Impact of Source Region on the $\delta^{18}$O Signal in Snow: A Case Study from Mount Wrangell, Alaska

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ABSTRACT

The stable isotopic composition of water in ice cores is an important source of information on past climate variability. At its simplest level, the underlying assumption is that there is an empirical relationship between the normalized difference in the concentration for these stable isotopes and a specified local temperature at the ice core site. There are, however, nonlocal processes, such as a change in source region or a change in the atmospheric pathway, which can impact the stable isotope signal, thereby complicating its use as a proxy for temperature. In this paper, the importance of these nonlocal processes are investigated through the analysis of the synoptic-scale circulation during a snowfall event at the summit of Mount Wrangell (62°N, 144°W; 4300 m MSL) in south-central Alaska. During this event there was, over a 1-day period in which the local temperature was approximately constant, a change in $\delta^{18}$O that exceeded half that normally seen to occur in the region between summer and winter. As shall be shown, this arose from a change in the source region, from the subtropical eastern Pacific to northeastern Asia, for the snow that fell on Mount Wrangell during the event.

1. Introduction

The stable isotope ratio of oxygen in precipitation is an important source of information on the earth’s hydrological cycle (Epstein and Mayeda 1953; Dansgaard 1964; Jouzel et al. 1997; Araguás-Araguás et al. 2000). Simply put, the slight differences in the mass of water with various isotopic compositions results in temperature- and vapor pressure–dependent fractionation that can be used to infer information on the atmospheric pathway taken by the water from the source to the deposition region (Dansgaard 1964; Araguás-Araguás et al. 2000). It is conventional to use the $\delta$ notation {i.e., $\delta^{18}$O = 1000[(R$_{\text{sample}}$ - R$_{\text{VSMOW}}$)/R$_{\text{VSMOW}}$] where R$_{\text{sample}}$ = $[^{18}$O/$^{16}$O] and R$_{\text{VSMOW}}$ is the corresponding ratio for the Vienna Standard Mean Ocean Water (VSMOW)} to express the isotopic composition of water (Coplen et al. 1996).

Starting with the work of Dansgaard (1964), an empirical spatial relationship relating mean annual temperatures and mean annual $\delta^{18}$O in precipitation has been identified that allows one to interpret ice core records of $\delta^{18}$O as paleotemperature proxies (Jouzel et al. 1987; Cuffey et al. 1995; Petit et al. 1999). However, the use of this so-called isotope thermometer, which is based on spatial gradients in temperature and $\delta^{18}$O, to reconstruct temporal changes in temperature at a given ice core site is controversial (Boyle 1997; Jouzel et al. 1997; Cole et al. 1999; Hendricks et al. 2000; Holdsworth 2001). This controversy arises from a number of different nonlocal atmospheric processes, such as changes in atmospheric circulation (Werner et al. 2000; Holdsworth 2001; Kriinner and Werner 2003) as well as moisture source changes (Johnsen et al. 1989; Boyle 1997; Kavanaugh and Cuffey 2002; Bradley 2006).


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et al. 2003), which can also impact the δ18O record at a given site.

Indeed, a number of studies have shown that δ18O, when sampled on an event basis, is often unrelated to the local temperature at the sampling site (Lawrence et al. 1982; Gedzelman et al. 1989; Gedzelman and Lawrence 1990; Noone and Simmonds 2002; Burnett et al. 2004; Treble et al. 2005). Instead, the δ18O values were found to be related to the track of the storm that generated the precipitation (Lawrence et al. 1982), its location relative to the sampling site (Gedzelman and Lawrence 1982, 1990; Gedzelman et al. 1989), or its moisture source (Noone and Simmonds 2002; Burnett et al. 2004; Treble et al. 2005).

The Gulf of Alaska region of northwestern North America is of climatological importance for a variety of reasons. Most notably, it is located at the end of the major North Pacific storm track (Blackmon 1976; Hoskins and Hodges 2002) along the main atmospheric pathway for the moisture that enters the Mackenzie River basin, which covers 20% of the Canadian landmass and which supports the fourth-largest river flowing into the Arctic Ocean (Lackmann et al. 1998; Stewart et al. 1998; Smirnov and Moore 1999, 2001). Furthermore, the region is located in the center of the Pacific North America (PNA) teleconnection pattern (Wallace and Gutzler 1981; Barnston and Livezey 1987), an important mode of climate variability that is associated with the extratropical response to ENSO (Horel and Wallace 1981; Gershunov and Barnett 1998; Trenberth et al. 1998).

The region contains a number of mountains, including Mount Bona Churchill, the Eclipse ice field, Mount Logan, and Mount Wrangell, in which ice cores have been extracted that are being used to examine past climate in this region (Holdsworth et al. 1992; Wake et al. 2001; Fisher et al. 2004; Zagorodnov et al. 2005; Yasunari et al. 2007). Indeed, the snow accumulation record from the first Mount Logan ice core has been shown to include a signature of the PNA and ENSO as well as the associated tropical Hadley and Walker circulations (Moore et al. 2001, 2002a,b, 2004). Surface snow pit samples from various elevations on Mount Logan show a discontinuity in the δ18O with elevation that suggests a different source region for the precipitation that falls at low elevations as compared to that at higher elevations (Holdsworth et al. 1991).

Mount Wrangell (62°N, 144°W; 4317 m MSL) is a shield volcano that will be the subject of this paper. Mount Wrangell has a particularly high accumulation rate of approximately 3 m water equivalent per year (Yasunari et al. 2007). Data from the summit indicate that approximately 50% of the annual accumulation occurs between the end of July and the end of September (Kanamori et al. 2008). Furthermore, much of this accumulation occurs during relatively short periods that are associated with large extratropical cyclones over the Gulf of Alaska. In particular, between June and December 2005, 17 such events were observed, with 7 of these events resulting in accumulations in excess of 0.45 m (Kanamori et al. 2008). All significant accumulation events on Mount Wrangell also resulted in precipitation events at Cordova (Fig. 1), the closest National Weather Service station on the Gulf of Alaska (Kanamori et al. 2008). In addition, the annual accumulation at Cordova is approximately 2445 mm—comparable to the 2750 mm accumulation measured by Kanamori et al. (2008) at the summit.

The annual variation of δ18O in precipitation at the closest Global Network of Isotopes in Precipitation station (Whitehorse in the Yukon Territory) is on the order of 11.25‰ (IAEA/WMO 2006). This is in agreement with the annual range in δ18O values from the first Mount Logan ice core (Holdsworth et al. 1992). In this paper, we will consider a precipitation event on 7 August 1980 on Mount Wrangell in which a decrease in δ18O of 8.2‰ was observed during a single day in which the temperature at the sampling site was approximately constant. We will use a number of observations from the region, diagnostics from the North American Regional Reanalysis (NARR), and an idealized isotope model to show that this decrease was the result of a change in source region for the snow—from the subtropical eastern Pacific to northeastern Asia—that fell on Mount Wrangell during the event.

2. Methods

Surface meteorological data from the National Weather Service stations at Cordova (60°32'N,
145°45′W; 1.5 m MSL) and Yakutat (59°30′N, 139°39′W; 1 m MSL) will be used to provide information on the timing and duration of the precipitation event. The Cordova precipitation data are available as 3-h accumulations and these were converted to hourly averaged accumulations. The Yakutat precipitation data are available as hourly accumulations. Yakutat is also the closest radiosonde site, and these data will also be used to characterize the vertical profile and timing of the moisture fluxes associated with this event.

Our primary tool for the creation of atmospheric diagnostics associated with this case will be the North American Regional Reanalysis. NARR was created to provide a long-term consistent climate dataset for North America (Mesinger et al. 2006). It uses the NCEP Eta Model and its three-dimensional variational data assimilation (3DVAR) system that includes direct assimilation of satellite radiances and precipitation, with lateral boundary conditions provided by the NCEP–DOE AMIP-II reanalysis (Kanamitsu et al. 2002). The model covers the North American continent and adjoining oceanic regions, including much of the North Atlantic and the North Pacific (Mesinger et al. 2006). NARR has a temporal resolution of 3 h and a horizontal resolution of 32 km with 45 levels in the vertical, of which 15 levels are below 600 mb.

Figure 1 shows the NARR topography in the region of interest. The high topography of the Western Cordillera is clearly captured. Mount Logan and Denali stand out as the highest topography in the region, although their heights are significantly underestimated, indicating that there is topographic structure that is underresolved by NARR.

The direct assimilation of precipitation data into NARR allows for the possibility of an improved representation of the hydrological cycle, although there are as of yet no studies on this topic in the region of interest. In the adjoining Mackenzie River basin, Szeto et al. (2008) showed that NARR tends to underpredict warm season orographic precipitation. Despite this bias, NARR is able to close the water budget of the basin to within 6%, a residual similar to that of ERA-40 and a significant improvement over the original NCEP–NCAR reanalyses (Kalnay et al. 1996; Szeto et al. 2008). In the continental western United States, NARR is able to capture the orographic modulation of precipitation by the coastal ranges, the Sierra Nevada, and the Rocky Mountains (Guirguis and Avissar 2008).

In addition to standard meteorological fields such as the sea level pressure, precipitation rate, 10-m wind, and geopotential and horizontal wind fields, NARR will also be used to compute components of the atmospheric water vapor budget (Peixoto and Oort 1992) that can be expressed, under relatively modest assumptions, as

\[ P - E = \frac{\partial W}{\partial t} - \nabla \cdot Q, \]

where \( P \) is the precipitation rate, \( E \) is the evaporation rate, \( W \) is the precipitable water \( W = \int_0^h q \, dp \), and \( Q \) is the vertically integrated moisture flux \( Q = (1/q) \int_0^h q \, \nabla \cdot dp \). In the above, \( g \) is the acceleration due to gravity, \( q \) is the specific humidity, \( \mathbf{V} \) is the horizontal velocity, \( p \) is the pressure, and \( p_s \) is the surface pressure. In addition, the moisture flux at a specific level in the atmosphere is given by \( q = q \mathbf{V} \).

We also applied an idealized model of \( \delta^{18} \)O distillation to back trajectories from Mount Wrangell to estimate the magnitude of isotopic changes associated with changes in moisture transport pathways. Back trajectories were calculated at 6-hourly intervals using HYSPLIT (Draxler and Hess 1998) and driven by NCEP–NCAR reanalyses and NARR data during the period of interest. Trajectories were initiated from an array of points from 61° to 63°N and 145° to 143°W between 4300 and 4400 m MSL, spanning the summit region of Mount Wrangell at 62°N, 144°W at a height of 4317 m MSL, and then were used to calculate a mean pathway. Only the last 48 h of each back trajectory was used so as to provide more robust estimates of the Rayleigh distillation. The use of multiple trajectories guarded against the transport pathways being overly sensitive to starting location, particularly given the coarse resolution of the reanalysis data.

A simple iterative \( \delta^{18} \)O depletion scheme based on the Rayleigh model as implemented in Dansgaard (1964) was applied using the humidity history of the back trajectories, similar to the techniques of Rozanski et al. (1982) and Kurita et al. (2004). Using the formulation of Gat (1996), the ratio \( R \) of heavy to light isotope in condensed water at some point along the trajectory is given by

\[ R = R_0 f^{(a-1)}, \]

where \( R_0 \) is the isotopic ratio of the initial quantity of moisture; \( f \) is the fraction of water remaining; and \( a \) is the fractionation factor between phases, in this case dependent on temperature. We applied this distillation scheme iteratively to points along the trajectory path according to

\[ R_t = R_{t-1} \left( \frac{q_t}{q_{t-1}} \right)^{\alpha(T_t)-1}, \]

where \( R_0 \), \( q_t \), and \( \alpha(T_t) \) are the isotopic ratio, specific humidity, and fractionation factor at time \( t \), respectively.
The temperature-dependent fractionation factor \( \alpha(T) \) was determined using the empirical model described in Clark and Fritz (1997), using the temperature \( T \) along the trajectory. The fractionation factor for the vapor-liquid transition is given by

\[
10^3 \ln \alpha = 1.137 \left( \frac{10^6}{T^2} \right) + \left[ -0.4156 \left( \frac{10^3}{T} \right) \right] + (-2.0667),
\]

and the fractionation factor for the vapor-ice transition is given by (Gat 1996)

\[
10^3 \ln \alpha = 1.137 \left( \frac{10^6}{T^2} \right) + \left[ -0.4156 \left( \frac{10^3}{T} \right) \right] + 1.03333.
\]

As a compromise between pure Rayleigh distillation and the observed moisture history of the air parcel, which may include isotopic recharge from air parcel mixing or surface evaporation, the following approach was taken. To ensure continuous moisture loss, the specific humidity along the trajectory was smoothed according to a monotonically decreasing three-parameter sigmoidal model, from the point of maximum humidity. Distillation was then calculated between this starting point and Mount Wrangell.

In the absence of observed \( \delta^{18}O \) vapor observations, the initial isotopic ratio \( R_o \) at the trajectory origin was estimated using mean \( \delta^{18}O \) fields from the 45-yr NASA GISS ModelE GCM simulations of Field et al. (2010). This follows the approach suggested by Jouzel and Koster (1996) and is similar to that implemented in the isotopic trajectory analyses of Helsen et al. (2007) and Sodemann et al. (2008). ModelE was run at a 4° × 5° horizontal resolution with 20 vertical levels and forced with interannually varying sea surface temperature and sea ice fields from HadISST, version 1.1 (Rayner et al. 2003; Schmidt et al. 2006). The initial vapor \( \delta^{18}O \) was interpolated from the ModelE layers above and below the trajectory origin’s initial height. Neither the modeled \( \delta^{18}O \) or underlying prognostic fields are constrained by observed meteorology during the August 1980 event, but this approach was felt to be sufficient to capture large changes in initial isotopic composition between, for example, warm oceanic and cold continental sources.

3. Observations

In 1980, one of us (C.S.B.) was conducting glaciological studies at the summit of Mount Wrangell. Detailed measurements of the snow layers in hand-excavated pits were made to depths of 4 m. Samples for determining density and stable isotope ratios were taken and analyzed as done previously on the Greenland ice sheet (Benson 1962). The departure from the summit was delayed by a storm that provided an opportunity to sample and study a single storm layer, which appeared homogeneous. The storm began on the evening of 6 August and continued until 9 August; the storm weakened on 8 August, but its intensity increased again on 9 August. On 10 August, the weather cleared and the 50 cm of new snow deposited during the storm was sampled carefully for \( \delta^{18}O \) analysis at 10-cm intervals. The \( \delta^{18}O \) values in the bottom 30 cm changed gradually from \(-21.5_{\text{oo}}\) to \(-24.5_{\text{oo}}\) and then decreased abruptly, with the top 20 cm being in the range of \(-29.5_{\text{oo}}\) to \(-29.7_{\text{oo}}\) (Fig. 2). Changes of this magnitude were not observed in an individual storm unit during pit and core studies on extended oversnow traverses on the Greenland ice sheet (Benson 1962). The present paper is our attempt to explain this change in isotopic values in what was a homogeneous stratigraphic unit deposited in a single storm.

The storm can be seen in nearby surface and upper-air measurements. Figure 3 shows the mean sea level pressure and hourly precipitation rate at Cordova and Yakutat for the period 6–11 August 1980. A large drop in sea level pressure occurred during this period, with the minimum occurring at both sites late on 9 August. The minimum pressure was lower at Cordova, as was the magnitude of the pressure drop. The onset of precipitation was earlier at Cordova, occurring around 0400 UTC 7 August [2000 local time (LT) 6 August]. The precipitation started approximately 12 h later at Yakutat [1600 UTC (0800 LT) 7 August]. At Cordova, there appeared to be two pulses of heavy precipitation, one that peaked at 1400 UTC (0600 LT) and the other at 0000 UTC 8 August (1600 LT 7 August). Both of these peaks were also observed at Yakutat with the aforementioned lag of approximately 12 h. There were also precipitation events at Cordova and Yakutat on 9 and 10 August that were uncorrelated as to timing and magnitude and were not related to the event under

![Figure 2: Depth (cm) vs $\delta^{18}O$ (%o) for the snowfall that fell on Mount Wrangell on 7 Aug 1980.](image-url)
consideration. The accumulation of precipitation at Cordova on 7 August, that is, from 0000 to 2359 LT, is shown in Fig. 4a. During this event, approximately 50 mm of precipitation fell. Assuming a 10:1 ratio between snowfall and the water equivalent, this value is consistent with the observed snowfall on Mount Wrangell. Assuming that the rate of accumulation at Mount Wrangell was similar, the reconstructed time series of $\delta^{18}O$ during the 7 August event is shown in Fig. 4b. As one can see, there is a tendency toward more depleted values of $\delta^{18}O$ during the event with a large change occurring between 1300 and 1700 LT. Comparison with the Cordova precipitation time series (Fig. 3b) shows that this transition is approximately aligned with the period of reduced precipitation in between the two pulses of heavier precipitation. In other words, the less depleted $\delta^{18}O$ values were associated with the earlier precipitation maximum, with the more depleted values being associated with the later maximum.

Figure 5 shows the time series of temperature and moisture transport at 3000 and 4000 m MSL for the period 6–11 August 1980 derived from radiosonde data at Yakutat. At both heights during this event, the temperature (Fig. 5a) was approximately constant. The moisture transport at both heights shows a broad peak through this period with a maximum around 1200 UTC 8 August. There are secondary maxima at 3000 m MSL around 0000 UTC 7 and 10 August. Figure 6 shows the vertical profile of the moisture transport derived from the Yakutat sounding at 0000 and 1200 UTC 7 and 8 August 1980. For all the soundings, the maximum in moisture transport occurs at around 3000 m MSL, with the largest transport occurring at 1200 UTC 8 August. There is also evidence of a secondary peak at approximately 2000 m.
4. Diagnostics

Figure 7 shows the sea level pressure, 10-m wind, and precipitation rate fields from NARR at 0000 UTC 6–9 August 1980. On 6 August (Fig. 7a), two synoptic-scale weather systems were present in the region, a high pressure system over the northwestern Pacific with a center close to 50°N, 150°W and a low pressure system over the Bering Strait with a center close to 57°N, 175°W. The evolution of the flow in the region can be seen to be the result of the movement and interaction of the two circulation systems. At 0000 UTC 6 August (Fig. 7a), the two systems had just begun to interact in the vicinity of the Alaskan Peninsula. In this region, two distinct regions of enhanced precipitation were present, one to the south of the peninsula along the northern side of the high pressure system and the other to the north of the peninsula along the leading edge of the low pressure system. By 0000 UTC 7 August (Fig. 7b), the low pressure system had moved eastward and intensified resulting in an enhancement of the pressure gradient along the Alaskan Peninsula. At this time, there was a band of precipitation between the two systems that extended northward into Alaska. There was some evidence of orographic modulation of the precipitation along the Alaska Range as well as precipitation in the vicinity of Cordova. Twenty-four hours later at 0000 UTC 8 August (Fig. 7c), both systems had moved eastward resulting in a clockwise rotation to the band of enhanced pressure gradient that lead to a more zonal orientation.
to the flow. Because of this change, the heaviest precipitation associated with the interaction of the two systems was at this time occurring along the Gulf of Alaska coast in the vicinity of Cordova and Yakutat. By 0000 UTC 9 August (Fig. 7d), falling pressures along the Alaskan Peninsula as well as the continued eastward movement of the two parent systems resulted in a southeastward movement of the band of enhanced flow so that it was now situated between Cordova and Yakutat.

Figure 8 shows the precipitable water from NARR at 0000 UTC 6–9 August 1980. The evolution of this field again shows the influence of the two weather systems whose interaction has been noted above. At 0000 UTC 6 August (Fig. 8a), the presence of the two separate moisture streams in the vicinity of the Bering Sea and Alaskan Peninsula was evident. The highest values of precipitable water, in excess of 35 mm, were associated with the subtropical moisture stream situated to the south of the peninsula. The largest values of this field in the high-latitude stream, in excess of 30 mm, were situated over the western Bering Sea. At this time, there was a narrow region of low precipitable water that was situated between these two maxima. Over western Alaska, there was evidence of the merging of the moisture streams associated with the two weather systems. The leading edge of this moisture pulse at this time was situated just to the west of Cordova. By 0000 UTC 7 August (Fig. 8b), the two moisture streams present in the vicinity of the Alaskan Peninsula had merged into one that had become more elongated as the result of the movement of the two weather systems in the region of interest (Fig. 7b). Over the next 48 h (Figs. 8c,d), this moisture stream interacted with the high topography of the Western Cordillera, resulting in a sharp gradient in precipitable water along the coastline of the Gulf of Alaska in the vicinity of Cordova and Yakutat. There was also evidence of a southward recirculation of some of this moisture because of the presence of the high pressure system (Figs. 8c,d).

Figure 9 shows the vertically integrated water vapor flux from NARR at 0000 UTC 6–9 August 1980. Again, the picture presented by this field is consistent with the results presented above. In particular, the presence of two distinct moisture pulses at 0000 UTC 6 August (Fig. 9a), one of a subtropical origin and the other of a high-latitude origin, that merged over the next 24 h (Fig. 9b) and subsequently were advected toward the Mount Wrangell region. Over the next 48 h (Figs. 9c,d), the moisture pulse reached this region and convergence occurred as a result of the interaction with topography. Of particular interest is the presence of transport into northwestern Canada that began on 8 August (Fig. 9c) and that was fully developed on 9 August (Fig. 9d). Given the topography in the region, it is clear that this transport is not occurring at the surface.
The details of this upper-level transport are provided in Fig. 10, which shows the moisture transport at 650 mb, the approximate height of Mount Wrangell, from NARR at 0000 UTC 6–9 August 1980. One can again see the separation of the two moisture streams at 0000 UTC 6 August (Fig. 10a), as well as their merging over the next 24 h and advection toward Mount Wrangell (Fig. 10b). One can now more clearly see that the pulse of moisture that reached Mount Wrangell on 7 August was associated with the subtropical stream along the leading edge of the low pressure system, while the moisture that arrived later in the day and into 8 August was associated with the merged moisture stream. The advection of the moisture into northwestern Canada on 8 and 9 August is also apparent (Figs. 10c,d).

In Fig. 11, we show 144 h (6 day) back trajectories for air parcels that were situated at the summit of Mount Wrangell at 0000 and 1200 UTC 7 August as well as at 0000 UTC 8 August. Also shown is the monthly mean surface temperature for August 1980 from the NCEP–NCAR reanalyses. The back trajectories were also computed with NARR and during the period of interest; the average horizontal and vertical root-mean-square differences between the two were 130 km and 800 m, respectively. The back trajectories clearly show the influence of the two distinct pathways identified in Figs. 7–10. The 0000 UTC 7 August back trajectory was situated over the subtropical eastern Pacific on 1 August at a height of approximately 3 km. Over the next day, it moved southward and descended to approximately 2 km as part of an anticyclonic pathway that over the subsequent 5 days directed it toward Mount Wrangell while undergoing a gradual ascent. In contrast, the 1200 UTC 7 August and 0000 UTC 8 August back trajectories both were situated over northeastern Asia 6 days earlier. Both trajectories were initially displaced northward as a result of a low pressure system over the Sea of Okhotsk (not shown). Subsequently, both trajectories were displaced southward and then directed toward the Mount Wrangell site as a result of the cyclonic circulation associated with the low pressure system over the Bering Strait.

Finally, Fig. 12 shows the δ18O in precipitation at Mount Wrangell as calculated by the Rayleigh distillation model described in section 2. These results are based on the back trajectories as calculated from the NCEP–NCAR reanalyses fields at a 6-h resolution over the 48-h period from 1200 UTC 6 August to 1200 UTC 8 August 1980. The model results show a transition from less depleted δ18O values prior to 0000 UTC.
7 August 1980 to more depleted values after that time, which is the result of a shift from southerly to easterly flow, seen in Fig. 7. The shift is consistent with the hypothesis that there were two distinct moisture streams, an earlier stream of subtropical origin and a later stream of extratropical origin, which contributed to the precipitation that fell on Mount Wrangell on 7 August 1980. In addition, our Rayleigh-based estimate of the final isotopic composition is of the same magnitude as that observed.

5. Discussion

The isotope thermometer, the use of spatial gradients in temperature and δ¹⁸O to reconstruct temporal changes in temperature at an ice core site, is an important tool in paleoclimate research (Jouzel et al. 1987, 1997; Boyle 1997). However, evidence exists that nonlocal atmospheric processes such as changes in atmospheric circulation or moisture source changes can complicate the interpretation of the δ¹⁸O record at a given site (Werner et al. 2000; Holdsworth 2001; Kavanaugh and Cuffey 2002; Bradley et al. 2003), but clear case studies where these nonlocal processes play a role in determining the δ¹⁸O record are rare.

In this paper, we describe one such event that occurred during a storm on Mount Wrangell in south-central Alaska, during which the summit temperature was approximately constant (Fig. 5). However, the δ¹⁸O variation that occurred during the storm exceeded half the annual variation typical of the region (Fig. 2).

Surface and upper-air data from nearby stations, back trajectories, and NARR were used to diagnose the changes in atmospheric circulation that occurred during this event and that, as we argue, are responsible for the large variation in δ¹⁸O record. Most importantly, we have presented evidence that there were two distinct moisture streams that arrived at Mount Wrangell during the storm. Evidence for this includes two distinct maxima in the precipitation at nearby surface stations (Fig. 3). In addition, the NARR fields during the event indicate the presence of two distinct moisture plumes (Figs. 7–10). The back trajectories indicate that these two plumes had very different source regions (Fig. 11). The back trajectory during the early part of the storm, at 0000 UTC 7 August, had its origin over the subtropical eastern North Pacific, while those 12 and 24 h later originated over northeastern Asia. The first subtropical plume would, because of the higher temperatures in its source region, have been less depleted in δ¹⁸O. The
second would have been more depleted in $\delta^{18}O$ as a result of the lower temperatures in northeastern Asia. This change in the characteristics of the incoming moisture would lead to the observed variation in $\delta^{18}O$. The modeled $\delta^{18}O$ distillation along the back trajectories during the event is broadly consistent with this interpretation (Fig. 12).

Pfahl et al. (2012) recently analyzed one of the extratropical storms sampled by Gedzelman and Lawrence (1990) using an isotopically equipped regional climate model to interpret a similarly large isotopic shift in precipitation over the eastern United States. Given the magnitude of the observed isotopic shift during the event, the 1980 case study for Mount Wrangell considered here is another strong candidate for more detailed analysis, given the importance of the region for reconstructing North Pacific climate variability using isotopic proxies.

In that context, this case study supports the hypothesis that $\delta^{18}O$ data in ice cores from the Gulf of Alaska region contain information on the moisture source region with less depleted values being associated with a warmer subtropical source and more depleted values being associated with a colder high-latitude source. This study is consistent with the analysis of the Mount Logan ice core that indicated its snow accumulation record contained an ENSO signature as well as the associated tropical Hadley and Walker circulations (Moore et al. 2001, 2002a,b, 2004). A case study of an extreme weather event on Mount Logan also suggested that the sub-tropics, rather than local evaporation over the Gulf of Alaska, was the source for the snow that fell during the event (Moore and Holdsworth 2007).

With respect to the stable isotopes records from the region, two independent ice cores from Mount Logan both show a significant drop in $\delta^{18}O$ during the middle of the nineteenth century (Holdsworth et al. 1992; Fisher et al. 2004). Field et al. (2010) used a GCM equipped with isotope transport physics to show that less depleted levels of $\delta^{18}O$ in the Gulf of Alaska region were associated with a deeper Aleutian low as a result of the stronger southerly flow that advected moisture from warmer source regions toward the mountain, thereby providing an explanation for the observed drop in $\delta^{18}O$ that occurred in the middle of the nineteenth century. Our results support this idea and, like Field et al. (2010), are in disagreement with the conclusions reached by Fisher et al. (2004), who used an empirical model with prescribed moisture transport characteristics to argue that an intensification of the Aleutian low would result in depleted levels of $\delta^{18}O$ as a result of the greater distance traveled by the air parcels from their subtropical source region to the Gulf of Alaska region. The back trajectories for this case (Fig. 11) indicate that the distance traveled from the subtropical and extratropical sources is similar.

In closing, the stable isotopic composition of water in ice cores is an important source of information on past climate variability with the underlying assumption that there exists an empirical relationship between the concentration for these stable isotopes and a specified...
local temperature at the ice core site. There are, however, nonlocal processes, such as a change in source region or a change in the atmospheric pathway, that have been proposed to impact the stable isotope signal, thereby complicating its use as a proxy for temperature. However, case studies that explicitly demonstrate the impact of these nonlocal processes are rare. In this paper, we investigated the importance of these nonlocal processes through the analysis of the synoptic-scale circulation during a snowfall event at the summit of Mount Wrangell in south-central Alaska. During this event there was, over a 1-day period in which the local temperature at the ice core site. There are, how-

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