METHODS AND RESULTS OF DEFINITIVE AIR-PRESSURE MEASUREMENTS [1]

By DR. H. KOSCHMIEDER, Director

[Staatliches Observatorium, Danzig]

(Translated by W. W. Reed)

I. HISTORICAL

The following air-pressure measurements were made on the Schneekoppe (1,604 meters). The history of air-pressure measurements on mountains reaches far into the past and furnishes much that is worthy of note. Hence there will be given at the outset a brief historical review, which will best make clear to those who are not meteorologists the difficulties and problems in air-pressure measurements on mountains.

Soon after Torricelli's famous experiment in the year 1644 there followed the first air-pressure measurement on a mountain, which was made by Pascal, through Perrier, on the Puy de Dome on September 19, 1648. The observation gave the result expected by Pascal, namely, that the barometric height decreased with increasing elevation of the point of observation and again reached its former reading when the barometer was returned to the original elevation. Through this result Pascal had at hand a new proof of the incorrectness of the "*horror vacui*" and proof of the correctness of his view on pressure—"it is certain that very much more air lies at the foot of a mountain than at its summit"—as written to Perrier in a letter published not long ago. The boldness of Pascal's view appears from the same letter in which he emphasizes the words "we must not lightly set aside fundamental principles held from early times unless we are forced thereto by convincing and irrefutable proof." Through the experiment Pascal was now in possession of the proof. The significance of his results is best shown by the improvement made in the physics of measurement in the decades following and the resultant laws of gases.

The hypsometric formula was derived by Halley in 1686, but consideration was first given to the influence of the temperature of the air by Kästner in 1775. In substance, Kästner's formula still serves in practical reckoning. The final step in the development was the hypsometric formula derived by Laplace in 1805. Laplace proceeded from the basic equation:

$$(1)\quad -dp = g\rho d_z$$

in which p indicates the pressure, ρ the density, g the acceleration of gravity, and z the vertical coordinate, positive upward. Herein Laplace introduced the density as a function of the temperature t, the pressure p, and the vapor pressure e. An approximation to the integral is:

$$(2)\quad \log\frac{p_1}{p_0} = -\frac{1}{18400}\cdot\frac{1-0.377\left(\frac{e}{p}\right)m}{1+\alpha\, t_m}\cdot(z_1-z_0)$$

This relation permits the calculation of:

z_1-z_0, when p_1, p_0, t_m, and e_m are measured. (Case a.)
p_0, when z_1-z_0, p_1, t_m, and e_m are measured. (Case C.)
t_m, when z_1-z_0, p_1, p_0, and e_m are measured. (Case c.)

and, indeed, this formula has all three applications in abundant measure.

In the years following, the formula was taken over by those who have to deal in a professional way with air pressure measurements, thus chiefly by meteorologists. The formula came into daily use in the reduction of the barometric height to sea level (case C) as soon as there was a daily weather service, that is, as early as 1863, when LeVerrier established the first weather service.

As the first mountain observatories began to function there were found in the observations collected from mountain and valley stations many marked departures from the relation shown in formula (2). Their cause was recognized to lie in the fact that as the mean temperature, t_m, required in reduction there was necessarily employed the arithmetical mean of the air temperatures observed at mountain and valley stations, which value is admissible only when the temperature is a linear function of the height. It frequently happens that this condition is not even approximately fulfilled.

But this was not all. It appeared that with very high wind velocities, such as occur for the most part only on mountains, but are observed there very frequently, there are found regular departures such that the pressure at the mountain station is measured too low in relation to the pressure at the valley station. One of the first to verify this "lowering of the varometric height by the wind" was Montigny (1851), who became well known through his labors in the field of atmospheric optics. It must be emphasized, however, that when the phenomenon becomes especially noticeable at mountain stations it is not at that time limited to those points. Although the phenomenon was the subject of frequent discussion in later years it first found its final confirmation as a fact of observation through several investigations by G. von Elsner.[2] The material for these investigations is found in the observations at several mountain stations, the Schneekoppe especially, and on the Eiffel tower.

Von Elsner compared the air pressure values observed on the Schneekoppe (barometric height 1,610 meters), p_s in the following table, with the air pressure values at Arnsdorf (barometric height 454 meters) and Zillertal (barometric height 397 meters) reduced to the level of the Schneekoppe, p (reduced). He then obtained the amount of the lowering of values measured in the Schneekoppe relative to the values reduced to that level, and this lowering clearly increased with increasing wind velocity as is shown in Table 1.

TABLE 1.—*Wind velocity and lowering of pressure on the Schneekoppe*

	Wind velocity in meters per second						
	0	11	15	18	22	27	32
Difference in pressure, observed—reduced, mm	0.1	0.1	−0.3	−0.7	−1.0	−1.5	−2.0
Number of observations	12	350	317	213	141	137	47

In order to meet at once the objection that the derived departures might be a result of insufficient determination of the mean air temperature used in the reduction,

[1] Author's abstract of Methoden und Ergebnisse definierter Luftdruckmessungen. Forschungsarbeiten des Staatlichen Observatoriums, Danzig. Heft I. Danzig, 1928.

[2] Abhandlungen des Preussischen Meteorologischen Instituts, Bd. IV, Nr. 8. 1913. Meteorologische Zeitschrift, 1926, p. 201 and 1927, p. 99.

von Elsner compared the corresponding values at two elevations on the Eiffel Tower 50 and 313 meters, respectively, above sea level, and found the fully concordant result given in Table 2.

TABLE 2.—*Wind velocity and lowering of pressure on the Eiffel Tower (313 meters above sea level)*

	Wind velocity in meters per second				
	20.0–0.9	20.0–21.9	22.0–24.9	25.0–29.9	30.0
Difference in pressure, observed− reduced, mm	0.1	−0.3	−0.6	−0.8	−0.9
Number of observations	60	49	29	13	3

Now the values here given are mean values, whose origin is always difficult to discover. Therefore, Von Elsner adduced examples of convincing individual cases, one of which is given in Table 3.

TABLE 3.—*Wind velocity, pressure, and temperature on the Schneekoppe, August 23, 1922*

	2 p. m.	3 p. m.	4 p. m.	4:45 p. m.	5 p. m.	6 p. m.
Wind velocity (m. p. s.)	18	20	25	33	31	24
Difference in pressure, observed−reduced, mm	−0.9	−1.0	−1.3	−3.4	−3.1	−1.6
$\frac{1}{2}(t_1+t_0)$, °C	14.8	14.1	11.7	11.1	10.9	10.0
t'_m	11.0	10.0	6.8	−0.1	0.5	4.4
$\frac{t_1+t_0}{2}-t'_m$	3.8	4.1	4.9	11.2	10.4	5.6

In the foregoing table t'_m is the calculated mean temperature. (Case c.) The values in the last line are the errors that would be made by using the arithmetical instead of the true mean of the temperature, provided p_s is correctly measured. According to our present knowledge of the thermal structure of the atmosphere such temperature errors are to be considered out of the question.

By these investigations the "lowering of the barometric height by the wind" was verified as a fact of observation. There remained the question of its explanation.

Von Elsner expressed the opinion that the suction effect of the wind on the building housing the barometer appeared to be the most probable cause. A theoretical explanation of this phenomenon was given by another, but I was able to show [3] that in it the integrals of the equations of motion which relate to a stream line were erroneously related to the vertical. Thus far we have considered the historical march of development, to which I will now add my investigations.

II. DEFINITIONS AND PROBLEMS

For the sake of convenience some definitions may well be introduced.

The pressure may be designated briefly as *static pressure* $\bar{p}$ when the pressure decrease in the vertical is determined only by the distribution fo air masses in the vertical. This is the case in quiet air or in air moving without acceleration, horizontally, and in a straight line, irrespective of the values that the wind velocity may have in the different stream channels. Here $\bar{p}$ is a function of the height (z) alone, and there holds the equation:

$$\frac{d\bar{p}}{dz}+g\rho=0$$

[3] Meteorologische Zeitschrift. 1926, p. 246.

The pressure may be designated briefly as *dynamic pressure* $\tilde{p}$ when the pressure decrease in the vertical is not determined by mass distribution in the vertical alone. This is the case just so soon as the rectillinear, unaccelerated movement of the air is disturbed by any obstruction whatsoever. Then in general $\tilde{p}$ is a function of all three coordinates and there holds the equation:

$$\frac{\delta\tilde{p}}{\delta z}+g\rho\pm0$$

In general, rectilinear, unaccelerated wind movement, and, with it, static pressure within the limits of the accuracy of pressure measurement, may be assumed over a plain. Accelerated movement and with it dynamic pressure effects are brought about (or shown in the record—Translator) (1) by all mountain barriers, (2) by the building that houses the barometer, and (3) by the pressure-measuring apparatus and even by the pressure-decreasing apparatus. The disturbances of the pressure and velocity fields produced (or indicated—Translator) by these three hindrances will be designated as orographic, building, and instrumental.

The instrumental disturbance necessitates the use of a pressure-decrease apparatus in addition to the barometer. With the aid of this it is possible to eliminate the instrumental disturbance. Through a further following of this idea the disturbance caused by the building can be segregated.

The disturbance due to the building is of importance, since up to the present the measurement of pressure has always been made with a barometer suspended in a building. While in the absence of the building the pressure in a space about ten times the size of the building is (even on mountains) evidently a function of the height alone, through the building disturbance it evidently becomes a function of all three coordinates in the vicinity of the building.

The pressure measured in the building itself is plainly a mean value; this is due to the fact that there takes place an equalization of pressure through every opening of the room in which the barometer is exposed. The greater the amount of opening $\Delta\rho$ permitting an equalization of pressure, the greater the weight of the pressure $\tilde{p}$ at the point $\Delta\rho$ in determining the mean, so that the pressure measured in a room p_s is represented by:

$$p_s=\frac{\Sigma\tilde{p}\Delta\rho}{\Sigma\Delta\rho}$$

in which the sum is to be taken over all openings permitting equalization. Naturally, such openings are always present, but the geometrical arrangement is entirely a matter of chance and can by no means be taken into the calculation (windows, doors, chimneys, etc.). The geometrical arrangement changes from one observatory to another; indeed, at *one* observatory it will not be the same through the year (deposit of silver thaw, etc.). From what precedes it is seen that so soon as the building disturbance becomes noticeable the pressure measurement in a room gives a mean value that is in general not correctible; that is, *it is no longer definitive.* There is further complication due to the fact that a given geometrical arrangement can give very different effects with different wind directions.

In contrast to the first two disturbances the *orographic disturbance* can not be eliminated. As the result of this disturbance the pressure in a widely extended region, many times as large as the area covered by the mountain, is a function of all three coordinates of space. There are, perhaps, marked pressure differences between windward and leeward sides and more or less periodic pressure oscillations to leeward. However, the processes on the lee side are to be given notice merely as regards characteristic features, so it will be well to pass over this matter of uncertainty. By *pressure on a mountain summit* there will be understood that pressure which is measured at the earth's surface, *on the windward side*, and in closest proximity to the summit.

There is now the two fold problem: (*a*) To indicate a practicable method of measurement which will permit continuous definitive measurement, and (*b*) to determine quantitatively the building and the orographic disturbances.

III. METHOD OF MEASUREMENT

After several futile attempts I solved the first problem by recourse to a very simple pressure-decrease apparatus. A flat, circular plate, 28 cm. in diameter, was perforated at the center and into the perforation there was carefully inserted a small tube 3 mm. in diameter; the plate was then placed on the ground over a water drain. The opening of the plate was connected through a tube 8 mm. in diameter and about 60 m. long (inside a drain pipe) with the interior of an aneroid box placed in the barometer room.

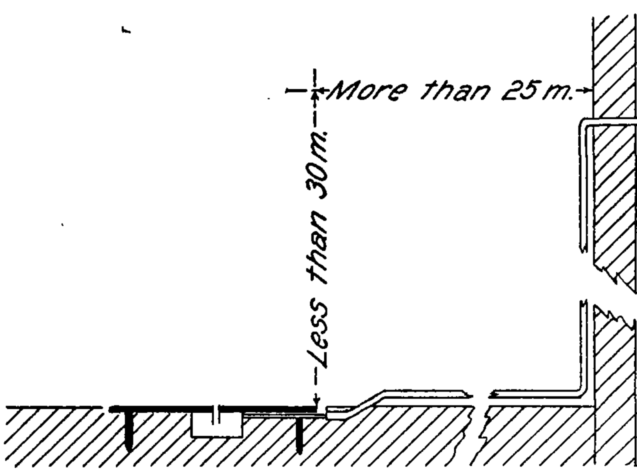


FIG. 1.—Pressure-decrease apparatus

If there occurs in the room a fall or rise in pressure relative to the pressure at the opening in the plate then there follows a bending of the aneroid box, the amount of the bending furnishing a measure for the pressure deficit or pressure excess in the room. This bending can be recorded; and for this purpose I used an ordinary commercial pressure-difference recorder which was kindly placed at my disposal by the Askania factory in Berlin.

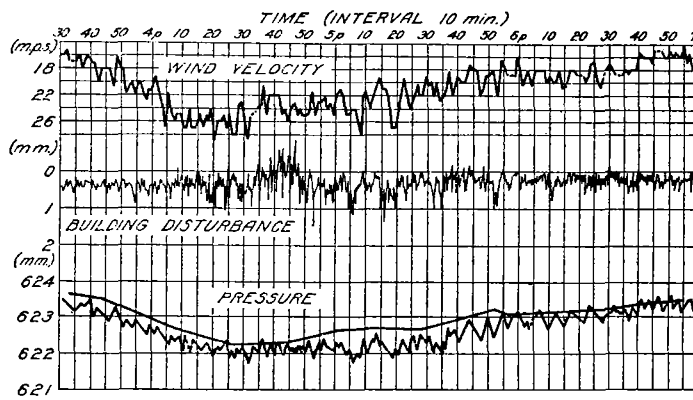
The system described[4] has two important advantages: (1) The pressure-decrease apparatus has no movable parts, a feature of importance in securing continuous functioning; and (2) the opening is in the stratum of lightest wind, a condition that is of importance in accuracy of measurement.

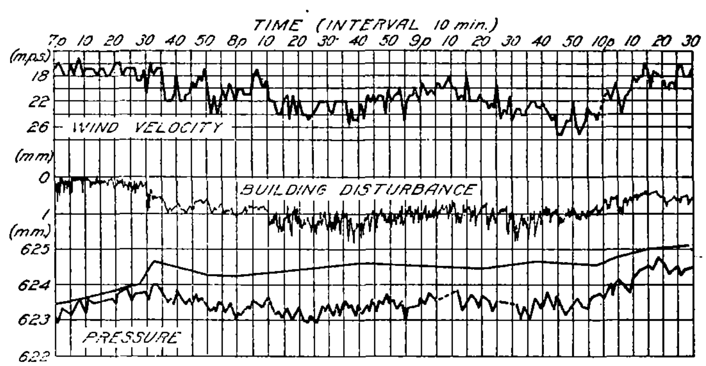
In my full publication[5] there is discussion in detail of six possibilities of error and it is shown that the total error in the measured pressure differences does not exceed 0.2 mm., even with a wind velocity of 30 m. p. s. at the height of 2 meters above the ground.

IV. BUILDING DISTURBANCE

The measurements show two cases: (*a*) With SSW. to SW. winds the building disturbance is practically negligible, with changing sign of departure, and there is no agreement with the march of wind velocity (fig. 2), and (*b*) with WSW. to NNW. winds it is, on the contrary, noticeable, the pressure difference between the room and the circular plate (deficiency of pressure in the room) showing even in small details a change from time to time paralleling the change in wind velocity (fig. 3, wind up to 7:30, SW.; thereafter, a change).

With measuring arrangement unchanged, case *a* changes to case *b* as soon as the wind changes from SW. to WSW.-NNW., and vice versa. Figures 2 and 3 give an example of this.





FIGS. 2 and 3.—Wind velocity, building disturbance and atmospheric pressure 3:30 to 7 p. m., and 7 to 10:30 p. m., respectively, on June 8, 1927

The different behavior of the building disturbance is explained by an observation which I owe to the observer at the Schneekoppe, whose presentation is reporduced unchanged in Figures 4 and 5.

With WSW.-NNW. winds (fig. 4) the building and the anemometer exposed on its roof lie to the windward of the mountain in a steadily directed current; on the contrary, with SSW.-SW. (fig. 5) winds the building now lies, in a current so extremely shifting that there can be no thought of a real wind direction, while the anemometer is found in the SW. current. Agreement can not be expected between the wind velocity measured in the steady SW. current and the building disturbance produced by the altogether unsteady current. The fact that with SSW.-SW. winds the building disturbance remains small is readily understood in view of the continual change in wind direction in the immediate vicinity of the building.

Figure 6 shows the dependence of the building disturbance on the velocity of the wind. In it we see that

[4] The possibility of this system was pointed out, independent of myself, by O. Schrenk in the Meteorologische Zeitschrift, September, 1927. It was used in my measurements as early as April, 1927.

[5] Methoden und Ergebnisse definierter Lufdruckmessungen. Forschungsarbeiten des Staatlichen Observatoriums, Danzig. Heft. I. 1928.

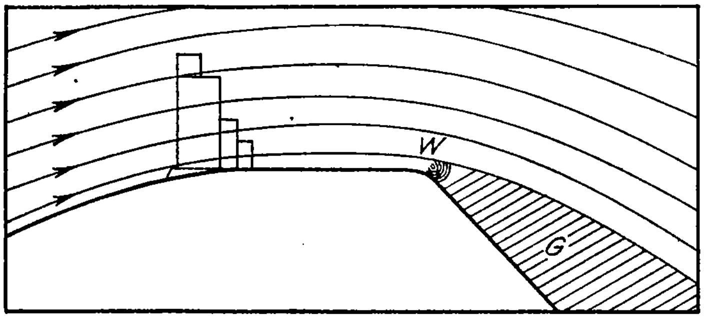


FIG. 4.—Fog circulation with N.-NW. winds; whirl found only at W. In the space G, wind direction mostly *downward*, rarely *upward*

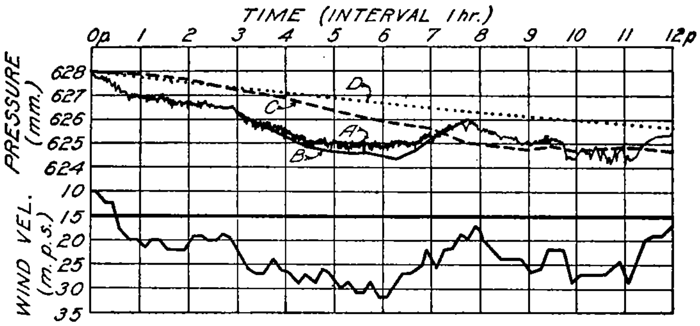


FIG. 7.—Pressure and wind velocity on September 9, 1927
A. Pressure in room (barograph)
B. Pressure corrected for building disturbance
C. Pressure reduced from Arnsdorf (static condition)
D. Pressure in the undisturbed field (free air)

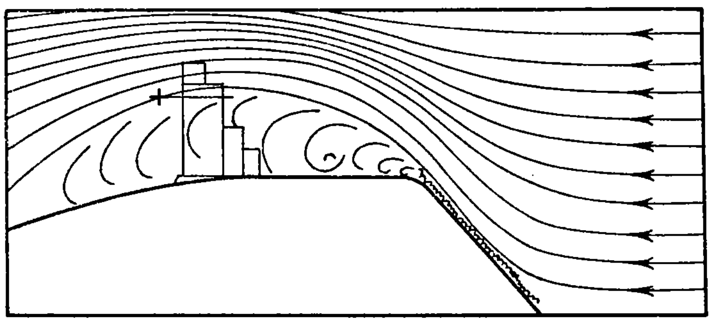


FIG. 5.—Fog circulation with S.-SW. winds, in the summer only; conditions in winter not clear. The limit almost always lies at the point marked by +.

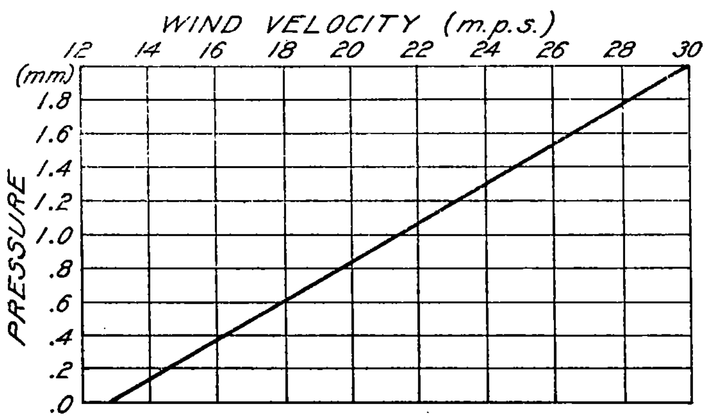


FIG. 6.—Building disturbance on June 8 and 20, 1927

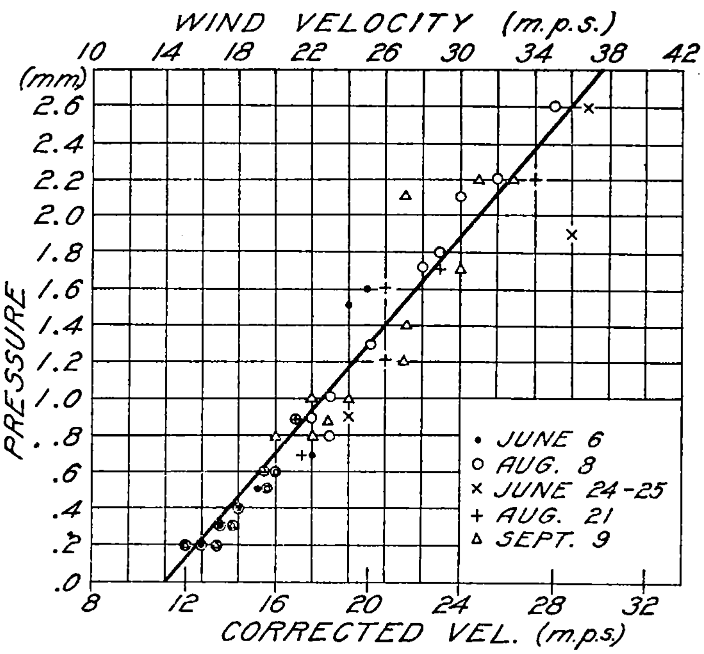


FIG. 8.—Orographic disturbance

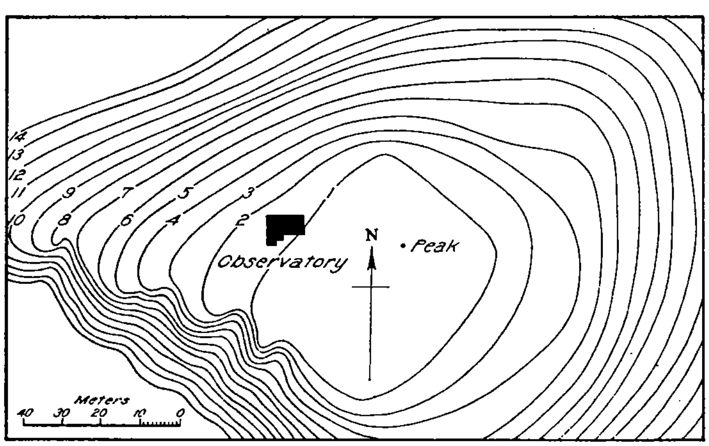


FIG. 9.—Contour map of the Schneekoppe

this disturbance is practically unnoticeable for wind velocities up to 14 m. p. s., but amounts to 2 mm. with a velocity of 30 m. p. s. (In the reproduction the details of the original have been omitted.)

The fact that the building disturbance can reverse the sign of the pressure change is of special importance in meteorological questions. In several instances it could be shown that with increasing wind velocity there was, after the elimination of the building disturbance, a pressure rise, while the barograph in the barometer room traced a marked fall.

V. OROGRAPHIC DISTURBANCE

An obvious proof of the existence of an orographic disturbance is, strictly speaking, possible only when comparison is made between pressure values on a mountain and pressure values actually *measured* in the immediate vicinity, at 10 to 20 km. distance, at the same elevation in the free air. A rather long time will pass before the meteorologist is given the opportunity to make such a comparison. In order to arrive at results in this direction the question must be approached in a different way.

In common with Von Elsner our first thought will be to compare the pressure observed on the mountain, now corrected for the building disturbance, with the pressure measured at a valley station, reducing pressure at the valley station to the elevation of the mountain station by means of Laplace's formula. But in order to do this it is necessary to know the mean temperature of the air column between stations, and, of course, in the free atmosphere. Now the temperature on the mountain peak certainly does not coincide with the temperature in the free air at the same elevation. This is proven by observations, and H. von Ficker[6] made it plain in a very full discussion. So then this method can not be pursued.

The following method of consideration appears to be the only way in which the question is to be discussed. If an orographic disturbance is present it must increase with the wind velocity, and then, too, the maxima and minima of pressure and velocity must occur exactly simultaneously and in opposite sense. If, on the other hand, there is a pressure disturbance which is caused by distribution of masses and, thus, is not connected with the locality, but occurs also in the undisturbed field (the free air), then the extremes of pressure and velocity must show a shifting of phase such that the maxima of velocity and the maxima of pressure change will coincide. (Of course the highest velocities are expected to be encountered during pressure rise and conversely.)

Since the meteorologist knows of no relation between wind velocity and pressure, but knows of a very decided relation between wind velocity and pressure gradient—that gradient which, to give a first approximation, is found in the direction at right angles to the current direction in the horizontal plane. (Cariolis' law.) The relation between wind velocity and pressure gradient is manifest on every weather map; at the center of the low pressure region there can be found for the most part weak winds and on the border, on the contrary, strong to stormy winds. Now, if we substitute for the conditions that are adjacent in point of space those that succeed them in point of time, there results the statement expressed above.

In this direction detailed investigation was made of five individual cases, one of which is reproduced in Figure 7. This shows plainly that the pressure and velocity curves present the same phases and that the maxima of wind velocity coincide with the minima of air pressure. In this we have demonstration of the orographic disturbance.

We come now to the question of the quantitative determination of the orographic disturbance $p - p$, that is, the determination of the difference between pressure in the undisturbed field, the free air, $\bar{p}$ and the pressure on the mountain peak, building disturbance having been eliminated, $\tilde{p}$. This determination is made here under two assumptions. The first assumption is that the pressure on the mountain peak is at the most just as high as the pressure in the undisturbed field. There were selected those velocity values at which the force of the wind is certainly too low to produce a noticeable orographic disturbance, a velocity of 12 m. p. s. being taken as the critical velocity relative to orographic disturbance. When such (low) values were lacking auxiliary values not too greatly in excess of 12 m. p. s. were selected, and to the pressure values there were applied corrections previously obtained for the lower velocities and naturally small. At the standard (low) and auxiliary values of velocity the pressure observed on the Schneekoppe (and corrected but little) is now obviously equal to the pressure at the same elevation in the field undisturbed by the mountain.

The second assumption is that the course of pressure in the undisturbed field is rectilinear between the standard and the auxiliary values. This is the most obvious assumption and it leads to the clearest results. Another assumption probably suggests itself, yet it would bring about a much greater scatter in the final result. In addition the assumption of rectilinear course used in the evaluation leads to a good explanation of simultaneous meteorological processes, which is not the case with the other assumption.

Under these two assumptions the five different cases were evaluated for points of time which satisfied the given conditions; for the wind velocity measured there was calculated the difference between pressure in the undisturbed field and pressure on the mountain after the elimination of the building disturbance, that is, the orographic disturbance was segregated. Figure 8 shows the result. It is seen that the scatter is extremely small, which argues well for the working hypotheses introduced. Figure 8 also shows that under the assumption that 12 m. p. s. is the critical velocity, the orographic disturbance on the Schneekoppe, with winds from SSW.–SW., amounts to about 1 mm. for a velocity of 18 m. p. s. and to about 2 mm. for a velocity of 25 m. p. s.

There is yet a word to be said with reference to the relation between building and orographic disturbances. with SSW.–SW. winds there occurs no noticeable building disturbance, while there is a marked orographic disturbance. On the other hand, with WSW.–NNW. winds there appears no noticeable orographic disturbance, while there is a marked building disturbance. With a wind velocity of 30 m. p. s. the building and orographic disturbances differ by as much as 30 per cent, but the order of magnitude is always the same. There is, therefore, the inclination to suspect some error. The question was debated carefully, but had to be answered in the negative.

The difference is to be explained by the topography of the Schneekoppe. (Fig. 9.) The steepest slope of the peak is that toward the southwest, therefore the oro-

[6] Meteorologische Zeitschrift, 1913, p. 278.

graphic disturbance will be at the maximum with SW. winds. On the other hand the building then lies on the lee side and the building disturbance becomes unnoticeable. Toward WSW.-NNW. winds the peak presents a slope that is considerably less steep, and the orographic disturbance becomes very small. On the other hand the building now lies to the windward and the building disturbance can become quite marked.

VI. SIGNIFICANCE OF RESULTS

In conclusion something may be said relative to the significance of the results. One who is not a meteorologist will very properly raise the question: Have these pressure differences of 1 to 2 mm.—that is, 2 to 4 per cent of error in observation—really such significance that a paper such as this should be devoted to them? The meteorologist will answer in the affirmative on these grounds.

1. The investigation gives for the first time a measure of the accuracy of air pressure determination and shows that building and orographic disturbances in the cases here cited can amount to twenty to thirty times the probable error in daily observations.

2. Building and orographic disturbances have the appearance of indications of a pressure tendency in the undisturbed field (the free air) which can be opposite to the true pressure tendency. This knowledge is of significance in the explanation of meteorological processes.

3. At present pressure observations at mountain and valley stations are used to determine the mean temperature of the air column below the mountain station. (Case c.) Now on the Schneekoppe an error of 1 mm. in the pressure measurement—and this frequently occurs—corresponds to an error of 3° C. in mean temperature. That this is a rather large value is learned from the fact that through more than a decade there was carried on a controversy as to whether or not the temperature on a mountain peak is 1° to 2° C. lower than the temperature in the free atmosphere at the same elevation; that is, whether or not the mean temperatures of the columns of air differ from each other by 0.5° to 1.0° C.

Herewith there is adduced proof that considerable significance attaches to the results.

THUNDERSTORMS IN THE LOS ANGELES DISTRICT

By CHARLES CLIFFORD CONROY, Ph. D.

(Author's abstract)

Since January 1, 1884, 164 days with thunderstorms have been noted in Los Angeles, and 52 others have been recorded in the immediate vicinity. The monthly distribution of these storms is interesting. March is the month of greatest frequency, followed in turn by April, January, September, February, May, August, July, June, October, November, and December. Seasonally, the minimum belongs to the last three months of the year. There is a secondary minimum in June, and a secondary maximum in late August and September. By 3-month periods, January, February, and March, have 36.5 per cent of all the storms; April, May, and June, 26.2 per cent; July, August, and September, 24.5 per cent, and October, November, and December, 12.8 per cent. The first half of the calendar year has 62.2 per cent, and the second half has 38.8 per cent.

The hourly distribution shows a maximum at 3 p. m., and a minimum at 6 a. m. There is a secondary maximum at 3 a. m., a fact somewhat suggestive of oceanic influence. The yearly numbers of storms vary from 10 in 1919 to none in 1891 and 1915. Periods of pronounced frequency occurred in the four years 1905–1908, the three years 1918–1920, and in 1926–27. On the other hand, no thunderstorms at all were recorded from January 27, 1914, to September 30, 1916. The data at hand furnish no conclusive evidence of any progressive numerical increase of thunderstorm activity in the Los Angeles area. Nor is there any evidence of a relationship of local thunderstorm frequency to the sunspot period.

Three types—not mechanical, but types of occurrence—may be distinguished: that of the winter, when the thunderstorm takes place at the end of a pronounced disturbance, and along a windshift line, or when local convection occurs during a heavy winter rain. A second type depends upon the presence of a low-pressure area whose center is on or near the Mexican line. Los Angeles is then at or near the northern limit of such areas, and the barometer is unsteady. The third, or summer type, depends upon the well-known "Sonora" condition, and is especially evident when the center of the Colorado River "low" is somewhat northwest of its usual place and when a second "low" is mapped over Oregon or southwestern Idaho. The temperature and humidity are often quite high, even after the storm.

Of the entire list of 164 thunderstorm days, only some 20 afforded fairly severe storms, and only one—or rather the series of storms on June 30–July 1, 1918—can be described as violent. Some minor damage has been recorded in the city twenty-five times. Of late years, however, petroleum tanks have been struck and destroyed in different parts of California, and this is at present the principal problem in the prevention of destructive effects.