Comparison of glacier-inferred temperatures with observations and climate model simulations

Diandong Ren[1] and David Karoly[1]

[1] A reconstructed temperature history for different regions of the globe was prepared by Oerlemans (2005) from length changes of 169 glaciers. In this study, we compare the glacier-inferred temperature variations over 1900–1990 with observed and climate model simulated temperatures for the global average and for five regions: Southern Hemisphere, northwest America, Atlantic, Asia, and the Alps. There is reasonable agreement between the glacier-inferred temperature trends and the observed temperature trends for the globe and in four of the five regions (except northwest America, NWAme). The trends for the globe and in these regions are significantly different from zero, cannot be explained by natural variability (again except for NWAme), and are consistent with the model-simulated response to anthropogenic forcing in all regions. Hence, it is likely that the glacier length reductions are outside the range of natural variations and due in part to regional warming associated with increasing concentrations of greenhouse gases in the atmosphere. **Citation:** Ren, D., and D. Karoly (2006), Comparison of glacier-inferred temperatures with observations and climate model simulations, *Geophys. Res. Lett.*, *33*, L23710, doi:10.1029/2006GL027856.

1. Introduction

[2] Climate change and its wide range of possible impacts have been recurring topics in both the refereed scientific literature and in the popular media [*Intergovernmental Panel on Climate Change (IPCC)*, 2001]. The observed global-mean temperature increased over the twentieth century by about 0.6°C and most of this warming over the last fifty years is likely to have been due to the increase in greenhouse gas concentrations [*IPCC*, 2001]. Observed reductions in glacier lengths in many regions of the globe have been used as independent evidence that the observed warming is real and having significant impacts [*Dyurgerov and Meier*, 2000]. However, while the global-scale temperature increase over the 20th century has been attributed to anthropogenic climate forcing [*Mitchell et al.*, 2001], no studies have sought to attribute the glacier length reductions to anthropogenic climate forcing. There are a number of reasons for this, including the need to relate glacier length variations to regional temperature and precipitation variations, the increase in the natural variability of temperature at the regional scales relevant to glaciers compared with global scales, and the difficulties for climate models in simulating climate variations in alpine regions relevant to glaciers.

[3] Recently, *Oerlemans* [2005] estimated low-frequency temperature variations for five regions from length variations of 169 glaciers; 15 in the Southern Hemisphere (SH), 27 in Northwest America (NWAme), 17 in the Atlantic, 17 in Asia, and 93 in the European Alps. A linear inverse model, adjusted for each glacier, was used to infer temperature variations from the glacier length variations, assuming no effect from precipitation variations. A global-mean temperature anomaly series for 1834 to 1990 series was then constructed from a weighted average of the regional temperatures, using weights of 0.5 for the SH, 0.1 for NWAme, 0.15 for the Atlantic sector, 0.1 for the Alps, and 0.15 for Asia (as shown in Figure 1).

[4] Here, we assess the glacier-inferred temperature variations through comparison with observed surface temperature variations from lower level stations around the glacier locations and through comparison with regional temperature variations from climate model simulations. The comparison with observed temperatures will help to determine whether the glacier length variations provide a reliable estimate of low frequency regional temperature variations and the possible importance of the neglect of precipitation variations. The comparison with modeled temperature variations allows an assessment of the significance of the inferred temperature variations and their likely cause. Recent studies have identified an anthropogenic influence in regional temperature variations [*Karoly and Wu*, 2005; *Knutson et al.*, 2006], which gives greater confidence that this analysis will help to identify the causes of the glacier-inferred temperature variations, and hence the glacier length variations.

2. Data and Methodology

[5] Regional temperature variations for the five different regions for 1900–1990 from *Oerlemans* [2005] and the locations of the 169 glaciers from that study have been used. Observed global gridded near-surface temperatures prepared by the Hadley Centre (UK Met Office) and the Climatic Research Unit, University of East Anglia (HadCRUT3) [*Brohan et al.*, 2006] were used as the observational temperature data set. These data have been prepared from monthly mean station data, generally from low elevation long term stations over land. The analysis was limited to the period after 1900 to increase the data coverage in the HadCRUT3 data set.

[6] An estimate of the temperature variations at each glacier location was provided using the temperature anomalies from the closest $5° \times 5°$ latitude-longitude grid box from the HadCRUT3 data. This assumes that the low elevation temperature anomalies available from HadCRUT3 follow similar low frequency variations to the higher

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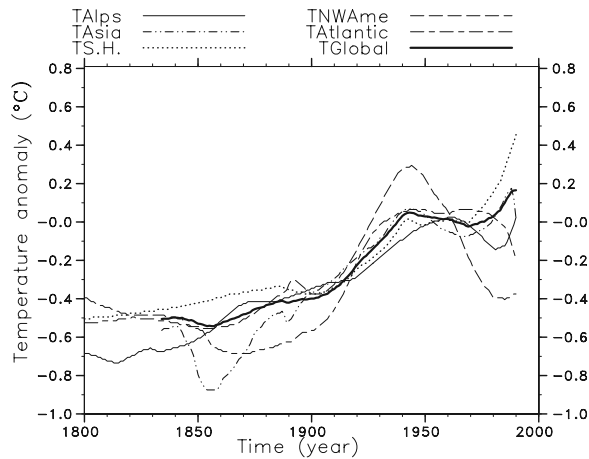
Figure 1. Regional and global temperature anomaly time series, relative to 1960–90 average, inferred from glacier length. Adapted from *Oerlemans* [2005, Figure 3].

elevation temperatures affecting the glaciers. Regional average temperatures were obtained for each region by averaging over all the glacier locations.

[7] Coupled ocean-atmosphere climate models have been used to provide estimates of the natural variability of temperatures at the glacier locations and the temperature response to imposed changes in external radiative forcing factors. Output from nine climate models developed by seven different research groups has been used in this study. Simulations with these models were run as part of a coordinated series of simulations by the modeling centers for the IPCC Fourth Assessment Report. Their IPCC IDs are: NCAR CCSM3, CGCM3.1, ECHAM5, GFDL CM2.0 and CM2.1, MIROC3.2 (medres), MRI GCM-IIb, NCAR PCM, and UKMO-HadCM3. Some information on these

models, including their atmospheric resolution and original references are included in Table 1, together with the three-letter acronyms that we use for each model. While a larger number of models were available, we selected these nine based on the number of available ensemble members, the length of the control runs, and the model resolution.

[8] An estimate of the natural variability of temperature at the glacier locations is obtained from the pre-industrial control runs (PICNTL) of the different models. These runs are constant external forcing simulations that represent the natural internal variability of the climate system. The lengths of the individual control runs from the different models are given in Table 1. We have a total duration of about 4000 years of control simulations for all the models.

[9] Model simulations of the climate of the 20th century come from an experiment called the 20th Century Climate in Coupled Models (20C3M) simulations. These simulations include changes in greenhouse gas concentrations and aerosols as observed in the atmosphere, to represent the changes in anthropogenic radiative forcing of the climate, together with estimated changes in solar irradiance and volcanic aerosols, to represent changes in natural radiative forcing factors. To reduce uncertainty in the response to the different forcing factors, ensembles of simulations with the same external forcing but different initial conditions have been made with each model, with the number of ensemble members listed in Table 1. We used 100-year simulations (1900–1999) from the 20C3M runs, and have a total of 33 20C3M ensemble members for all the different models. The differences between the different ensemble members provide an estimate of the uncertainty in the climate response due to internal climate variability and the differences between the different climate models.

[10] An estimate of the temperature variations at each glacier location from each model was provided using the temperature anomalies from the set of model grid boxes

Table 1. Model Specifications

Model Name; Institution; and Reference	Acronym	Horizontal Resolution	PICNTL Run Length, years	20C3M Run[a]
CCSM3; National Center for Atmospheric Research; *Collins et al.* [2005]	CCS	1.4° × 1.4°	220	(7)
CGCM3.1 (T47); Canadian Centre for Climate Modelling and Analysis; *Kim et al.* [2002]	CGC	2.8° × 2.8°	900	(5)
ECHAM5/MPOI-OM, Max Planck Institute for Meteorology, Germany, ECHAM5/MPI-OM; *Jungclaus et al.* [2005]	ECH	1.875° × 1.875°	331	AF[b] only (3)
GFDL-CM2.0/2.1; US Dept. of Commerce/NOAA/Geophysical Fluid Dynamics Laboratory; *Delworth et al.* [2006]	GFD	2.5° × 2°	400/500	(3/3)
MIROC3.2 (medres); Center for Climate System Research (The University of Tokyo), National Institute for Environmental Studies, and Frontier Research Center for Global Change; *K-1 Model Developers* [2004]	MME	2.8° × 2.8°	500	(3)
Coupled Model Parallel Climate Model; National Center for Atmospheric Research; *Washington et al.* [2000]	PCM	2.8° × 2.8°	501	(2)
UKMO-HadCM3; Hadley Centre for Climate Prediction and Research/Met Office; *Gordon et al.* [2000]	HCM	3.75° × 2.5°	341	(2)
MRI GCM IIb; Meteorological Research Institute(Japan); *Kitoh* [1995]	MRI	2.8° × 2.8°	350	(5)

[a]Number in parentheses is the ensemble number.
[b]AF: Anthropogenic forcing.
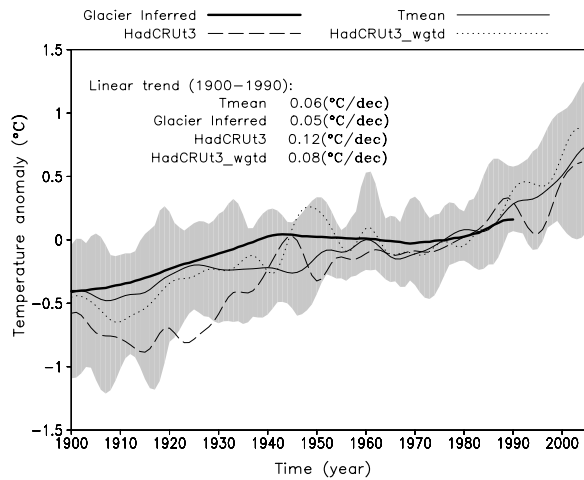
Figure 2. Smoothed global temperature anomaly time series relative to 1960–90 as simulated by 20C3M runs and from the observations. The ensemble average temperature at the glacier locations (Tmean) from the 20C3M runs is shown with the thin solid line, with the upper and lower bounds from the ensemble of 46 20C3M runs shown by the gray shading. Observational temperature time series inferred from the glaciers is shown by thick solid line, while the temperatures calculated from the HadCRUT3 observations is shown averaged from the glacier locations (HadCRUT3) and weighted according to Oerlemans (2005) (HadCRUT3_wgtd). The time series from HadCRUT3 extend to year 2005 while temperature inferred from glacier lengths end at 1990.

covering a $5° \times 5°$ latitude-longitude region surrounding the glacier location. For the higher resolution models, this corresponded to 9 model grid boxes, whereas for the coarser resolution models, this corresponded to 4 model grid boxes. Regional average temperatures were obtained for each region by averaging over all the grid boxes for the glacier locations.

3. Results

[11] Low frequency variations of the global mean temperature over the 20th century estimated from the glaciers (*Glacier inferred*), the ensemble mean from the climate model simulations (T_{mean}), the area-weighted HadCRUT3 observational data (*HadCRUt3*), and the weighted-average of the HadCRUT3 observations (*HadCRUt3_Oerlemans_Wgt*) are shown in Figure 2. The upper (T_{max}) and lower (T_{min}) limits of the low frequency temperature variations from the set of 20C3M simulations are shown to provide an estimate of the uncertainty.

[12] All 'mean' temperature time series are well bracketed by T_{max} and T_{min}. The *HadCRUt3_Oerlemans_Wgt* and the *Glacier inferred* (i.e., the two observed time series weighted the same way) agree closely with each other and with T_{mean} as well. However, glacier-retrieved temperature series are 'smoother' than modeled and the HadCRUT3 temperature series, apparently due to the smoothing process [*Stineman*, 1980] applied to the glacier-inferred temperatures. On multi-decadal time scales, there is a strong resemblance between the two observational and the model ensemble

mean temperature series: the general small decreasing trend from the 1940s to 1960s, and the steady increase trend thereafter. From the century long time series, we also see clearly the weak cooling phase in the middle of the past century. The 90-year trends of the modeled (T_{mean}), *Glacier inferred*, and *HadCRUt3_Oerlemans_Wgt* are respectively 0.063, 0.056, and 0.078°C per decade, rather close among the three.

[13] Figure 3 is a set of histograms of the linear trend of temperature over the past 90 years for the globe (Figure 3, Global) and the five regions (Figure 3, Alps, Asia, Atlantic, S.H., and NWAme). The PICNTL temperature series is resampled using a 90-yr window shifting every 50 years. This way, 290 sub-samples are produced. For the 33 20C3M runs, the observational, and the glacier-inferred data, area-averaged temperature time series from years 1900 through 1990 are used to calculate the 90-year linear trends. There are a total of 46 sub-samples for the 20C3M runs. The number of trends that falls between a certain value range is divided by the total number of trend estimation (290 for
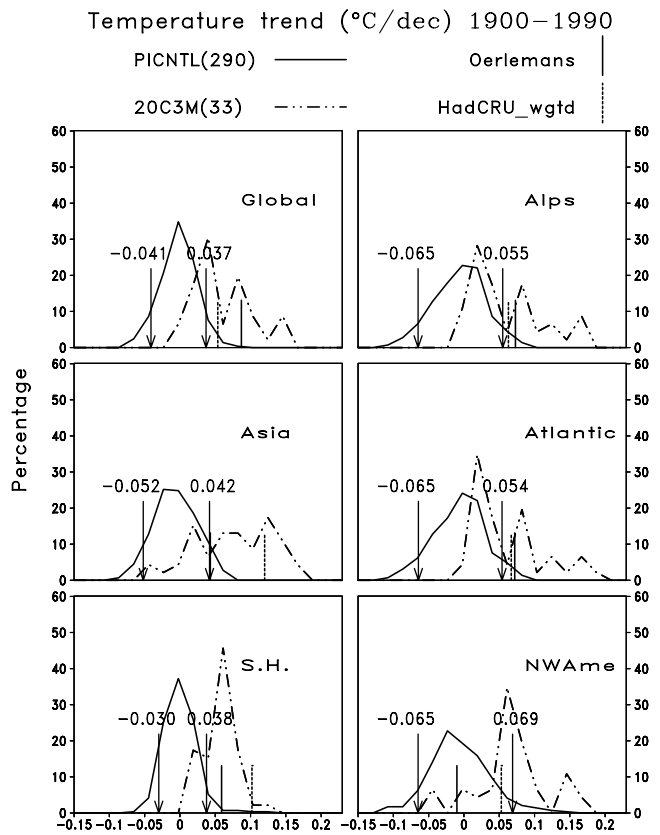
Figure 3. Histograms of the temperature trends over the past 90-yr for the globe and the five regions. The PICNTL temperature series is resampled using a 90-yr window and shifted every 50-yr. The linear trend is calculated for each resampled time series (solid line histogram). Trends from the 20C3M ensemble for 1900–90 are shown by the dash-dotted histogram. Trends estimated from the glacier-inferred temperatures are shown as the solid vertical lines, while those from the HadCRUT3 observed temperatures are shown as the dashed vertical lines. The upper and lower bounds of the 90% confidence interval for trends due to natural variability are shown using the downward arrows.

PICNTL and 46 for 20C3M) to obtain a histogram of the temperature trend. For observational data, trend values are shown as vertical lines in the plots.

[14] Except for the NWAme, the observed 90-yr trends are larger (0.063–0.12°C per decade) than the upper bound of the trends due to natural variability (90% critical value bounds, shown as down-pointing arrows) as shown in Figure 3, but are consistent with the trends from the 20C3M ensemble runs. *Oerlemans* [2005] attributed the marked cooling in the NWAme region after 1940, which seems to be at odds with the substantial retreat observed for most glaciers during the past 20 years, to the fact that many records from North America are not up to date and end in the period of 1975 to 1990.

[15] The consistency of the glacier-inferred temperatures with the observed temperatures indicates that snowfall variations are likely to have been a small contributor to the long term changes in glacier length. The glacier-inferred temperature trends for the globe and in the regions (apart from NW America) cannot be explained by natural variability and are consistent with the model-simulated response to anthropogenic forcing. Hence, it is likely that the glacier length reductions are outside the range of natural variations and due in part to regional warming associated with increasing concentrations of greenhouse gases in the atmosphere.

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Title:
Comparison of glacier-inferred temperatures with observations and climate model
simulations

Date:
2006

Citation:
D., & Karoly, D. (2006). Comparison of glacier-inferred temperatures with observations and
climate model simulations. Geophysical Research Letters, 33, doi: 10.1029/2006GL027856.

Publication Status:
Published

Persistent Link:
http://hdl.handle.net/11343/32779