Analysis of Intense Poleward Water Vapor Transports into High Latitudes of Western North America

ALAIN ROBERGE, JOHN R. GYAKUM, AND EYAD H. ATALLAH
Department of Atmospheric and Oceanic Sciences, McGill University, Montreal, Quebec, Canada

(Manuscript received 8 August 2008, in final form 4 June 2009)

ABSTRACT

Significant cool season precipitation along the western coast of North America is often associated with intense water vapor transport (IWVT) from the Pacific Ocean during favorable synoptic-scale flow regimes. These relatively narrow and intense regions of water vapor transport can originate in either the tropical or subtropical oceans, and sometimes have been referred to as Pineapple Express events in previous literature when originating near Hawaii. However, the focus of this paper will be on diagnosing the synoptic-scale signatures of all significant water vapor transport events associated with poleward moisture transport impacting the western coast of Canada, regardless of the exact points of origin of the associated atmospheric river. A trajectory analysis is used to partition the events as a means of creating coherent and meaningful synoptic-scale composites. The results indicate that these IWVT events can be clustered by the general area of origin of the majority of the saturated parcels impacting British Columbia and the Yukon Territories. IWVT events associated with more zonal trajectories are characterized by a strong and mature Aleutian low, whereas IWVT events associated with more meridional trajectories are often characterized by an anticyclone situated along the California or Oregon coastline, and a relatively mature poleward-traveling cyclone, commonly originating in the central North Pacific.

1. Introduction

Intense precipitation during the cold season on the North American west coast is believed to often be caused by poleward-traveling extratropical cyclones (Lackmann and Gyakum 1999). The amount of water vapor and heat transported is so important that it may cause significant flooding in the mountains (Colle and Mass 2000; Neiman et al. 2002; Ralph et al. 2006). This is caused by the combination of intense orographic precipitation and fast snowmelt, which may also initiate mudslides (Lackmann and Gyakum 1999). This has an impact on various human aspects, such as the security and the economy of the local area, but also affects the hydrological and climate systems (Smirnov and Moore 1999, 2001). These moisture transport phenomena are characterized by elongated plumes of moisture extending from the tropics to northern latitudes (McGuirk et al. 1987, 1988; Iskenderian 1995). In fact, these plumes of moisture influence both seasonal climate anomalies, as well as the global water cycle (Ralph et al. 2004). Actually, by partitioning significant transient moisture fluxes from the ambient flow, Zhu and Newell (1998) came to the conclusion that almost all of the moisture transport between the tropics and higher latitudes occurs within filamentary structures of the type that we study in this paper.

It is helpful to understand the structure of the moisture flux to understand the behavior of these “atmospheric rivers” (Zhu and Newell 1998), and their consequences on northwestern North America. These storms transport plumes of concentrated moisture and heat content, and have been subject to many studies. However, the literature does not seem to agree on a common terminology for these plumes of moisture. Sometimes called Pineapple Express events (Lackmann and Gyakum 1999); they have also been termed moisture bursts (McGuirk et al. 1987), tropical intrusions, cloud bands, atmospheric rivers (Zhu and Newell 1998), moisture conveyor belts, tropical plumes, etc.

In their study of this phenomenon, Lackmann and Gyakum (1999) started with an investigation of flooding to build up a dataset and look for the synoptic characteristics leading to this type of event. Using precipitation

Corresponding author address: Alain Roberge, Atmospheric and Oceanic Sciences, McGill University, 805 Sherbrooke St. West, Montreal, QC H3A 2K6, Canada.
E-mail: alain.roberge@mail.mcgill.ca

DOI: 10.1175/2009WAF2222198.1

© 2009 American Meteorological Society
data to select cases, the authors generated composites of 500-hPa heights, and the corresponding anomalies, to study the behavior of the atmosphere prior to a flooding event over the west coast. The results revealed that the events start with anomalous ridging over the Bering Sea, continue with a negative 500-hPa height anomaly over the Gulf of Alaska during the following few days, and end with a positive anomaly over the southwestern United States and Pacific Ocean. The trough and ridge pattern leads to enhanced geostrophic southwesterly flow into the northwestern United States (Neiman et al. 2008). In a representative case study, Lackmann and Gyakum (1999) observed a strong southwesterly flow that likely contributed to the significant poleward moisture transport. Finally, the release of latent heat over the mountains may produce a large-scale "chinook" wind that is associated with wintertime warming over inland regions of North America. However, their study only focused on one type of synoptic regime, and did not examine the origin of the moisture.

A Lagrangian perspective using trajectories (Reap 1972; Wernli and Davies 1997; Knippertz 2005) is a useful tool to examine the origin of the moisture (Bao et al. 2006). Furthermore, trajectory analysis is carried out to physically interpret the connection between the poleward moisture transport and the evolution of the area of maximum tropospheric-integrated moisture transport. In fact, the horizontal flux of moisture is directly related to the storm tracks, and more precisely, the warm conveyor belt (see Carlson 1980; Browning 1986; Eckhardt et al. 2004) of low pressure systems. Moreover, it has been found that the moisture convergence that is present along the elongated moisture transport structure is associated with the rising air in the warm conveyor belt next to the cold front (Bao et al. 2006).

Nevertheless, very few of these studies examined events affecting Canada. In their study on the water budget of the Mackenzie River basin, Smirnov and Moore (1999, 2001) stated that moisture pulses similar to Zhu and Newell's (1998) definition of atmospheric rivers, coming from the Pacific Ocean from midlatitude cyclones, were responsible for a significant part of the incoming moisture during the cold season into the Mackenzie River basin (also discussed in Lackmann et al. 1998). However, the synoptic conditions for a Pineapple Express event reaching British Columbia, and even further into the Mackenzie River basin, may differ greatly from the synoptic conditions associated with significant moisture transports affecting the California coast. Moreover, the idea of using a Lagrangian perspective with a larger dataset could be used to define Pineapple Express events (Stohl et al. 2008).

The purpose of this study is to exploit these ideas to address the following questions: 1) What are the main regime conditions related to the moisture's origin in intense water vapor transport (IWVT) events reaching high latitudes of western North America? 2) What are the synoptic conditions associated with such phenomena before and after? 3) Is the temperature of the atmosphere over North America affected by these events? Answering these questions will give more insight about the meteorological conditions leading to intense precipitation events in the high latitudes of western North America during the cold season.

To address these questions, we will construct a dataset of the most intense poleward water vapor flux from data of vertically integrated poleward water vapor transport over the northeastern Pacific. Then, a trajectory analysis will be performed on each case found to fully examine the characteristics of the air parcels' movement for the previous 5 days. Finally, a composite climatology will be performed to understand the synoptic conditions that occur prior to IWVT events reaching the high latitudes of western North America, as well as their impacts on the weather, the thickness field in the following days, and precipitation anomalies along the coast of British Columbia.

The remainder of the paper will be organized as follows: the methodology for the selection of cases, the geography, the data, and the methodology used in the computation of trajectories and the partition of cases, will be summarized in section 2; subsequently, the results of the trajectories and the composite climatology will be discussed in section 3; the next section describes the synoptic conditions leading to IWVT events observed in this study, as well as its consequences later on; and, finally, a summary and a concluding discussion will appear in section 4.

2. Methodology

Satellite images from the University of Wisconsin—Madison Web site (the Space Science and Engineering Center Satellite Inventory Browser, available online at http://dcdbs.ssec.wisc.edu/inventory/) have been used for motivational purposes, and to locate the geographical coverage of the IWVT events reaching high latitudes of western North America. Second, the National Centers for Environmental Prediction—National Center for Atmospheric Research (NCEP–NCAR) global reanalysis data (Kalnay et al. 1996) between October and February (Lackmann and Gyakum 1999) from 1948 to 2005 were employed to construct the dataset. The NCEP–NCAR global reanalysis is a global grid with time coverage of 4-times-daily, and daily and monthly values from 1948 to the present. Its resolution is approximately every 2.5°. The NCEP–NCAR global reanalysis was chosen because of its spatial coverage over the entire Pacific Ocean, as
well as its time coverage, which allowed us to study a 57-yr time period. However, it is important to note that our domain lies mostly over the ocean, and there are concerns on the reliability of the water vapor content values used in the computation of water vapor transport vectors, especially prior to the inclusion of satellite data in the late 1970s (Lackmann and Gyakum 1999).

a. Selection criteria

IWVT events can vary in spatial structure, intensity, and longevity. Therefore, objective selection criteria have been defined in order to build a consistent and reproducible dataset. The literature generally agrees that these events consist of an elongated structure of clouds starting from the region of Hawaii to the west coast of North America during the cold season. They also bring important amounts of water vapor, which causes copious rainfall when they reach the western cordillera (Lackmann and Gyakum 1999; Colle and Mass 2000; Ralph et al. 2006; Neiman et al. 2008). Therefore, the IWVT events of interest in this study are the ones that bring substantial water vapor transport, which will be defined later, into western Canada and occasionally Alaska.

Thus, the area of interest where the atmospheric river needs to reach high latitudes of western North America was defined as being located between 45° and 55°N and also between 160° and 120°W (see Fig. 1). This area was settled upon after an analysis of the characteristics of northward water vapor transport events in both the NCEP–NCAR global reanalysis, as well as an examination of the infrared satellite images of numerous IWVT events. Satellite images have proven to be effective in identifying cloud patterns of extratropical cyclones (Thepenier and Cruette 1981; Kuhnel 1989). The conclusion of these observations found that intense poleward water vapor transport in locations west of the box indicated, never directly impacted Canada. This is important, because the goal of this study is concerned largely with the mechanisms and impacts of these IWVT events into northern Canada. Furthermore, the north–south limits seem to be in agreement with Smirnov and Moore (2001), who identified the area between 45° and 55°N to indicate the location of the atmospheric river approaching the Mackenzie River basin during the cold season.

To find IWVT events with significant water vapor transport, we identified the times where the northward water vapor transport exceeded two standard deviations above the mean within the area of interest. Water vapor transport was calculated as the dot product of the layer-averaged mixing ratio and the layer-averaged wind vector within each tropospheric layer in the NCEP–NCAR reanalysis, extending from 1000 to 300 hPa [Eqs. (1a) and (1b)]. Even though there are some issues concerning the water vapor in the reanalysis data over the ocean, the data are in general agreement with global hydrological measurements (Mo and Higgins 1996).

The resulting water vapor transport vectors were then averaged to get the water vapor transport integrated over the troposphere (up to 300 hPa). Additionally, in order to use the northward component of the water vapor flux, only the positive $v$ values were processed [Eq. (1b); see Howarth 1983; Zhu and Newell 1998]:

$$Q_A = \frac{1}{g} \int_{1000 \text{hPa}}^{300 \text{hPa}} qu dp$$  
(1a)

$$Q_\phi = \frac{1}{g} \int_{1000 \text{hPa}}^{300 \text{hPa}} qv dp,$$  
(1b)

where $Q_A$ and $Q_\phi$ are the water vapor flux in latitudinal and longitudinal components, $q$ is the mixing ratio, $u$ and $v$ are the latitudinal and longitudinal components of the wind, respectively, $g$ is the gravitational constant, and $p$ is the pressure (hPa).

The statistical method used to identify each event was chosen according to the distribution of the maximum northward water vapor transport within the area of interest. Among those times, an event was identified as a succession of at least four periods of 6 h (for a total of 1 day), where the northward water vapor transport was greater than two standard deviations above the mean. Finally, each event had to be at least 1 week apart, as a means of establishing an occurrence as
an independent synoptic event. A total of 112 events from 1948 to 2005 were identified from these criteria.

b. Trajectory methodology

Trajectories are used as a basis of typing or separating various moisture transport events. Here, the trajectories can act as indicators of the large-scale flow regime, and consequently they are particularly useful for the formulation of synoptic-scale composites. To facilitate these computations, backward trajectories were produced (Reap 1972; Wernli and Davies 1997; Knippertz 2005; Stohl et al. 2008), thereby providing detailed information about the parcels’ motion with time. While this can help identify the regions in which the moisture for a given event likely originated, it is important to note that we do not claim any precise tracing of the origin of the moisture in any given precipitating cloud. Rather, we are more interested in the large-scale flow configurations and dynamics that are associated with the significant poleward transport of moisture.

First, it was important to consider where the highest water vapor transport was located within our region of interest, and to identify the location of the maximum water vapor transport values. Maps of water vapor transport isopleths [Eqs. (1a) and (1b)] were generated for that purpose (see Fig. 1). They were generated using the General Meteorology Package (GEMPAK; Koch et al. 1983) and are computationally consistent with the water vapor transport used in the selection criteria, except that both \( u \) and \( v \) components were used. Furthermore, to compute the backward trajectories, we used the full wind field \( (u, v, \omega) \) to calculate the origin of the parcels up to 5 days before the event. Trajectories were computed in clusters, all originating 5 days before and ending at 500 hPa within the area of the greatest water vapor transport values of the selected IWVT events. Note that the ending area of the trajectories in Figs. 2–4 is smaller than the area of interest shown in Fig. 1, so as to remove unrelated trajectories.

The matter of the choice of level of the starting point of the trajectories is a topic that merits some discussion here. For the purpose of this study, the starting level is taken to be 500 hPa, because it allows the trajectories to be traced for a full 5 days. Starting trajectories at 850 hPa, for instance, result in trajectories that often end after a period of 24–48 h. This results from the fact that the parcel trajectories are often characterized by ascent as they approach our target area. Consequently, these backward trajectories intersect the lower boundary (the ocean) rather quickly, resulting in a termination of the trajectory. However, while the choice of 500 hPa as an ending point is expedient, it does raise some questions as to the representativeness of the trajectories in terms of whether they actually locate the origins of the highest transports of both heat and moisture. Intuitively, one would suspect that these IWVT events are characterized by significant warm air advection, resulting in a veering wind profile with respect to height. This would suggest that trajectories would change rapidly depending on the ending level. However, it should be noted that the strongest temperature advections often precede the strongest moisture transports. To investigate this issue further, a comparison of the classifications arrived at by our methodology versus the classifications arrived at using the Hybrid Single Particle Lagrangian Integrated Trajectory model (HYSPLIT; available online at http://ready.arl.noaa.gov/HYSPLIT.php) trajectories with the starting level of the trajectories, taken to be at both 850 and 700 hPa, was performed for a subset of 56 of the events in our study. The HYSPLIT model was chosen because the trajectories do not terminate upon reaching the surface. While not shown here, the results indicate that approximately 20% of the cases would change classification bins. By far, the category that is most strongly impacted is our “southwest” category, because a number of these events would be classified as “south” events using the HYSPLIT model. However, as will be illustrated later in this paper, the dynamical differences in the composites between the south and southwest classifications are relatively minor compared to the differences between the west classification and either the south or southwest categories. Consequently, our conclusion is that the current methodology is sufficiently robust to justify the conclusions presented later.

A common feature observed in all of the events is that the air parcels are slowly rising in time as they approach time zero at 500 hPa (see Figs. 2a, 3a, and 4a). Because rising motion would significantly increase the relative humidity of the parcel, a relative humidity tracer was also used to see the evolution of water vapor within each parcel, and confirm that they are saturated at 500 hPa in our region of interest (see Figs. 2b, 3b, and 4b). The trajectories that ended with a relative humidity of 90% and higher were the ones chosen for the analysis.

Surprisingly, more than a third of the events (41 of the 112) did not have any trajectories originating equatorward of 30°N within the tropics (note this number is slightly smaller when using the HYSPLIT model trajectories). As will be shown later, the synoptic-scale structures of these events differ significantly from cases where the moisture transport is from subtropical latitudes. In fact, the trajectories indicate three different patterns, two of which are from the subtropics as the origin of the air parcels. The idea to partition the events into these three types was then considered. The partitioning into types was necessary to separate the different patterns, and therefore reduce the amount of smearing in the composites considerably. The
idea is to find clear synoptic signatures that lead to similar significant water vapor transport events.

Whereas the origin of the air parcels differs in each case, they can generally be grouped among the following three different types: south, southwest, and west cases. A total of 37 events were labeled as south events, 34 as southwest events, and 41 as west events. South events are events where the atmospheric river comes from the
area of Hawaii (160°W), or east of it, as well as below 30°N. Southwest events are found where the atmospheric river comes from west of Hawaii and below 30°N. Finally, the west events come from the western Pacific, where the air parcels traveled exclusively poleward of 30°N. When cases showed parcels originating over a variety of locations, equivalent potential temperature ($\theta_e$; see Figs. 2c, 3c, and 4c) was used to identify the trajectories with the largest $\theta_e$. These trajectories are then used in the final classification of the event. The use of $\theta_e$ values also determined the accuracy of the trajectory program. In fact, all trajectories that did not come into contact with the boundary layer held a relatively constant $\theta_e$ value as expected, because $\theta_e$ is conserved in

**Fig. 3.** Same as Fig. 2, but for 49 backward trajectories lasting 5 days and ending at 1200 UTC 24 Oct 2003. This IWVT event was considered a southwest event, owing to the trajectories originating west of Hawaii.
moist-adiabatic processes. This method adds more objectivity to the partitioning methodology.

c. Compositing methodology

Once the trajectories have been computed for all cases, the next step was to regroup similar events together and generate composites of various meteorological fields to get an idea of the synoptic conditions prior and posterior to these events. To understand the evolution of the fields for the week centered on the day of the event, daily composites for each field were acquired using the NCEP–NCAR global reanalysis (Kalnay et al. 1996). Finally, the events were averaged together according to their type—south, southwest, or west—to be...
able to generate composite maps. This means that seven composites of each field were generated for each type, with each covering a different day. Field composites include 1000–500-hPa thickness, mean sea level pressure, water vapor transport vectors, water vapor convergence, and vertical velocity. To compute anomalies, a monthly weighted climatology was used for each type, according to the number of cases within each month, using a 1971–2000 monthly climatology. For example, the south climatology used the months of October–February, with October weighting 11/37 of the climatology, and so on (because 11 of the 37 cases were in October). A total of seven composites of 1 day were generated, starting 3 days before the day of the event, until 3 days after. Additionally, Student's \( t \) test statistics were performed on the anomalies in order to find the statistically significant areas:

\[
\text{test statistics } t = \frac{\bar{x} - \mu_0}{s/\sqrt{n}}. \tag{2}
\]

This Student's \( t \) test is based on \( (n - 1) \) degrees of freedom, where \( (\bar{x} - \mu_0) \) is the anomaly, \( s \) is the standard deviation of the type of events, and \( n \) is the number of cases for each type.

For a dataset of 34, 37, and 41 events, the 95% significance \( t \)-test value roughly corresponds to a value of 2.0. The 95% significance line is plotted on top of the anomaly and average fields. It is important to note that the further the time is from the time of the event from the dataset, the more smearing occurs, which decreases the anomaly amplitudes and their significance.

Moreover, maps of tropospheric-integrated water vapor transport vectors and water vapor convergence were also generated and plotted with the 700-hPa height field. The choice of the 700-hPa heights is justified, because it is the level where the product of the mixing ratio and the winds is maximized, because winds usually increase with height and mixing ratio usually will decrease with height (see Fig. 9 in Knippertz and Martin 2007). Water vapor convergence is the negative component of the divergence of the water vapor transport vectors. High correlation exists between large-scale water vapor convergence and the observed rainfall rate (Kuo and Anthes 1984).

3. Results

a. Trajectory results

1) SOUTH EVENTS

South events (originating near to and east of Hawaii and south of 30°N) were the only cases where a noticeable anticyclonic circulation west of the United States was apparent (see Fig. 2). This was observed from the curvature of the trajectories, and will later be confirmed on the mean sea level pressure anomalies. This synoptic condition favors winds from the southwest, east of Hawaii, transporting the heat and water vapor poleward from that area. Most of the air parcels are slowly rising from the boundary layer toward the end point at 500 hPa (see Fig. 2a). Note that two different patterns were observed in the south cases: the first shows the trajectories curving anticyclonically (also observed in McGuirk et al. 1988) from the coast of Mexico and California, whereas the second type showed trajectories curving cyclonically from the islands of Hawaii.

2) SOUTHWEST EVENTS

Southwest events [where the air parcels originated in the area west of Hawaii (west of 160°W) and south of 30°N] take a longer and narrower path, and are characterized by a direct flow from the subtropics to the North American west coast (see Fig. 3). Again, the air parcels are slowly rising from the boundary layer until they reach the chosen ending point at 500 hPa (see Fig. 3a). A less amplified Pacific wave train, compared to the south events, is probably the cause of the increased southwesterly flow and will be confirmed with the composite results.

3) WEST EVENTS

West events (where only a few air parcels traveled below 30°N) have parcels that originate in the western Pacific, and their trajectories have a zonal orientation (see Fig. 4). A farther extent into the west suggests stronger winds and possibly a stronger Aleutian low. The synoptic condition will be mainly discussed in the composite section. Unlike the two other types, the air parcels are not coming from the planetary boundary layer. The air parcels do rise with time (from 700 to 500 hPa), but not to the same extent as in the south and southwest cases (from 900 to 500 hPa; see Fig. 4a). Some of these cases do reach latitudes below 30°N, although in the western Pacific near Japan they follow a sinusoidal path before reaching the area of interest.

b. Composite results

According to the trajectories, the air parcels that transport this significant amount of water vapor originated from different areas depending on the event. The trajectories' curvature also shows that the midlatitude cyclones are responsible for the important heat and water vapor transport within the area of interest. The path of those storms influences the trajectories the air parcels use. Although every event shares similar features, such as the water vapor transport and convergence, the three types also have important differences.
1) SOUTH EVENTS

The south type is characterized by a trough–ridge pattern positioned over the northeastern Pacific and the west coast of North America, respectively. The northeastern Pacific trough is the weakest in this composite, which is possibly an artifact of the significant poleward movement of individual cyclones in this composite (see Figs. 5b and 6b). This synoptic pattern is generally the result of one or more midlatitude cyclones traveling northeast from the subtropics east of Hawaii, which is combined with a relatively strong anomalous high pressure system over the Pacific Northwest and British Columbia (up to 8 hPa greater than the weighted climatology). These features result in a significant anomalously southerly flow that transports sensible and latent heat poleward, as indicated by the strong positive anomalies in the 1000–500-hPa thickness field (see Figs. 6b,c). The meridionally amplified flow is supported by an analysis of the trajectories of the individual events comprising the composites (not shown). The importance of the anticyclone–cyclone couplet is indicated by the anticyclonically curving trajectories from the area west of Mexico, and the cyclonically curved trajectories originating from near the Hawaiian Islands, toward the area of interest. This variance in the southerly flow partly explains the weaker negative pressure anomalies seen in the composite compared to the southwest and west events as a result of more important smearing. There is also strong water vapor convergence values found at the leading edge of the IWVT event (see Fig. 7b). Furthermore, there is evidence of ascending motion as the moist and warm air travels from the trajectories, and the satellite images are confirmed with vertical wind maps (see Figs. 8a–c). This confirms the conclusion of Bao et al. (2006) that the leading end of the band of water vapor was more the cause of water vapor convergence than direct transport from the tropics. The south cases also show an indication of a downstream trough over eastern North America (not shown), which is a consequence of the trough and ridge couplet behind it. Even though the south events show the most intense southerly flow from the tropics, they

![FIG. 5. Time sequence of sea level pressure (solid black line) for 5 days centered on the event for the (a)–(c) south cases, (d)–(f) southwest cases, and (g)–(i) west cases. SLP anomalies are shaded with a 4-hPa interval, with dark to light shades being negative anomalies and light to dark shades indicating positive anomalies. The solid black lines represent the total mean sea level pressure field, with an 8-hPa interval. The gray dashed lines represent the 1000–500-hPa total thickness field with 120-m intervals. The dotted dashed lines represent the 95% significance level of the anomalies. Note that (a),(d), and (g) are anomalies of 2 days before the event, (b),(e), and (h) are anomalies at t₀, and (c),(f), and (i) are anomalies 2 days after the event.](image-url)
also show the weakest warming over North America in both strength and coverage over the following days (see Figs. 6c,f,i). In fact, the maximum thickness anomaly seen 2 days after the event is 30 m weaker than the maximum observed in the southwest and west composites (with a maximum of 120, 150, and 150 m, for south, southwest, and west cases, respectively). However, its extent goes north well into the Yukon and Northwest Territories. Warming over this area has been discussed in previous studies, and has been associated with subsiding air on the lee side of the mountains (Szeto 2008) and warm air advection.

2) SOUTHWEST EVENTS

The southwest cases are characterized by a much stronger negative sea level pressure anomaly throughout its week evolution when compared with the south cases. The minimum pressure of the total field is 992 hPa, compared to 1004 hPa in the south events, which corresponds to an anomaly of −16 hPa, compared to −10 hPa in the south events. However, this anomalous trough does not extend as far south into the subtropics as in the south composite (see the 95% significance line in Figs. 5b,e).

This pattern is explained by midlatitude cyclones originating more to the west (see Figs. 5a,d), compared to the south events that travel northeastward toward the Aleutians. This is also observed in the trajectories, where the air parcels originate farther west before curving north toward the area of interest. Trajectories also suggest that the flow is channeled efficiently by the strong low and high pressure systems observed in the composites (see Fig. 5e). Moreover, the same negative sea level pressure anomaly weakens as the positive sea level pressure anomaly develops westward. Also, the vertical motion (see Figs. 8d–f) is also in agreement with the slow rising motion seen in the trajectories before they reached the area of interest (see Fig. 3a). As in the south events, orography is responsible for greater vertical motion and most possibly precipitation along the coast of British Columbia and Alaska. The ridge anomaly over western North America is of the same magnitude as the one in the south cases (positive anomaly of 8 hPa), but does not extend as far north. In the thickness field, the strength of the warming is more intense over western North America and is shifted farther south compared to the South cases, with an anomaly that is 30 m greater at the peak 2 days.

FIG. 6. Same as Fig. 5, but for the time sequence of 1000–500-hPa thickness (dashed black line). Thickness anomalies are shaded with a 30-m interval, with dark to light shades being negative anomalies and light to dark shades indicating positive anomalies. The dashed black lines represent the total 1000–500-hPa thickness field with a 120-m interval. The dotted–dashed lines represent the 95% significance level of the anomalies.
after the event. Again, the leading edge of the IWVT event coincides with the largest water vapor convergence values (see Figs. 7d,e).

3) West Events

The west events differ greatly from the south and southwest cases, resulting from the very weak ridge over western North America as compared to the other events (see Figs. 5b,e,h). Other differences include a central Pacific trough that does not extend as far south as the other types, and has a much stronger negative sea level pressure anomaly. The actual central pressure is similar to the southwest cases (minimum of 993 hPa in the total field and anomaly of \(-16\) hPa in both types), but does cover a larger area (see Figs. 5e,h). This synoptic pattern generates a flow that is stronger and more zonal compared to the south and southwest events. The significant vertically integrated poleward water vapor transport values are the result of stronger winds transporting water vapor from regions at higher latitudes compared to the south and southwest cases. This is observed in the trajectories (see Fig. 4a), where the air parcels originate from the western Pacific and travel east until they finally curve poleward in the area of interest. In the thickness field, the main differences are that the warming takes place more to the north compared with the south and southwest events. It is also stronger and stays strong for a longer period. In fact, the maximum thickness anomaly reaches a maximum of 150-m above the weighted climatology 2 days after the event (see Fig. 6i) and stays strong with a 120-m maximum anomaly the following day (not shown). Finally, even though the flow is not bringing subtropical air into the area of interest, the warming over western North America of the west events is similar to the southwest cases in intensity and greater in area coverage. This may be a result of more abundant diabatic warming over the mountains from a perpendicular flow from the ocean toward the western cordillera.

4. Summary and concluding discussion

The concepts of ascending air parcels and water vapor transport are summarized in the composite cross sections shown in Fig. 9. The cross sections here are generally oriented along the bulk parcel trajectories for each of the composites. It is important to remember that the trajectories that were chosen are near or at saturation, and consequently can be expected to travel along...
isentropes of equivalent potential temperature. Therefore, it can be surmised from the cross section that isentropic ascent is occurring, which is consistent with the trajectories displayed in Figs. 2–4. Moreover, it can be discerned from the cross sections that the atmosphere is roughly equivalent barotropic in the region of the greatest moisture transport, because winds throughout the profile are unidirectional. This suggests that many of the systems responsible for significant moisture transport are either mature in nature or are associated with the warm sector of robust western Pacific cyclones.

Figure 10 is a conceptual drawing for the synoptic conditions for each type of IWVT event. They are based on the sea level pressure anomaly evolution discussed in section 3 (see Fig. 5). The low and high pressure systems have been roughly positioned according to the negative and positive anomalies seen in those figures. We already noted that the atmosphere shows properties of an equivalent barotropic atmosphere in the vicinity of the low pressure anomalies (see Fig. 9), which suggests that the lows in Fig. 10 are both at the surface and in the upper troposphere. Even though the three synoptic types have their differences, all of the cases share similarities. In fact, they all show significant low pressure systems traveling northeastward, or eastward, bringing important water vapor amounts within their warm conveyor belt. Every case also shows significant warm air advection in North America. This is consistent with the conclusion of Lackmann and Gyakum (1999). However, the synoptic conditions and the wind conditions relating to the event determine where the warming will be located. For example, the Mackenzie River basin shows cooler temperature anomalies in the composites of Lackmann and Gyakum (1999), whereas our cases show positive thickness anomalies. Invariably, the flow in each of the cases is subject to significant orographic ascent, because the flow impinges on the significant terrain along the western coast of North America. The relatively moist air mass in conjunction with the steepness of the terrain is undoubtedly responsible for significant windward precipitation (Alpert 1986). A survey of monthly precipitation totals for coastal and near-coastal stations indicates that even a single IWVT event can have a significant impact on the monthly precipitation anomalies. For instance, the Northwest Regional Airport, Terrace–Kitimat, located roughly near the center of the British Columbia (BC) coastline, showed a monthly precipitation anomaly of ~28%–42% over the climatological average for any month that had at least one event (Table 1). These positive anomalies represent the largest
of those observed along the British Columbia coast. These results (Table 1) also show that south and west cases produce similar monthly precipitation anomalies on average, whereas the southwest cases produce more important rainfall along the coast. It is important to note here that the terrain in the area of consideration can wreak havoc with precipitation totals, which are dependent upon the flow and terrain configuration. However, Terrace–Kitimat Airport was chosen here because of its central location along the BC coastline, as well as its location in a junction of two river valleys that stretch both south and west of the airport. This tends to minimize any rain shadow effects that may be experienced on the leeward side of significant terrain.

The precipitation-related impacts of our randomly chosen cases shown in Figs. 2–4 were also substantial. For example, Terrace–Kitimat Airport received maximum 2-day totals of 111.2, 46.8, and 32.2 mm for the respective south, southwest, and west events. These 2-day values represent 58%, 25%, and 18% of the monthly climatological values. Furthermore, these events contributed to the respective monthly (percent of climatology) values of 340 (177%), 217 (117%), and 297 (163%) mm. Clearly, our individual events have substantial positive influence on precipitation totals.

The partitioning of the composites, through the locations of the origins of the trajectories, reveals areas where key anomalies can be identified up to 72 h prior to the event. It is hoped that the partitioning of the events in this way will add to the insight presented by previous work through a reduction in the smearing of any composite analysis. For instance, Neiman et al. (2008) found that these atmospheric rivers in the cold season were generally meridionally orientated and originated in the
subtropics. This is somewhat at odds with our results, which indicate that several important IWVT events are associated with more zonal flows. Differences in methodology may account for some of the discrepancies, particularly with respect to the use of satellite data in the identification of events. However, by regrouping events with similar trajectories, significant details with respect to the nature of the inception of the important synoptic anomalies are revealed. It is believed that his methodology can be employed in various synoptic typing studies to partition different flow regimes.

Second, the impact of an IWVT event over North America may be more important than what was discussed earlier in this study. It was shown that the flow configuration associated with diabatic heating contributes to an intensification of the ridge over western North America, which has important weather, economical, and social impacts. For example, the ridging observed over North America has been observed in the past as a precursor to drought events over the Canadian prairies, because it brings warm and dry air over the area (Nkemdirim and Weber 1999; Bonsal and Wheaton 2005). In fact, a composite of 11 significant moisture transport events into western Canada during the 1999–2004 prairie drought (not shown) reveals a pronounced warm 1000–500-hPa thickness anomaly in excess of +120 m (about 6°C), which covers virtually all of the Yukon, the western region of the Northwest Territories, British Columbia, Alberta, and Saskatchewan. The associated anticyclonic flow of the thermal wind extends from the Canadian Pacific coast and eastward to the western region of the Hudson Bay in Manitoba.
Table 1. Average difference (%) of monthly precipitation totals between British Columbia coastline stations and a weighted climatology between 1971 and 2000 for each type. Terrace–Kitimat Airport (1068130) is the station in bold.

<table>
<thead>
<tr>
<th>Station</th>
<th>South</th>
<th>Southwest</th>
<th>West</th>
</tr>
</thead>
<tbody>
<tr>
<td>2101300</td>
<td>8.39</td>
<td>15.79</td>
<td>0.60</td>
</tr>
<tr>
<td>1068130</td>
<td>42.43</td>
<td>27.93</td>
<td>31.05</td>
</tr>
<tr>
<td>1054920</td>
<td>14.27</td>
<td>1.87</td>
<td>3.04</td>
</tr>
<tr>
<td>1060841</td>
<td>−14.54</td>
<td>8.65</td>
<td>−8.71</td>
</tr>
<tr>
<td>1026270</td>
<td>−5.48</td>
<td>8.48</td>
<td>−3.30</td>
</tr>
<tr>
<td>1021261</td>
<td>−13.73</td>
<td>7.30</td>
<td>−8.41</td>
</tr>
<tr>
<td>1038205</td>
<td>−8.25</td>
<td>4.72</td>
<td>−8.42</td>
</tr>
<tr>
<td>1025370</td>
<td>−20.29</td>
<td>0.12</td>
<td>−18.32</td>
</tr>
<tr>
<td>1018620</td>
<td>−23.39</td>
<td>−0.31</td>
<td>−24.97</td>
</tr>
</tbody>
</table>

The warming also impacts the snow cover over northern Canada and Alaska, as well as the ice cover of the local lakes and rivers. This can have important consequences on the climatology of the area because of the significance of snow cover on temperature. This was specifically observed on the so-called winter and ice roads within the Northwest Territories. Ice roads are an important socioeconomic aspect of the northern communities over the winter, because it is the most affordable transportation method to bring equipment and goods. Therefore, a significant warming resulting from an IWVT event may lead to a delay in the ice and winter road construction, shortening the time it may be functional (Knowland et al. 2009, manuscript submitted to Arctic).

Furthermore, the amount of water vapor transported by the IWVT events may affect the hydrology of the impact area by dramatically increasing the water vapor income of a river basin (Smirnov and Moore 1999, 2001). In turn, intense precipitation may have various feedbacks on the local weather of the surrounding areas.

Acknowledgments. This research has been sponsored by the Natural Sciences and Engineering Council (NSERC) Discovery Grant, and by an International Polar Year (IPY) NSERC Grant.

REFERENCES


——, ——, G. A. Wick, J. D. Lundquist, and M. D. Dettinger, 2008: Meteorological characteristics and overland precipitation impacts of atmospheric rivers affecting the west coast of North.


