TOPOGRAPHY VERSUS AIR MASSES.

A Discussion of the Phenomena Associated with the passage of Air Masses over the Irregularities of the Earth's Surface.

THESIS

by

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TOPOGRAPHY VERSUS AIR MASSES.

PART 1.

The following paper deals with the effects of the Earth's topographic features upon the physical propertiesof air masses. The subject is an extensive one and no attempt will be made at an exhaustive study at this time, but rather a general treatment will be outlined, the detail of which will be attempted at a later date.

It will first be necessary to list the general types of air masses with which we shall deal before observing their trajectories and investigating the changes which they undergo as a result of passage over different types of surfaces. These general types include:

1. Tropical.
   a. Tropical Continental TC
   b. Tropical Maritime TM
2. Polar.
   a. Polar Continental PC
   b. Polar Maritime PM

These two groups are named according to the regions of the Earth where they obtain their initial properties. Since the Earth's surface consists of land and water, substances having totally different thermal properties, we must differentiate between air masses obtaining their initial properties over land surfaces or over water surfaces, as indicated by the sub-classifications a. and b. under both the polar and the tropical headings. Furthermore we must make allowances for alterations in the properties of these air masses as they are transported far over the Earth's surface in the general atmospheric circulation. We shall later add these so-called transitional air masses to our classification, but first we must consider the properties of the principal types and discover how they move over the Earth's surface. The latter entails a discussion of the general circulation of the atmosphere.

Tropical Continental (TC) air obtains its initial properties over dry hot land surfaces as, for example, over the Sahara Desert or the desert regions of North America. This air is thus identified at any time of the year by its extreme dryness and high temperature, the latter also leading to a very steep lapse rate. Thunder showers do not occur in this air however unstable it may be due to its very low moisture content although the instability often leads to whirlwinds which on occasions may assume the proportions of miniature tornadoes.

Tropical Maritime (TM) air on the other hand is very moist and also warm, a combination which invariably leads to a lapse rate only conditionally stable, i.e. a lapse rate lying between the adiabatic lapse rate for dry air and that for saturated air at the temperature of the air in question.

Polar air masses originate in high latitudes as the name implies, therefore they are characterised by low temperatures and low specific humidities especially during the winter months. This is true particularly of the PC air masses, which are also identified by a very stable lapse rate in winter, usually with a marked temperature inversion, due either to radiation cooling, subsidence in a semi-permanent anticyclone, or both. In summer the only distinctive characteristic of this air mass is its dryness.

Polar Maritime (PM) air is more moist and warmer, at least in the lower layers, than the PC air. This is evident from the fact that the water surface is relatively much warmer than the land surface at the same latitude in the polar regions, particularly in winter. This warmth of the lower layers leads to a less stable lapse rate in the polar maritime air than in the polar continental.

Now that we have characterised the general types of air masses we wish to know how they move over the Earth's surface and what effects may be noted due to their passage over the largest irregularities of the Earth's surface, namely the oceans or the continents. As we shall see by a discussion of the general circulation, large latitudinal air displacements are possible, a fact which we shall use to determine how the initial properties of the Polar or Tropical air masses become altered. There have been numerous theories advanced on the subject of the general circulation of the Earth's atmosphere, but perhaps the most complete and most modern has been given by V. Bjerknes, whose results will be briefly summarised here.

Circulation on a Uniformly Frictional Non-rotating Earth---Let us begin by developing the circulation which would prevail if the Earth were a non-rotating globe made of a uniformly frictional material. The necessary and sufficient condition for the existence of a general circulation in the atmosphere is the unequal supply of heat in the form of insolational energy to the atmosphere in the equatorial and polar regions. It follows that the great excess of solar radiation received in the tropical regions over that received in polar regions must tend to maintain a higher temperature in the Earth's atmosphere in the tropics. This means a lifting of the isobaric and a sinking of the isosteric surfaces in equatorial regions and the reverse in polar regions. Thus numerous solenoids are formed running parallel to the latitude circles, and the tendency to a marked circulation between tropics and poles is established according to the circulation principle developed by V. Bjerknes^1.

This principle, essential to all atmospheric circulations, is illustrated diagramatically in Fig. 1, which represents a cross-section of the atmosphere above a warm source A and a cold source B. The dotted lines V_0, V_1 etc. represent isosteric surfaces and the solid lines P_0, P_{-1} etc. represent the isobaric surfaces. Isosteric surfaces are surfaces of equal specific volume. A unit solenoid is the prism formed by the intersections of adjacent isobaric and isosteric surfaces,

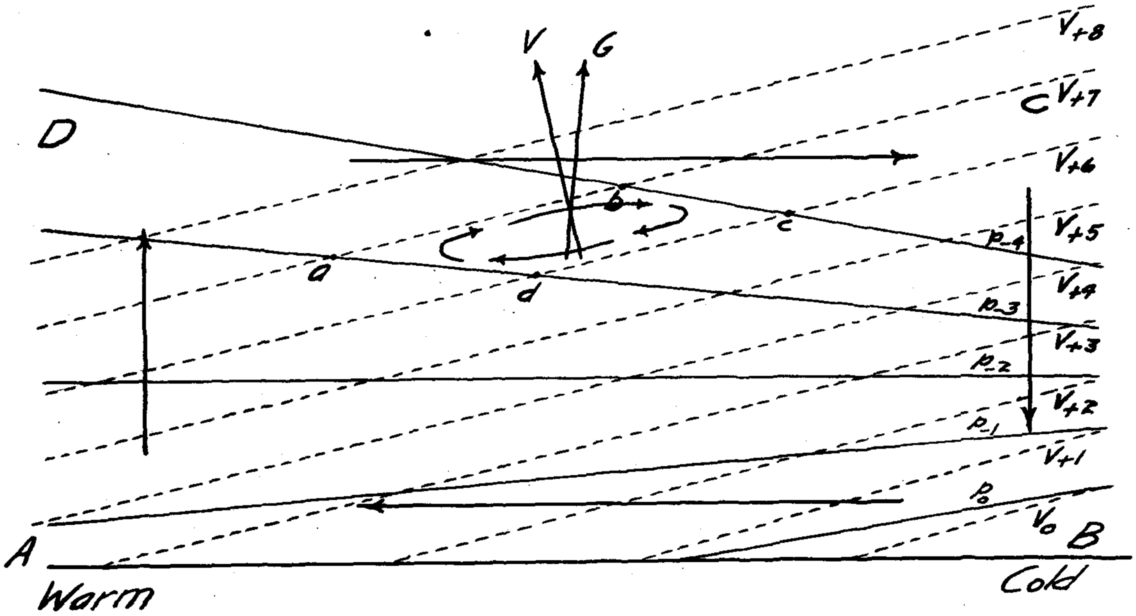


Figure 1.

Circulation principle after V. Bjerknes.

thus abcd in the sketch would be a cross-section of a unit solenoid. The circulation of the system is indicated by the large arrows and its acceleration is determined by the number of solenoids enclosed in the area ABCD. The directions V and G are normal to the isosteric and isobaric surfaces respectively and the tendency of the circulation is to bring them into coincidence.

The circulation thus set up will be equatorward below and poleward aloft. Thus under these conditions the general atmospheric circulation would consist of one large direct circulation system between the equator and each pole. A steady circulation would result wherein the frictional forces tending to check it would require the performance of work by the thermodynamic system in overcoming this resistance. This would result in the consumption of a part of the excess heat received in the equatorial regions. If Q is the excess of effective insolational over emitted terrestrial radiation in the equatorial half of the system, and Q' is the excess of emitted terrestrial over effective insolational radiation in the polar half of the system, the thermodynamic effeciency of the system would be $\frac{Q-Q'}{Q}$. Actually however the Earth is rotating, a fact which results in the complete breakdown of this single direct uniform circulation between equatorial and polar regions.

Effects of Earth's Rotation upon the General Circulation---There are two general effects of the rotation of the Earth upon atmospheric circulation which we must consider, namely the so-called horizontal deflective force and the conservation of angular momentum.

The first of these effects is an apparent deflection in the direction offlow in an air current which deflection is in reality due to the rotation of the plane of reference beneath the moving air. In practise this effect is represented by a fictitious force acting always at right angles to the linear velocity of the air current referred to the Earth's surface. It is evident from the fact that this fictitious force acts always at right angles to the velocity of the air current that it can never produce any linear acceleration of the velocity but merely a change of the direction of flow. Thus in the northern hemisphere air flowing from high to low pressure will be continuously deflected to the right until an equilibrium velocity (gradient wind) is reached parallel to the isobars such that the pressure gradient force is just balanced by the horizontal deflecting force (frictionless rectilinear flow). When this state is reached all air flow from high to low pressure will cease except as the piling up of air masses in the equilibrium zone steepens the pressure gradient, or as the retarding effect of friction near the ground slows up the velocity of flow sufficiently to permit of a certain component of the velocity directed across the isobars. It can be seen that an equatorward moving branch of the circulation in the northern hemisphere will rapidly be deflected to a westward moving current, and that any poleward moving branch will be deflected to an eastward moving current. It is also to be noted that the horizontal deflective force is a maximum at the poles and decreases to zero at the Equator since the force is a function of the sine of the latitude.

If the second effect of the Earth's rotation held true, the conservation of angular momentum, enormous east-west velocities and west-east velocities would be produced in the case of large latitudinal air displacements. Air moving from the equator toward the poles would soon acquire tremendous west-east velocities and air moving from the poles toward the Equator would soon attain great east-west components. This effect actually is greatly minimized due to internal friction of atmospheric strata, and friction of the air with the Earth's surface. When isolated portions of the atmosphere are considered the effect is damped even more by the pressure forces exerted by the remaining atmosphere. However, in the case of regular interzonal air movement of entire circumplanetary atmospheric rings, as for example in the case of the trade winds, zonal accelerations of a complete ring is possible without the resistance of an opposing pressure force. In such cases, however, it is a question whether the zonal velocities are to be attributed entirely to pressure gradient acceleration and subsequent deflection, or in part to the conservation of the angular momentum of circumplanetary air rings which are displaced latitudinally by the prevailing pressure gradient. The practical result in any case is the same since the effects of the horizontal deflective force and the conservation of angular momentum are always in the same sense.

It can be seen from this brief statement of the effects of the rotation of the Earth upon moving air particles that the single direct circulation between the Equator and each pole as described above for a non-rotating earth would be quite impossible on our rotating globe. Instead of a single direct circulation between equator and either pole, there result several smaller zonal circulations, within each of which more or less uniform east-west and west-east velocities prevail at the Earth's surface.

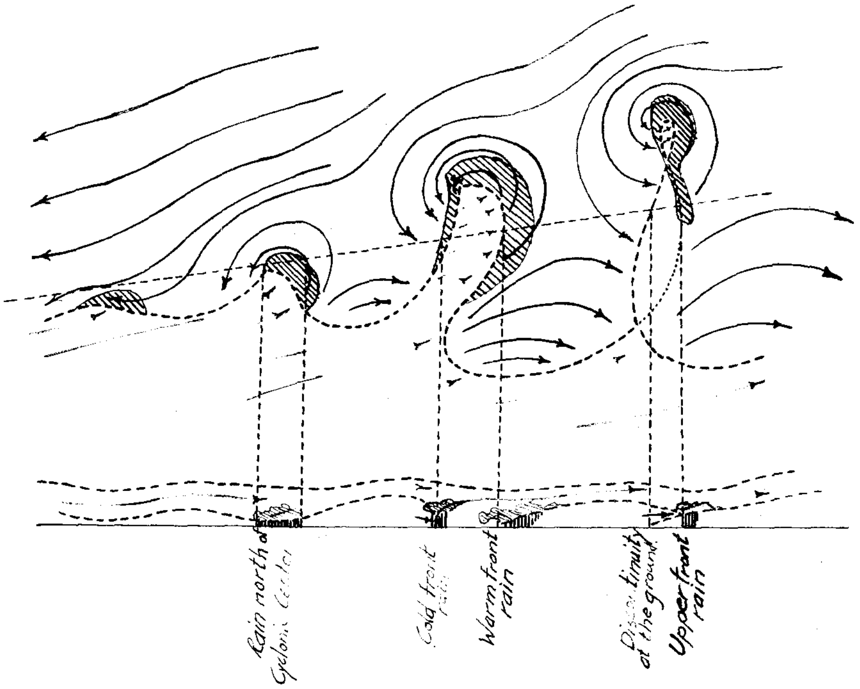
Circulation of the Sub-Tropics (Trades-Antitrades)---The maximum effect of insolational heating is felt in equatorial regions, in consequence of which a lifting of the isobaric and a sinking of the isosteric surfaces is effected and the establishment of circulatory exchange of air with more northerly latitudes, in accordance with the circulation principle. However, owing to the horizontal deflective force of the Earth's rotation, a deflection of the typical northward and southward moving air currents takes place, so that the southward moving current approaches the Equator as a north, northeast, and eventually close to the Equator, an east wind and the northward moving current as a south, southeast and east wind. These are the well-known trade winds. These winds become deeper as they approach the Equator (thermal), where they join as one great westward current of air extending to high elevations. At the Equator, however, they rise above the Earth's surface, leaving the belt of calms at the surface known as the doldrums. Thus at the Equator the atmosphere as a whole is deficient in angular momentum relative to the Earth's surface, or in other words, is rotating more slowly.

The upper branch of the subtropical circulation has its source in the upper levels of the strong westward current of air which has initially been fed in by the trades, at the same time that it was heating and rising. Under the influence of the pressure gradient the air aloft gradually flows out towards the poles, the current on the North Hemisphere being deflected as it moves poleward first towards the north and eventually toward the east. This current is known as the anti-trades. Already at approximately 30° N. or S. this current appears as an eastward flow, which has cooled sufficiently to be sinking to the Earth's surface in the high pressure belts at these latitudes. From these high pressure belts the descending air of equatorial origin may feed into the general west winds to the north, or into the trades to the south (North Hemisphere) and work back toward the Equator. This southward moving branch closes the path of the sub-tropical link in the general circulation between equatorial and polar regions. Only that part of the anti-trades which continues poleward from the subtropical HIGHS with the general westerlies of middle latitudes may take part in the complete circulation. The high pressure belts of the Horse Latitudes are essential to the link in the general circulation, which exists in the sub-tropics. Dynamically the existence of such a closed link is necessitated by the deflecting force, which checks the northward movement of the equatorial outflow at about latitude 30° and permits only a very slight northward progress of the air from that point, due to friction. Consequiently in these latitudes a piling up of air masses occurs, or a high pressure belt is formed, such that a gradient is established towards the Equator at the ground, the gradient which is necessary for the existence of the trades.

The Circulation of the Polar Caps---In the polar regions the prevailing circulation, as pointed out by many modern writers, appears to be a thermodynamic direct partially closed circuit, as in the tropics. It is, however, less regular and less strongly developed than the trade-antitrade circulation. Apparently there is a sinking of cold air masses over the ice-covered Arctic, and this air moves southward under the influence of the prevailing gradient, being deflected gradually southwestward and westward. At about latitude 60° or a trifle northward from there, this cold current reaches the southern limit of any regular progress. Here it may in part be warmed sufficiently to rise and return poleward aloft as the upper branch of the polar circulation, in response to the reversed gradient aloft, but in part it moves southward in irregular outbreaks of cold polar air at the ground, giving rise to the phenomena so well known as cold waves. Through the first 3 or 4 kilometers above the ground there is normally a rather marked and persistent discontinuity (the polar front) between the prevailing westerlies to the south and easterlies to the north, and correspondingly at the ground there must be a trough of minimum pressure between these two wind systems. At a few kilometers elevation this minimum disappears, and a poleward gradient with prevailing westerly winds prevails from the equator to the poles. Since there is always some slight movement of air masses across isobars from higher to lower pressure as a result of frictional forces, there is normally a gradual northward flow of air from equatorial regions through the middle latitudes into the polar circulation at high levels. Thus air of southerly origin, under normal conditions, is continually feeding into the polar circulation aloft. Hence there is a gradual accumulation of cooling air masses over the arctic regions, which means a growing southward pressure gradient at low levels, the prevailing gradient mentioned above. Eventually there follows a pucking out of cold air at some favorable point along the polar front, and a great outflow of excess polar air masses into the prevailing westerlies occurs. This effects a damming up of the normal air flow and establishes longitudinal pressuregradients counteracting the horizontal deflective force. This in turn permits the outflow of air from the arctic regions to move far southward and eventually to pass into the trade wind circulation. It is to be noted that these outbreaks of polar air are not to be considered as the normal state of affairs but rather as the irregularities in the circulation of middle latitudes which permit of the exchange of air between polar and equatorial regions at the surface. These southward moving currents invariably lead to northward moving currents to their east as will be discussed presently under the circulation of the middle latitudes.

Circulation of the Middle Latitudes:---From the sub-tropical belts of high pressure to the polar troughs of low pressure there is normally a pressure gradient at the ground which makes the intervening regions one of prevailing westerly winds. These are, therefore, practically speaking, gradient winds. Since this surface flow is just the reverse of that of a thermodynamically direct circulation between northerly and southerly latitudes, it may be said that the circulation of middle latitudes is a reverse circulation maintained by the two direct circulations bounding it to the north and to the south. In other words, it is a forced circulation, the force being applied by the sub-tropical belt of high pressure and the sub-polar belt of low pressure which are maintained by the two direct links in the general circulation. The source of these westerly currents is to be found in the westerly currents of sinking air of equatorial origin in the sub-tropical high pressure belts. As already mentioned part of these sinking masses feeds into the trades and returns equatorward while part feeds into the general westerly winds of middle latitudes and finds its way gradually northward. At the polar front the gradual northward progress of these westerly currents takes place primarily in the upper levels, as the colder surface easterly winds are overrun by the warmer west winds above. The fact of the existence of a polward pressure gradient in middle latitudes to the height of 18 kms. or more raises the question as to how the equatorward flow of air to compensate the poleward flow in the prevailing westerlies takes place. The explanation is to be found in the great irregular outbreaks of air from the arctic regions, in the manner described in the preceding section When an excess of air has accumulated in the arctic, eventually a general equatorward movement of the polar air masses occurs at some point. The establishment of such an outflowing current from the polar regions invariably favors the establishment of a northward moving current of warm air on its east side, with the existence of a trough of minimum pressure between the two, the pressure gradient counteracting the deflective force. In such a trough between two oppositely directed air currents occur the interactions which constitute a cyclone family. In mentioning a cyclone family a word of explanation is inorder. We cannot dwell upon this important subject in detail at present but refer the reader to the well know papers by J. Bjerknes and H. Solberg[2]. It must suffice here to briefly describe the phenomenon and to include a sketch of an idealised cyclone family to which reference may be made later.

The formation of the mother cyclone is due primarily to heating and colling of adjacent areas and is perhaps best explained at present by Exner's[3] barrier theory. According to this theory the cold air outbreak towards the south takes place freely between a cyclonic and westward-lying anticyclonic center of action, the normal westward movement which should result from the Earth's deflective force being checked by the eastward pressure gradient. Since the warmer air to the south normally constitutes a westerly air current with a slight northerly component, the breaking out of the cold air along the polar front into this warm air flow effects a certain obstruction or damming up of the current. In the lee of the cold air mass a partial vacuum results, so that the warm air is drawn in from the southwest or south around the cold air mass, the trough of lowest pressure lying between the two currents. This low pressure is caused both by the lee effect of the cold air barrier, and by the normal lightness of the overlying warm air. The following high pressure, or anticyclone, is caused both by the greater density of the cold air of the polar outflow, and by the damming up and consequent piling up of the westerly current. This constant force of the westerly current, expressed in the strong eastward pressure gradient, imparts an eastward movement to the cold air barrier at the same time that it is spreading southward and sinking. Thus both the cyclone and anticyclone move first southeastward then eastward from the position of the initial thermally caused low and high, becoming in this way the normal migratory cyclone and anticyclone of the lower atmosphere. Between the warm and cold current there is a discontinuity surface of the cold front type, while further to the east, where the northward moving warm air current meets the cold air at the polar front, there is a discontinuity of the warm front type (see Fig. 2). These discontinuities are less clearly marked in the primary cyclone than in the secondaries, therefore the secondaries are usually characterised by a more intense interaction between the air masses. The kinetic energy of the strong circulation set up during such a developement is supplied by the potential energy of the initial vertical mass distribution, or the adjacent warm and cold air masses. As the process continues, the cold air sinks and spreads both southward and eastward, eventually displacing entirely at the ground the warm air current to the east of the cold outflow, i.e. an occlusion has taken place. From this point the disturbance diminishes in intensity, but


Rain north of Cyclonic Center
Cold front rain
Warm front rain
Discontinuity at the ground
Upper front rain

the southward transport of cold air in the anticyclone has usually established a very abrupt temperature discontinuity or front at the southern limit of the cold air outbreak. Fronts established in this way are much more abrupt than those which grow up through heating and cooling of adjacent air masses. Unless the condition of stationary equilibrium is rigidly fulfilled at this abrupt front, a secondary disturbance is bound to develope, which under favorable conditions becomes more intense than the weakening primary.

If due to instability a new outbreak occurs along this front a secondary is formed. Now if the outbreak is such that occlusion also takes place in this cyclone the front is displaced still further south to a new equilibrium position. This process may be repeated until finally an outpouring of cold air into the trades circulation occurs. When this transport of cold air directly from the polar to the tropical regions has been effected, the polar front which has been moving southward is temporarily broken, and is subsequently re-formed far to the north on the cessation of the outflow of cold air. The whole sequence of disturbances, from the first thermally formed cyclone and anticyclone in the far north, the occlusion of the primary cyclone and consequent accentuation of the polar front with the subsequent secondary disturbances, down through the final occluding disturbance which terminates the series with the outflow of cold air into the trades, J. Bjerknes has called a cyclone family. The entire series occurs on one continuous section of the polar front separating a vast warm current of tropical origin on the one side from the cold current of polar origin on the other side. Usually these two currents move eastward at the same time that the cold outflow, and consequently the polar front with its successive disturbances is moving southward. The polar front itself lies along the trough of minimum pressure between the two air currents. The sketch (Fig 2) shows such a cyclone family in horizontal and vertical section.

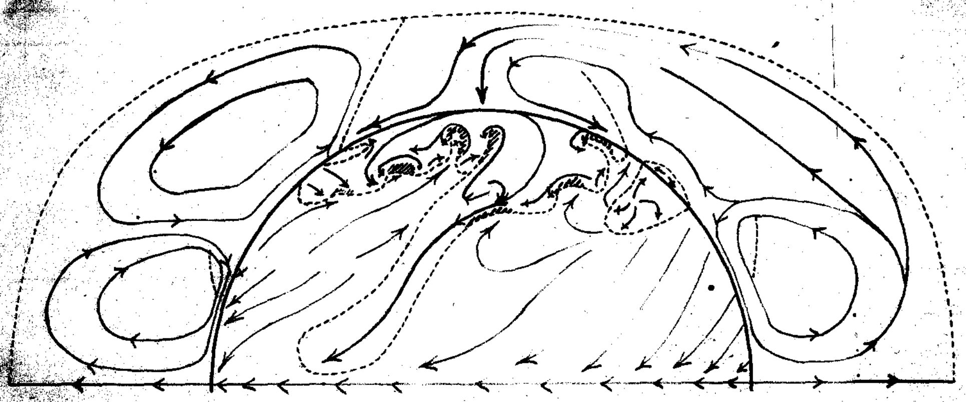
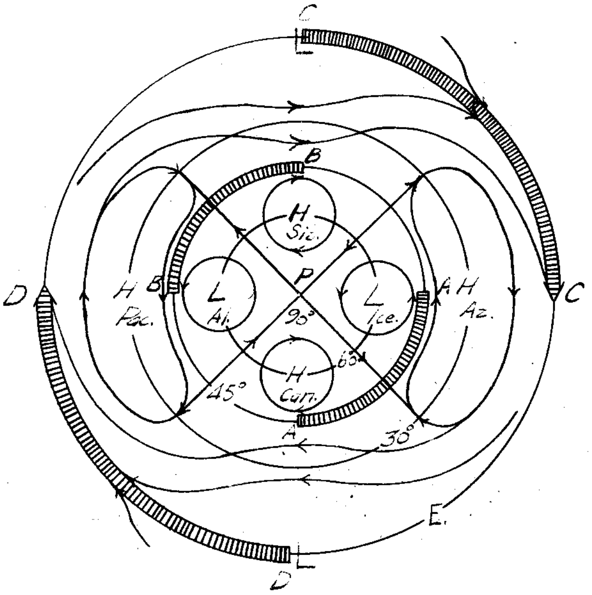


Figure 3.

Schematic representation of the general atmospheric circulation after V. Bjerknes.

circuits. This has been proved by observation with respect to the trade-antitrade circulation and it is probably also true for the partially closed polar circuit. However, the circulation of the middle latitudes is less violent, the polar outbreaks being milder as indicated by the less severe winters of the southern hemisphere. This may be directly attributed to the lack of land surface in this hemisphere. This may be made to appear even more striking when one considers that the southern hemisphere should have a more severe winter than the northern hemisphere, astronomically speaking, since winter in the southern hemisphere occurs when the Earth is farthest from the Sun and consequently traveling slowest thus making the winter season on the southern hemisphere longer than winter on the northern hemisphere.

The way in which the actual distribution of land and water and consequent variations in surface temperature on the northern hemisphere in winter work out in the mean is excellently shown by the following schematic representation taken from Bergeron[4] (Fig. 4). This scheme represents the principal featuresof the normal air movements of the northern hemisphere in winter. The most inportant "centers of action" i.e., semi-permanent cyclones and anticyclones of such persistence that they are to be found on pressure charts representing mean conditions for the season, are indicated by L and H respectively. These are the cyclones and anticyclones, best marked in winter, which form over relatively warm ocean and cold continental regions. The continuous light lines indicate lines of flow, the direction being indicated by the arrows. It will be noticed how the air movements take place around these centers of action as if they were two sets of interlocking wheels, and how the air currents of tropical or polar origin are brought from southerly to northerly or from northerly to southerly anticyclonic and cyclonic circulations. In this way the irregular distribution of land and water helps to effect the interchange of air masses between equatorial and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polar regions. It will be noticed that there are certain narrow zones, indicated by the heavy lines AA and BB, where currents of polar and tropical origin are brought together. These are regions where there is a tendency to the formation of very steep poleward temperature gradients and consequently atmospheric discontinuities, or fronts. To use Bergeron's term, they are regions of frontogenesis. Even the surface ocean currents tend to favor the sharpening of poleward temperature gradients in these two zones. To the north of the zone AA there flows in general from the northeast the cold Labrador current, on the opposite side from the southwest the warm Gulf stream, corresponding to and perhaps in part the consequence of the prevailing air flow. Similarly, to the north of the zone BB there flows from the northeast the cold ocean current from the Bering straits and on the opposite side the warm Japanese current from the southwest. These regions are therefore the ones most favorable for the development of the migratory cyclones and anticyclones, and the rapid movement of the formations. The regions AB and BA on the contrary are regions of divergent air flow, hence of front destruction or to use Bergeron's term frontolysis. They are therefore regions of degenerating or filling cyclones, and of slow movement. This scheme agrees perfectly with the observed cyclonic and anticyclonic activity of these regions. The equatorial zones DD and CC represent regions of closely converging trade systems, of well-marked doldrums, favorable for the development of tropical hurricanes. The regions CD and DC are characterised rather by weak divergence, or probably almost parallel flow of the two trade systems, therefore prevailing east winds which are unfavorable to the genesis of tropical hurricanes.

In the summer time conditions are essentially different due to the fact that the land is the relatively warm surface now instead of the ocean. The low pressure areas over the ocean disappear or are greatly weakened whereas the highs are strengthened, while the highs over the land surfaces give way to low pressure. This of course reduces the poleward temperature gradients which in turn diminish the intensity of the general circulation. This is the explanation of the relatively weak polar outbreaks in summer with the resulting weak cyclonic activity.

Another important consequence of this reversal of conditions over the oceans and continents with the changing seasons is the establishment of the monsoon systems which result. As can be seen from the figure we shall have a flow of air from the continents toward the oceans in winter since due to friction some air is diverted across the isobars from high toward low pressure. In summer when relatively low pressures prevail over the land surfaces due to insolational heating the air flow will be from the oceans toward the continents. The classical example of this seasonal reversal in air flow is, of course, the India monsoon. However this influence may be traced in all parts of the world as observations have shown. Land and sea breezes arise from the same causes on a smaller scale their period being diurnal in contrast to the seasonal period of the monsoons.

Transitional Types of Air Masses.---Now that we have developed the general circulation we must next discuss the changes which the initial polar or tropical air masses must undergo during their journeys to lower of higher latitudes respectively. This is necessary so that we may know the properties of the air masses with which we shall deal in studying in some detail the effect of minor irregularities in the Earth's surface on the air currents passing over them. For example we shall investigate the effects of a mountain barrier upon air of polar origin that has perhaps moved far south or upon air of tropical origin that has moved far to the north etc. As we shall see, the effects in the two cases are quite different.

As we have seen the two main types of air masses (Polar and

Tropical) may acquire their initial properties over land or over water surfaces, thus we must consider the trajectories of both these air masses separately. In addition to this we must differentiate between these trajectories as to whether they lie over land or water surfaces. Considering all possible combinations we have the following general types of transitional air masses:

1. Transitional Tropical Continental. NTC
    a. Properties modified by passage over water surface. NTCm
    b. Properties modified by passage over land surface. NTCc
2. Transitional Tropical Maritime. NTM
    a. Properties modified by passage over water surface. NTMm
    b. Properties modified by passage over land surface. NTMc
3. Transitional Polar Continental. NPC
    a. Properties modified by passage over water surface. NPCm
    b. Properties modified by passage over land surface. NPCc
4. Transitional Polar Maritime. NPM
    a. Properties modified by passage over water surface. NPMm
    b. Properties modified by passage over land surface. NPMc

In determining the properties of the transitional air masses we shall assume a northerly component in the motion of the tropical air masses and a southerly component in the motion of the polar air masses, which is in agreement with our scheme of the general circulation in a broad sense.

NTCm air is initially very dry and is characterised by an unstable lapse rate. If this air passes over the ocean for considerable distances the lapse rate in the lower levels will be stablised due to the cooling effect of the water surface. In passing far to thenorth this air will have had sufficient time to acquire considerable moisture and will for this reason become "foggy". In this respect it is similar to NTMm air which has traveled far northward over the ocean.

NTCc air will be modified somewhat similarly to NTCm and NTMm only to a lesser degree, at least in winter. If this air passes far to the north it eventually passes over land covered with vegetation and may acquire large amounts of moisture due to its relatively high temperature. The lower layers are also cooled thus tending to stabilise the lapse rate. In the summertime the lower layers may pick up considerable moisture without being cooled much and consequently give rise to thunder showers as is attested by observations of the iar moving out of the desert regions in the southwestern portion of the United States. When this air has passed for some distance over less arid country it picks up enough moisture to become quite showery.

NTMm air differs from NTCm air in that the former was originally very moist and had a lapse rate only conditionally unstable. For this reason the lapse rate of this air becomes stabilised much sooner on its journey north than that of the NTCm air and thus gives rise to fog much sooner. This type of air is observed very frequently on the west coast of Europe, often as far north as Norway. A method for determining either of these types of air is to compare the air temperatures with those of the ocean over which they are passing. The air temperatures should be slightly higher than those of the adjacent ocean since the air was originally very warm and has only been cooled by passage northward over a continually cooler surface. As can be readily seen this test is also applicable to polar air which has traveled far to the south. In thiscase the air temperatures should be lower than those of the ocean. Since NTCm and NTMm air masses which have passed far to the north have become stable we should also expect to recognise them by means of their condensation forms, i.e. either fog or stratified cloud forms, both of which indicate stable stratification of the air.

NTMc air is initially very warm and moist and usually only conditionally stable. In winter if this air passes to the north and then over land it quickly becomes stable and may even give rise to dense fog or stratus clouds. This type of air is a frequent visitor along the European coasts and is sometimes also observed along the coast of California. This type of air is quite different in summer. Now the land surface is even warmer than the ocean and consequently what stability the air may have had is soon destroyed upon its passage inland. The farther south this occurs the less stable will the air become. This accounts for the heavy instability showers which are of practically daily occurence along tropical coasts and on tropical islands. Any irregularities of the land surface only tend to give the air an added impetus upward intensifying the phenomenon. This type of thing is observed regularly during the summer months in the states bordering the Gulf of Mexico. The air coming in off the Gulf is TM air and is soon converted to NTMc which due to its high specific humidity and unstable lapse rate gives rise to copious showers.

NPCm air should resemble NPMm in most respects except that the moisture content would be lower due to its very low initial specific humidity. However with a long passage over the ocean it would be able to acquire considerable moisture and would then be truly NPMm air. Such is probably the case with air that has originated in Siberia and has crossed the Pacific to the west coast of America. Researches on this matter are now in progress and should yield interesting results.

NPCc air probably undergoes little change in winter since the surface over which it passes is always cold enough to maintain the stable lapse rate of this air. This is attested by the fact that as far south as Texas the upper air observations in these currents show temperature inversions. This air mass is very rare in California due to the barrier set up by the Sierra Nevada Mountains, but is very common in the Middle West and the Eastern states. It is frequently associated with the well known cold waves, which are nothing more than passages of cold fronts in a cyclonic disturbance. In the summer months due to heating from the ground this air mass loses its original stability when moving far south, but remains relatively dry.

NPMm air has initially a rather low specific humidity and a stable lapse rate. When it moves far south in winter the stability of the lower layers is destroyed and the moisture content is increased, since it moves continually over warmer waters. In summer due to the upwelling of water from ocean depths along the coasts, a well-known phenomenon, the lower levels again become stable, since the upwelled water is usually very cold. This gives rise to fogs along the coasts adjacent to the upwelling areas. This seasonal difference in the NPMm air is very noticable along the California coast. In the spring outbreaks of polar maritime air usually lead to instability showers, whereas during summer this air brings with it the well-known fogs of the California coast.

NPMc air in winter is usually characterised by a stable lapse rate and a fairly low specific humidity. If it has passed rather far to the south before passing over the land its lapse rate will be perhaps only conditionally stable, but with its passage over the cold land surface its stability is restored. Very often this air is forced over a mountain mass due to cyclonic activity and loses the greater part of its moisture. The air is then characterised by quite a low specific humidity, which is however, higher than that of PC or NPCc air. In summer this air may reach the coast having a stable lapse rate. This will be quickly destroyed by contact with the warm ground upon a short passage inland. However thunder showers do not develope in this air massdue to its rather low specific humidity, except in very mountainous regions. This is the case during the summer in California. In winter California is frequently visited by NPMc air which has had most of its moisture removed by passage over the mountains of Oregon and Washington to the north. The air usually moves in over these latter states in the lee of a cyclonic disturbance and frequently stagnates over the Great Basin region. If this is the case air flows from the Great Basin out over California as a cold dry current. It may be mentioned that this air mass plays a very important role in the formation of dense winter fogs in the Great Valley of California, a phenomenon which will be discussed in some detail later. When this event occurs during summer California is visited by a very hot dry current since the Great Basin region is very hot during this season and the current is dynamically heated as it passes down from the region which has an average altitude of about 4500 feet.

It can be seen from this brief summary of the transitional air masses what a profound effect the type of surface over which the air passes may have upon its properties, at least in the lower layers, and after all it is usually with the lower layers that we are concerned, i.e. the troposphere.

PART 2.

We have heretofore only been concerned with the effects of land and water surfaces taken as a whole upon the various air masses. Now we shall add to this discussion some of the effects due to large irregularities in the land surfaces such as mountains, canyons, valleys and the like.

<u>Lapse Rates and Vertical Motion</u>---In dealing with the passage of air masses over large obstacles such as mountain ranges it will be advantageous to know whether the air will resist vertical motion and curve around the object or will rise and pass over it. This property of an air mass is largely dependent upon its lapse rate.

If, for example, the air mass in question has a lapse rate equal to the adiabatic lapse rate for dry air any particle of air transported through a given height for any reason will find itself always at the temperature of its surroundings, providing the process takes place adiabatically and without condensation. Thus the particle is in equilibrium with its surroundings at all times and tends to remain at any level to which it may be transported. The entire air mass in question is then said to be in neutral equilibrium.

Now let us consider an air mass which has a lapse rate less than the adiabatic for dry air. In this case any particle of air transported to a new level will have a temperature differing from its surroundings in such a way that it will immediately seek its initial position, thus it resists any vertical motion. If the particle in question is transported to higher levels it will be colder than the surrounding atmosphere at the same level and will sink; if it be transported to levels lower than its initial position it will be warmer than its surroundings and will be forced to again ascend if allowed its freedom. In this case then the atmosphere is said to be in stable equilibrium.

Finally let us consider an air mass having a lapse rate greater than the adiabatic for dry air. A particle of air displaced upward will find itself in colder surroundings and will thus be forcedto rise still farther; any condensation that takes place adds still more impetus to the rise due to the heat of condensation liberated in the process. A particle which is displaced downward in this air mass for any reason will be colder than its surroundings and will thus tend to sink still farther. Thus an air mass having a lapse rate exceeding the dry adiabatic will favor vertical movements once initiated. This air mass is said to be in unstable equilibrium.

These remarks may be summarized as follows:

1. Localized portions of an air mass in neutral equilibrium tend to remain at any level to which they may be transported.
2. Localized portions of an air mass in stable equilibrium resist any vertical morion in proportion to the stability of the air mass in question.
3. Localized portions of an air mass in unstable equilibrium when

given an impetus either toward higher or lower levels tend to accelerate the motion thus produced.

The condition of neutral equilibrium is so rarely attained in the atmosphere that we may eliminate it from the present discussion.

The Effect of Mountain Ranges upon Stable and Unstable Air Masses.

It can be readily seen from the above considerations that particles in a stable air mass tend to resist passage over a mountain mass or over any other obstacle for that matter, since they resist any vertical motion. However if the gradient is such that sufficient energy is available to accomplish the work required in raising the air to a height which will allow it to pass over the obstacle the air may successfully negotiate the object in its path provided there be no horizontal outlet. Normally the stable air will simply curve around the obstacle entirely avoiding any vertical displacement. It is, however, impossible for all air to escape laterally when a high, long mountain range stands in its way. This results in a damming up of the air flow by such extensive ranges. This is shown on synoptic charts by high pressure on the windward side of the ranges and relatively low pressure on the leeward side. No wind velocities over the ranges such as the resulting gradient would require are observed since the mountain ranges prevent the dissipation of the potential energy of the air masses by preventing their contact at lower levelts. The pressure gradient is meaningless except that it indicates that the air masses on the two sides of the mountains are of different weight.

In unstable air, however, when the air reaches the mountains it is gibon an upward impetus which it retains, even accelerating as its temperature differs more and more from the surrounding atmospheric temperatures. Huge cumulo-nimbus clouds over mountain ranges on summer days are caused in this way. These effects often lead to the severe thunder showers of mountainous regions.

Orographical Precipitation---In flowing against an extensive mountain range all the air can not escape laterally, as has been said, thus some must be forced to ascend. If the ascent is sufficient, forced condensation will result thus giving tise to orographical precipitation, or at least to cloudiness. This phenomenon is well developed along the California coast during the summer months. NPm air moves in off the Pacific Ocean continually during this period and, as we have learned, is stable at this time of the year due to its passage over a cold water belt lying off the California coast. The gradient is very steep in this region during the summer months and this air is forced to ascend the coast ranges which have an average height of about 2000 feet. These ranges are so extensive and lie so close to the shore throughout their length that the air can not do anything but climb them. In so doing clouds are formed on the windward slopes and in Northern California where the air is coldest a constant drizzle prevails. The air is coldest here not only due to the higher latitude, but to the fact that the ocean water over which it passes is at lower temperatures than at any other point along the coast even as far north as British Columbia. Since this air is stable it seeks its former level after passage over the ranges and in so doing is dynamically heated during the descent and the clouds are dissolved.

A rather interesting example of this sort of thing is described by Byers[5] in referring to the summer fogs of Central California. He speaks of the phenomenon as follows: "In the San Francisco Bay region, it is usually impossible for the inflowing fog to extend beyond the Golden Gate in the daytime. A fog bank often is seen waiting outside the Gate for the sun to lower to the horizon before entering the San Francisco Bay. As the fog passes through the Gate in mid-afternoon, it becomes mixed with the warm land air and evaporates.

Another factor which prevents the fog from moving in over the bay is the adiabatic warming as it rolls over the hills and descends the leeward sides. Almost any summer afternoon the observer on the Bay can see the fog pouring over the hills of San Mateo and Marin counties and descending their eastern slopes like a waterfall. It descends only a hundred meters or so when it disappears like a great torrent which suddenly becomes subterranean in character. The wind blows over these hills all summer long, almost never ceasing. Hence it becomes a wind which follows the relief, descending the leeward slopes and taking on an ascending movement on the windward slopes.

Day after day in the summer the fog may be seen descending the hills on the western side of the Bay and disappearing about midway down their slopes owing to adiabatic warming. Then there are no clouds whatsoever over the Bay. But farther to the east, over the Berkeley and San Leandro hills, the cloud reappears by movement of the air up the hill front. Thus it comes about that on most days the cloud first occurs as a fringe around the Bay. As the sun lowers and the air becomes cooler, the cloud bank on the hills to the east gradually extends farther and farther westward. On the other side of the Bay the fog begins to move inland until the two cloud banks come together. The Bay itself is the last to be covered."

Researches have shown that pure orographical precipitation in stable air masses can never amount to much, but in the case of unstable air great amounts can be added to the pure orographical precipitation since any initial upward impulse given to the air will be favored. If, for example, air which has been showery over the sea passes inland and encounters an extensive mountain range large amounts of precipitation may be recorded in these regions.

Bjerknes and Solberg[6] have given some good quantitative data on this problem. They find that in regions along the western coast of Norway where no rain occurs along a narrow coastal strip the maximum 24 hour precipitation in the mountains to the east never exceeds 5 mm.

Since no rain has occurred along the immediate coast this precipitation in the mountains may be considered as purely orographic. However, regions just north of this, where showers occur over the sea, receive as high as 30 mms. for the 24 hours. Two reasons may be cited for this effect.

1. Upon passing inland the showers are retarded and may even be stopped by the mountain barrier, hence allowing much more precipitation to fall in the region of slowest progress than over the open sea. The mutual distances of showers passing in off the sea will also be decreased and a piling up against the mountains will result. The zones of maximum precipitation will, in general, be located in the areas where the showers for topographical reasons are obliged to move most slowly, provided, of course, that the intensity of the shower is undiminished.

2. The air which was showery over the sea must have been at least conditionally unstable. Thus any vertical movements initiated by the mountains are favored by this air giving rise to much more rain than in the case of stable air which would have resisted the vertical displacement and curved around the mountains as best it could, giving very little precipitation, as in the case of the pure orographical rain to the south.

Of further interest is the fact that the zones of high amounts of precipitation are interrupted at the mouths of the larger fjords, indicating that the air has been able to enter horizontally along the fjords and starts its ascending motion first at the eastern end of the fjord. The highest amounts of precipitation are always found farther inland wherever a large fjord exists.

Corresponding to the tendency of stable air currents to curve around obstacles, strong winds will blow around the terminus of a mountain range, and it seems even as if the convergence of air passing around the corner itself, must lead to a sort of orographical precipitation. This effect has especially been observed in easterly currents passing around the southern corner of Norway at the southern extremity of the Scandinavian ranges. Here the currents give rise to strong local gales accompanied by slight rain or snowfall without any relation to cyclones or their secondaries.

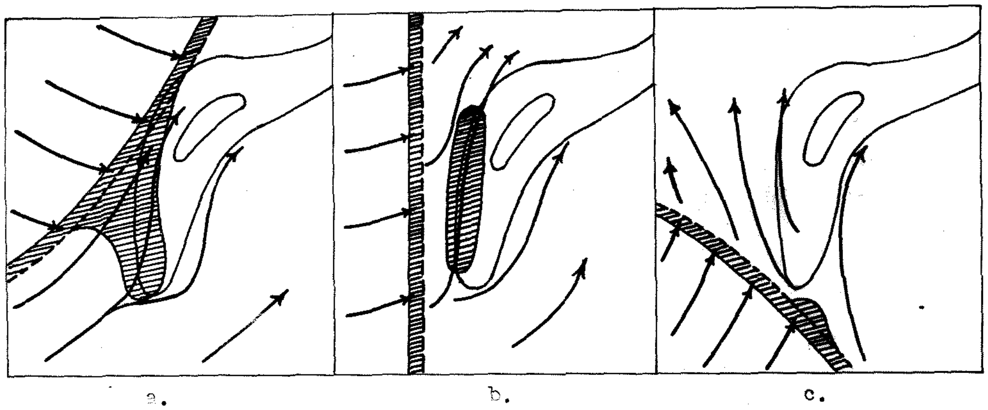
A good example of orographical precipitation in unstable air passing over high mountains is offered by the India Monsoon during the summer monts. This air blows in off the Indian Ocean and is very warm and moist with a lapse rate only conditionally stable. Upon passage inland it is heated from the ground and becomes even more unstable. When it reaches the Himalaya mountains it is forced to ascend and favors the motion, giving rise to large amounts of precipitation. Due to its initial warmth and high moisture content little cooling is necessary to relieve it of great quantities of moisture. It must climb so high in surmounting this lofty mountain mass that by the time it reaches the plateaus of Tibet it is too dry to give any more precipitation. If the barrier presented by these mountains were removed the aridity of these regions would be greatly diminished.

Effect of Mountain Range upon Approaching Cold Front-- Another influence of mountain ranges upon precipitation is the fact that their presence often provokes prefrontal rains at the approach of a cold front in a cyclonic disturbance. From Figure 2 it can be seen that the cold front is the surface bounding the cold polar air on the one side and the warm tropical air of the warm sector on the other. This surface has a negative slope and propagates in such a manner as to displace the air of the warm sector. This tropical air escapes horizontally everywhere except in the lower levels just in advance of the front. Here the oncoming front displaces the warm air vertically causing the squally cold front rain at the immediate front and for short distances to the rear as shown in the sketch.

Now let us consider a N-S mountain range to be present in the warm sector with a SW-NE cold front approaching from the northwest, as shown in Figure 5 a. The front reaches the northern portion of the mountain mass first and in so doing forms with the mountains a triangular cul-de-sac into which the warm air enters. Since the warm sector is composed of tropical air which has moved far north, the air is stable and does not readily pass over the mountains, but would normally curve around them avoiding any vertical displacement. Due to the oncoming cold front, however, this warm air is forced to find its way out over the mountains and gives rise to precipitation, indicated by the shaded zone in the figure. Further to the south where this effect is not present the usual cold front precipitation zone is indicated.

The same sort of prefrontal cold front rain developes even when the front direction is parallel to that of the mountain range (Fig.5 b). The warm current flowing along the channel between the mountains and the cold wedge will be pressed together on a strip which gradually becomes narrower. The first effect of this process will be an increase of wind velocity in the warm current, which tends to maintain unaltered transport of air. The continued advance of the cold front makes it impossible for all warm air to be brought away horizontally, and parts of it must begin to escape vertically. From this moment, formation of prefrontal rain begins along the mountain slopes (indicated by the shaded zone on(Fig.5 b) and persists till all warm air is completely driven away over the mountain ridge. Also this sort of rain may last several hours and render considerable amounts of precipitation as in the first case.

In Fig. 5 c a cold front is shown approaching the range from the



a. b. c.

Figure 5

Combined Orographical Precipitation and Cold Front

Precipitation after J. Bjerknes.

south. In this case the warm air finds an easy escape from the cold wedge simply by curving around the mountains and no prefrontal rain developes, except perhaps at the southern extremity of the range to a slight extent.

This phenomenon occurs all over the world in regions where the topography is favorable and is more or less accentuated by local conditions. For example, on the west coast of Norway[7] the phenomenon is well marked due to the lofty mountain ranges near the coast and to the fact that well defined cold fronts are frequent in their occurrence. The same effect is produced on the Pacific coast, but usually to a lesser degree since the cold fronts are rarely as well developed, and the high mountains are further inland. As will be noted from Fig. 4 the Pacific coast is a region of frontolysis and thus the fronts are as a rule occluded before reaching the mainland.

Effects of Mountain Range on Passage of Warm Front-- The action of a mountain range upon a warm front although similar to the phenomenon just described in that much precipitation is provoked functions quite differently. Figure 6 represents a vertical section through a warm front surface passing a mountain range.

The warm front surface, which has usually a smaller inclination than that of the mountain slope, will reach the ridge and its passes while still a part of the cold air is lying below the slope. The cold mass will have no opportunity to escape as the way over the mountain ridge is already blocked by the overlying warm air. The lower part of the warm front surface will accordingly become stationary, supported by the mountains, and the corresponding rain zone will persist at the same place for a long time, giving rise to considerable precipitation. The upper part of the moving warm front surface with appertinent upper clouds will, however, pass over the mountain range without any hindrance.

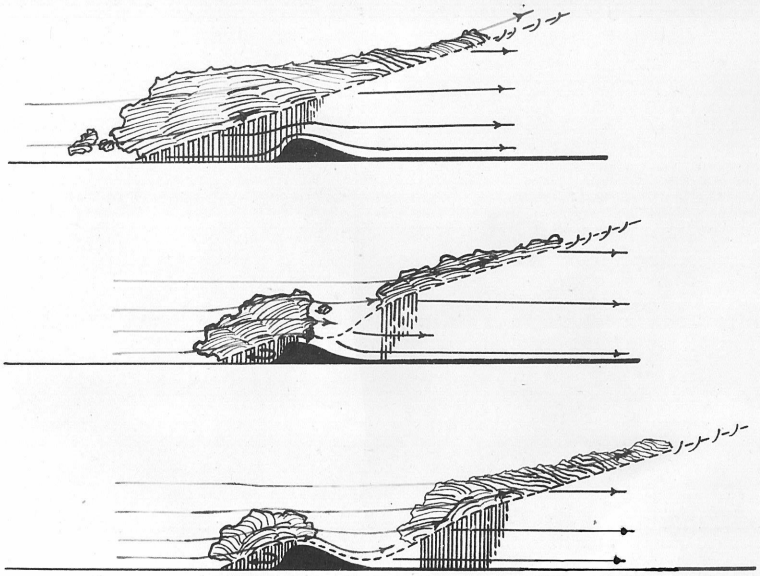


Figure 6.

A Warm Front Passing a Mountain Ridge, after Bjerknes.

The lee side of the mountains may consequently receive rain from clouds lying high enough to pass over the ridge. Frequently even this rain is prevented by the descending motion induced on the lee side of the mountains. This descending notion which first developes in the cold mass, may also suck down the warm air so that the cloud cover in that air must dissolve. Arriving afterwards over plain country the descending motion ceases, and the cloud system of the warm front regenerates.

This type of thing occurs in California when rain of the warm front type occurs, which is not very frequently since most of the fronts passing over California are occluded and of a feeble cold front nature. However, during the winter 1931-1932 several rains of the warm front type were observed. It was noted that on the windward slopes of the coast ranges and the Sierra Nevadas long continued precipitation occurred whereas in the Great Valley the precipitation during these periods was not steady and the amounts recorded relatively small. It is to be emphasized that this precipitation can in no way be orographical since the cold air, as mentioned above, has no means of escape over the mountains. This phenomenon is common to all regions of similar topography which are visited by cyclonic dusturbances with well defined warm fronts.

Manner in which Mountain Ranges Provoke Formation of Secondary Cyclones-- The damming effect of mountains upon approaching air masses (stable) will always tend to occlude a cyclone more rapidly since it will allow the cold front to close up the warm sector more quickly than is ordinarily the case; over the ocean, for example. The mountains stop the warm front until the cold front arrives and cuts off the warm sector entirely. This phenomenon often gives rise to a secondary cyclone at the southern extremity of the mountains. At the moment when the warm sector of an old cyclone is cut off, two branches of the cyclonic bound-

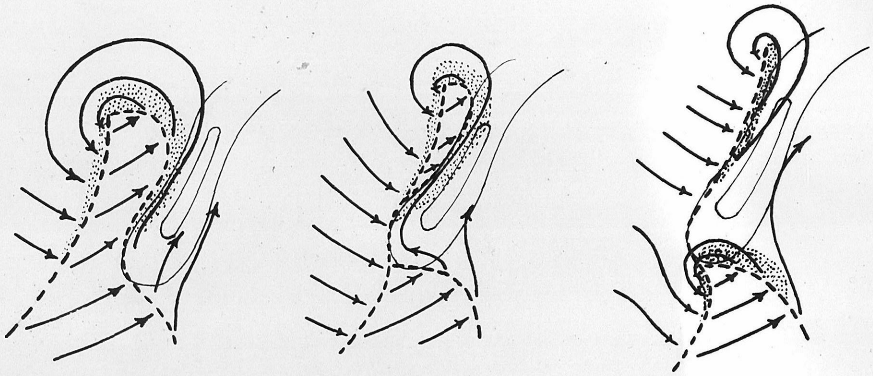


Figure 7.

Formation of Secondary Cyclone due to Damming Effect of High Mountain Ranges.

ary join south of the place, where both sides of the warm sector have closed together. In our case this will be just south of the mountains and if a secondary cyclone forms it will at once have the structure of a well-shaped young depression: a large warm sector projecting into colder regions. This process is illustrated diagramatically by Figure 7.

This type of secondary cyclone forms very often in California at the southern extremity of the Sierra Nevada mountains when a warm front passes over California. The high Sierras retard or even stop the warm front and allow the cold front to close up the warm sector all along the mountains. As pointed out by Byers[8] this type of California occlusion can therefore be responsible for the formation of a type of cyclone which has long puzzled those who have analyzed the situation on the basis of pressure alone. This type of LOW is what is generally known in this country as the South Pacific cyclone, which, of course, should not be confused with the desert "heat LOW" which persists in these regions during the hot summer months.

This same type of secondary cyclone has been refered to by Bjerknes and Solberg[9] as forming at the southern end of Scandinavia, therefore at the southern extremity of the Scandinavian mountain ranges. In Norway this is known as a "Skagerak Cyclone" derived from the body of water off the southeastern coast of Norway of the same name.

Foehn Winds-- The descending motion on the leeward slopes of mountain ranges as shown in the situation depicted by Figure 6 brings us to the next topic for discussion, the Foehn. This interesting phenomenon was first noted in the Swiss Alps over fifty years ago and has since been observed in other mountainous countries throughout the globe. It is characterised by very low humidities and high temperatures. For this reason it was first believed by the Swiss meteorologists and others to have its origin in the Sahara Desert. This theory was, however, soon exploded since the Foehn winds were found to be most pronounced during the winter season when even the temperatures of the Sahara would be relatively low, and the effect was also found to exist in Greenland, a locality which surely could not be influenced by a region as far distant as the Sahara Desert. Finally it was discovered that the winds only occured when excessive gradients existed over the mountains chiefly during cyclonic disturbances, and then Hann[10] attibuted the Foehn to the dynamical heating of the air as it rapidly descended the leeward slopes of the mountains, an explanation which is today generally accepted.

From Fig. 6 it can be seen that the air moving down the leeward slopes of the mountains is air which is retreating from the approaching warm front, in response to the prevailing pressure gradient. This air thus relinquishes its place to the new air pouring down the slope. After the upper part of the moving warm front surface passes over the mountain range even the warm upper air is sucked down by the retreating cold wedge and the cloud cover on the lee side of the mountain is dissolved to the characteristic form of Foehn clouds, alto-stratus lenticularis. With the arrival of the cold front the Foehn will immediately cease.

The original retreating cold wedge and the warmer air which moves in after the upper part of the warm front surface passes over the mountain are both stable currents and thus tend to follow the valleys down which they flow. For this reason the streamlines may be constricted by narrow, steep sided valleys and the wind velocities attain high values. The air moving rapidly down such valleys thus has no chance to lose heat by radiation and takes full advantage of the dynamical heating which it undergoes. In the Swiss Alps researches have shown that the increase in temperature in the descending air very closely approximates the adiabatic rate for dry air, i.e. 1° C. for every 100 meters descent.

The fact that the Foehn is more pronounced in the winter season may be accounted for by the lapse rate usually prevailing in the atmosphere during this time of year. Normally the lapse rate is much less in winter than in summer, therefore air descending from a given height will show a greater increase in temperature over the original surface air in winter than in summer. In the Swiss Alps during summer foehn winds it has been observed that a descent of 2000 meters yields to the air only a temperature about 6° C. higher than the air which it displaces, whereas in winter the difference amounts to 12° or 14°. The Foehn occurs most frequently in winter and has higher velocities, because the cyclonic activity is most prevalent during this season.

The effect of the foehn winds at Innsbruck on the northern slopes of the Alps during the winter months is sufficient to increase the mean temperature to such an extent that it is comparable with mean temperatures of regions 3° in latitude farther south.

Foehn winds are common to all regions of the Earth where the gradients and topography are favorable, but often receive names coined locally. For example, in the United States the foehn winds occurring just east of the Rocky Mountains are called Chinooks, while similar winds occurring in South America at the eastern foot of the Andes at San Juan in the Argentine Republic are called Zondas.

The similarity of these two winds was brought out long ago by Davis[11]. The Zonda was attributed to volcanic activity in the Andes by the natives but was recognized as a foehn wind from a description given by Nathaniel H. Bishop (Boston 1869) in an account of a remarkable journey--"AThousand Mile Walk Across South America." The following is a portion of the description of the Zonda as given by Bishop.

"During the latter part of August (winter on the southern hemisphere) as I was standing upon the saline desert, a few miles east of San Juan, my attention was attracted by a cloudof dust that appeared to roll through the air as it approached me. I started for a shelter, and had hardly reached it when the Zonda swept past, filling the air with fine yellow sand. The temperature of the previously sultry atmosphere suddenly rose many degrees, and the occupants of the neighboring huts were affected with severe headaches. I noted with a compass the course of the wind, which was west. All night and through the following day and night, the wind continued blowing with undiminished force. Each hour the vane beside the hut was consulted, and the same course as at first was always observed. A few hours before the wind ceased the sand showers were exhausted. The greatest heat was during the first few hours; and this is always the case if the Zonda commences during the day. After continuing thirty-six hours the change came. It was instantaneous. The hot wind seemed cut off at right angles by a cold wind from the south. The change would not have occupied more than forty seconds. The south wind lasted twenty hours and was as violent as the hot Zonda."

This is entirely analagous to the Chinook winds of the eastern slopes of the Rocky Mountains, the hot wind being immediately shut off with the passage of the cold front in the cyclonic disturbance which has given rise to the foehn. In the northern hemisphere the cyclonic center lies to the north and the cold front wind has a strong northerly component while in the southern hemisphere the cyclonic center is to the south and the cold front wind has a southern component.

Foehn winds are quite common in California but the dynamics of the phenomenon are essentially different from the cases just cited, being more of the nature of a Bora, a topic to be taken up shortly.

Formation of Secondary Cyclones due to Foehn Winds---Due to the high temperatures associated with foehn winds it is conceivable that some sort of a discontinuity surface might arise between this air and adjacent colder air. If such is the case a cyclonic disturbance may easily be generated. As a matter of fact this actually does occur quite often, as the following example will serve to illustrate.

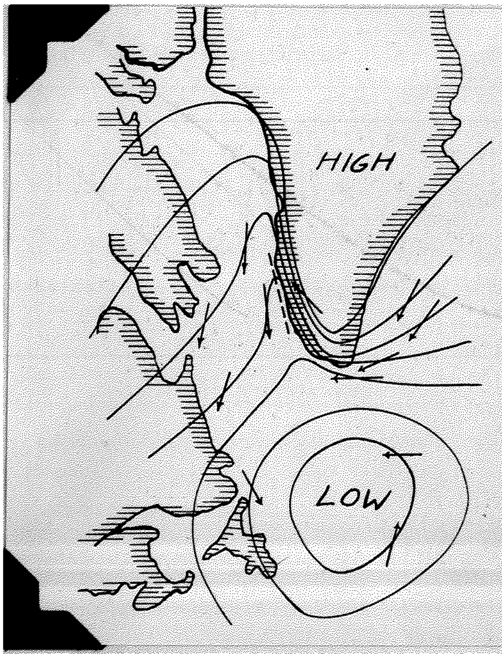


Figure 8 a.

First step in formation of Labrador secondary.

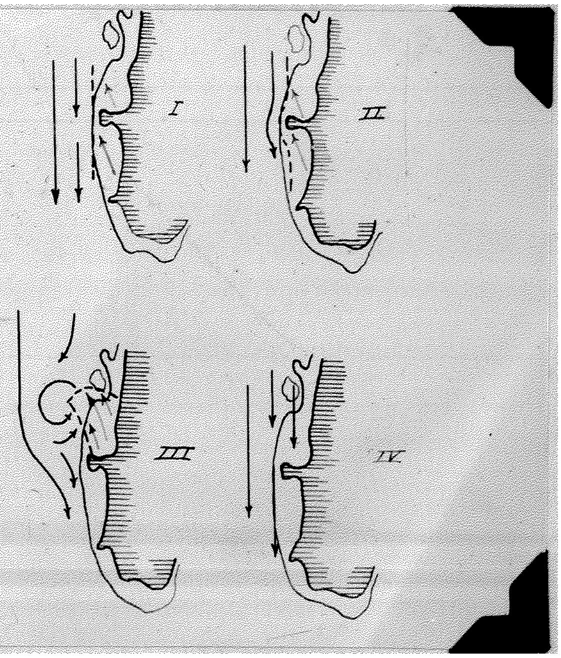


Figure 8 b.

Stages of development of Labrador secondary.

Schnieder[12] in a discussion of the foehns of Greenland attributes the formation of Labrador secondary cyclones to this action. This type of secondary often observed forming from a deep Labrador LOW is quite different from ordinary secondary cyclones which are observed in that it forms to the north of the primary and moves north. Usually secondaries form to the south of the primary cyclone and move eastward. Schnieder points out that when a deep depression is present in the Labrado region a great amount of air moving around the northern portion of the LOW is deflected around the south end of Greenland at Cape Farewell (Fig. 8 a) Some of the air is carried over the southernmost part of the great Greenla ice mass and in descending the western slopes is dynamically heated, arriving at the coast as a warm current. This is a southerly current whereas the air to the west is a coldnortherly current thus giving rise to a discontinuity surface between the two air masses. It is to be noted that this effect is created by the fact that the Greenland anticyclone and ice mass extend as a wedge into the Labrador LOW and crowd the isobars at the southern end of Greenland giving rise to the high wind velocities necessary to transport some of the air over the high ice plateaus. A cyclonic disturbance readily developes along this discontinuity thus formed since equilibrium along such a surface is rarely attained. The cyclones formed in this manner travel northward because researcheshave shown that cyclones propagate in approximately the direction of the air movement within the warm sector, which in this case is northwest.

The intensity of these secondaries is dependent upon the energy received at the beginning dur to the temperature contrast developed by the Foehn. Figure 8 b, shows the various stages in the development of such a secondary from the initial establishment of the discontinuity to the final occlusion and death of the cyclone leaving only a northerly current along the coast. Since the air in the warm sector of this depression is extremely dry no precipitation is to be expected.

The Bora---This is a name given to winds which often blow down steep slopes that separate high, snow-covered plateaus or mountain ranges from adjacent bodies of relatively warm water. Thus when an anticyclone covers such a region, during winter, the surface air becomes very cold and correspondingly dense until, unless otherwise dissipated, it overflows restraining ridges, or drains away through passes and gaps. In many instances the air as it leaves the snow fields, is so cold that, in spite of dynamical heating, it reaches the sea at freezing temperatures. Such a current must also be very dry as it always occurs in PC, NPC or NPMc air, all of which are very dry. The NPMc air may be initially fairly moist, but most of its moisture will be forced out on its ascent to the high regions where the bora originates.

Such currents occur over California at most any time of the year. In the winter it frequently occurs that NPMc air descends from the Great Basin to the east. This air upon its arrival at the coast is sometimes colder that the air it displaces in spite of its dynamical heating in the descent and represents a true bora. In the spring or fall such a current is much warmer than the air which it replaces and represents a foehn type wind after it has made its way down into California.

A bora of special interest occurs frequently on the west coast of Norway and has been described by Sandstrom,[13] in one of his interesting atmospheric studies, as follows: "In winter, as one steams along the northwest coast of Norway, there is frequently opportunity to observe a peculiar meteorological phenomenon. Fine weather prevails over a narrow strip along the coast, while a heavy bank of cloud is visible out to seaward. Of course, coastwise traffic is greatly favored by this fair-weather strip and takes full advantage of it. Throughout this zone of fine weather prevails a cuttingly cold wind so strong that one can

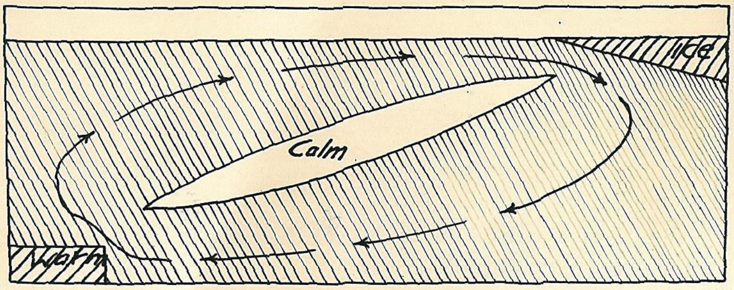


Figure 9 a.

Laboratory model of Bora circulation after Sandstrom.

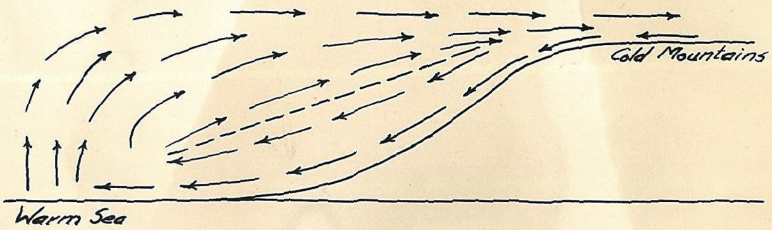


Figure 9 b.

The Bora as it occurs along the northwesterm coast of Norway after Sandstrom.

scarce stand against it when on deck. The maximum velocity of this wind is attained near shore, where the water is whipped upinto whirls and miniature waterspouts. Evidently the wind here plunges down upon the water from above, and with great force.

Upon leaving the steamer and travelling inland up the mountain slopes on skis, strong head winds oppose progress. This easterly wind is still very strong on the great divide of the Scandinavian Peninsula. But observations of the cloud caps on the highest peaks of the range show that a westerly wind is blowing at those great altitudes. It is clear that a lively interchange of air between the North Atlantic Ocean and the continent is taking place above the Scandinavian highlands. This exchange takes place along either side of a glide surface whose altitude above the ground at the divide may be estimated at about 1000 meters. In fact, at the kite station Vassijaur it proved almost impossible to raise the kites above that level, evidently because they there encountered a glide surface through which they cannot pass, since the wind has opposite directions on the two sidesof this surface, and therefore calm must prevail at the glide surface itself. The altitude of this glide surface decreases to the Atlantic Ocean. The air below this surface flows toward the west, and above the surface it flows toward the east."

Figures 9a and 9b illustrate this bora as actually observed along the coast of Norway and in experiments carried out by Sandstrom[14] in the laboratory. Fig. 9a represents a trough of water with a warm and a cold cource placed similarly to those giving rise to the bora. A circulation is set up exactly analagous to that of the bora even to the calm region between the oppositely directed currents.

This phenomenon is common to all regions of the Earth and will, of course, vary in intensity as the topography is favorable or unfavorable to it. It will be best developed in high latitudes where regions of ice and snow are abundant, for example, in Greenland and Antarctica. Observations have shown that cold winds, sometimesof hurricane force, blow off of these latter ice covered regions continually.

Topography and High Inversion Fog---Another important and interesting phenomenon in which topography plays an important role is the formation of fogs in connection with a subsiding anticyclone in air of polar maritime origin.

It has long been known that the air in stationary anticyclones is slowly settling. This downward displacement of air results in a slow temperature increase within a large part of the anticyclone which results in a decrease of the vertical temperature lapse rate. Generally one or several well-marked temperature inversions develope, especially along the borders of the sibsiding anticyclone. The formation of these inversions has been treated analytically by a number of writers[15] and need not be discussed in detail here. The principal point to bear in mind is that the increase in temperature is due not only to a downward movement of the air in the anticyclone, but also to a simultaneous spreading out which decreases the thickness of the various layers.

Such a sinking and spreading out of the upper layers of a stagnant anticyclone usually produces a series of subsidence inversions in the free atmosphere above a resting layer close to the ground, and a sliding out of air along the periphery of the anticyclone. These layers have been variously named--"subsidence inversion"--being the generally accepted English term.

The foregoing discussion explains the initial formation of isothermal or inversion layers at higher levels but does not explain why fog forms in the layer below these inversions, nor does it explain why the largest inversions are usually concentrated relatively close to the ground. Willett[16] has investigated high inversion fog in Europe and finds that its formation is dependent upon the previous history of the air mass. It occurs particularly in stagnant maritime polar air outbreaks. This air has passed sufficiently far over the sea to have acquired a moderate amount of water vapor in the lower layers and hence a higher relative humidity than when it left its source. When this cold maritime air reaches the continent its movement will slow down or cease, and a gradual subsidence will take place.

Below the level of maximum subsidence, turbulence will tend to maintain a fairly steep lapse rate. Turbulence will favor the transportation of dust, smoke and moisture upward to the base of the lowest inversion layer, which will act as a blanket, effectively limiting the height of turbulence. Thus the dust, smoke and moisture are trapped and there is formed directly below the inversion layer a layer of air which gradually increases in water content, dust, etc. In typical cases over Europe, the relative humidity may vary from 60-70 per cent at the ground to 90-100 per cent directly below the inversion. The inversion layer therefore becomes a well-marked surfaceof discontinuity also with respect to relative humidity. Below it is a layer in which the relative humidity is increasing, while above, the relative humidity remain low and the skies clear.

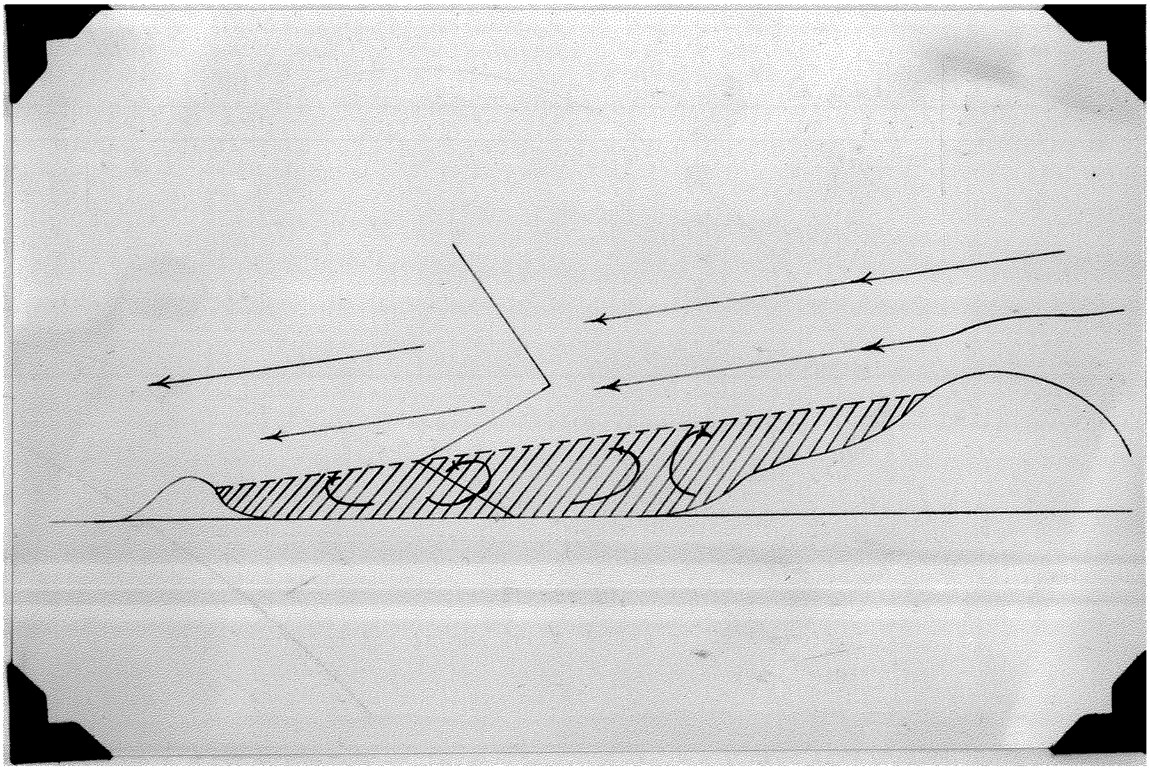
During the night this moist layer beneath the inversion will rapidly lose heat by radiation toward space since the dry air above the inversion is highly transparent. The ground below will likewise radiate towards space, but part of the heat lost will be retained and re-radiated downward by the lower moist layers. The effective radiating surface is thus displaced from the ground up to the top of the moist layer immediately below the inversion. If the loss of heat at this surface is sufficiently large, condensation will take place and stratus or high fog will form at the base of the inversion. For fog formed in this way the term "high inversion fog" has been introduced.

After sunrise, the high albedo of the new cloud layer will, to a certain extent, prevent a normal heating of the moist layers below and consequently slow down or prevent the evaporation of the fog. The fog is also protected from mechanical dissolution by the strong inversion above, for, due to the high stability of this inversion layer, the turbulence in the upper rapidly moving layers is prevented from diffusing downward. Below the inversion, in the absence of high wind velocities and especially in enclosed basins, turbulence is just sufficient to keep the air well stirred, and is thus less detrimental to the fog. If these effects continue, the layer below the inversionis cooled to such an extend that the fog, after a few days, extends down to the ground.

This type of fog is prevailent during winter over wide areas in Europe, but Willett points out in his discussion that this type does not occur in North America because the maritime air sweeping in off the Pacific is always relieved of its moisture before passing over the Cascade and Sierra Nevada mountains. However, suppose that the topography is such that some of this originally moist air is trapped in intramont basins and never gets over the mountains. Thenif the air which does negotiate the mountains stagnates and the accompanying temperature inversions are developed streading over the airin these basins every escape for this air will be cut off.

This is precisely what happens in the winter in the Great Valley of California. As pointed out by W.M. Lockhart,[17] Lt. Comdr., U.S.N., the physical seclusion of the valley, surrounded asit is on all sides by high mountains, brings about almost complete freedom from outside atmospheric influences and reduces the number of controlling factors to an extent seldom realized except in laboratory experiments.

He has pointed out in a detailed discussion how the maritime air is trapped in the valley and remains there until subsidence begins in the remainder of the air mass which has passed over the mountains



(NPMc). Once the inversion spreads over the valley there is no hope of escape for the trapped air since the overlying air is warmer. Turbulence is just sufficient below the base of the inversion to maintain a steep lapse rate and to bring about the situation described in the general discussion above. This fog persists for days after once established and is not broken until the HIGH over the Great Basin moves east or a cyclonic disturbance moves in off the Pacific to the north.

Figure 10 represents a cross-section through the Great Valley of California showing the coast ranges to the west and the Sierra Nevada ranges to the east. The lapse rate in the air below the base of the inversion is represented as being equal to the adiabatic for saturated air at the prevailing surface temperature.

Mountain and Valley Breezes---These phenoména occur in any air mass and may be attributed directly to the topography of a region. They are usually of daily occurrence, the valley breezes blowing up the valleys and mountain slopes by day and the mountain breezes blowing down the steep ravines and valleys by night.

The valley breezes were first explained by Hann[18] as due to the difference in expansion of the columns of air over the valley and over the adjacent mountain under insolational heating. He stated that since the column over the valley would expand most due to its greater height a flow of air toward the mountain would result, which due to the topography would be obliged to ascend the slopes.

More recently this effect has been shown to be insufficient to account for most observed valley breezes. The explanation generally accepted now is that the valley breeze is due to the fact that the mountain slopes are very much warmer than the adjacent free atmosphere at the same levels.[19] The mountain slopes receive their heat not only from direct solar insolation but also from the diffuse radiation of the surrounding atmosphere. This accounts for the fact that valley breezes occur on the northern slopes of mountains as well as on the southern. From the circulation principle it is readily seen that the resulting air movement will have an ascending tendency on the mountain slopes and a descending tendency over the lowlands. In summer, when this action is a maximum, showers may easily develope over mountainous regions, the discussion of which will be left to the next section.

The mountain breezes are more easily explained. At night the rather dry clear air above mountainous areas leads to active terrestrial radiation toward space with the resultant cooling of the surface layers. These levels will be colder than the adjacent levels of the free atmosphere and thus the air will simply drain away to lower levels. Since this air is very stable it will follow ravines, canyons and valleys in its journey to the lower levels and under favorable topographical conditions may attain considerable momentum rushing out of the mountains upon an adjacent plain with destructive force.

These mountain and valley winds are common to all mountainous regions of the globe and only vary with the topography and the season, the valley winds being more pronounced in summer and the mountain winds attaining their greatest strength and longest duration in the winter.

Topography and Local Showers---Showers developing as a result of insolational heating are made to fall in "local showers" due to detailed topography of land surfaces. These showers are not to be confused with the instability showers formed over the sea during all seasons which, of course, can not be connected with any orographical influences.

The local ascending currents (convective currents) giving rise to local showers, will start where air masses have become warmer than their surroundings in the same levels. The topography and natural disposition of the ground for receiving sunshine heat will thus contribute to the determination of the starting places for these currents. As to the further maintenance of convective air currents, the stability of the air is of decisive importance.

As to the effects of convective currents, their content of moisture must be considered. The greater the content of moisture, the greater the resulting amounts of precipitation will be. Thus local showers in tropical regions usually yield much higher amounts of precipitation than those of higher latitudes, both due to the higher moisture content of the tropical air and to the initial high temperature of the air, a condition which requires only relatively slight cooling to provoke heavy rainfall.

Mountainous topography is especially fitted for starting places of strong ascending currents. Provided that the mountains are not snow covered the air will be heated stronger at the mountain slopes than in the free atmosphere at the same level. This heating gives rise to the circulation mentioned as valley breezes in the preceding section and produces an additional ascending tendency over the higher parts of a region, and a descending tendency over the lower regions. The result will be that the general ascending tendency will be concentrated above the relatively higher parts of the country, over adjacent plains and valleys even descending currents may develope. The stability of the air will determine the height of the local convective currents.

The strong ascending current leading to the formation of cumulonimbus clouds will always be accompanied by descending currents beneath in the cloudless space. In unstable atmosphere, this current will reach the ground with lower temperature than the surrounding air. More cold air will be formed by the falling rain under the cloud and will join the cold descending air. The entire cold mass thus formed will tend to spread underneath the neighboring air forcing it to ascend. In this ascending air new cloud masses form amalgamating with the existing cumulo-nimbus increasing the cloud growth. On flat ground and in the absence of upper winds the cold air would spread symetrically in all directions and likewise make the cumulo-nimbus cloud grow symetrically. This case which is, of course, very improbable and perhaps even unrealizable will have no practical importance.

In reailty either the shape of the ground or upper winds will make the cloud grow asymetrically and determine the direction of propagation. On sloping ground the cold air produced under the shower will tend to flow downwards in the direction of greatest inclination. Later, when the cold mass has attained some velocity, the deviating forceof the Earth's rotation will also act upon it and give it a tendency to move to the right (North Hemisphere) of the steepest gradient of the ground. During its propagation the cold air will displace all warm air lying in its way forcing it to ascend and share in the growth of the cumulo-nimbus cloud. The energy for the maintenance of the moving shower may in this case partly be derived from the potential energy of the initial stage of cold and heavy air stored on the top of a slope. Under such conditions, the unstable stratification of the atmosphere which is necessary for the maintenance of showers in flat country, may be dispensed with. So for instance, showers may develope strongly over the mountains and maintain their strength during their movement down the mountain slopes, but then dissolve as soon as they reach flat regions.

The upper wind which alone determines the propagation of showers over flat country also influences showers formed over mountains. A shower formed over a mountain peak or isolated block will have opportunity to choose any direction favored by the upper wind and moves therefore downwards on the lee side of the mountains. Showers formed over salient heights of bigger mountains cannot choose all directions for propagation. If the upper wind blows towards the higher mountains the showers will have difficulty to follow up the slopes, and the conflict of forces usually leads to the destruction of the showers. It is thus a general rule that no local showers form on the windward slopes of mountains. On the other hand showers develope easily on the leeward slopes. Especially favored are such showers which by the upper winds are blown towards the coast and there profit by the convergence in front of the sea breeze. Also on a flat country the most favorable place for the formation of local showers is along the coast where upper winds blow from the land towards the sea.

These upper winds are usually limited to the layers above the height of the mountain ranges. If they reach down to the ground they will produce orographical cloud covers or even orographical rain on the weather side of the mountains and Foehn phenomena on the lee side. In such situations no local showers have opportunity to develope on the weather sideon account of the lacking sunshine and the conflict of propelling forces for local showers, on the lee side on account of the dry descending Foehn air, which permits no formation of rain.

All these principles are born out in extended studies of local showers which have been conducted in a very close network of stations in Norway by J. Bjerknes and H. Solberg.[20]

In tropical regions merely the arrival of the moisture laden sea-breeze may provoke local showers if the topography lends assistance. An admirable example of just this sort of thing was given long ago by Espy in an account taken from a letter received from C. Williams, of Providence, R.I. (Fourth Met. Report, 1854, p. 202). From observations made during a stay of three weeks at Hawaii, in the tropical Pacific, in 1815, Williams says that every day, "soon after the sea-breeze set in, say about nine o'clock, a cloud began to form around the lofty conical mountain in that island, in the form of a ring, as the wooden horizon surrounds the terrestrial artificial globe, and it soon began to rain in torrents and continued through the day. In the evening the sea-breeze died away, and the rain ceased and the cloud soon disappeared, and it remained entirely clear till after the sea-breeze set in the next morning---I was particularly struck with the phenomenon of the cloud surrounding the mountain when none was ever seen in any other part of the sky, and none there till after the sea-breeze set in in the morning, which it did with wonderful regularity. The mountain stood in bold relief, and from where the ship lay its top could always be seen above the cloud, even when it was densest and blackest, with the lightning flashing and the thunder rolling as it did every day. I passed up through the cloud once, and I know thereforehow heavily it rains, especially at the lower side of the cloud. This rain never extends beyond the base of the mountain, and all around there is eternally a cloudless sky."

<u>Back-set Eddies in Airflow over Mt. Peaks</u>---Just as back-set eddies appear in ocean currents when a portion of a coast juts far out into the main current, so also do we find back-set eddies in air currents flowing with considerable velocity over mountain peaks or even steep-sided mountain ranges. In strong winds the pressure to theimmediate leeward of such peaks is, more or less, reduced, and the result is a gentle flow of airup the lee side--a return or eddy wind--and there into the main current, thus maintaining the eddy.

An example of such a circulation is given in Figure 11. It represents the airflow over the Matterhorn, one of the high peaks of the Alps, as indicated by K.M. Douglas.[21]

The phenomenon is sometimes visible through condensation to the lee of mountain peaks. The reduction of pressure to the lee of a peak when the velocity of the airflow is sufficient lowers the temperature of the air below the dew-point, thus forming a cloud. This type of cloud has been called a banner cloud since it resembles a great white flag floating from a high mountain peak.

An interesting example of this back-set eddy occurs in southern

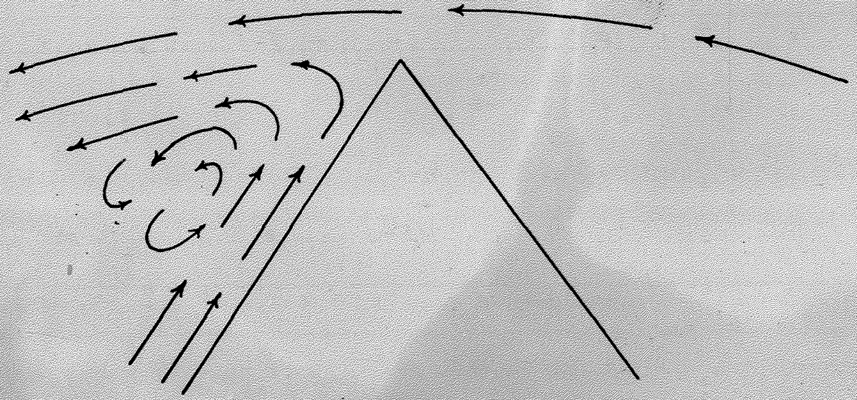


Figure 11.

Circulation over the Matterhorn according to Douglas.

California during strong Foehn winds, known locally as Santa Anas.[22] Normally the so-called Great Valley of southern California east of Los Angeles is protected from continental influences by the rather high mountain ranges to the north, namely the San Gabriel and San Bernardino Mountains. These are fault-block mountains with very steep southern slopes. When a moderate gradient directed from the Great Basin region over these rangesinto Southern California exists, as is frequently the case in winter, a flow of air takes place which is usually limited to the passes, notably Cajon Pass, a roughly north-south pass between the San Gabriel Mountains to the west and the San Bernardino Mountains to the east. This, of course, is due to the stability of the air which is usually NPMc air.

However, when the gradient is directed straight across the mountains and is sufficiently strong the air is carried right over the mountains. In this case the sections directly south of the San Gabriel Mountains, which extend east and west, usually are not affected, but the wind is likely to appear at the surface about 10 miles south of the mountains. Under these conditions slow eddy currents carry heavy dust into the districts near the mountains, which make it appear locally that a west wind of 6 miles per hour or less is causing a dust which blots out the sun and limits visibility to about 500 feet.

It is also interesting to note that in the summer when the NPMc air is very warm and usually with an unstable lapse rate this far south it blows over the mountains in a similar situation but never gets down into the valley as it does in winter when it is stable. This is also due to the fact that in the summer cooler NPMm air is usually present in the valley below preventing the warmer air from descending.

Cliff-Eddies---Another type of back-set eddy arises when the air blows directly against a cliff. In this case the streamlines are obliged to separate somewhat analagous to the case of air passing an

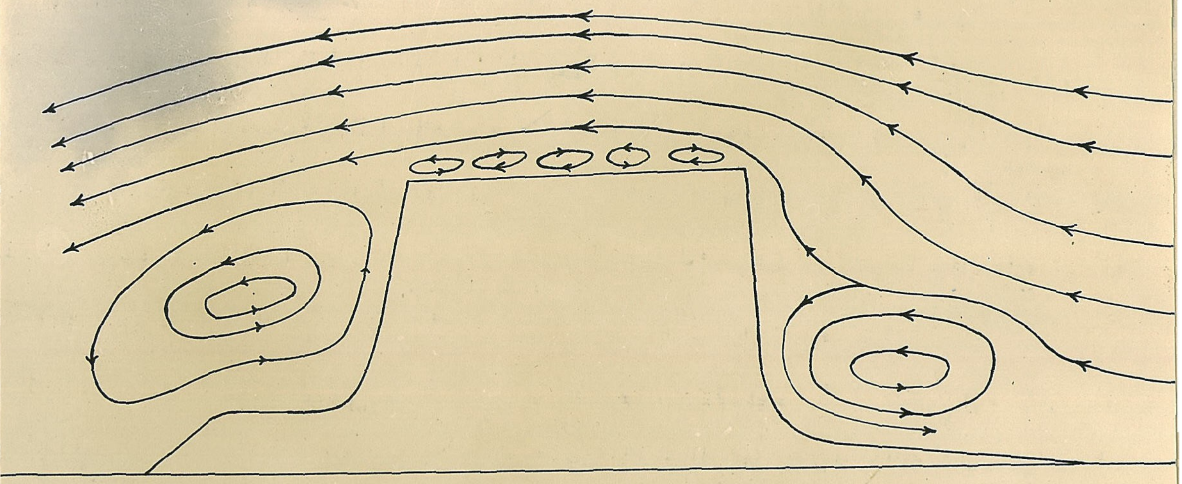


Figure 12.

Circulation over the island of Helgoland, according to Ahlborn.

airfoil. The upper brance passes over the cliff while the lower forms a back-set eddy. When the air blows over a cliff the eddy formed to the lee is similar to theback-set eddy described in the case of airflow past a mountain peak or range.

These cliff eddies have been well illustrated by Ahlborn[23] on a model of the island of Helgoland which is situated off the German coast in the North Sea. He observed the flow of water past the model and arrived at the streamlines reproduced in Figure 12. The separating of the streamlines on the forward side with the resulting formation of a gack-set eddy may be noted as well as the usual eddy formed to the lee of the obstruction. A crowding of the stream-lines over the top of the model may be observed which leads to relatively high velocities. The flow near the top surface as can be seen from the figure is turbulent. These observations were verified in the field by the use of no lift balloons and by observation of cloud forms over the island. Similar investigations yield the same results in the case of air flow over Gibralter.

Flow in Constricted Areas---The mention of crowding of stream-lines brings us to a discussion of air flow through deep gorgesor canyons where the stream-lines are also crowded giving rise to analagous phenomena. As has been mentioned this crowding of the lines of flow leads to high velocities in the air current due to the fact that the tendency toward the conservation of momentum must prevail. This is not so noticable in unstable air where at the entrance to a gorge some air may escape vertically, however, in stable air currents the effect is very marked as the following examples will illustrate.

Since the establishment of a Weather Bureau Station in the Columbia River Gorge, easterly gales have been found to prevail in the gorge during winter whereas in adjacent areas such as Portland, Oregon no such conditions are noted. We can attribute this directly to the very nature of the gorge.

When Lewis and Clark explored down the Columbia River in 1805, they found a passageway from the great interior plains of comparative simplicity, with a few sections of rapids and narrows which required portage of their canoes and supplies. By a water-grade route they made their way through a mountain barrier which averages four to eight thousand feet in height, with peaks within 25 miles to thenorthward and southward rising to eleven and twelve thousand feet. The immediate slopes of this great gorge tower three and four thousand feet directly from the water's edge. While the river itself winds about to some extent with the gorge thegeneral direction of this great cut in the Cascade Mountains is east-west. This gorge offers passage from the interior plains to the coast not only to human traffic, but also to the air of the Great Basin and Colorado Plateau areas when the gradient is so directed.

During late fall and winter anticyclones often stagnate over these latter regions with the result that air movement takes place toward the western coast. The air converges at the eastern entrance to the Columbia Gorge and thus seeks a way to the sea through this ideal passage. The stream-lines become restricted in the gorge with resulting high velocities in the air current.

Records from Crown Point,[24] a Weather Bureau station situated in the Gorge about 24 miles east of Portland in the Cascades and at about 700 feet above the river, will give an idea of the tremendous velocities attained by this current of stable NPMc of NPCc air. In November 1930 the NE wind at Crown Point averaged 33.2 miles per hour. The most remarkable period was from the 22nd to the 26th inclusive, when the wind blew from the NE every hour of the 120 of the period and averaged 40.1 miles per hour! Velocities as high as 120 miles per hour were recorded during this period. Equally remarkable is the fact that during this period the wind at Portland, which is outside the Gorge and to the west, averaged only 5.6 miles per hour from this direction. It may be added that there are no mountain ranges between the two stations to interfere with the airflow.

Another case of this phenomenon occurs during the Santa Ana winds of Southern California referred to in a previous section. These winds attain velocities of from 40 to 50 miles per hour in the Cajon Pass during the winter months while no abnormal velocities are recorded short distances on either side of the main current.

Whirlwinds.---During clear, calm summer afternoons, particularly during a dry spell when vegetation is parched and the ground strongly heated, dust whirls often develope, and occasionally travel considerable distances before losing their identity. The flatter the region, the more barren, the hotter the surface, and the quieter the air, the more violent such whirls become. Hence, level deserts are especially frequented by such winds, amounting at times to violent storms, though never more than a few meters in diameter. The developement of these storms in which convection is strong is due to extreme surface heating which leads to instability of the atmospheric strata. If, because of any disturbance, an unusually large volume of warm air breaks through the lower stratum to cooler regions, then it rises in columnar form producing a chimney-like draft. Once established this column may retain its intetrity as long as the air that is forced into it from the base is warm and light.

The incoming air is almost certain to be directed to one side of the center of the rising column, and, as the angular momentum thus established tends to remain constant, a correspondingly vigorous whirl is developed as the place of ascent is approached that gathers up such loose materials as dust, straws, leaves, etc. Furthermore, this rotation remains the same, whether clockwise or the reverse, though the details of how it does so are, perhaps, not fully understood.

When these whirls pass on to regions where the surface air is not so strongly heated--over bodies of water, for instance, or green vegetation--they no longer are fed with air relatively so light and, as a rule, quickly come to rest. Naturally, too, their frequency varies with topography, ground covering, latitude, season, and time of day. Thus they are most frequent of afternoons and least of early mornings, most likely to occur during summer and fall and least during winter and spring, most generally found in tropical air masses, are more numerous over barren surfaces; and, finally, more favored by level regions than by irregular and broken ground.

An interesting example has been cited by Picet[26] who reports observing a dust whirl near Cairo, Egypt that began on a small sand mound, remained stationary for nearly 2 hours, then, in response to a gentle breeze wandered away, but maintained its sharply defined outlines and great altitudes until lost in the distance, more than 3 hours later, or about 5 hours afterits inception.

A storm was described recently in an issue of the Monthly Weather Review[27] which I cannot help but feel was a very violent whirl of this kind from the author's description. It was attributed to be a small tornado and was described in part as follows: "An intense storm resembling a small tornado occurred at the Leonard Creek Ranch, Humbolt County, Nev., at about 1 p.m. July 24, 1931. The ranch is located in a narrow canyon which opens into the northern edge of the Black Rock Desert, a level arid region about 60 miles long and 15 to 20 miles wide. The country immediately surrounding the rance is mostly very low hills with rather high mountains rising a few miles to the north. The storm appeared to have a whirling motion and was of considerable violence along a short and very narrow path. It occurred during the period of warmest weather of record in the middle Plateau region." He also goes on to say that the storm came from the south (from the desert) and seemed to break up immediately after leaving the ranch (probably due to its passage over the low hills mentioned in the description).

Conclusion---In closing a word might be said regarding the practical value of such a study. Perhaps the most important results from such researches will be the more accurate determination of the properties of transitional air masses which are essential to accurate weather forecasting. To know just how much moisture an air mass acquires after a certain passage over the ocean and to know what temperature changes take place are of high importance in determining the interactions between this air mass and one which has perhaps acquired totally different properties. These are all studies which are under way at the present time, the results of which will be of much practical as well as theoretical value. It can be seen from some of the topics discussed that we can no longer rely upon merely pressure and temperature values for accurate weather forecasting, but must consider the properties of the air masses involved as well as the effects of the terrain over which they are passing upon them. Therefore detailed researches along the present lines should yield to the forecaster much information regarding the vactors inbolbed in the determination of the interactions of the various air masses, the very basis of modern meteorology.

Another important application of such studies occurs in the field of aviation. As we have seen, under certain conditions eddies may be formed as air passes over a mountain range the intensities of which vary occording to the wind velocities involved. Such currents may prove treacherous to the inexperienced pilot and well deserve detailed investigation. The downdrafts andupdrafts associated with air currents passing over mountains should be avoided as much as possible at all times. The updrafts may be made visible by cumulus clouds, but the treacherous downdrafts may be entirely invisible.

The present paper has merely scratched the surface of the vast field of research available upon this subject and it is hoped that at some future date the various topics may be discussed in much more detail, since each one considered herein is worthy of individual detailed treatment.

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