Reconstruction of Late 18th Century Upper-air Circulation Using Forensic Synoptic Analysis

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Introduction

In this study I attempt to develop an outline of the general atmospheric flow around the time of 1785 C.E., in North America. The results of my reconstruction of daily weather in the year 1785 in the northeastern part of North America imply a relatively cold flow over central and eastern North America for most of the year (McNally, 2004). The source of the colder air is to the north and west, and I begin with the assumption that a north to northwest flow from north central Canada was prevalent for most of the year. By comparing proxy data from other locations around the world to identify the location of the polar front (or edge of the polar cell), it is possible to outline a general flow around the northern hemisphere resulting in one similar to that theorized by Lamb (1977), and described as a "short-circuit cross-polar" flow, around the edge of a displaced and possibly larger polar cell.

This flow suggests storm tracks that would provide the precipitation necessary for the development of the Laurentide and Scandinavian ice sheets. Storms would travel up the east coast of the United States and recurve northward into eastern Canada. An additional track would supply the moisture for northern Europe. This circulation, also independently described by Flohn (1969), is similar to that which may have been prevalent at the onset and during the dissipation of the most recent glaciation (Figure 1).

Wexler (1956) has suggested that a hypothetical reduction of 20% in insolation, whether from reduced solar output or from volcanic effects, would result in a circulation characterized by a broad trough over eastern North America. Lamb (1977) notes that this is similar, although weaker, to the circulation around 1800 C.E. Both are characterized by a strong and persistent trough in eastern Canada, extending down the east coast of the U.S. This would result in a prevalent cold flow to the northeastern United States from Canada. These patterns may be representative of a transitional period between major warm and cold regimes in the northern hemisphere.

Studies covering the 1780s are sparse, and concentrate on the possible cooling from volcanic effects in 1783-1785. However, valuable data can be extracted to arrive at the outline of the prevalent flow by following the cooling signal, or lack of it, in these proxy studies. Additionally, numerous analyses exist focusing around the year 1816, following the eruption of Tambora, some of which do extend back to 1785. The dust veil index (DVI) for the 1816 time period is very high, as is that in 1785 (3000 and 1000 respectively vs. 1680-1974 C.E. average of 475, Lamb, 1972). Some additional inferences may be drawn from and comparisons made to the 1816 data. Both 1785 and 1816 followed moderate (M+) ENSO events, and the differences between the resultant effects also suggest the presence of a generally cold cross-polar flow in 1785.

Most of the cooling effect from Tambora in 1815 occurred in the year immediately following the eruption. Mid-latitude effects from the eruptions in 1783 appear to have lingered for two years (Kington, 1992). Generally, although the decade of the 1780s was already colder than normal in many areas, the cold cross-polar flow appears to be amplified by the effects of the 1783-1785 high-latitude volcanic events in both Iceland and Japan. This amplification is also supported by the findings of Quinn and Neal, outlining the possible combination of effects from the El Chichon eruption and the El Niño of 1982-1983 (Quinn and Neal, 1983b). It would appear, then, that additional forced cooling from reduced insolation when occurring in a generally cooler period might trigger the cross-polar flow.

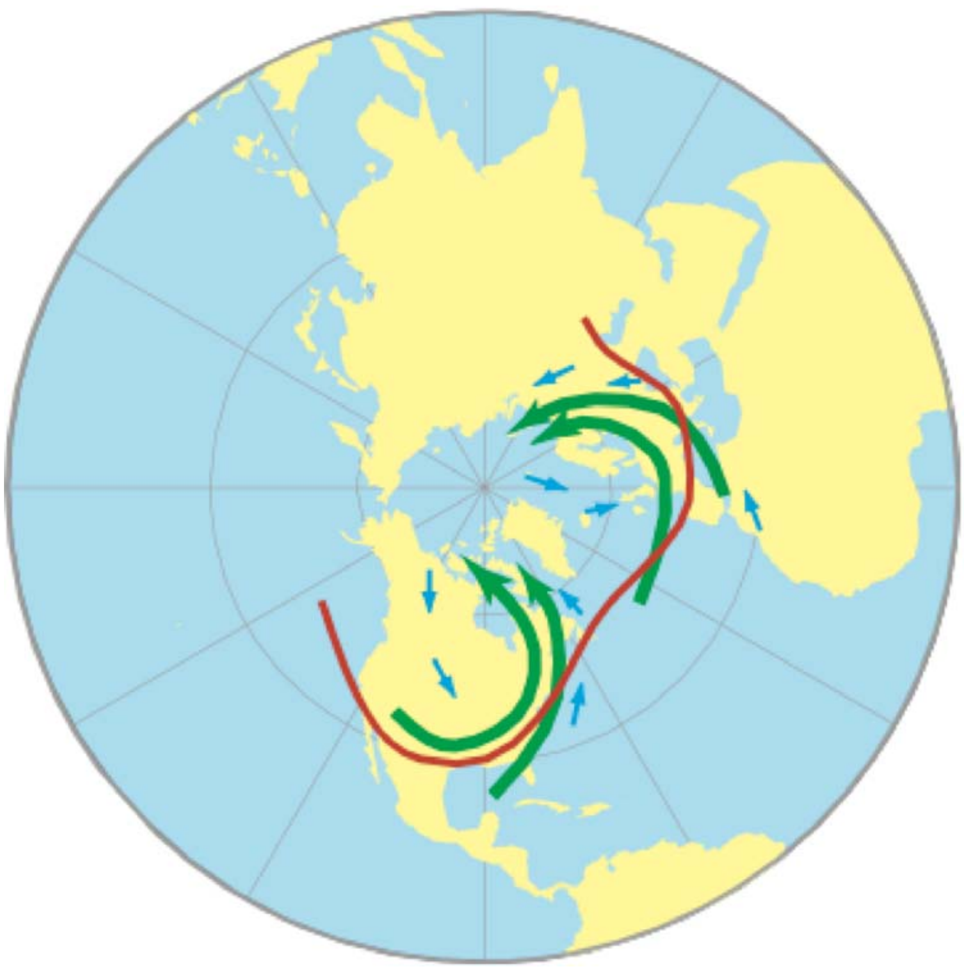

Fig. 1. Short-Circuit Flow, from Lamb, for the onset of the Würm/Wisconsinan glaciation. Thin line denotes average 5300 geopotential meter surface to 500 mb thickness for January. Short arrows denote prevailing surface wind. Broad arrows indicate storm tracks.

It would also appear that this cross-polar flow "short-circuits" the normal general atmospheric circulation, particularly at polar latitudes above 60° north. This flow develops brief, yet strong polar outbreaks at the southern end of the cross-polar route in Canada and the eastern United States. This further supports the finding of split-flow in the jet stream that may, in fact, sometimes have three branches. An expanded or displaced polar cell, evidenced by a polar front further south than normal in North America, may take on very different circulation characteristics from the usual, or normal, polar cell of today. These differences are most pronounced in North America, the North Atlantic Ocean, western Europe, and central Asia. The preferential cooling in these areas may point to a displacement of the polar cell to those areas, as opposed to a wholesale expansion. I begin the reconstruction, then, with the assumed northwest cold flow in Canada, west of Hudson Bay.

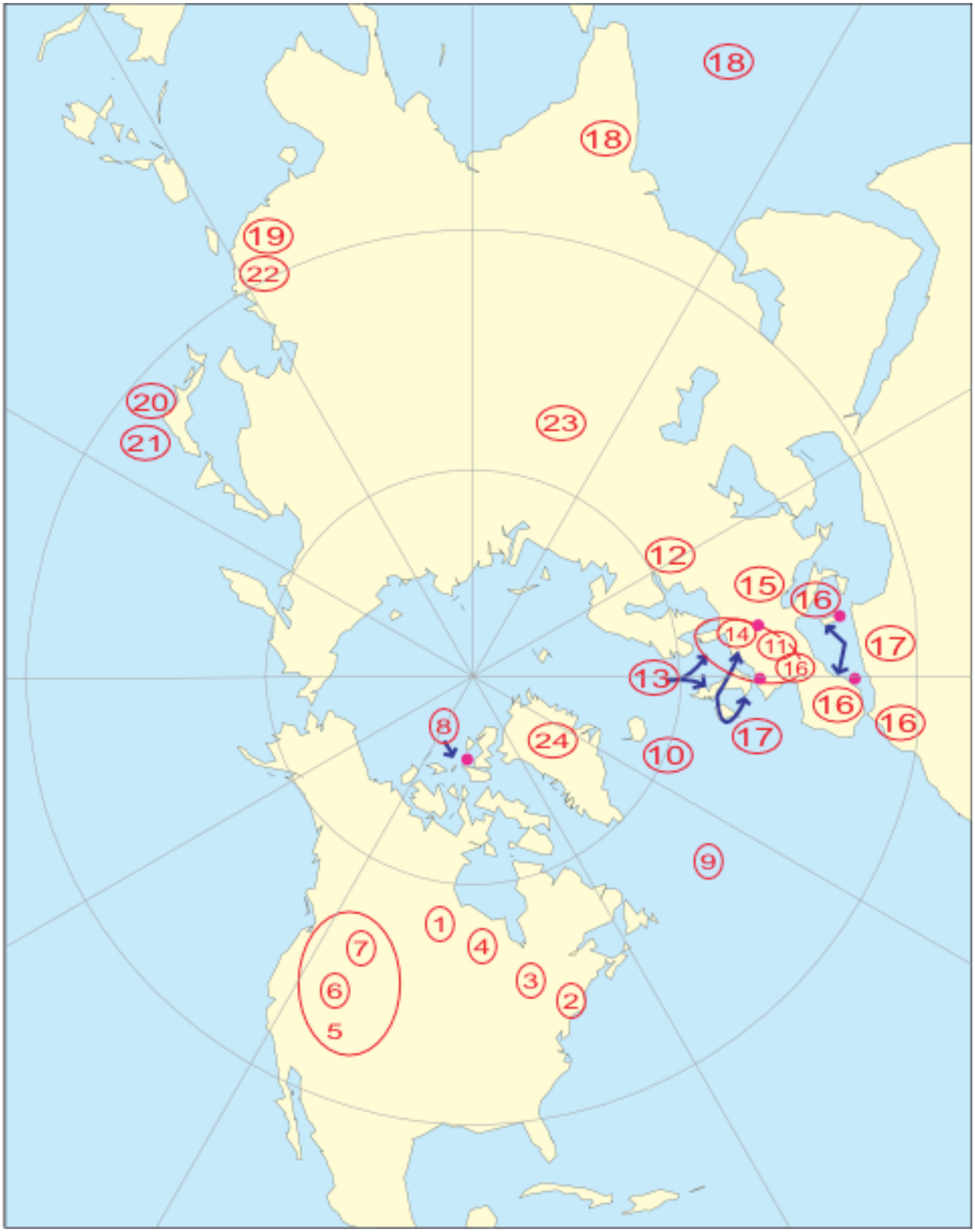

Fig. 2. Data Points for Reconstruction of Prevalent Flow in 1785, C.E. See Table 1 for data types used.

Table 1. Data points, sources, and descriptions

Data Point	Source	Description
1	McNally	Documentary and observational data forensic synoptics
2	Baron	Documentary and observational data content analysis
3	Crowe	Documentary evidence triangulation and extrapolation
4	Fayle	Radial and height increment tree growth analysis
5	Lough	Tree ring chronologies, regression analysis
6	Luckman and Colenutt	Latewood marker tree ring chronologies
7	Fritts and Shao	Standardized tree ring width measurement, spatial arrays
8	Alt, et al	Isotope and melt percent values, synoptic analogues
9	Lamb	Monthly mean MSL from observations
10	Ogilvie	Documentary evidence
11	N.H. Gazette and Pfister	Documentary evidence, newspaper, diaries
12	Schove	Tree ring analysis
13	Moberg	Historical observations
14	Wood	Historical observations
15	Bednarz and Trepinska	Width and maximum density tree ring studies
16	Serre Bachet, et al	Tree ring width
17	Serre Bachet, et al	Dendroclimatological and documentary reconstruction
18	Roy	Documentary evidence, Delhi wheat prices,
19	Wang and Zhang	Documentary evidence, Qing Yu Lu
20	Tsukamura	Synoptic analogues
21	Mikami and Tsukamura	Documentary evidence, freeze dates, diaries
22	Huang Jiyaou	Documentary evidence, dryness/wetness grades
23	Borisenkov	Documentary evidence, religious chronicles
24	Meeker and Mayewski	Ice core evidence, ion series

North America

In addition to my results, content analysis by Baron and Gordon (1985) shows that the early 1780s in eastern Massachusetts, in general, exhibit shorter growing seasons, more winter days with fair-sky conditions, more summer days with thunderstorms, and more winter snowfall days than the remainder of the decade. Both shorter growing seasons and more winter days with fair-sky conditions indicate a prevalence of clearer Arctic or polar air masses in both summer and winter. The variability and vigor of the atmospheric circulation at other times of the year can be deduced from the more frequent summer thunderstorms, indicating an active summer Alberta storm track. More winter snowfall days would indicate more frequent and slower-moving winter storms. Generally, when not under the direct influence of polar air masses, the northeast could be construed to be near the polar front, its southern edge determined by the storm tracks in eastern North America. These results concur with mine.

Crowe (1992), in his reconstruction of temperatures for Toronto, Ontario, Canada, finds significant effects from the volcanic activity in the summer of 1816, but very little variation during the 1783-1785 time period. Mean July temperature in 1816 (16.1°C) is more than 3° below the 50-year running mean, while 1783-1785 are all within 1° of the 50-year running mean. The similarities in the July mean temperatures of 1783-1785 would indicate a persistent pattern, consistent with the interior of a cold air mass as opposed to the dramatic effects in 1816. Again, assuming that the polar front is generally south of the area in 1785, the effects of the weaker volcanic activity would not be expected to appear in data from so far inland, inside a continental air mass. Further north and west, and deeper into the continent, at Churchill, Manitoba, some cumulative effect on tree growth after Tambora is noted with white spruce (*Picea glauca*) and tamarack (*Larix laricina*) studies (Fayle, et al., 1992), but no major effect is found, further supporting the presence of a continental air mass, which is assumed to be present in 1785.

Tree ring chronologies for the western part of North America developed by Lough (1992) show no large deviation from a long-term (1602-1960) mean. As the chronologies are reconstructed from sites at middle latitudes in the western third of the continent, this result is not surprising. In fact, the continentality expected from these interior sites in the southwestern part of Canada and the western USA, within and east of the Rocky Mountains, would prevent or at least dampen the detection of any signal from the east or north. These areas are under the effects of semi-permanent continental pressure patterns and away from the assumed cold northwest flow east of the Rocky Mountains, which marks the westward extent of the polar cell. They would not necessarily exhibit the sensitivity that would be expected in locations more proximate to the cross-polar flow, such as the area further north in central Canada or in northeastern North America.

Luckman and Colenutt, (1992) conducted additional studies in the high-elevation Canadian west, above 50°N. Their results support the assumption that this region is out of the cross-polar flow, and influenced more by a flow from the Pacific Ocean. Although there is some reduction in radial tree growth, which could be attributed to a general cooling, wide variation is found in the mid-1780s. This would be consistent with an onshore flow from the Pacific; any stabilizing continental effects would be expected further east and south. At these higher latitudes, the effects of this stronger zonal flow would be exhibited here in the Canadian Rockies as compared to the region near the United States-Canada border. As they are not, thus ruling out a zonal flow extending into the center of the continent, a strong cold northwest flow in central Canada may be additionally supported, while still implying a general flow from the Pacific.

In the western United States, Fritts and Shao (1992) reconstructed temperature and precipitation from a variety of spatial arrays of sites. These areas included the Columbia Basin, the California valleys, intermountain basins, southwest deserts, the northern high plains and the southern high plains. Throughout the entire area, temperature and precipitation data for the period from 1750 to 1800 show very little variation from the norm, with the exception of the temperature reconstruction for the high plains data set. There is a colder than normal period which stretches from 1770-1790 and it is found only in the high plains data set. In the absence of any other large deviations over the time frame, one may assume that persistent cold affected only the high plains, which is consistent with a steady northwest flow from northern Canada. The southern high plains are apparently unaffected, which supports the cold northwest flow from central Canada curving eastward towards the Great Lakes and the northeastern United States, and south of Toronto. This western edge of the circulation in 1785 is also consistent with Lamb's suggested flow.

Arctic and Iceland

In a cross-polar flow, Arctic locations in northern Canada would be directly in the path of continental air masses migrating across the North Pole from Asia. In any flow, evidence of volcanic activity would be found in high Arctic ice. Indeed, a marked signal is present in ice cores from the Agassiz and Devon sites in the high Canadian Arctic (Alt, et al., 1992). However, similarities in the effects from both the 1815 and 1783-1785 eruptions show that the period of both was one of general cooling in the Arctic. Brief episodes of further cooling followed both eruptions as well. Circulation patterns following each, however, are different.

Alt et al, (Alt, 1985, 1987, Alt, et al, 1985), using previously developed analogues, further conclude that the general synoptic pattern around the time of the Tambora eruption is similar to that in 1972, as characterized by the presence of a strong 500 millibar (50kPa) vortex centered near northern Greenland (Figure 3). No analog is presented for 1785. The western edge of this circulation is in a similar location to that of the 1785 cross-polar flow. The eastern side, however, shows a return flow poleward from the central North Atlantic Ocean. In contrast, my results indicate that the circulation in the 1780s appears to continue eastward as a strong zonal flow across the Atlantic. In the case of 1785, the center of the vortex (Icelandic Low) would most likely be depressed further southward and expanded eastward. This may explain Alt's findings, where the circulation pattern after the Laki eruption was different from that of Tambora. This expansion and eastward shearing of the low pressure vortex will also be identified in the European data discussed below.

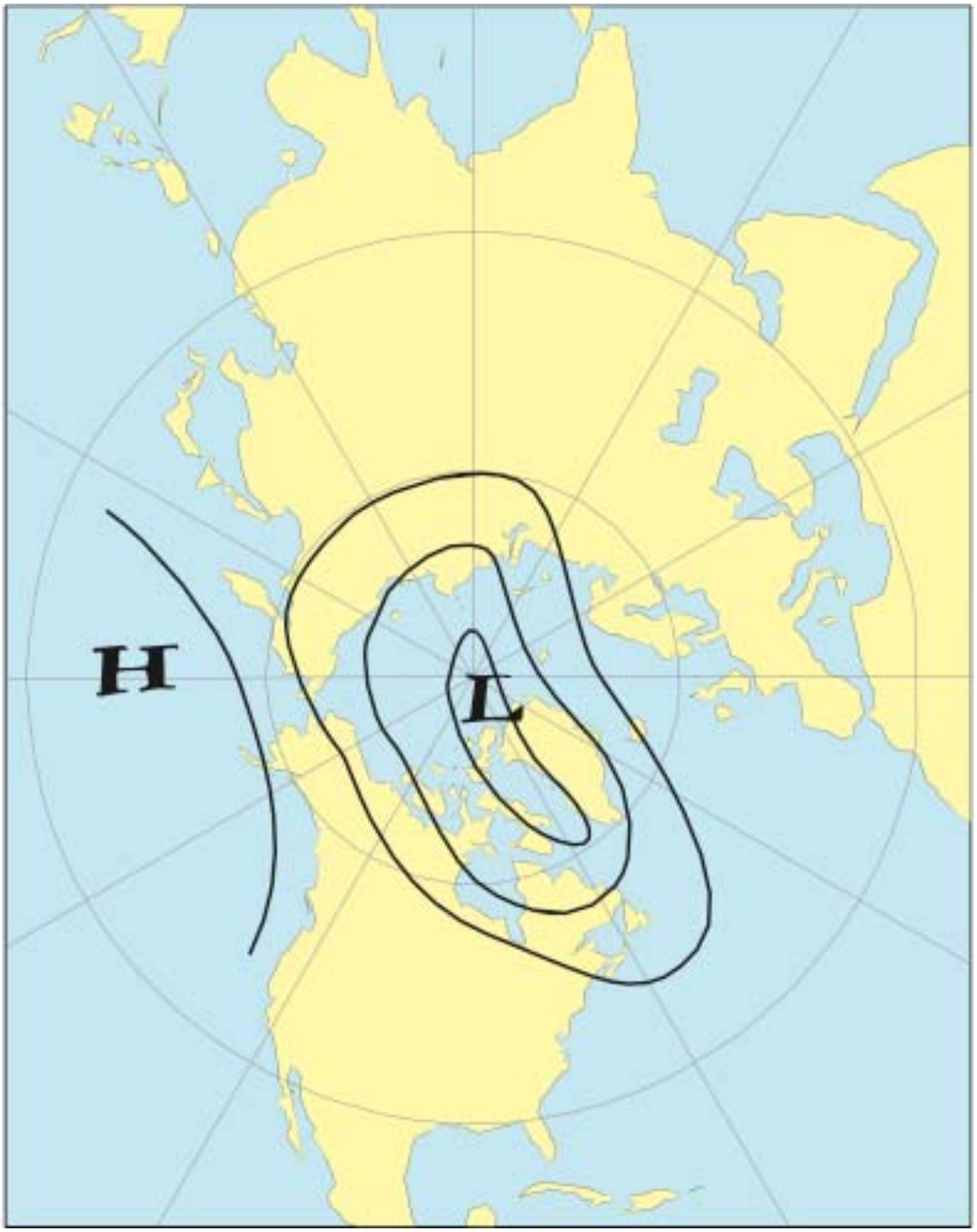

Fig. 3. Summer Circulation of 1972, analogous to 1816, from Alt.

Ogilvie (1992) studied sea ice records for the area around Iceland and shows that on a decadal scale the 1780s contained the greatest amount of sea ice on record. The series extends back to 1501. There is a positive correlation between sea ice incidence and temperature (Bergthorsson, 1969, Ogilvie, 1981, 1984a), and the cold regime thus inferred could be caused by an increase in the flow around the semi-permanent high over Greenland and an extended low pressure area in the Atlantic Ocean. It is possible that a Rex block may have developed, similar to the one in Figure 4, but displaced northward. This circulation pattern agrees with the flow around the high pressure area over Europe as well, and can help explain the mechanism by which northern Europe is both colder and drier than normal.

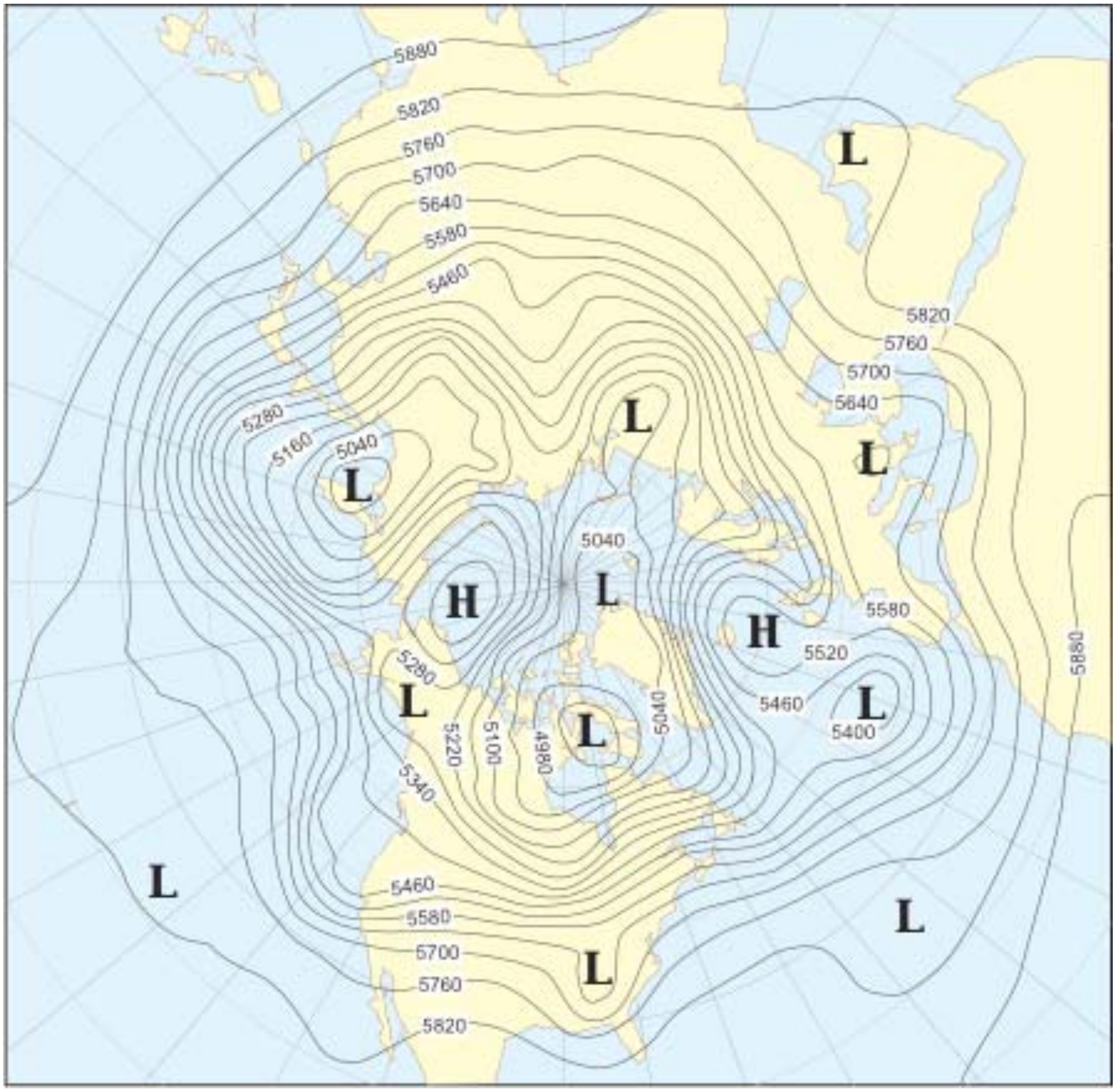

Fig. 4. 500 mb (50 Kpa) Circulation in mid-March, 2002. Note Rex block (high north of low) in eastern Atlantic, forcing split flow upstream.

Atlantic Ocean and Europe

Lamb (1992) refers to a pattern similar to that in 1785 in reconstruction of pressure patterns for the summer of 1816 over the Atlantic Ocean and western Europe. Broad zonal flow north of 40°N to 50°N in the Atlantic Ocean is driven by broad low pressure from 50°N to 60N. This also agrees with Alt, et al and Ogilvie above. The increased pressure gradient between the (Icelandic) low pressure to the north, which is displaced southward and sheared eastward from the normal position near Greenland and the subtropical (Bermuda) high to the south drives a strong flow from central and eastern North America across the Atlantic over a flattened ridge. This would also force the north side of the subtropical (Bermuda) High in the Atlantic to be sheared eastward, increasing the advection of more moist maritime air into southern Europe (Figure 5). The implication for stronger surface winds in the ocean under the core of the flow is borne out by observations from ships of being “blown off the coast” and unable to make ports in North America before supplies ran out (Bermuda Gazette, 1785).

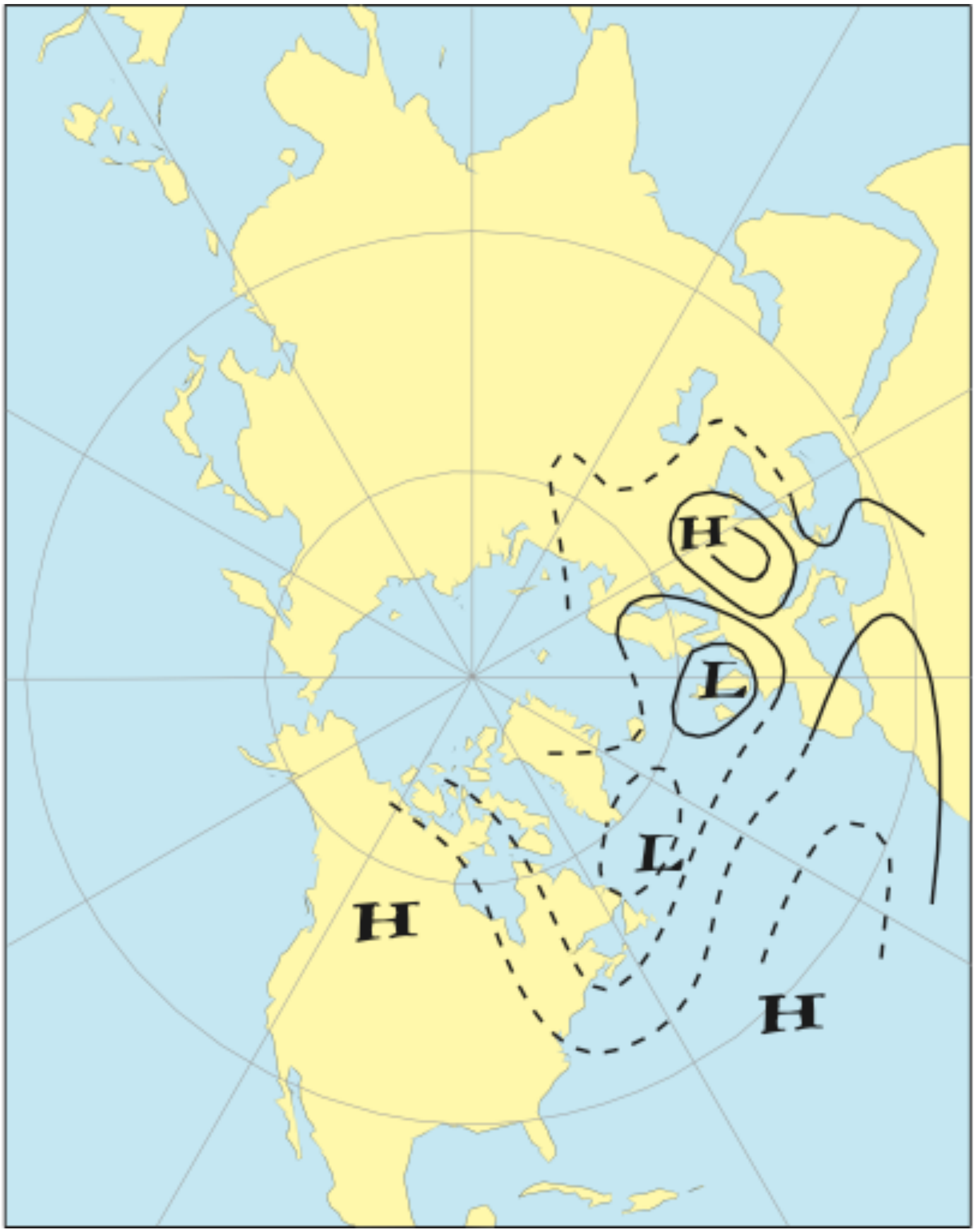

Fig. 5. Reconstructed flow for July, 1816, after Lamb. Dashed lines inferred by Lamb.

High pressure in northern Europe is larger in this flow, which , if present in 1785, may explain the very hot, dry summer in England (Fowle's Gazette, 1785), as well as conditions that are drier and warmer than normal in Switzerland (Pfister, 1978, 1992), and drought in Finland (Schove, 1954). The northern edge of the flow continues across northern Europe, and then curves poleward, aided by a strong high pressure ridge in central Asia. Arctic air masses originating in central and eastern Asia then follow the flow eastward and then northward, eventually crossing over the Arctic, and completing the short-circuit cross-polar flow. A split in the flow from its southern edge into west-central Asia is implied, with an eastward displacement of the subtropical high over the Asian subcontinent supplying the moisture for storm tracks to the east.

Northern Europe, under the influence of cooler and moist air transported rapidly across the North Atlantic Ocean could be expected to be cooler, on average, with similar variability as that which is noted in the northeastern part of North America. The average temperatures as reconstructed for three stations in central England, Uppsala, Sweden, and De Bilt, the Netherlands, do indicate that a cooling period began by 1780, reaching a minimum in 1785 (Moberg, 1996). Wood (1992) notes that average January temperatures for six European cities (Stockholm, Copenhagen, Edinburgh, Berlin, Geneva and Vienna) are below the 31-year normal in 1780 and 1781, above normal for 1782 and 1783, well below normal (greater than 1σ) for 1784, and near normal for 1785 and 1786. The dry summer in England and cooler July readings in western and northern Europe can be explained by the presence of a persistent high pressure ridge over Britain and the Baltic, the eastern side of which allows cold advection into Europe proper.

Further south and east in Europe, the general cooling noted above for the decade is seen in tree ring studies from the Alps and Tatra mountains (Bednarz and Trepinska, 1992). The general cooling is evident through the decade of the 1780s, and is most likely the result of summer outbreaks of the cold air on the eastern side of the high pressure ridge over Britain and the Baltic before its return northward in eastern Europe. The sensitivity to increased variation as well as a more pronounced cooling trend is evident more in the Tatra mountains than in the Alps, implying that the Tatras in Poland are closer to the edge of the flow, and thus closer to the edge of the polar front. Switzerland and central Europe remain under the influence of the expanded continental high and implied upper ridge.

Dendroclimatic reconstructions from tree ring widths in southwestern Europe and northwestern Africa for the 1780s (Serre-Bachet et al, 1992) help to define the southern stream of the split flow, south of the Rex block, from the eastern Atlantic Ocean. Reconstructions of the temperature for eastern France and Rome indicate cooling, which would support a cold flow from off the eastern side of the northern European ridge. Precipitation records do not extend from the present back to 1785. Serre-Bachet, et al also analyzed reconstructions of temperature at four grid points on the Jones (Jones et al., 1985) network. For 1785, the English Channel grid point (50°N, 0°W) shows little variation from normal, although colder temperatures are indicated in the ensuing decade. The Mediterranean grid point (40°N, 10°E) shows a 7-year cooling trend is already underway, reaching a minimum in 1785. The grid point in southern Poland (50°N, 20°E), shows rapid cooling over a 6-year period, while the grid point in eastern coastal Spain (40°N, 0°W) is near the maximum of a 12-year rise which peaks in 1783.

It is evident from the tree ring studies in the Tatra Mountains above that the cooler flow in Poland can be supported. The English Channel area, away from both the northern and southern branches of the split flow, is less affected by anomalous conditions, which is consistent with a ridge overhead. Precipitation data from Morocco, which is the lowest (driest) in the record from 1500-1975, and the warmer temperatures in Spain could support either the eastward displacement of the subtropical high or, more likely, of an African ridge extending northward and westward. In either case, a strong flow across the Atlantic, curving both north and south of Britain, can be inferred.

India and Asia

In India, regular weather observations do not commence until 1792, but wheat prices in Delhi (Roy, 1972) do show a marked increase in 1782 and 1783. The immediate cause may be tied to ENSO activity and a failed monsoon. This might be affiliated with a northern hemispheric circulation anomaly, in that a reduced flow from the west, part of which has turned poleward, might allow a stronger high and ridge to develop over the Indian subcontinent. A split in the flow would be implied. However, an eastward migration of the monsoon, causing the spike in wheat prices would be consistent with both an El Niño event and the eastward displacement of other pressure systems in eastern Africa. There is no corresponding anomaly in wheat prices in 1810-1820 (Pant, et al, 1992).

A split flow can be inferred from ion-concentration studies of GISP-2 ice cores (Meeker and Mayewski, 2002). They constructed sea level pressure anomalies for winter (December, January and February) and spring (March, April and May) during the Little Ice Age (LIA) (1400's to 1800's C.E. in this study) from a proxy series extending back 1400 years BP. Results do show reduced pressure across the north Atlantic and into south central Asia during the LIA. This would support both a southern split from the cross-polar flow and an eastward migration of high pressure systems over the Indian sub-continent.

In a very broad sense, Borisenkov (1992), using documentary evidence, finds that the 30-year seasonal averages in mid-Russia show little difference from normal for the autumn, winter, and spring, but higher than normal readings for the 1780-1800 period. This nearly 1°C anomaly is only slightly lower than that reconstructed for the 1800-1830 period, which is the highest in the entire 1501-1900 record. Warmer conditions in the summer would be consistent with the prevalence of continental air masses that may be advected northward in the cross-polar flow, modifying (cooling) over the pole, and then arriving in North America as cold outbreaks in summer.

China, Japan and the Pacific Ocean

Generally wetter weather in eastern China can be noted at Nanjing and Suzhou in 1785 from the Qing Yu Lu or the Clear and Rain records (Wang and Zhang, 1992). References to the year 1816 indicate severe flooding in eastern China as well, as a result of an eastward retreat of the subtropical high, (Huang Jiayou, 1992). The Yangtze and Yellow river basins would be affected in both cases, and a parallel might be drawn to the 1780s. However, in 1816, the polar front in Japan shows no change from normal, and, in fact, the summer was warmer and longer than normal, implying a more prevalent meridional flow (Tsukamura, 1992). In 1785, increased zonal flow and eastward migration of regular pressure patterns, including the displaced monsoonal flow over India, is already assumed. The increased rain in 1785 may have come from tropical cyclones hitting land further south than normal.

Polar air masses from central Asia would be steered towards the pole in a cross-polar flow, prior to arriving at the east Asian coast. Continuing in the cross-polar flow, these continental air masses would be directed southward from the Arctic, and become the source for the notable cold outbreaks in eastern North America. Any expansion of cold air masses in Asia in the summer, however, might affect Japan, which is on the eastern edge of this flow. This would be expected to be found in cooler summer conditions, without any attendant increase in storminess. In fact, during the 1780s, and from 1783-1785 in particular, Japan did suffer extraordinarily cool and wet summers, leading to famine conditions from poor rice harvests (Mikami and Tsukamura, 1992). Lake Suwa, Japan, froze 22 days earlier than the decadal average, which is earlier than any other year in the series from 1772 to 1794 (Wood, 1992).

The fact that there is evidence for zonal flow in eastern Asia and Japan in 1785 would also point to a more sensitive response somewhere in the western part of North America. A strong zonal flow over the northern Pacific, unlike the meridional flow established for the decade of 1810-1820 above, could be then be responsible for the signal from high Rocky mountain trees in the southwestern Canadian study cited above (Lough, 1992, Luckman and Colenutt, 1992). This does not preclude a quasi-meridional flow over a flattened ridge in the Pacific, similar to that in the Atlantic, but does imply an onshore flow from the west in the Canadian Rockies.

Thus, the circulation pattern of the entire northern hemisphere can be outlined, showing the “short-circuit” cross-polar flow, excluding those areas which would not be directly affected, such as southeastern Asia westward to the Indian Ocean. The efficiency with which this flow can drive polar outbreaks from the continental source regions of east and central Asia, the Arctic, and northern Canada, eventually arriving in northeastern North America, then appears viable.

Tropics and Southern Hemisphere

Evidence of a more pronounced zonal flow across the Pacific Ocean at lower tropical latitudes might be found in the increased total particulate deposition and decreased $\delta^{18}O$ values in the Quelccaya ice cap in Peru. This is observed for the first half of the decade, with maxima at 1783-1785 (Thompson and Mosley-Thompson, 1986). In the southern hemisphere, data are sparse, but tree studies of sub-tropical to sub-Antarctic species in South America (Villalba and Boninsega, 1992) do show decreased temperature, perhaps in response to the Laki-Asama events, after 1783 at 37-39° south latitude for a one year period, very little, if any response at 41° south latitude, and a pronounced response three to seven years later at 54° south latitude. It would appear that more data and research are required to identify the propagation of a signal through the prevailing westerlies in the stronger global circulation pattern in the southern hemisphere.

ENSO effects

Quinn's (1983b) research does indicate an amplification of anomalous patterns when ENSO and volcanic events occur simultaneously. With the results below, combined with the disconnect from the main flow noted above, it is much more reasonable to assume that the cross-polar flow would exist with little direct connection to ENSO activity. The years preceding 1785 did show increased ENSO activity, with which with many weather events worldwide can be associated.

Deficient floods in the Nile River are associated with ENSO activity 80.3% of the time from the mid-1500's to today (Quinn, 1993a), and in strong events, the correlation is higher. Record drought in Chile, a characteristic of Little Ice Age climate patterns (Quinn and Neal, 1992), is in evidence through the beginning of the 1780s. The drought conditions are broken only by the very strong ENSO event of 1782-1784. Another established teleconnection with El Niño and the northeast is a warmer winter (United States Dept. of Commerce, 2002). As this was certainly not the case in 1785, this can give more weight to the strength and persistence of the cross-polar flow.

Additional teleconnections associated with El Niño activity include drought in eastern and northern Australia, an east monsoon drought over Indonesia, and drought in northeast Brazil. Quinn has found that southern California also experiences higher rainfall during El Niño years about 87% of the time (Quinn, 1993a). These effects, although expected, could not be proved or disproved with the data used in this paper.

There is a general suppression of tropical storm activity in both the Atlantic and Pacific Ocean during El Niño years (Dong, 1988, Gray and Schaeffer, 1991, O'Brien, et al, 1996). This reduction in the number of storms does not preclude hurricane development. In fact, one might expect to find fewer, stronger and faster moving storms due to the more vigorous steering currents at upper levels of the atmosphere, and the larger temperature gradient between the colder-than-normal ocean waters to the north and the warm tropics. Dixon points out that there are fewer hurricanes in an El Niño year, yet the frequency of landfall of those that do occur in an El Niño year is slightly higher (Dixon, 1996).

In summary, the climatic conditions associated with the very strong (VS) El Niño of 1782-1784 and the moderate (M+) event of 1785-1786, can help to develop the picture of northern hemispheric circulation in 1785. The tropics and areas affected directly by the El Niño appear to behave independently of the high latitude westerlies and cross-polar flow, exhibiting the hallmarks of a cooler climatic regime resembling the Little Ice Age. This reconstruction, with the apparent disconnection between the cross-polar flow and tropical southeast Asia, raises an interesting question for future research: Did the eastern displacement of the pressure and wind systems from the Indian Ocean to eastern Asia allow the polar cell to drift toward North America and the Atlantic Ocean, or was the preferential movement of the polar cell to those areas the forcing factor? Figure 6 represents the reconstructed complete short-circuit cross-polar flow for 1785, C.E.

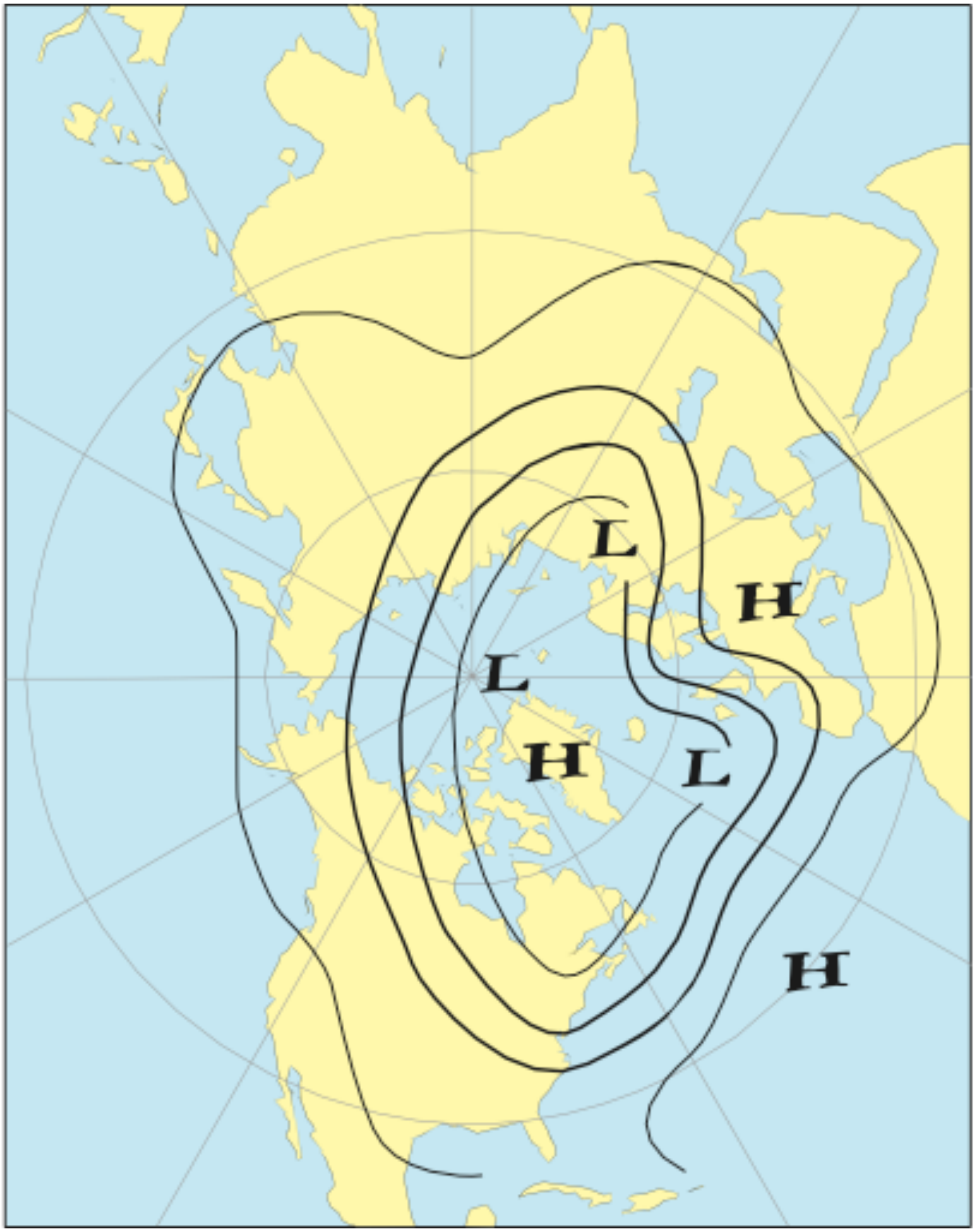

Fig. 6. Reconstructed short-circuit cross-polar flow for 1785, C.E.

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