The 25–27 May 2005 Mount Logan Storm. Part I: Observations and Synoptic Overview

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ABSTRACT

In late May 2005, three climbers were immobilized at 5400 m on Mount Logan, Canada’s highest mountain, by the high-impact weather associated with an extratropical cyclone over the Gulf of Alaska. Rescue operations were hindered by the high winds, cold temperatures, and heavy snowfall associated with the storm. Ultimately, the climbers were rescued after the weather cleared. Just prior to the storm, two automated weather stations had been deployed on the mountain as part of a research program aimed at interpreting the climate signal contained in summit ice cores. These data provide a unique and hitherto unobtainable record of the high-elevation meteorological conditions associated with an intense extratropical cyclone. In this paper, data from these weather stations along with surface and sounding data from the nearby town of Yakutat, Alaska, satellite imagery, and the NCEP reanalysis are used to characterize the synoptic-scale conditions associated with this storm. Particular emphasis is placed on the water vapor transport associated with this storm.

The authors show that during this event, subtropical moisture was transported northward toward the Mount Logan region. The magnitude of this transport into the Gulf of Alaska was exceeded only 1% of the time during the months of May and June over the period 1948–2005. As a result, the magnitude of the precipitable water field in the Gulf of Alaska region attained values usually found in the Tropics. An atmospheric moisture budget analysis indicates that most of the moisture advected into the Mount Logan region was preexisting water vapor already in the subtropical atmosphere and was not water vapor evaporated from the surface during the evolution of the storm. Implications of this moisture source for understanding of the water isotopic climate signal in the Mount Logan ice cores will be discussed.

1. Introduction

Mount Logan, Canada’s highest mountain, is located in the heavily glaciated Saint Elias Mountains of the Yukon Territory just to the east of the Gulf of Alaska (Figs. 1 and 2). The mountain is situated in a region of significant climatological importance. For example, it is located at the end of the major North Pacific storm track (Blackmon 1976; Hoskins and Hodges 2002) along the main atmospheric pathway by which water vapor enters the Gulf of Alaska (Newell and Zhu 1994; Lackmann et al. 1998; Smirnov and Moore 2001). Much of this moisture rains out on the upwind side of the Western Cordillera leaving only upper-level moisture available for transport into northwestern North America (Asuma et al. 1998; Lackmann et al. 1998; Smirnov and Moore 1999). The extreme height of Mount Logan [5959 m above sea level (ASL)] is such that it intercepts much of this upper-level moisture (Moore et al. 2003).

An ice core containing a 300-yr record of annual snow accumulation extracted from the summit region of Mount Logan contains a number of climate signals associated with El Niño–Southern Oscillation, the Pacific decadal oscillation, the Pacific–North America teleconnection, as well as the Walker and Hadley circulations (Moore et al. 2001, 2002a,b, 2003, 2004). As discussed in Holdsworth et al. (1992) and Moore et al. (2003), many of these signals are not present in the precipitation record at Yakutat, Alaska (Fig. 1), located at sea level only 125 km from Mount Logan. It has been
proposed that this discrepancy is the result of the fact that the surface and upper-level moisture transports in the region are only weakly coupled (Moore et al. 2001, 2003). The concept of two distinct moisture streams is consistent with surface snow pit samples from various elevations on Mount Logan (Holdsworth et al. 1991). These data show a discontinuity in the oxygen isotope ratio with elevation that suggests a different source region for the precipitation that falls at low elevations as compared to that at higher elevations.

Quantitative information on the mechanism or mechanisms through which these tropical climate signals occur in the ice core is at present still unclear. Extratropical cyclones are known to be associated with moisture transport in the region (Asuma et al. 1998; Lackmann et al. 1998; Smirnov and Moore 1999, 2001) and so it is reasonable to assume that the climate signals arise as a result of the modulation in the track, intensity, and moisture source region of these systems by larger-scale atmospheric circulations, such as ENSO (Shapiro et al. 2001). To improve our understanding of these mechanisms, as well as details of the vertical structure of the moisture transport associated with Gulf of Alaska cyclones, a network of automatic weather stations (AWS) was established on Mount Logan in May of 2005. These new systems complement existing AWS established in 2000–01 by a consortium coordinated by the Geological Survey of Canada to provide high-frequency meteorological data (wind speed and direction, humidity, pressure, and temperature) at various elevations on the mountain.

During the installation of the network, an approaching extratropical cyclone resulted in a period of particularly severe weather on Mount Logan on 25–26 May 2005. The plight of three descending climbers trapped by the storm on the Arctic Institute of North America (AINA) pass (5400 m ASL) was the focus of attention throughout North America (Bjarnason and Jardine 2005; D’Oro 2005; Mickleburgh 2005). Observations by Gerald Holdsworth, who had just established the AWS at the King Col site at 4130 m ASL, indicate that the weather changed around noon (local time) on the 25 May when snow started to fall and whiteout conditions commenced. The temperature was approximately −12°C at 1700 local standard time. The wind speed increased late on 25 May and remained high throughout the night with peak wind speeds estimated to be on the order of 15 m s⁻¹. Temperatures also increased to approximately −5°C during this period. The winds remained high and gusty on 26 May and temperatures dropped to −15°C during the night of 26 May. At 5400 m ASL, the winds on 26 May were also gusty, with speeds estimated to be in excess of 30 m s⁻¹ (L. Billy 2005, personal communication). Conditions improved on 27 May allowing for the trapped climbers to be rescued late in the day. During the storm, approximately 48 cm of low-density snow accumulated at the King Col site. Using a standard density of 0.1 g cm⁻³, this corresponds to approximately 48 mm of water. Similar amounts of low-density snow also fell at 5400 m ASL. At Yakutat, 41 mm of rain fell on 26 May with an additional 12 mm on 27 May.

In this paper, we will use data from two AWS along with surface and sounding data from Yakutat, Alaska, satellite imagery, and the National Centers for Environmental Prediction (NCEP) reanalysis (Kalnay et al. 1996; Kistler et al. 2001) to characterize the synoptic-scale conditions associated with this storm. Particular emphasis is placed on the water vapor transport associated with this storm and the source region for the precipitation that fell near the summit.
2. Synoptic overview

The evolution of the storm is depicted in Fig. 3, which shows Moderate Resolution Imaging Spectroradiometer (MODIS) true-color composite satellite imagery from 23 to 26 May 2005. In particular, the images show the evolution of the system from a weak region of low pressure centered at 38° N, 152° W on 23 May (Fig. 3a) to a mature extratropical cyclone over the Gulf of Alaska centered at 54° N, 144° W on 26 May, with a well-developed comma-shaped cloud field extending southward from the low’s center (Fig. 3d). The southerly flow ahead of the cold front was associated with the warm conveyor belt (WCB) that transports heat and momentum poleward (Harrold 1973; Semple 2003).

Figure 4 shows the evolution of the sea level pressure, 10-m wind, and surface latent heat flux throughout the period of interest from the NCEP reanalysis. The convention used is that positive latent heat fluxes are associated with evaporation from the surface (Moore and Renfrew 2002). At 1200 UTC 23 May, one can see the low pressure center and the concomitant cyclonic circulation situated near 38° N, 150° W. The system did not undergo an appreciable deepening as it moved northward. However, the presence of a region of high pressure to the east did result in large pressure gradients producing surface wind speeds on the order of 15 m s⁻¹. On 25 and 26 May (Figs. 4c,d), one can see evidence of a deeper low pressure system approaching the Gulf of Alaska from the west. However, this system...
became stalled just north of the Aleutian Islands. With regard to the latent heat flux field, one can see that the largest fluxes occur along the southern flanks of the regions of high pressure in the subtropics. Presumably in these regions, the advection of colder and drier air from the high latitudes allows for a large transfer of moisture from the ocean’s surface. At higher latitudes, the latent heat flux was significantly smaller and on occasion was negative indicating that condensation was occurring as warm and humid subtropical air came into contact with colder sea surface temperatures.

The upper-level flow associated with this storm is shown in Fig. 5. On 23 May, there was a weak upper-level short-wave trough present with an axis along 165°W (Fig. 5a). Over the next 3 days, the trough moved eastward amplified, extending into the subtropics (Figs. 5b–d). During this time, its orientation along with the positioning of the surface low was favorable for the long-range transport of subtropical moisture toward the Gulf of Alaska. In the Mount Logan region, temperatures on the 500-mb surface rose by approximately 10°C between 23 and 26 May as warmer air from the south was advected into the region.

The 6.7-mm brightness temperature from the Geostationary Operational Environmental Satellite (GOES) imager provides information on the water vapor in the upper troposphere between 500 and 200 mb (Soden and Bretherton 1993). In addition, given the large gradient in water vapor across the tropopause, this channel is also sensitive to the presence of tropopause folds (Wimmers et al. 2003; Wimmers and Moody 2004). Figure 6 shows this channel from the GOES West satellite throughout the period of interest. The moisture stream associated with the developing system on 23 May can be seen in Fig. 6a, as well as the approaching upper-level trough. On subsequent days, the moisture’s movement is apparent as the system tracks northward and matures (Figs. 6b,c). Finally on 26 May (Fig. 6d), one
has a well-developed intrusion of upper-tropospheric water vapor extending from the subtropics to the Gulf of Alaska, as well as an adjacent region of low humidity that is indicative of the presence of the dry intrusion or tropopause fold.

We conclude this section with Fig. 7, which shows back trajectories for parcels that were situated in the Mount Logan region (60°N, 140°W) at 1200 UTC 26 May. Trajectories are 96 h in length and are shown for parcels that ended up at 500, 2000, 3000, and 5000 m ASL. The trajectories were computed using the Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) model (Draxier and Hess 1998). The source region for the air parcel that ended up at 500 m on Mount Logan is over the Gulf of Alaska. This parcel did not experience any significant vertical movement. In contrast, the air parcels that ended up at 2000, 3000, and 5000 m have more complex trajectories and underwent large vertical displacements. For example, the air parcel that ended up at 5000 m on Mount Logan originated in the subtropical North Pacific at 2000 m near 30°N, 140°W. The 3000-m trajectory had a similar path to that at 5000 m, while the air parcel that ended up at 2000 m underwent a descent from approximately 2500 m and had a source region over the extratropical North Pacific near 45°N, 150°W. Also shown in Fig. 8 is the relative humidity of the air parcels along the various trajectories. There is a distinct difference in the evolution of the humidity along the 500- and 2000-m trajectories as compared to that along the 3000- and 5000-m ones. In particular, the air parcels along the two lower-level trajectories underwent a dramatic moistening over the last 12–24 h of their journey. This is quite different than what happened along the two upper-level trajectories, where there was a moistening from 24 May onward.
3. In situ observations of the storm

During this event, two AWS on Mount Logan were operational and as a result they provide a unique dataset with which to document the meteorological conditions on the mountain associated with this weather system. One of the stations was situated on a rocky outcrop close to the Ogilvie Glacier ($60^\circ37'\text{H}11032^\circ$, $140^\circ47'\text{H}11032^\circ$; elevation 2929 m). This system measured wind speed and direction, pressure, specific humidity, and temperature. The other system was situated at the King Col site ($60^\circ35'\text{H}11032^\circ$, $140^\circ36'\text{H}11032^\circ$; elevation 4130 m). This system measured pressure and specific humidity and temperature. Both systems were supplied by Campbell Scientific Canada. Figure 8 shows photographs of the locales for these two AWS. For this paper, we will use hourly averaged values of the various meteorological fields. To provide a context for the AWS measurements, we will also make use of observations from the National Weather Service Office at Yakutat ($59^\circ39'\text{N}, 139^\circ37'\text{W}$, elevation 12 m). The surface data at this location are available as 3-hourly values, while sounding data are available daily at 0000 and 1200 UTC. Figure 1 gives information on the relative locations of Mount Logan and Yakutat. The AWS are approximately 120 km from Yakutat.

The time series of the various meteorological fields from the three locations is shown in Fig. 9. With regard to the pressure field, the anomaly time series (Fig. 9a) show that the amplitude of the pressure fall associated with the system was highest at sea level and diminished with height. The timing of the maxima in pressure was coincident at all three locations, while that of the minima associated with the storm was lagged at higher elevations by approximately 12 h. The temperature time series (Fig. 9b) indicates that the fluctuations are typically in phase at the three sites with the amplitude tending to decrease with height. All three stations experienced a warming between 25 and 26 May that was associated with the approaching low pressure system. Temperatures continued to rise on Mount Logan until 27 May. This may have been associated with the second
low pressure system that was entering the region (Figs. 4 and 5). With regard to specific humidity, the most significant feature at all three sites was the pronounced moistening that was associated with the arrival of the storm on 26 May (Fig. 9c). The magnitude of this change was largest at Yakutat. On 27 May, all sites experienced a pronounced reduction in the specific humidity. This was most likely associated with the arrival of the dry slot (Fig. 6d). In addition, the King Col site showed another dramatic moistening near 1800 UTC 27 May that did not occur at the Ogilvie Glacier site. Finally, the wind speed time series (Fig. 9d) clearly shows that there is little correlation between the Ogilvie Glacier and Yakutat sites. In addition, wind speeds at the Ogilvie Glacier site are considerably higher than those at Yakutat. Indeed, maxima in wind speeds at Ogilvie Glacier near 1200 UTC 24, 1200 UTC 25, 000 UTC 26, and 1200 UTC 27 May are associated with minima in wind speeds at Yakutat.

Yakutat sounding data from the height of the storm, 1200 UTC 26 May, are shown in Fig. 10. Wind speeds at the 3000- to 5000-m levels were on the order of 20 to 25 m s$^{-1}$ and were considerably higher than the hourly averaged values observed on Mount Logan. In contrast, as described in the introduction, climbers on the mountain at these levels observed peak wind speeds to be on
the order of 15 to 30 m s\(^{-1}\). This may be the result of the observed gusty nature of the wind that may represent the complex and highly turbulent nature of the interaction between the large-scale wind field and topography (Wood 2000). Also shown in Fig. 10 is the magnitude of the water vapor transport, defined as

\[ q = qV, \]  

where \( q \) is the specific humidity and \( V \) is the horizontal wind. The profile shows the presence of two maxima in the transport, one near 1.5 km and a larger one near 3.5 km.

4. The hydrometeorology of the storm

We conclude our description of the characteristics of this storm with a discussion of the water vapor transport associated with it. We will emphasize the synoptic-scale characteristics of this transport as depicted in the NCEP reanalysis. Our starting point will be the conservation of water vapor in an atmospheric column (Peixoto and Oort 1992; Smirnov and Moore 2001). If one ignores the flux of water vapor across the upper boundary of the column, diffusion, and the liquid and solid phase transports of water, then conservation of water vapor requires that

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

where \( P \) is the precipitation rate, \( E \) is the evaporation rate (both at the surface), \( W \) is the precipitable water

\[ W = \frac{1}{g} \int_{0}^{p_s} q \, dp, \]  

and \( \mathbf{Q} \) is the vertically integrated water vapor transport

\[ \mathbf{Q} = \frac{1}{g} \int_{0}^{p_s} q \, dp. \]  

In the above integrals, \( p \) is the pressure with \( p_s \) being the surface pressure and \( g \) is the acceleration due to gravity.

Problems have been identified in the NCEP reanalysis with all terms in the water vapor conservation Eq. (2). For example, the reanalysis does not assimilate satellite-based retrievals of water vapor (Trenberth and
As a result, there is an underestimation in the precipitable water field over the tropical ocean Eq. (3) in the reanalysis as compared to retrievals of the same field from the Special Sensor Microwave Imager (SSM/I) instrument (Wentz 1997; Trenberth and Guillemot 1998). Errors have also been identified in the latent heat flux, that is, evaporation, field in the reanalysis, which lead to an overestimate in the magnitude of this field in conditions characterized by high wind speeds and large air-sea temperature differences (Moore and Renfrew 2002; Renfrew et al. 2002). The reanalysis also underestimates the magnitude of the precipitation over the oceanic tropical interconvergence zones (Trenberth and Guillemot 1998). In addition, the terms in Eq. (2) are a mixture of analyzed fields (pressure, wind speed, specific humidity) and short-term forecast fields (precipitation and evaporation) in the NCEP reanalysis.

Notwithstanding these issues, the hydrometeorological fields from the NCEP reanalysis have been used in a number of studies. For example, Mo and Higgins (1996) compared the atmospheric moisture fields in the NCEP reanalysis to those in the National Aeronautics and Space Administration (NASA) Data Assimilation Office (DAO) reanalysis. They found overall agreement between the two reanalyses, although there were some regional differences. Trenberth (1999) used the hydrometeorological data from the NCEP reanalysis to examine the role of advection and evaporation in the recycling of atmospheric moisture and found that for a typical marine extratropical cyclone approximately 70% of the storm’s precipitation came from water vapor already in the atmosphere at the time of its formation. Cohen et al. (2000) investigated the interannual variability in the meridional component of the vertically integrated transport of the atmospheric water vapor in the NCEP reanalysis. They found that the zonal mean of this field was similar to that derived from the radiosonde-based estimate of Peixoto and Oort (1992) but that the magnitudes were larger. Allan et al. (2002) compared the NCEP reanalysis precipitable water field over the Tropics to that from the NASA Water Vapor Project (NVAP) water vapor dataset (Randel et al. 1996) that is a blend of radiosonde and satellite data. Apart from a systematic bias between the two, Allan et al. (2002) concluded that precipitable water vapor field from the NCEP reanalysis was in “excellent agreement with observations.” There is clearly some uncertainty with regard to the quality of the hydrometeorological fields in the NCEP reanalysis. Nevertheless, it represents the only readily available dataset that allows one to compute all the terms in the water conservation Eq. (1) for this event.

With these caveats in mind, we show in Fig. 11 the precipitable water Eq. (3) from the NCEP reanalysis during the period of interest. On 23 May (Fig. 11a), one can see a clear meridional gradient in the field with larger values in the Tropics. The maxima, near 35°N, 150°W, on this day was associated with the nascent cyclone identified in Figs. 3a and 4a. It is interesting to note there is a pronounced minimum in the latent heat flux field in this region at this time (Fig. 4a) suggesting that this moisture anomaly was present prior to the formation of the disturbance. On subsequent days, the northward movement and intensification of the low pressure system resulted in an elongation and northward extension of this anomaly leading to values of precipitable water in the Gulf of Alaska region as high as 25 mm on 26 May (Fig. 11d). The southward trans-
port of dry air behind the low resulted in the development of minima in the precipitable water field of 10 mm as far south as 30°N on 25 May (Fig. 11c). An examination of the statistics of the 6-hourly precipitable water field from the NCEP reanalysis during the months of May and June from 1948 to 2005 indicate that anomalies of this magnitude occur less than 1% of the time.

As a check of the precipitable water from the NCEP reanalysis, we show in Fig. 12 the same field retrieved from the SSM/I dataset (Wentz 1997) during the period of interest. A comparison of the two figures indicates, apart from the finescale structure present in the SSM/I precipitable water field that is absent from the coarser resolution NCEP reanalysis field, there is good agreement.

Figure 13 shows the vertically integrated water vapor transport Eq. (3) from the NCEP reanalysis during the period of interest. The figure shows the northward advection of a pulse of moisture from the subtropics on 23 May (Fig. 13a) into the Gulf of Alaska region on 26 May (Fig. 13d). This advection was associated with the track of the low pressure system identified in Figs. 3 and 4 and resulted in the extension of the filamentary precipitable water feature into the Gulf of Alaska region (Figs. 11 and 12). An examination of the statistics of the 6-hourly vertically integrated water vapor transport from the NCEP reanalysis during the months of May and June from 1948 to 2005 indicates that the magnitude of the transport into the Gulf of Alaska region associated with this storm occurs less than 1% of the time.

Figure 14 shows the precipitation rate and sea level pressure from the NCEP reanalysis during the period of interest. As the low pressure system under investigation intensifies from 23 to 26 May, its precipitation field also
becomes larger in magnitude with the highest values to the north and east of the low. On 26 May, the precipitation rate in the Gulf of Alaska region attained values in excess of 2 mm h\(^{-1}\) (Fig. 14d).

Given the characteristics of the NCEP reanalysis and the systematic errors that exist in all the hydrometeorological fields, one cannot expect that water vapor is conserved in the dataset (Trenberth and Guillemot 1998). It is nevertheless instructive to attempt to diagnose the magnitude of the various terms in Eq. (1). Figures 15 and 16 show the rate of change of precipitable water, precipitation–evaporation, and the divergence of the vertically integrated water vapor transport at 1200 UTC 23 and 26 May 2005. On 23 May (Fig. 15a), there exists a dipole in the rate of change of precipitable water field with the positive pole near 40°N, 140°W and the negative pole near 38°N, 170°W. Examination of the precipitation–evaporation field at this time (Fig. 15b) indicates that in the vicinity of the positive pole, there was a net flux of water out of the atmosphere with the opposite occurring in the vicinity of the negative pole. The divergence of the vertically integrated water vapor transport has a tripolar structure with a region of convergence near 40°N, 140°W and regions of divergence near 38°N, 170°W and 28°N, 140°W. This suggests that at this time in the storm’s evolution, the developing anomalies in the precipitable water field, the filament of high values of \(Q\) extending northward near 40°N, 140°W and the minima in \(Q\) near 35°N, 160°W (Figs. 11a,b), are the result of the convergence/divergence in the integrated water vapor transport field rather than surface fluxes.

On 26 May, there are two dipoles in the rate of change in the precipitable water field (Fig. 16a). There is a meridional dipole along 140°W that is associated with the storm under investigation, as well as a zonal
dipole centered near 40°N, 170°W that is associated with the cyclone approaching the Gulf of Alaska from the west (Figs. 4c,d). With regard to the storm under investigation, the meridional dipole indicates that there is an increase in the precipitable water in the vicinity of Mount Logan and an elongated region, collocated with the filamentary structure in Fig. 11d, extending southward to the Hawaiian Islands where there is a decrease in precipitable water. At this time, the precipitation-evaporation field is positive in the vicinity of Mount Logan indicating that this region is a sink for atmospheric water vapor. As was the case, on 23 May, the divergence in the vertically integrated water vapor transport field (Fig. 16c) tends to compensate for the changes in the precipitable water field.

5. Summary

The characterization of the weather in a particular mountainous region of course requires in situ data. In this regard, the 26 May 2005 event on Mount Logan provides an excellent case study as two weather stations were deployed on the mountain just prior to the onset of the high-impact weather. The weather stations were deployed as part of an initiative to understand the climate signals contained in an ice core extracted from the summit region of Mount Logan (Holdsworth et al. 1992; Moore et al. 2002a,b, 2004). These data provide a unique and hitherto unobtainable record of the high-elevation meteorological conditions associated with an extratropical cyclone in the Gulf of Alaska region. They were used along with surface and sounding data from the nearby town of Yakutat, Alaska, satellite imagery, and the NCEP reanalysis to characterize the synoptic-scale conditions associated with this storm.

This particular storm evolved out of a poorly organized disturbance along a trailing cold front over the subtropical North Pacific on 22 May. Over the next 4 days, the system intensified and moved northward.
reaching the Mount Logan region on 26 May as a well-defined extratropical cyclone (Figs. 3 and 4). The system was associated with a well-defined upper-level trough and a tropopause fold (Figs. 5 and 6).

Back trajectories suggest that 2000–3000 m appear to be the approximate height at which there exists a separation in trajectory characteristics, with those ending up at lower heights in the Mount Logan region tending to have a source near the surface in the Gulf of Alaska region, while those at higher elevations tend to have a more distant source region (Fig. 7). The air parcels that end up at higher elevations on Mount Logan on 26 May for the most part have meridionally oriented trajectories that rise as the air parcels travel from the subtropics to the Gulf of Alaska region. Such trajectories are what one would expect for parcels moving along the cold frontal zone in a typical extratropical cyclone. In contrast, the air parcels that end up at lower elevations have cyclonic trajectories with a nearby source region. These air parcels did not undergo any significant vertical motion. Such trajectories are consistent with the low-level cyclonic circulation associated with an extratropical cyclone. The relative humidity of the air parcels along the lower-level trajectories also had a markedly different evolution as compared to that of the upper-level trajectories. In particular, the low-level air parcels underwent a rapid moistening during the final 12–24 h of their journey, while the upper-level parcels underwent a more gradual moistening over most of their movement from the subtropics to the Mount Logan region. This suggests that different mechanisms are responsible for the moistening of the two sets of air parcels.

The automatic weather station data from the Mount Logan sites indicate that the storm was associated with a drop in pressure, an increase in temperature, an increase in specific humidity, and an increase in wind speed (Fig. 10). In comparison with data from Yakutat,
The magnitude of the pressure drop was reduced on Mount Logan by approximately 50%. There was also a slight phase lag in the timing of the pressure minima on Mount Logan that is consistent with a system that tilts westward with height. Other observations of the storm from the Mount Logan AWS include a dramatic drop in specific humidity after its passage, which may be the result of the intrusion of dry stratospheric air associated with a tropopause fold (Figs. 6 and 7). Wind speeds during the storm were also higher on Mount Logan than in Yakutat (Fig. 9). Sounding data from Yakutat indicated the presence of two distinct maxima in the water vapor transport field (Fig. 10).

The movement and evolution of the cyclone resulted in a filamentary intrusion, characterized by tropical values of precipitable water, that extended into the Gulf of Alaska region (Figs. 11 and 12). Based on the NCEP reanalysis dataset, values of the precipitable water field in the Gulf of Alaska region as high as those found on 26 May occur less than 1% of the time in May and June. The intrusion was associated with a pulse of water vapor that was transported from the subtropics to the Gulf of Alaska region (Fig. 13). An analysis of the sources and sinks of precipitable water suggests that this filamentary intrusion was primarily the result of the convergence of preexisting water vapor in the atmosphere associated with a pulse of moisture that was transported northward by the cyclone (Figs. 15 and 16). The surface flux of water, precipitation minus evaporation, was for the most part positive indicating that the cyclone was losing moisture to the surface (Fig. 14). As a result, the evaporation of water from the surface...
makes only a minor contribution to this filament. This is consistent with Trenberth (1999) who argued that surface evaporation only contributes approximately 30% of the moisture that falls as precipitation in a typical marine extratropical cyclone.

6. Conclusions

In addition to the specifics of this case, the analysis presented in this paper has several implications for our knowledge of atmospheric water vapor transport, as well as for our understanding of climate expressions contained in ice cores. Numerous studies have highlighted the role that the vertically integrated water vapor transport field has in diagnosing the presence of large-scale streams of moisture, or “rivers,” in the atmosphere (Newell et al. 1992; Newell and Zhu 1994; Zhu and Newell 1994). This study along with others (Smirnov and Moore 1999, 2001) emphasizes that on a day-to-day basis, these moisture streams are highly localized in space and on these time scales are better characterized as “pulses.”

This paper has also shown that there are filamentary structures in the precipitable water field that may provide another way to diagnose the presence and structure of organized moisture streams in the atmosphere. With regard to the interpretation of the climate signal in the Mount Logan ice core, this work supports early studies that have suggested that the Tropics and subtropics are the source of the moisture that falls as snow high up on the mountain (Moore et al. 2001; Holdsworth and Krouse 2002; Moore et al. 2002b, 2003).
Back trajectories furthermore suggest that there exists a separation in the source region for air parcels that end up in the Mount Logan region with parcels above approximately 3000 m having a distant source, while those that end up in lower elevations have a more local source. The sounding data from Yakutat also indicated the presence of two local maxima in the water vapor transport field, one near the surface and the other near 3.5 km. This separation is consistent with the observed discontinuity in the isotopic ratio of oxygen with elevation that is observed on Mount Logan (Holdsworth et al. 1991; Holdsworth and Krouse 2002).

This paper serves to confirm the important role that extratropical cyclones play in providing the moisture that ultimately ends up in a given high-latitude ice core (Johnsen et al. 1989; Newell and Zhu 1994; Holdsworth and Krouse 2002). In addition, the water vapor budget study carried out in this work serves to emphasize the small role that evaporation associated with a particular cyclone plays in the water vapor transport toward a particular ice core site. This perspective is strikingly different from the commonly held view in the glaciology community that the stable isotope record in an ice core is to first order a function of the temperature difference between the ocean surface where the water vapor formed and the ice core site where the precipitation formed (Johnsen et al. 1989; Grootes 1995; Jouzel et al. 1997; Kavanaugh and Cuffey 2002). Rather, this study shows that what is of fundamental importance is to recognize that there is a large reservoir of water vapor in the tropical and subtropical atmosphere that can, through the action of an extratropical cyclone, form the filamentary structure that extends northward toward the ice core site. It is this pathway from tropical reservoir to ice core site that has to be modeled if we are to improve our understanding of the climate signal contained in the stable isotope record in the Mount Logan and other ice cores. Finally, this analysis does not address the important cloud microphysical processes that are of course important in the production of precipitation from the water vapor that has been transported to the Mount Logan region. This aspect of the problem will be addressed in subsequent work.

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