An Airflow Case Study Over the San Juan Mountains of Colorado

JOHN D. MARWITZ

Dept. of Atmospheric Resources, University of Wyoming, Laramie 82070

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ABSTRACT

On 12 February 1973 an airflow case study was documented across the San Juan Mountains in southwest Colorado. The main observation system was an NCAR Queen Air aircraft. Several supplementary observations were available from the weather modification project being conducted in the area. The airflow data were synthesized and compared with previous laboratory simulation results over the same area. The orographic cloud contained a number of imbedded convective clouds which had an important effect on the airflow and vertical diffusion processes. A precipitation efficiency was derived using a technique which avoided most of the critical assumptions of previous attempts.

1. Introduction

On 12 February 1973 an NCAR[1] Queen Air (304D) was flown over the San Juan Mountains in southwestern Colorado. The airflow and precipitation efficiency of the existing orographic cloud were observed. This mountain was chosen because of the large amount of supporting data which were available in conjunction with the Colorado River Basin Pilot Project being conducted under sponsorship of the Bureau of Reclamation.

There have been numerous studies of gravity-initiated oscillations of the airflow above and downwind of mountain ranges and mountain peaks. In general, gravity oscillations can be classified as lee waves, lee vortices (rotors), and hydraulic jump (analog) airflow. The observational and theoretical studies on lee waves and lee vortices are well illustrated by Corby (1954), Queney *et al.* (1960) and Holmboe and Kleiforth (1957). Long (1954) and Kuettner (1958) were among the first to suggest an analogy between the "hydraulic jump" type flow (long familiar to engineers) and the strong surface winds often observed in the lee of mountains. In recent years the *WA*ve *M*omentum *FL*ux *EX*periment (WAMFLEX) and its predecessor, the Colorado Lee Wave Program, have obtained multiple-aircraft observations on each of the three above gravity-initiated type oscillations (e.g., Lilly and Toutenhoofd, 1969, and Vergeiner and Lilly, 1970). In addition, several new numerical models have been developed to simulate the observed airflow (Danielsen and Bleck, 1970; Vergeiner, 1971; Houghton and Kasahara, 1968).

The WAMFLEX aircraft flights were typically conducted in the lee of the mountain and above the orographic cap cloud when it existed. Very little data are available from the above programs either in the cloud or in the subcloud region upwind of the mountain. This is the region of prime importance from a weather modification point of view. Members of the Atmospheric Resources Department at the University of Wyoming have emphasized this region for the past few years and have presented some of the results at meetings and in progress reports to our sponsor (Dirks *et al.*, 1970, and Staff, 1972). These studies were conducted over Elk Mountain and the Medicine Bow Mountains in Wyoming and are in the process of being prepared for publication.

The most notable effort to simulate the airflow over a mountain range in a laboratory wind tunnel was made by Orgill *et al.* (1971). The three mountains which were simulated in the laboratory were Elk Mountain in Wyoming, Climax-Eagle River in Central Colorado, and the San Juan Mountains. These are the first comprehensive field observations available over the San Juans to compare with the laboratory results. The laboratory simulations were originally made to assist in determining the proper locations for ground generators to seed the area.

2. The San Juan topography

The San Juan River has its origin in the San Juan Mountains northeast of Farmington, N.M. The headwaters of the San Juan River are near Summit Peak (13,272 ft). Other peaks in the area extend above 14,000 ft. The San Juan River descends rapidly and passes Farmington at 5500 ft. The Continental Divide runs north-northeast from southwestern New Mexico

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[1] The National Center for Atmospheric Research (NCAR) is sponsored by the National Science Foundation.

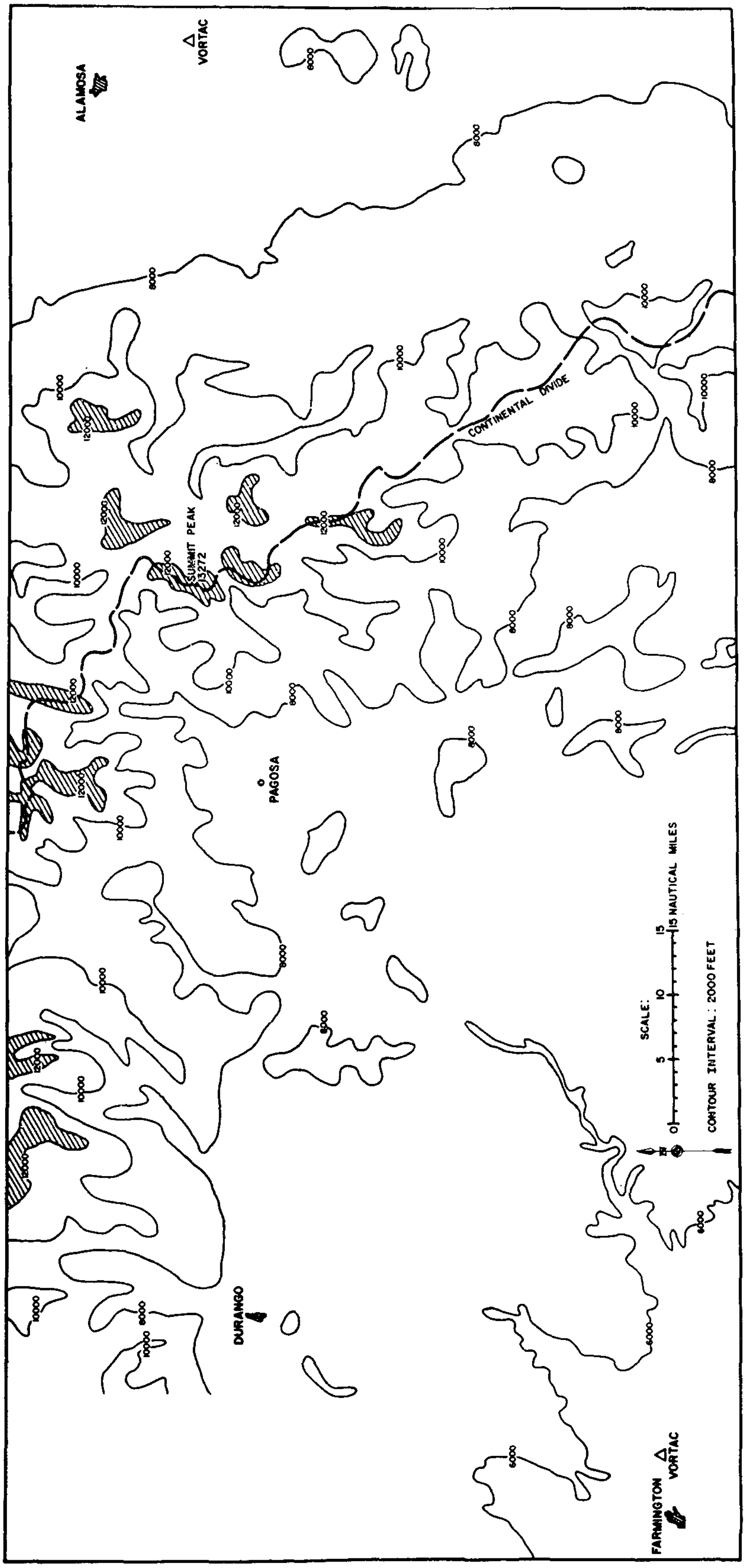

FIG. 1. Topography of the San Juan Mountains between Alamosa, Colo., and Farmington, N.M.

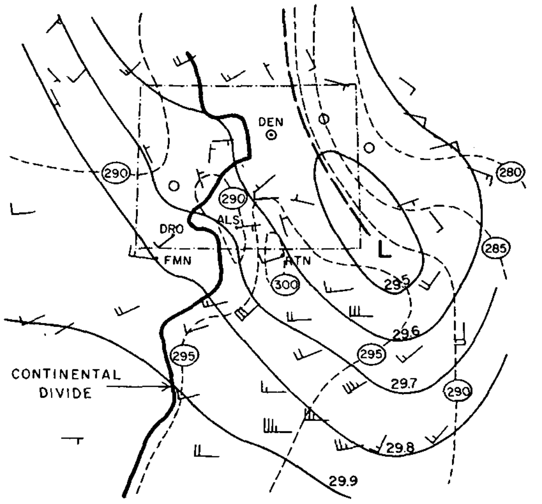

FIG. 2. Surface synoptic map for 1000 MST 12 February 1973. Solid lines are altimeter settings (inches of Hg) and dashed lines are potential temperature (°K). Conventional wind barbs are as indicated.

to near Santa Fe (Fig. 1). From there it extends north into Colorado along the San Juan Mountains. At a point ~30 mi north of the Colorado-New Mexico line, the divide turns toward the west before again proceeding northward. The Continental Divide surrounding the San Juan Valley is curve shaped and opened toward the west. Alamosa, Colo., on the other hand, is located in the San Luis Valley. The San Luis Valley is a closed valley, i.e., there are high mountain ranges surrounding the valley. The valley is relatively flat and at an altitude of ~7500 ft. Being a closed valley cold air is often trapped in the valley so that a substantial horizontal pressure gradient is required to flush it out.

3. Description of weather

The surface map for 1000 (all times Mountain Standard) for 12 February 1973 is shown in Fig. 2. It can be seen that the surface low has moved to the Oklahoma panhandle region and a strong pressure gradient exists across southern Colorado, New Mexico and west Texas. The pressure unit chosen to display the pressure gradient is the altimeter setting rather than the sea level pressure. In mountainous regions isochrones of altimeter settings describe the true pressure gradient much better than the more commonly used sea level pressures. The sea level pressures and altimeter settings are both obtained by adding a fixed thickness (geometric altitude of the station) of fictitious atmosphere to the observed station pressure. In the case of sea level pressures the mean temperature of the fictitious atmosphere is determined by assuming a constant lapse rate (6 C km^{-1}) downward from the average station temperature. The average temperature is based on the present temperature and the previous 12-hr temperature. Altimeter settings, on the other hand, assume the fictitious atmosphere has the properties of an ICAO Standard Atmosphere. When attempting to determine the true pressure gradient across a mountain range and only one side has undergone a dramatic change in temperature during the past 12 hr, the sea level pressure will necessarily indicate an erroneous pressure gradient. Therefore, when strong subsidence and hence warming has recently occurred in the lee of a mountain range or when a cold front has been recently blocked by the mountain range, the sea level pressure gradient will indicate a substantial error. On the other hand, the altimeter setting will indicate a truer index of the pressure gradient. This is especially so when the stations are at equal altitudes and also when their surface temperatures are both near the ICAO Standard Atmosphere for their altitude as Farmington and Alamosa were on this day.

An examination of the surface winds in Fig. 2 indicates that throughout southern Colorado, New Mexico and West Texas the surface air was moving over the Continental Divide and descending to the surface in the lee of the Continental Divide. The exception was Alamosa where the surface winds were from the east and the potential temperature was 288K. At this time (1000) the nocturnal inversion had not broken, and the airflow over the San Juan Mountains did not descend into the San Luis Valley. From the

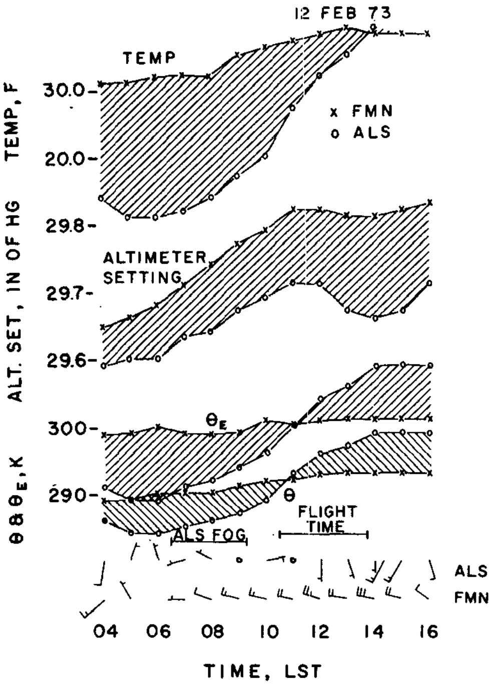

FIG. 3. Time series of surface temperature, altimeter setting, potential temperature (θ), and equivalent potential temperature (θ_E) for Farmington (FMN) and Alamosa (ALS). Hourly surface winds using conventional wind barbs are as indicated.

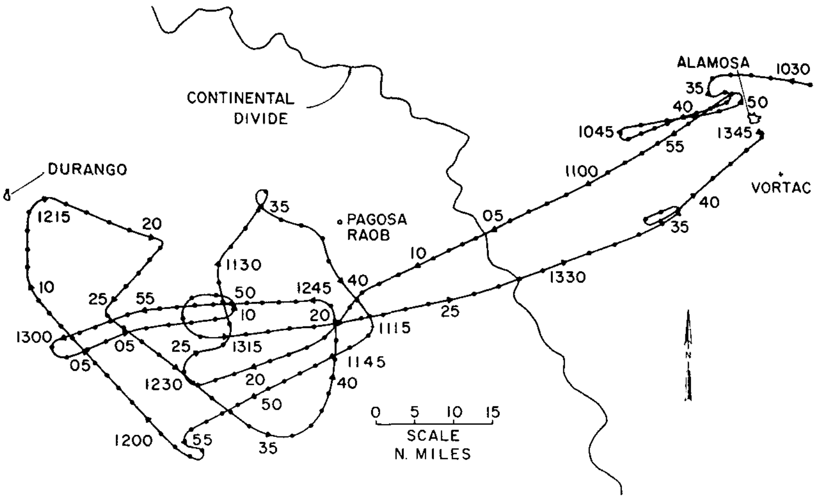

Fig. 4. Flight track of aircraft from 1029 to 1345.

potential temperature field, it may be noted that the air in the lee of the Colorado and New Mexico Rocky Mountains (i.e., behind the surface low) was substantially warmer than the air ahead of the surface low. The warmest air on the map was at Raton, N.M. (300K).

The surface winds across eastern New Mexico and west Texas have a velocity of 20–30 kt and are ageostrophic. The geostrophic wind was ~50 kt. Surface winds are typically ageostrophic in the lee of mountains in which the parcels are under the influence of a substantial pressure gradient force.

It is informative to inspect the hourly sequence of certain surface data on either side of the San Juan Mountains surrounding the flight time. The stations selected were Farmington, N.M. (FMN), on the upwind side and Alamosa, Colo. (ALS), on the downwind side. Shown in Fig. 3 are the time series at FMN and ALS of temperature (T), altimeter setting, isobaric equivalent potential temperature (θ_E), potential temperature (θ), and winds. Also indicated in Fig. 3 are the periods of time when fog was reported at ALS and the period of time of the flight. Surface fog was still present in the valley at 1030 northwest of ALS when the aircraft first arrived to begin the flight. Of significance is the differences between the time series of T, θ and θ_E at FMN and ALS. These parameters were nearly constant at FMN while they increased steadily at ALS. The fact that θ_E at ALS eventually exceeded θ_E at FMN was at first disconcerting since θ_E should be conservative if the air at FMN eventually arrives at ALS. We will see later that the excessive θ_E at ALS was due to a very shallow moist layer. The fact that θ at ALS eventually exceeded θ at FMN by 6C was due to latent heat release.

The surface winds at FMN and ALS are also noteworthy. The winds at FMN were 10–25 kt from the west throughout the daylight period. On the other hand, the surface winds at ALS were light and variable until 1200 when the pressure gradient from FMN and ALS began to increase. Southwest winds of 15 kt developed at ~1415 (shortly after the aircraft landed at ALS to refuel). It appears that after 1200 subsidence in the form of a lee wave developed over ALS, thus replacing the cold air with a much warmer column of air and therefore lowering the surface pressure. At 1415 the southwest winds finally reached the surface at which time the winds changed direction and increased in speed.

Special rawinsonde, precipitation, surface wind and surface temperature data were obtained by EG&G, Inc., and WSSI[2] over and upwind of the San Juan Mountains. These observations were taken under contract with the Division of Atmospheric Water Resources Mangement, Bureau of Reclamation. The data were kindly made available for this study. The surface winds and rawinsonde data obtained upwind of the San Juan Mountains clearly indicated that the surface air was moving from the west-southwest at 10–15 kt and, hence, up and over the mountain. All stations had nearly the same potential temperature (293K) which agreed well with that observed by the aircraft while flying upwind of the mountain and below cloud base.

4. Results

a. *Aircraft track*

The track of the aircraft is presented in Fig. 4. The aircraft arrived over ALS at 1030. A thin fog bank was still located northwest of the airport. The research flight began from the southeast edge of the fog bank. A race track pattern oriented along a WSW-ENE heading was maintained while climbing. By 1100 the

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[2] Western Science Services, Inc., Ft. Collins, Colo.

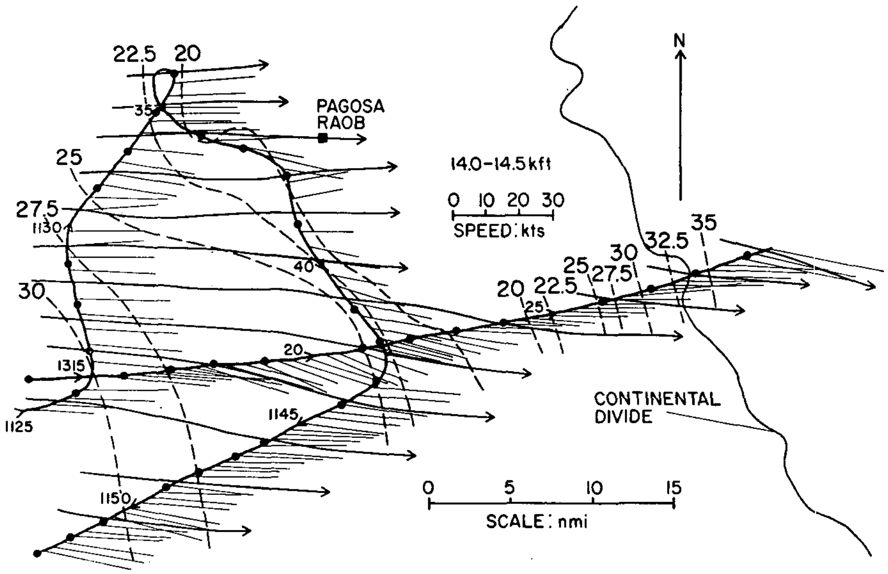

FIG. 5. Streamline and isotach patterns for 14,000 to 14,5000 ft MSL from aircraft's Doppler wind system. Tracks occurred from 1125 to 1153 and from 1314 to 1329.

plane was over the downwind edge of the cloud with the pilot attempting to pass through the tops of the cloud. The orographic cloud top was distinct and no other clouds were above.

At 1112 the aircraft passed over an abrupt decrease in cloud tops from ~18,000 to ~14,000 ft. The higher cloud tops had distinct cumuliform characteristics. During the flight the large convective clouds were thought to be associated with individual mountain peaks. Later analysis indicated they probably developed along the upwind base of the San Juans and remained relatively stationary with respect to the ground.

From 1125 to 1155 a box pattern was flown near 14,000 ft at the top of the extensive stratiform cloud upwind of the mountain. The flight from 1135 to 1142 was along the leading edge of the steep wall of mostly cumuliform clouds. At 1155 the aircraft was descended from 14,000 to 8500 ft through a break in the overcast. From 1200 to 1300 the aircraft was flown at 8500 ft in the figure-eight pattern at cloud base while maintaining visual contact with the ground. Very light snow was falling along those flight segments near the mountains. At 1300 an Instrument Flight Rule (IFR) clearance was obtained at the minimum enroute altitude for the return flight through the cloud. After exiting the downwind edge, a sounding near the downwind edge of the mountains was obtained after which the aircraft was landed at ALS for refueling.

b. Airflow results

The flight data obtained from 1125 to 1153 and 1314 to 1329.5 while flying between 14,000 and 14,500 ft are presented in Fig. 5. The flight from 1135 to 1143 was along the leading edge of the wall of stationary convective clouds. The convective clouds were located ~18 n mi upwind of the Continental Divide, i.e., along the 8000-ft contour (see Fig. 1). The streamline indicates that the air on the upwind side of the San Juans was flowing directly toward the mountains from 270°±15° with no apparent difluence occuring around individual mountain peaks. The isotach and streamline patterns show clear evidence of horizontal convergence in that the speed decreases from 30 to 20 kt. The most rapid deceleration (i.e., vertical divergence) occurred at the upwind base of the San Juans where the wall of convective type clouds was observed. The minimum speed was observed ~12 n mi upwind of the Continental Divide with rather marked acceleration recorded from that point to just past the Divide. On the lee slope of the mountains, speeds exceeding 35 kt were observed.

The flight data obtained near cloud base (~8500 ft) from 1200 to 1300 are presented in Fig. 6. The winds at cloud base were from 260°±10° with little indication of difluence around the small mountain peaks. The amount of deceleration in the area of observations was even less than at 14,000 ft as presented in Fig. 5. The winds only decelerated from 25 to 20 kt. The winds at 8500 and 14,000 ft rather clearly indicate that the air was flowing up and over the San Juans.

Fig. 7 contains analog traces from both a Rosemount and a reverse flow temperature transducer. The traces are from 1320 to 1340 while the aircraft was flying near 14,500 ft on the downwind leg through the cloud. At 1329.5 the plane exited from the cloud and ~1 min later a descent in the lee of the cloud and mountain was begun. From the traces it may be seen that the

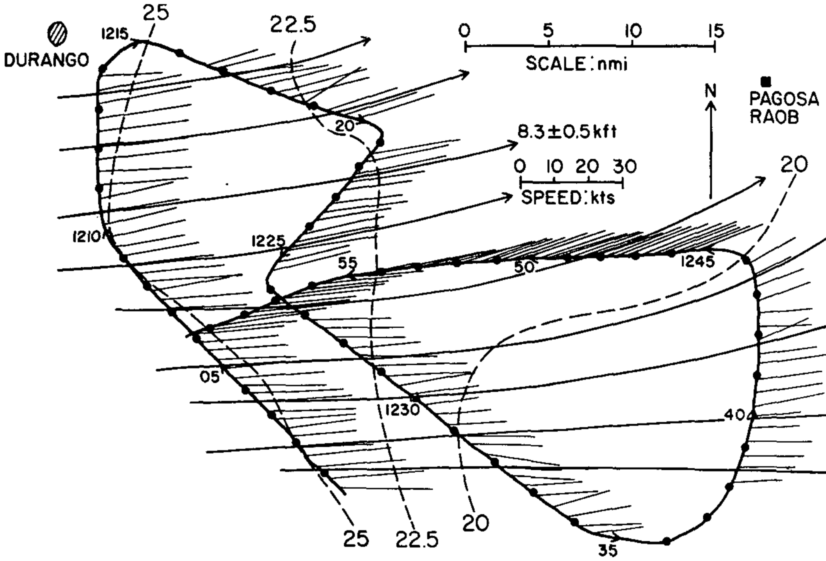

Fig. 6. Streamline and isotach patterns for 8300±500 ft MSL from aircraft's Doppler wind system. Tracks began at 1200 and ended at 1300.

two instruments tracked within 0.5° of each other prior to 1327.5 and after 1333. From 1327.5 to 1329.5 (while still in the cloud) the Rosemount temperature system was 1C colder than the reverse flow system. For the first 3 min after exiting the cloud, the Rosemount temperature system was 2–3C colder than the reverse flow system. From 1327.5 to 1333 the Rosemount system probably accumulated a layer of ice and was, therefore, recording the ice bulb temperature. The ice bulb depression was 1C inside the downwind edge of the cloud and increased to 3C in the dry air outside the cloud. When the ice finally sublimated away at 1333, the two systems again agreed.

Fig. 8 is a vertical cross section across the San Juans in which an attempt has been made to synthesize the available aircraft and rawinsonde data into a consistent airflow pattern. Outside the cloud (i.e., upwind, on top and downwind) potential temperature is conservative and can be used to establish a streamline. Inside the cloud (and outside) equivalent potential temperature (θ_E) is conservative. Unfortunately, the vertical distribution of θ_E was nearly constant in the cloud-producing layer and, therefore, could not clearly establish the streamlines. Using the available horizontal wind data from the aircraft and the rawinsonde data from Pagosa, Colo., a set of streamlines was determined by considering the mass continuity and thermodynamic processes. The cloud boundaries, streamlines and isotach patterns are presented in Fig. 8. Even though the wind profile was rather uniform over Farmington (upwind of the mountain range), an interesting velocity profile was observed at Pagosa. The surface winds decreased to less than 5 kt while the winds at 11,000 ft were still at 30 kt. At 16,000 ft the winds decreased to 15 kt; above 16,000 ft they again increased. From mass continuity considerations the streamline for the air originating at 8000 ft was clearly deflected upward by the wall of stationary convective clouds. On the downwind slopes the cloudy air accelerated to 35 kt. No pronounced hydraulic jump or lee wave was evident downwind of the mountain.

A comparison between these field observations and the laboratory simulations by Orgill *et al.* (1971) is appropriate. The laboratory models simulated the Climax Colorado region, Elk Mountain and the San

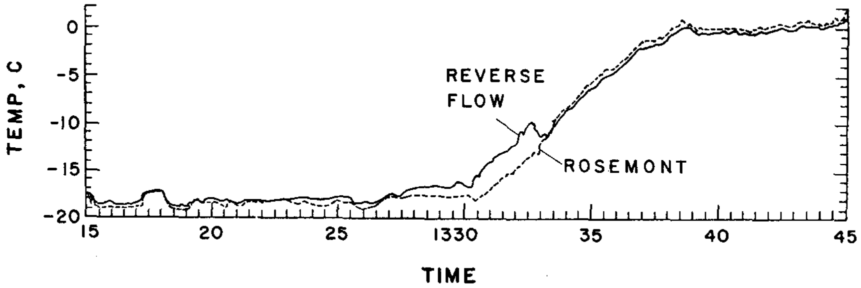

Fig. 7. Analog traces of static temperature from the reverse flow and Rosemount transducers on the aircraft from 1315 to 1345.

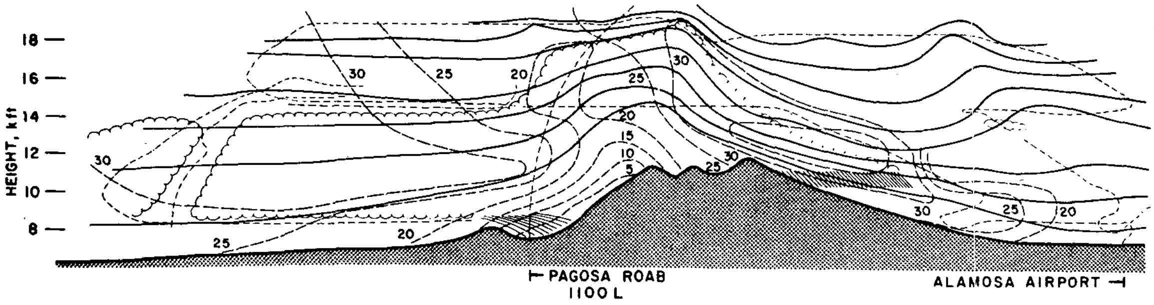

FIG. 8. Vertical cross section across San Juans. Dash-dot lines are tracks of aircraft and the Pagosa rawinsonde, solid lines are streamlines, dash lines are isotachs (kts), and cloud outline is scalloped.

Juans. The diffusion studies in the laboratory simulations rather clearly showed that surface-released aerosols would rapidly diffuse throughout the subcloud and cloud layers. The diffusion in the laboratory model was due primarily to surface-induced mechanical turbulence and not to free convection since the air in the wind tunnel had absolute thermodynamic stability. On the other hand, these field observations indicate that stationary free convection was prevalent near the upwind base of the mountain and that a large percentage of the subcloud air was transported upward in the free convection currents and mixed throughout the orographic cloud. It is proposed that the free convection which was prevalent in the field case study probably served the same function with respect to diffusion as surface-induced mechanical turbulence served in the laboratory simulations.

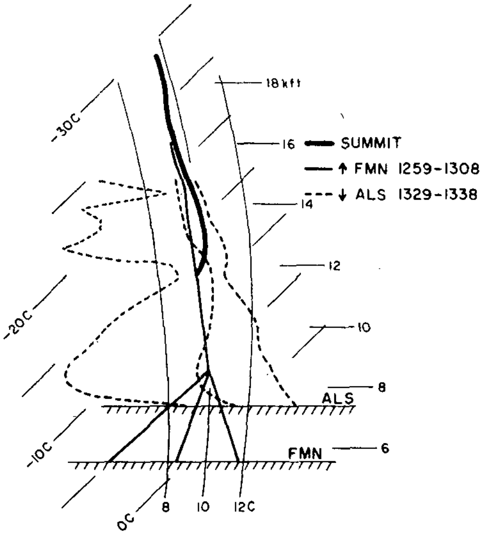

FIG. 9. Thermodynamic soundings over the summit of the San Juans (wide line), over Farmington (thin line), and over Alamosa (dashed lines). In cases where the air is not saturated the lines are (from right to left) temperature, wet bulb and dew point. The vertical scale is pressure altitude, the isotherms are skewed from lower left to upper right, and wet bulb potential lines (8, 10 and 12C) are nearly vertical.

Another interesting comparison between the field and laboratory results are the horizontal velocities. Horizontal velocities were apparently not measured in the laboratory simulations of the San Juans but were presented for Climax and Elk Mountain. The laboratory results indicated that below the temperature inversion the horizontal velocity increased as the air moved up the front side of the mountain. By comparison the field study indicated that as the air approached the upwind side of the San Juans it decelerated at all levels. These field observations would violate mass continuity on an infinite two-dimensional mountain. Substantial amounts of the cloud and especially of subcloud air were probably transported vertically by the free convective currents. Because the mountain range curves toward the west in this region, it seems likely that the air near cloud top diverged around the convective clouds and continued to diverge down the lee side of the San Juans. More studies under different synoptic and thermodynamic conditions are needed to firmly establish the types of airflow and the importance of free convection in orographic clouds.

c. *Precipitation efficiency*

Elliot and Hovind (1964) obtained an estimate of the precipitation efficiencies for wintertime orographic clouds over a wide and a narrow mountain range in California. Their efficiencies varied from 17 to 27% with an unstable air mass over a wide mountain barrier being most efficient. Their estimates of precipitation efficiencies were obtained by calculating the ratio of precipitation on the mountain to the amount of liquid condensate. The condensate was calculated using an upwind rawinsonde and a numerical cloud model (Myers, 1962). The Myer model assumes that the stable layer near mountain top height on the upwind sounding is a nodal surface. The model further assumes that vertically uniform divergence (convergence) occurs in the column of air between the orographic barrier and the nodal surface, i.e., the Bernoulli equation applies.

Dirks (1972) was able to improve on the above technique in some important ways by utilizing a wellcalibrated aircraft in his studies. He obtained accurate upwind and downwind aircraft soundings from which water vapor depletions were calculated. To obtain the amount of condensate a material surface at the top of the orographic clouds was deduced by comparing the potential temperatures on the upwind and downwind soundings to those observed at the top of the cloud. He then assumed uniform vertical divergence (convergence) between the ground and the material surface (cloud layer) and applied the Bernoulli equation to individual layers within the cloud layer to calculate the condensate. His technique was applied to the Medicine Bow Mountains in Wyoming and produced efficiencies from 40 to 65%.

Since the aircraft used in the present study was equipped with a Doppler wind finding system, the critical assumptions in the above studies were not necessary. Even though θ_E is conservative one cannot reliably establish the in-cloud streamlines by penetrating the cloud since the lapse rate of θ_E is often near zero. As discussed in the previous section, the rawinsonde and Doppler winds were utilized with the concept of mass continuity to deduce the streamlines in Fig. 8. In this manner the Bernoulli assumptions were avoided. The soundings upwind, over and downwind of the mountain are presented in Fig. 9. The cloud top temperature was -28C at 490 mb. From Figs. 8 and 9 the precipitation efficiency was determined to be 62%. Since the winds were available, it was possible to derive the condensation rate and the precipitation rate. They were 52 and 32 kg $\sec^{-1}$ m^{-1}, respectively. Since there were only two recording precipitation gages in the vicinity of the flight path, the derived precipitation rate could not be compared with an observed precipitation rate.

Certain other significant observations can be seen in Fig. 9. The previously mentioned observation from Fig. 3 that the θ_E value at ALS exceeded that at FMN is seen to be due to the shallow moist layer over ALS. Sublimation from snow cover near ALS or evaporation of precipitation particles near the downwind edge of the cloud appears to have increased the moisture in the surface layer. It may also be seen that latent heat release has warmed the air over ALS by $\sim$5C. The last observation was that the air over FMN between 8000 and 16,000 ft is conditionally unstable by $+1$C while that over ALS is stable. This is consistent with the observed convective clouds and indicates that sufficient convective overturning and hence stabilizing occurred while the air passed over the mountain.

5. Summary

An airflow case study was obtained over the San Juan Mountains in southwestern Colorado. An orographic cloud with a significant number of imbedded convective clouds was present. The cloud top temperature and pressure was -28C and 490 mb, respectively. The aircraft system recorded Doppler winds plus the standard state parameters. The Doppler, rawinsonde and surface winds revealed that the air was moving up and over the barrier. Using the observed winds and temperature with mass continuity and thermodynamic concepts, it was possible to synthesize a rather reasonable vertical cross section. These field observations were compared with previous laboratory simulation studies over the same mountains. It was concluded that the free convection probably served the same function as the mechanical turbulence served in the laboratory as regards vertical mixing of surface-released aerosol particles. The free convection appears to have transported substantial quantities of the low-level air to the top of the cloud near the upwind base of the mountain; thus, the low-level winds decreased markedly on the upwind slope. By comparison in the laboratory the airflow accelerated up and over the mountain at all levels. Utilizing the aircraft soundings of temperature, dew point and winds with the vertical cross section, it was possible to derive the precipitation efficiency (62%) and precipitation rate (32 kg $\sec^{-1}$ m^{-1}).

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