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LEWIS AND CLARK'S CONTRIBUTIONS TO METEOROLOGICAL SCIENCE

At the dawn of the nineteenth century, the climate of the trans-Mississippi West was virtually unknown. The information that existed was sparse and anecdotal. This changed dramatically with the signing of the Louisiana Purchase in 1803, which formally set the stage for acquiring the first systematic weather measurements of the trans-Mississippi West. In a now famous June 20, 1803 missive, President Thomas Jefferson instructed Captain Meriwether Lewis to plan and carry out an expedition to the Pacific to observe and record a broad range of natural history subjects, including the

> …climate, as characterised by the thermometer, by the proportion of rainy, cloudy & clear days, by lightning, hail, snow, ice, by the access & recess of frost, by the winds prevailing at different seasons, the dates at which particular plants put forth or lose their flower, or leaf…[1]

Lewis and Clark's weather observations are well known and commonly quoted in the literature. Their contributions to meteorological science,[2] however, have yet to be fully explored. This article represents a beginning step in this exploration, and is motivated by several questions. Given the state of meteorology at the time, could Lewis and Clark have measured more than simply temperature? Compared to today, was the nearly continuous rainfall at Fort Clatsop characteristic or uncharacteristic for that region? And can the weather observations recorded by Lewis and Clark aid in our understanding of global climate change?

In order to provide the historical context for addressing these questions, the conceptual framework for the expedition and the scientific preparation needed for its execution are first reviewed. A brief chronology of the development of meteorological science up to the time of Lewis and Clark is presented, followed by highlights and explanations of Lewis and Clark's weather observations as they journeyed through the climate zones.[3] A preliminary comparison between Fort Clatsop's weather and present-day is presented, and Lewis and Clark's meteorological legacy is discussed in light of today's concerns about global climate change.

The Expedition: Conceptual Framework and Scientific Preparation

Thomas Jefferson's conceptualization of a transcontinental expedition to explore the interior of North America began several decades before Lewis and Clark's departure from St. Louis. Surrounded by a westering philosophy in his early childhood and concerned by threats of British and French efforts to colonize portions of the West for commercial purposes, Jefferson made three unsuccessful attempts prior to 1794 to launch expeditions to explore the trans-Mississippi West.

By 1800, Jefferson was uniquely positioned to propose and implement a broad-based exploratory mission of the West. He was elected the third President of the United States and thus had political clout as well as access to government resources. He was a member of the American Philosophical Society (APS) in Philadelphia and communicated with the most learned scientific men of the time. He presided over the signing of the Louisiana Purchase, which wrested from France a vast region of unknown resources and unknown climate. He had a long history of intellectual curiosity about ethnography, geography, science, and climate, particularly of the land west of the Mississippi.

Jefferson was ready to organize and launch an expedition to carry out his dream of finding an overland route to the Pacific Ocean – the so-called Northwest Passage. On January 18, 1803, Jefferson submitted a letter to Congress requesting a $2,500 special appropriation to fund an exploratory expedition to the "Western ocean" for the purposes of commerce and science.[4] To lead this expedition Jefferson chose his personal secretary, Captain Meriwether Lewis, whom Jefferson believed to be the most qualified person to lead the expedition, despite Lewis's lack of formal scientific training. In a letter to Robert Patterson, professor of mathematics at the University of Pennsylvania and member of the APS, Jefferson wrote:

> If we could have got a person perfectly skilled in botany, natural history, mineralogy, astronomy, with at the same time the necessary firmness of body & mind, habits of living in the woods & familiarity with the Indian character, it would have been better. But I know of no such character who would undertake an enterprise so perilous. To all the latter qualities Capt. Lewis joins a great stock of <scientific> accurate observation on the subjects of the three kingdoms which are found in our own country but not according to their scientific nomenclatures.[5]

Lewis spent the greater portion of 1803 preparing for the expedition. Part of this time was spent receiving "professional" scientific training and advice in surveying, botany, and medicine from Jefferson's fellow APS members: Patterson, Ellicott, Barton, Wistar, and Rush. Professor Robert Patterson provided instruction on various scientific instruments. Major Andrew Ellicott provided instruction on surveying. Benjamin Smith Barton, who wrote the first American textbook on Botany, advised on the collection of scientific data. Casper Wistar, who wrote the first American textbook on anatomy, advised on zoology. And Dr. Benjamin Rush, the preeminent physician of the time, counseled on medical issues. By the second week in June Lewis completed his crash courses in the sciences. To round out his scientific training, Lewis also purchased several scientific books that would serve as his traveling library. These books included *Elements of Botany* by Barton, *Elements of Mineralogy* by Kirwan, *A Practical Introduction to Spherics*, and *The Nautical Almanac and Astronomical Ephemeris*.

In late June there were two key communiqués. On June 19th Lewis wrote a letter to longtime friend and former military superior, William Clark, asking him to co-lead the expedition. Clark accepted several weeks later.[6] On June 20th, Jefferson wrote a letter to Lewis, which formally laid out the plans for conducting an exploration of the trans-Mississippi West. The letter is remarkable for its far-reaching vision, clarity of scientific goals, and ultimate impact on our Nation's history. Jefferson wrote:

> …The object of your mission is to explore the Missouri river, & such principal stream of it, as, by it's course and communication with the waters of the Pacific ocean, …, for the purposes of commerce…You will take ,<*careful*> observations of latitude and longitude, at all remarkeable points on the river…make

yourself aquainted …with the names of the nations and their numbers,…their language; their ordinary occupations in agriculture…Other objects worthy of notice will be the soil and face of the country…; the animals of the country; …the mineral productions;…climate[7]

The letter formally mapped out a broad-based mission whose objectives were to provide new information on the economic, ethnographic, geographic, and scientific aspects of the West. Executing the mission required the cooperation of several branches of government, funding for supplies and equipment, and scientific training in several disciplines. As noted by historian James Ronda, this was the United States' first foray into what is now called "big science."[8]

From late June until the end of August, most of the time was spent obtaining additional supplies, maps, and books, commissioning men for the expedition, purchasing a pirogue, and having a keelboat made in Pittsburgh. The keelboat was completed on August 31st. By 11 o'clock that morning the boats were loaded and Lewis and several recruits were headed down the Ohio River for their rendezvous with Clark.

On August 31st Lewis makes the first entry in what is known as the Lewis and Clark Journals. September 1st marks the first entry about the weather, and on September 2nd Lewis recorded the first temperature of the expedition.

Lewis and Clark rendezvoused in mid October on the north side of the Ohio River in Clarksville, Indiana Territory. After a couple of weeks in Clarksville selecting enlisted men for the expedition, the party moved down the Ohio then up the Mississippi. On December 13th, 1803, they arrived at their winter camp on the Wood River, near the mouth of the Missouri River. Lewis and Clark would spend five months at the Wood River camp. During their stay at the camp they were busy collecting and describing the local flora and fauna, practicing using their celestial instruments, and recording the daily weather.

On May 21st, 1804, the Corps of Discovery was on the eve of its epic journey.[9]

Development of Meteorological Science up to the Time of Lewis and Clark

The earliest theories of weather and climate can be traced back to the philosophers of ancient Greece. Hippocrates and Aristotle, for example, proposed climate theories that related the character tendencies of the various peoples of the world to the warm, cold, and middle zones on Earth. Their theories were based on an axiomatic approach, wherein self-evident truths were postulated and built upon by deductive reasoning to reach conclusions about the natural world. It wasn't until the Enlightenment and the emergence of the scientific revolution in the seventeenth century that this Aristotelian philosophy was replaced with rationalism and the scientific method.

Francis Bacon's crystallization of the scientific method in the seventeenth century is rooted in systematic, controlled observations or experiments that lead to hypotheses. If through further work the hypotheses are found to be valid, theories may be formulated that lead to generalizations about the natural world. These theories are then further refined by additional observations and experiments. Not surprisingly, the advent of the scientific method coincides in large part with the invention of scientific instruments.

By the time the Lewis and Clark expedition came to fruition in the early nineteenth century, several scientific instruments had been invented that became an integral part of the expedition. Among these instruments were an octant and sextant for determining

latitude, a theodolite and chronometer for determining longitude, a telescope, a surveying compass, and a spirit level.

Lewis and Clark also carried three thermometers, which had been invented more than 175 years before the expedition. Jackson speculates that the three thermometers were similar to those described by Jefferson in a June 5, 1805 letter to Isaac Briggs: "The kind preferred is that on a lackered plate slid into a mahogany case with a glass sliding cover, these being best on exposure to the weather."[10] As noted by Jackson and Moulton, there is indirect evidence to suggest that the thermometers were purchased in Philadelphia. The first piece of evidence is based on Lewis's January 3rd, 1804 journal entry: "a Verry Cold blustering day <the Merkery?> in Doneyan Co: Thermometer one oClock in the open air the <quicksilver> mercuria fell to 21 D. below the freezing point…"[11] Moulton notes that Doneyan Co may actually be a reference to John Donegan (or Denegan) and Joseph Donegany (Donegani), who were building thermometers in Philadelphia in 1785.[12] The second piece of indirect evidence, which has been noted by Jackson, is that Lewis and Clark were recording temperatures prior to their Wood River camp, thus dispelling any suggestions that the thermometers may have been purchased in St. Louis.

In January 1804, while at the Wood River camp near the mouth of the Missouri, Lewis described in his weather diary two experiments that he conducted in order to determine the accuracy of the thermometer he had been using for his temperature observations. Lewis wrote,

> By two experiments made with Ferenheit's Thermometer which I used in these observations, I ascertained it's error to be 11° too low or additive +— I tested it with water and snow mixed for the friezing point, and boiling water for – the point marked boiling water.—[13]

Lewis's experiments raise two questions. First, were the experiments carried out on all three thermometers and, if so, were they in error by the same amount? Second, were the temperatures recorded prior to the experiments correct? These questions cannot be readily answered. Nevertheless, the fact that Lewis conducted these experiments underscores the importance he assigned to accurately measuring the temperature, and provides confidence that the temperatures Lewis and Clark recorded are qualitatively if not quantitatively accurate.

The barometer was more than a century and a half old by the time Lewis and Clark placed their paddles in the Missouri River. At the time it was well known that the barometer measured the pressure of a column of air above the gauge and could also be used to measure elevation. The fragility of the barometer, however, made it impractical for transport. Lewis and Clark did not carry a barometer. Even if they did, the connection between barometric pressure and air masses and fronts was unknown. Such knowledge would have to wait for the development of the telegraph in 1843 when the contemporaneous acquisition of weather data over large areas began. The theory of air masses and weather fronts didn't occur until around 1920, more than a century after Lewis and Clark.

During Lewis and Clark's time, meteorological science was still in its infancy. The study of meteorology was confined to isolated observations recorded in personal diaries. From Ancient Greece to Colonial America, meteorological science made very few advances. Lewis and Clark's observations were made at the threshold of what Fleming

has called the "expanding horizons" in meteorology,[14] when more reliable meteorological instruments began to emerge allowing for the systematic acquisition of weather data.

The Climate Zones: Philadelphia to Fort Clatsop

Climate classification as we know it today was developed about a century after Lewis and Clark. Among the most widely used climate classification systems is the Köppen system. First developed by Vladimir Köppen (1846-1940) in the early twentieth century, this empirical system classifies climate based on temperature, precipitation, and distribution of vegetation. The boundaries that distinguish the various climate classes in the Köppen system or any other climate classification system are not true boundaries; rather, they are transition zones that evolve over space and time. Because the climate transition zones of today likely differ from those of the early nineteenth century, they are used here only as a means for qualitative comparison.

Figure 1 shows the Lewis and Clark outbound trail superimposed on the various Köppen climate classes for the conterminous United States. At the time of Lewis and Clark, the climate of the trans-Mississippi West was unknown. Even Jefferson, who was arguably the most knowledgeable meteorologist of the time, assumed that the expedition would traverse a "moderate climate,"[15] a characterization that contrasted sharply with reality. As Lewis and Clark would learn, the continental climate of the Northern Plains, the highland climate of the Rocky Mountains, and the marine west coast climate of the Pacific Northwest were unlike anything they experienced in the East.

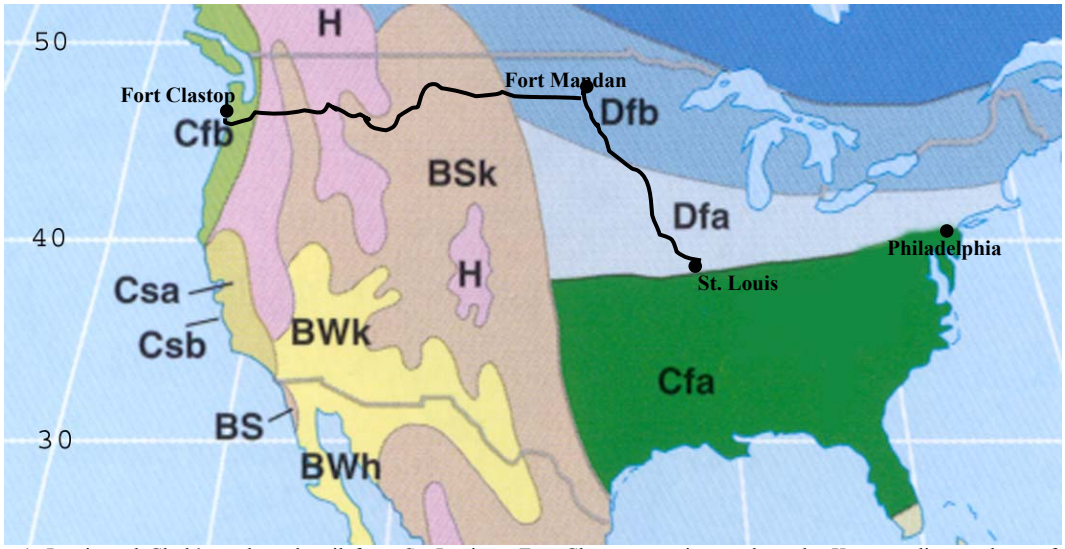

Figure 1. Lewis and Clark's outbound trail from St. Louis to Fort Clatsop superimposed on the Köppen climate classes for the conterminous United States. These classes and their characteristics are: BSk=mid-latitude steppe (semi-arid); BWk=mid-latitude desert (arid); BS=mid-latitude steppe; BWh=subtropical desert (arid); Cfa=humid subtropical climate (hot summer, no dry season); Cfb=marine west coast climate (mild throughout the year, no dry season, warm summer); Csa=Mediterranean (dry, hot summer); Csb=Mediterranean climate (dry, warm summer); Dfa=humid continental climate (severe winter, no dry season, hot summer); Dfb=humid continental climate (severe winter, no dry season, warm summer); H= highland climate (cold climate due to elevation).

Philadelphia resides at the boundary between what the Köppen system broadly classifies as humid subtropical and humid continental climates, classes Cfa and Dfa, respectively. Virginia and Washington D.C. are in the Cfa climate zone and the lower Missouri River is in the Dfa climate zone. Lewis's home state of Virginia and Clark's

home state of Kentucky are in the Cfa climate zone. The Cfa and Dfa climate zones would serve as the benchmarks for comparison between Lewis and Clark's climate experiences and those they would encounter during their journey west.

September 1st marks the first journal entry about the weather, wherein Lewis speculates about the origin of the fog on the Ohio River:

> …the Fog appears to owe it's origin to the difference of temperature between the *air* and *water* the latter at this season being much warmer than the former; the water being heated by the summer's sun dose not undergo so rapid a change from the absence of the sun as the air dose consequently when the air becomes cool which is about sunrise the fogg is thickest and appear to rise from the face of the water like the steem from boiling water…[16]

Lewis was describing evaporation-mixing fog, or steam fog. Steam fog forms when cold air moves over warm water. Provided the water is warmer than the unsaturated air above, water will evaporate into the air. If the water vapor content of the air increases to the point of saturation, condensation may occur resulting in fog. Because the air near the water is warmer than the air directly above, the warm air rises, which produces condensation vapors that appear as steam. In the Ohio River valley steam fog forms when the cool air of the surrounding hills moves down the sides of the valley over the warm water of the Ohio River.

Lewis's speculation about the origin of the fog touches on two key scientific points, neither of which was fully understood by science at the time. One is related to condensation and evaporation and the other to the difference in specific heat capacity[17] between water and air. First, Lewis states that the "Fog owe[s] it's origin to the difference between the *air* and water." Lewis's statement is indeed correct and is related to the role of temperature in the condensation and evaporation of water vapor. Although instruments to measure the amount of water vapor in the atmosphere were around since the fifteenth century, theories regarding the condensation and evaporation of water vapor were only beginning to emerge in the mid eighteenth century.[18] A full explanation of the processes involved in the formation of fog would have to wait until the late nineteenth century when the kinetic theory of gasses was well established and the seminal experiments on condensation were being carried out.[19]

Lewis's second point regards "…the water being heated by the summer's sun dose not undergo so rapid a change from the absence of the sun as the air…" Lewis is making a statement about how the difference in specific heat capacity between water and air favors fog formation in the morning. Specifically, it takes a greater amount of heat energy to heat a given mass of water than an equivalent mass of air. Thus the water cools or warms more slowly than the air, so that fog is favored in the early morning when the water is generally warmer than the air. Like condensation and evaporation, the scientific foundation for explaining Lewis's observation on specific heat had yet to be fully developed.

At 6:00 a.m. on May, 22, 1804, under cloudy skies, the Corps of Discovery began its first full day as a unit, moving upstream against the powerful Missouri River. Until the party reached the site of their winter quarters at Fort Mandan near present-day Bismarck, North Dakota in November, the party toiled against powerful river currents, recorded information on flora and fauna new to science, traded with the local Indian tribes, and made weather observations on a daily basis.

From St. Louis to Fort Mandan, the party traveled through what the Köppen system broadly classifies as a humid continental climate. This climate class is characterized by severe winters and no dry season and has two sub-classes that are distinguished by summertime temperature; Dfa for hot summers and Dfb for warm summers. From St. Louis to today's North Dakota border the climate class is Dfa; from the North Dakota border to Fort Mandan the class is Dfb.

The party traveled through the heart of the Dfa climate zone during summer, when the heat and humidity can be oppressive. July and August were spent traveling from central Missouri to about today's South Dakota border. The capriciousness of the continental summertime climate was evident in many of Lewis and Clark's journal entries. Oppressive humidity followed by dry, northerly winds; torrential downpours and high winds followed by calm; and dense fog followed by sunshine. Weather extremes were common.

On July 6, 1804, between present-day Kansas and Missouri, Clark commented on the heat and oppressive humidity and speculated on whether its source was the Missouri River or "Some other cause":

…A verry warm day [it's] worthy of remark that the water of this river or Some other cause, I think that the most Probable throws out a greater preposn. [proportion] of Swet [sweat] than I Suppose Could pass thro: [through] the humane body…[20]

On July 14, Clark describes an isolated convective storm that nearly capsized a boat:

th[e] atmispeir [atmosphere] became Suddenly darkened by a blak & dismal looking Cloud, … in this Situation a Violent Storm of Wint from the N.E. (passing over an Open plain, struck the boat nearly <broad Side>…[21]

On July 29, while on the Missouri between present-day South Dakota and Iowa, Lewis notes the destruction caused by an apparent tornado:

… above this high land & on the S. S. passed much falling timber apparently the ravages of a Dreadfull harican which had passed obliquely across the river from N.W. to S.E. about twelve months Since, many trees were broken off near the ground the trunks of which were Sound and four feet in Diameter,…[22]

During October 1804, the party crossed into the Dfb climate zone in today's North Dakota. By early November the party was at the site of their winter quarters, Fort Mandan, named after the local Mandan Indians. Located about 45 miles[23] northwest of present-day Bismarck, North Dakota, the region is notorious for its severe winters. Frigid air originating in the high northern latitudes often dives south into North Dakota producing blizzards and among the coldest temperatures in the conterminous United States. During their stay at Fort Mandan, Lewis and Clark experienced the biting cold of a Northern Plains winter.

While at Fort Mandan, Lewis and Clark systematically recorded the daily weather, producing the first long-term, systematic tabulation of weather data west of the Mississippi. Comments on the weather were included in the regular journal entries as well as in a separate weather diary. The weather diary also contained tables (see Table 1 below) that listed the weather observations. These tables, which were similar to Jefferson's weather tables, included the temperature, wind direction, and state of the

river. The temperature and wind direction were recorded twice a day, at sunrise and at 4o'clock, which Jefferson believed to be the coldest and hottest times of the day, respectively.[24]

Table 1.
The first five entries in Lewis and Clark's January, 1805 weather diary.[a]

Day of the Month	Ther. at ☼ rise[b c]	Weather[d]	Wind at ☼ rise	Thert. at 4 P.M.	Weather	Wind at 4 P.M.	River Rise Or fall	River Feet	River Inches
Jany. 1	18 a	s	S E.	34 a	f	N W	r	1	
2	4 b	s	N W	8 b	f a s	N.			
3	14 b.	c	N.	4 b	s	S E			
4	28 a	c a s	W.	18 b	c	N W	r		21/2
5	20 b	c	N. W.	16 b	s	N. E.	r		2

Sources: [a] From *The Journals of the Lewis & Clark Expedition*, by G. Moulton (Ed.), 1987 (vol. 3, pgs. 281-284), Lincoln: University of Nebraska Press. Copyright 1987, University of Nebraska Press. Only the first five entries of the month are listed here. [b] The symbol ☼ denotes sunrise. Lewis and Clark used a circle with a dot in the center to denote sunrise. [c] Temperature is in degrees Fahrenheit. The letters *a* and *b* after the temperature indicate above and below zero, respectively. [d] Lewis and Clark's weather notations are first defined at the end of January 1804, the month when the they first began listing their weather observations separately from their regular journal entries [see Moulton, 1986 (vol. 2, pgs. 168-169)]. The notations are as follows: s=sunny, c=cloudy, a=after (c a s means cloudy after sunshine), f=fair. In the river column Lewis states that the r "means risen in the last 24 hours ending at sunrise." Moulton vol. 2, p. 169.

Since the party's arrival at Fort Mandan in early November, 1804 to their departure in early April, 1805, cold temperatures and strong winds were commonplace:

[November 13] …large quantity of drift ice running this morning the river has every appearance of closing for winter
[December 28] …the [wind] blue verry hard last night. The frost fell like a shower of snoe
[February 10] …This morning was Cloudy after a slight snow in the course of the night the wind blue very hard from N. W. altho' the thermometer stood at 18^0 Above naught the violence of the wind caused a degree of could [cold] that was much more unpleasant than that of yesterday when thermometer stood at 10^0 only above the same point…

The average temperature for December, January and February was 4 degrees above zero, 3 degrees above zero, and 11 degrees above zero, respectively. The December through February temperature averaged 4 degrees above zero. For a 10 day period in January the temperature at sunrise averaged 21 degrees below zero. During this period the maximum sunrise temperature was 11 degrees below zero and the minimum 40 degrees below zero.

Arlen Large has compared Lewis and Clark's temperatures at Fort Mandan with the averaged (1951-1980) temperatures at Bismarck and found Fort Mandan's January through March averaged temperature to be about 8 degrees colder.[25] Such comparisons must be viewed with caution, however, owing to differences in the respective microclimates, the unknown manner in which the temperatures were recorded at Fort Mandan and the possible inaccuracies in the thermometers used by Lewis and Clark.

In early April, when the ice had broken up on the Missouri, the 33 member party loaded their boats and proceeded on. The party was slowly entering terra incognita, where the geography, Indian cultures, and climate were virtually unknown. The party was entering into present-day Montana and a climate that was outside of their life experience – the steppe climate of the Northern Plains (Köppen climate class Bsk).

The mid-latitude steppe climate is arid; potential evapotranspiration[26] exceeds precipitation. The winters are severe and the summers hot and dry. Summer precipitation most often is associated with thunderstorms, which are accompanied by powerful winds, dangerous lightning, large hail, and torrential rain. Flash floods are common. Lewis and Clark experienced all of the extremes of the steppe climate of the Northern Plains.

Lewis found the low humidity noteworthy enough to carry out a crude experiment:

> [May 30, 1805]... circumstances indicate our near approach to a country whos climate differs considerably from that in which we have been for many months. the air of the open country is asstonishingly dry as well as pure. I found by experiment that a table spoon full of water exposed to the air in a saucer would evaporate in 36 hours when the mercury did not stand higher than the temperate point at the greatest heat of the day; my inkstand so frequently becoming dry put me on this experiment.[27]

The periods of very low humidity were often punctuated by severe thunderstorms, which were accompanied by torrents of rain, hail and flash floods. One such storm occurred on June 27th, upstream of the Three Forks of the Missouri, which was recorded in Lewis and Clark's weather diary:

> At 1 P M a black cloud which arose in the S W. came on accompanied with a high wind and violent thunder and Lightning; …for about 20 minutes during this storm hail fell of an innomous size driven with violence almost incredible, when they struck the ground they would bound to the height of ten to 12 feet… after the rain I measured and weighed many of these hail stones and found several weighing 3 ozs. and measuring 7 inches in cirumference…[28]

Two days after this storm another one occurred that produced a flash flood that nearly resulted in loss of life. Lewis wrote:

> the rain appeared to descend in a body and instantly collected in the rivene and came down in a rolling torrent with irristable force driving rocks mud and everything before it…so suddon was the rise of the water that before Capt C could reach his gun and begin to ascend the bank it was up to his waist and wet his watch; and he could scarcely ascend faster than it arrose till it had obtained the debth of 15 feet with a current tremendious to behold. one moment longer & it would have swept them into the river…[29]

By early August the party was in the shadow of the continental divide. Preparations were being made to cross the divide in the Bitterroot Mountains, the most formidable mountain crossing yet attempted by citizens of the United States. Supplies that weren't essential were being cached for the return trip. Supplies that were needed were being packed for overland transport. Lewis and a few other men set out ahead of the main party for a reconnaissance and to garner, if possible, geographical information from the Shoshone people. After obtaining the necessary information, Lewis's group eventually joined the main party and by mid August was heading towards their September crossing of the continental divide.

The crossing of the divide was arduous. Steep cliffs, confusing and narrow ravines, and lack of game were exacerbated by the cold temperatures of the highland climate (Köppen climate class H). Traveling was dangerous. The horses frequently fell and on September 3rd the last of the three thermometers was broken. Clark summed up the situation on September 16th: "…began to Snow about 3 hours before Day and Continud all day…I have been wet and as cold in every part as I ever was in my life…"[30]

The grueling trek across the Bitterroot Mountains was completed by late September. The sense of accomplishment and joy of having successfully completed the crossing was evident in Lewis's September 22nd journal entry:

> … the pleasure I now felt in having triumphed over the rocky Mountains and descending once more to a level and fertile country where there was every rational hope of finding a comfortable subsistence for myself and party can be more readily conceived than expressed…[31]

Upon exiting the mountains the party was fatigued and hungry, and many of the men were suffering from gastrointestinal disorders. Fortunately for the party, contact was made with the Nez Percé people, who provided them with food and horses. The Nez Percé also provided the party with important geographical information that indicated they were within striking distance of the rivers that would ultimately take them to the Pacific Ocean.

In preparation for their journey to the coast, dugout canoes were made and on October 7th the party was on the Clearwater River heading for the junction with the Snake River. In three days the party reached the Snake River and two weeks after that the Columbia River. As the party traveled down the Columbia from the east to the west side of the Cascade Mountains, there was a dramatic change in climate. The steppe climate east of the cascades rapidly transitioned into a marine west coast climate. The arid, thinly timbered landscape of the steppe gave way to one that was moist and heavily timbered.

The marine west coast climate of the Pacific Northwest is distinguished by mild temperatures throughout the year, no dry season and a warm summer. The region is renowned for powerful, moisture-laden storms that buffet the region throughout the winter. Upon the party's arrival to the region in early November, rain, fog, and strong winds were becoming increasingly common. By mid to late November, powerful storms were occurring almost daily. The inclement weather and the lack of permanent shelter were proving extremely difficult to the party. Clark wrote:

> [November 22, 1805] …the wind increased to a Storm from the S.S.E. and blew with violence throwing the water of the river with emence waves out of its banks almost overwhelming us in water, O! how horriable is the day…[32]

Establishing their winter quarters and obtaining shelter was of paramount importance. On November 29th Lewis and several men set out in a dugout canoe from their camp on the south side of the Columbia to search for a suitable site for their winter quarters. After several days out, Lewis found a site on today's Lewis and Clark River. Lewis returned to the main party with the news on December 5th. On the morning of December 7, under fair skies, the party departed present-day Tongue Point and paddled up the Lewis and Clark River to the site of their winter quarters, which is located about 5 miles southeast of present-day Astoria, Oregon.

The journey from St. Louis, Missouri to Fort Clatsop covered about 4,000 miles, spanned seven seasons, and traversed through six climate zones.

Fort Clatsop Weather: December 8, 1805 – March 23, 1806

Weather observations-

On December 8, 1804, the party began the first full day at the site that would become Fort Clatsop, named after the local Clatsop Indians. In the morning, after a night of moderate rainfall, Clark and five men set out under cloudy skies to set up a salt-making camp along the coast in what is now Seaside, Oregon. Lewis dispatched several hunters to procure meat, while the bulk of the party began felling trees for the construction of their winter quarters, which were completed on December 30th. From December 9th through the end of the month it rained every day.

Since arriving at Fort Clastop, Lewis made only two journal entries, neither of which was weather related. Clark, on the other hand, made daily journal entries, which refer repeatedly to the inclement weather and its affect on the party:

[December 11th] rained all the last night moderately we are all employed putting up huts or Cabins for our winter quarters. Sergeant Pryor unwell from a dislocation of his Sholder, Gibson with the disentary, Jo. Fields with biles on his legs, & Werner with a Strained Knee. The rained Continued moderately all day.[33]
[December 16th] rained all the last night we Covered our Selves as well as we Could with Elk Skins, & Set up the greater part of the night, all wet …[34]
[December 18th] …rained and snowed alturnitely all the last night and the gusts of Snow and hail continue untill 12 oClock, Cold and a dreadfull day wind hard and unsettled, we continue to work at our huts, the men being but thinly dressed, and no Shoes causes us to do but little …[35]

The New Year began the same way December ended – wet. Awakening to moderate rain and "… the discharge of a volley of small arms, which were fired … to usher in the new year …"[36], Lewis looked forward to spending the next New Year back in the East. With the beginning of the New Year, Lewis's several week hiatus from making journal entries ended. Among his New Year entries were comments about the weather:

the changes of the weather are exceedingly suddon. Sometimes tho' seldom the sun is visible for a few moments the next it hails & rains, then ceases, and remains cloudy the wind blows and it again rains; these visicitudes of the weather happen two three or more times half a day.[37]

Although Lewis and Clark noted in October a change in climate as they paddled down the Columbia from the east to the west side of the Cascades, they now realized that they were in a winter climate that was foreign to them. The nearly relentless rainfall and relatively mild temperatures of the Pacific Northwest contrasted sharply with the cold, snowy winters that Lewis and Clark experienced in the East. The distinct climate of the Pacific Northwest is noted by Lewis on January 3rd, when he writes, "I am confident that the climate is much warmer than in the same parallel of Latitude on the Atlantic Ocean tho' how many degrees is now out of my power to determine."[38] Indeed, Fort Clatsop and Bangor, Maine are at about the same latitude, yet Fort Clatsop is characterized by mild temperatures throughout the year, whereas Bangor is characterized by a severe winter and a warm summer.

At the time of the expedition, the connection between latitude and climate was well known. The ancient Greeks were among the first to make this connection. In fact, climate derives from the Greek word *klima*, meaning inclination, underscoring the

connection between climate and the inclination (or height) of the sun above the horizon, which depends on time and latitude. Not fully known at the time of Lewis and Clark, however, was the role that ocean currents and land-sea heating contrasts played in climate, factors that largely account for the differences in the climates between the Pacific Northwest, Central Plains, and the East Coast.

From the beginning of the party's stay at Fort Clatsop on December 8th until their departure on March 23rd, the weather remained stormy. Of the 106 days that the party stayed at Fort Clatsop, there were 90 days of precipitation, of which there were 17 days of snowfall. There were only 12 days without precipitation; the sun shone fair for only six days. The monotony of the rainfall was commented on by Clark on their day of departure from Fort Clatsop:

> at this place we had wintered and remained from the 7th of Decr. 1805 to this day and have lived as well as we had any right to expect,…, not withstanding the repeeted fall of rain which has fallen almost constantly…[39]

Weather comparisons-

Although prolonged periods of rainfall are common for the Pacific Northwest, it is unclear to what extent Lewis and Clark's winter experience was typical or atypical for that region. In order to shed light on this question, preliminary comparisons are made between Lewis and Clark's weather observations at Fort Clatsop and those of present-day. Because there are no formal, long-term weather observations available for Fort Clatsop, the data from Astoria, Oregon is used as a proxy. Astoria climatological data is used to form averages for three comparisons: 1) number of precipitation days; 2) number of snow days; and 3) prevailing wind direction.[40]

Before comparing Lewis and Clark's observations with those of present-day, it is instructive to first consider some of the difficulties and uncertainties that are associated with such comparisons. For example, comparison is made between data obtained at two different locations. Although these locations are only about 5 miles apart, differences in the microclimates may exist owing to local differences in terrain and vegetative cover. It also is unclear if Lewis and Clark distinguished between light rainfall and the droplets that condense on the forest canopy and fall to the ground. Did they simply refer to both situations as rain? Additionally, the early nineteenth century was at the tail end of the Little Ice Age, a time of very wet and variable conditions in northern latitudes.[41] Was the transition out of the Little Ice Age climate a factor in producing the weather experienced at Fort Clatsop? With these caveats in mind, the various comparisons are presented below.

Figure 2 shows the number of days with measurable precipitation[42] and snow for Fort Clatsop and Astoria. The numbers for Astoria are based on a 38 year average, spanning 1961 through 1999.

Astoria averaged 73 days of precipitation between December 8th and March 23rd. The highest number of precipitation days for this period was 88, which occurred during the winters of 1971-1972 and 1974-1975. The lowest number of precipitation days was 50, which occurred during the winter of 1984-1985. The number of precipitation days measured by Lewis and Clark was 90. By today's standards, the number of precipitation days for the winter of 1805-1806 was abnormally high.

Lewis and Clark recorded 17 days of snowfall. This is more than five times Astoria's 3 day average and two days more than its 15 day maximum, which occurred during the winter of 1968-1969. By today's standards, the number of snowy days for the winter of 1805-1806 was abnormally high.

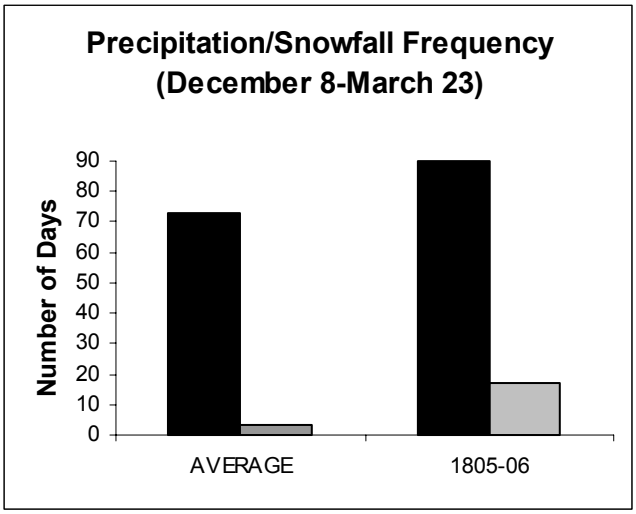

Figure 2. The number of days of precipitation (black) and snowfall (grey) between December 7 and March 23 for (a) Astoria, Oregon averaged between 1954 and 1999 (left column) and for (b) Fort Clatsop, Oregon for the winter of 1805-1806 (right column). The precipitation numbers include both rain and snow.

Lewis and Clark recorded the wind direction throughout their journey. At Fort Clatsop during December, the wind direction was recorded only once a day, though it's unclear at what time. From January through their departure in late March they recorded the wind direction twice a day, at sunrise and at four o'clock. The location and manner in which they made their wind observations is unknown. Did they estimate the wind direction from within the confines of the fort, or did they estimate the wind direction from within the forest canopy? Did they base their estimates on the surface wind, which is often turbulent, particularly within forest canopies, or did they base their estimates on the wind direction just above the forest canopy? Despite these questions and uncertainties, two factors provide confidence that Lewis and Clark's wind direction observations were accurate. First, they made a large number of wind observations, which tends to reduce random error. Second, they were extraordinarily accurate in their descriptions of the flora and fauna, and there is no reason to believe they weren't equally as accurate in their weather observations.

The wind directions recorded by Lewis and Clark were compared with those of Astoria. Lewis and Clark's observations are based on eight compass headings: south (S), southeast (SE), west (W), southwest (SW) etc. A given compass heading indicates the direction from which the wind is blowing. A southwest wind means the wind is blowing *from* the southwest. Astoria's observations for wind direction, which begin in 1985, are averaged for fourteen years (1985-1999) and, consistent with Lewis and Clark's observations, are assigned eight compass headings. In order to simplify the comparisons, the wind data for both Fort Clatsop and Astoria were grouped into four bins, E-SE, S-SW, W-NW, and N-NE. The E-SE and S-SW bins contain the most entries and thus are deemed the prevailing wind directions.

Figure 3 shows the two prevailing wind directions, E-SE and S-SW, for Fort Clatsop and present-day Astoria. The differences in the prevailing winds between the winter of

1805-1806 and present-day averaged conditions are dramatic. At Astoria, the E-SE winds are about a third more frequent than the S-SW winds. In sharp contrast, at Fort Clatsop, the S-SW winds were about four times as frequent as the E-SE winds. The persistence of the S-SW winds was noted by Lewis on January 1st: "…the wind blows by squalls most generally and is almost invariably from S. W."[43]

An approximate relationship between wind and pressure was formulated by the mid-nineteenth century Dutch meteorologist Christoph Buys-Ballot. This relationship is now called Buys-Ballot's law. The law states that in the Northern Hemisphere, if we stand with our backs to the wind, lower pressure will be on our left and higher pressure on our right. Thus, if the wind is from the south, lower pressure will be to the west and higher pressure to the east. Buys-Ballot's law can therefore provide qualitative information about the location and movement of the high and low pressure systems that characterize mid-latitude weather. Simply put, Lewis and Clark's wind observations can provide qualitative information on the position of the northern Pacific storm track during the winter of 1805-1806.

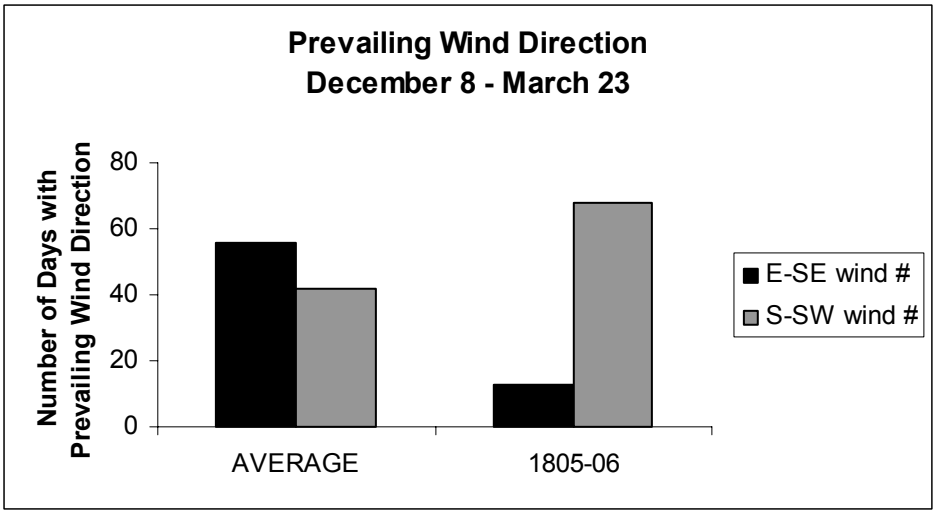

Figure 3. The prevailing wind direction between December 8 and March 23 for (a) Astoria, Oregon averaged between 1961 and 2001 and for (b) Fort Clatsop, Oregon for the winter of 1805-1806.

Application of Buys Ballot's law to the prevailing wind directions shown in figure 3 yields three conclusions: 1) during the winter of 1805-1806 the low pressure systems and thus storm track were predominantly W-NW of Fort Clatsop; 2) the 1805-1806 storm track was persistent; the low pressure systems W-NW of Fort Clatsop were about four times more common than those occurring to the S-SW; 3) the position of the 1805-1806 storm track was dramatically different than its present-day averaged position, which is predominantly to the S-SW of the Fort Clatsop region.

Based on comparisons with averaged conditions for present-day Astoria, the winter of 1805-1806 at Fort Clatsop was atypical. The frequency of precipitation, the frequency of snowfall, and the persistent southwesterly winds were all dramatically different than present-day. What accounts for these dramatic differences? There are several possibilities. The position of the storm track within a given year or between given years can be quite different than its long-term averaged position. This intra-seasonal and inter-annual variability may simply be due to the natural variability inherent in thermally driven, rotating stratified fluids such as the atmosphere. The emergence out of the Little

Ice Age climate may also have been a factor, or there may have be some external forcing process such as the anomalous warming or cooling that takes place in the equatorial eastern Pacific during El Niño or La Niña events. In fact, other than the change of seasons, El Niño and La Niña have the greatest impact on the global atmospheric circulation. During La Niña, for example, the Pacific storm track is displaced north of its climatological position, resulting in above normal precipitation and below normal temperatures for the Pacific Northwest, which is consistent with the weather at Fort Clatsop. Work is currently under way to test the hypothesis that the wet, cold winter that Lewis and Clark recorded in 1805-1806 may have been a La Niña year.

Lewis and Clark departed Fort Clastop on March 23rd, 1806. They continued to make daily weather observations on their return trip. At 12 o'clock on September 23rd, 1806 the party arrived to St. Louis and "…were met by all the village and received a harty welcome from it's inhabitants…"[44]

Pursuant to Jefferson's instructions, Meriwether Lewis and William Clark successfully completed an expedition that spanned more than 28 months and covered more than 8,000 miles. They recorded for science more than 170 new plant species and more than 120 new animal species. They recorded the first systematic weather observations west of the Mississippi. And they produced hundreds of pages of cartographic, ethnographic, and scientific information that continues to add to our knowledge and spark our imagination two-hundred years later. The expedition is etched deep in our nation's psyche, serving as a benchmark for achievement and scientific discovery.

Lewis and Clark's Meteorological Legacy

> A change in our climate is taking place very sensibly. Both heats and cold are become much more moderate within the memory even of the middle-aged. Snows are less frequent and less deep. …The elderly inform me the earth used to be covered about three months in every year. …[45]

Thomas Jefferson penned these words more than two-hundred years ago, yet they resonate with today's concerns about anthropogenic influences on global warming. Jefferson's comments on climate change were made in the absence of broad-based empirical data or knowledge of the complex processes that affect regional and global climate. Today's concerns about climate change are based on large-scale, long-term observations and sophisticated mathematical models of the atmosphere that carry out millions of arithmetic operations per second. The reliability of these models for assessing and predicting climate change is determined in part by their ability to simulate past climates. Thus the reconstruction of past climates via instrumental and proxy data is central to the validation and development of climate models today.

The Lewis and Clark journals provide the first systematic instrumental and proxy data of the trans-Mississippi West. The continuous temperature measurements at Fort Mandan and the keen descriptive comments on the weather throughout the journey can be combined with documentary, dendroclimatic, and ice core evidence to form a more complete picture of the regional and global weather patterns during the early nineteenth century. Lewis and Clark's weather observations add another small piece to the climate puzzle, serving as an overarching link between early nineteenth century climate data and our efforts to model climate change today.

Lewis and Clark's spirit of adventure, quest for knowledge, and careful observations of nature provide the seeds for scientific discovery today. Their weather observations, for example, have yet to be fully examined and have the potential for shedding additional light on the atmospheric circulation patterns that affected the weather at Fort Mandan and Fort Clatsop. The preliminary analysis of the Fort Clatsop weather presented here indicates that the winter of 1805-1806 in northwestern Oregon was significantly different than present-day. Is the difference due to changes in the global atmospheric circulation that occurred near the end of the Little Ice Age, or was 1805-1806 a La Niña year? Or perhaps the unusual winter of 1805-1806 was simply part of the atmosphere's inherent natural variability. Addressing such questions is what makes the Lewis and Clark journals so relevant to meteorological science today.

Acknowledgments. This work was supported in part by a grant from the Lewis and Clark Trail Heritage Foundation. Thanks are due Foundation members Ludd Trozpek and the late Bob Shattuck for their encouragement to pursue this work. Thanks also are due Laura Concannon, Professor Eugene Cordero, Dr. Steve Grattan, and Dan Hodyss for discussions regarding this work.

Notes

1. Jackson, D. (Ed.). (1978). *Letters of the Lewis and Clark Expedition, with Related Documents*: 1783-1854 (2nd ed., vol. I, p. 63). Urbana: University of Illinois Press.
2. Meteorology, or meteorological science, is the study of the physics, chemistry and fluid dynamics of the atmosphere. Meteorology derives from the Greek word *meteoros*, meaning "high in the air." At the time of the ancient Greeks, anything that fell from the sky or was seen in the air was called meteors. At about 340 B.C., Aristotle published a book on natural philosophy entitled *Meteorlogica*, which sought to explain weather and climate as well as astronomy and other subjects based on a philosophical approach.
3. Weather is the state of the atmosphere – its temperature, humidity, wind direction and speed, etc. - at any given time and place. Climate is the long-term behavior of weather.
4. Jackson p. 12
5. Jackson p. 21
6. Owing to the slowness of the mail delivery at that time, Lewis didn't receive Clark's affirmative response until the end of July.
7. Jackson pgs. 61-63
8. Ronda, J. (1998). 'So Vast an Enterprise': Thoughts on the Lewis and Clark expedition. In J. Ronda (Ed.), *Voyages of Discovery: Essays on the Lewis and Clark Expedition* (pp. 1-28). Helena, Montana: Montana Historical Society Press.
9. Clark and the party departed their Wood River camp on May 14th, while Lewis tended to some last minute business in St. Louis. Lewis and Clark and the party were united on May 21st and started their first full day of their journey on May 22nd.
10. Jackson p. 75. Jefferson to Briggs, June 5, 1804, microfilm, series 1, reel 30, Jefferson Papers, Manuscripts Division, Library of Congress, Washington, D.C.
11. Moulton, G. (Ed.). (1986). *The Journals of the Lewis & Clark Expedition* (vol. 2, p. 145). Lincoln: University of Nebraska Press.
12. Moulton p.146
13. Moulton p. 169
14. Fleming, J. R. (1990). *Meteorology in America, 1800-1870.* Baltimore and London: The Johns Hopkins University Press.

15. Jackson p. 12
16. Moulton p. 67
17. Specific heat capacity is defined as the amount of energy required to raise the temperature of one gram of a substance one degree Celsius. The specific heat capacity of water is about four times that of air. Thus, if we had equal masses of water and air, it would take about four times as much heat energy to raise the temperature of the water one degree Celsius than the air.
18. Middleton, W. E. K. (1969). *Invention of the Meteorological Instruments*. Baltimore: The Johns Hopkins Press.
19. Mason, B. J. (1957). *The Physics of Clouds*. London: Oxford University Press.
20. Moulton p. 352
21. Moulton pgs. 376-377
22. Moulton p. 427
23. Although the International System of Units (SI) is the standard for denoting units of measurement, particularly in the scientific literature, we adopt here the English System for ease of comparison with the distances listed in the Lewis and Clark Journals.
24. Jefferson, T. (1955). *Notes on the State of Virginia* (W. Peden, Ed., p. 78). Chapel Hill: University of North Carolina press. (Original work published 1785)
25. Large, A. L. (May 1986). "…It Thundered and Lightened': The Weather Observations of Lewis and Clark. *We Proceeded On*, 12 (no. 2), p. 8.
26. Potential evapotranspiration is defined as the quantity of moisture, if it were available, that would be removed from a given land area by evaporation and transpiration, where transpiration is defined as the process by which water contained in plants is transferred to the atmosphere as water vapor.
27. Moulton, G. (Ed.). (1987). *The Journals of the Lewis & Clark Expedition* (vol. 4, p. 221). Lincoln: University of Nebraska Press.
28. Moulton p. 348
29. Moulton pgs. 341
30. Moulton, G. (Ed.). (1988). *The Journals of the Lewis & Clark Expedition* (vol. 5, p. 209). Lincoln: University of Nebraska Press.
31. Moulton p. 229
32. Moulton, G. (Ed.). (1990). *The Journals of the Lewis & Clark Expedition* (vol. 6, p. 79). Lincoln: University of Nebraska Press.
33. Moulton p. 122
34. Moulton p. 126
35. Moulton p. 130
36. Moulton p. 151
37. Moulton p. 259
38. Moulton p. 259
39. Moulton, G. (Ed.). (1991) *The Journals of the Lewis & Clark Expedition* (vol. 7 p. 8). Lincoln: University of Nebraska Press.
40. The Astoria climate data were obtained from the Oregon Climate Service Web site http://ocs.oce.orst.edu/.
41. The Little Ice Age spanned about three and a half centuries, beginning about 1500 and ending about 1850. This period was characterized by anomalously cold conditions in the North Atlantic and Europe. Portions of the North Atlantic froze while glaciers expanded in the European mountains. In Switzerland, for example, at the time of the Lewis and Clark expedition, Phister has shown that the temperature was below normal and the precipitation above normal. From Pfister, C. (1992). Monthly temperature and precipitation in Central Europe 1525-1979: quantifying documentary evidence on the weather and its effects. In: *Climate Since A.D. 1500* (R. S. Bradley and P.D. Jones, Eds.). London: Routledge, 118-142.
42. Trace amounts of precipitation were excluded from the tally.
43. Moulton, G. (Ed.). (1990). *The Journals of the Lewis & Clark Expedition* (vol. 6, p. 259). Lincoln: University of Nebraska Press.

44. Moulton, G. (Ed.). (1993) *The Journals of the Lewis & Clark Expedition* (vol. 8, pgs. 370-371). Lincoln: University of Nebraska Press.
45. Jefferson p. 80