8

REGIONAL WEATHER SURVEY, PART II
Rocky Mountains and the Mountains of New England

Chapter Highlights:

- ✓ Detailed information on the weather and climate of the Rocky Mountains as well as the mountains of New England.

The Rocky Mountains (Rockies) are composed of a vast number of smaller mountain ranges that extend from central New Mexico and central Arizona, into British Columbia and Alberta. The Rockies are approximately 2500 km (1500 mi) in length and vary in width from 250 km (155 mi) to about 650 km (400 mi). The height of these mountains vary from range to range, the tallest peaks being located in Colorado and northeast Utah. In addition to the mountains, large portions of the Rockies consist of intermontane valleys and in some regions, elevated plateaus. In fact, most of the region which we call “the Rockies” consists of a plateau that has an average height of 1500-2000 m (4,900-6,500 ft). On top of this plateau are interspersed mountain ranges that provide an additional 1000-2500 m (4,900-8,200 ft) of relief. In order to facilitate this discussion on the weather and climate of the Rockies, the material has been divided into two sections. The first of which covers Utah, Colorado, New Mexico and Arizona in what we will call the southern Rockies, while the second covers all of the range to the north.

Since the Rockies cover such a large area, there are considerable regional weather and climate differences that should be taken into account in this type of survey. For example, when a major snow producing weather system moves into the Wasatch, it does not necessarily mean that the San Juans of Colorado are going to receive heavy snow as well. Likewise, when the Front Range of Colorado receives heavy snow, quite often the mountains of central Colorado only receive light amounts of snow. This chapter will consider a number of these weather regimes in some detail.

The Southern Rockies

To start this survey let us consider position of the polar jet stream over the southern Rockies. In general, due to the cooling of the interiors of the continents during the winter, the polar jet stream often reaches its southern most trajectory over the middle of the continents (North America, Europe, Asia). For example, when the polar jet moves on shore over the west coast in the winter, quite often its trajectory will continue southest into northern Arizona and New Mexico before curving back towards the northeast. When the polar jet stream extends into the southern tier of states it produces the coldest temperatures of the year, as cold Arctic air moves down from high latitudes. The day-to-day or even week-to-week position of the polar jet, as was discussed in Chapter 4, varies considerably. On any given day the polar jet could be located over Arizona or Alberta, or any point in between. As a rule of thumb, when the polar jet is located in the northern Rockies, you should not expect any major weather systems in the southern Rockies. This does not disqualify mesoscale or local-scale weather systems from developing. Skiers should note that it does not take a large weather system to produce 10-15 cm (4-6 in) of dry powder snow over the higher mountains of the southern Rockies. In fact, a considerable amount of the annual snowfall at most ski resorts in the region is produced by weak weather systems or from purely orographic lifting of moderately moist air.

Another important factor concerning winter snowfall in the southern Rockies is that the moisture is for the most part is transported from the Pacific Ocean. This means that it has had to travel either over the Cascades or Sierras as well as over the Great Basin. As a result, the lowest kilometer of the troposphere in the Rockies is very dry, the bulk of the moisture is in the middle-troposphere (700-500 mb). There is one important exception to this last point as we shall discuss in the section on the San Juan Mountains. The fact that the lowest kilometer (3,280 ft) or so is dry and the bulk of the moisture is carried in the middle-troposphere means that the lifting of air as it flows over large mountains is the primary producer of precipitation, more so in the Rockies than in the Cascades.

Figure 8.1 shows the principal storm tracks for the southern Rockies, including the summer monsoon flow from the Gulf of California. During the winter the predominate storm track is from the northwest-to-southwest. Other flow regimes include north to northeasterly flow which produces cold, relatively dry conditions. Residents of the eastside of the Rockies are well acquainted with low-level easterly winds which produce upslope flow. We will study this regime in some detail later in this section, nevertheless, when low-level easterly flow occurs in conjunction with mid-tropospheric flow from the southeast-to-southwest, the Front Range of Colorado generally receives its largest snowfalls of the season.

Figure 8.2 displays several 500 mb flow patterns for major precipitation producing storms. The actual precipitation received in any given mountain range within the Rockies, of course, depends on the path of the jet stream and direction of moisture bearing winds (Changnon *et al* 1993). In Figure 8.2a for example, this type of low amplitude ridge can produce moderate amounts of precipitation at higher elevations, with almost no precipitation occurring at lower elevations (Hjmerstad 1970).

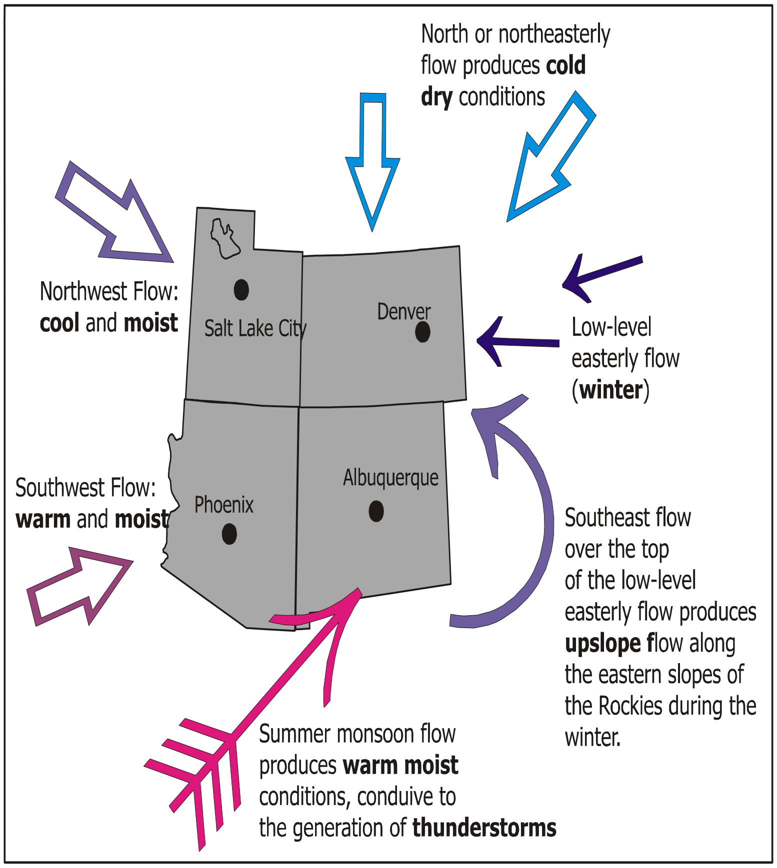


Figure 8.1- Southern Rockies flow regimes.

Climate data for selected valley and mountain stations is displayed in Figures 8.3 and 8.4. The wettest region of Arizona for example is along the Mogollon Rim and the area around Pinetop. The mid-elevation climate stations from Sedona north all have similar amounts of annual precipitation. The temporal distribution of precipitation in this area is bi-modal (has two peaks). The first occurs in winter and the second occurs in the July-September period as a result of increased thunderstorm development. In addition, the number of days per year with a trace or more of precipitation, is noticeably higher in the region around Pinetop than it is in the area north of Flagstaff. This is a direct result of the increase in moisture in eastern Arizona, New Mexico and southern Colorado due to the transport of moisture from the Gulf of California during the second half of summer. In Figure 8.3 notice the difference in annual precipitation and temperature between Bright Angel Ranger station (2561 m or 8,400 ft) and the bottom of the Grand Canyon represented by Phantom Ranch (784 m or 2,570 ft). Air within the Grand Canyon tends to be dry, causing what precipitation that does fall into the top of the canyon to either evaporate or sublimate on its long descent to the bottom of the canyon.

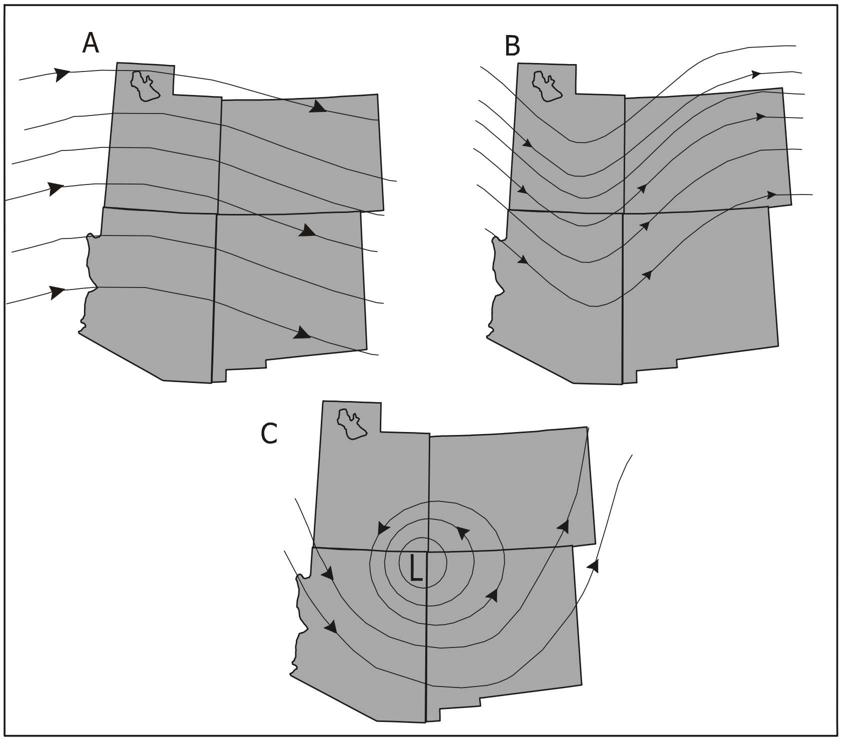


Figure 8.2- 500 mb flow patterns for major precipitation events in the southern Rocky Mountains. A) low amplitude ridge or zonal flow, B) shortwave trough, C) fourcorners cut-off low.

The White Mountains and Mogollon Rim are areas of high thunderstorm activity and cloud-to-ground lightning from July through early September. One of the interesting aspects of lightning strikes across Arizona is the time of day that the peak number of strikes occur, it varies widely across the state (Watson et al 1994). On the Mogollon Rim and White Mountains for example, the highest frequency of strikes occurs around 2 pm, in the central mountains around and to the southeast of Prescott, the peak occurs around 4 pm. In the southeast corner of the state a broad peak exists between 4 pm and 10 pm.

The wettest region in Utah is the Wasatch Mountains where from 100-150 cm (39-59 in) of annual precipitation is measured. This is should come as no surprise since the Wasatch is the first large mountain range that westerly flow encounters east of the Cascades or Sierras. The mountains of southern Utah are considerably drier than the Wasatch, in large part due to the fact that they are much smaller and hence do not disrupt westerly flow as much as their counterparts in the north. The seasonal distribution of precipitation in northern Utah is a function of elevation. Salt Lake City for example, has a slight spring precipitation maximum, although the month-to-month variation is not that large. Alta on the other hand has a very distinct winter precipitation maximum (December through March), with a typical winter month receiving 300-400% more precipitation than the typical summer month. The number of days with measurable precipitation in the Wasatch is about double that of the mountains and plateaus of southern Utah.

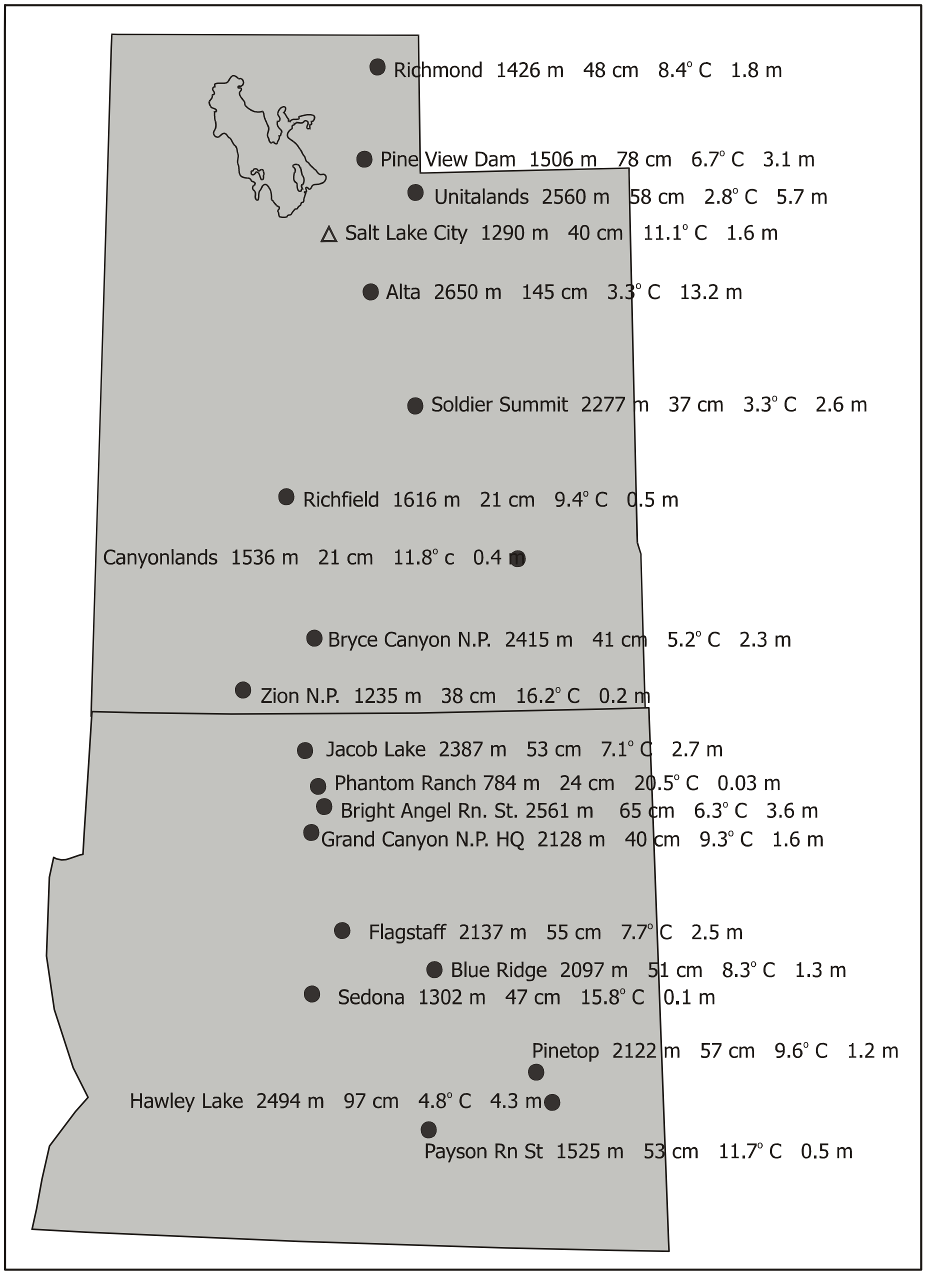


Figure 8.3- Climate data for northern Arizona and Utah. Data sequence is: elevation (m), annual precipitation (cm), annual temperature (C), and annual snowfall (m).

In northern New Mexico annual precipitation varies between 35 and 45 cm (14-18 in), for the 2000-2500 m (6,500-8,200 ft) elevation range as shown in Figure 8.4. The annual average increases as one moves toward the Colorado border. There is a prominent summer (July-September) maximum in precipitation in this region due to thunderstorm development. At many mid-elevation stations, winter is the driest of the four seasons. Average monthly winter precipitation at Santa Fe for example, is on the order of 25-35% of a typical summer month. Hikers and climbers should note that some of the highest frequency of cloud-to-ground lighting in the western US occurs in the mountains of New Mexico, especially in the Apache and Gila National forests as well as the northern mountains around Taos.

In Colorado it is difficult to identify any one particular range as being wetter than another.

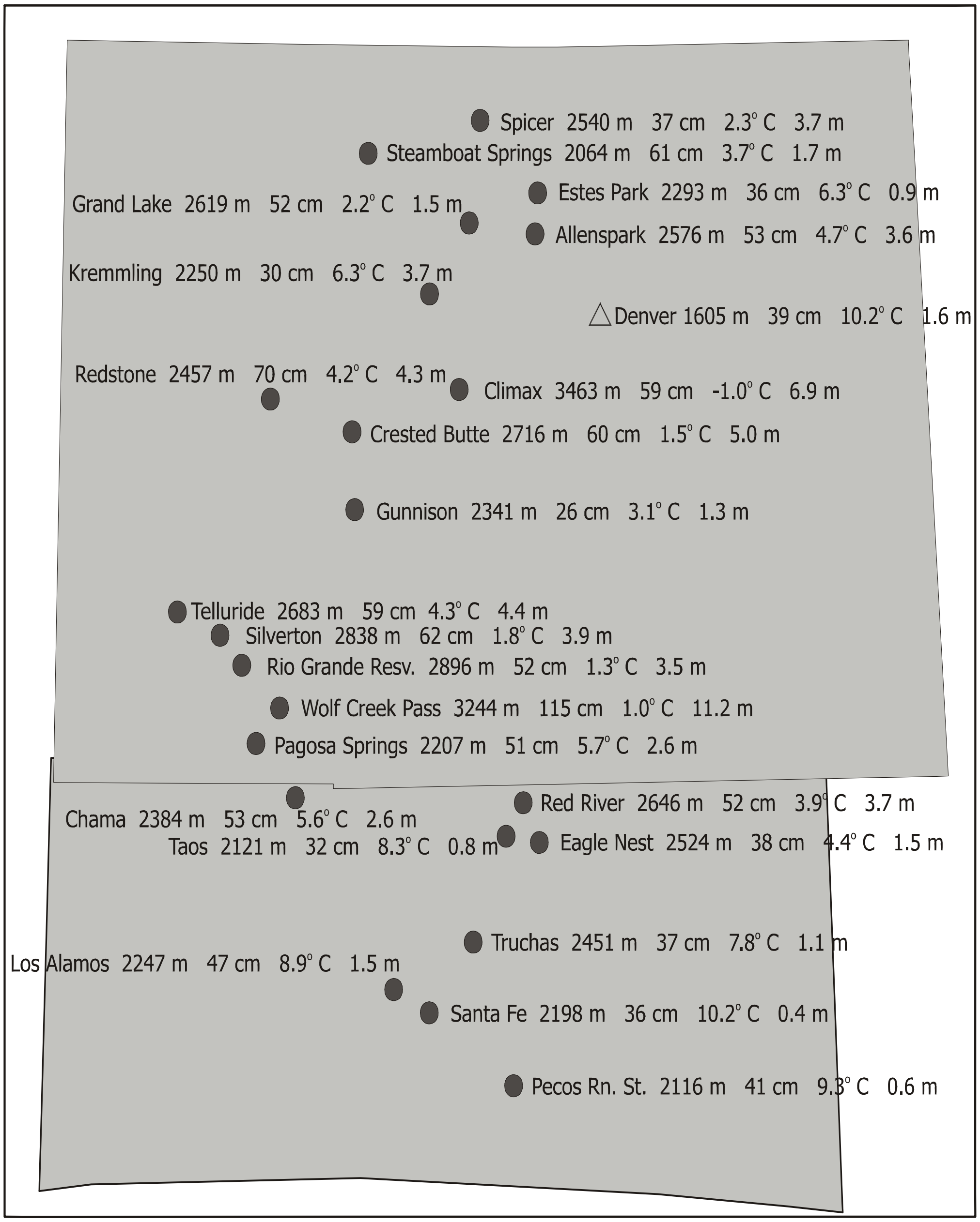


Figure 8.4- Climate data for northern New Mexico and Colorado. Data sequence is: elevaton (m), annual precipitaton (cm), annual temperature (C), and annual snowfall (m).

Annual precipitation in the Colorado Rockies is controlled by elevation and by the height of upstream terrain. When a storm moves across the state from a given direction, certain mountain ranges tend to be favored for precipitation while others are not. For example, when a low is located over the Four Corners region, moisture moves into Colorado from the southwest. This produces considerable amounts of precipitation in the San Juans, moderate amounts in the central Colorado Rockies and either light amounts or no precipitation in the northern ranges. With a low positioned in northern Utah, the northern half of the Colorado Rockies receives the bulk of the precipitation. In cases with moist northwest flow, the northern and central ranges tend to receive the heaviest precipitation.

Since the mountain ranges that comprise the Colorado Rockies vary in size and height, the amount of mountainous terrain upstream of a particular observation point should also be factored into the precipitation equation. This is particularly true in the San Juans and central mountains, where the leeward side of the range (with respect to prevailing storm track) can be quite dry while the windward slopes receive large amounts of precipitation.

Wasatch and Uintas

The Wasatch mountains receive considerably more precipitation than the Uintas because the Wasatch are upstream of the Unitas in relation to the westerly storm track. Annual precipitation in the Wasatch is 65-150 cm (25-59 in), and 65-75 cm (25-29 in) in the Uintas. Although the Wasatch mountains are quite narrow, they are the first substantial mountain barrier that moist westerly winds have to flow over east of the Cascades and Sierras. The height and especially the steepness of the Wasatch produces some of the wettest conditions in all of the southern Rockies. As a result, air moving into the Unitas contains considerably less moisture than it did when it first entered the Wastach.

In Figure 8.5 precipitation at six climate stations that form a west-to-east transect across the Wasatch Mountains is displayed. Notice the sharp increase in precipitation in the mountains, and the sharp decline in the lee of the mountains. The ratio of annual precipitation at the foot of the Wasatch (Midvale, Salt Lake City) compared to the mountains is on the order of 1:3.5. However, this varies from storm-to-storm, so be careful applying this ratio to every storm. Williams and Peck (1962) noted that the ratio is largest for storms that have large orographic lifting. In other words, synoptic-scale troughs and lows produce widespread weak uplift along frontal boundaries, which is independent of orographic lifting. When frontal lifting occurs the ratio of precipitation that falls at high and low elevations is reduced. Conversely, when frontal lifting is weak but orographic lifting is strong, the ratio increases dramatically. Figure 8.5 also displays the number of days per year where the precipitation meets or exceeds the ‘moderate’ threshold (>13 mm or 0.5 in). As you can see there is about a fourfold increase in the number of days meeting or exceeding this criteria from the lowlands to the mountains. This example shows just how much influence steep terrain has on the formation of precipitation.

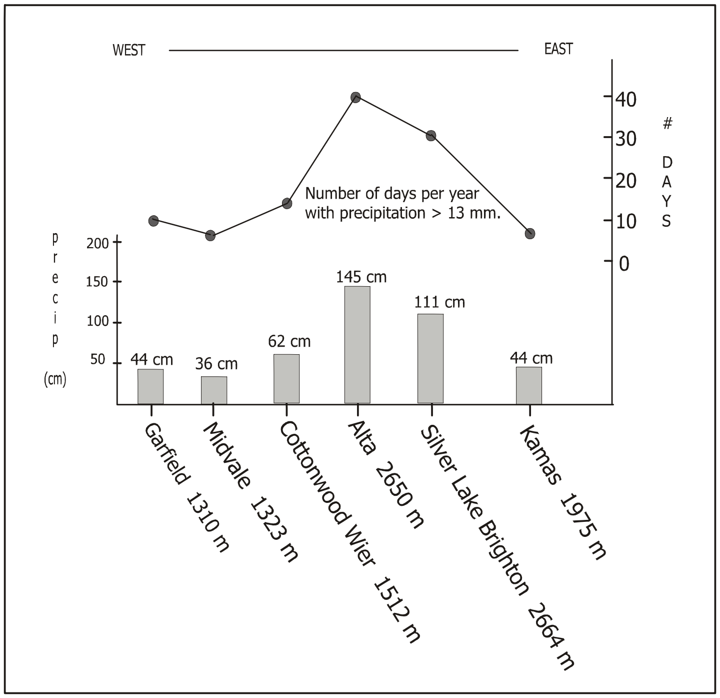


Figure 8.5- West-to-east transect across the Wasatch Mountains. Vertical bars represent annual precipitaton (cm) and the dots are the number of days per year with precipitation exceeding 13 mm (0.5 in).

Snowcourse and snotel data for the Wasatch and Uintas indicates that the amount of snow on the ground in the spring and early summer is a function of not only the amount of winter snow accumulation, but the amount of melting and snowpack consolidation that has occurred during the spring. The amount of spring melt is tied into the mean daily temperature at the site, which is controlled by elevation and cloud cover. The areas with the deepest April 1st snowpack are the central Wasatch in the vicinity of Alta and Snowbird, where the long-term average is about 250 cm (98 in). In addition, the snowcourse at Ben Lomond Peak has a long term average of 245 cm (96 in). The snotel sites in the Uintas on the other hand, which are located at a mean elevation of about

2800 m (9,200 ft), average 75-100 cm (30-40 in) of snow on the ground as of April 1st, with several of the higher sites (3300+ m) averaging 150 cm (59 in). We examined the daily precipitation and snowfall records for climate stations such as Alta and Silver Lake Brighton to see if any winter trends could be detected. What we found is that during the December trough March period, there is no multi-day period that has a better chance of receiving new snow than any other period. Therefore, when you book that week long ski vacation five months in advance, feel at ease that the time slot you selected has a equal chance as any other period when it comes to receiving fresh powder on the slopes.

In the summer months, northeast Utah is a region of considerable convective activity in the lowlands as well as in the mountains. Cloud-to-ground lightning, as well as moderate to large hail, are all real threats to mountain travelers. As we noted in Chapter 5, convective activity generally starts in the early to mid-afternoon and diminishes in late evening or at night. About the only thunderstorm data collected by the NWS occurs at first order weather stations, like Salt Lake City (SLC) airport. The peak month for thunderstorm activity at SLC is August, followed by July, with June and September being in a close tie for third.

San Juan Mountains

The San Juan Mountains of southwest Colorado extend some 200 km (120 mi) west-to-east and about 125 km (75 mi) north-to-south. This range is large enough that there are distinctive areas that receive heavy or light amounts of precipitation from a given storm, depending on the position of the jet stream. For example, when Wolf Creek Pass (3244 m or 10,600 ft) receives a large amount of new snow, Telluride usually receives considerably lighter amounts. When a 500 mb trough or low is positioned over Arizona, as depicted in Figure 8.2a,b the stage is set for the southern San Juans to receive large amounts of snow. This is a favorable pattern for the generation of heavy snow because moisture from the Gulf of California and Pacific Ocean off of Mexico, is added to the moisture that was transported with the original storm.

It is instructive to compare climate station data taken from Pagosa Springs (2207 m or 7,240 ft) with data from Wolf Creek Pass. From Figure 8.4 note that Pagosa Springs receives about 44% of the annual precipitation that is measured at Wolf Creek Pass. The average number of days per year with a trace or more of precipitation is 97 at Pagosa Springs and 117 at Wolf Creek Pass, which are fairly similar. However, the number of days with moderate or heavy precipitation at Wolf Creek Pass is three times (29 days) the number of days at Pagosa Springs (10 days). This comparison shows the ability of steep terrain to greatly enhance the background precipitation on the local-scale. It is also interesting to note that Telluride (2683 m or 8,800 ft) and Rico (2698 m or 8,850 ft) have about the same number of days with light amounts of precipitation as Wolf Creek Pass, but less than half of the number of days with moderate or heavy precipitation.

The western and northwestern regions of the San Juan's can receive moderate snowfalls from a southwesterly flow, but in order to do so, a trough or low has to be positioned over southwestern Utah-northwestern Arizona. Depending on the strength of the storm, moisture from the Gulf of California and the Pacific Ocean off of Baja California may or may not be transported into the region. Flow from the west and northwest tends to favor heavier snow in the western and northern San Juan's, at which time stations like Wolf Creek Pass tend to receive light amounts of snow.

The monthly distribution of precipitation between various stations in the San Juan's is interesting. For example, at Silverton (2838 m or 9,300 ft) and Telluride the wettest month is August, compare this with Wolf Creek Pass where the wettest month of the year is March.

In the following paragraph we will present a short case study of a storm that occurred between March 28-30, 1998, and which produced widespread heavy snowfall across the San Juan's. The 500 mb low center was located over central California and southern Nevada during the time of heaviest snowfall (Figure 8.6). The polar jet axis was positioned over central New Mexico, nevertheless the 500 mb winds in the southern San Juan's were from 30-40 ms^{-1} (65-90 mph).

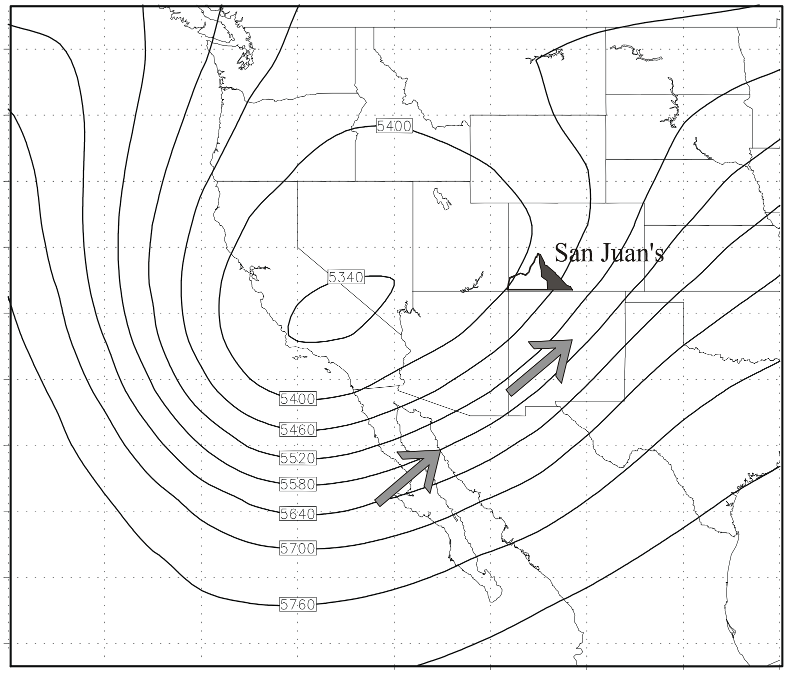


Figure 8.6- March 29, 1998 500 mb height field. Arrows indicate core of jet stream winds.

Figure 8.7 shows precipitation amounts for select snotel sites around the San Juans. Notice how the southern and southwestern stations received the largest amounts of snow (measured as water equivalents), while the northwestern and northeastern stations received much lighter amounts. The different precipitation totals measured at Red Mountain Pass, Lizard Head Pass, and Molas Lake is probably due to local orographic effects, rather than due to any significant differences in the synoptic-scale flow or the transportation of moisture from afar.

Basically, there are two precipitation maxima in the San Juan's, the first occurs in March and is a result of the southern trajectory of the polar jet stream. The second maximum is in August and corresponds with the southwest monsoon. The southwest monsoon (which is sometimes called the Mexican Monsoon) starts to develop sometime around late June or early July. When it occurs, southwest winds transport moisture into the region from the eastern Pacific, and the Gulfs of California and Mexico (Douglas *et al* 1993). There are times when this moisture is transported as far as northern Utah and southern Wyoming, but it primary impact is over Arizona, New Mexico and

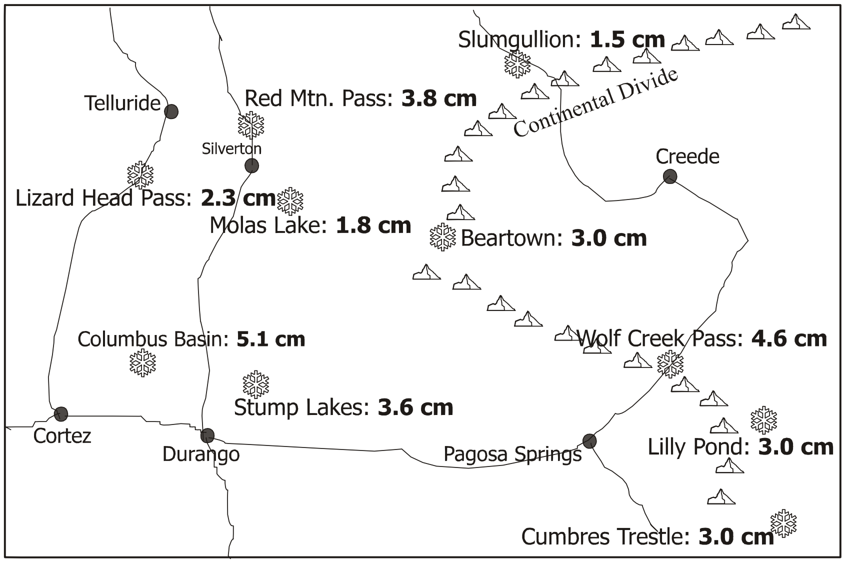


Figure 8.7- Precipitation (water equivalent) measured at select snotel sites in the San Juan's during the March 29, 1998 snowstorm. One centimeter of water equivalent equals anywhere from 10-20 cm (4-8 in) of snow.

southern Colorado. During mid-summer the subtropical jet stream moves northward to a position around 25°- 30° N. With cooler dry air to the north of the subtropical jet, the stage is set for the outbreak of vigorous convection and thunderstorms over the southern Rockies. Most thunderstorms develop on days when the mid-tropospheric winds are light to moderate. The driest months in the San Juans are May and June. This corresponds with a period when the polar jet stream has moved north and before the onset of the summer monsoon.

Temperatures in the San Juans are a function of elevation to a large degree. However keep in mind that during the winter months, the air in the bottom of valleys may be as cold or colder than at elevations 500 m or even 1000 m higher (1,640-3,280 ft), due to persistent valley inversions. A comparison of monthly temperatures between Wolf Creek Pass and Telluride indicates that the monthly mean temperatures for each station are similar, as one would expect based on the fact that both stations are located within the same climate zone. However, when comparing the monthly temperature range (average monthly high and average monthly low), Telluride has a noticeably larger range. In fact, monthly lows at Telluride are equivalent to those at Wolf Creek Pass which lies some 560 m (1,800 ft) higher, due to persistent temperature inversions at Telluride. During the summer months, Telluride is warmer due to its lower elevation and due to the fact that the heating of the valley keeps the valley atmosphere several degrees warmer than the free atmosphere.

Central Colorado Rockies

This group of mountains lies between Grand Junction to the west and Denver to the east, with Gunnison to the south and Interstate 70 to the north. The region is split in two by the Continental Divide, which has a height of about 4100 m (13,500 ft). This is the area that Hjermstad (1970) did his snow distribution study that we have referred to a number of times previously. In that study, the author found that the distribution of snow across this region is in large part controlled by the mid-level (700-500 mb) wind direction. For example, along the Western Slope at elevations below 2500 m (8,200 ft), southwest flow produces the biggest snowstorms of the season. Above 2500 m (8,200 ft) however, the biggest snowfalls of the year generally occur when the flow is from the northwest. This does not mean that the mountains do not receive any snow when the snow is from the southwest, it simply suggests that the observed amounts are less than when the flow is from the southwest. East of the Continental Divide, heavy snowfall events occur when the mid-tropospheric flow is from the southeast or south. Overall, annual precipitation decreases from west-to-east in the central mountains.

Why is there such a difference in the spatial distribution of winter precipitation between southwest and northwest flow? We have mentioned this difference in earlier sections, and will now give a brief explanation. Figure 8.8 depicts southwest and northwest flow patterns with the associated vertical motion fields (ascending and descending regions). With a trough (or low), there is ascending motion to the east of the trough axis and descending motion to the west. These vertical motion patterns are a result of the a number of atmospheric processes, which we will not attempt to explain at this time. The region of ascending motion is linked to the development and movement fronts. From Chapter 5 you should recall that precipitation forms in areas of ascending air. Therefore, in large synoptic-scale storms like the one depicted in Figure 8.8a, precipitation forms by frontal lifting, which is independent of orographic lifting. This should not be understood to mean that precipitation formed in areas of synoptic lifting, cannot be further enhanced by orographic lifting. It does however explain why areas upstream and downstream of mountains (non-orographic), receive precipitation during this type of flow pattern.

In Figure 8.8b, a small amplitude ridge (this feature can also be called a shortwave ridge), and its associated vertical motion field is displayed. Notice that when the flow is from the northwest, the overall motion is downward to the east of the ridge axis. This type of synoptic pattern in and of itself does not produce very much precipitation. However, when this type of flow moves over a mountain range, low and mid-tropospheric air is forced over the mountains, the ascending motion can be about 10 times as great as the synoptic-scale descending motion. The net result are localized areas of strong orographic lift and the subsequent development of precipitation over the mountains. It is for this reason that northwest flow produces little snowfall at low elevations, but can produce substantial snowfall at higher elevations. This also illustrates the important point that you have to be careful correlating weather data from the low elevation stations (Glenwood Springs for example), to the mountains (Vail Pass); sometimes there is a high correlation, but most of the time the correlation is pretty low. In addition, since many storms contain both a trough and a ridge as depicted in Figure 8.8, there may be periods during the storm when frontal lifting may dominate, and other times when orographic lifting overwhelms all other types of vertical motion. Also, the path which a particular storm takes will determine what mountain ranges receive heavy precipitation and which ranges get bypassed.

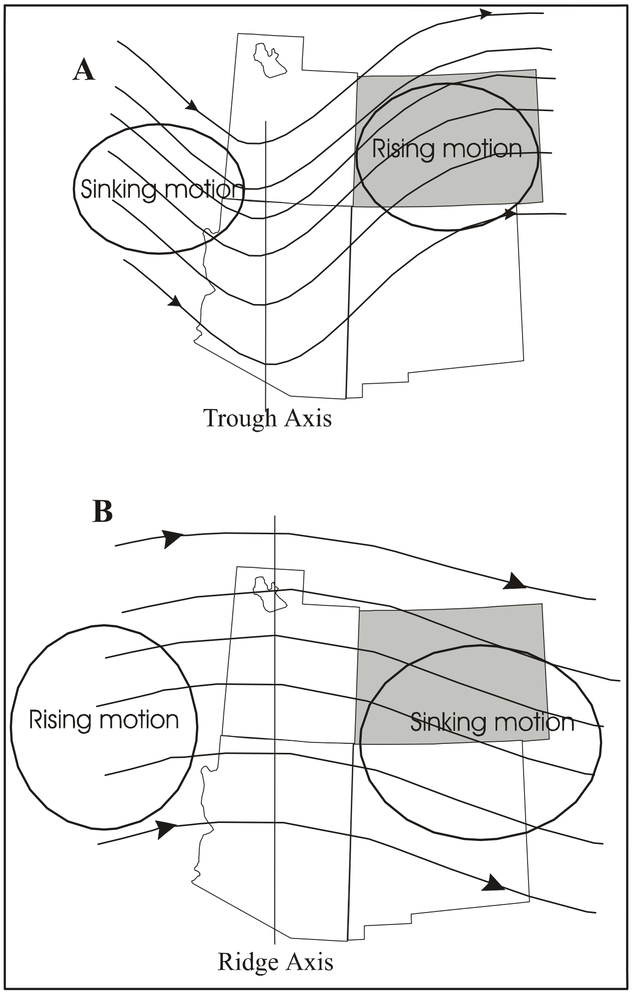


Figure 8.8- Vertical motion fields associated with synoptic-scale disturbances. A) trough pattern. B) ridge pattern.

The one high elevation climate station in the central mountains is at Climax (3463 m or 11,360 ft), which should be quite representative of most of higher elevations within this region (Figure 8.9) The wettest month on average is April, although from the November through May monthly totals are quite similar. By June there is a definite drying trend, this is short lived however, as the July and August convective season produces an increase in rainfall. The driest period is September and October. With regard to mean monthly temperatures, Climax runs about 2-3^{o} C (3.5-5.5^{o}) cooler than Wolf Creek Pass, primarily due to the fact that the station at Climax is 220 m (720 ft) higher and several hundred kilometers north.

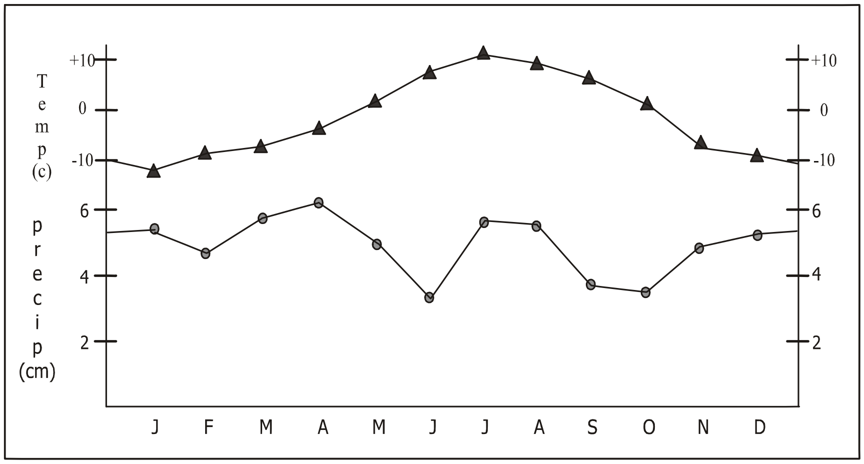


Figure 8.9- Mean monthly precipitation (circles) and temperature (triangles) at Climax, Colorado.

Note that ranges such as the Sangre De Cristo Mountains are very dry due to their location downstream of the San Juans and central mountains, with respect to westerly winds. Likewise many of the valleys that cris-cross large mountain ranges tend to be very dry as well. A prime example is the along Highway 24 between Leadville and Salida. This is a deep narrow valley, where most of the moisture falls on the higher terrain bordering the valley. Because of very dry air within these valleys, what little precipitation that does fall over the valley often evaporates or sublimates before it reaches the ground.

Thunderstorm formation over Colorado has been studied by Banta and Schaff (1987), they suggest that thunderstorms are best developed on days when the 500 mb wind speed is less than 12 m/s (26 mph). This same study also indicates that thunderstorm development also depends to some degree on the wind direction.

Front Range

The eastern slopes of the Rockies are distinct from the rest of the range when it comes to winter precipitation. Local residents know that easterly flow is required in order for the Front Range and foothills to receive any significant snowfall. There are two basic flow patterns that can produce snow in the region, both involve low-level flow from the east. In reality the surface winds can range from north-to-southeast, with northeast and east being the most common. This occurs when a surface high is located over the central or northern Midwest. As this cold air moves towards the Front Range, it slows down and forms a blocked layer that extends into eastern Colorado. Since this shallow cold air is also quite dry, moisture has to be transported into the region from another source. It turns out that moisture is transported into the region by a upper level low or a trough located in northern Arizona or northwestern New Mexico. This pattern often produces southeast flow (700-500 mb) over the top of the cold air located at the surface (Figure 8.10a). When this occurs it is referred to as *overrunning*.

As the moist southeast flow is lifted up and over the cold air dome, precipitation forms in areas of uplift. Typically, clouds that form in this process have a cigar or elongated shape, some 100 km (62 mi) in length and 50 km (31 mi) in width (snow bands). To an observer on the ground snow bands may not be distinguished from the overcast skies, nevertheless they do show up very well on weather radar. These snow bands move around as the storm evolves, causing snowfall distribution across the Front Range to be very inhomogeneous. For example, it is common for an area to receive moderate to heavy snow, while an area 20 km (12 mi) away receives light amounts. In addition, with this type of pattern it is not uncommon for the region between Interstate-25 and the foothills to receive considerably more snow than the Front Range itself.

The second type of Front Range storm is a slight deviation from what was just described. In this new scenario cold air damming occurs over eastern Colorado, but now the middle and upper-level flow is from either the northwest or southwest (Figure 8.10b). Without the presence of a dome of cold air which is typically 500 m to 1000 m deep (1600-3200 ft), upper-level winds would descend down along the eastern slopes of the Front Range, creating warm dry conditions at the surface.

Of course there are multiple variations of the two storm patterns that were just described. In addition, smaller-scale terrain features such as Palmer Divide and Cheyenne Ridge, help modify storms by either producing upslope or downslope flow. When heavy snowfall does occur in the Front Range, it is usually confined to the east side of the Continental Divide. Generally, a storm that produces moderate or heavy snow in the vicinity of the foothills, would only be expected to produce light snow over Winter Park.

It should also be noted that since the distance from the Continental Divide to the base of the Front Range is on the order of 50 km (31 mi), there are locations in the middle of this region that do not receive very much precipitation during the winter at all. In addition, the bottom of deep canyons are also very dry, this becomes evident as one drives up the Poudre and Big Thompson canyons, and the Interstate 70 corridor near Idaho Springs.

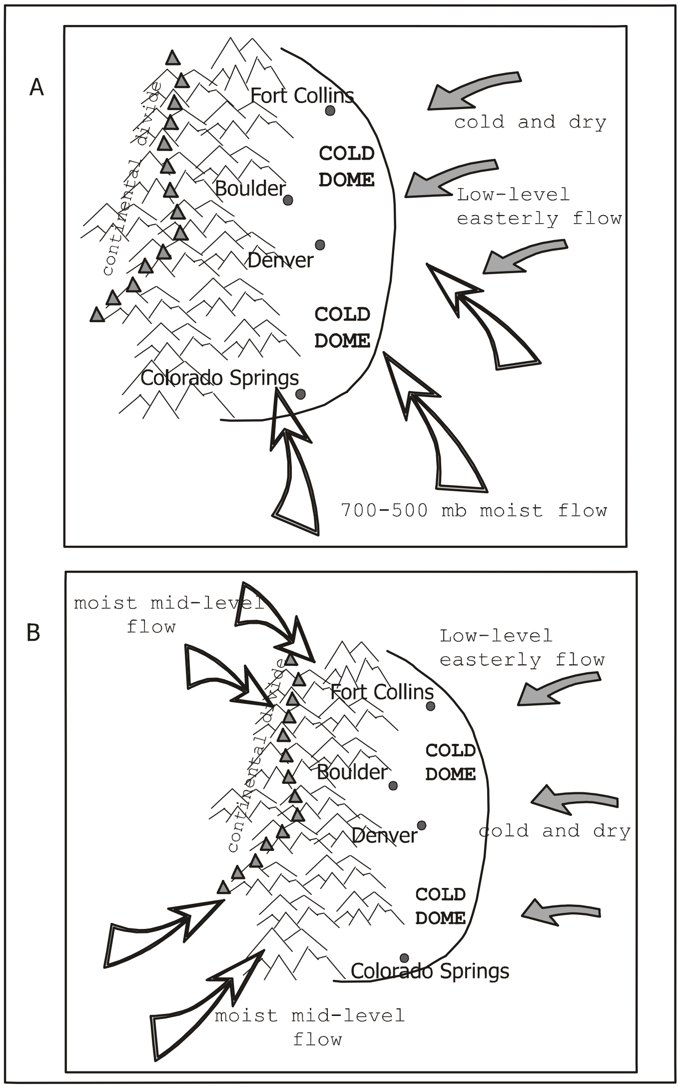


Figure 8.10- Two Front Range snow producing flow regimes. A) low-level easterly flow (upslope) with 700-500 mb flow from the southeast suppling the moisture. B) like in (A) but moisture is either from the southwest or northwest.

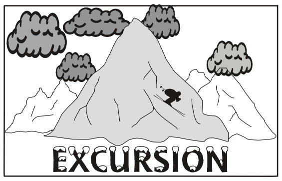
The seasonal distribution of precipitation in the Front Range is highly correlated to elevation. A number of studies have indicated that near the Continental Divide, the maximum in annual precipitation occurs during the winter months. At elevations below 3000 m (10,200 ft) maximum precipitation occurs in April and May as a result of convective rainfall. Along the base of the Front Range maximum precipitation shifts to July and August, this time in response to large convective systems that form to the lee of the mountains, as moisture is transported into the region from the Gulf of Mexico.

Temperature patterns in the Front Range are consistent with the rest of the southern Rockies. In mid-winter expect air temperatures at higher elevations to range between -10° C and -16° C (12° and 3° F). During mid-summer temperatures often range from 3° C to 13° C (38-55° F) at these same elevations.

The Front Range is also well known for its strong downslope windstorms that occur during the cooler months of the year. The requirements for a downslope windstorm are strong westerly winds in the 700-500 mb layer, and a stable layer or inversion just above the Continental Divide. If a dome of cold air is entrenched to the east of the Front Range, then as was noted above, downsloping winds will have a difficult time reaching the surface. The strongest surface winds occur in areas where the descending winds are funneled through gaps and passes in the mountains. Over the course of a typical winter, 5-8 downslope storms will occur in this region, with one or two of these storms able to produce damaging winds. During these more powerful events, windspeeds of 40-50 ms^{-1} (90-125 mph) in the foothills are possible. Most of these events last 6-12 hours. Obviously these wind events play havoc with the snowpack in the Front Range, creating large drifts in places and scouring the snow in others. The distribution of snow in the Front Range on the local-scale is a function of the wind more than any other factor. Down at the base of the Front Range some of these high wind events turn out to be chinooks, where there is a dramatic rise in air temperature, and a significant melting of the snowpack.

Cold air damming often leads to the formation of barrier jets along the east side of the Front Range. Since the low-level flow is from the east, unlike other ranges where barrier jets are common, this jet flows from north-to-south. This features are not that common, however when they do occur they can produce moderately strong northerly winds (10-15 ms^{-1} or 22-44 mph) between the Front Range and Interstate 25.

Like all areas in the southern Rockies, the Front Range has frequent thunderstorms during the summer months. From mid-April through early June, small cumuli form over the Front Range by mid morning. As the day progresses these clouds grow in size and move eastward over the plains. Rainfall during the summer months in the Front Range typically occurs in the late afternoon and early evening hours. Over eastern Colorado in contrast, rain typically occurs in the late evening and at night. Since thunderstorms are frequent in the Front Range, there is naturally also a high incidence of cloud-to-ground lighting strikes. Most bolts make their appearance in the late afternoon and in the early evening hours. An old Chinese proverb we once heard sums it up pretty well: “hike early, or die later.”



Wind Drift Glaciers of the Eastern Rockies

South of the Canadian border, the Rocky Mountains are pretty much devoid of glaciers except in a few locations such as Rocky Mountain National Park (RMNP), the Wind River Range, and Glacier National Park. In order for a small alpine glacier to exists, snow accumulation must exceed losses due to melting. A glacier does not disappear the first few years that melting exceeds snowfall, nevertheless, it does not take long for a small glacier to begin to retreat or thin. If the southern Rockies are not glacier-friendly at the present time, then why do small cirque glaciers exist in select locations? The answer can be found in one word: wind. Note that the three mountain regions that do have small cirque glaciers, straddle the Continental Divide. For example, as the Continental Divide cuts across RMNP, it tends to be quite broad, several kilometers in width as a matter of fact. This high elevation plateau is a good place for snow to be deposited. The problem is that being a high elevation site, it also has a high frequency of strong winds. These westerly winds blow freshly deposited snow eastward off of the divide. As air flows over the steep east slopes of the Divide, the wind loses its ability to carry the snow. As a result, the snow is deposited on the lee slopes, especially in areas where the terrain forms an amphitheater or a cirque (Latin for "bowl shape."). By late spring or early summer the amount of snow accumulation on the Taylor, Andrews, or Tyndall glaciers in RMNP can exceed the surrounding non-glacier, non-wind blown areas by 700% (Outcalt 1965). Just as the strong winds nourish these small glaciers, excessive amounts of wind blown snow on the leeward slopes of the Continental Divide also creates high avalanche danger that can last well into early summer.

In the present climate regime, glacier development in the southern Rockies is not possible because conditions are too dry. It is interesting to speculate what increase in snowfall would be required before glaciers could develop. It would probably require at least a doubling of the present winter precipitation, and a substantial decrease in summer temperatures as well.

Northern Colorado

The northern part of the Park range, specifically the higher elevations to the east of Steamboat Springs, is one of the wettest locations in Colorado. The area around Buffalo Pass receives somewhere on the order of 120 cm (47 in) of precipitation during the winter, with an annual precipitation near 165 cm (65 in). It is not hard to see why when you look at a map. The Park Range is the first major topographic feature that northwesterly flow encounters in hundreds of kilometers. It is interesting to compare this area with Wolf Creek Pass. The Park Range has more days with light snowfall, but Wolf Creek Pass has more days with heavy snowfall. This fits in well with the conceptual model that the southern San Juans receives its major snowstorms from moist southwest flow, while the Park Range which primarily derives its snow from drier westerly and northwesterly flow. Since westerly and northwesterly flow is drier than southwesterly flow, it takes more days of light snowfall to make up the difference. As it happens, westerly and northwesterly flow is more common over northern Colorado than southwesterly flow is in the San Juans. The net result is that the area around Buffalo Pass is the snowiest location in the state.

Southern Rockies Weather Summary

* Synoptic-scale snowfall distribution primarily a function of mid-level wind direction and elevation. Areas with little upstream terrain generally receive the most snow.

* Mesoscale and local-scale snowfall distribution is a function of orographic enhancement and wind speed. The amount of snow on the ground at any given time is highly dependent on wind redistribution.

* When a trough or low is positioned over the Four Corners region, considerable amounts of sub-tropical moisture is added to the flow, producing heavy snowfall events in the San Juans.

* Most of the region has two precipitation maxima, one in the winter and the other in late summer.

* Since many of the higher peaks in the southern Rockies lie in the middle-troposphere, strong winds are common, especially during the winter.

* From July through September, as the subtropical jet stream migrates northward, moisture from the Pacific Ocean and Gulf of California is transported over the Southern Rockies. This monsoonal flow produces frequent and intense thunderstorms over the mountains.

* Cloud-to-ground lighting is frequent throughout the region during the summer.

* Downslope windstorms and chinooks are most notable in the Front Range during the cooler months of the year.

WEB National Weather Service

Flagstaff	**www.wrh.noaa.gov/flagstaff**
Salt Lake City	**www.wrh.noaa.gov/saltlake**
Grand Junction	**www.crh.noaa.gov/gjt**
Albuquerque	**www.srh.noaa.gov/abq**
Denver	**www.crh.noaa.gov/den**
Pueblo	**www.crh.noaa.gov/pub** (see their lightning page)

Niwot Ridge, Colorado-	**http://culter.colorado.edu:1030**
Colorado Climate Center-	**http://climate.atmos.colostate.edu**
Colorado Avalanche Center-	**http://geosurvey.state.co.us/avalanche**
Utah Avalanche Center-	**www.avalanche.org/~uac**
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So. Utah Avalanche info.-	**www.avalanche.org/~lsafc**
Forest Service National Avalanche Center-	**www.avalanche.org/~nac**

The Northern Rockies

The weather and climate of the northern Rockies is in many respects distinct from the climate of the southern Rockies. In fact the climate of northern Idaho and northwest Montana, is more closely related with the climate of the Cascades, than with the rest of the Rockies to the south. This is not too surprising since the mountains of northern Idaho lie within 500 km (300 mi) of the Pacific Ocean. In addition to differences between the northern and southern Rockies, there are some major west-to-east differences in precipitation and temperature regimes within the northern Rockies.

Select climate stations that are located in or adjacent to the mountains are shown in Figures 8.11,12. The decrease in annual precipitation from the northwest to the southeast is evident in these figures. The winter storm track in the northern Rockies ranges from the southwest-to-northwest, the same as it is throughout western North America. The area surrounding Yellowstone National Park (referred to as Yellowstone), for example, receives its largest winter snowstorms when the flow is from the southwest. In contrast, large snowstorms occur in Glacier National Park (Glacier) when the storm track is more from the west. Mountains further to the east are favored for winter precipitation when the flow is either from the north-northwest or south-southwest. In addition, the eastern slopes of the northern Rockies receive snow from upslope events (easterly low-level flow), similar to what we described in the section on weather patterns of Colorado's Front Range.

The two wettest regions within the northern Rockies are northern Idaho and northwest Montana, in the vicinity of Glacier. These two regions receive roughly 60% of their annual precipitation between November and March. In contrast, the annual precipitation in Yellowstone is evenly distributed throughout the year (Figure 8.13). The eastern slopes of the northern Rockies on the other hand located within a continental climate zone, receive their heaviest precipitation in May and June.

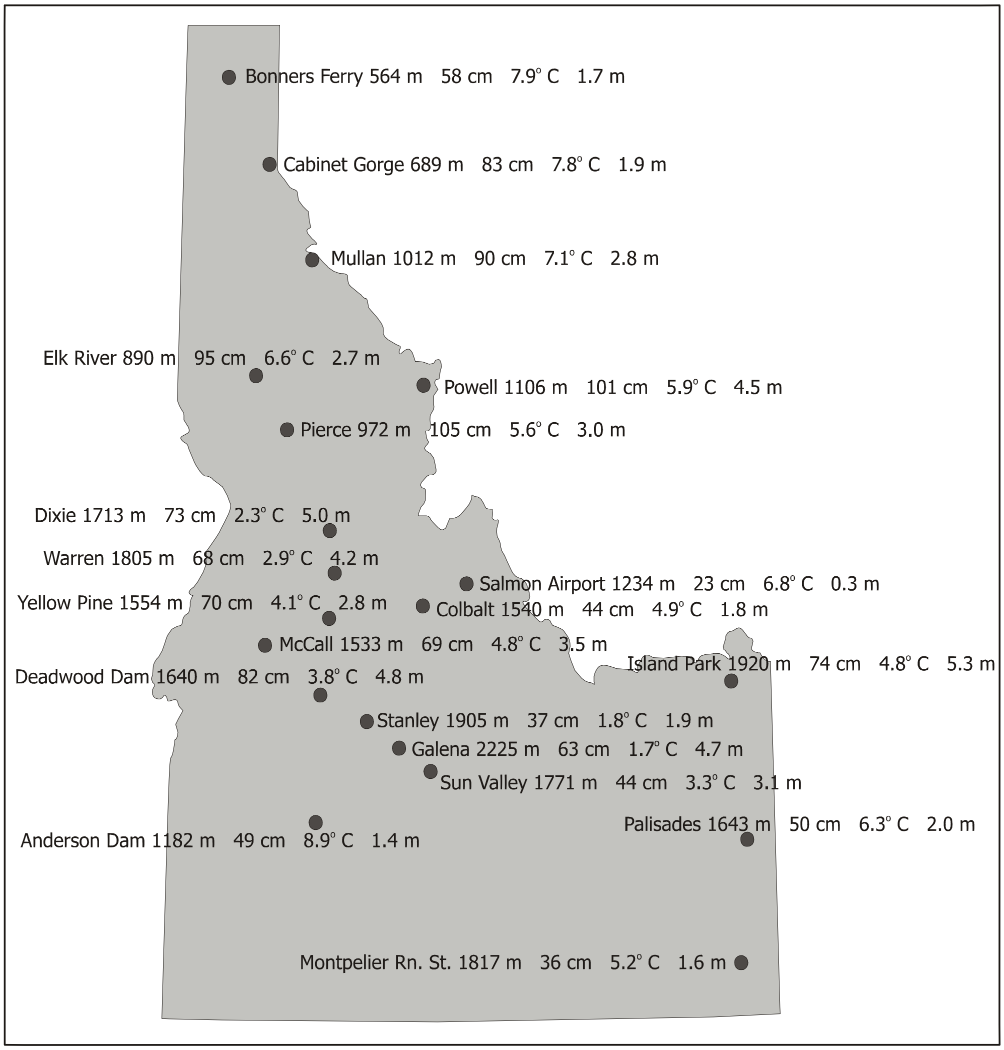

Figure 8.11- Climate data for Idaho. Data format is: station name, elevation (m), annual precipitation (cm), annual temperature (C), and annual snowfall (m).

The winter precipitation maximum in the western mountains occurs as a result of the polar jet stream transporting moisture inland from the Pacific Ocean. The polar jet stream migrates north and south over the northern Rockies between the months of October and April. Since the Rockies are some 300-600 km (200-400 mi) wide, the amount of Pacific moisture that is carried to the eastern mountains is greatly reduced. The May and June precipitation maximum in the eastern mountains can be explained in the following manner. In late spring and early summer there is rapid heating of the lower atmosphere over the northern Great Plains. In the mid-troposphere however, the air remains cool and dry, this makes the troposphere over the eastern mountains conducive to generation of cumulus clouds. Evaporation and sublimation of the mountain snowpack in May and June provides the moisture for the generation of towering cumulus and cumulonimbus clouds. By July the moisture supply in the mountains is diminished, which in turn causes a reduction in convective rainfall during the remainder of the summer. You may be wondering if the southwest monsoon, which begins in July in Arizona, has any effect on precipitation in the northern Rockies? Overall its impact is minimal, although from time to time large amounts of water vapor is transported into the northern Mid-West and Great Lakes regions.

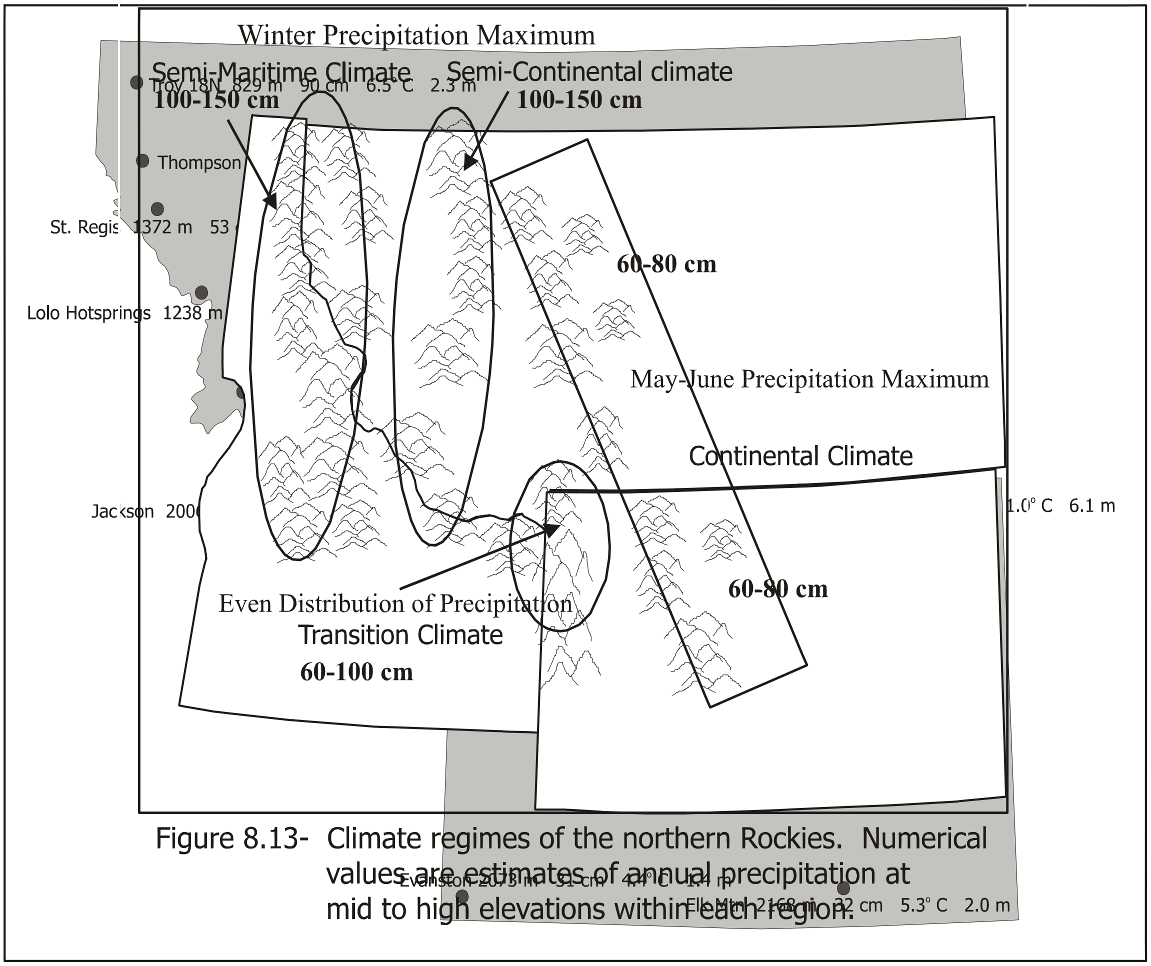

Figure 8.13- Climate regimes of the northern Rockies. Numerical values are estimates of annual precipitation at mid to high elevations within each region.

Figure 8.12- Climate data for Wyoming and Montana. Data format is: station name, elevation (m), annual precipitation (cm), annual temperature (C), and annual snowfall (m).

Temperature patterns in the northern Rockies are primarily controlled by elevation and secondarily by latitude and longitude. Northern Idaho and northwest Montana are influenced to some degree by the Pacific Ocean, this results in slightly warmer winters and slightly cooler summers when compared to the ranges that lie further to the east.

Yellowstone and Teton National Parks

The greater Yellowstone area consists of an elevated plateau which has an average height of about 2300 m (7,500 ft). Surrounding the plateau on the east and south are mountains that range in height from 3000 to 4000 m (10,000-13,000 ft). Yellowstone, being the oldest of the national parks, has a long history of meteorological observations, much of which is displayed in Figure 8.14. On average most of the Yellowstone/Teton plateau receives between 50 and 70 cm (20-30 in) of annual precipitation. Even though there are no climate stations in the mountains, limited data from snotel stations indicate that precipitation in the mountains is significantly higher than on the plateau. The time at which snow on the ground obtains its greatest seasonal depth is a function of elevation; in Yellowstone it occurs in late March-early April, and in the surrounding mountains generally between the middle and the end of April. Precipitation is spread fairly evenly over the year, there being a slight maxima in December-January and again in May-June. In Figure 8.14 notice how a station like

Jackson, which is located in a valley, receives considerably less precipitation than more 'open' sites to the north. Of course the mountains around Jackson receive considerably more snow than what is measured in the valley itself.

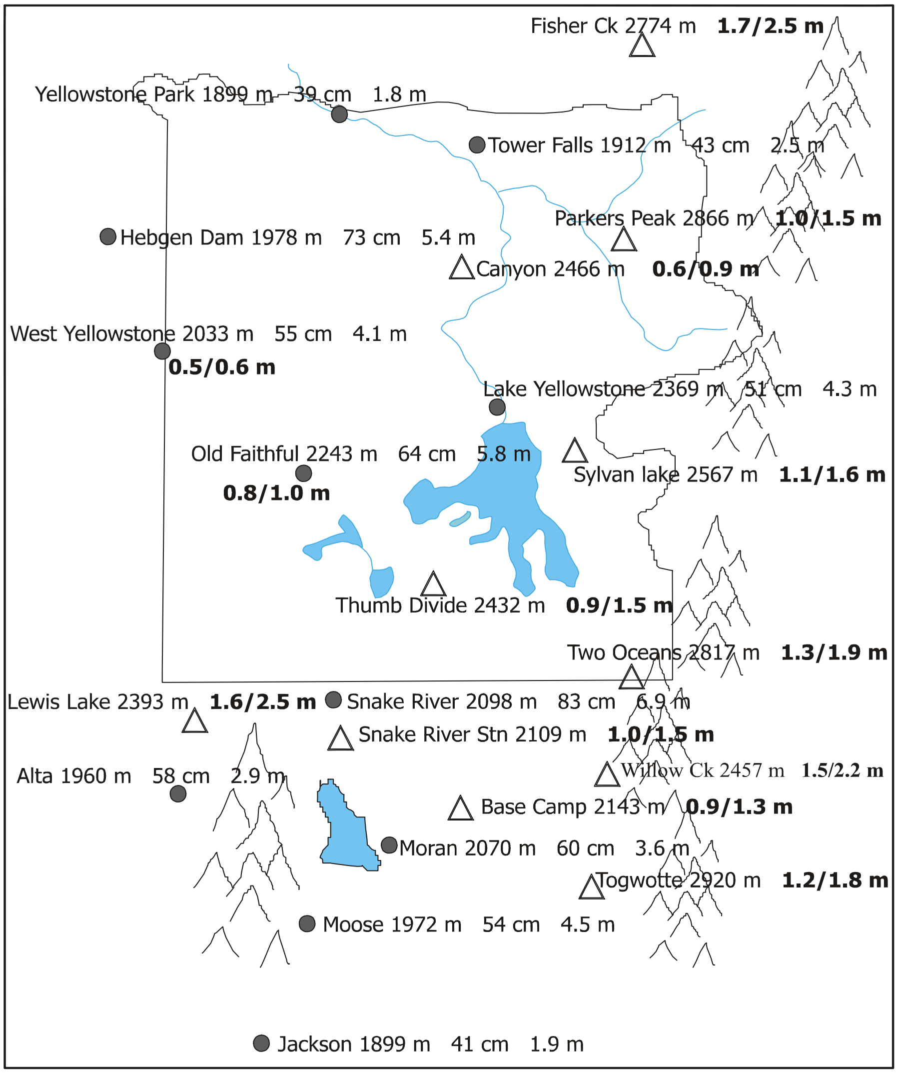

Figure 8.14- Climate data (solid circles) and snotel data (triangles) for stations in Yellowstone and Teton National Parks. Climate data consists of: station name, elevation (m) annual precipitation(cm), and annual snowfall. Snotel data consists of: station name, elevation, first of the month snow depth for February/April. There are several sites where a climate and snotel station are co-located.

Data from the climate station at Moose (1972 m), located on the east side of the Tetons, indicates that during midwinter, measurable precipitation occurs one out of every two days. This does not mean that it snows every other day. It may snow lightly for three for four days straight, and then not snow again for a week. From July-October, precipitation occurs about once every four days. During the summer however, we have to be careful interpreting rainfall data since convective rain showers have limited spatial coverage. What this means to the backcountry traveler is that it rains in the area much more frequently than rainfall data from one or two fixed climate stations indicates. Therefore you should anticipate the development of thunderstorms in the area on most summer afternoons. As a result of frequent thunderstorm activity, prudent climbers and hikers should be concerned about and monitor cloud-to-ground lightning during the late afternoon and evening hours. Climbers should also note that during the summer, overnight lows can be quite cool. The average minimum temperature for July and August at the Moose climate station is +5° C (41° F). This means that above 2500 m (8,200 ft), the overnight temperatures frequently dip below freezing. The coolest overnight temperatures will typically occur on cloudless nights when the winds are light.

Most people are aware that during the winter, Yellowstone is one of the coldest locations in the continental USA where daily observations are recorded. Table 8.1 lists monthly mean and extreme temperatures for the months of November through April from the climate station at Lake Yellowstone (2369 m or 7,770 ft).

It is readily apparent from this table that winters are cold in Yellowstone and that from time to time temperatures can become life threatening. If you are going to travel in this region in the winter, you should be equipped to deal with temperatures below -30° C (-22° F). Since the Yellowstone area is often referred to as the nations icebox, we compared average monthly temperature data from Lake Yellowstone with several other well know "cold spots" around the country. By comparison, Lake Yellowstone has slightly colder mean monthly temperatures than Fraser, Colorado (2610 m or 8,560 ft), although the mean monthly minimum temperatures at Fraser are a degree or two colder than Lake Yellowstone. We also compared Lake Yellowstone with International Falls, Minnesota. Lake Yellowstone is significantly warmer than International Falls, at least from December through February.

In March, International Falls warms up considerably faster than Lake Yellowstone, and remains warmer throughout the summer. As a result, Lake Yellowstone has an annual temperature that is 2.7° C (4.9° F) cooler than International Falls. In order to see how winter temperatures in Yellowstone compared against higher elevation sites, We compared Lake Yellowstone to Climax, Colorado (3463 m). Monthly averaged winter temperatures indicate that the Yellowstone area is slightly colder than Climax, despite being 1090 m (3,600 ft) lower.

Table 8.1 Lake Yellowstone winter temperatures

	Ave. High	Ave. Low	Extreme High	Extreme Low
November	+1 °C	-11 °C	+17 °C	-34 °C
December	-4	-16	+9	-42
January	-6	-19	+7	-46
February	-2	-18	+13	-46
March	+1	-16	+14	-42
April	+6	-10	+18	-32

So why are winter temperatures in the Yellowstone area so cold? It is a combination of the elevation, near continuous snow cover, and most of all, the fact that the plateau is surrounded by mountains. These mountains essentially trap cold air over the plateau allowing deep temperature inversions to form. Even though Yellowstone is not considered your typical valley, during the winter cold air becomes stagnant like in any other valley. The coldest winter temperatures occur when the northern Rockies are under the influence of a surface high with a large amplitude 500 mb ridge positioned over western Canada. Once cold air becomes trapped in Yellowstone, the only way it can be replaced by relatively warmer air is if a deep trough or low moves into the area from the west. In this situation cold continental air that has been sitting over the northern Rockies is exchanged with warmer maritime air from the West Coast.

Glacier and Waterton Lakes National Parks

These two parks incorporate some of the most rugged terrain in all of the northern Rockies. As was alluded to earlier, this area is one of the wetter spots in the northern Rockies. Annual precipitation at higher elevations is on the order of 150 cm (60 in) with the heaviest precipitation occurring during the winter. The precipitation gage at Flattop Mountain (1920 m) in Glacier NP for example, receives 49% of its annual precipitation between the months of November and February.

Figure 8.15 shows climate and precipitation data for a few stations in and near Glacier NP. The relatively low annual precipitation at West Glacier (960 m) is due to its low elevation. The large contrast in precipitation between Flattop and Many Glacier is interesting. It probably reflects differences in elevation and more importantly, differences in the surrounding topography. Monthly averaged precipitation for these two sites indicates that the largest difference occurs in the winter. We would speculate to say that there is probably considerably more orographic lift occurring in the vicinity of Flattop than around Many Glacier.

Table 8.2 provides a sample of temperatures a hiker or climber could expect during the summer at intermediate elevations within Glacier NP. The proper way to interpret this data is as follows: The range of high temperatures during May is roughly between 19° and 2° C (66° and 36° F). What is readily apparent is that the range of high temperatures is much larger than the range of low temperatures. At this particular elevation the overnight lows are for the most part below freezing until mid-June. The <u>warmest high temperatures</u> occur when the axis of a high pressure ridge is located to the east of Glacier NP. This allows warm air from the Great Basin to move into western Montana. However,

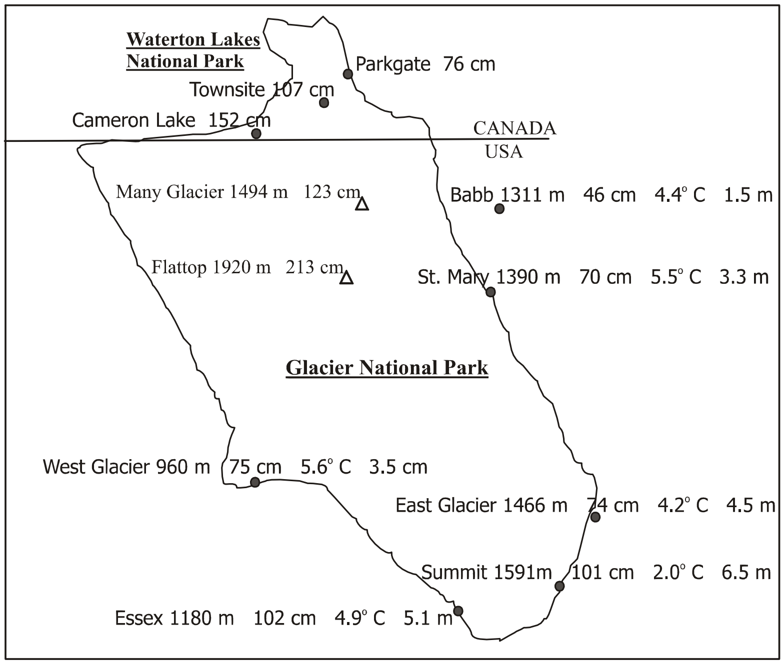

Figure 8.15- Climate (circles) and snotel data (triangles) for Glacier and Waterton Lakes National Parks. Climate data consists of: station, elevation (m), annual precipitation (cm), annual temperature (C), and annual snowfall (m). Snotel data consists of: station, elevation (m), and annual precipitation (cm).

temperatures can be quite cool at night when winds are light and the sky is free of clouds. The coolest high temperatures occur when a synoptic-scale trough or low moves over the region. Keep in mind that temperatures in May and early June are dependant on the amount of snow on the ground. At higher elevations in Glacier NP, the first accumulating snowfall of the season typically occurs during the second half of September.

Table 8.2: Temperature range at Flattop Mountain (1920 m)

Month	High Temp. Range	Low Temp Range
May	19° to 2° C	3° to -8° C
June	20 to 3	5 to -3
July	25 to 9	10 to 1
August	27 to 8	10 to -1
September	24 to 3	8 to -5

Strong winds at higher elevations are a common occurrence in both Glacier and Waterton Lakes, especially during the winter when the polar jet lies overhead. The east side of Glacier NP as well as communities along Highway 89, frequently experience strong chinooks during the winter. Environment Canada (Canadian Weather Service) estimates that chinooks on average occur four to five times per month on the eastern side of Waterton Lakes. These chinooks cause rapid melting of the snowpack as well cause rapid rises in leeside temperatures. Chinooks are so efficient at melting snow because strong winds cause a continuous flow of dry air over the snowpack. In addition to chinooks, low-level winds are often accelerated as they flow through the narrow canyons of Glacier and Waterton Lakes. A good indicator of the frequency and strength of the winds at higher elevations are the numerous small cirque glaciers located on the eastern side of the Continental Divide. Strong winds blow snow from the windward slopes over the crest of the divide where it is deposited in the cirques and bowls of the eastern slopes.

Thunderstorms are common throughout the summer months, in large part due to the warming of the plains to the east. Unlike the Rockies to the south, northern Idaho and northwest Montana have a relative high frequency of synoptic lows and troughs move over the region during the summer months. These disturbances often work in conjunction with convection to produce periods of moderate to heavy rain across much of the region.

Forecasting: Chinooks and downslope windstorms

Here are some suggestions to help you forecast chinooks. First of all recall that the conditions that lead to a downslope windstorm or chinook are: moderate to strong summit-level winds, the wind direction should be close to being perpendicular to the long-axis of the mountains, and finally the air in the middle troposphere has to be stable.

Step One- Choose one of the forecast models (ETA, AVN) from one of your favorite web sites. Pull-up the 700 mb wind speeds. The reason you want this level is because it is close to summit level for most of the larger mountain ranges in the western USA. As a rule of thumb, the winds at this level should be around 20 ms^{-1} (45 mph) or greater.

Step Two- Check on the 700 mb wind direction if you were not able to in step one. If 700 mb winds speeds (wind barbs or wind vectors), you can use the 700 mb height field as a default. Remember that at this height (3300 m), the direction of the wind is parallel to the height isolines. You will easily be able to tell the wind direction, which for the western USA should be from the northwest to southwest. Determining wind speeds from the height field is more difficult. The closer isoline spacing the stronger the winds, but estimating actually speeds takes some practice.

Step Three- Now you need to determine if the middle troposphere is stable or not. Most likely you will not be able to access a vertical cross-section of surface-to-500 mb temperatures. If you can get a forecast or current sounding from a nearby station, use it. You want to see if the lapse rate between 850 mb and 500 mb is less than about 6^{o} C km^{-1}. In lieu of a sounding or vertical cross-section, pull-up the 850 mb temperatures, noting what the temperatures are in the area of interest. Repeat this for the 500 mb level. Since the average height difference between 850 and 500 mb is about 3800 m (± 200 m), if the temperature difference is less than 23^{o} C (41^{o} F), then the layer is stable.

This procedure may be difficult to do depending on the availability of model data. One suggestion is to wait for a chinook to be forecasted in an area of interest to you, then try this procedure to see what key weather elements the forecasters are looking at.

Banff and Jasper National Parks

The weather and climate of the northern tip of the Rockies is quite similar to what was just described for Idaho and Montana. The bulk of moisture that eventually falls as snow and rain in is transported from the Pacific Ocean. The largest winter storms of the season occur when a trough or low forms over or north of Vancouver Island,. This produces strong southwest winds over British Colombia. Since there is considerable mountainous terrain between Banff-Jasper and the Cascades, the wettest region in this part of the Rockies lies to the west (upstream) of the Continental Divide. This includes the Bugaboo's, Glacier National Park, the Selkirk and Columbia mountains; where annual precipitation is on the order of 125-150 cm (50-60 in). In Banff and Jasper National Parks, annual precipitation is on the order of 100-125 cm (40-50 in). In contrast the climate stations in the towns of Banff and Jasper, which are located to the lee (east) of the Continental Divide, only average about 40 cm (16 in) of annual precipitation.

Most of the climate stations in eastern British Colombia have a winter and summer maximum in precipitation. Winter precipitation is heaviest from Nov-Jan, this is followed by a two-fold decrease in monthly precipitation in February and April. In May, precipitation starts to increase, with the second maximum occurring in July-August. The February-April precipitation minima is due to the fact that the polar jet lies for the most part lies well to the south of the region. Due to the decrease in precipitation during the second-half of winter, the snowpack at the mid-elevation sites reaches its maximum depth usually sometime in February. To the east of the Continental Divide, there is a single precipitation maximum that corresponds to the summer convective season. Thunderstorms are a common throughout the region. Many of the larger cumulonimbus clouds develop over the Rockies then move eastward onto the plains of Alberta during the evening.

In the elevation range of the climate stations in the region (500-1000 m), mid-winter temperatures range from -5° C to -15° C (23° to 5° F), obviously it can get much colder than this when the region is under the influence of high pressure and the skies are free of clouds. During the summer temperatures at this same elevation range from 10° C to about 25° C (50° to 77° F), which means that at an elevation of 3000 m (9,800 ft) expect temperatures on the order of -4° C to 10° C (27° to 50° F).

One noteworthy feature of this stretch of the northern Rockies are the size of some of the glaciers in Jasper National Park, especially when compared to the Rockies of Montana and Wyoming. The annual precipitation in Jasper N.P. is roughly equivalent to what occurs in northern Idaho and Montana, however, the annual temperature in Jasper is considerably cooler. This brings up an important point, many mountain glaciers were much larger in preceding centuries. What we see today are much smaller remnants which continue to slowly melt and recede.

To the east of the Continental Divide, chinooks are very common during the cooler months of the year. These strong winds cause a very large rise in temperatures at the base of the Rockies, along with a rapid snowmelt.

Northern Rockies Weather Summary

* Northern Idaho and northwest Montana are considerably wetter than the rest of the range. This is a result of a much higher frequency of synoptic disturbances moving over the northern region during the summer and winter.
* The eastern ranges have a May-June precipitation maximum, northwest Wyoming and eastern Idaho have a fairly even distribution of precipitation throughout the year, while the north has a pronounced winter maximum.
* Downslope windstorms and chinooks are common in winter at the base of the eastern Rockies.
* Summer-time Convective rainfall and cloud-to-ground lightning are common over much of the region.
* Winter temperatures in some of the higher elevated valleys and uplands, such as Yellowstone, can periodically be extremely cold.

WEB National Weather Service

Billings	**www.crh.noaa.gov/billings**
Missoula	**www.wrh.noaa.gov/missoula**
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Pocatello	**www.wrh.noaa.gov/pocatello**
Riverton	**www.crh.noaa.gov/riw**
Spokane	**www.wrh.noaa.gov/spokane**
Boise	**www.wrh.noaa.gov/boise**

Forest Service National Avalanche Center - **www.avalanche.org/~nac**

Bozeman Avalanche Center-	**www.mtavalanche.com**
Glacier Avalanche Center-	**www.glacieravalanche.org**

Jackson Avalanche Center- **www.jhavalanche.org**
Canadian Avalanche Association- **www.avalanche.ca**
Canadian Weather- **www.weatheroffic.com** or **www.cmc.ec.gc.ca**

Professional Profile
An Interview With Nolan Doesken

Nolan Doesken is the assistant state climatologist for Colorado. He has been involved in collecting and analyzing climate data in Colorado for over 20 years. Nolan has had a fascination with snow since his youth. In 1996 he co-authored a book on the fundamentals of snow meteorology and snow measurement techniques. Check out the Colorado Climate Center at: http://climate.atmos.colostate.edu

Q1- Why are the central Rocky Mountains renown for dry powder snow?
ND- Basically it is a combination of our high elevation and interior continental location. A lot of snow falls at temperatures well below the freezing point and from airmasses that have been stripped of low-level moisture from upstream mountain ranges. The result is that these clouds are somewhat lacking in supercooled water, so ice crystals are not so heavily rimed as is common in warmer maritime areas. The result is snow that is poor for making snowballs, but great for skiing and snowboarding.

Q2- Is there very much seasonal snowfall variability across Colorado?
ND- We have known for many years that seasonal snowfall patterns often favor either the northern Rockies or the southern Rockies, but rarely both. It is however a fairly recent discovery that these changing patterns are often associated with El Nino and the Southern Oscillation and the resulting changes in ocean currents and sea surface temperatures thousands of miles away. Here in Colorado we often see our northern mountains (Winter Park, Vail, Steamboat, etc.) have excellent snow years while the southern mountains (Wolf Creek, Purgatory, etc.) are getting lousy snows. When our southern mountains are getting buried, northern Colorado snowpacks are often thin. There are winters like 1977, when the entire region is dry, and there are likewise occasional winters when the whole state is buried in deep snow. But as a rule, one regions bounty is another’s woe.

Q3- What are some of the difficulties in measuring snowfall amounts?
ND- Measuring snow seems so simple to the casual onlooker- just take a ruler and stick it in the snow. That’s fine and good until you begin to comparing data from different location and different observers. The reality is that measuring snow in a consistent and accurate fashion is much harder than people realize. The reasons are pretty obvious, when you think about it. Measuring snow is like shooting at a moving target. Snow melts, snow settles over time (densification), and of course it blows and drifts. Three good observers can measure the same snowfall and come up with distinctly different answers. We have found that the more frequently an observer takes a snow measurement,

the more snow they are likely to report.

The Mountains of New England

The weather in the mountains of New England like most of the rest of North America is dictated primarily by mid-level westerly winds. This should not be taken to mean that the winds are always out of the west, however what it does mean is that the long-term average wind direction in the middle-troposphere is from the west. In actuality there are a number of important flow patterns (primarily winter time) that you should be able to recognize in Figure 8.16. 1) northwest or northerly flow from Canada, 2) southwest or southerly flow from the Ohio valley or mid-Atlantic Seaboard, 3) easterly or southeasterly flow from the Atlantic Ocean, and; 4) east to northeast flow from a Nor'easter. These Nor'easter's are not very common, however they produce large amounts of rain or snow. Many of these storms are remnants of tropical storms that have re-intensified as they move over the warm water of the Gulf Stream. They typically develop very rapidly and hence are called cyclogenic 'bombs' by forecasters.

Remember that cooler air moves into New England when the flow originates from Canada. When the dominate flow direction is from the southwest (trough), the air mass over New England will be warmer and somewhat wetter when compared to north or northwesterly flow (ridge). Storms that move in from the Atlantic are wet and start-off warm but temperatures may cool as the flow becomes more north or northeasterly.

Adirondacks

Since the Adirondacks cover a large portion of northern New York, there is considerable variation in the distribution of rain and snow. For example, annual precipitation varies from 130 cm (51 in) over the southwest and central Adirondacks to about 100 cm (39 in) in the vicinity of Lake Placid. Annual snow fall is distributed in a similar fashion, the southwest and central mountains typically receive from 380-460 cm (150-180 in), while the eastern slopes receive on the order of 250-305 cm (100-120 in). There is a slight increase in monthly precipitation from June through September, but overall precipitation is remarkably uniform over the course of a year. In January for example, snowfall occurs on 12-15 days out of the month. In July, expect measurable rain to occur 8-12 days out of the month. During the summer a considerable amount of rain falls during thunderstorm activity.

Temperatures across this region are a function of elevation, two weather stations on opposite sides of the range but at the same elevation will have similar monthly and seasonal temperatures. On a daily basis however, there can be noticeable temperature differences across the range as a result of cold or warm air masses moving into or out of the region. The majority of the climate stations in this region are located at an elevation of about 500 m (1,700 ft). At this elevation typical January temperatures range from -1° to -15° C (30° to 5° F). In addition, the number of days in January where the minimum temperature is below -18° C (< 0° F), is on the order of 12 to15. In July expect a temperature range of 10° to 26° C (50° to 80° F), fortunately very few days get hotter than 32° C (90° F). At higher elevations allow for cooler temperatures than what is listed above, especially in the summer.

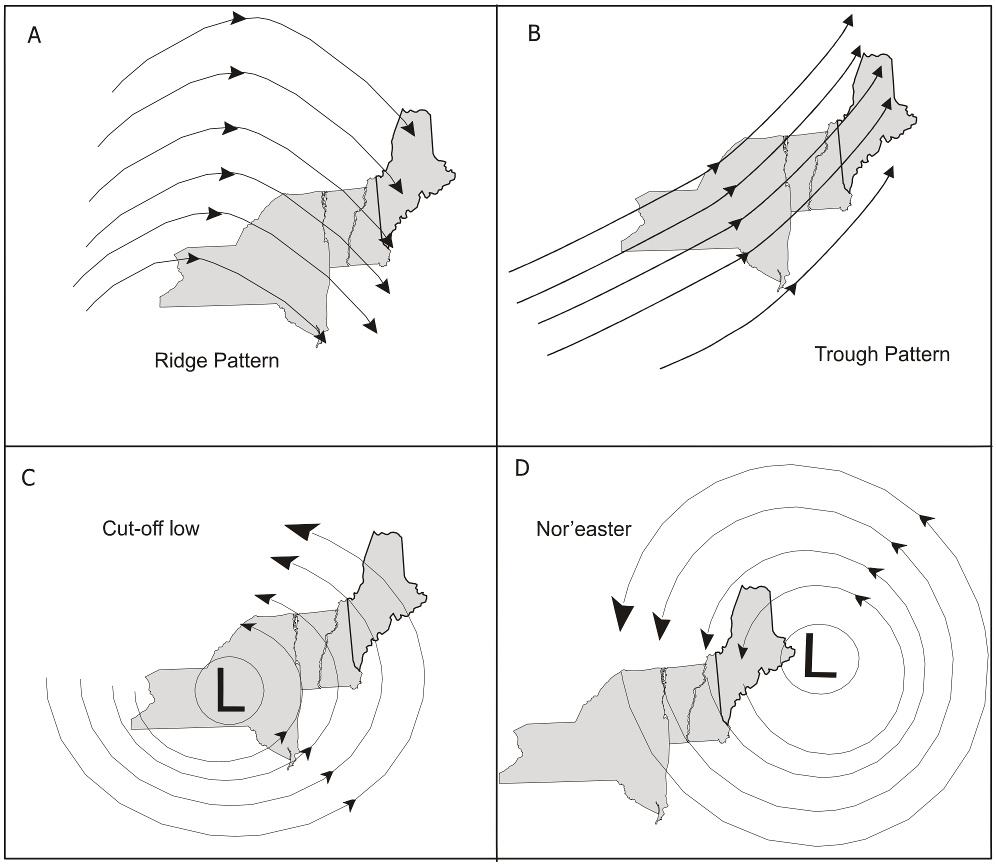


Figure 8.16- Four fairly common flow regimes of New England.

White Mountains

The White Mountains of New Hampshire are in many respects the centerpiece of New England mountains, in large part due to the fact that there are eight mountains that exceed a mile in height (1600 m). Since the early 1930's a non-profit weather observatory has been located atop Mount Washington (1915 m or 6,280 ft). Through the years the Mt. Washington Observatory (MWO) has gained a reputation as a credible organization who's mission is to document the harsh climate of the Presidential Range, and to disseminate this information to the public.

An examination of the climate record of northern New Hampshire clearly shows the influence of elevation on annual precipitation, as displayed in Table 8.3. Like all of New England precipitation is distributed quite evenly over the 12 months of the year, although at the MWO November and December receive the highest precipitation. Average annual snowfall is 645 cm (254 in) at the observatory but somewhere around 200 cm (80 in) in the surrounding low-lands, away from the Presidential Range. At MWO the December through March monthly average snowfall is about 104 cm (41 in). Like any other mountainous area, there is considerable year-to-year variation in snowfall in the Presidential Range. In addition, the actual amount of snow that lies on the ground at any given time not only depends on the amount that fell from the sky, but how much of the snowpack has been re-distributed by the wind after it fell. This is apparent to anyone who has seen or been to the top of Mt. Washington during the winter. Snow accumulates in depressions in the landscape and in the forest much better than it does in wind exposed areas.

Table 8.3: Climate data for northern New Hampshire

Station	Elevation (m)	Annual Precip. (cm)	Ave. Jan Temp. (C)	Ave July Temp (C)
Benton	366	93	-8°	19°
Berlin	283	107	-10°	19°
Errol	390	98	NA	NA
1St Conn. Lk.	506	113	-13°	17°
Jefferson	376	122	NA	NA
Lancaster	262	93	-10°	19°
Mt. Washington	1915	251	-16°	9°
North Conway	162	122	-8°	20°
Pinkham Notch	612	150 est.	-10°	17°

Temperatures in the White Mountains are primarily a function of terrain configuration (valley versus ridge) and elevation. In Chapter 3 you learned that temperatures in general decrease with increasing height, the main exception occurs in the presence of a temperature inversion. When a inversion does occur, the rule of thumb which states that air temperature decreases with height is temporarily invalid. Since temperature inversions occur frequently during the winter months throughout the mountainous terrain of New Hampshire (this applies to all of the mountainous terrain of New England), they are an important factor in the wintertime climate of the region. What all this means to the mountain traveler is that during the winter the air temperature at higher elevations is not as cold as you may think it is based on the current temperature at the base of the mountains (not accounting for windchill). Notice in Table 8.3 how the average January temperature for Mt.

Washington is not that much colder than temperatures at surrounding low-land stations. Also notice that during the summer the temperature difference is significantly larger. Overall, there will be a larger difference in air temperature between the base of the mountain and the summit during summer rather than during the winter.

Without a doubt the most important meteorological element in the White Mountains is the wind. Above treeline the seasonally averaged wind direction is northwest-to-southwest. This does not mean that significant winds do not blow from other directions as well, however when they do occur they are typically of short duration. The windiest months are October through April where monthly average wind speeds run about 33% higher than during the summer. Keep in mind however that strong or very strong winds can occur on any given day of the year. In a review of high winds that occurred on Mt. Washington between 1980 and 1997, Keim and Edminster (1998) found the 18 year average of wind gusts greater than 56 m/s (125 mph), was 8.7 per year, while the average for gusts greater than 63 m/s (140 mph) was 2.2 per year. We want to emphasize that these are gusts of wind, in other words- short burst (a few seconds) of very strong winds. There is a big difference between sustained winds, which are averaged over several minutes, and gusts. When the sustained winds are high, there is a greater chance that strong gusts will occur as well.

The obvious question that has to be addressed is: why is Mt. Washington so windy, and is it unique to the region? There are several considerations: first, the mountains of New Hampshire and northwestern Maine separate two contrasting climatic zones, the maritime zone to the east and the continental zone to the west and north. During the winter months the continental zone is much colder than the maritime, this produces higher pressure over northern New England and Canada. Since air moves from higher pressure to lower pressure, the lower tropospheric winds are from the west or northwest across much of the region. Secondly, the polar jet stream is frequently located over New England, as illustrated in Figure 8.16. The strongest winds in the polar jet lie well above the tops of the mountains of New England, but from time to time very strong winds can be found in the middle and even lower troposphere.

On December 4, 1980 a 81 m/s (178 mph) wind gust was recorded at the observatory atop Mt. Washington. The 850 mb height field and sustained wind speeds for this event are displayed in Figure 8.17. Notice that the flow is north-to-northwest over New England at this level (850 mb is close to the height of the mountains in this region). Prior to and at the time of this event, very cold air was located in Quebec with much warmer air over coastal New England. This helped the intensify the low that is positioned over Nova Scotia. Free atmospheric winds at 850 mb were on the order of 30-35 m/s (65-80 mph). Although not shown, the 500 mb low center was positioned near Long Island, while the axis of the polar jet stream was located along a line from Buffalo to Philadelphia. Not only were the winds at Mt. Washington very gusty, but the average daily wind speed for December 4th , was a phenomenal 53 m/s (117 mph). Strong winds continued into December 5th, but not with the same intensity.

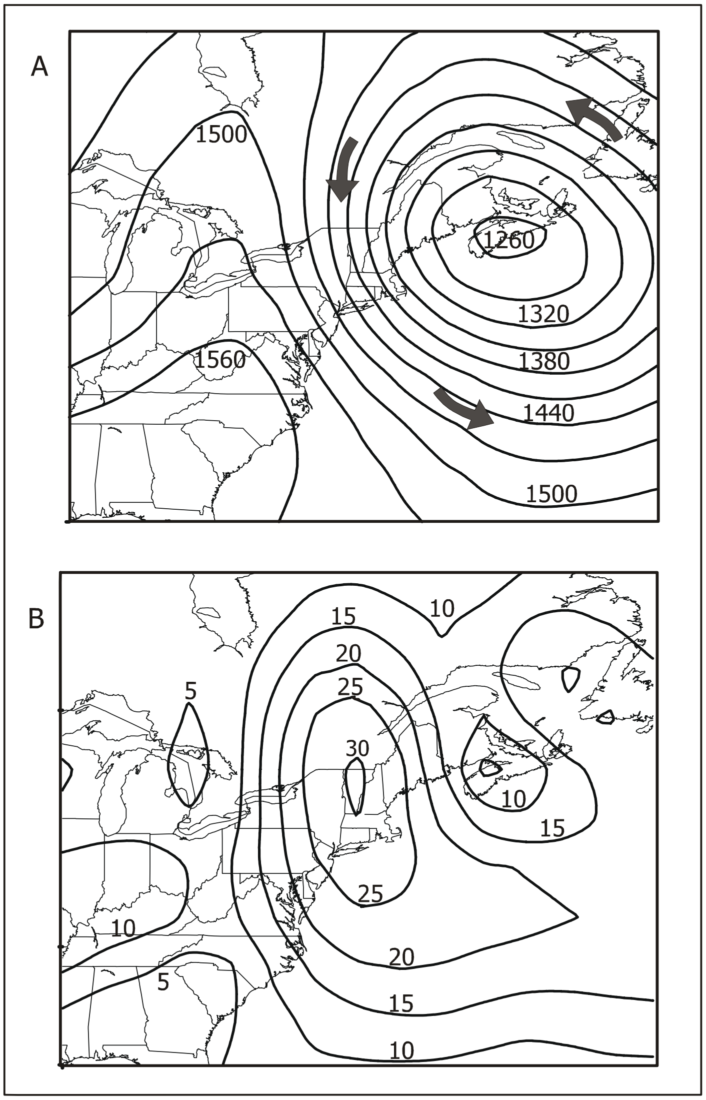
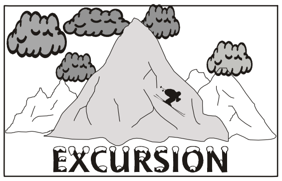


Figure 8.17- December 4, 1980 windstorm. A) 850 mb heights (m), B) sustained wind speeds (m/s). A peak wind gust of 81 m/s (178 mph) was measured at the Mt. Washington observatory during this storm.

In retrospect, during the night of December 3, a strong temperature inversion centered around 800 mb (1900 m or 6,200 ft) developed over New England. This height corresponds closely with the elevation of the highest peaks in the White Mountains. What appears to happen is that strong free atmospheric winds, which are generated by the synoptic-scale pressure gradient, are amplified as they flow between the ground and the inversion. How such strong gusts are generated we do not believe anyone fully understands at this time. What we do know is that most of the big wind events that have been recorded by the MWO, have a duration on the order of 12-24 hours, although longer events do occur. Winter travelers to the higher terrain of the White Mountains should note that strong wind speeds 'ramp-up' over a period of 3-6 hours. In other words, you will not get blasted with a 50 m/s (110 mph) gust during a period when the winds are otherwise light. As wind speeds increase however, the likelihood that very strong gusts will materialize also increases.

It is interesting to speculate whether the high winds frequently observed on Mt. Washington are common on other high mountains of New England as well. There is not much in the way of data to support a definitive answer to this question, nevertheless we would speculate that most of the higher peaks of Maine, New Hampshire, and Vermont also have very strong winds. Winds at higher elevations in the Adirondacks on the other hand are probably not as strong or frequent as they are in the mountains to the east, simply because of their more continental location. One important aspect that is extremely difficult to account for is: what role does local topographic affects play in Mt. Washington wind events. This could only be determined if additional wind sensors (anemometers) were placed on a number of higher peaks in the region. This would also make a good high resolution computer model research project.



Acid Rain

In the mid and late 1980's the topic of acid rain was one of the most popular environmental issues in the media. By the mid 1990's however there was little mention of it. So what is acid rain and has the problem gone away? First, acid rain is defined as natural occurring rain or snow that has a pH <5.6. This occurs when dust and organic cloud condensation nuclei are replaced by sulfur dioxide (SO_2) and nitrous oxides (NO_x) . SO_2 and NO_x are commonly emitted into the atmosphere during the burning of coal and other fossil fuels. It should be no surprise than that the northeastern USA was the region with the greatest acid rain problem. The area of concern was eastern Ohio, northern West Virginia, Pennsylvania, large parts of New York including the Adirondacks, as well as parts of Vermont. There was considerable media interest in the fact that so-called "pristine" lakes of the Adirondacks had very high acid levels. This illustrates the fact that atmospheric pollutants area transported considerable distances from their place of origin.

Secondly, the acid rain problem has not disappeared. However, due to stricter regulations on coal during industries since the late 1980's, the amount of SO_2 and NO_x released in the atmosphere each year has been cut considerably. This in turn has lead to a decrease in the amount of acid entering lakes and waterways of the northeastern USA, although the pH in these bodies of water remains low. The environmental impacts of acid rain (and snow) are: the death of certain kinds of fish species, it also destroys certain kinds of bacteria and microorganisms in soils, and it has been know to weaken or kill some species of spruce trees. Sulfates are also a major producer of haze, which causes lower visibility in mountainous regions, even though the sulfates originate hundreds of kilometers away from the mountains.

New England Summary

* Even distribution of precipitation throughout the year.
* Considerably higher amounts of precipitation in the mountains than at their bases.
* Considerable winter fluctuations in air temperatures in response to changing air masses. The coldest air arrives with flow from the north and northwest while the warmest air is transported by southerly or southwesterly flow.
* Warmest temperatures during the summer occur when a quasi-stationary (slow movement) ridge of high pressure is located over over the Great Lakes or New England.
* Thunderstorms primarily occur in June, July and August.
* Strong winds are a common occurrence at higher elevations especially during the winter months.
* Occasionally powerful storms develop off the coast of New England, producing strong easterly winds and transporting large amounts of moisture into the region. These are not good times to be in the mountains.

WEB Mt Washington Observatory- **www.mountwashington.org**
Avalanche Center- **www.tuckerman.org**
National Weather Service
Albany- **www.erh.noaa.gov/er/aly**
Burlington- **www.erh.noaa.gov/er/btv**
Portland- **www.erh.noaa.gov/er/gyx**
Caribou- **www.erh.noaa.gov/er/car**