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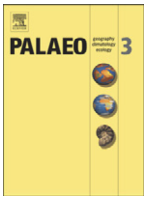

River incision, circulation, and wind regime of Pleistocene Lake Bonneville, USA

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A R T I C L E I N F O

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A B S T R A C T

Pleistocene Lake Bonneville of the western U.S. and its associated alluvial systems present a unique opportunity to understand the relationship between prevailing winds of the time, lake circulation, and river incision. The lake underwent a catastrophic flooding event ~18,300 yr B.P. resulting in the incision of streams entering the lake along its eastern border. Incision patterns of twelve streams and rivers suggest that they were influenced by the prevailing circulation in the lake at the time. In order to match patterns of river incisions, simulations of lake circulation were performed with a state-of-the-art numerical model for the maximum transgressive (Bonneville) lake elevation. Simulations were conducted using the forcing of westerly and easterly prevailing winds. Simulated circulation can be described in terms of simple geostrophic balances in which the currents are generally cyclonic (counter clockwise) for westerly winds and anti-cyclonic (clockwise) for easterly winds. Irregularities in lake shorelines and bathymetry cause localized variation of this general pattern. Comparison of model output with the deflected stream incision patterns suggest that prevailing winds during the Pleistocene in the Great Basin of North America were westerly and that, unlike the interior of North America, the continental ice sheet did not exert significant influence on the climatological wind patterns of the Great Basin.

1. Introduction

Paleoclimate studies have long benefited from a symbiotic relationship between numerical models and paleoclimate proxies. While this relationship has worked particularly well for understanding climate variables such as precipitation and temperature, field evidence of paleowind direction and magnitude is more difficult. Analysis of dunes and associated sedimentary features is the most obvious and widely employed methodology (e.g., Allen, 1982; Kocurek, 1999). Fallen trees can provide indications of ancient wind directions where they are preserved in the geologic record (Allen, 1998). Ancient pyroclastic deposits sometimes have asymmetric thickness that can be used to infer wind direction (Fisher and Schmincke, 1984; Oviatt and Nash, 1989). More recently, isotopic and geochemical analyses of loess and dune deposits have shown promise in understanding the provenance and hence, wind direction (Aleinikoff et al., 2008; Muhs et al., 2008). The sediments, shorelines and geomorphology of lakes have occasionally been used to estimate wind strength (Krist and Schaetz, 2001; Adams, 2003).

Both field and modeling studies suggest that the wind regime during the last glacial maximum (LGM) was considerably different from that of the modern atmosphere. General circulation models (GCMs) indicate that continental ice sheets modified the climate of the northern hemisphere by splitting the jet stream and steering the southern component considerably further south than the modern jet stream (Kutzbach and Wright, 1985; Manabe and Broccoli, 1985; Rind, 1987; Bush and Philander, 1999; Whitlock et al., 2001). If so, increased precipitation caused by storms tracking along the southern arm of the jet stream resulted in a significantly wetter climate that led to large pluvial lakes in the Great Basin of North America. Recent, more detailed regional circulation models (RCMs) suggest the northern branch of the jet was stronger than the southern branch during the LGM and that both arms show distinct seasonality (Bromwich et al., 2004, 2005).

The GCM and RCM studies also suggest that continental ice sheets set up a very large, quasi-permanent high pressure cell over much of North America that produced anticyclonic surface circulation. The prevailing surface winds over much of the central part of the continent were predominantly easterly (Kutzbach and Guetter, 1986; Thompson et al, 1993) with a strong katabatic component during the winter (Bromwich et al., 2004). These model results are corroborated by studies of eolian features in Saskatchewan (David, 1981), Alaska (Lea and Waythomas, 1990), the Pacific Northwest (Barnosky et al., 1987) and New England (Thorson and Schile, 1995) as well as indirect evidence from continental diatoms found off the coast of North America (Sancetta et al., 1992). The field and climate model studies are contradicted by paleowind analysis of Pleistocene dunes in the Great Plains of North America that indicate prevailing winds were from the west in approximately the same fashion as modern atmospheric circulation patterns (Wells, 1983; Muhs and Bettis, 2000; Aleinikoff et al., 2008; Muhs et al., 2008).

Particularly problematic is atmospheric circulation in the intermountain west of North America where mountain topography

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produces localized variations in surface winds unrelated to mean global circulation patterns. Paleowind analysis in the Great Basin region of western North America during the LGM is especially sparse. The complex topography of the region and coarse grid spacing of GCMs and RCMs make conclusions of model results suspect. The most detailed RCM atmospheric model of North America to date for the LGM suggests that the prevailing winds in the Great Basin were easterly, but very weak (Bromwich et al., 2004, 2005).

2. Lake Bonneville and associated alluvial systems

Lake Bonneville was the largest pluvial lake of the Pleistocene period in the Great Basin of the western United States. The lake is believed to have formed in response to the regional climate which was both wetter and cooler during the LGM (e.g., Thompson et al., 1993). The bathymetry of the lake can be roughly separated into a large, deep eastern basin; a large, but somewhat shallower western basin; and the relatively small, shallow Sevier basin to the south (Fig. 1).

While the Bonneville basin has seen a number of lake transgressions and regressions during the Quaternary, the most recent lake cycle is believed to have begun ~30–32,000 yr B.P. The maximum transgression of this lake cycle established the Bonneville shoreline between ~18,300 and 17,800 yr B.P. During this time of the maximum transgression, there is evidence of sapping and groundwater seepage at the Zenda threshold in southern Idaho that was a prelude to a catastrophic flood (Janecke, pers. comm.). Following the flood, the lake stabilized at the Provo shoreline between 17,400 and perhaps as late as 14,300 yr B.P. (Oviatt, 1997; Godsey et al., 2005).

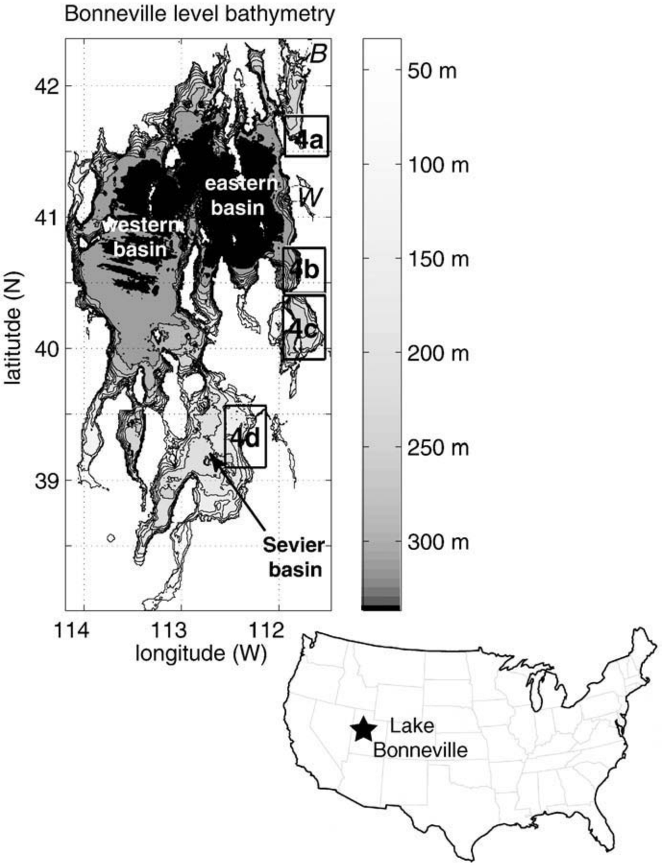

Fig. 1. Location and paleobathymetry of Lake Bonneville at the maximum transgressive (Bonneville) shoreline elevation. Paleobathymetric data have been corrected for isostatic rebound (Bills et al., 2002). The major sub-basins of the lake are show along with the location of the Bear River (B) and Weber River (W). The east–west lineations in the western basin may represent Holocene alluvial features. Outlined areas refer to the detailed areas shown in Fig. 4.

The nature and duration of the Bonneville flood has been the subject of paleohydraulic studies. The volume of water of the flood is estimated to be ~4750 km^3 (O'Conner, 1993) and maximum discharge was ~0.8–1.0 × 10^6 m^3 s^{-1}, a discharge comparable to the modern Amazon River (Jarrett and Malde, 1987). Were flow to persist at maximum discharge, the flood would have lasted ~2 months; in all likelihood, the discharge decreased over a considerably longer period of time as the hydraulic head during the flood at Zenda was also decreasing with time (O'Conner, 1993). Although the flood produced a distinctive marker bed in the deep sediments of the lake (e.g., Oviatt et al., 1994) and likely had a significant impact on lake circulation in the immediate vicinity of the Zenda threshold, the main physical effect in the larger portions of the lake would have been a gradual lowering of lake level over a period of weeks or months.

A number of streams and rivers discharged into Lake Bonneville. The most important of these include the Bear, Weber, and Provo Rivers which today constitute the major freshwater inputs to Lake Bonneville's successor, the Great Salt Lake. The Sevier River was no doubt an equally important contributor to the water balance of Lake Bonneville although today it discharges into the Sevier playa to the south of the Great Salt Lake basin. Lesser rivers and streams were concentrated along the eastern edge of the lake, where the high mountains and mountain glaciers of the Wasatch Front provided abundant freshwater sources. River discharge from the Weber and American Fork Rivers at the time of Lake Bonneville is estimated to have been approximately double modern discharge rates (Lemons et al., 1996), a somewhat greater number than the results of RCM simulations of the "lake effect" produced by Lake Bonneville (Hostetler et al., 1994).

Where streams enter lakes, they are subject to two dominant influences: (1) the Coriolis force which in the northern hemisphere tends to deflect river discharge to the right (e.g., Masse and Murthy, 1990) and (2) currents in the lake (Fig. 2). During the period in which the Bonneville flood was taking place, rivers and streams entering the lake between the Bonneville and Provo shorelines would have been deflected in a fashion reflecting these forces and thus be recorded as incisions in the poorly consolidated Bonneville sediments between

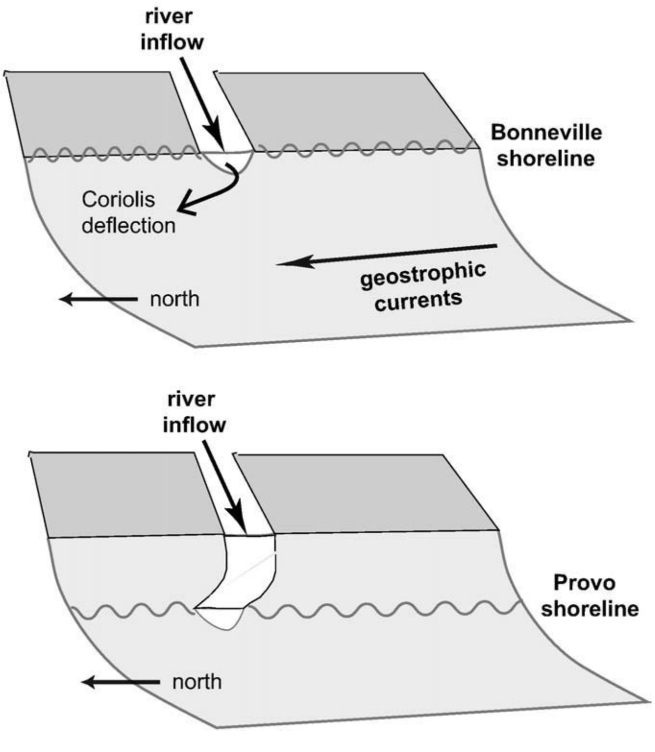

Fig. 2. Idealized flow of a stream into a large lake where is can be deflected to the right by the Coriolis force or come under the influence of prevailing currents in the lake.

these two shorelines. In order to evaluate the behavior of streams and rivers entering Lake Bonneville at the time of the flood, a survey of modern alluvial systems in the Bonneville basin was conducted in order to find streams (1) with significant modern perennial discharge and (2) exit points from the mountain front between the Bonneville and Provo shorelines and whose discharge would thus been subjected to lake forces prevalent during the flood.

In general, the only substantial modern streams and rivers of the Bonneville basin are along the eastern edge where mountains of the Wasatch Front or Wasatch Plateau provide the necessary watershed area and orographic lift to produce significant precipitation, snow pack, and perennial runoff. Streams discharging from smaller mountain ranges of the Basin and Range province in the central and western portions of the Bonneville basin have significantly smaller drainage areas and modern discharges (Fig. 3).

The Provo elevation of Lake Bonneville for some important alluvial systems (e.g., Bear and Weber Rivers) is upstream of the mountain front meaning that during the Bonneville flood, these rivers and streams were discharging into canyons and valleys and would not have been influenced by currents in the main part of the lake. Twelve significant streams and rivers were identified in which the mountain front discharge points are between modern Bonneville and Provo shorelines (Table 1). Five are located in Salt Lake Valley, four in Utah Valley, two in Cache Valley, and one in the Sevier basin (Fig. 4). All but one of the alluvial systems discharged into small sub-basins or relatively shallow portions of the lake along the eastern shore (Fig. 1). The exception (Sevier River) is a relatively large river with headwaters in the Wasatch Plateau of central Utah. The distance between the mountain front and the Provo shoreline of the 12 alluvial systems varies from 1 to 22 km.

Detailed 2-m DEM data from a LiDAR survey of the Wasatch Front (encompassing the Mill Creek, Emigration, Parleys Creek, Big Cottonwood, and Little Cottonwood alluvial systems) and 5-m autocorrelated DEM data for the other 7 streams were downloaded from the State of Utah's Automated Geographic Resource Center (http://www.gis.utah.gov/). These data were used to compute the least-squared vectors of the drainage 1 km upstream from the mountain front and downstream from the mountain front to the Provo shoreline of each stream. Present day elevations of the Bonneville and Provo shorelines were taken from Personius and Scott (1992) for the Salt Lake Valley, Machette (1992) for Utah Valley, McCalpin (1989) for the Cache Valley, and Currey (1982) for the Sevier Basin.

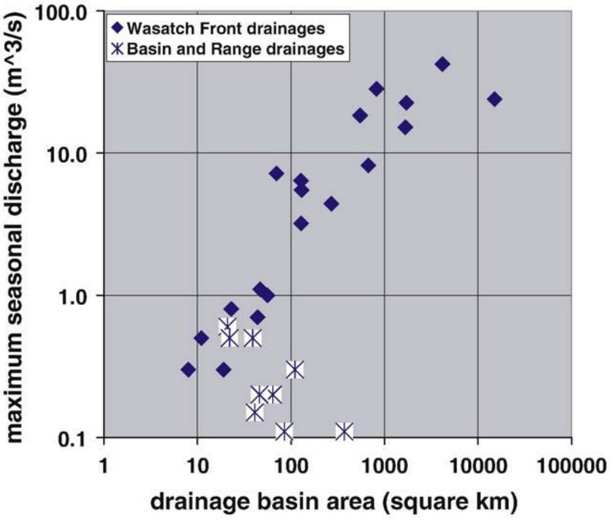

Fig. 3. Maximum surface discharge of streams located near modern elevations of the Lake Bonneville showing the difference between drainages from the Wasatch Front and those in the Basin and Range. All data from the U.S. Geological Survey (http://www.waterdata.usgs.gov/ut/nwis/sw/).

Table 1
Summary of characteristics of streams and rivers entering Lake Bonneville.

Name	Maximum modern discharge [a] (estimated Pleistocene discharge in parentheses) (m^3/s) [b]	Vector 1 km upstream from river mouth (r^2)	Downstream distance between river mouth and Provo level (km)	Vector downstream from river mouth to Provo level (r^2)	Apparent deflection of stream by lake forces	Mass flux of lake model (western wind simulation) within 1 km radius of discharge point (m^3/s)
Logan Canyon	18.4 (36.8)	287° (0.91)	2.0	252° (0.84)	35° southward	239
Blacksmith Fork	8.2 (16.4)	287° (0.73)	3.0	321° (0.98)	34° northward	77
Emigration Creek	1.1 (2.2)	246° (0.81)	2.0	261° (0.62)	15° northward	271
Parleys Canyon	3.2 (6.4)	239° [c]	1.5	274° [c]	35° northward	89
Mill Creek	1.0 (2.0)	267° (0.29)	2.0	289° (0.91)	22° northward	161
Big Cottonwood Creek	6.4 (12.8)	282° (0.87)	1.5	311° (0.91)	29° northward	97
Little Cottonwood Creek	7.2 (14.4)	289° (0.90)	1.5	328° (0.97)	42° northward	25
American Fork	5.5 (11.0)	259° (0.84)	2.5 (upper) 2.5 (lower)	245° (0.81) 206° (0.75)	14° southward 53° southward	267
Provo River	22.6 [d] (44.6)	199° (0.87)	6.5	188° (0.89)	11° southward	161
Hobble Creek	4.4 (8.8)	251° (0.85)	3.0	284° (0.61)	34° northward	171
Spanish Fork	15.2 (30.4)	291° (0.37)	4.0	258° (0.17)	35° southward	403
Sevier River	24.0 [e] (48.0)	259° (0.19)	10 (upper) 12 (lower)	262° (0.49) 228° (0.97)	3° northward 31° southward	202

[a] From U.S. Geological Survey records.

[b] 2 times modern flow after Lemons et al. (1996).

[c] DEM calculation not possible due to highway construction; estimated from aerial photo.

[d] Value from upper Provo River upstream of irrigation withdrawals.

[e] Possible upstream water withdrawals.

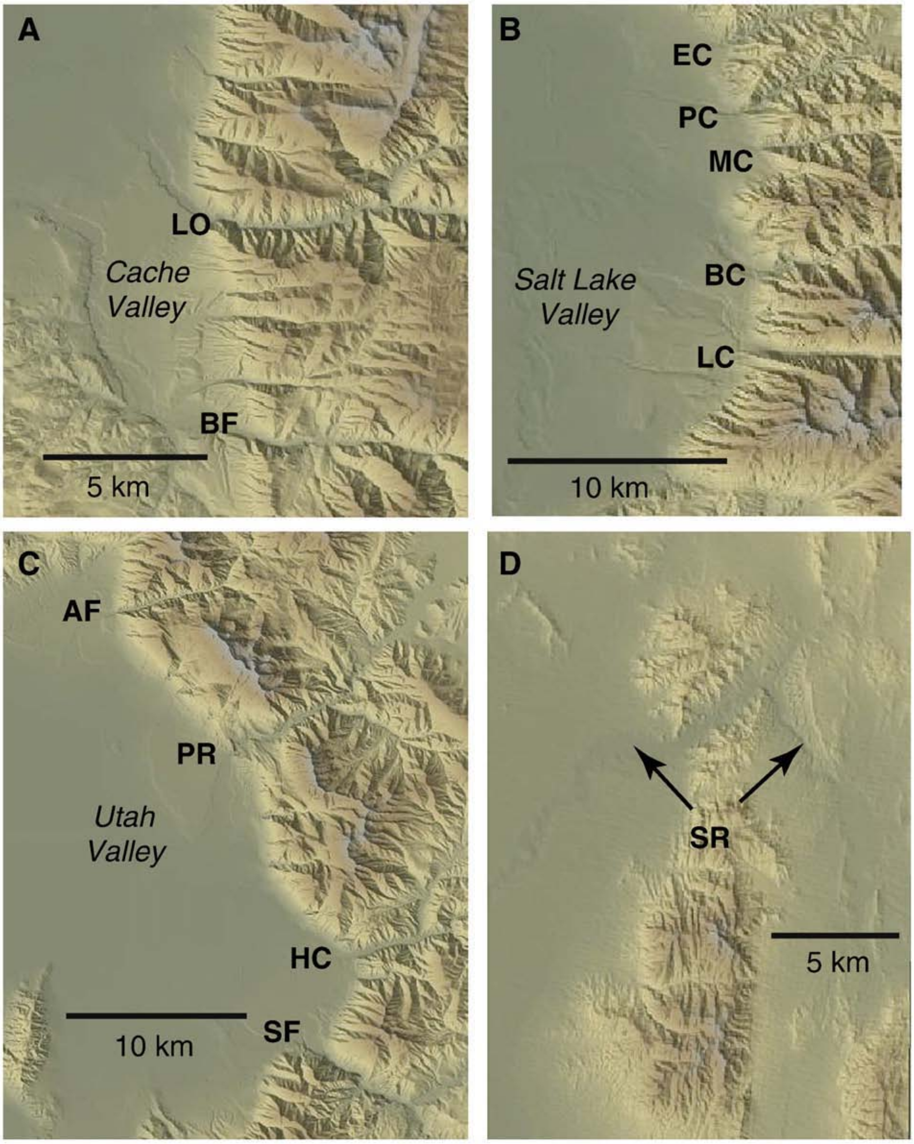

Fig. 4. Location of streams along the Wasatch Front in which the discharge point is between the Bonneville and Provo shorelines. (A) Cache Valley, LO = Logan River, BF = Blacksmith Fork and (B) Salt Lake Valley, EC = Emigration Canyon, PC = Parleys Canyon, MC = Mill Creek, BC = Big Cottonwood, LC = Little Cottonwood, (C) Utah Valley, AF = American Fork, PR = Provo River, HC = Hobble Creek, SF = Spanish Fork, and (D) Sevier Desert, SR = Sevier River.

Deflection of the downstream vector relative to the upstream vector represents the influence of lake circulation on the stream incision during the period of the Bonneville flood as the lake regressed from the Bonneville to the Provo shoreline. Seven streams showed deflection to the north (e.g., Fig. 5A) and four (Logan, American Fork, Provo, and Spanish Fork Rivers) showed deflection to the south (e.g., Fig. 5B). The Sevier River traverses a very broad area between its point of discharge and the Provo shoreline with initial small deflection to the north and significant southward deflection downstream (Table 1).

3. Circulation modeling and analysis

3.1. Modern lake circulation

Given the role Lake Bonneville circulation played in river incision, a review the relevant literature of large modern lakes from both observational and theoretical perspectives is worthwhile. Observations of large lakes and inland seas has shown that circulation consists of single or multiple gyres that are dominantly cyclonic (counterclockwise). This is a consequence of the geostrophic balance of prevailing westerly winds raising the surface elevation on the eastern edge of the lake which in turn leads to relatively strong boundary currents on the eastern side of the lake and more dispersed return flow on the western side (e.g., Beletsky et al., 1999) (Fig. 6A). Easterly winds produce the opposite circulation pattern (Fig. 6B). This generalized picture can be complicated by factors such as horizontal surface water temperature gradients (e.g., Emery and Csanady, 1973). Enhanced cyclonic circulation during the winter can also result from the thermal contrast of land and surface water temperatures leading to a localized low pressure system over the lake that produces cyclonic wind stress curl (e.g., Schwab and Beletsky, 2003).

Wind-forced winter circulation in lakes is more intense than summer circulation, both because winter winds tend to be stronger and because thermally induced, 2-layer lake systems in the summer tend to produce relatively weak, counter-rotating gyres operating more or less independently of each other. These features of lakes have been recognized observationally and theoretically for decades (e.g., Csanady, 1967; Bennett, 1974). Coastal jets within a few km of shorelines are a common feature of large scale lake circulation (e.g., Csanady and Scott, 1974).

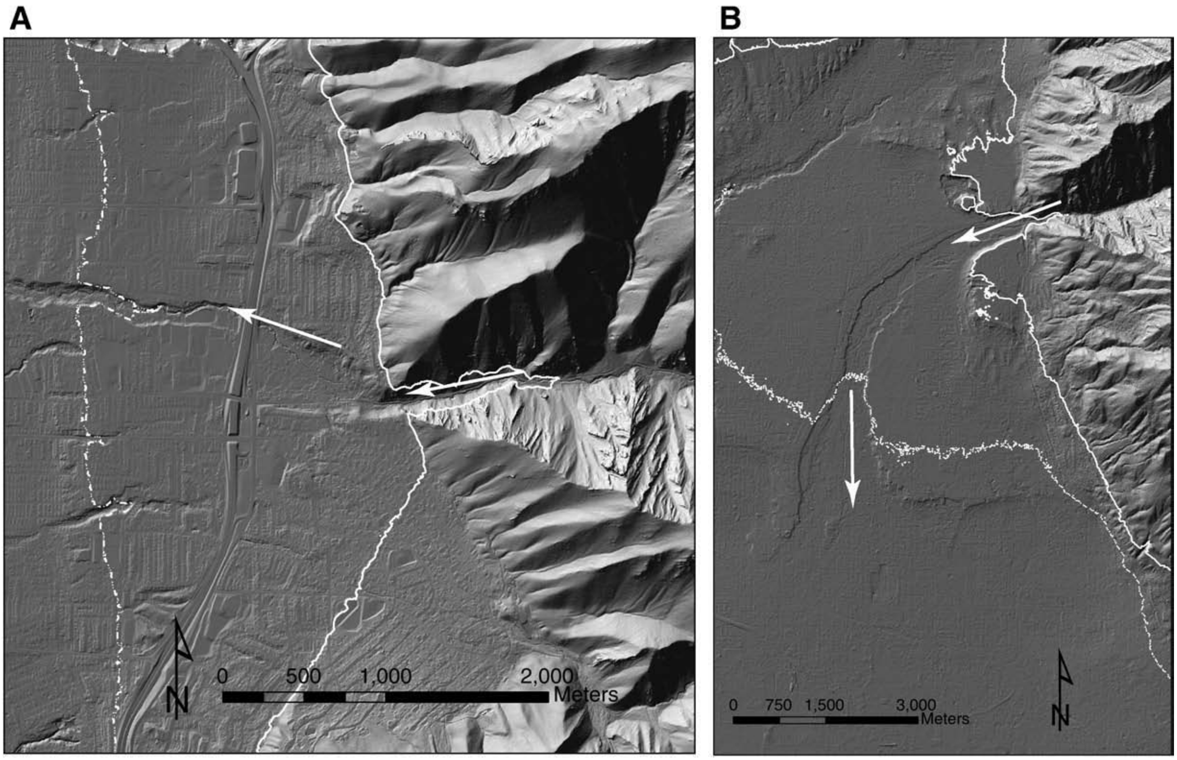

Fig. 5. Examples of streams entering Lake Bonneville in which stream flow and incision during the Bonneville flood was deflected (A) northward (Mill Creek) and (B) southward (American Fork). The solid white line represents the Bonneville shoreline and the dashed white line is the Provo shoreline.

The Great Lakes along the midwest border of the U.S. and Canada have been studied in particular detail from both observational and modeling perspectives. Of the Great Lakes, Lake Michigan has received the most study and fortuitously, has dimensions (~500 × 100 km, maximum depth ~300 m) similar to those of Lake Bonneville (~475 × 180 km, maximum depth ~300 m). Lake Michigan is separated into two major sub-basins and unlike Lake Bonneville has a relatively uniform coastline.

The mean circulation in Lake Michigan consists of cyclonic gyres centered around the two major sub-basins with smaller anti-cyclonic gyres near the ridges separating the two sub-basins (Beletsky et al., 1999; Beletsky and Schwab, 2001). As in most large lakes worldwide, winter circulation is more intense than summer circulation. Even so, mean winter winds result in relatively modest mean currents of 1.3–2.2 cm/s with maximum currents near the shorelines of between 7.9 and 11.7 cm/s (Beletsky and Schwab, 2001).

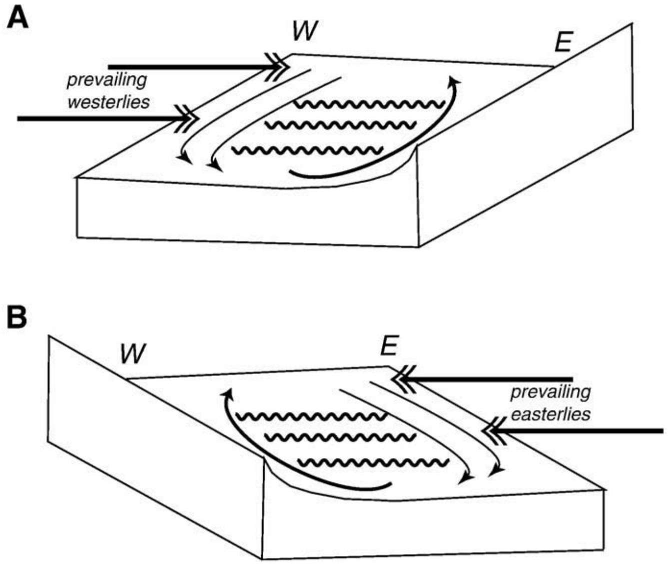

Fig. 6. Cartoon showing development of geostrophic currents in response to (A) westerly winds and (B) easterly winds.

3.2. Lake Bonneville modeling

In order to understand Lake Bonneville circulation, a so-called “primitive equation” numerical model was used to study Lake Bonneville. Primitive equation models solve the differential equations governing the conservation of momentum, heat, and mass in fluids to produce detailed fields of velocity, temperature, and solute concentration. The numerical model used in this study is the POM (Princeton Ocean Model), a computer code with a decade long record of successfully predicting circulation, temperature, and solute concentrations in a variety of marine and lacustrine settings (e.g., Oey et al., 1984; Jewell et al., 1993; Beletsky and Schwab, 2001). The model uses the level 2.5 turbulence closure scheme of Mellor and Yamada (1982) in order to parameterize water turbulence and mixing. The model employs a σ-coordinate system in which vertical spacing is proportional to water depth.

DEM data with a grid spacing of 500 m were used for the bathymetry of the simulations. These data were corrected for isostatic rebound due to water unloading since the Pleistocene (Wambeam, 2001; Bills et al., 2002) and have 472 × 963 horizontal nodes. All model simulations were conducted at an average Bonneville shoreline elevation of 1551 m a.s.l.

No surface heat flux or thermal stratification was included in the model. Justification for this simplification comes from the belief that in a much colder glacial climate, the lake water column during ice-free times was thermally homogenous for much of the season, particularly during ice-free conditions of the late spring when prevailing surface winds of modern mid-latitudes are most intense (Peixoto and Oort, 1992) and seasonal runoff of the streams relatively large. Even when large lakes

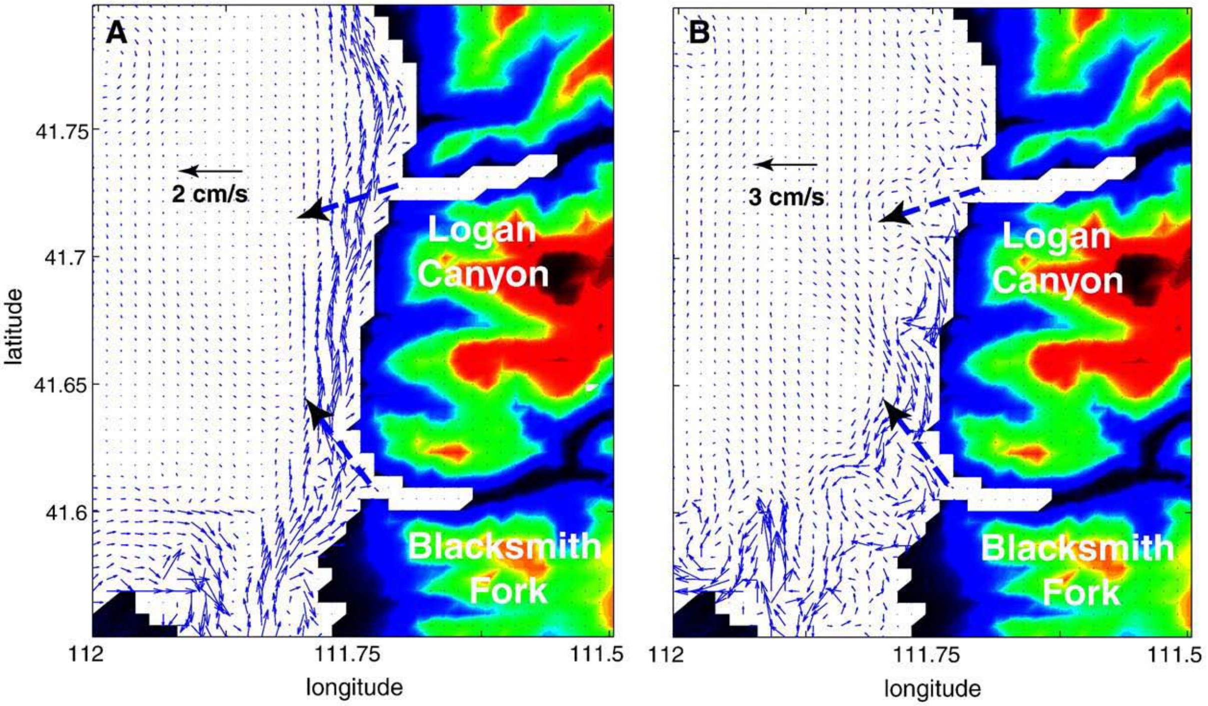

Fig. 7. Details of model lake circulation in Cache Valley for (A) westerly winds and (B) easterly winds.

such as Bonneville are thermally stratified, the surface layer, which would have been most relevant to deflection of incoming streams, exhibits cyclonic behavior similar to that of thermally homogenous lakes (e.g., Csanady, 1967; Bennett, 1974; Beletsky and Schwab, 2001). Because only a non-stratified water body was modeled, a relatively small number of vertical levels (7) were employed in the simulations. Wind stress transmitted to the lake surface was done using a simple relationship between wind speed and surface shear stress (Gill, 1982). No attempt was made to model river discharge into the lake *per se*, the justification of which is discussed below.

Wind stress curl (horizontal gradients of wind velocity) has been documented as a factor influencing circulation in large unstratified lakes due to the localized low pressure system that forms over the central portion of lakes as a result of the thermal contrast between surface and air temperature (Schwab and Beletsky, 2003). Numerical simulations of Lake Michigan run with uniform wind fields show less intense circulation relative to wind fields with significant wind stress curl, although overall circulation patterns are the same. In the case of Lake Bonneville, the regions with streams entering the lake are in relatively small sub-basins (Cache, Utah and Sevier Valleys) and the

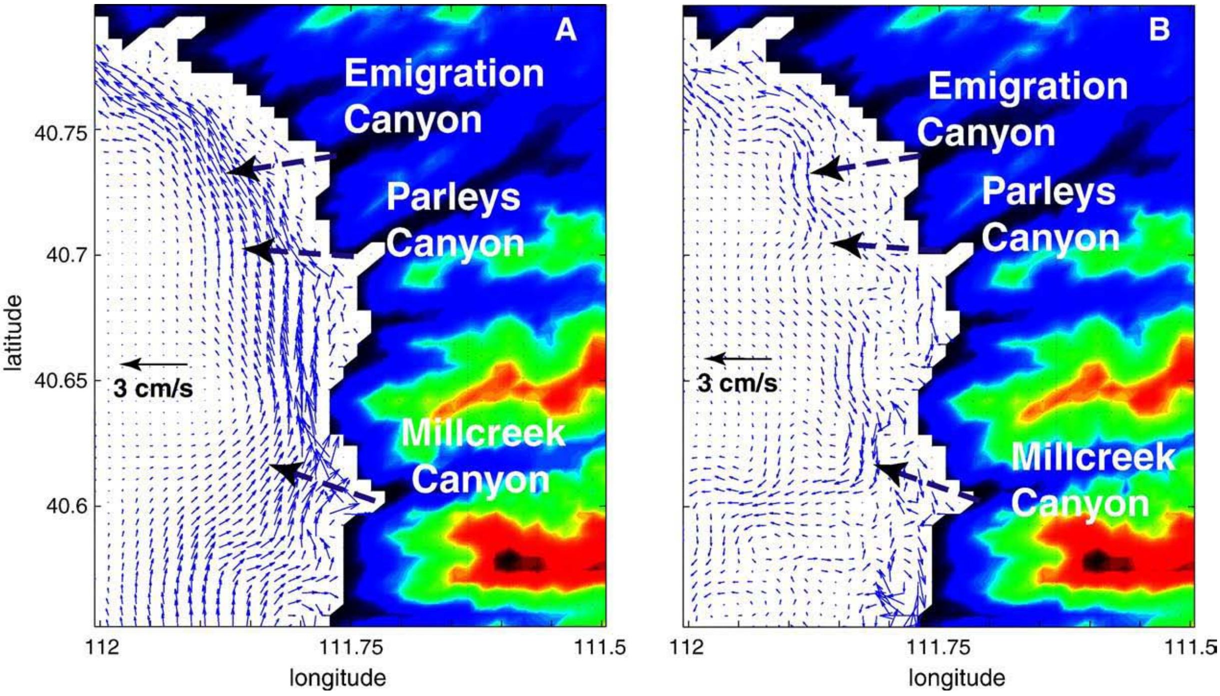

Fig. 8. Details of model lake circulation in northern Salt Lake Valley (A) westerly winds and (B) easterly winds.

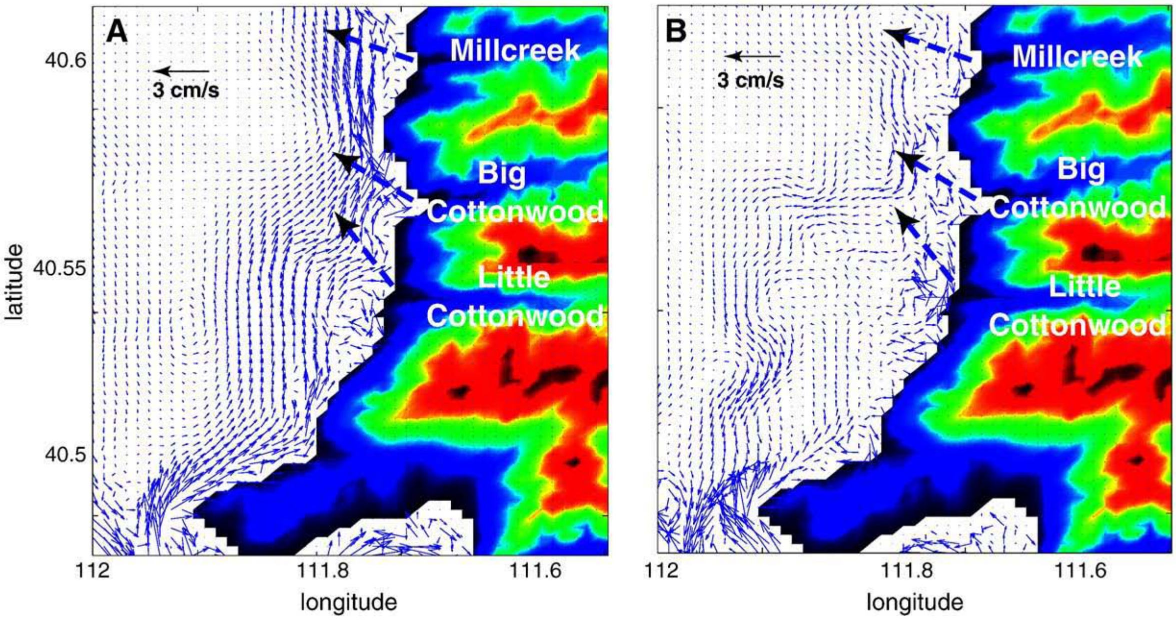

Fig. 9. Details of model lake circulation in southern Salt Lake Valley (A) westerly winds and (B) easterly winds.

southwest corner of the Salt Lake Valley (Fig. 2 and 4). Whereas wind stress curl may have been a factor in overall Lake Bonneville circulation, it was probably less of a factor in the smaller sub-basins which are the focus of this study.

Two model simulations of 20 days duration were run, one with prevailing westerly winds, the other with prevailing easterlies. The westerly simulation was meant to simulate the modern wind field while the easterly wind field was meant to simulate winds hypothesized to have been produced by the high pressure of the continental ice sheet. The most detailed atmospheric modeling of the Pleistocene of North America has been conducted by Bromwich et al. (2004, 2005) whose regional climate simulations for the late winter/early spring suggest surface wind magnitudes of ~3 m/s. This magnitude was used for both easterly and westerly winds in this study.

The Coriolis force tends to deflect river input to the right as rivers flow into lakes. The amount of deflection is related to the strength of the river plume. For instance, the discharge of large river plumes such as the Niagara River of Lake Ontario (discharge ~7000 m^3/s; Masse and Murthy, 1990) or the Thompson River of Kamloops Lake in British Columbia (discharge ~1000 m^3/s; Hamblin and Carmack, 1978) extend several kilometers into the lake and clearly show deflection to the right upon discharge. The extent of smaller stream discharge is obviously considerably less and appears to have not been studied in as much detail.

The general features of the model output fit the classic picture of circulation in large lakes with significant localized variations. Model output using westerly wind inputs shows separate cyclonic gyres in the large western, eastern, and Sevier sub-basins of Lake Bonneville. Similar circulation patterns can be seen in the smaller Cache and Utah Valley sub-basins (Figs. 6A, 7A, and 8A). The maximum velocities for both the westerly and easterly simulations are 8–9 cm/s, somewhat higher than maximum winter current magnitudes reported for the Great Lakes (3.7–9.5 cm/s) (Beletsky et al., 1999).

Relatively strong, coherent coastal currents along the eastern sides of the basin are a common feature of the westerly wind simulations.

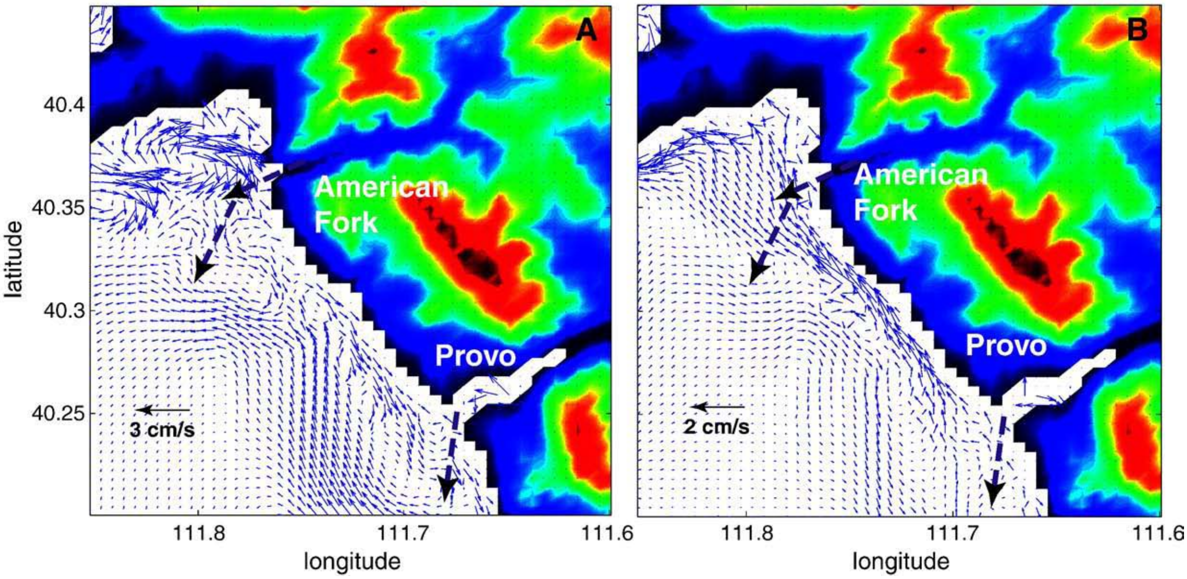

Fig. 10. Details of model lake circulation in northern Utah Valley (A) westerly winds and (B) easterly winds.

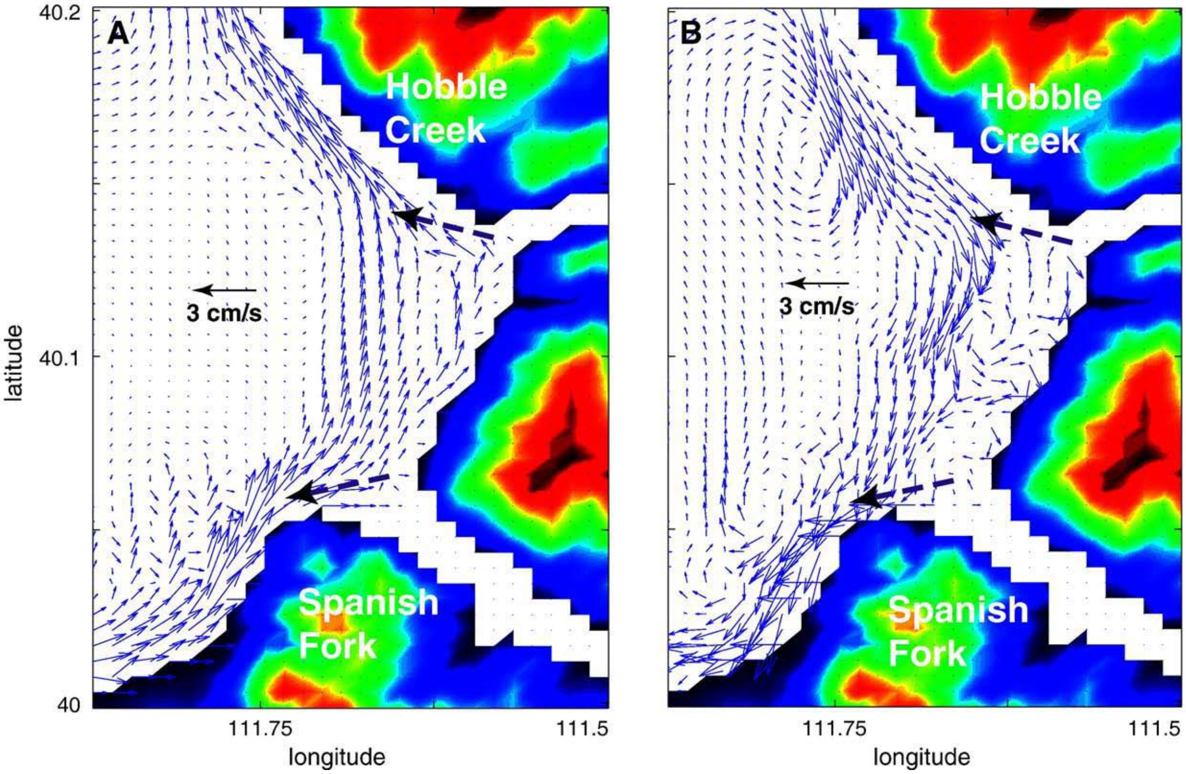

Fig. 11. Details of model lake circulation in southern Utah Valley (A) westerly winds and (B) easterly winds.

For prevailing easterly winds, anticyclonic gyres with weak coastal currents along eastern sides of the basin are the rule. For the Cache, Utah Valley and Salt Lake Valley sub-basins, maximum velocities are generally 3–3.5 cm/s (Figs. 7A, 8A, 9A, 10A, 11A, and 12A). For westerly wind forcing, the relatively small Utah Valley sub-basin shows a large retroflection caused by the Traverse Mountains to the north, resulting in smaller anti-cyclonic sub-gyres in which the flow is the reverse of the main gyre (Fig. 10A). A similar small retroflection is also seen in the Sevier basin simulation (Fig. 11A).

Despite the relatively small velocities of coastal currents in Lake Bonneville, the computed shore parallel mass flux of the currents is large relative to the assumed river discharges (Table 1) even when

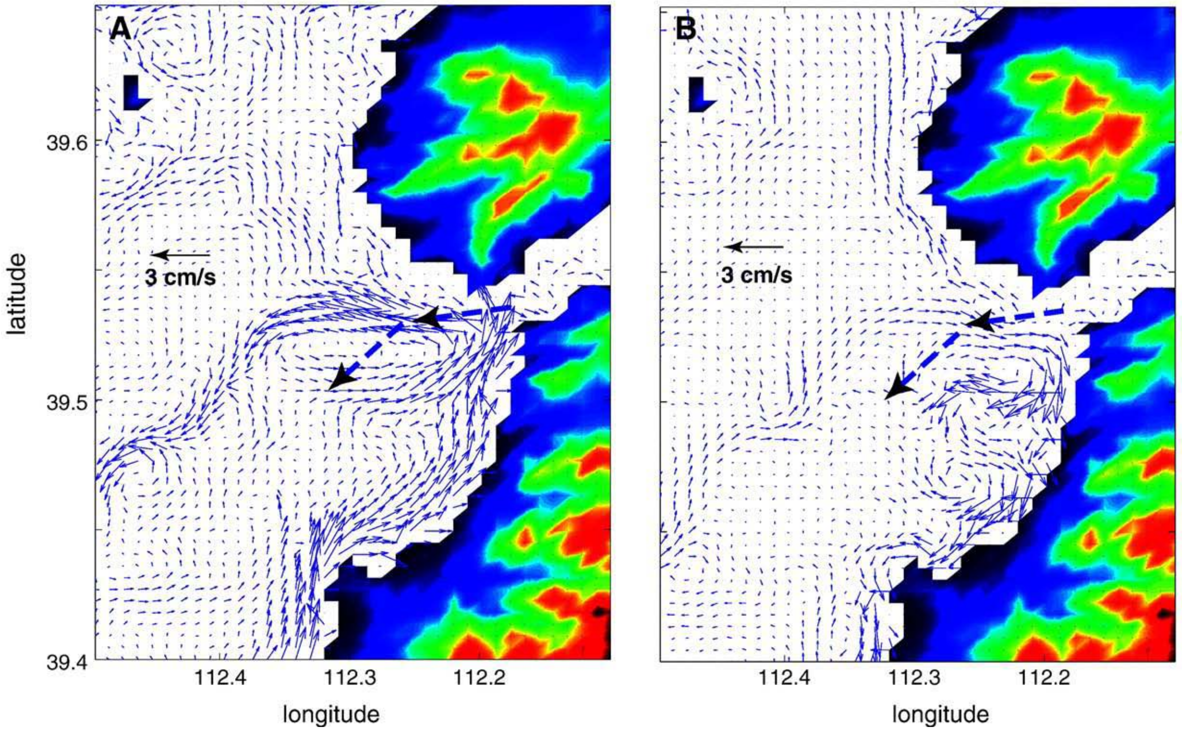

Fig. 12. Details of model lake circulation in Sevier River (A) westerly winds and (B) easterly winds.

Late Pleistocene stream discharges are considered to be double that of modern values (Lemons et al., 1996). For this reason, stream discharges were considered to be insignificant components of the overall lake circulation and were not incorporated directly into the model simulations.

The deflection of the streams flowing into Lake Bonneville as shown by the results of numerical model lake circulation suggests that the prevailing winds at the time of the Bonneville flood were westerly. A very strong south-to-north boundary current for westerly winds is modeled in the Cache Valley (Fig. 7A) where Blacksmith Fork Canyon discharge has been deflected to the north. Outflow from the Logan River however, appears more compatible with the models forced by easterly winds (Fig. 7B).

A similar circulation pattern can be seen in Salt Lake Valley. Strong flow to the north modeled for the westerly wind simulations is reflected by the Emigration, Parleys, Millcreek and Big Cottonwood discharge points (Figs. 8A and 9A). Somewhat chaotic circulation in both westerly and easterly simulations appears adjacent to the Little Cottonwood drainage (Fig. 9A, B).

In Utah Valley, cyclonic circulation is modeled in the southern half of the valley (adjacent to the discharge points of the Spanish Fork River and Hobble Creek) (Fig. 11A). However, the model forced by westerly winds shows a localized, anti-cyclonic (clockwise) gyre in the northern portion of the valley (Fig. 10A) possibly due to the irregular shoreline and land salient in that portion of the valley. Three of the four streams in Utah Valley (American Fork, Provo, and Hobble Creek) have deflections that match the westerly wind model results (Figs. 10A and 11A). Spanish Fork more accurately matches the easterly wind simulation (Fig. 11B), however this river has a sinuous and poorly defined exit channel as suggested by the poor correlation of the DEM points outlining the stream exit (Table 1).

Model outflow of the Sevier River is somewhat complicated. This river has the largest drainage area of all those analyzed in this study and distance from the mountain front to the Provo shoreline is ~22 km, far greater than the other eleven alluvial channels (Table 1). Outside the mountain front, the channel veers north for ~5 km before veering sharply to the south. The westerly wind model produced a small, tight gyre that reflects this general pattern (Fig. 12A).

4. Discussion

The large North American continental ice sheet no doubt played an important role in the climate dynamics of the Pleistocene of North America. The degree to which the ice sheets influenced prevailing wind directions in portions of North America well to the south of the ice sheets, however, remains unresolved. The lake circulation simulations from this study suggest that currents in Lake Bonneville were predominantly cyclonic. The orientation of the incised river channels formed during the Bonneville flood suggest that the prevailing winds over the lake during the Late Pleistocene were from the west and not influenced by the high pressure produced by the ice sheet. The only other known paleowind measurement of the Bonneville basin is from distribution of Pahvant Bute ash in the Sevier basin which suggests wind mostly from the west, with a significant north and south component (Oviatt and Nash, 1989).

It is important to emphasize that the prevailing climatological winds considered in this study are not the same as winds produced by the extratropical cyclones and low pressure systems which are typical of mid-latitude climate. As detailed in the analysis of Lake Bonneville spits (Jewell, 2007) and other shoreline features (Schofield et al., 2004), these strong, but transitory winds may well have been influenced by the continental ice sheets. Winds produced by mid-latitude low pressure systems and associated storms produce much stronger currents (several 10 s of cm/s in the Great Lakes; Beletsky et al., 1999), significant wave heights, and are generally considered to have been the major force constructing shoreline geomorphic features in Lake Bonneville. These are not the features considered in this study, a distinction sometimes not made in previous studies (e.g., Krist and Schaetz, 2001).

It is also important to emphasize that Bonneville flood was a relatively short-lived (order of months) event relative to the existence of the lake. While the modeled geostrophic balances of Lake Bonneville circulation presented here are meant to represent the response to climatological winds, it is possible that the flood occurred during a time in which climatological winds and geostrophic circulation were not operative in the lake.

The river incisions of Lake Bonneville produced during the Bonneville flood may represent a one-of-a-kind opportunity to document the mean currents of an ancient lake and their relationship to the paleowind field. Nevertheless, careful study of other geomorphic features such as the distribution, composition, and thickness of bottom sediments may lend themselves to validation with a numerical circulation study similar to the one presented here in order to establish wind directions in other lakes of the geologic record.

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