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FOEHN WIND CYCLO-GENESIS

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(With 8 figures)

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Zusammenfassung: Im Herbst und Winter bilden sich häufig in den kanadischen Provinzen Saskatchewan und Alberta, östlich der kanadischen Rocky-Mountains, primäre Tiefdruckgebiete aus, sobald die in weiterer Ausdehnung vom Osthang der Gebirge in die Ebene hinabströmenden Föhnwinde dort auf die kalte kontinentale Polarluft treffen, die sich während der genannten Jahreszeiten dort gewöhnlich befindet. Die erwähnten Föhnwinde entströmen den kräftigen Hochdruckgebieten, die sich über den Hochebenen des Great-Basin (Fig. 1) und des Columbia-Plateaus bilden. Diese werden im Westen von der Sierra Nevada und den Cascade-Mountains, im Osten von den Rocky-Mountains begrenzt. Der Luftkörper, welcher die Föhnwinde bildet, entstammt ursprünglich dem nördlichsten Teil des Pazifischen Ozeans. Bei seiner Wanderung über die hohen Gebirge gibt er seine Feuchtigkeit ab und gelangt als trockene, warme Luft in die Ebene, wo er auf die trockene, sehr kalte kontinentale Polarluft trifft. Er bildet dann den warmen Sektor der Tiefdruckgebiete, die sich an der Grenze zwischen den beiden Luftkörpern ausbilden und durch die großen Temperaturgegensätze sehr kräftig werden können. Trotzdem sind die Niederschläge in ihrem Bereiche infolge der großen Trockenheit der beiden Luftkörper gewöhnlich unbedeutend. Solange das Hochdruckgebiet über den Hochebenen die Föhnwinde östlich der Rocky-Mountains unterhält, bilden sich immer wieder Tiefdruckgebiete der erwähnten Art aus und wandern südöstlich längs der Grenze zwischen der warmen Föhnluft und dem außerordentlich kalten Luftkörper nördlich und östlich davon. Die mehrfache Wiederholung des ganzen Vorganges wird dadurch begünstigt, daß im Rücken jedes Tiefdruckgebietes ein kräftiger Strom kalter kontinentaler Polarluft einsetzt, der wieder auf den warmen Föhnluftstrom trifft. Als Beispiel wird die Entwicklung einer Serie von drei Tiefdruckgebieten dieser Art zwischen dem 9. und 15. November 1933 gegeben.

According to modern theories regions of cyclo-genesis arise where convergent flow occurs between air masses of different characteristics, provided significant temperature differences exist. Such a flow tends to form a discontinuity surface or front between the masses and to produce large amounts of potential energy of mass distribution along the frontal zone. If the conditions for stable equilibrium are not rigidly maintained along the front, the colder mass may move forward into the warmer current or vice versa. In any case there occurs a compensating flow in the adjacent mass, the whole process giving rise to the genesis of a cyclonic disturbance. The kinetic energy of the resulting cyclone is provided to a large measure by the initial potential energy of mass distribution; although, of course, the heat of condensation liberated in the event that the warm mass is particularly moist furnishes a minor portion. A detailed discussion of the formation, maintenance, occlusion and final death of the cyclone is beyond the scope of the present paper. I merely wish to emphasize at this point the importance of convergent flow in constrasting air masses for furnishing the potential energy necessary for the genesis and subsequent maintenance of the extra-tropical cyclone.

In the descending motion associated with foehn phenomena relatively high temperatures are frequently attained by the air mass involved. Frequently the dynamical heating of a column of air in this manner is capable of creating extreme temperature differences between the foehn current and adjacent masses. If the foehn reaches large proportions, that is effects sufficient mass transport, enough potential energy of mass distribution, arising from the contrast between this air and adjacent masses, may become available to initiate the formation and maintenance of a cyclone of major importance. Secondary cyclones of foehn origin are not uncommon and have been treated in some detail in the past. SCHNEIDER[1]) has discussed a particularly interesting type occurring off the west coast of Greenland during the southeast foehns of that region. We are concerned here not with the formation of secondary cyclones but with the foehn genesis of primary cyclones, a situation requiring rather unique meteorological and topographic conditions.

During the late fall and early winter rather intense anticyclones frequently build up over the high level regions of the Great Basin and Columbia Plateau in the northwestern United States (Fig. 1). They are usually the result of an influx of Polar Pacific (P_p) air to the lee of an occlusion occurring off the Washington and Oregon coasts. The outflow from such an anticyclone causes a steepening of the pressure gradients over the Rocky Mountains to the east and the Sierra Nevada Mountains to the west, due to the damming effect of these great natural barriers upon the stable air masses always associated with them. If the anticyclone be maintained with undiminished intensity, there will occur

[1]) SCHNEIDER, LEONARD R., Greenland West-coast Foehns. M. W. R. April 1930.

eventually an outflow from the region, causing foehn phenomena east and north of the Rockies and west and south of the Sierras. In southern California these winds occur with only moderate pressure gradients over the mountains to the north and east due to the low level passes in the region which offer an easy entrance to the air from the Great Basin. They are so persistent in late fall and early winter as to be classified as a winter monsoon bringing unseasonably high temperatures and low humidities to the area, and thus providing the mild winter climate of the district[1]). This foehn, however, is not flowing into a region which is normally exceedingly cold and therefore great contrasts in temperature between this air and the masses to the south and west do not readily arise. Occasionally a cold front lies just off the California coast under such circumstances and the outflow of foehn air from southern California forms a weak secondary cyclone along this front, usually giving rise to little precipitation due to the dryness of the air forming the warm sector of the disturbance.

More important for our present discussion is the extensive foehn resulting from an outflow from the Columbia Plateau anticyclone into the comparatively low level provinces of Alberta and Saskatchewan east of the Canadian Rockies. These regions are normally occupied at this season by very cold Polar Continental (P_c) air masses and during the marked foehn which occurs when the pressure gradients over the Rockies are strong, large temperature differences arise between the foehn current and the air to the east and northeast. Temperature differences in a few hundred miles not infrequently exceed 60° F. under such conditions. This is not purely a surface phenomenon since in the foehn an entire column of air has undergone compressional heating, thus producing in the region between this air and the P_c air to the northeast a tremendous density of solenoids, which indicates, of course, vast amounts of available potential energy of mass distribution. The movement fo the foehn air into regions formerly occupied by P_c masses constitutes a breakdown of any stability which might have existed at the initial formation of the discontinuity between the air masses, and a cyclone is quickly generated along the great warm front which first appears on the synoptic chart as the boundary between the foehn and the very cold P_c air to the northeast. There is, of course, active overrunning of the P_c current by the foehn air as indicated by three hourly pressure decreases

[1]) Krick, Irving P., Foehn Winds of Southern California. Gerl. Beitr. Geophys. **39** (1933) 399—407.


BERRY'S RELIEF MAP OF
UNITED STATES
A base for charting geography and history facts
SCALE
APPALACHIAN MTNS.
BLACK HILLS
ALBERTA
SASKA-TCHEWAN
CANADIAN ROCKY MTNS.
ROCKY MTNS.
COLUMBIA PLATEAU
GREAT BASIN
CASCADE MTNS.
SIERRA NEVADA MTNS.

Fig. 1.

in advance of the front which often exceed 0.2 inch. The foehn current which now constitutes the warm sector of the disturbance has a southward component and the whole disturbance moves off to the southeast rather than to the east or northeast as is usually the case with the high-level cyclones of this region.

The foehn air of these disturbances is usually a Transitional Polar Pacific mass (N_{P_p}). It is initially quite dry regardless of its maritime origin, since air moving into the Great Basin or Columbia Plateau from the Pacific Ocean must lose a good deal of its moisture in crossing the mountains to the west or even in accomplishing the 4000 to 6000 ft. ascent to this region. The descent of this air east of the Rockies further reduces the relative humidities and usually the specific humidities will be lower than those at the surface in the Great Basin due to the fact that the air forming the foehn usually originates at levels approximating the altitudes of the summits of the passes or crests over which it pours into the lower areas to the east. This sliding out of the air at high levels is assisted by the intensification of low level temperature inversions by subsidence and radiation effects and is entirely analogous to the situation in the foehns of the Los Angeles Basin described in a previous paper[1]).

It is interesting to note that as long as the Columbia Plateau anticyclone is maintained with undiminished intensity a continual series of such cyclones will be generated. This is readily understood when one considers the fact that these disturbances move off to the southeast along the P_c—N_{P_p} front in accordance with the direction of the current in the warm sector, and cause to their north a fresh movement of P_c air into the region southwest of Hudson Bay. The convergence of this southward moving cold mass with the warm foehn air descending the eastern slopes of the Canadian Rockies will result in the genesis of a new cyclone with an intensity proportional to the temperature differences arising between the air masses.

Disturbances of this nature may become very intense due to the sharp contrasts in temperature which have been occasioned. Practically the entire kinetic energy of the disturbance is provided by the initial potential energy of the system since the air forming the warm sector is extremely dry and no appreciable condensation takes place within the disturbance until after the air has crossed the Great Lakes and picked up small amounts of moisture. Even then the heat of condensation released is negligible.

[1]) Krick, op. cit. in fn. 1, p. 58.

This type of cyclone has its maximum intensity at the ground and in the lower levels since the greatest temperature contrasts arise here. For this reason, strong surface winds occur within the cyclone which may blow dust or snow rendering the passage of the disturbance rather disagreeable, regardless of the lack of precipitation associated with it. These disturbances propagate quite rapidly whereas the normal cyclone passing eastward along the International Boundary is a slow moving affair being usually no more than an occluded front which has passed over the mountains east of the Gulf of Alaska. In such a case no large temperature contrasts are to be noted at the surface and the maximum activity of the disturbance remains at high-levels unless a source of warm air is encountered and regeneration takes place.

A typical situation of this kind occurred during the period November 9 to November 15, 1933. Three such cyclones were generated during this period due to a continual foehn maintained east of the Canadian Rockies by a well developed anticyclone centered over the Great Basin and Columbia Plateau. At the beginning of the period the anticyclone was not the usual eastward extension of the Pacific anticyclone, but a westward extension of a large anticyclone consisting of P_c air which had moved southward from its source region and subsided over the central United States. At least at low levels the air in the Great Basin anticyclone was Transitional Polar Continental (N_{P_c}) with characteristically low specific humidities; about 2 g./kg. in this case. Subsequently Transitional Polar Pacific air ($N_{P_{pc}}$) played a role of increasing importance, forming the major portion of the foehn air. However, for the present discussion this is of little importance since both these air masses are characterized by low specific humidities and a stable stratification whenever they appear at this season in the regions under discussion.

For the sake of clarifying the discussion, daily synoptic charts for the period under consideration have been included. The charts are constructed from synchronous data compiled at 5 A. M. Pacific Standard Time. Each full barb on the wind arrows represents approximately one unit on the Beaufort scale. The pressure field is indicated by isobars drawn for each tenth of an inch. The principal fronts have been represented as follows: cold fronts by heavy solid lines, warm fronts by double lines, cold front type occlusions by broken lines and warm front type occlusions by dotted lines. The symbols adjacent to the fronts indicate the recent life history of the air masses involved. In this connection the local classification of American air masses developed at the Massachusetts Institute of Technology has been closely followed. The elementary symbol represents the type and source region of the mass, for example, P_c (Polar Continental or Polar Canadian). To denote transitional types the letter N precedes the elementary symbol. Occasionally this latter portion if followed by a c or an m to indicate that the modification of the air mass has been due to continental or maritime influences respectively. For a complete classification and description of the American air masses the reader is referred to a paper on the subject by H. C. WILLETT[1]).

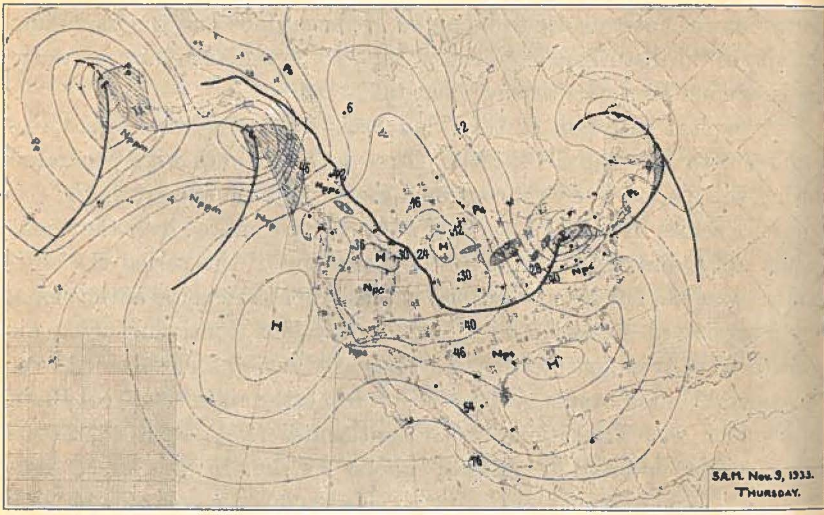

Fig. 2.

On the synoptic chart of November 9, (Fig. 2), we observe an anticyclone centered over the Columbia Plateau and the plains of South Dakota east of the Rockies. The portion of this anticyclone west of the Rockies is what remains of the previous outbreak of P_c air mentioned above. The eastern portion of this anticyclone is the result of a southward flow of fresh P_c air to the rear of the cyclone centered over the Great Lakes and will simply move south and east as the migratory anticyclone associated with it. This difference between the air masses in the anticyclone is indicated by the cold front paralleling the eastern slopes of the Rockies and the symbols adjacent to it denoting the air masses involved. A cyclone centered in the Gulf of Alaska is occluding

[1]) WILLETT, H. C., American Air Mass Properties. Mass. Inst. Techn. Met. papers, Vol. II, No. 2.

along the coast of British Columbia. The progress of the warm front is blocked by the lofty mountain ranges paralleling the coast thus facilitating the occlusion by the cold front to the west. At this time of the year the occlusions in this region are usually of a warm front type, the abnormally high ocean temperatures in these latitudes causing the air behind the cold front to be warmer than the air lying along the coast of British Columbia east of the warm front. Normally the eastward progress of even the portion of the warm front surface lying above the crest of the mountains ceases during occlusion and only the upper front of the occlusion finally passes over the mountains and proceeds eastward as a rather weak high level disturbance. However, in the first foehn cyclone of our series the anticyclone to the south assists the upper front of the above mentioned occlusion over the Canadian Rockies, giving rise at the same time to foehn phenomena east of the mountains which in turn produce considerable amounts of available potential energy of mass distribution between this air and the cold P_c air to the northeast. This activity results in the regeneration of the dying cyclone and transports the level of maximum activity from high levels to the surface. This cannot be considered as the genesis of a primary cyclone since an upper front would probably have passed over the region anyway; however, subsequent disturbances appear to owe their origin entirely to the convergence of the foehn air with that to the northeast.

On the November 10 map (Fig. 3) we note that only an occluded front off the coast of British Columbia marks the cyclone which was centered over the Gulf of Alaska the previous day. Foehn phenomena are observed east of the Rockies as far south as Colorado as indicated by the warm front extending southward into this area. The upper front of the disturbance has been omitted since the maximum intensity is now at lower levels. The foehn in this case is perhaps not as pronounced as subsequently, but it is nevertheless quite apparent when one compares the temperatures of the foehn area with those of the preceding map. For example, at Battleford, Saskatchewan, the temperature increase during the period is 36° F., while farther south at Rapid City, South Dakota, just east of the Black Hills, the increase has been 28° F. The foehn air in Canada has been indicated on the chart as Transitional Polar Pacific ($N_{P_{pc}}$) and the subsequent increasing pressures in the Columbia Plateau anticyclone are no doubt due to an inflow of this type of air over the region resulting in the usual eastward extension of the Pacific anticyclone.

On November 11, (Fig. 4), we note a steepening of the pressure gradients over the Rockies, a condition favoring an intensification of the foehn. The cyclone of the previous day is now centered just west of the

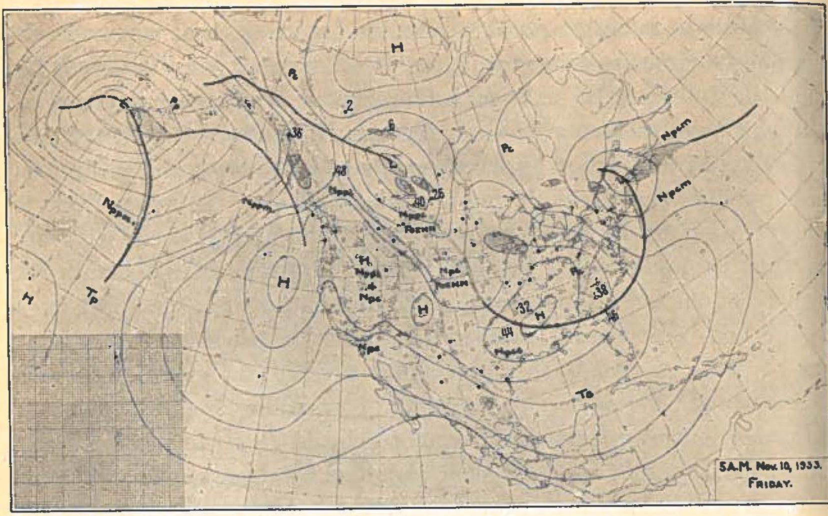

Fig. 3.

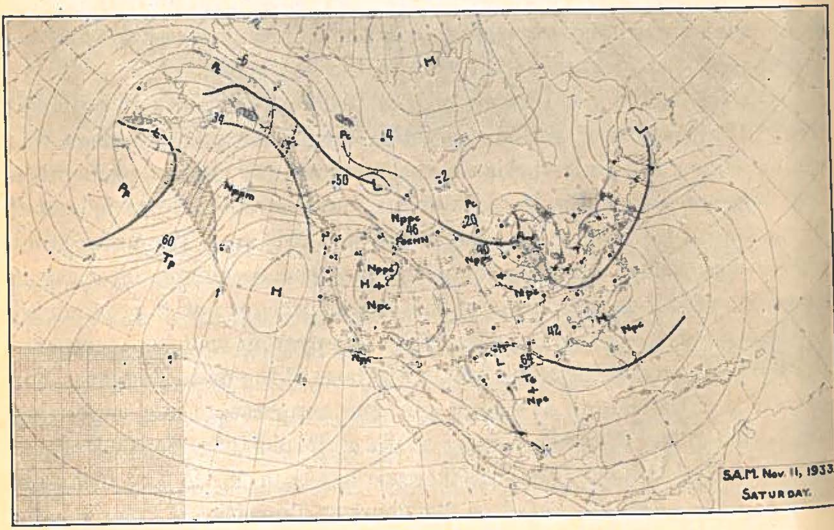

Fig. 4.

Great Lakes region and is feeding cold P_c air into the region southwest of Hudson Bay. The temperature at the Pas, Manitoba, for example, has dropped 10° F. since the previous map. The convergence of this cold current with the warm foehn air about to descent the eastern slopes of the Rockies will favor the genesis of a new cyclone having an intensity proportional to the temperature difference between these two air masses. This tendency is already apparent in the distribution of the isobars east of the Rockies. The cyclone off the Aleutian Islands in the North Pacific in this case is too far removed to effect the formation of this cyclone, therefore we must regard this case as the genesis of a primary rather than

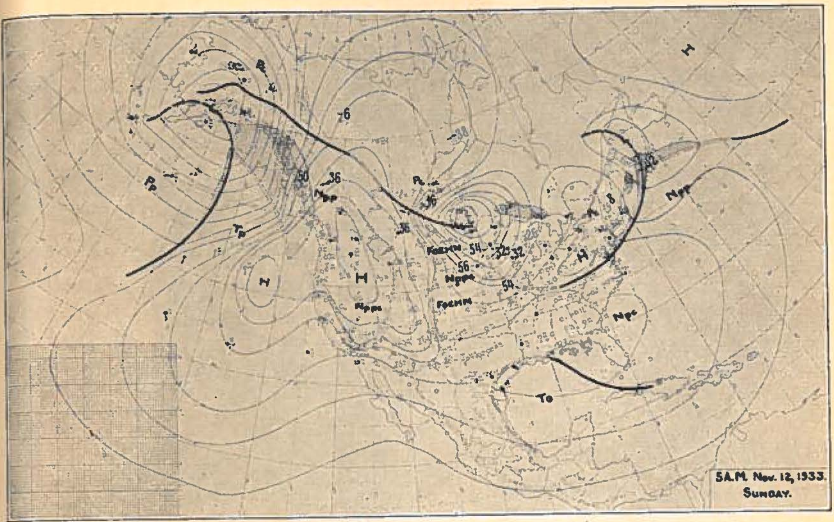

Fig. 5.

of a secondary disturbance. The formation of subsequent cyclones in the region results from an entirely analogues process since no fronts from the Gulf of Alaska are observed to cross the mountains before November 16, by which time the Columbia Plateau anticyclone has subsided and moved eastward.

The synoptic chart of November 12, (Fig. 5), shows the intense disturbance which has developed from the contrast between the foehn which forms its warm sector and the surrounding P_c air. It is interesting to note the almost complete lack of precipitation accompanying the phenomenon due to the low moisture content of the air masses involved. The absence of precipitation is certainly not due to a lack of active overrunning on the part of the warm air since very sharp temperature contrasts and marked convergence in the flow may be noted along the warm front, as well as marked pressure drops during the three hours prior to the observations at all stations in advance of this front. Duluth, Minnesota, for example, records a pressure drop of 0.24 inch. The only precipitation occurring in advance of the warm front is north of Lake Superior and Lake Michgan, the air moving up rapidly from the south having picked up sufficient moisture in crossing the lakes to produce a miniature warm front precipitation in overrunning the colder air to the north.

The great contrasts in temperature between the foehn air of the warm

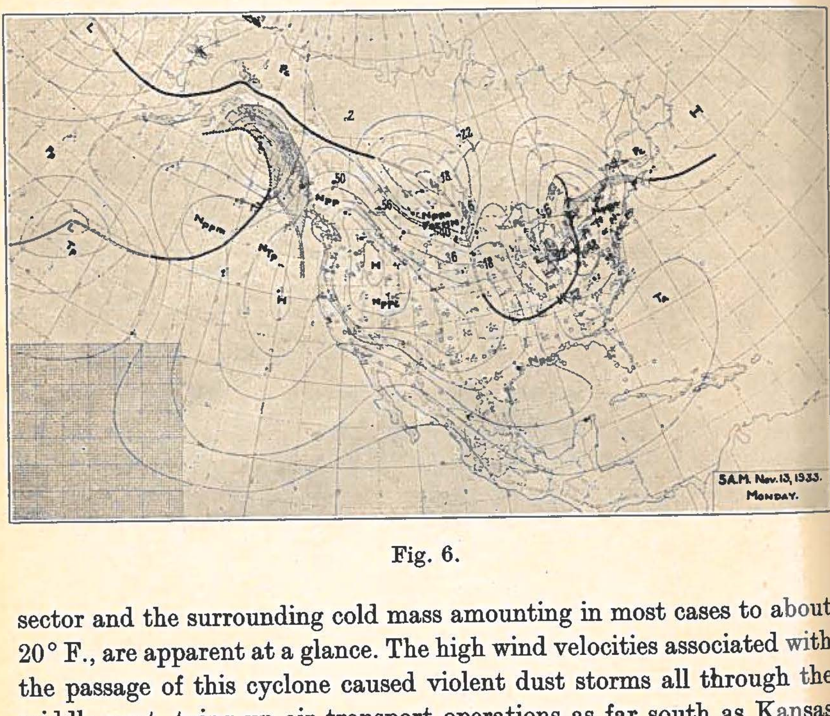

Fig. 6.

sector and the surrounding cold mass amounting in most cases to about 20° F., are apparent at a glance. The high wind velocities associated with the passage of this cyclone caused violent dust storms all through the middle west, tying up air transport operations as far south as Kansas City. The situation favors the genesis of another such cyclone since the pressure continues to build up in the Columbia Plateau anticyclone and very cold P_c air is again being brought into the area east of the Canadian Rockies in the lee of the present disturbance as indicated by the very large three hourly pressure increases behind the cold front. An increase of 0.40 inch may be noted at the Pas.

The synoptic chart for November 13, (Fig. 6), shows the initial stage in the development of the final cyclone of this series. The intensity of the foehn and the tremendous horizontal temperature gradients produced between this air and the P_c to the northeast may perhaps be better appreciated by a comparison with temperatures elsewhere on the map. At Calgary, Alberta, in the foehn air just east of the mountains we note a temperature of 56° F.; the temperature at Tampa, Florida, on that morning! The comparison is even more significant when one considers the fact that at Tampa the sun has been shining for several hours while at Calgary the sun is still below the horizon. Thus we have contrasts between the foehn and the P_c air to the northeast of the order of those which

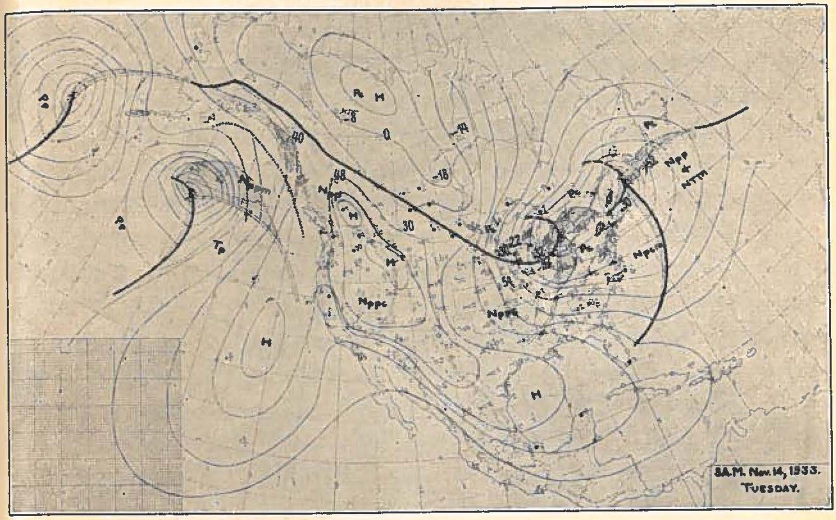

Fig. 7.

would arise if the P_c air were transported southward adiabatically and in the absence of subsidence affects to the Gulf of Mexico. In such a case we should certainly anticipate the development of a violent disturbance.

We note the intensification of the foehn of southern California on this day due to the steepening of the pressure gradients over the mountains to the north. This results in foehn phenomena at various points along the coast as far north as San Francisco. Ordinarily only southern California benefits by the mild foehn weather in such a situation, since the lofty Sierras prevent the air from reaching the surface farther north when only moderate pressure gradients exist.

The chart of November 14, (Fig. 7), indicates that subsidence has begun in the Columbia Plateau anticyclone. Another anticyclone has put in an appearance to the north apparently due to a fresh movement southward of P_c air, the temperature at Ft. Simpson, British Northwest Territory, having dropped 10° F. during the past 24 hours. The presence of this anticyclone together with the subsidence of the Columbia Plateau anticyclone will put an end to the foehns east of the Rockies by destroying the pressure gradients necessary for their genesis. We note that the cyclone of the day before has deepened and moved southward in accordance with the southward component in the foehn air of the warm

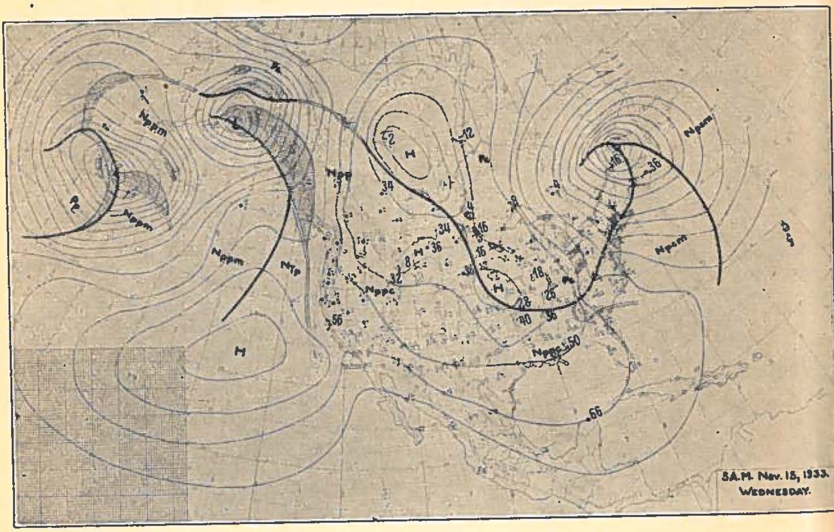

Fig. 8.

sector. This unusual wind direction in the warm portion of the cyclone accounts for the peculiar position of the warm front in the disturbance. This is rather significant in this case since we note that the front parallels the Appalachians to the east. Usually the warm fronts of cyclones in this region lie normal to these ranges and encounter no particular difficulty in negotiating them, but in our present case the progress of the portion of the front lying below the crest of the mountains will be stopped, causing an occlusion of the cold front type to take place along the western slopes. This prevents the increasing temperatures along the central and south Atlantic coast which occur at a warm front passage. This may be noted by a comparison with the previous cases where the warm fronts are normal to the Appalachians.

The chart of November 15, (Fig. 8), indicates an increase in the intensity of the anticyclone moving south over Canada and a further subsidence in the Columbia Plateau anticyclone together with a slow eastward movement. This situation excludes the possibility of further genesis of foehn cyclones in the region for the present. The warm sector of the cyclone in the east has disappeared due to occlusion west of the Appalachians, with the exception of some of the warm air which found its way around the southern extremity of the ranges. Since the occlusion is of the cold front type the mountains will not prevent its ultimate passage, indeed near the center of the cyclone where the pressure gradients are very marked a portion of the occluded front has passed over the mountains as indicated. A warm front type occlusion has occurred in the disturbance centered over the Gulf of Alaska and it is the upper front of this occlusion which appears over Alberta, Canada, the following day as mentioned above. This is the normal high level disturbance usually observed moving eastward over the Canadian Rockies and need not be discussed here. The foehn has ceased now even in southern California as indicated by the temperatures along the coast and the formation of a ground fog at San Diego. The foehn air returning from the Pacific having picked up a shallow layer of moisture produced a dense ground fog in all coastal areas the following morning, aided by intensive nocturnal radiation though the transparent upper layers.

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