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Climate downscaling for estimating glacier mass balances in northwestern North America: Validation with a USGS benchmark glacier

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[1] An atmosphere/glacier modeling system is described for estimating the mass balances of glaciers in both current and future climate in order to estimate their probable future contributions to rising sea level. Dynamically downscaled output from a regional atmospheric model, driven by global atmospheric reanalysis, is used to force a precipitation-temperature-area-altitude (PTAA) glacier mass balance model with daily maximum and minimum temperatures and precipitation. The modeling system is verified by hindcasting the mass balances of Gulkana Glacier, a U.S. Geological Survey (USGS) benchmark glacier in the Alaska Range, U.S.A., during a ten-year period from October 1994 to September 2004. The mass balances simulated with the atmosphere/glacier modeling system are comparable to the USGS measurements, and are also in good agreement with the meteorological station observation-forced PTAA simulations. The results suggest this is a promising approach for realistic estimation of the future mass balances of the glaciers of northwestern North America.
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1. Introduction

[2] Airborne laser altimetry [*Echelmeyer et al.*, 1996] has shown that glaciers in Alaska, U.S.A., Yukon, Canada, and northwestern British Columbia, Canada have suffered rapid ice loss. From the mid-1950s to the mid-1990s these glaciers contributed about 52 ± 15 $km^3\ yr^{-1}$ water equivalent (w.e.) to rising sea level, accounting for approximately 5 to 9% of the observed global mean sea-level rise during that time period. From the mid-1990s to 2000–01 these glaciers lost mass almost twice as rapidly, at a mean rate of about 96 ± 35 $km^3\ yr^{-1}$ w.e., again accounting for roughly 5 to 12% of the observed mean sea-level rise during this recent period of more rapid increase [*Arendt et al.*, 2002]. If global warming continues as projected by the most recent climate model simulations for the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (AR4) [*IPCC*, 2007], thinning and retreat of these glaciers, as well as other mountain glaciers worldwide, is likely to accelerate [*Meier et al.*, 2007]. There is thus strong motivation to develop quantitative methods for estimating how much melting glaciers are likely to contribute to rising seal level during the 21st century.

[3] Glacier mass balance modeling, forced by various meteorological data, is widely-used. *Tangborn* [1999] and *Schneeberger et al.* [2001] have used observational data in their glacier modeling, which is a necessary approach for calibrating model performance. *Reichert et al.* [2001] and *Radić and Hock* [2006] used general circulation model (GCM) outputs, and *Raper and Braithwaite* [2006] used both climate data and GCM outputs in their mass balance modeling. Most of these glacier mass balance models require temperature and precipitation data near the glacier of interest as the forcing inputs. However, there is always a concern about applying climate reanalysis data or the results from global climate models on a local scale, due to their coarse resolution. This is especially true for precipitation, which is highly dependent on the local topography. *Serreze and Hurst* [2000] found that the National Center for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) reanalysis and the Forty-year European Re-Analysis (ERA-40) all have notable errors in their precipitation field. Glacierized areas are often characterized by complex topography and thus the representation of complex terrain by high resolution regional models is needed to accurately simulate precipitation as well as surface temperatures.

[4] In this study we verify an atmosphere/glacier hierarchical modeling approach, in which we employ a high resolution regional model to conduct dynamical downscaling of global modeling results and provide temperature and precipitation inputs for a glacier model, to perform glacier mass balance simulations. The regional model used is the Arctic MM5, which is based on the Pennsylvania State University (PSU)/NCAR Mesoscale Model (MM5) coupled to a thermodynamic sea ice model [*Zhang and Zhang*, 2001] and a mixed layer ocean model [*Kantha and Clayson*, 1994]. The glacier model used is the Precipitation-Temperature-Area-Altitude (PTAA) mass balance model [*Tangborn*, 1999], which was developed to use daily maximum and minimum temperatures and precipitation at low-altitude weather stations near the glacier of interest as inputs. The low-altitude observations tend to have higher density and accuracy than the observations at high altitude. In this study, the PTAA model uses the MM5-downscaled temperatures and precipitation interpolated to the locations of the low-altitude meteorological stations near the glacier of interest as inputs in combination with the area-altitude distribution of the glacier to simulate the

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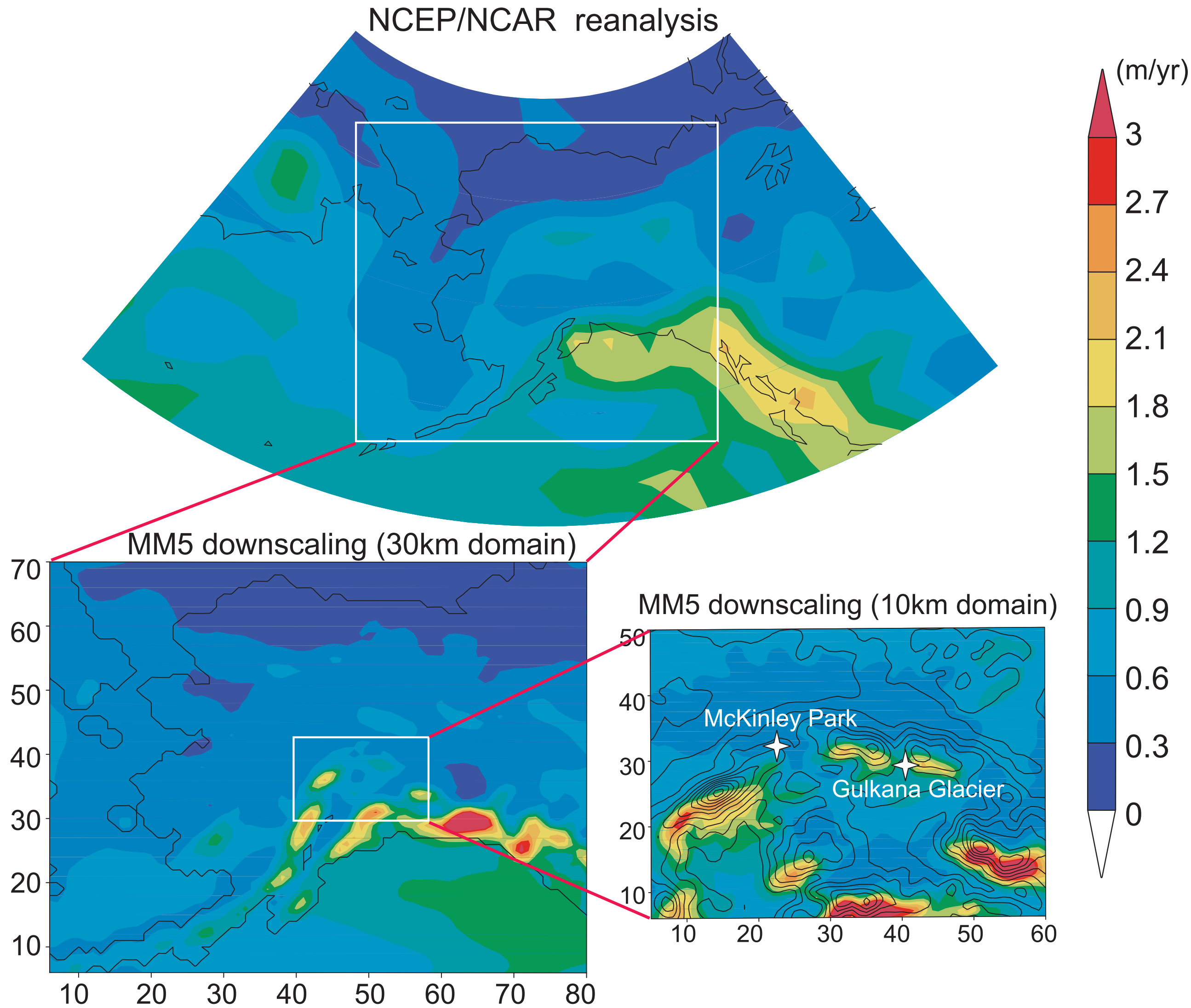

Figure 1. A comparison of 10-year annual mean precipitation between the NCEP/NCAR reanalysis and the high resolution MM5 downscaling over the regional modeling domains, in which the locations of Gulkana Glacier and McKinley Park station are marked with white stars in the 10 km domain and the black contour in the 10 km domain represents topography.

glacier mass balances. This atmosphere/glacier hierarchical modeling approach exploits the strength of each model. The goal of this study is to validate this hierarchical modeling approach for estimating glacier mass balances by showing its capability of reproducing the measured mass balances to an acceptable degree of accuracy.

2. Modeling Design and Gulkana Glacier

[5] Two nested domains were set up for the regional climate downscaling in this study – the mother domain has a resolution of 30 km and covers Alaska along with parts of northwestern Canada and northeastern Russia, while the nested domain has a resolution of 10 km and is located over glacierized regions of interest. The model physics used in this Arctic MM5 simulation include: the Dudhia simple ice microphysics scheme; the Grell convective parameterization; the RRTM radiation scheme; the Mellor-Yamada planetary boundary layer scheme; and the land surface model NOAH-LSM, with which the thermodynamic sea ice model and mixed layer ocean model are coupled. A 10-year downscaling of the global NCEP/NCAR reanalysis data was conducted for the period October 1994–September 2004. In order to perform this long-term simulation with the Arctic MM5 model, the four-dimensional data assimilation nudging was applied to the coarse MM5 domain over the entire simulation period. Figure 1 compares 10-year annual mean precipitation between the coarse resolution NCEP/NCAR reanalysis and the high resolution MM5 downscaling, in which the high resolution afforded by downscaling significantly enhances the low-resolution climate information.

[6] Gulkana Glacier (Alaska Range, U.S.A.) was selected for this study because it is a well-measured USGS benchmark glacier that enables us to evaluate the accuracy of our hierarchical modeling method (For applications of this method to two large Alaska glaciers measured with small aircraft laser altimetry, see *Bhatt et al.* [2007] and *Zhang et al.* [2007]). The USGS has measured the mass balance on Gulkana Glacier since 1966 as part of a program to document long-term glacier and climate trends. These

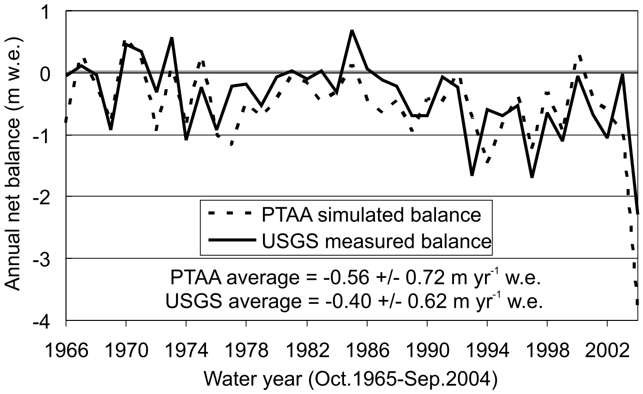

Figure 2. USGS-measured (solid line) and PTAA-simulated (dashed line) annual mass balance for Gulkana Glacier during the water years 1966–2004.

measurements indicate that Gulkana Glacier is rapidly shrinking, with an averaged annual balance of -0.40 ± 0.62 m yr^{-1} w.e. over the period 1966–2004 (Hereinafter, the plus/minus ranges represent the standard deviations of the values). The USGS measurements were verified by *Cox and March* [2004] and are taken as having negligible error. The PTAA-simulated mass balances forced by the meteorological observations from McKinley Park and Big Delta stations during 1966 to 2004 were compared with USGS measurements as shown in Figure 2. The PTAA model reasonably captures the annual variability of the net mass balance for Gulkana Glacier. The average PTAA-simulated annual balance over the same time period was -0.56 ± 0.72 m yr^{-1} w.e. The difference between the simulation and measurement is 0.16 m yr^{-1}. We take this as the error of PTAA mean mass balances for decadal to multi-decadal simulations, which is an acceptable accuracy, considering the constant area altitude profile used in the PTAA simulation.

[7] The large difference between the measured and simulated balance in 2004 is likely to be related to the impacts of Alaska wildfire during the summer of 2004, in which the scattering impact of fire emissions on the solar radiation isn't included. As a result, the simulated mass balance is too negative, which also contributes to a relatively large variation in the simulated mass balances.

3. Results

3.1. Validation of MM5-Downscalings With Observations

[8] The MM5-downscalings were first validated with surface observations. The PTAA uses daily temperatures and precipitation at the weather stations of McKinley Park and Big Delta to model the Gulkana Glacier. Thus the MM5-downscaled temperatures and precipitation at the 10 km model resolution were interpolated to the locations of McKinley Park and Big Delta stations by employing the Cressman interpolation technique, taking the land type and elevation information into account. Since the weather stations are located on land, land-ice grid points were excluded from the interpolation. The elevation limits were set to exclude grid points with elevations higher or lower than the station elevation by 100 meters from the interpolation since interpolated values show much more sensitivity to elevation than to horizontal distance.

[9] The differences between the interpolated MM5-dowscalings and the observations for the McKinley Park and Big Delta stations over the entire simulation period were analyzed in order to estimate the model biases and adjust the MM5 results accordingly. Systematic biases exist in the MM5-downscalings. Both daily maximum and minimum temperatures are too cold in MM5, with maximum biases during spring and fall when snow is present. MM5 tends to produce excessive precipitation throughout the year except during summer. The model biases have a seasonal cycle, so mean monthly biases for minimum and maximum temperatures and precipitation were calculated by taking the difference between the monthly averages of station observations and MM5-downscalings over the 10-year simulation period. The MM5-downscaled daily maximum and minimum temperatures and daily precipitation were then corrected based on the mean monthly bias between the 10-year averaged observations and MM5-downscalings. The detailed calculation was described by *Zhang et al.* [2007]. A quantitative comparison of 10-year averaged temperature and precipitation at McKinley Park for observed station data, uncorrected MM5-downscalings, and corrected MM5-downscalings (Table 1) shows that the biases between observed station data and MM5-downscalings have been significantly reduced.

[10] We also applied the same method of bias analysis and correction to the NCEP/NACR reanalysis for comparing with the MM5-downscalings. The bias-adjusted 10-year averaged daily temperature and precipitation for McKinley Park station and comparisons with the observations are shown in Figure 3. The corrected MM5-downscalings show good agreement with the observations, while the corrected reanalysis agrees well with temperature but not with precipitation. The reanalysis doesn't capture the high frequency variability of daily summer precipitation, which is necessary for realistically simulating glacier mass balances with the PTAA model (see Section 3.3).

3.2. Validation of Glacier Mass Balance Modeling Using USGS Measurements

[11] The PTAA model uses the bias-reduced MM5-downscalings (daily maximum and minimum temperatures and precipitation) as inputs in combination with the area altitude distribution of Gulkana Glacier to simulate the Gulkana Glacier mass balances. The simulated annual mass balances for the time period October 1994 to September 2004 were compared with the USGS measurements as well as the PTAA simulations forced by the station observations (Figure 4a). The MM5-downscaling forced mass balances match the USGS measurements reasonably well. There is

Table 1. Ten-Year (Oct.94–Sep.04) Averaged Daily Temperature and Precipitation at McKinley Park Station

Variables	Observations	Uncorrected MM5-Downscalings	Corrected MM5-Downscalings
Temperature, °C	−2.09	−4.69	−2.09
Precipitation, mm d^{-1}	1.05	1.17	1.03

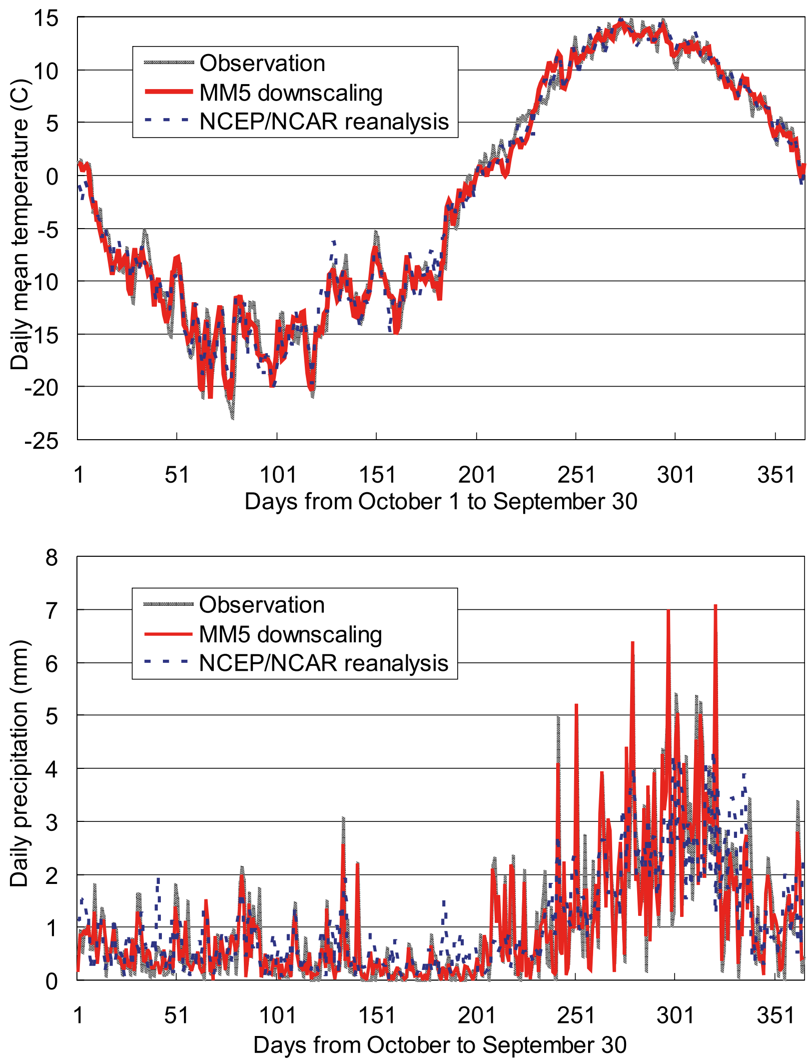

Figure 3. Observed (grey), MM5-downscaled (red), and NCEP/NCAR reanalysis (blue) daily mean temperature (top) and daily precipitation (bottom) at McKinley Park, averaged over Oct.1994–Sep.2004.

also a good agreement between MM5-downscaling and station observation forced mass balances. The averaged mass balance forced by the MM5-downscalings over October 1994–September 2004 is -0.86 ± 1.04 m yr^{-1} w.e., which is very close to the USGS-measured average balance -0.88 ± 0.70 m yr^{-1} w.e. for the same period (Table 2).

[12] The PTAA model also computes the mass balance variables within each element of altitude in the area altitude profile. The 10-year averaged accumulation and ablation profiles over October 1994–Septemebr 2004 that were forced by both the MM5-downscalings and the station observations match very well (Figure 4b). The accumulation ranges from about 0.3 meter (w.e.) at the terminus of Gulkana Glacier (1158 meters) to 1.2 meters (w.e) at top of Gulkana Glacier (2440 meters). On the other hand, the ablation on the lower Gulkana Glacier is about 3.8 meters (w.e) and then gradually decreases to 0.3 meter (w.e.) at the top of Gulkana Glacier. For the whole glacier, 10-year averaged accumulation is about 0.8 meter (w.e.) and the ablation is about 1.6 meters (w.e.). Over the 10-year simulation period, the annual accumulation doesn't change very much, but there is a significant trend of increasing annual ablation (not shown), which results in an increasingly-negative mass balance.

3.3. Sensitivity of PTAA Model to Meteorological Inputs

[13] Sensitivity experiments were performed to evaluate the PTAA model sensitivity to the uncorrected MM5-downscalings and to the temporal variations in the forcing inputs. When the uncorrected MM5-downscalings were provided to the PTAA model, the modeled mass balance of the Gulkana Glacier over the 10-year simulation period is 0.52 m yr^{-1} w.e. (Table 3), which is a significant discrepancy from the measurement (-0.88 ± 0.70 m yr^{-1} w.e.). When the combination forcing inputs, i.e., observed temperatures (or precipitation) and the uncorrected precipitation (or temperatures), were used to forced the PTAA model, the simulated mass balance (-0.42 m yr^{-1} w.e.) forced by the observed temperatures and uncorrected precipitation shows the least discrepancy from the measurement, suggesting the correction of MM5-downscaled temperatures is critical for realistically modeling the mass balances of the Gulkana

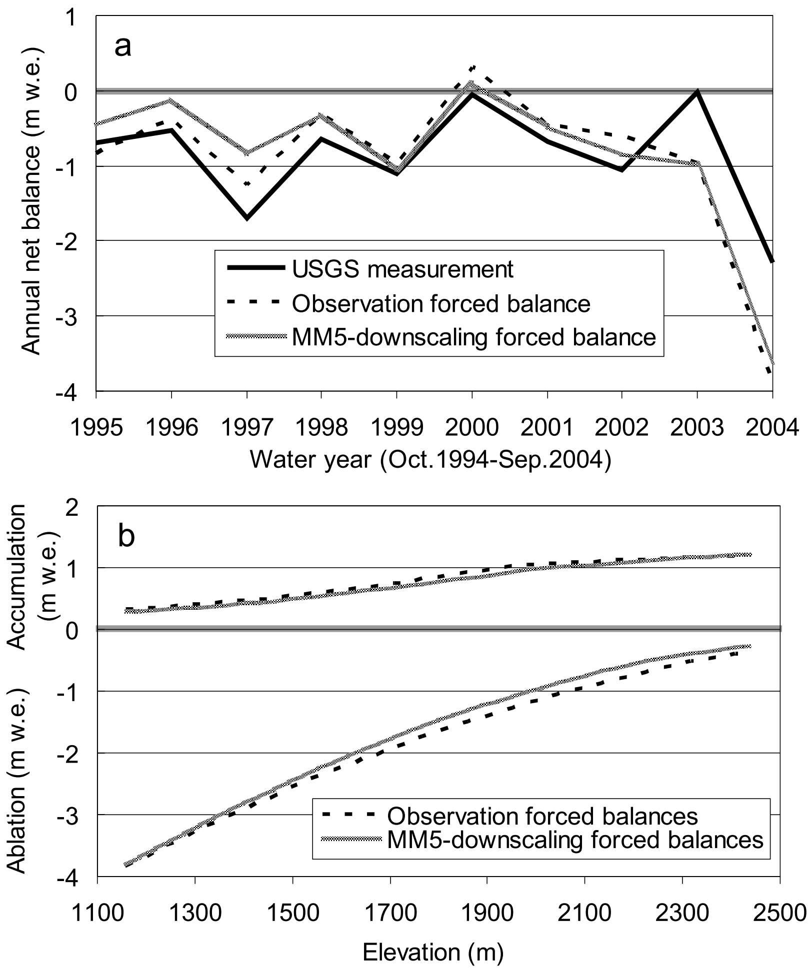

Figure 4. (a) USGS measured (black solid line) and PTAA-simulated annual mass balances using observed (dashed line) and MM5-downscaled (grey solid line) temperatures and precipitation during the water years (1995–2004). (b) PTAA-simulated mass balance profiles (accumulation and ablation) using MM5-downscaled (grey solid lines) and observed (dashed lines) temperatures and precipitation averaged over the time period of Oct.1994–Sep.2004.

Glacier, or the similar glaciers, which have relatively strong ablation.

[14] In addition, unlike some glacier mass balance models [e.g., *Radić and Hock*, 2006], which use the monthly mean meteorological data as forcing inputs, the PTAA model was designed to use high-frequency daily meteorological data for realistically generating the glacier mass balances. To evaluate the sensitivity of the PTAA model to the temporal variations in the forcing inputs. We smoothed the MM5-downscalings by calculating monthly means of the daily data and then using a cubic spline to construct slowly varying daily data. When the PTAA model was forced with the smoothed temperatures and precipitation, the simulated mass balance for the Gulkana Glacier over the 10-year simulation period is 0.95 m yr^{-1} w.e., about 1.8 m yr^{-1} w.e. more positive than the measurement. Once again, when the combination forcing inputs, i.e., smoothed temperatures (or precipitation) and observed precipitation (or temperatures), were used to forced the PTAA model, significant differences in the simulated mass balances (particularly ablation) exist (Table 4). The smoothed precipitation leads

Table 2. Ten-Year (Oct.94–Sep.04) Averaged Net Mass Balance for Gulkana Glacier[a]

USGS Measurement	Observation Forced PTAA Simulation	MM5-Downscaling Forced PTAA Simulation
−0.88 ± 0.70	−0.94 ± 1.14	−0.86 ± 1.04

[a]Unit: m yr^{-1} w.e. The ± ranges represent the standard deviations of the balances.

Table 3. Comparisons of 10-Year (Oct.94–Sep.04) Averaged Net Mass Balance for Gulkana Glacier Simulated With the Combined Forcing Inputs: Observed Temperatures and Precipitation and Uncorrected MM5 Temperatures and Precipitation[a]

Forcing Inputs	Mass Balance
Uncorrected MM5 T and P	0.52
Uncorrected MM5 T and observed P	0.13
Observed T and uncorrected MM5 P	−0.42

[a]Unit: m yr^{-1} w.e. Note: “T” for temperature and “P” for precipitation.

Table 4. Comparisons of 10-Year (Oct.94–Sep.04) Averaged Net Mass Balance for Gulkana Glacier Simulated With the Combined Forcing Inputs: Observed Temperatures and Precipitation and Smoothed Temperatures and Precipitation[a]

Forcing Inputs	Mass Balance
Smoothed T and P	0.95 (0.03)
Observed T and smoothed P	0.93 (0.05)
Smoothed T and observed P	−0.48 (1.20)
Observed T and P	−0.94 (1.77)

[a]Ablation is in parentheses. Unit: m yr^{-1} w.e. Note: "T" for temperature and "P" for precipitation.

to a relatively weak ablation (0.05 m yr^{-1} w.e.) compared to that forced by the observed precipitation (1.77 m yr^{-1} w.e.) due to more cloudy days in the smoothed data, suggesting that the high frequency daily data, especially the high frequency precipitation produced by the high resolution regional modeling, is essential for accurate glacier mass balance simulation with the PTAA model.

4. Summary

[15] The atmosphere/glacier hierarchical modeling approach described here, exploiting the strength of each model, has been developed for estimating climate-forced changes in glacier mass balance. This hierarchical modeling system was applied to Gulkana Glacier, a well-measured USGS benchmark glacier, by establishing a regional modeling domain over Alaska/NW Canada/NE Russia, with a nested high-resolution domain over the glacierized regions of Alaska, using the Arctic MM5 model. A 10-year downscaling of the NCEP/NCAR reanalysis data over the modeling domain was conducted. MM5-downscaled daily maximum and minimum temperatures and daily precipitation were interpolated to the locations of the McKinley Park and Big Delta weather stations, which were then used to force the PTAA model to simulate the mass balance of Gulkana Glacier. Comparisons between the MM5-downscaled daily temperatures and precipitation and the observations at the weather stations over the entire 10-year simulation period show that the MM5-downscalings have a correctable bias and that the bias-reduced MM5 results match the observations reasonably well.

[16] Gulkana Glacier mass balances simulated by the PTAA model, in which the bias-reduced MM5-downscalings were used as the forcing inputs, were compared to the USGS measurements for the 10-year hindcast period. The comparisons show that this atmosphere/glacier hierarchical modeling system realistically simulated the mass balances of Gulkana Glacier. This atmosphere/glacier hierarchical modeling approach thus provides a basis for quantitatively estimating future climate-forced changes in glacier mass balance.

[17] Our sensitivity evaluations of the PTAA model to the MM5-downscalings show that correction of the MM5-downscalings for bias is essential for realistically modeling glacier mass balances. Bias correction of the MM5-downscaled temperatures is critical, particularly during the transit seasons (i.e., spring and fall).

[18] In addition, significant biases between the PTAA-estimated Gulkana mass balances based on smoothed MM5-dowscalings and the USGS measurements suggest it is necessary to provide the PTAA model with the high-frequency daily meteorological inputs, not smoothed monthly data, to achieve realistic simulation of glacier mass balances.

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