The North American Ice Sheet, Atmospheric Circulation, and the Climates of Western North and South America at the Last Glacial Maximum

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Introduction

One of the more coherent and robust features of the late-Quaternary paleoenvironmental record is the latitudinal pattern of alternating positive-and-negative moisture anomalies at the Last Glacial Maximum (LGM) that can be observed along the western portions of North and South America. From north to south, these anomalies include:

- drier-than-present conditions in the highest latitudes of North America (poleward of 60 N);
- wetter-than-present conditions in the latitudinal band spanned by the Cordilleran ice sheet (50-60 N);
- drier-than-present conditions in the Pacific Northwest (40-50 N);
- wetter-than-present conditions in California, the southwestern U.S., and northern Mexico (roughly 20-40 N);
- generally drier-than-present conditions in the tropics of both continents and subtropics of South America (say, 20 N to 25 S);
- wetter-than-present conditions in the midlatitudes of South America (25-50 S); and finally
- drier-than-present conditions at the southern tip of South America (poleward of 50 S).

These patterns have been expressed in syntheses of paleoenvironmental data for western North and South America, including those by Barnosky et al. (1987), Markgraf (1989), Thompson et al. (1993), Kohfeld and Harrison (2000), Markgraf et al. (2000), Bradbury et al. (2001), Ledru and Mourguiart (2001), and Whitlock et al. (2001).

The latitudinal zonation of these anomalies, and their location along the western edge of the continents implicates circulation changes as their cause, and in the midlatitudes in particular, changes in the location or strength of the westerlies. In the Northern Hemisphere, the obvious sources for major perturbations of the circulation are the LGM ice sheets themselves, which over North America and the adjacent North Atlantic and North Pacific Oceans include the combined bulk of the Cordilleran, Laurentide, and Greenland Ice Sheets. However, it is also the case that variations in the latitudinal gradients of net radiation, and in turn temperature, can modulate the large-scale circulation, as demonstrated in some of John Kutzbach's earlier work with Bryson and Shen (Kutzbach et al., 1968). That observation, and the latitudinal extent of the likely circulation perturbations, suggest that the general glacial-age boundary conditions--including atmospheric

[1] Cathy Whitlock, Bob Thompson, Vera Markgraf, Steve Hostetler, and Sandy Harrison contributed to this paper and to the presentation at the Kutzbach symposium.

composition (greenhouse gasses and aerosols), and sea-surface temperatures and ocean circulation--are also potential contributors.

The aim of this short paper is to review some of the ideas about the impact that the ice sheets and other glacial-age boundary conditions had on atmospheric circulation, and in particular on the westerlies over the western portions of the Americas. These ideas can be grouped into those that arose in the "pre-COHMAP" era, those from the initial COHMAP simulations (and others done in the early 1980s) and the companion data-model comparisons (as represented by the key paper of Kutzbach and Wright, 1985), and those from subsequent simulations and data-model comparisons.

These ideas all involve some combination of 1) direct perturbation of the circulation by the ice sheets (the "rock-in-a-stream" effect), 2) increases in the latitudinal temperature gradients in both hemispheres (promoting faster or latitudinally shifted westerlies), and 3) propagation of changes in the Northern Hemisphere to the Southern. This last explanation potentially includes all of the mechanisms for explaining interhemispheric (a)synchrony of millennial-scale climate variations, but at the LGM in specific, this idea can be thought of as the effect that a permanent northern winter would have had on the globe.

LGM circulation patterns: glacial anticyclones and latitudinal shifts in the westerlies

Simulations by Kutzbach et al. (1998) for the LGM using CCM 1 (Fig. 1) illustrate some of the features that enter into the discussion. The right-hand panels in the figure illustrate the circulation anomalies, or differences between the LGM and present, for January and July, in the upper atmosphere (at the 500mb level) and at the surface. In the upper atmosphere, the notable features are the broad swath of faster westerlies in the midlatitudes of the Northern Hemisphere in January, which represent a southward shift in, and intensification of, the present-day wintertime westerly flow. In the Southern Hemisphere in January (summer), a region of stronger westerly flow, flanked by two bands of weaker flow describe a band of winds at the same latitude as at present, only stronger. In July, faster westerlies are again present south of the ice sheet and in northwestern North America, while in the Southern Hemisphere, the dual band of fast westerlies notable in this model and others has strengthened and shifted poleward.

At the surface in the Northern Hemisphere in both January and July, the circulation anomalies clearly show the development of a prominent region of high pressure and anticyclonic winds over the North American ice sheets (the "glacial anticyclone"). In the northern winter (January) the Aleutian and Icelandic lows are better developed at the LGM than at present, while in summer several negative sea-level pressure anomalies flank the ice sheet. In the southern winter (July), a region of negative sea-level pressure anomalies extend along the northern edge of Antarctica, and occur again in a band at the latitude of southern South America. The principal LGM circulation anomalies thus include: (a) the glacial anticyclone over the North American ice sheet; (b) equatorward displacement and strengthening of the upper-level flow south of the ice sheet in North America; (c) intensification of the Aleutian and Icelandic lows; and (d) a set of circulation adjustments in the Southern Hemisphere that feature strengthening of the westerlies at the latitude of southern South America, combined with a poleward shift evident in the winter (July) and narrowing of the band of fastest westerlies in the summer (January).

Pre-COHMAP ideas about the LGM circulation

An early and explicit depiction of the potential influence of the LGM ice sheets on circulation appears in a discussion of the North American ice sheets by W.H. Hobbs (1911). (His Fig. 8, clearly depicts an expanded "glacial anticyclone" over North America.) Hobbs articulated a conceptual model for high-latitude circulation that featured the causes and consequences of such large anticyclones (i.e. Hobbs, 1926), based on the rather sparse "present-day" observations of the conditions over and around Greenland and Antarctica that were available at the time. These ideas did not fare well when later observations came to hand, in particular, those for the upper air (see Hare, 1951, p. 961, but see also Hobbs, 1948). Hare's discussion of the applicability of Hobbs's conceptual model (which is a bit more succinct than Hobbs's own) does list two features of Hobbs's ideas that continue to be invoked when explaining the anticyclones in current simulations: 1) intense radiative cooling of the atmosphere above a high, white, ice sheet, and 2) subsidence, divergence and anticyclonic "outflow" (with adiabatic warming of the descending air, as a consequence. Because Hobbs's ideas about present-day polar climatology and glacial anticyclones were discounted, his proposal for large glacial anticyclones at the LGM were also (e.g. Flohn, 1953).

On his way toward explaining the controls of the Pleistocene lakes in the Great Basin, Antevs (1925) considered Hobbs's ideas, and some of the contemporary arguments concerning it, and concluded that "The generally accepted opinion of anticyclones above the Pleistocene ice-sheets, accordingly, seems to be correct." Antevs added to the model of LGM circulation by proposing that around the glacial anticyclone, the Icelandic and Aleutian lows were displaced equatorward, and likely expanded their influence, suggesting that "The cyclone which now occurs in winter over the northernmost portion of the Pacific Ocean was much more strongly developed and perhaps reached over the Great Basin, where it possibly met the Atlantic low… (p. 60)." Later, Antevs (1948) introduced displacement of the storm track into his explanation, arguing that "Ultimately the western [Canadian] ice sheets became so large, and the glacial anticyclone so strong that the storm tracks were pushed off their normal courses… (p. 170)." He also proposed a mechanism for the particular chronology of lake-level variations in the Great Basin, related to the northward migration of the storm tracks as the ice sheets diminished in size.

In the 1950s and 1960s, the main focus of Quaternary paleoclimatology seems to have been on explaining climatic variations as opposed to reconstructing or synthesizing conditions for a particular time. Mitchell's (1965) review chapter in the Wright and Frey (1965) *Quaternary of the United States* volume is representative, along with the volume of *Meteorological Monographs* he edited, that included Kutzbach et al. (1968). That volume also included a chapter by Eriksson (1968) that discussed the interactions between the ice sheets and atmosphere primarily from an energy-balance perspective, which led him to observe that "differences in conditions between the hemispheres during glacial periods--if real--would probably have led to rather interesting changes in atmospheric circulation…" He suggested that if Northern Hemisphere temperatures were lower than Southern Hemisphere ones, this could have led to a southward shift of circulation and surface-climate patterns (in both hemispheres) and not "merely a compression of climatic zones in low latitudes (p. 85)."

There were, however, several attempts made at reconstructing or depicting LGM Northern Hemisphere circulation features (or changes between then and present), including those by Willett (1950), Flohn (1953), and Bryson and Wendland (1967) that included discussion of some or all of the features of the circulation changes that were later the focus of simulations with climate models. All of these studies used reconstructions about surface-climate conditions from paleoclimatic ("proxy") evidence, and then used those in turn to infer circulation characteristics. The most substantial effort was that of Lamb and Woodroffe (1970) that employed concepts and tools that had been used earlier by Lamb to reconstruct circulation over the past several hundred years. Lamb and Woodroffe (1970) used the surface-climate characteristics to infer 1000-500mb thickness, and from those upper-level, and in turn, surface circulation features. They described the rock-in-a-stream effect of the ice sheets as follows: “Whenever these great ice barriers lay in the path of the mainstream of the meandering upper westerly winds, they must have induced great lee troughs and tended to produce a train of large waves downstream around the hemisphere, as the Rockies and the high mountain plateaus of Asia do today (p. 38).” Their reconstructions of the circulation displayed a number features that are prescient of later simulations, including: 1) displacement of the circumpolar vortex and concomitant development of the polar anticyclone over northeastern Canada; 2) “great meridionality” of the surface winds particularly over the Atlantic sector; 3) little “seasonal change of vigor, or latitude of the main circulation features;” and several others that emerged particularly from analyses of conditions subsequent to the LGM.

The 1970s saw the first simulations of LGM conditions using GCMs, including those done by Williams, Barry and Washington (1974), Gates (1976), and Manabe and Hahn (1977). These simulations are notable not so much for the climates they depicted, but instead for the pathways they initiated, and for their focus on the globe as opposed to just the Northern Hemisphere. The Williams et al. (1974) simulation, for example, shows some equatorward displacement of surface features in the Northern Hemisphere, but little impact of an imposed ice sheet on upper-level flow (although the ice sheet in those simulations was rather flat). Similarly, while Gates’s (1976) simulation shows a glacial anticyclone over North America and equatorward displacement of surface pressure features in the Northern Hemisphere, it also showed large positive pressure anomlies over the southern high latitudes, in constrast to nearly all subsequent simulations. Manabe and Hahn’s (1977) simulation focused mainly on the tropics, but showed a small glacial anticyclone and apparent southward shifts of circulation features across both hemisphere (during the northern-summer interval focused on in these simulations).

COHMAP-era ideas

What might be thought of as second-generation simulations of LGM conditions were completed in the 1980s, and included those done using then-current versions of the NCAR (Kutzbach and Wright, 1985; Kutzbach and Guetter, 1986), GFDL (Manabe and Broccoli, 1985; Broccoli and Manabe, 1987), and GISS (Rind, 1987) models. All of these studies featured comparisons of the simulations with paleoclimatic “observations,” but the most substantial of these were those done as part of COHMAP, including Kutzbach and Wright (1985), the COHMAP *Science* article (COHMAP Members, 1988); and the “COHMAP book” (Wright, et al., 1993).

In Kutzbach and Wright (1985) there appeared the first of several “cartoons” of the LGM Northern-Hemisphere circulation (their Fig. 11), with others to follow in COHMAP Members (1988), and for North America in Kutzbach (1987), Barnosky et al. (1987), and Thompson et al. (1993). Among these are the rather stylized sketch of the impact of the ice sheet and its retreat on the circulation over North America that appeared in Kutzbach and Webb (1991), and was further discussed in the chapter on the conceptual basis for understanding late-Quaternary climates from the COHMAP book (Kutzbach and Webb, 1993). Over North America, the main features of the LGM circulation that were highlighted in the cartoons were the glacial anticyclone expressed in the surface winds, and a “split jet” in the upper atmosphere. These features were also clearly expressed in the vector-wind maps that appeared in Kutzbach and Guetter (1986) and the “model output” chapter of the COHMAP book (Kutzbach et al., 1993), but it was the cartoon depiction that probably had the greatest influence on the paleoclimate community. (In some cases, perhaps too much influence, inasmuch as the cartoons, rather than the model output itself, became the focus of data-model comparisons, particularly those involving the reconstruction of paleowind directions (e.g. Muhs and Bettis, 2000, (their Fig. 13), but see also Sweeny et al., 2004, (their Fig. 1) for a counter-example.) In addition to the circulation features around North America, these simulations also hinted at Southern-Hemisphere circulation changes, namely a poleward shift in the latitude of the strongest westerlies, although that feature was evident more in the trend in circulation anomalies across the different time-slices than in the LGM anomalies themselves.

Similar circulation changes can be seen in the simulations with the other models mentioned above. Rind's (1987) sensitivity-test simulations (see Peteet, 2001) using the GISS model are notable in that he attempted to decompose the overall LGM circulation into components related to the area of the ice sheet, its height, SSTs, etc.) In doing so, Southern Hemisphere circulation changes were shown to be related more to general LGM temperature anomalies (including SSTs, and sea-ice limits) than to the direct influence by the ice sheets. In a similar fashion, Broccoli and Manabe (1987) examined the separate effects of the ice sheets, atmospheric carbon dioxide concentration, and land albedo on the LGM climate. Of interest here is their demonstration of Southern Hemisphere high-latitude temperature responses to both ice sheet size and carbon dioxide concentration, which jointly provide a mechanism for general glacial-age boundary conditions to evoke a Southern-Hemisphere response distinct from the ice-sheet dominated Northern-Hemisphere response.

A sequence of simulations using CCM 1 (which included a mixed-layer ocean, thereby obviating the need to specify SSTs) appeared in a special issue of *Quaternary Science Reviews* (Webb and Kutzbach, 1998) and might be regarded as the third generation of simulations that focused on the LGM and subsequent intervals. The main features of the circulation for the LGM derived from these simulations have already been discussed while describing Fig. 1 above. In addition to providing a basic description of the model output, Kutzbach et al. (1998) also summarized the simulated climates by expressing them as biomes, while other papers focused on data-model comparisons in particular regions (Bartlein et al., 1998; Webb et al., 1998), or on the components of the overall changes in simulated climates through sensitivity tests (Felzer et al., 1998; see also Felzer et al. 1996). Kutzbach et al. (1998) also commented on the existence of drier-than-present conditions in the tropics, relating them to moisture-balance changes and indirectly to changes in the latitude of the ITCZ.

As an addition to the standard portrayals of model output, Bartlein et al. (1998) attempted to show directly the circulation features that previously had been depicted in cartoon form (and in a similar fashion, Whitlock et al. (2001), used "small multiples" to show both the seasonal and progressive changes in simulated variables). Pursuing an idea John Kutzbach had, Webb et al. (1998) examined the joint effects of both dynamic (i.e. the glacial anticyclone and the attendant subsidence) and thermodynamic (i.e. surface water- and energy-balance) controls of the simulated climate of eastern North America (see also Bartlein et al., 1998, for similar analyses for other regions.) As Rind (1987) and Broccoli and Manabe (1987) had done previously, Felzer et al. (1998) demonstrated using sensitivity-test simulations that the direct effects of the ice were confined to the Northern Hemisphere, while reduced carbon dioxide, and its influence on temperature and hence sea ice, were responsible for high-latitude anomalies in the Southern Hemisphere.

At the point of publication of the *Quaternary Science Reviews* special issue, the combination of interrelated components of the LGM circulation over North America that included a) an equatorward-displaced jet stream (with a weaker northern branch or split jet), b) a glacial anticyclone over the ice sheet, and c) intensified Aleutian and Icelandic lows could be seen to be as robust a feature in late-Quaternary paleoclimatic simulations as the enhanced Northern Hemisphere monsoon was in mid-Holocene simulations. These features were explained by a relatively straightforward conceptual model, elements of which had been discussed earlier, well before the era of climate-model simulations. The general southward shift of all circulation features (as might accompany the development of a "permanent northern winter"), and the particular circulation changes that influenced the Southern Hemisphere in general and South America in specific were less clearly expressed in these simulations.

Post-COHMAP ideas

More recent paleoclimatic simulations that focus in some part on LGM atmospheric circulation features over the Americas include those that have examined: 1) the Southern Hemisphere/South America westerlies issue in particular, 2) further details of the impact of the ice sheets on circulation, 3) the variations among models using the PMIP LGM simulations, and 4) the impacts of coupling between the ocean and atmosphere. In a set of related papers, the location and strength of the southern westerlies were examined for the South American sector a) in a sequence of time-slice simulations including the LGM by Valdes (2000), and b) at the LGM in particular for the Southern Hemisphere as a whole by Wyrwoll et al. (2000). Both studies used the UGAMP model, and Valdes (2000) also compared those simulations with the set of PMIP simulations for the LGM. The UGAMP model used was of higher spatial resolution that CCM 1, but overall the simulations are quite similar, particularly in the January/July contrast in circulation around southern South America that also appears in Fig. 1 (e.g. the dual zone of faster westerlies in the southern winter). Both UGAMP studies examined atmospheric circulation statistics that allowed depiction of the storm track location. Valdes (2000) noted cooling at the edge of Antarctica and a weak increase in storminess over the eastern Pacific, and in his comparison across PMIP models further noted a poleward shift of the mean southern westerlies among all models (albeit with considerable model-to-model variability). Changes in zonal wind speeds for the Pacific sector shown in Fig. 6 of Wyrwoll et al. (2000) provide another way of illustrating this shift. Wardle (2003) used an index of anticyclonicity to define the equatorward edge of the southern westerlies and found similar small latitudinal adjustments. The southward shift of the southern westerlies, and the focusing of the storm track at high latitudes as proposed by Markgraf (1989, see also Whitlock et al. 2001) are supported by these simulations and storm-track analyses.

The impact of ice-sheet elevation on storm tracks in the Northern Hemisphere (Kageyama and Valdes, 2000) and on circulation and climates in regions distant from the ice sheets (Hostetler et al., 1999) were explored using sensitivity tests with other models that were of higher resolution than those used earlier, and produced much the same kind of result as earlier simulations. Hostetler and Bartlein (1999) used the output of the latter simulation to force a regional-scale climate model for the western United States, which provided a picture of the mediation of the large-scale circulation (i.e., the glacial anticyclone and equatorward-shifted westerlies) by the complicated physiography of the region.

Other analyses and data-model comparisons of the multiple PMIP simulations provide some additional information. Although North America was not a specific focus of Kageyama et al.'s (2001) analysis, maps of LGM anomalies that allow comparisons to be made between simulations of LGM conditions with specified SSTs and those with computed SSTs (using mixed-layer models) show amplified responses over North America in the computed SST simulations. Comparisons of a synthesis of paleoclimatic data in tropics (Farrera et al., 1999) with the PMIP simulations (Pinot et al., 1999) show the impact of water-balance changes on tropical aridity at the LGM noted earlier.

There is a growing number of simulations of LGM climates that have been performed with coupled OAGCMs, including those by Bush and Philander (1999), Kitoh and Murakami (2002), Liu et al. (2002), Kim et al. (2003), Hewitt et al. (2003), and Shin et al. (2003, which might be viewed as a fourth-generation instance of a COHMAP-family simulation and data-model comparison), plus many others perfomed with intermediate-complexity models. There are no real surprises in these simulations, apart from the observation that could be made that the inclusion of a fully coupled ocean greatly increases the range of configurations that atmospheric circulation can exhibit and still be physically consistent (in a model) with huge ice sheets and lower-than-present carbon dioxide concentrations.

Summary

Although small in terms of the area directly affected (in comparison with the global monsoon), the North American ice sheet played the role of a 500 lb (or 227 kg) gorilla[2] in the climate system, that extended its reach[3] deep into the Southern Hemisphere. Around North America, the ice sheet deflected the storm track equatorward, and along with the influence of the glacial anticyclone generated by the intense cold, produced the clear latitudinal pattern of moisture anomalies in the western United States. Farther afield, the influence of the North American ice sheet (and its Scandinavian companion), together with that of lower carbon dioxide at the LGM, reduced global temperatures, which in the Southern Hemisphere led to increases in sea-ice extent, and strengthening of the southern westerlies. Finally, by remaining in place the year round, the northern ice sheets locked the world into a permanent (northern) winter, which like at present, pushes the zonal circulation toward the Southern Hemisphere.

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[2] 500 lbs is on the heavy side for an adult male lowland gorilla (which incidentally has the great species name *Gorilla, gorilla, gorilla*). (http://www.zoo.org/educate/fact_sheets/gorilla/gorilla.htm).

[3] 8 ft (2.4 meters), fingertip-to-fingertip, or a little less than the height of the rock on the U.W. Madison Campus commemorating the career of the pioneering paleoclimatologist T.C. Chamberlin.

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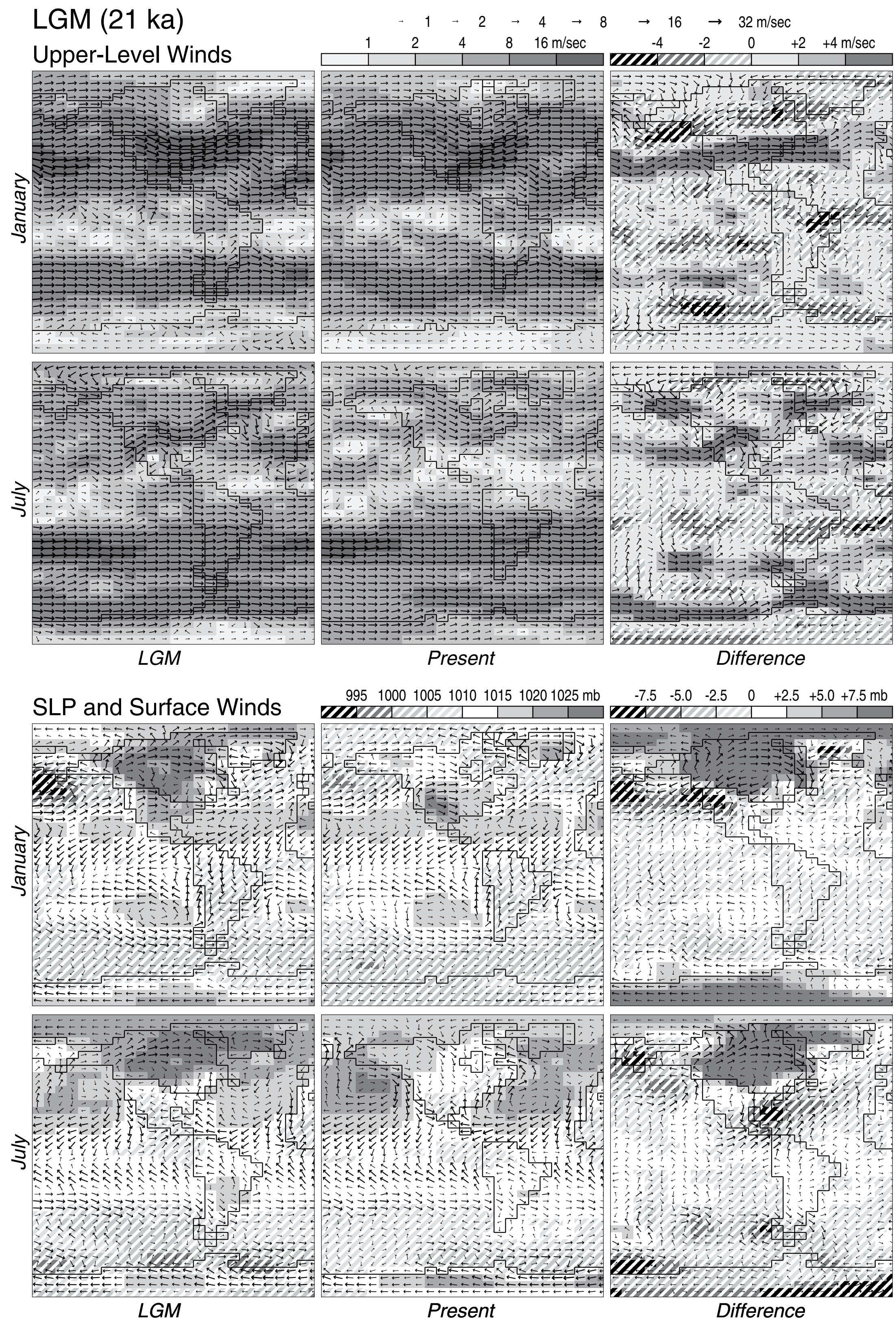

Figure 1: Last Glacial Maximum (LGM) circulation features, based on simulations using CCM 1 by Kutzbach et al. (1998). Upper-level winds are at the 500mb level.