Geological Field Trips in Southern Idaho, Eastern Oregon, and Northern Nevada

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Late-Pleistocene Equilibrium-Line Altitudes, Atmospheric Circulation, and Timing of Mountain Glacier Advances in the Interior Northwestern United States

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Abstract

We reconstructed equilibrium-line altitudes for late-Pleistocene glaciers in eastern Oregon, central and northern Idaho, and western Montana. Over 500 cirque to small valley glaciers were mapped where moraines and other evidence for ice margins could be confidently interpreted on digital topographic maps. Equilibrium-line altitudes (ELAs) were estimated using the accumulation-area ratio method. Spatial patterns of ELAs show a strong correspondence to present-day precipitation patterns. Modern dry regions have relatively high ELAs (*e.g.*, 2,600–2,900 m at about lat 44.5°N. in the Lost River and Lemhi Ranges south-central Idaho), whereas wetter regions at similar latitudes have considerably lower ELAs (*e.g.*, 2000–2200 m in mountains southwest of McCall, Idaho). Steep eastward increases in ELAs across larger massifs such as the Wallowa, Sawtooth, and central Bitterroot Mountains reflect orographic effects on westerly flow. The Columbia River basin of eastern Washington and Oregon provided a lowland corridor for moist, eastward-moving Pacific air-masses, producing anomalously low ELAs in bordering ranges (*e.g.*, <1,800 m around lat 46.5°N. in the Clearwater River drainage of northern Idaho currently the wettest region of the study area). Smaller-scale features such as the Salmon and Payette River canyons also appear to have acted as conduits for atmospheric moisture. Overall, the ELA data point strongly toward a moisture source in the north Pacific Ocean. General circulation climate model results indicate that at the last continental glacial maximum, an anticyclone centered over the continental ice sheets and southward deflection of the jet stream should produce dry conditions in the interior northwestern United States. Our results suggest that the anticyclone is weaker than in some previous simulations, and easterly winds are not clearly indicated across the study region. By 15 ka, northward retreat and decline in continental ice-sheet elevation caused contraction of the anticyclone, and winter westerlies from the north Pacific continued to strengthen across the study area until 12 ka. An associated increase in snowfall may have allowed more precipitation-sensitive mountain glaciers to remain near their maxima or expand during the post-late glacial maximum period, before the dramatic warming into the early Holocene. Similar positions and topography of continental ice sheets during buildup prior to the late glacial maximum also might promote glacial advances by focusing strong westerly flow on mountain ranges of the interior northwest. Further dating of mountain glacier advances is necessary to test these hypotheses.

Introduction

We mapped perimeters and reconstructed equilibrium-line altitudes (ELAs) for small late Pleistocene alpine glaciers in the interior northwestern United States east of the Coast and Cascades Ranges and south of the continental glacial limit (fig. 1 and 2). This region has a high density and continuity of glaciated mountains, especially in central Idaho. Last-glacial moraines (*i.e.*, those usually attributed to the "Pinedale glaciation" of the Rocky Mountains, *e.g.*, Porter and others, 1983) are commonly well displayed in the field and on topographic maps.

Climatic Significance of Regional ELAs

Equilibrium-line altitudes of alpine glaciers are a function of a suite of local and regional climatic and topographic

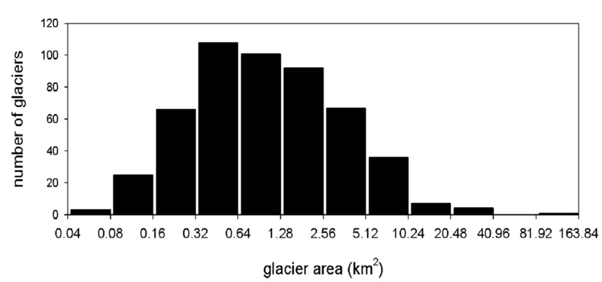

Figure 1. Distribution of total surface area of reconstructed glaciers (log_2 scale).

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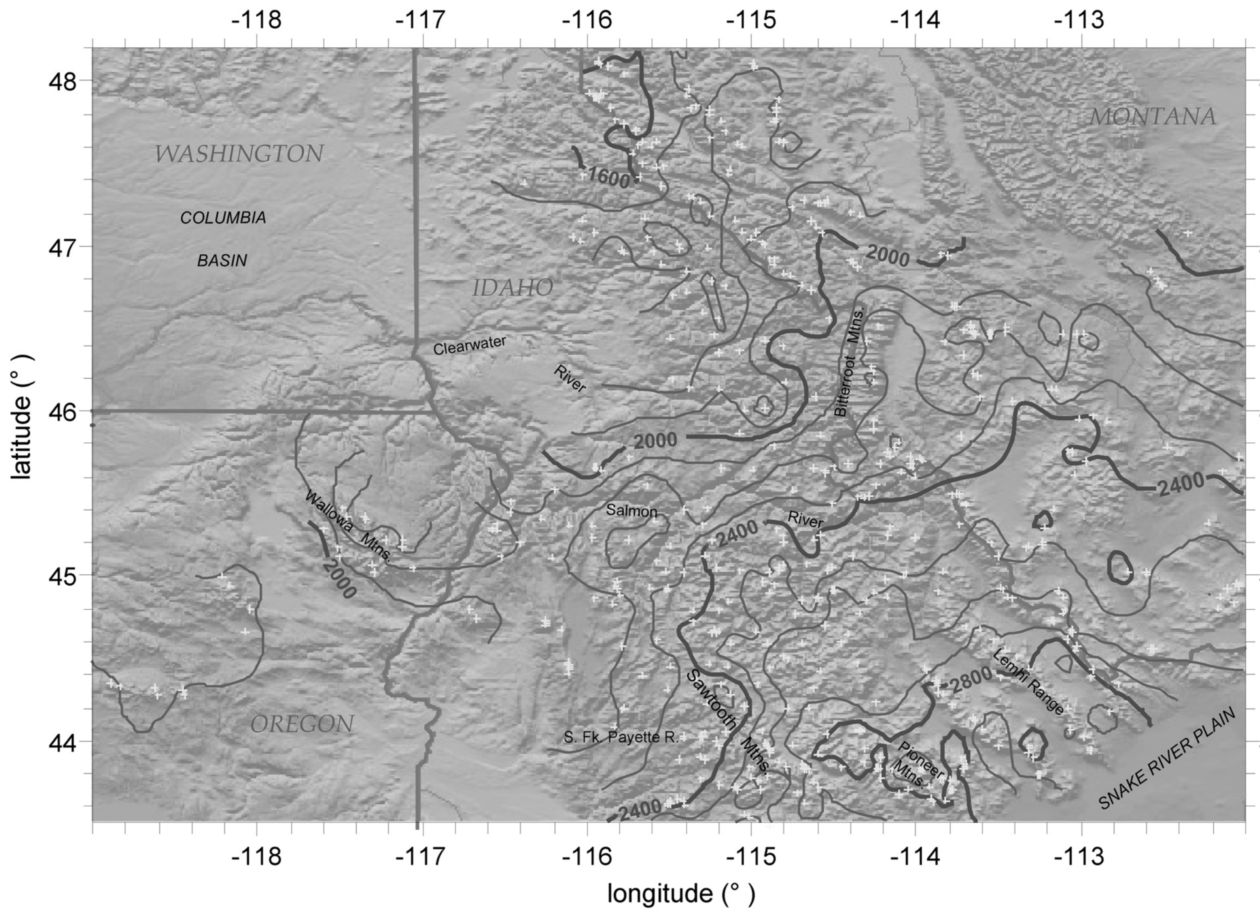

Figure 2. Contour map of last-glacial ELAs for glaciers of all aspects (but mostly northwest through east aspects) produced using a kriging routine; data points shown by white crosses. Contour interval 50 m.

factors that affect mass balance including air temperature, precipitation, patterns of wind erosion and deposition of snow, and insolation. In general, glacier mass balances are most strongly controlled by winter precipitation in coastal regions and by summer temperatures in continental interiors (*e.g.*, Hostetler and Clark, 1997). The regional pattern of ELAs, however, is influenced by proximity to moisture sources and prevailing wind directions, as well as by latitudinal changes in insolation and temperature (*e.g.*, Porter and others, 1983; Leonard, 1984; Locke, 1990).

Previous Work

A small-scale contour map of cirque-floor elevations for the entire Western United States was compiled by Porter and others (1983), which shows a similar overall pattern to our results, but considerably less detail. Locke (1990) reconstructed ELAs for western Montana using a variety of methods and discussed their relative accuracy. We consider data to be most reliable where obtained by the AAR method from relatively small glaciers reconstructed where ice-affected areas are clear, and include those data here, along with some newly generated ELA data for western Montana.

Methods

We used commercial software with digital raster USGS topographic maps to map late-Pleistocene glaciers and measure areas and elevations. We estimated ELAs by applying the observation that the accumulation area of small modern alpine glaciers is approximately 65 percent of the total surface area (Meierding, 1982; Locke, 1990), in other words, the AAR method. Because ELAs produced by this method will generally have smaller uncertainties for small glaciers, we concentrated mostly on reconstruction of cirque to small valley glaciers with total area of 0.1 to 10 km^2 (fig. 1). The margins of ice-affected areas were identified in part through erosional features, including the tops of cirque headwalls and oversteepened trough valley walls, and the lower limits of U-shaped valley profiles. Mapped lower ice margins were marked at least in part by lateral and terminal moraines. Glaciated

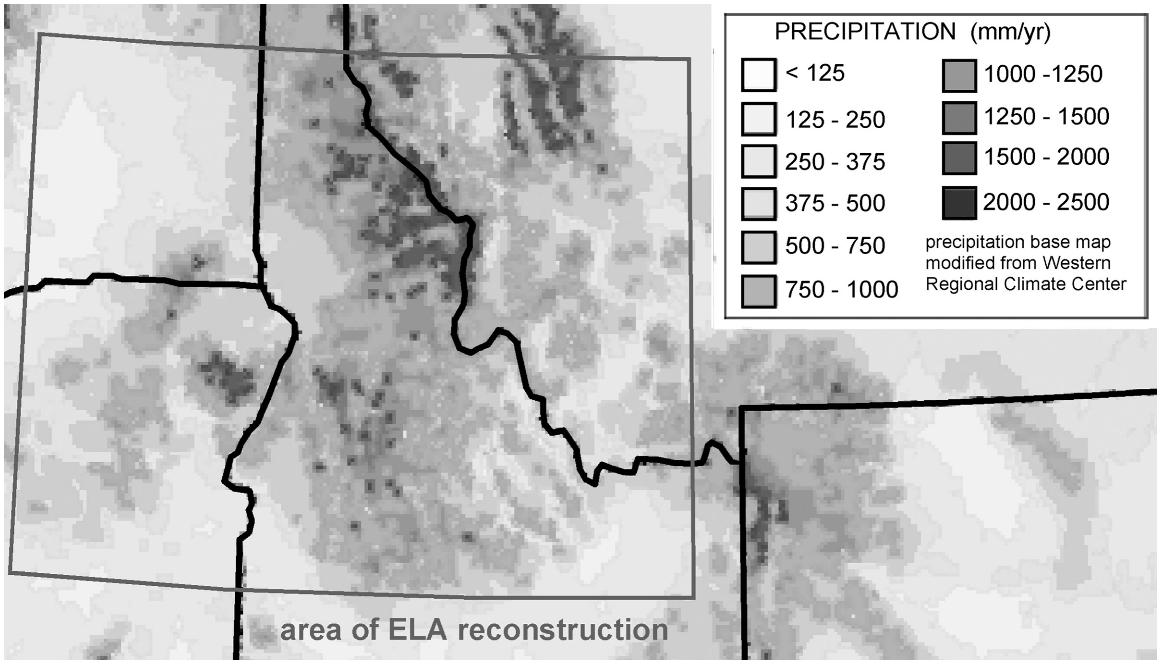

Figure 3. Map of mean annual precipitation in the interior northwestern United States; compare to figure 2.

cirques and valleys without clear evidence of ice margins were rejected. Where nested moraine sequences were identified, we assumed that the innermost large, well defined, sharp-crested, and relatively continuous moraine set represented the last local glacial maximum (typically termed "Pinedale" glaciation; Porter and others, 1983). Narrow, lower, and discontinuous moraine ridges were sometimes identified in larger glacial valleys, typically well upvalley from major moraines. These were considered recessional moraines and were not used in ELA reconstruction. We obtained a total of 510 ELAs for the study area.

To consider atmospheric circulation patterns and their possible effects on moisture delivery to glaciers in the study area, we used the GENESIS (v. 2) atmospheric general circulation model (GCM) to simulate winds over North America at 21 ka (late glacial maximum, LGM), 15 ka, 12 ka, and the present. The major boundary conditions that were systematically changed include ice-sheet extents and elevations (from Peltier, 1994), and orbital configurations. Simulation results reported here include near-surface (993 mb) and lower-troposphere (866 mb) wind vectors to describe the response of the lower atmosphere to the imposed boundary conditions.

Results

Late-Pleistocene ELA Reconstructions

Equilibrium-line altitudes range from about 1600 m in the northern study region near Lookout Pass along the Montana-Idaho border to about 3000 m in the Basin and Range mountains north of the eastern Snake River Plain (fig. 2). The overall pattern of ELAs generally mimics the present-day pattern of precipitation, where low ELAs correspond to high annual precipitation (figs. 2 and 3). There is a general eastward rise in summit elevations and a trend to colder winter climates from west to east across central Idaho, but late Pleistocene ELAs nonetheless rise steeply toward the east, including along the route of this field trip. For example, the average gradient from the West Mountains southwest of McCall, Idaho, to the Beaverhead Mountains at similar latitude on the Montana border is about 2.5 m/km. Locally, large eastward increases in ELA are present across the Wallowa Mountains in eastern Oregon and the Sawtooth Mountains of Idaho, suggesting that these prominent highlands caused significant precipitation shadows in a dominant westerly flow of moisture. The eastward rise in ELAs is as steep as 6.6 m/km from the western Sawtooth Mountains to the central Pioneer Mountains. Anomalously high ELAs in the high-altitude core of the Pioneer Mountains are consistent with diversion of low-level moist airflow around this relatively large massif, as observed elsewhere by Meierding (1982), Porter and others (1983), Leonard (1984), and Locke (1990). These relations indicate a strong precipitation control on ELAs.

A zone of relatively low ELAs extends eastward across northern Idaho and into northwestern Montana, probably from penetration of moist Pacific air masses across the Columbia Basin lowlands and up the Salmon and Clearwater River canyons. The highest ELAs were found in Idaho in the central Pioneer Mountains and the southern Lost River and Lemhi Ranges and the Beaverhead Mountains, where a combination of precipitation shadows and moist airmass diversion up the eastern Snake River Plain result in a dry climate (similar to the results of Porter and others, 1983). Local heating of the low, arid Snake River Plain also may create warmer conditions in adjacent mountains. Not surprisingly, glaciers on west through southeast aspects have higher ELAs than the local average. East-facing glaciers are abundant regardless of mountain ridge orientation and other large-scale topographic controls, and approximately equal numbers of east, northeast, and north-facing glaciers are included in the dataset. Less than 10 percent of the data are derived from glaciers of other aspects, and west-facing cirques are notably uncommon over much of the study region, especially in the dry Lost River and Lemhi Ranges, and the Beaverhead Mountains. These observations are consistent with wind erosion of snow on west slopes and wind loading on the lee side of mountain ridges by westerly winds.

Locke (1990) found that late-Pleistocene ELAs in western Montana lie about 450 m lower than modern glaciers, which lie in topographically favorable sites for snow accumulation and preservation. Porter and others (1983), however, cite literature indicating that late-Pleistocene ELAs were generally about 1,000 m lower than present across the Western United States. No true glaciers are known in Idaho. Flint (1971) notes that elsewhere in the Rocky Mountains, the lower limit of perennial snowfields corresponds approximately to the ELA of small cirque glaciers in the same area. A few perennial snowfields are mapped on USGS 1:24,000 quadrangles, mainly in the Sawtooth Mountains. However, the mapped lower limits of these snowfields range widely in elevation, and the absence of modern glaciers even on suitable slopes rising up to 300 m above these limits show that they are a poor indicator of modern "ELAs." The lack of modern glaciation in cirques at the head of late-Pleistocene glaciated valleys in the Sawtooths implies a minimum last-glacial ELA depression of about 500 m relative to the present.

GCM Simulations

General circulation model results for January at the LGM (21 ka) show a glacial anticyclone (high-pressure system and clockwise circulation) centered over the continental ice sheet northwest of the study region (fig. 4). The main effect of the anticyclone, however, was to weaken the westerlies across this region, rather than to create persistent easterly flow. Easterly near-surface winds are modeled near the ice-sheet margin in the Central United States, but do not extend into the study region. Lower tropospheric flow over the study region was predominantly westerly, with persistent ridging creating northward deflection of winds and drier conditions (see 866 mb results). With weakening and contraction of the anticyclone by 15 ka, moisture supply in the interior northwest was probably enhanced by stronger westerly flow carrying Pacific airmasses into the interior. Although global ice volume was diminishing, increased snowfall may have sustained or caused advances of more precipitation-sensitive mountain glaciers in the study region. Higher-level ridging was reduced, and temperatures likely were somewhat increased, promoting greater winter precipitation. By 12 ka, the extent of the continental ice sheets was considerably reduced, and the western glacial anticyclone was absent. Greater transport of moisture into the interior northwest by strong near-surface and lower-troposphere westerly flow possibly could maintain some mountain glaciers until terminal Pleistocene warming raised ELAs to unsustainable levels.

Relation to Glacial Chronology

Numerical and calibrated ages for glacial advances are relatively rare in this region and are reported below in calendar years. Minimum limiting ^{14}C ages of 14 ka for Sawtooth Mountains advances in Idaho (Thackray and others, 2004) may provide evidence that increased precipitation maintained these mountain glaciers well after the LGM. Cosmogenic surface-exposure dating using ^{10}Be reveals major advances at both 21 ka and 17 ka in the Wallowa Mountains, however, suggesting that precipitation at the LGM was not limiting for ice accumulation in that area (Licciardi and others, 2000). Between these two ranges, near McCall, Idaho, Colman and Pierce (1986) used calibrated weathering-rind ages to estimate moraine formation at 14 ka, 20 ka, and 60 ka. These moraines were formed by an outlet glacier of an ice cap on the highlands between the North Fork Payette River and South Fork Salmon River, an area of relatively high modern precipitation in central Idaho (fig. 3). Although approximate, the McCall data indicate that near-maximum advances of this piedmont lobe occurred both well before and well after the LGM. Combined ^{3}He and ^{10}Be ages indicate a relatively late maximum advance of the northern Yellowstone outlet glacier at about 16.5 ka (Licciardi and others, 2001), which may have stemmed from an increased flow of moist airmasses up the Snake River Plain following the LGM. Licciardi and others (2003) also suggest that the late culmination of the Yellowstone glacial system may reflect the protracted interval of buildup and longer response time of the plateau ice cap (Pierce, 1979).

Conclusions

Overall, the ELA data imply that patterns of precipitation and wind flow generally similar to present existed during the time of maximum advances of these alpine glaciers, and that moisture originating in the Pacific was depleted by orographic effects as air masses moved eastward. Some paleoclimatic reconstructions indicate that the northwestern United States was significantly drier overall around the last continental glacial maximum (LGM) (*e.g.*, Whitlock and Bartlein, 1997; Locke, 1990). Easterly winds generated by the glacial anticyclone over the continental ice sheets have been implicated in this reduction of precipitation (*e.g.*, COHMAP, 1988; Bartlein and others, 1998). Nonetheless, our data show that the primary moisture source for alpine glaciers in the northwestern United

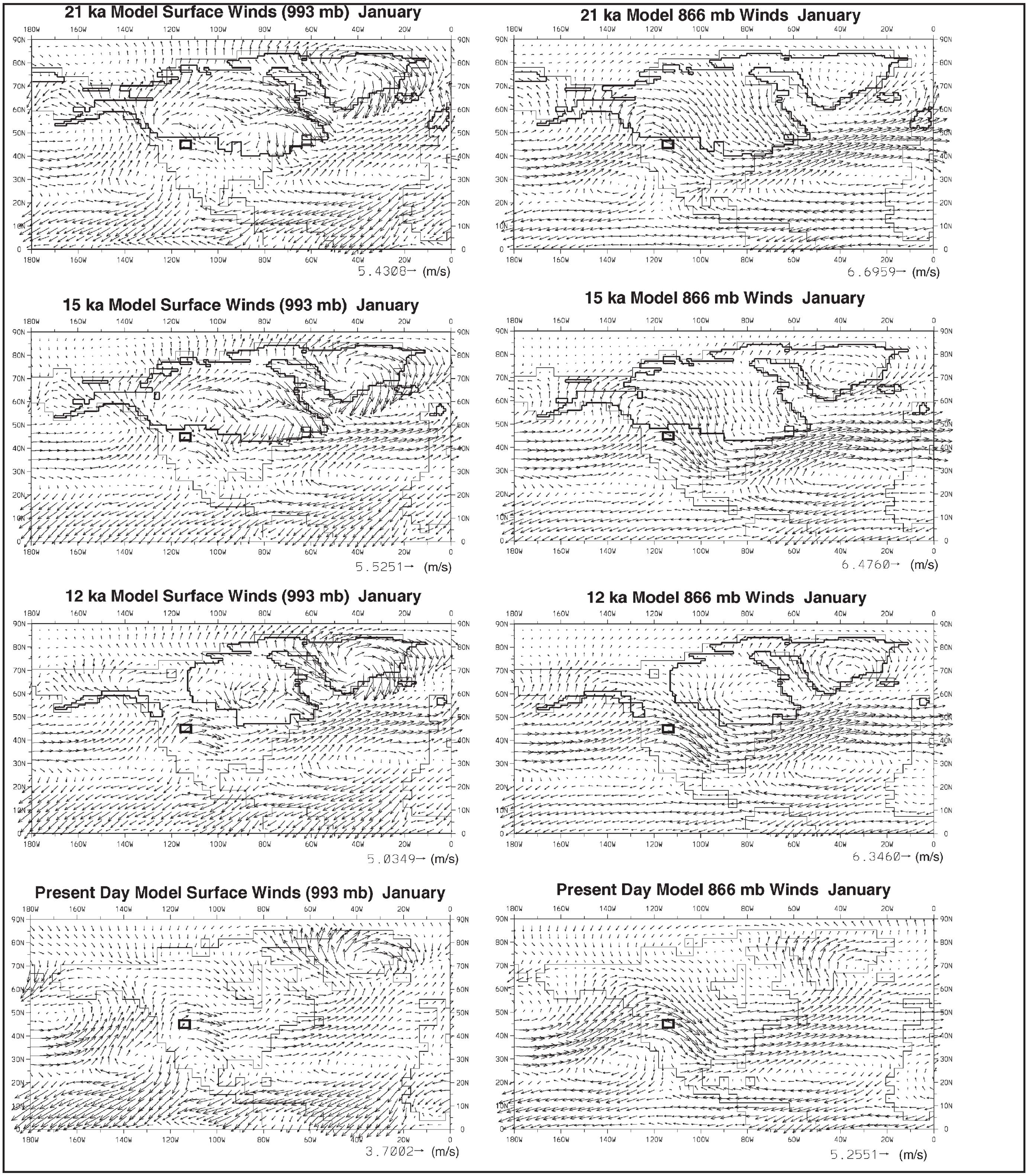

Figure 4. Modeled wind speed and direction over North America for 4-time periods from the LGM (21 ka) to present, for near surface (993 mb) and higher-elevation but still lower troposphere (866 mb) winds. Ice-sheet extent is shown by a heavy line; the small box outlines the central Idaho region (lat 43.5–45.5°N., long 113–117°W.).

States was clearly the North Pacific. The net effect of the glacial anticyclone was probably weakening of westerly flow during the LGM. Locke (1990) inferred that convergence of westerlies with katabatic easterly flow at the southern margin of the continental ice sheets caused lifting and enhanced precipitation, resulting in lower ELAs along the east flank of the Rocky Mountains in Montana.

Further understanding of glacial chronology in the interior northwest is necessary to test inferred changes in paleoclimatic conditions over the last glaciation, including decreased precipitation during the LGM, and later strengthening of westerlies and presumably increased precipitation. Rapid temperature changes in the latest Pleistocene probably also had a relatively large impact on small cirque and valley glaciers. In addition, the contrasting dynamics and response times of small mountain glaciers, mountain ice caps as in Yellowstone, and continental ice sheets are likely involved in asynchronous advances among these glaciers of vastly different spatial scales (*e.g.*, Gillespie and Molnar, 1995).

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