Air Flow over Complex Terrain in the Colorado Front Range

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D1 Site

Introduction

The occurrence of upslope, or easterly, winds in the Front Range of the Colorado Rockies is the focus of this study. These winds are important for several reasons, such as the proximity of a major urban area along the base of the Front Range and the associated air quality issues this proximity implies for the sub alpine forests and alpine zones of the Front Range.

Upslope winds are a common feature of the Front Range, particularly in the summer, although they do occur in every month of the year. One cause of upslope flow is thermal heating of the earth's surface. The Front Range faces east, so it receives the sun's energy first in the morning (more directly than the plains), which promotes rapid surface heating early in the day. As the sun's rays strike the surface, warming occurs. Then air immediately in the vicinity of this warming surface also begins to warm. The warm air is less dense than cool air and therefore will rise.

A second pathway to upslope flow is from large-scale synoptic circulation conditions. Upslope flow can occur when there is a low-pressure center to the south, or high pressure to the north, or just lower pressure to the west of the Front Range. These synoptic conditions can also be reinforced by thermal forces to produce an even stronger easterly flow than would otherwise occur.

The wind direction data used in this study are hourly vector means of 30 second samples from 1988-99.

This poster presents a characterization of the conditions favorable to upslope flow on many time scales.

Seasonal Characteristics

The highest frequencies of upslope occur at the lowest site C1 every month of the year, ranging from a maximum 31% of the time in May to a minimum of 18% in December and January (Figure 3). D1 has the second highest upslope frequency (22% July, 4% October), while the Saddle has the least (13% April and August, 3% January).

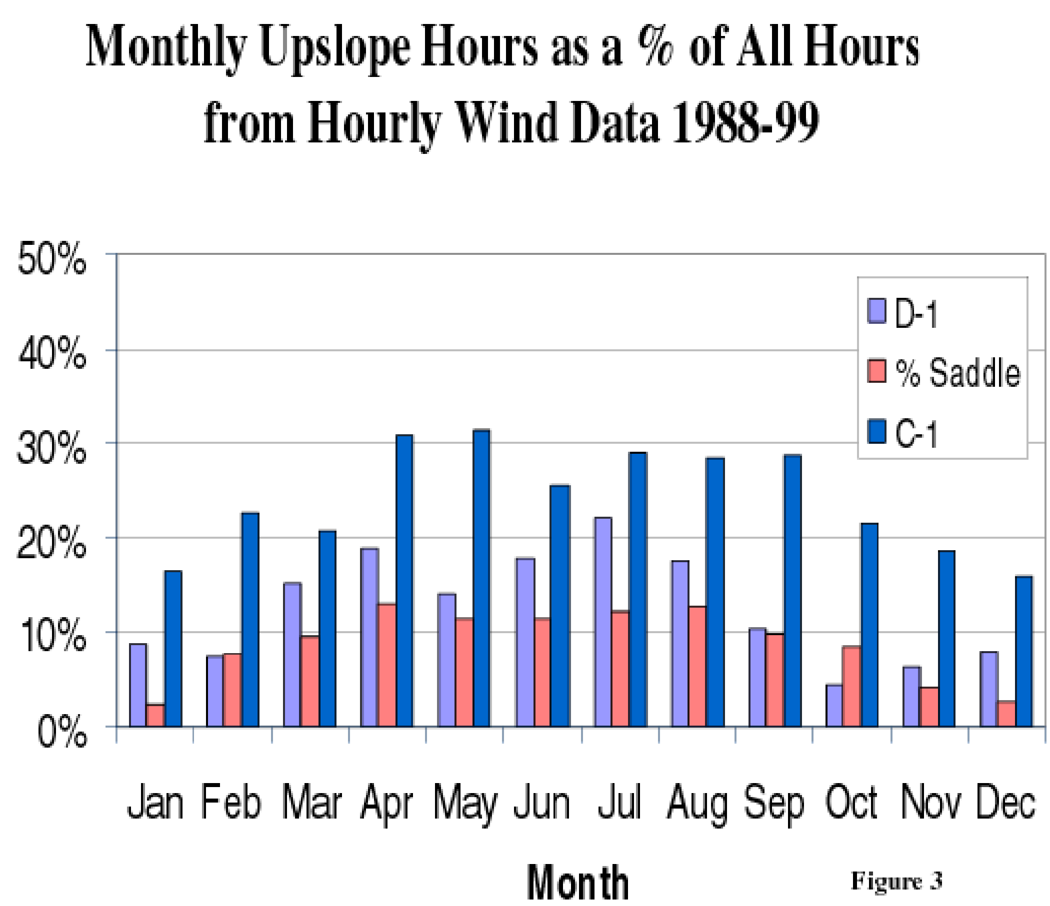


Figure 3

Diurnal Characteristics

Upslope frequencies show a pronounced daytime peak at all three sites during the summer (JJA) (Figure 4 a). Site differences are shown in the earlier onset of upslope flow at C1 and very low nocturnal frequencies compared to the higher sites, Saddle and D1.

Winter upslope occurrence (Figure 4 b) shows a weaker daytime peak at all sites, particularly at D1 where it is virtually absent. This lack of a diurnal signal suggests upslope at D1 is synoptically, as opposed to thermally, controlled.

The high relative frequency of upslope occurrence at D1, particularly in winter and at night may result due to the formation of a vertical eddy in the lee of the Continental Divide. This occurs under certain frequently occurring conditions of synoptic airflow and atmospheric stability, as opposed to local thermal heating.

Upslope Hours as a % of All Hours at D1, Saddle, and C1

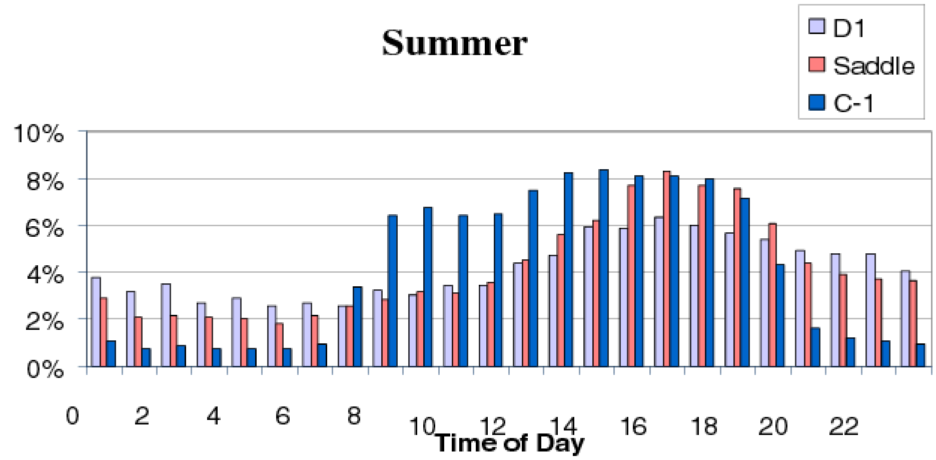


Figure 4a

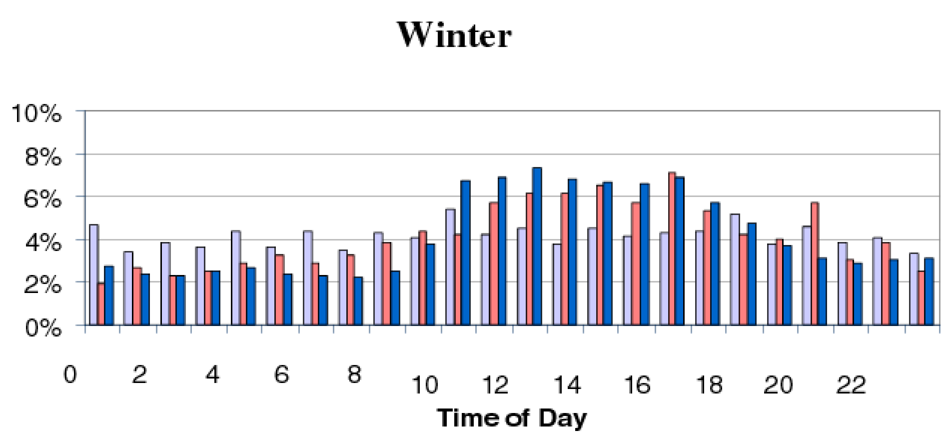


Figure 4b

Site Location

Niwot Ridge is in the Front Range of the Colorado Rocky Mountains, immediately west of Boulder and northwest of Denver, Colorado (Fig 1). This study uses data from three stations on Niwot Ridge:

Station	Elevation	Zone
D1	3739 m (12,500 ft)	alpine tundra
Saddle	3528 m (11,600 ft)	alpine tundra
C1	3024 m (10,000 ft)	forest

All stations are on the east, or lee, side of the Continental Divide.

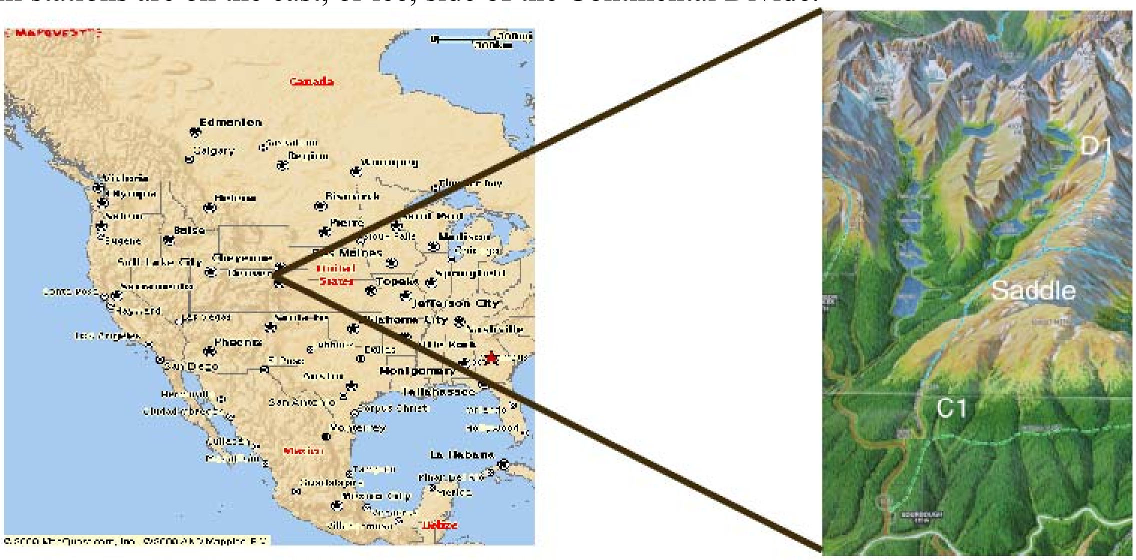
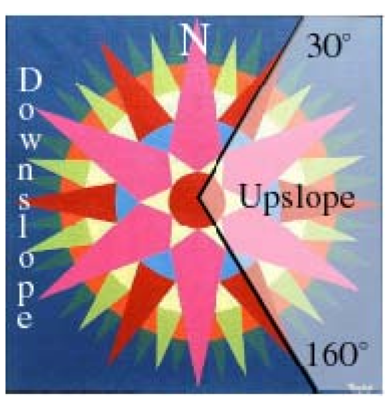


Figure 1

Flow Regimes

Eight flow regimes define the possible combinations of upslope and downslope airflow at the three sampling locations. The naming convention is to use U for upslope, D for downslope, and the order of the locations is D1, Saddle, and C1. Thus DUU means airflow is downslope at D1 and upslope at Saddle and C1.

Eight Flow Regimes:
1: DDD, 2: DDU, 3: DUD, 4: UDD, 5: DUU, 6: UDU, 7: UUD, 8: UUU



Seasonal and Diurnal Variability of Flow Regimes

Downslope at all three sites is clearly the dominant flow regime in all seasons, ranging from a maximum of 81% of all flow regimes in December to a minimum of 53% in August (Figure 5). Upslope flow at one, two, or three of the stations comprises the remainder of flow regimes.

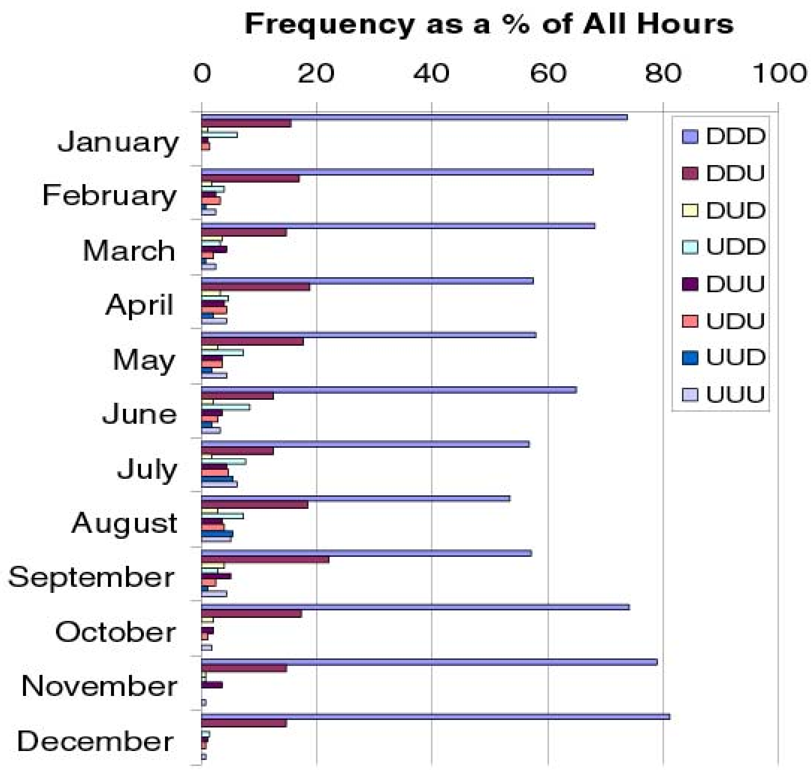


Figure 5

Diurnal variability of flow regimes has some seasonal differences, but overall there is a general pattern to the diurnal evolution. The progression, starting at midnight, is generally downslope at all three stations, with upslope developing at one or two stations in the morning and strengthening in the afternoon, then declining after sunset. In summer (Figure 6 a), upslope at all three stations is the dominant flow in the afternoons, whereas in winter (Figure 6 b) the dominant afternoon pattern is downslope at the highest station, D1, and upslope at the two lower stations.

Figure 6a

Summer

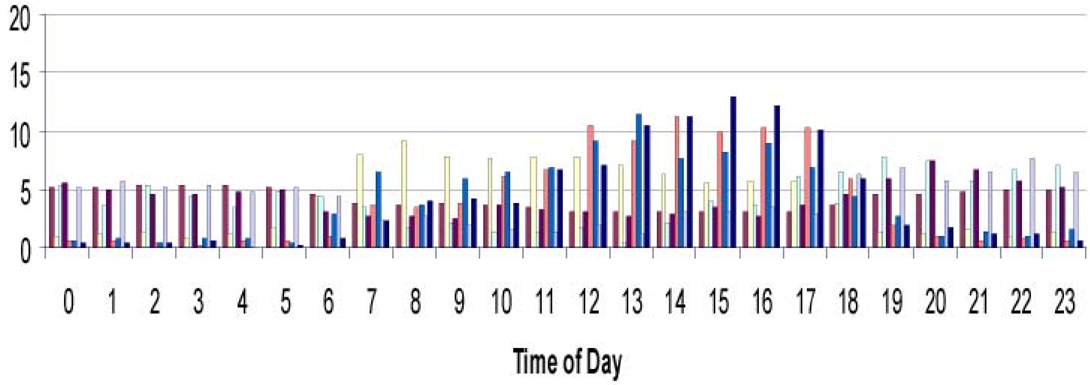
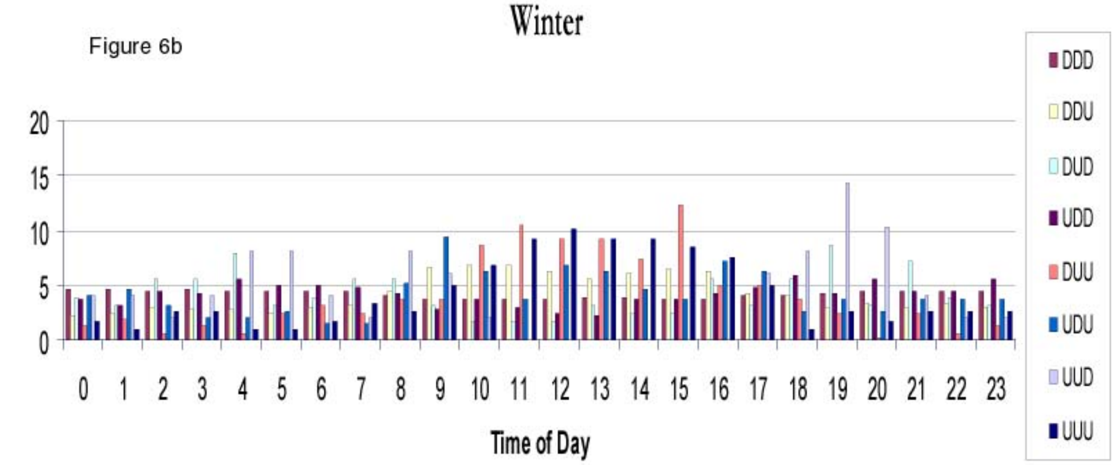


Figure 6b

Winter



Upslope at the two highest and downslope at the lowest station is common in the winter in the early pre-dawn morning, and post-sunset evening. This is not evident in the summer. In summer, though, from sunrise to noon, the flow is downslope at the two highest and upslope at the lowest station.

Flow Regime Persistence after 12 and 24 Hours

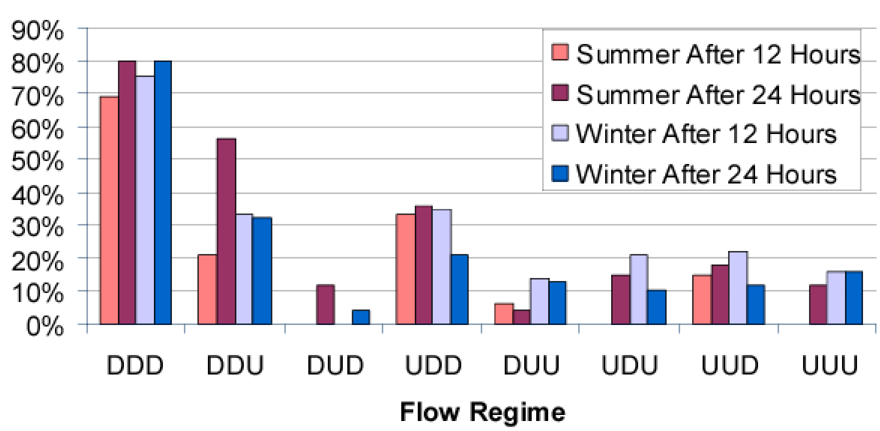
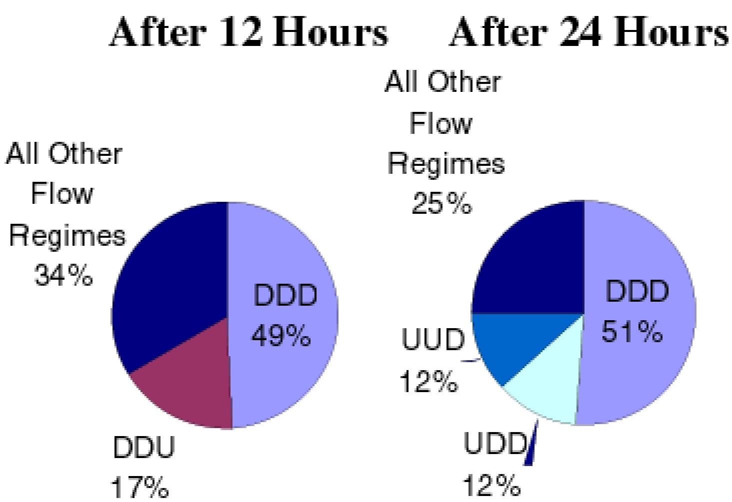


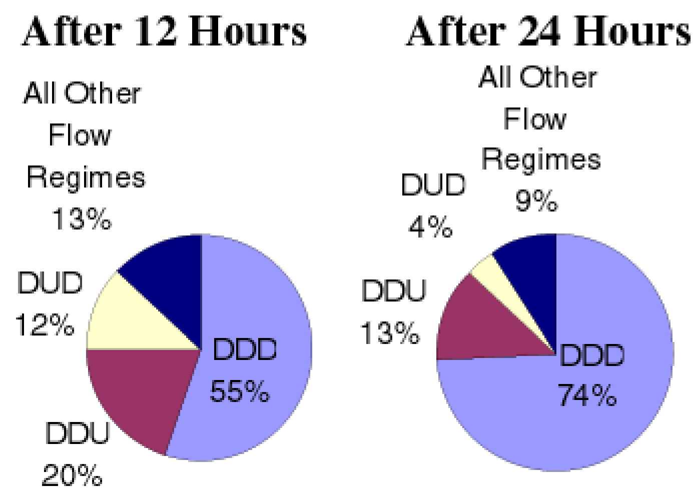
Figure 9

The tendency for a given flow regime to continue from one hour to the next is referred to as "persistence". The persistence is the same in winter and in summer for the four most persistent regimes, DDD, UDD, DDU, and UUU in that order. The fifth most persistent regime in summer, UUD, is the least persistent, or eighth, in the winter. The other three, UDU, DUU, and DUD, retain their respective rankings, relative to the seasonal shift of regime UUD.

The percentage survival rate for any given flow regime in summer is lower 12 hours later as compared to 24 hours later. This is in contrast to winter, when the flow regimes generally decay steadily through time. The apparent regeneration of a given flow from 12 to the 24 hour later time, suggests that in summer, flow is more controlled by localized solar heating, and winter flows are forced more by synoptic weather patterns. Figure 10 a and b show more detailed progression pathways through time.



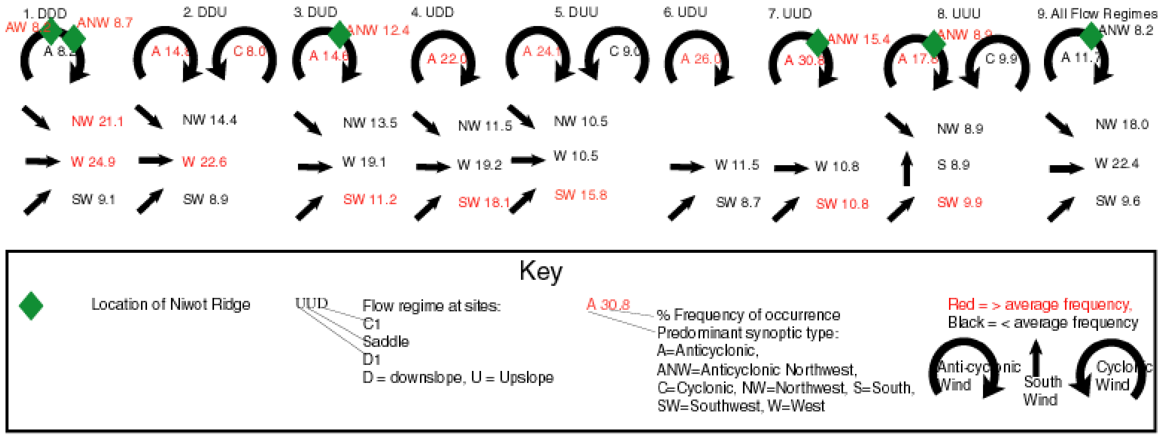
Summer
Figure 10a



Winter
Figure 10b

Synoptic Controls

The synoptic classification at 700 mb influences the development of flow regimes (Figure 7). The classification is based on objective indices derived from gridded pressure data. The more downslope regimes, especially DDD and DDU, occur frequently with straight westerly and north-westerly types, whilst upslope occurring at all three stations at the same time (UUU) is common under anticyclonic, cyclonic, southerly and south-westerly flow patterns. Anticyclonic conditions are also extremely common for the more upslope flow regimes (DUU, UDU and UUD).



The south-westerly flow often brings warmer and moister air which can be less stable than the colder drier air of a westerly or north-westerly pattern, and the anticyclonic and cyclonic conditions often denote calmer wind conditions that promote greater surface heating and higher upslope frequencies. For the UUU regime, easterly and northeasterly types are more common than under all other regimes, but still fall below the 8% threshold necessary for inclusion on Figure 7.

Thermal Controls: Free Air vs. Surface Temperatures

Figure 8a illustrates that the heating of the alpine tundra (D1) is the driving force behind the development of upslope flow (all flow regimes other than DDD). As surface air temperatures at D1 exceed those in the free-air at equivalent elevations by increasingly larger amounts, there is a higher probability of upslope initiation. There is little or no relationship at C1 (not shown). Thus during the day the likelihood of upslope regimes is increased when there is greater heating of the surface at D1 above the equivalent elevation free-air temperature (measured from Denver radiosonde data). The exception is flow regime UUU (8), which can occur either under conditions of great surface heating or forced synoptic flow. Hence the mean surface/free-air temperature difference is less than would be expected for this flow regime (Figure 8 b).

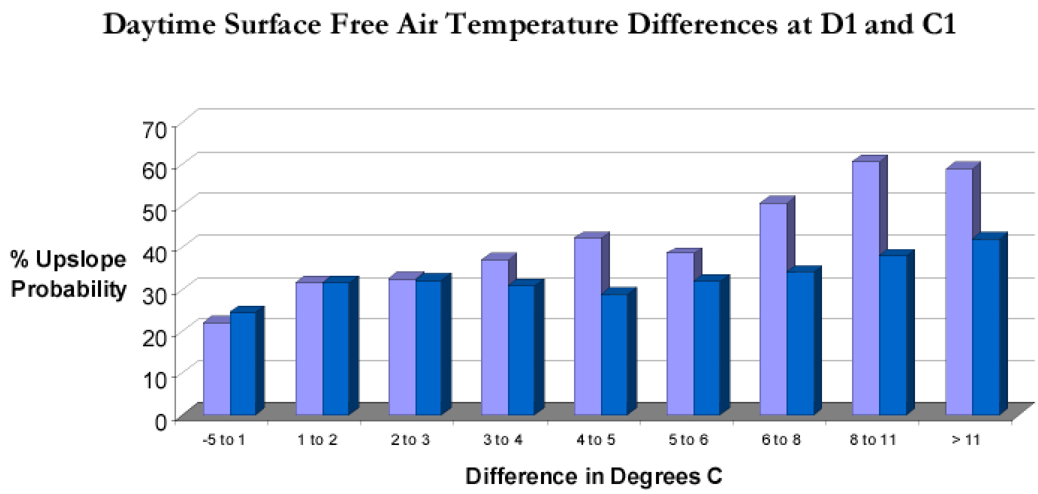


Figure 8a

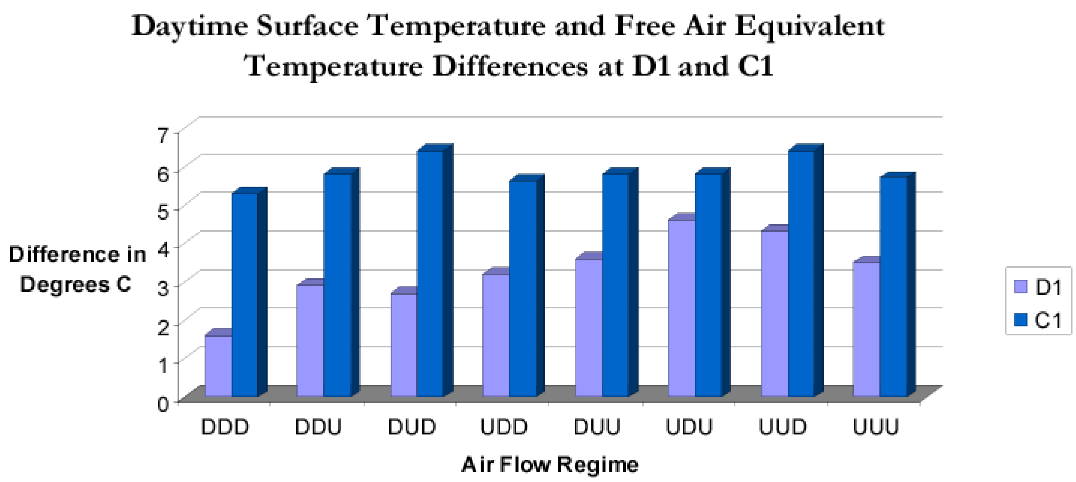


Figure 8b

Highlights

Strong seasonal and diurnal patterns are observed in the frequencies of upslope flow (airflow between 30 and 160 deg) at three sites on Niwot Ridge, Colorado. Upslope is most frequent at C1 (Fig. 3). Seasonal and diurnal patterns suggest that upslope airflow is initiated by surface heating and downslope radiative cooling.

Diurnal changes are most marked at the lower site C1, and least important at the upper site D1. Thus the diurnal signal decreases with elevation. (Fig. 4)

In winter the diurnal change in upslope frequency is weaker than in summer at all sites, and virtually absent at D1. (Fig. 4)

Upslope flow begins and ends earlier in the day in the lower, forested area (C1), compared to the alpine region (D1). (Fig 4)

Upslope flow regimes are most consistent at D1, both seasonally, and diurnally. This may be attributed to a vertical eddy developing in the lee of the Continental Divide occurring when larger scale synoptic weather patterns favor. (Fig. 4)

Eight flow regimes are identified based on combinations of flow at the three sites. Downslope at all three sites (DDD) is by far the most common flow regime. (Fig. 5)

The general diurnal evolution is downslope at night and upslope in the day. Upslope begins and ends earlier in the day at lower elevations. This progression is clearest in the summer. (Fig. 6)

Downslope at all three sites (DDD) occurs most frequently with a straight westerly, or northwesterly synoptic type. (Fig. 7)

The occurrence of upslope along the entire slope (UUU) can result from synoptic forcing (i.e. easterly flow). Upslope at only one or two of the stations is common under anticyclonic or cyclonic conditions, suggesting the importance of localized thermals. (Fig. 7)

Upslope occurrence is greater when the surface temperature is warmer than the free air, at the same elevation, suggesting that convection is important to upslope initiation. Downslope winds are more frequent in the reverse situation. (Fig. 8)

Upslope flow forcing initiates in the alpine zone rather than the forest below because the heating of the surface above free-air at D1 (rather than C1) has the strongest influence on upslope flow development. (Fig. 8)

In summer only, a given flow regime will disappear after 12 hours, but reappear after 24 hours. This suggests heating is the dominant air flow control in the summer, and synoptic conditions dominate in winter. (Fig. 9)

Future Directions: An Example of Additional Complexity

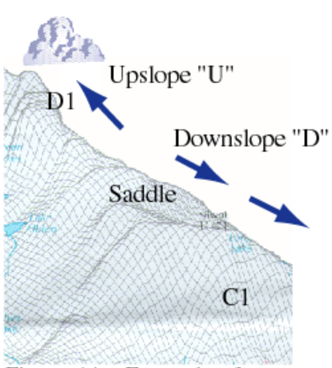


Figure 11a: Example of one possibleUDD Flow Regime

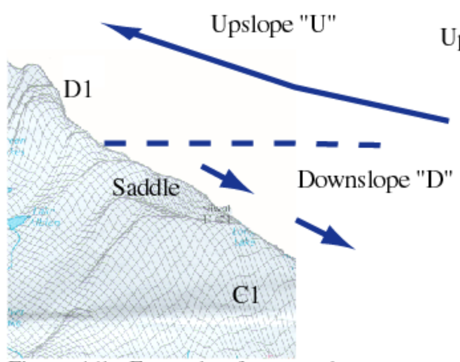


Figure 11b: Example of a second possible UDD Flow Regime

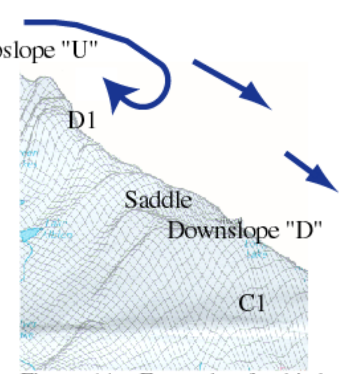


Figure 11c: Example of a third possible UDD Flow Regime

Figures 11 a - c illustrate the fact that one flow regime, UDD (4) does not uniquely describe the atmospheric circulation. In this example, upslope at D1 and downslope at the lower elevations can be described by at least three different processes or conditions.

1. Strong convective cell development above or to the west of D1 in an overall environment of subsidence.
2. An inversion boundary between Saddle and D1.
3. A vertical eddy, or rotor, forming over D1 during strong westerly flow over the continental divide just to the west.

Thus there is much further work possible in refining slope circulation conditions.