasa.gov/wais/>), to get started.

- Earth Science, Logistics, and Outreach Terrainbases (EarthSLOT; www.earthslot.org) is a suite of applications that facilitates 3D GIS and terrain visualization for improving our understanding of the Earth system, particularly in the Arctic.
- The "Climate Change and Sea Level" site lets users view dynamic global maps of coastal areas that are susceptible to sea-level rise (www.geo.arizona.edu/dgesl/research/other/climate_change_and_sea_level/sea_level_rise/sea_level_rise.htm). Users can define the region of interest, the amount of sea-level change (between 1 and 6 meters), and include geographical information, such as population, when generating maps.

This article focuses on the application of global climate system models for predicting changes in glacier mass balances. In the next issue, the featured International Polar Year track article will describe the ice-ocean modeling component of Earth system models. The interaction between the ice-ocean-atmosphere and solar radiation in the Arctic is thought to be one of the most important driving mechanisms of global climate. Understanding the details of these interactions in high latitudes is critical to making better predictions of future climate.

www.ipcc.org/development/themes.htm). The overall project has both an observational and modeling components, but this article's focus is on the modeling aspect, in which we use a set of hierarchical models (those with varied spatial-temporal scales and complexity) to estimate the environment's current state. This helps us develop an understanding of model biases (IPY theme 1 is to determine the current environmental state), which we can apply to better estimate future glacier mass balances (IPY theme 2 is to improve predictions about the region).

Analyzing future projections in GCMs forced with different greenhouse gas scenarios has given climate scientists some understanding of the expected large-scale response to anthropogenic climate change. However, it's unclear how the climate will change regionally. As Figure 1 shows, the representation of surface topography in Alaska and its surroundings is quite different in a global model with coarse resolution (hundreds of kilometers) than in a regional model with finer resolution (tens of kilometers). The former gives a poor representation of temperature and precipitation, so we must downscale the GCM information to address local issues, such as how climate change will affect local agriculture and human health. However, biases in our models (both regional and

global) and the lack of long-term observations make downscaling a nontrivial task, particularly in the Arctic.

Our main approach is to use dynamical downscaling on climate variables in which the coarse-resolution GCM output provides information about the atmosphere/ocean/ice system's state at a regional model's boundaries. We then integrate the regional model over time to produce high-resolution local information. We conducted two sets of simulations—a *hind cast*, which validates our prediction system by modeling the past, and a *forecast*, in which we make predictions regarding the future. Figure 2 outlines the forcing data sets for the hind cast and forecast as well as the hierarchical modeling's global/regional/local strategy, which exploits each model's strength. We tested the system's performance by simulating the past and estimate the future mass balances of two distinct types of glaciers—a large tidewater glacier (Hubbard) and a large surge-type glacier (Bering). The two are located in the high St. Elias and eastern Chugach Mountains in Alaska and NW Canada, and contain relatively large water equivalents.

Global Climate Scales

In our hierarchical modeling strategy, the regional

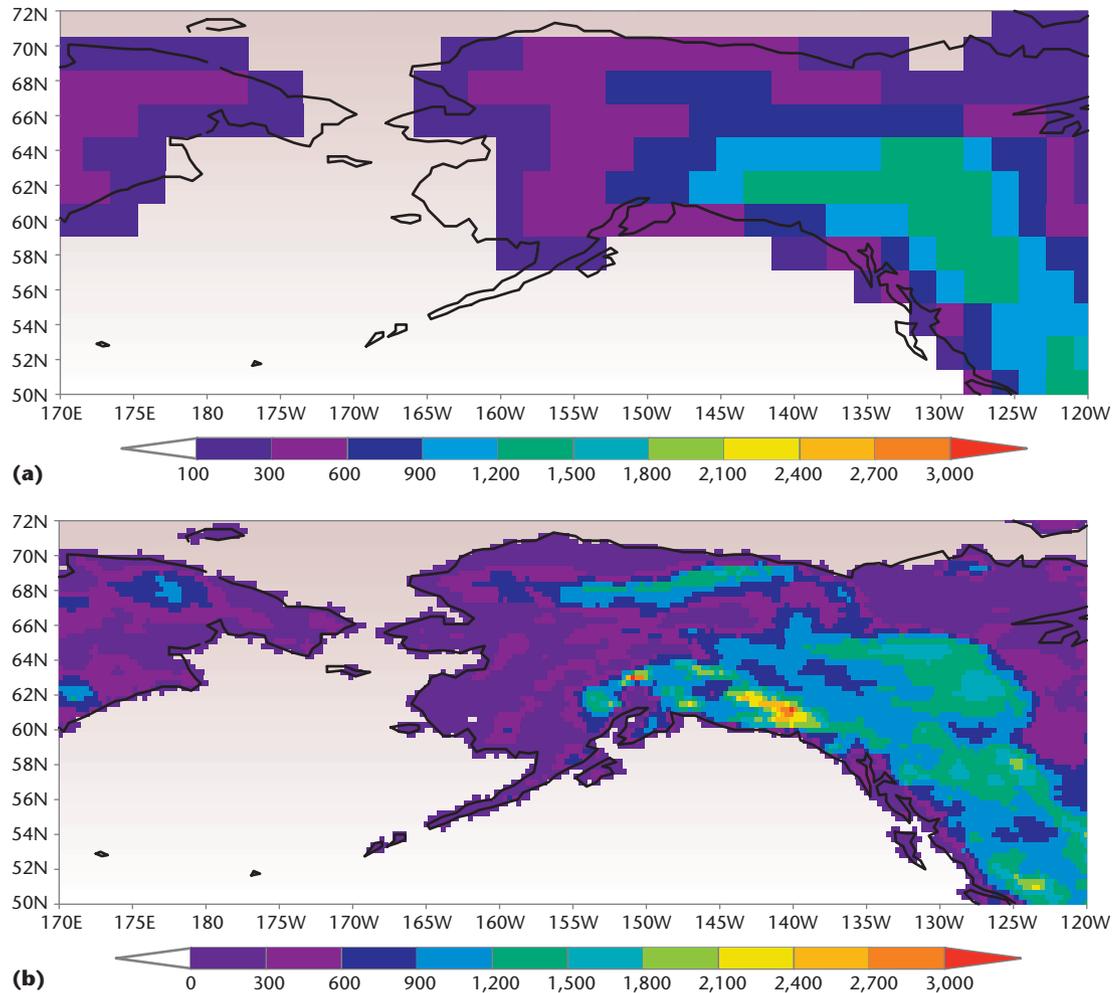


Figure 1. Topography of Alaska elevation (meters). Note the difference between the coarse global horizontal grid of roughly 200 km from (a) the US National Center for Environmental Prediction (NCEP) and (b) the regional horizontal scale of roughly 32 km.

model's boundaries include temperature, humidity, winds, sea-surface temperature, and several other meteorological variables from a GCM. We use version 3.0 of the US National Center for Atmospheric Research's (NCAR's) community climate systems model (CCSM3), which has four component models to represent the atmosphere (CAM3), ocean (POP1.4.3), sea ice (CSIM5), and land surface (CLM3). These models are linked through a flux coupler, which enables interaction between the components in a physically consistent manner. CCSM3 offers many improvements over previous versions, specifically in its parameterizations of cloud processes, aerosol-radiative forcing, land-atmosphere fluxes, and sea-ice dynamics.⁶

CAM3 is a global atmospheric general circulation model with 26 unevenly spread vertical levels;

it's based on the Eulerian spectral dynamical core, with triangular truncation at 31, 42, and 85 wave numbers and horizontal resolutions of approximately 3.75°, 2.8°, and 1.4°, respectively.⁷ The community land model (CLM) uses the same grid as the atmospheric model, but each grid box is divided into different land cover and plant types.⁸ The CLM has 10 subsurface soil layers and simulates the evolution of soil moisture and temperature. The ocean general circulation model is an extension of the parallel ocean program (POP) originally developed at Los Alamos National Laboratory.⁹ POP has 40 vertical levels and a uniform east-west resolution of 1.125° and a north-south resolution of roughly 0.5°, with greater resolution near the equator. The community sea-ice model (CSIM) shares the same grid as the ocean model

and predicts ice properties such as area, thickness, and velocity.¹⁰ The CCSM modeling suite can run in various configurations, from fully coupled (all model components are interactive) to specified ocean and ice as a lower boundary forcing for the atmospheric model.

CCSM3 is one of the primary tools used to predict future climate. In fact, NCAR conducted simulations using the fully coupled CCSM version of the model with various future greenhouse gas scenarios for the 2007 Intergovernmental Panel on Climate Change (IPCC) climate assessment report. In our study, we use the middle-of-the-road A1B scenario, in which carbon dioxide increases from 380 to roughly 700 parts per million (ppm) over the 21st century.¹¹ The GCM output from the A1B scenario simulation that's required for downscaling consists of variables with high temporal and spatial resolution, totaling roughly 300 Gbytes for every 10 years of downscaling. Accessing and manipulating this amount of data is now possible because of recent advances in computing power and the development of open source atmospheric sciences data-processing tools.

Regional Climate Scales

In our study, we used version 5 of a relatively high-resolution Arctic mesoscale model (MM5) for dynamical downscaling of global climate simulations, which gave us the temperature and precipitation inputs for the precipitation–temperature–area–altitude (PTAA) glacier mass balance model.¹² The Polar MM5, which includes a thermodynamic sea-ice model¹³ and a mixed-layer ocean model,¹⁴ is a 3D, nonhydrostatic regional model with a terrain-following sigma vertical coordinate. Complex topography is easier to represent with sigma coordinates, which represent the ratio of air pressure at some height above the surface-to-surface pressure, resulting in sigma values from 1 at the surface to 0 at the top of the atmosphere. MM5 offers multiple options for physical parameterization schemes and a nested-domain design that let us tailor simulations to the region or problem of interest. This feature also allows high-resolution simulations over a specific area while saving computational resources.

In Figure 3, the mother domain has a resolution of 54 km, covering Alaska and parts of northwestern Canada and northeastern Russia, whereas the nested domain has a resolution of 18 km and covers the heavily glaciated regions of Alaska and NW Canada. This domain configuration should provide an adequate representation of the overall synoptic environment that affects south-central Alaska (such as low-pressure systems from the north Pacific and

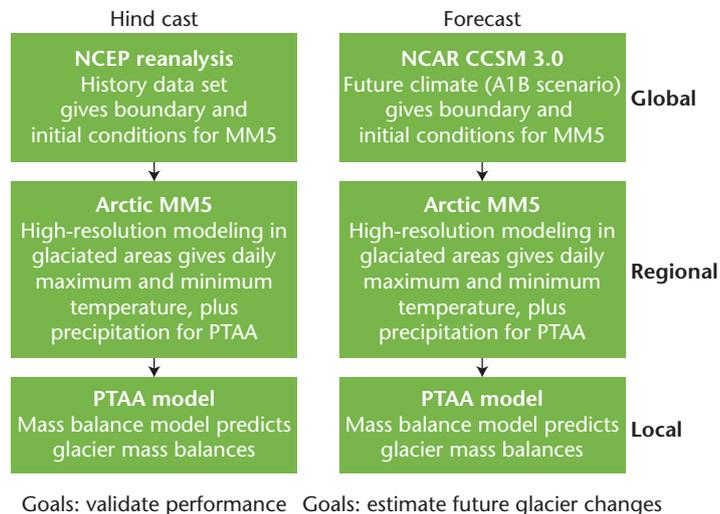


Figure 2. Atmosphere–glacier hierarchical modeling system. The hind cast (modeling the past) is displayed in the left column and the forecast on the right.

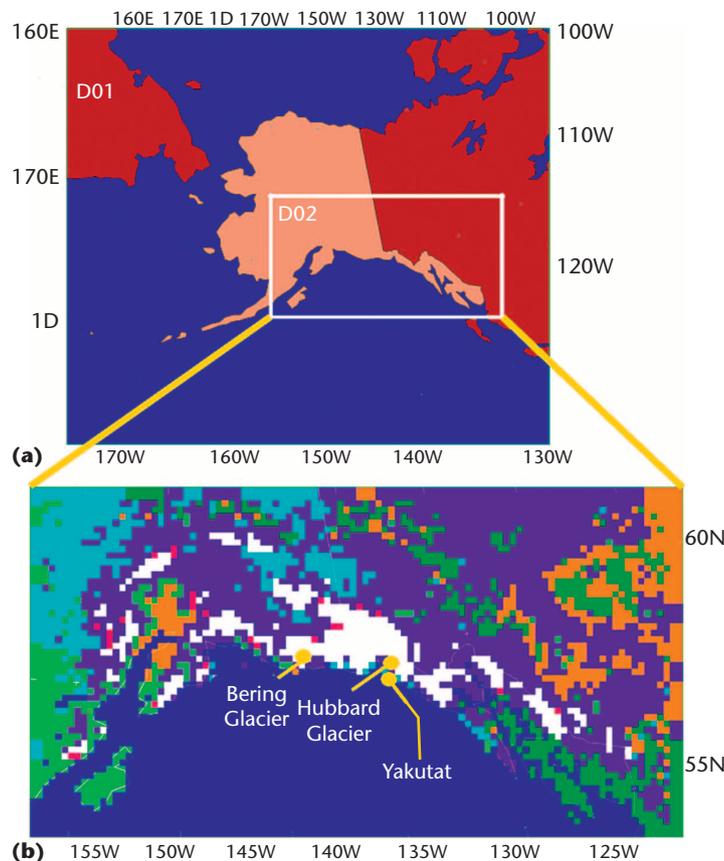


Figure 3. Regional model boundaries. The (a) regional model's domain configuration has a resolution of 54 km in the big domain and 18 km in the nested domain. Glaciated regions in the (b) nested domain appear in white grid boxes.

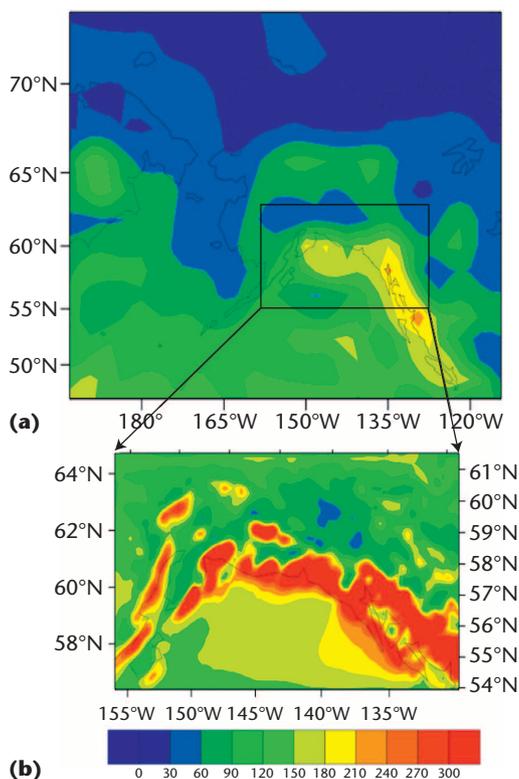


Figure 4. Precipitation in cm averaged over the period August 1995 to July 2005 (a) at a low resolution and (b) at the regional model's finer resolution. The higher resolution precipitation is produced by dynamical downscaling, in which a finer-scale regional model increases the spatial resolution of weather and climate information from the coarser-scale global climate model. Precipitation is strongly influenced by surface topography, and the downscaled precipitation better represents the observed precipitation over mountains.

high-pressure systems from Siberia and the Beaufort Sea), while also allowing for a finer and more detailed representation of the glaciated area's more immediate environs. We carefully analyzed MM5 results with observations from another study¹⁵ to determine the optimal model physics to apply MM5 in high latitudes.

We conducted a hind cast downscaling simulation of the period from October 1995 to September 2004 using boundary conditions from the US National Center for Environmental Prediction (NCEP)/NCAR reanalysis¹⁶ data to force MM5. As we mentioned, the hind cast validates the modeling system by providing meteorological observations to compare with the polar MM5's results.

Reanalyses are gridded meteorological fields produced by assimilating observations into weather forecast models¹⁷ and are treated as observations in climate variability studies. The differences between the NCEP/NCAR (Figure 4a) and downscaled precipitation are quite large (Figure 4b), particularly for the mountainous areas of south central Alaska in which topography plays an important role in precipitation development.

By comparing the downscaled temperature and precipitation data to observed station data, we built a hind cast simulation to quantify biases in the MM5 simulations. The PTAA model requires daily temperatures and precipitation at low-altitude stations near the glacier of interest, so to model the Bering and Hubbard glaciers we used observations from Yakutat, Cordova, and Juneau. We interpolated the MM5-downscaled temperatures and precipitation at the 18-km fine-scale model resolution to these stations while taking the land type and elevation information into account.¹⁸

The interpolated MM5-downscaled data and the observed station data reflect somewhat different local conditions and elevations, so we analyzed the biases between them for the Yakutat, Cordova, Juneau, and Sitka stations over the 10-year simulation period to estimate the model bias and adjust the MM5-downscaled results accordingly. Systematic biases exist in the MM5-downscaled temperatures for all stations. We found a warm bias in daily minimum temperatures and a cold bias in daily maximum temperatures, which was probably due to exceedingly high elevation (80 to 90 meters) in the interpolated data relative to the actual station elevations at Yakutat (9 m), Cordova (9 m), Juneau (4 m), and Sitka (5 m), as well as the land-surface treatment in the MM5 model.

The MM5 overestimated the precipitation at Cordova, Juneau, and Sitka and underestimated the precipitation at Yakutat for nearly all seasons. The model biases had an evident seasonal cycle, so we calculated mean monthly biases for minimum and maximum temperatures and precipitation by taking the difference between the monthly averages of station data and the MM5 downscalings over the entire simulation period.¹⁹

Figure 5 shows daily averaged temperature and precipitation for the 10-year period for the corrected downscaled (green line) and observed (red diamonds) data from the Yakutat station. The downscaled daily average temperatures in Figure 5a compare favorably with observations in both seasonal cycle and variability. The downscaled precipitation in Figure 5b also shows reasonable agreement with observations, except the ability to

capture all the peak rainfall events. A 10-year downscaling simulation using MM5 required one-to-two months of real time on one node of a 72-processor IBM Regatta computer at the Arctic Region Supercomputing Center and produced roughly 1 Tbyte of model output data.

We used the MM5-downscaled daily temperatures and precipitation forced by the A1B scenario in the CCSM3 simulation to provide inputs to the PTAA glacier mass balance model and project mass balance changes on the Hubbard and Bering glaciers from 1 October 2010 to 30 September 2018. Biases also exist between the 20th century CCSM3 simulations and the observed climate for the same period. Ideally, a comparison between downscaled CCSM 20th century simulations and observations would provide the best estimate of CCSM biases. Because of the high cost of performing additional downscaling integrations, however, we're currently using an ad hoc method of correcting for CCSM biases until we can perform the needed simulations.

We calculated the 50-year (1950 to 1999) monthly mean differences of daily maximum and minimum temperatures and daily precipitation between the CCSM3 20th century simulations and the NCEP/NCAR reanalysis data along each latitude band in the Alaska region. We applied both the bias corrections derived from the hind cast and the corrections resulting from the differences between the simulations and the reanalysis data to the future CCSM3-forced MM5 downscalings. We assumed that the biases and bias corrections identified and applied during the past simulations were characteristic of the future time period.

Glacier Climate Scales

The PTAA model helps determine a glacier's mass balance by using daily precipitation and temperature observations from low-altitude weather stations with long historical records.^{20,21} To produce realistic mass-balance results, the model takes into account each glacier's unique area–altitude distribution, which has embedded in its surface configuration a link to the past climate.

The area–altitude distribution is a rough approximation of the spatial orientation of the multitude of individual facets that define a glacier's surface and determine the glacier's mass balance in response to current meteorological conditions. Each facet's altitude and inclination come from the underlying bedrock's erosion over geologic time. The energy (by solar radiation and the turbulent transfer of heat from the surrounding air) and mass (mostly as snow) each facet receives also determine the glacier's total mass balance.

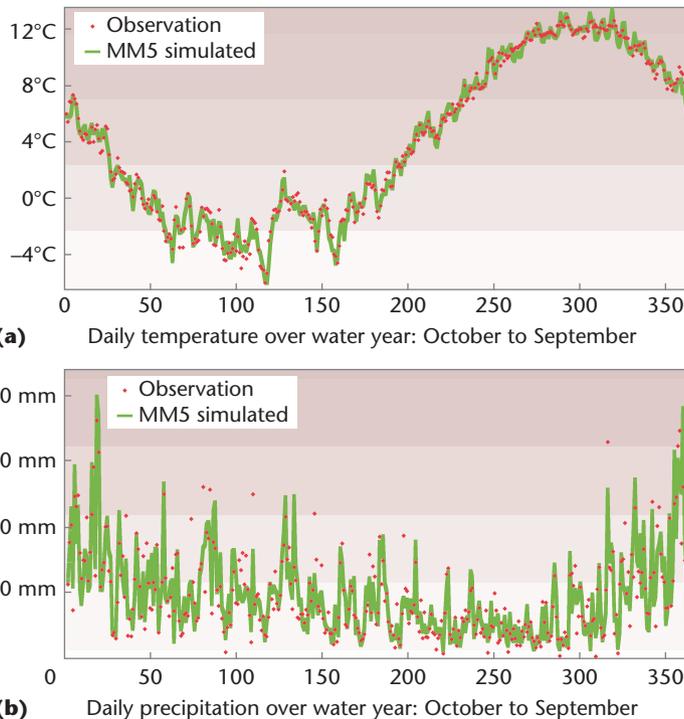


Figure 5. Average temperature and precipitation for 10-year period. (a) The Yakutat station's annual averaged daily mean temperature in °C from the 10-year hind cast; downscaled data is in red and observed station data is shown in red. (b) Precipitation in mm. We corrected the downscaled fields for seasonal biases and altitude.

We calibrated the PTAA model by minimizing the error we got from regressing several sets of daily balance variables with each other (for example, the balance versus the zero-balance-altitude or the balance exchange versus the accumulation-area ratio), which assumes an internal consistency in the link between mass balance and climate that the glacier's area–altitude distribution controls. Researchers have tested this model with observed forcing inputs on several well-measured glaciers in North America²⁰ and the Himalayas,²¹ and it has produced mass-balance hind casts that compare favorably with observed mass balances. Once we've calibrated the PTAA model for a given glacier, it can run on a desktop computer and finish a 50-year simulation on the order of seconds.

Our Results

We compared the projected mass balances versus elevation for the Hubbard and Bering glaciers from 1 October 2010 to 30 September 2018 with the hind cast balances (forced by the MM5 downscalings) and found that accumulation is projected to increase markedly on the higher reaches of both

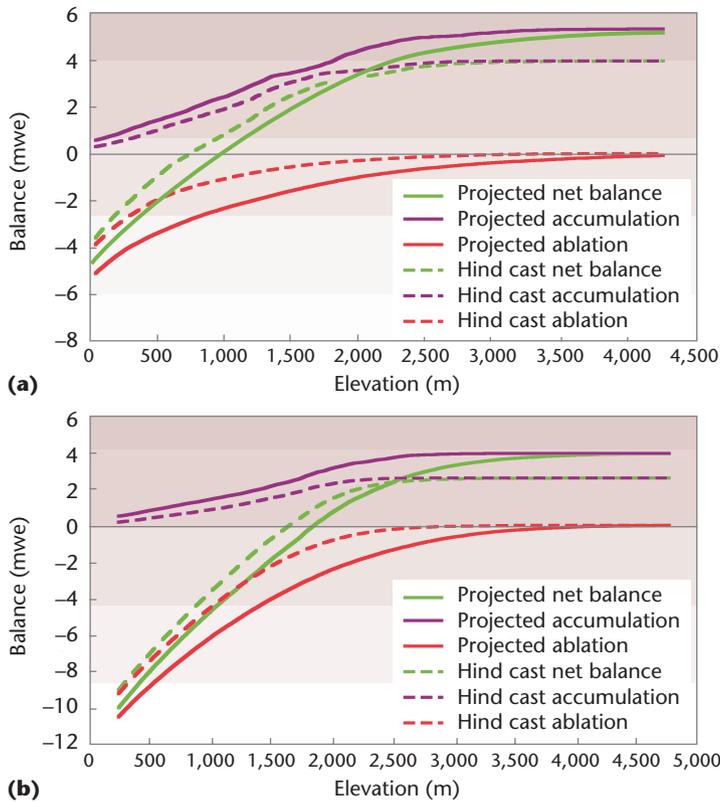


Figure 6. Our results. The (a) Hubbard and (b) Bering glaciers' mass balance (mean water equivalent, or mwe) profiles that the precipitation–temperature–area–altitude (PTAA) model simulates from a 15-km resolution regional climate model (MM5). (Purple shows accumulation, red shows ablation, and green is the net balance.) The hind cast (dashed lines) is for 1 October 1994 to 30 September 2004; future projections (solid lines) are for 2010 to 2018. The equilibrium line altitude divides the glaciers' net accumulation and net ablation regions and shifts roughly 250 meters up the mountain in the future projections.

the Hubbard (Figure 6a) and Bering glaciers (Figure 6b)—roughly 1 meter water equivalent (w.e.). We found that this is primarily due to increased precipitation, especially during winter under the CCSM3 A1B future climate scenario.

A recent study compared all the IPCC GCMs for the entire Arctic cap that project an increase in precipitation.²² The CCSM3 well represents this increase, and its projected precipitation change is within the ranges of several groups of models. *Ablation* refers to both melting and sublimation of ice, essentially representing glacial melt for the modeling results because the sublimation is very small. At low altitudes, our model projects ablation from 2010 to 2018 to be roughly -5 meters/year w.e. at the terminus of the Hubbard Glacier and -10.5 m/yr w.e. at

the terminus of the Bering Glacier, decreasing slowly to almost zero on the uppermost Hubbard Glacier and at 4,000 meters on the Bering Glacier.

Compared to the hind cast results, ablation will increase on the lower Hubbard and Bering glaciers primarily because of increased air temperatures, especially during summers in the CCSM A1B future climate scenario. The mean annual net mass balance for the Bering Glacier for the hind cast is -1.3 m/yr w.e. and for the projection is -2.0 m/yr w.e., suggesting increased melting in the next decade. Assuming a constant iceberg calving (when chunks of ice at the glacier face fall off into adjacent water) rate of $6.5 \text{ km}^3/\text{yr}$, the mean annual net mass balance for the Hubbard Glacier for the hind cast is 0.4 m/yr w.e. and for the projection is 0.3 m/yr w.e., which suggests slightly increased ablation. Iceberg calving plays an important and complicated role in the Hubbard Glacier's mass balance.¹⁹

The next step in our research is to estimate glacier mass balances for 2050 to 2059 and 2090 to 2099. We also plan to downscale by using other future scenarios to provide a range of forecast projections. This type of multidisciplinary research provides many self-contained projects that are appropriate for undergraduates. The last author listed on p. 67 was a student in our group in 2005, and she determined the biases between the downscaled and observed station data for us. Her analysis of these biases contributed to the development of our bias-correction strategy. Other potential undergraduate projects include analyzing the 20th century and future scenario simulations over Alaska to communicate expected climate change in a format that would help planners and scientists in other disciplines.

Most modelers who focus on climate timescale processes aren't directly involved in the IPY, but they'll gradually become more involved because new insights help improve subgrid-scale parameterizations in GCMs. Parameterizations are a major source of uncertainty in current climate models, and polar observations typically haven't been used in developing them. This makes polar climate simulations particularly prone to biases.

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