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An Aid for Forecasting Summer Maximum Temperatures at Seattle, Washington

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AN AID FOR FORECASTING SUMMER MAXIMUM TEMPERATURES AT SEATTLE, WASHINGTON

ABSTRACT

An objective forecast system for predicting summertime maximum temperatures for the following day in selected situations is described. The study is limited to days when temperatures are above normal. Seattle data are used for developing the system, but the parameters are effective in forecasting maximum temperatures for all cities in the Puget Sound Lowland and Willamette Valley from Seattle southward to Eugene, Oregon.

One predictor consists of the larger of the pressure differences between Seattle and Astoria or Seattle and North Bend, Oregon. The other predictor is the difference between 24-hour pressure changes at North Bend, Oregon, and Omak, Washington. It is anticipated that as the numerical surface prognostic charts become more accurate, pressure differences required for these predictors may be obtained from them. At that time, a 48-hour forecast as well as a 24-hour forecast will be feasible.

Verification statistics from an independent data sample indicate a 2.5 degree average temperature error for this objective system as compared to a 4.6 degree error for Seattle WSFO forecasts and 5.9 for the NMC (Klein-Lewis) product. A forecast of persistence would have given a 5.7 degree error.

I. INTRODUCTION

This study grew from an attempt to improve prediction of the onset of stratus from the Pacific coastal waters to the Puget Sound Lowlands at the end of a summer hot spell. The low ceilings and fog which result from the invasion of marine air into the interior valleys of western Washington and western Oregon not only hamper aviation interests but have a broad effect upon much of society. Forestry is vitally concerned as marine air lowers the threat of forest fires, aids in the control of fires in progress, and may permit logging to be resumed in the woodlands. A succession of warm summer days increases the air-pollution problem, but a marine push will terminate a pollution episode as a fresh-air mass moves into the Puget Sound Basin, sweeping the polluted air eastward toward the Cascades. The onset of stratus can lower maximum temperatures by fifteen degrees and is an important summer forecast problem.

After various parameters had been investigated in the exploratory stages of the study and variables had been chosen, it became apparent that in addition to being an aid in predicting when a cloud layer might be expected, they also provided strong clues to changes in maximum temperatures. At that point the study was enlarged to develop an objective forecast system that would predict changes of summer maximum temperatures during weather regimes when temperatures were above normal.

A definite need for such an objective forecast exists. Changes in Puget Sound Lowland summer warm-weather temperatures are most frequently due to changes in the lower layers of the atmosphere. The end or interruption of a warm spell is often caused primarily by a shallow layer of cool marine air from the coast invading the interior valleys on southwesterly winds. Conversely, hot temperatures result when air heated by the summer sun over the arid regions of eastern Washington, additionally warmed adiabatically in its transport across the Cascade Mountains, reaches the Puget Sound Lowland on easterly winds. Thus the Pacific Ocean provides a source of cool air and eastern Washington a source of warm air. Temperature fluctuations involving air masses from these two sources are due to wind-flow changes at low levels, which in turn are due to a few millibars variation in pressure at key areas.

The Klein-Lewis (1) objective temperature forecasts do not handle either of these situations well. These forecasts do an excellent job of correlating upper-air height and thickness changes with surface temperatures, but are not designed to deal with changes due to low-level air trajectory variations. Under clear skies, maximum temperatures are underforecast, and when the warm spell ends, the cooling effect of the onshore flow is underestimated.

This study attempts, as far as is possible, to separate temperature variations due to low-level meteorological effects from those caused by changes in the upper atmosphere such as the approach of an upper-cloud shield or cooling at higher elevations. The study is limited to summer months under fair-weather conditions when maximum temperatures are above normal.

II. PARAMETERS INVESTIGATED

It is apparent that to induce warm easterly low-level winds across the Cascades into the Puget Sound basin, surface pressure must be high over northeastern Washington and low over western Oregon. Conversely, low pressure over Washington and high pressure along the Oregon coast will cause cool marine air to blanket the interior valleys of western Washington. Weak gradients permit the summer sun to modify the marine air mass and cause lesser temperature changes.

Parameters investigated which reflect the above conditions were the 0000GMT pressure differences and 24-hour pressure changes at the following stations:

1. Pressure difference - North Bend, Oregon, minus Seattle;

2. Pressure difference - Astoria minus Seattle;

3. Pressure difference - North Bend minus Astoria;

4. Pressure difference - North Bend minus Omak, Washington;

5. The 24-hour pressure change at North Bend minus the 24-hour pressure change at Omak.

The 0000GMT data were chosen for two reasons: First, it marks the end of the most active six-hour period of pressure change during the day. On a hot summer day a five-millibar pressure fall frequently occurs at Seattle and Omak during this period. The beginning of marine flow over western Washington and western Oregon most frequently begins during the late afternoon following such pressure falls as nature seeks to correct the pressure imbalance that her high temperatures have created. Secondly, this is the time at which NMC numerical surface prognostic charts verify. As these charts become more accurate, pressure differences may be taken directly from them, making a 48-hour forecast a distinct possibility.

The first, second, and fifth of the above-listed variables showed the strongest relationship to subsequent change in maximum temperature at Seattle the following day. The others do not significantly improve the relationship. The first two complement each other, and best results were obtained by using the predictor which gives the strongest onshore flow on that particular day.

The first parameter, pressure difference North Bend minus Seattle, was first used over twenty years ago by Robert Kinzebach (at that time a meteorologist with Pan American Airlines) as a measure of the probability of coastal stratus invading the Seattle area during the night. The greater the pressure difference, North Bend minus Seattle, at 0000GMT (1600 PST), the greater the likelihood of stratus appearing at Seattle the following morning. Experience has shown the minimum value to be about two millibars, and when four millibars is reached, the probability of stratus becomes over ninety percent. When this pressure difference is large, marine air will flow from the coast toward the Puget Sound Lowland; and by a combination of advection and radiation, stratus will form by morning. This parameter has become a "bread-and-butter" forecast tool for summer aviation forecasting.

The fourth parameter, the pressure difference North Bend minus Omak, gave mixed results, i.e., when this pressure difference reached a maximum, cooling had long since occurred. The next logical step was to investigate pressure changes between these two points to see if this might hold an answer to the problem. As will be seen, the fifth parameter, the twenty-four-hour pressure change at North Bend minus the twenty-four-hour change at Omak, does provide a measure of the effect of day-to-day gradient changes over the Pacific Northwest. As the data were analyzed, it soon became apparent that large pressure rises at Omak during the past 24 hours indicate the tendency for easterly flow beginning or increasing across the state. If this rise is coupled with pressure falls during the past 24 hours along the Oregon coast, the gradient will be strengthened. If, on the other hand, lesser pressure rises are occuring at North Bend, while large rises are occurring at Omak, the offshore gradient will be muted. When pressures have risen more strongly on the coast, the tendency is for cooler westerly flow. Thus the twenty-four-hour pressure changes ending at 0000GMT have set the tendency for the following day's maximum temperatures.

The two predictor variables which in combination gave the most consistent and worthwhile results were, therefore:

a) Greater of pressure differences, Astoria minus Seattle, or North Bend minus Seattle.

b) Difference in 24-hour pressure changes: North Bend minus Omak.

III. DATA AND PROCEDURES

For this study a warm day was defined as one with maximum temperature two degrees above the daily normal. Normal maxima for Seattle range from 67 degrees on June 1, to 77 degrees in late July, to 69 degrees on September 15, the period covered by this project. Data for the years 1962 through 1967 were used to develop the forecast system, and data from 1968 through 1971 were for testing the system. Daily Seattle summer maximum temperatures were tabulated along with the respective 0000GMT sea-level surface pressure in millibars from Seattle, Astoria, North Bend, and Omak; the pressure differences and changes were then computed. Those days that met the criterion of two degrees warmer than the daily normal were then individually screened for the following exclusion criteria. (This was accomplished by consulting surface and upper-air charts and hourly aviation weather reports.)

Exclusion Criteria

1. Days marked by the passage of an upper trough that produced middle clouds or rain.

2. Days on which the surface pressure at Quillayute was higher than at Astoria or North Bend.

Since this study was designed to determine temperature changes primarily due to low-level meteorological effects, data from days when low clouds occurred with tops near or below three thousand feet are included. However, days on which a substantial middle cloud shield or rain occurred were necessarily excluded; for had they been considered, they would have biased the results by contributing cooling not attributable to surface pressure changes.

Occasionally cold marine air flows eastward through the Strait of Juan de Fuca and then southward over Puget Sound waters. An air mass with this trajectory causes lower temperatures at Seattle than does a southwesterly flow from the coast, as it is subject to an over-cold-water trajectory at all times until it reaches Seattle. This shallow air mass will not show the day-to-day warming that the pressure gradient will indicate. When this situation occurs, pressure is higher over northern Washington and lower over Oregon, a pressure distribution which normally would be followed by a warming trend. Unlike normal summer warm-weather situations, the surface pressure will be much higher at Quillayute than on the Oregon coast. Pressure will also be higher at Quillayute than at Bellingham, which in turn will have higher pressure than Seattle. This brings the marine air into southern Puget Sound. Reports of low clouds, especially over water, will also indicate that this weather pattern is occurring. A good example of this pattern occurred August 24 - 28, 1971.

After each day had been screened for the above exclusion criteria, there were 168 cases which formed the basis for Figures 1, 2, and 3. Figures 1 and 2 show the individual relationships between the two predictor variables and the subsequent change in the Seattle maximum temperature. These scatter diagrams suggest that these relationships are more nearly parabolic than linear. Both linear and simple parabolic curves were statistically fitted to the data, as shown by the curves on each of the scatter diagrams. These individual relatonships are shown primarily to strengthen justification for the spacing and orientation of the analysis of Figure 3.

Figure 3 shows one solution of the joint relationship between the two predictor variables and change in Seattle maximum temperature. Development data is plotted on the chart. As can be seen most clearly in Figures 1 and 2, the variability about any line of "best fit" for either of the variables is so great that only a highly smoothed or gross analysis of the joint relationship in Figure 3 is justified. The analysis is, therefore, confined to dividing the chart into "categories" of temperature change rather than attempting a continuous analysis. Despite the relatively few cases on the fringes of the plotted data, the much tighter gradients in the analysis, both on the right and top of the scatter diagram are justified by the obvious parabolic form of the individual relationships between the predictor variables and the predictand.

IV. RESULTS

Exactly the same procedures were followed in testing the forecast aid on an independent data sample from the years 1968-71 inclusive. Those dates between June 1 and September 15 of each year on which the maximum temperatures were two degrees or more above normal were tabulated. Each of these days was then screened for the two exclusion criteria. This screening resulted in 112 days which met the criteria of the study. The surface pressures at 0000Z (1600 PST) at Astoria, North Bend, Seattle, and Omak were then recorded for these 112 cases from which the two predictor variables were computed. Figure 3 was then entered with the pair of variables for each day and a temperature change forecast obtained.

Figure 4 shows a "graphical" verification of the analysis of Figure 3. The observed changes in maximum temperature are plotted in the body of the chart with the analysis from Figure 3 superimposed upon the data. The numbers in parentheses below each of the category labels are the average of the test data temperature changes within each category. These averages agree extremely well with temperature change categories determined from the developmental data except in the -9° category. However, only five test cases fell in this category, and the variation in this category in the developmental data is quite large; so the discrepancy is undoubtedly due to the small number of cases.

In Tables 1 and 2, results from the developmental and test data are compared. Also listed are results when the two data samples are combined. Figure 4 shows that the analysis developed from the developmental data "fits" the test data very well; so results from the combined data samples are indicative of what can be expected from operational use of the aid (on a reasonably large sample of cases).

In order to have an indication of the possible utility of the aid, a comparison was also made with both the computer-produced "Klein-Lewis" temperature forecasts based on the 1200Z runs, and the official maximum temperature forecast for the following day issued by the Seattle Forecast Office at around 1400 PST. This comparison is summarized in Tables 3 and 4. The comparison is based on only those days in the test data sample which met the study criteria and on only those days on which all three forecasts were available. The Klein-Lewis forecasts were not available for the 1970 months.

TABLE 1

AVERAGE AND EXTREME ABSOLUTE ERRORS IN FORECAST CATEGORIES OF MAXIMUM TEMPERATURE CHANGE. DEVELOPMENTAL, TEST, AND COMBINED DATA.

Category of Forecast Temperature Change	Number of Cases			Average Absolute Error			Extreme Absolute Error		
	Dev.	Test	Comb.	Dev.	Test	Comb.	Dev.	Test	Comb.
+9	2	1	3	1.50	2.00	1.67	3	2	3
+6	16	5	21	1.50	0.80	1.33	5	3	5
+5	25	21	46	1.08	1.67	1.35	5	5	5
+3	27	22	49	1.33	2.41	1.82	4	6	6
0	49	19	68	2.12	2.74	2.29	6	10	10
-5	14	22	36	2.79	3.05	2.99	9	11	11
-9	22	5	27	3.27	4.20	3.44	9	5	9
-12	13	17	30	2.15	3.06	2.67	5	7	7
All Cases	168	112	280	1.98	2.57	2.21	9	11	11

TABLE 2

CUMULATIVE PERCENT FREQUENCY DISTRIBUTION OF ERRORS

Error F°

	≤0	≤1	≤2	≤3	≤4	≤5	≤6	≤7	≤8	≤9	≤10	≤11
Development Data	20	52	69	81	90	96	97	98	99	100		
Test Data	15	36	55	75	87	91	94	96	98	98	99	100
Combined Data	18	46	64	79	89	94	96	98	99	99	99.6	100

This comparison points up quite clearly that the performance of the Klein-Lewis forecasts is very poor in these summertime above-normal-temperature situations. While the official forecasts improve upon the Klein-Lewis "guidance", it is obvious there is room for further improvement. The results from the objective aid show that in this particular class of situations, a marked improvement in forecasting these warm-weather-temperature changes in the Puget Sound region should result from a judicious use of the aid.

TABLE 3

COMPARISON OF AVERAGE AND EXTREME ERRORS FOR KLEIN-LEWIS, SEA WSFO, AND OBJECTIVE AID FORECASTS (TEST DATA)

Forecast	Number of Cases	Average Algebraic Error	Average Absolute Error	Extreme Error
Klein-Lewis	83	-3.70	5.92	-16
Seattle WSFO	83	-1.53	4.61	-15
Johnson Obj. Aid	83	-0.24	2.51	+11

TABLE 4

CUMULATIVE PERCENT FREQUENCY DISTRIBUTION OF ABSOLUTE ERRORS FOR KLEIN-LEWIS, SEA WSFO, AND OBJECTIVE AID FORECASTS (TEST DATA)

	Errors										
Forecast	≥0	≥1	≥2	≥3	≥4	≥5	≥6	≥7	≥8	≥9	≥10
Klein-Lewis	100	95	84	78	71	59	48	41	31	24	22
Seattle WSFO	100	100	83	73	54	43	36	25	13	11	8
Objective Aid	100	82	64	43	22	12	10	7	5	2	2

V. OPERATIONAL USE OF THE AID

The 0000GMT (1600 PST) pressure observations used in developing this objective aid are made some two hours after the afternoon forecast release time. However, by making two- to three-hour pressure-change forecasts for Seattle, Astoria, Omak, and North Bend, the aid can be incorporated into the afternoon forecast as well as the evening forecast. Experience has shown that such short-period pressure-change forecasts can be made with good reliability.

The aid is strictly applicable to only those days when the Seattle maximum temperature is two or more degrees above normal; but it can be very helpful in those cases when the maximum temperature is several degrees below normal and the 0000Z pressure distribution and 24-hour pressure changes are indicative of an existing, or a change to, offshore flow and the onset of a warm spell. When the aid is applied in such cases, the observed change in the maximum temperature will be an average of three degrees greater than Figure 3 would indicate.

Although those instances when a break in a warm spell was accompanied by rain were eliminated from the objective aid, they do constitute some of the most important summertime large temperature change events. Separate study of these cases revealed that the best strategy is to forecast a maximum temperature of 65°F for the following day when rain is expected with the marine push. Following is a list of those days both developmental and test data on which the pressure distribution was such that the aid would indicate a break in the warm spell, but the break was accompanied by rain.

Date	Max Temp (°F)	Max Temp Following Day (°F)	Temp Change (°F)	"Error" Using 65° as Forecast (°F)
July 18, 1965	86	66	-20	-1
June 19, 1967	87	61	-26	+4
June 25, 1967	80	67	-15	-2
June 18, 1968	81	67	-14	-2
June 25, 1968	87	71	-16	-6
July 9, 1969	83	63	-20	+2
September 11, 1969	81	66	-15	-1
June 26, 1970	76	60	-16	+5
Average		65	-18	2.87

Obviously, in order to capitalize upon this "climatological" fact that the maximum temperature at Seattle on rainy days following a warm spell in summer is near 65°, rain on the following day has to be accurately forecast.

Infrequently, the aid will be in error when a weak onshore gradient is accompanied by a deep layer of marine air and greater-than-expected cooling will occur. One such case took place on July 19, 1969, resulting in 16 degrees of cooling when 5 degrees was anticipated. Even less frequently, expected slight warming develops into large temperature increases when pressure increases over northeastern Washington during the night, increasing the offshore flow component. A case of this type occurred on July 29, 1971, when anticipated three-degree warming became 13-degree warming. These situations probably cannot be forecast correctly 24 hours in advance; however, the numerical surface progs, both PE and LFM, should be scrutinized closely for any clues to a strengthening of either onshore or offshore gradients during the forecast period. As can be seen in Table 2, such large temperature errors are infrequent, occurring in less than 1 percent of the cases.

Although the current maximum temperature has not been used as a predictor variable explicitly, part of the variability in temperature change is attributable to the initial maximum temperature. In very general terms, the lower the initial maximum the greater the warming with strong offshore flow, and the higher the initial maximum the greater the cooling with a strong onshore gradient.

VI. APPLICABILITY OF THE STUDY TO OTHER PACIFIC NORTHWEST CITIES

Geographically, cities lying in the interior valleys of western Washington and western Oregon, specifically Seattle and Olympia, Washington; and Portland, Salem, and Eugene, Oregon, have much in common. They all lie in the Puget Sound Lowlands or its southern extension, the Willamette Valley. A coastal range lies to their west and the Cascade Mountains to their east, and all are subject to invasions of marine air masses. One major feature, the Columbia River Gorge, through which easterly winds from the warm interior regions east of the Cascades have easy access to the lower Columbia and Willamette Valleys, causes temperatures in Oregon cities to react somewhat differently from those at the Washington cities in strong easterly flow situations.

In general, the temperature change forecast obtained from Figure 3 for Seattle can be applied to all of the lower Puget Sound and Willamette Valley cities with good success. Temperature changes at Olympia, of course, could be expected to be essentially the same as those at Seattle in all cases. For western Oregon cities, however, there are three situations which should be taken into account in attempting to apply the Seattle temperature-change forecast directly:

1. Additional screening of cases should be made for possible shower activity over southwestern Oregon and middle cloud cover over northwestern Oregon caused by development of an upper trough west of the northern California coast. Such a cloud cover would, of course, prohibit the air mass present at Portland, Salem, and Eugene from achieving its potential warming.

2. When easterly flow develops through the Columbia River gorge and the pressure at The Dalles, Oregon, is appreciably higher than at Portland, temperatures over northwestern Oregon will rise five to ten degrees more than the forecast temperature change for Seattle would indicate. This rapid warming is usually preceded by strong pressure rises at Omak and/or pressure falls at North Bend, causing large negative values of the North Bend minus Omak 24-hour pressure change parameter.

3. Normally all of northwestern Oregon and western Washington interior valleys cool the same day, but on occasion the cooling over Oregon will occur a day earlier. This may happen when the thermal trough is well defined over western Oregon, but does not extend northward to Seattle. A strong onshore pressure gradient will exist between the Oregon coast and the northern Oregon interior valleys, but the pressure difference between North Bend or Astoria and Seattle at 4 p.m. will be less than two millibars.

Another necessary pre-marine push ingredient in such situations is a thick layer of stratocumulus clouds along the Oregon coast. Marine air will then move past the coastal range into the Willamette and southwestern Washington interior valleys, but not penetrate northward as far as Seattle. A pressure difference less than two millibars between North Bend or Astoria and Seattle, therefore, does not ensure that cooling will not take place over the Willamette Valley.

Application of the forecast temperature changes for Seattle directly to the other cities, except for those cases eliminated because of an upper-trough situation described in item 1 above, resulted in the verification statistics shown in Table 5. These "forecasts" are from the independent data sample 1968-71.

TABLE 5

VERIFICATION OF SEATTLE TEMPERATURE CHANGE FORECASTS APPLIED TO OTHER PUGET SOUND AND WILLAMETTE VALLEY STATIONS

Station	Number of Cases	Average Absolute Error	Extreme Error
SEA	112	2.57	+11
OLM	110	2.90	+13
PDX	108	3.08	+19
SLE	102	3.10	+19
EUG	96	2.91	+13

The extreme errors shown in Table 5 for Olympia, Portland, Salem, and Eugene were all from the same forecast, July 15, 1970. On this day the maximum temperatures at these stations were OLM 96°, PDX 102°, SLE 101°, EUG 95°, while the SEA max was only 90°. Temperatures at all stations fell into the low 70s the following day, resulting in temperature drops of 25 to 31 degrees. The North Bend minus Seattle pressure difference was +5.2 mbs, and the 24-hour pressure change difference North Bend minus Omak was +10.1 mbs. The plot of these values on Figure 3 falls in the extreme upper right-hand corner, indicating maximum cooling. This reemphasizes that the higher the initial maximum temperature, the greater the temperature change is likely to be with strong onshore flow.

VII. SUMMARY

An objective aid has been developed for forecasting maximum temperatures for Seattle, Washington, on fair-weather, above-normal temperature days during the summer months. Tha aid is designed for use in the afternoon and evening forecasts for the maximum temperature the following day. A comparison of "forecasts" produced by the aid with both the Klein-Lewis computer-produced forecast and the maximum temperature forecast issued by the Seattle Forecast Office indicates that a marked improvement can be expected in maximum-temperature forecasts for this type of summertime weather situation.

It has also been shown that with some modification in selection of situations and meteorological judgment, the Seattle aid can be applied to other locations in the Puget Sound Lowland and the Willamette Valley of northwestern Oregon.

VIII. ACKNOWLEDGMENT

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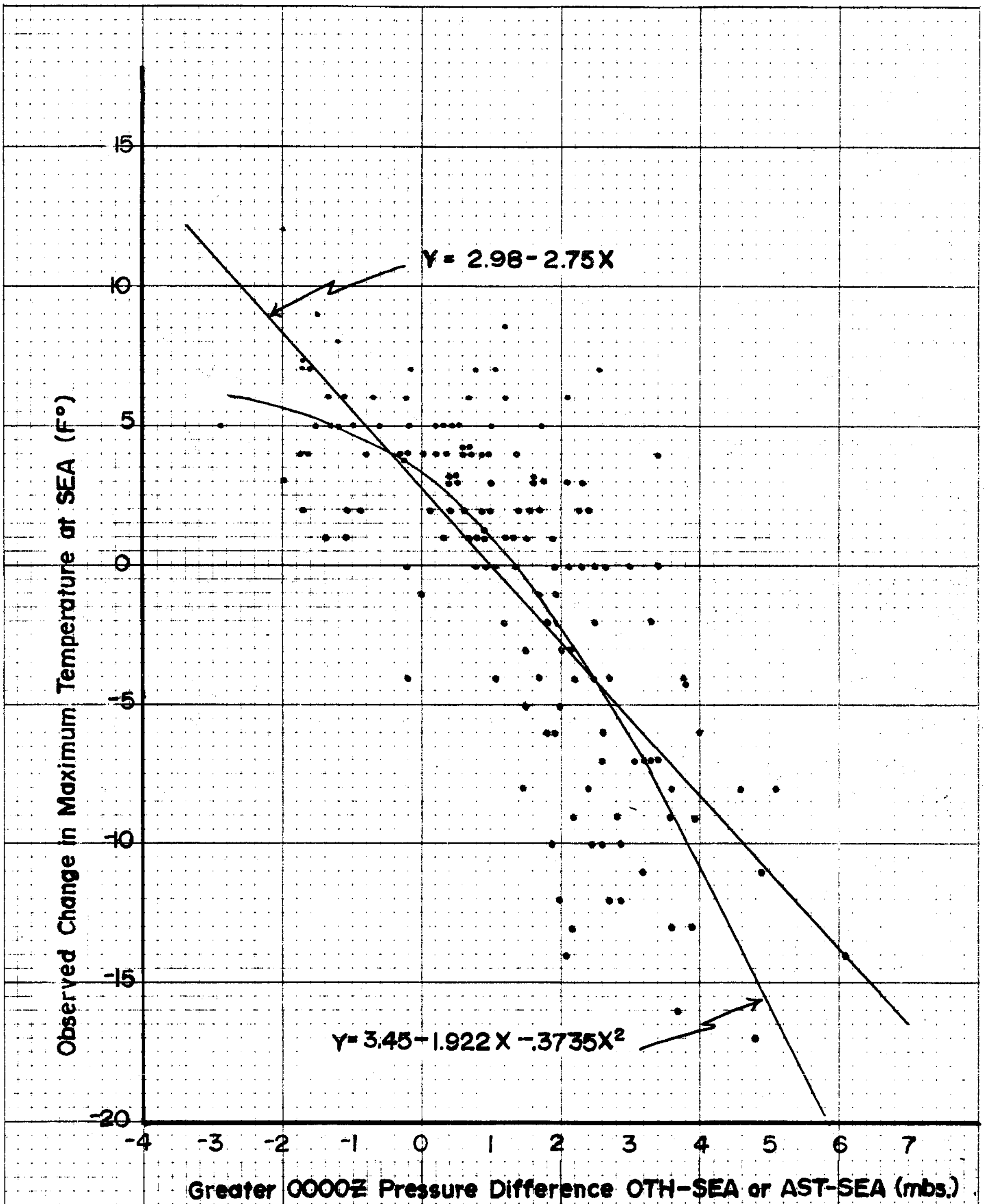

FIGURE 1. SCATTER DIAGRAM SHOWING RELATIONSHIP BETWEEN 0000Z SEA-LEVEL PRESSURE DIFFERENCE OTH-SEA OR AST-SEA TO SUBSEQUENT CHANGE (APPROXIMATELY 24 HOURS) IN MAXIMUM TEMPERATURE AT SEATTLE. STRAIGHT LINE IS LINEAR LEAST SQUARES REGRESSION FIT TO DATA. CURVED LINE IS PARABOLIC LEAST SQUARES REGRESSION FIT TO DATA.

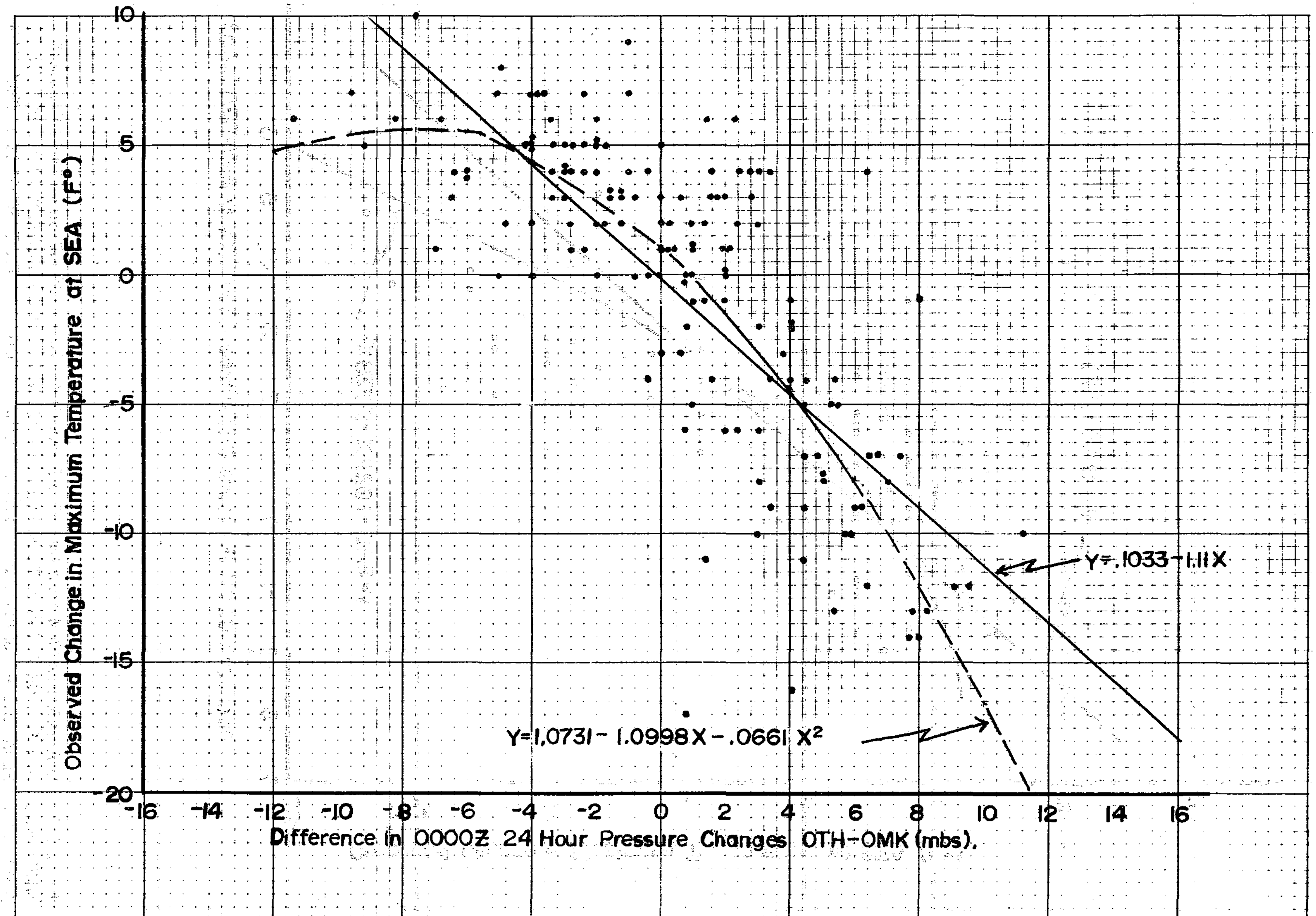

FIGURE 2. SCATTER DIAGRAM SHOWING RELATIONSHIP BETWEEN DIFFERENCE IN 24-HOUR PRESSURE CHANGES AT OMK AND OTH AT 0000Z AND SUBSEQUENT CHANGE (APPROXIMATELY 24 HOURS) IN MAXIMUM TEMPERATURE AT SEATTLE. STRAIGHT LINE IS LINEAR LEAST SQUARES REGRESSION FIT TO DATA. CURVED LINE IS PARABOLIC LEAST SQUARES REGRESSION FIT TO DATA.

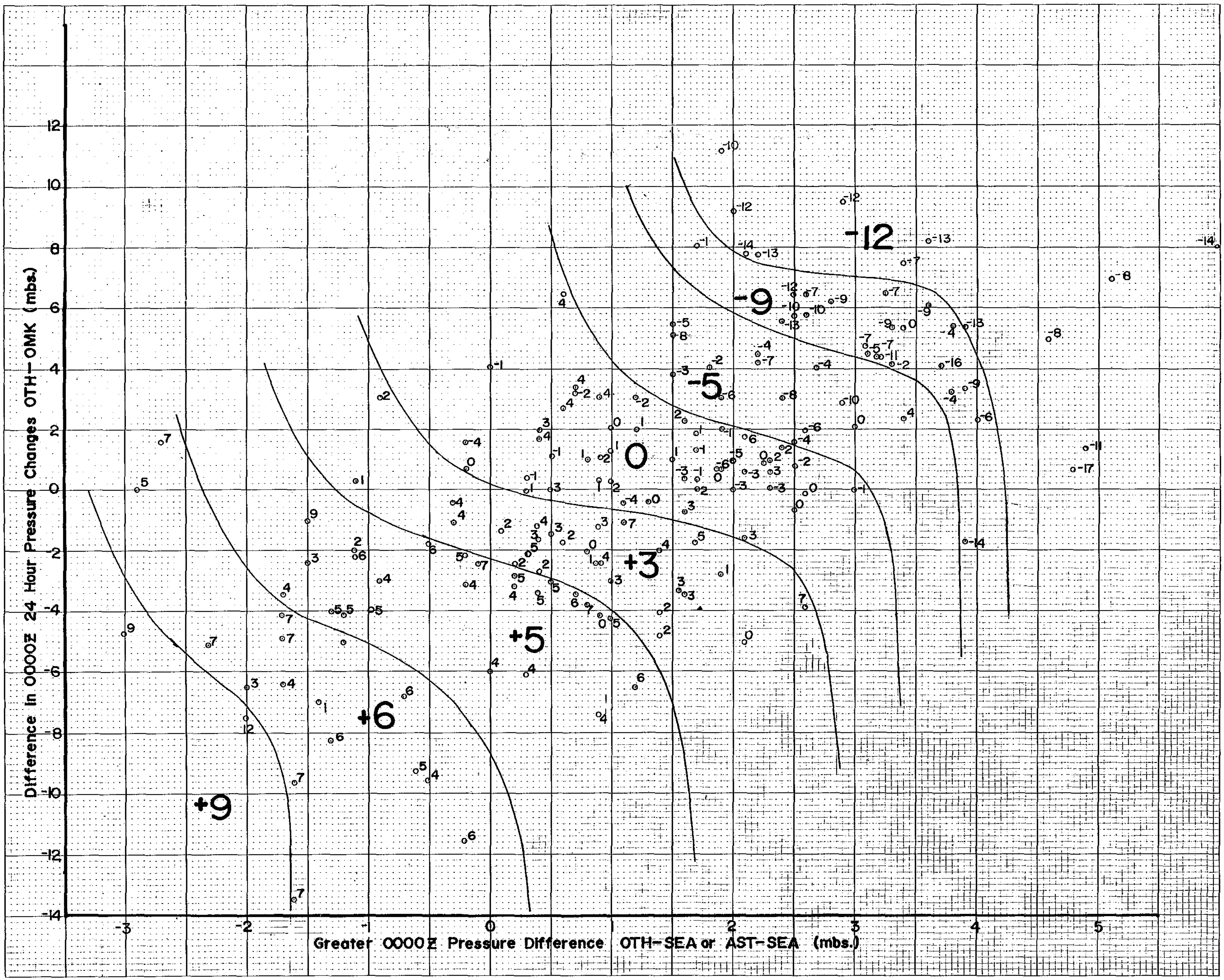

FIGURE 3. SCATTER DIAGRAM SHOWING RELATIONSHIP OF CHANGE IN SEATTLE MAXIMUM TEMPERATURE AS A FUNCTION OF BOTH 0000Z PRESSURE DIFFERENCES AND DIFFERENCES IN 24-HOUR PRESSURE CHANGES (DEVELOPMENTAL DATA). SEATTLE TEMPERATURE CHANGES ARE PLOTTED ON CHART. SEE TEXT FOR DISCUSSION OF ANALYSIS.

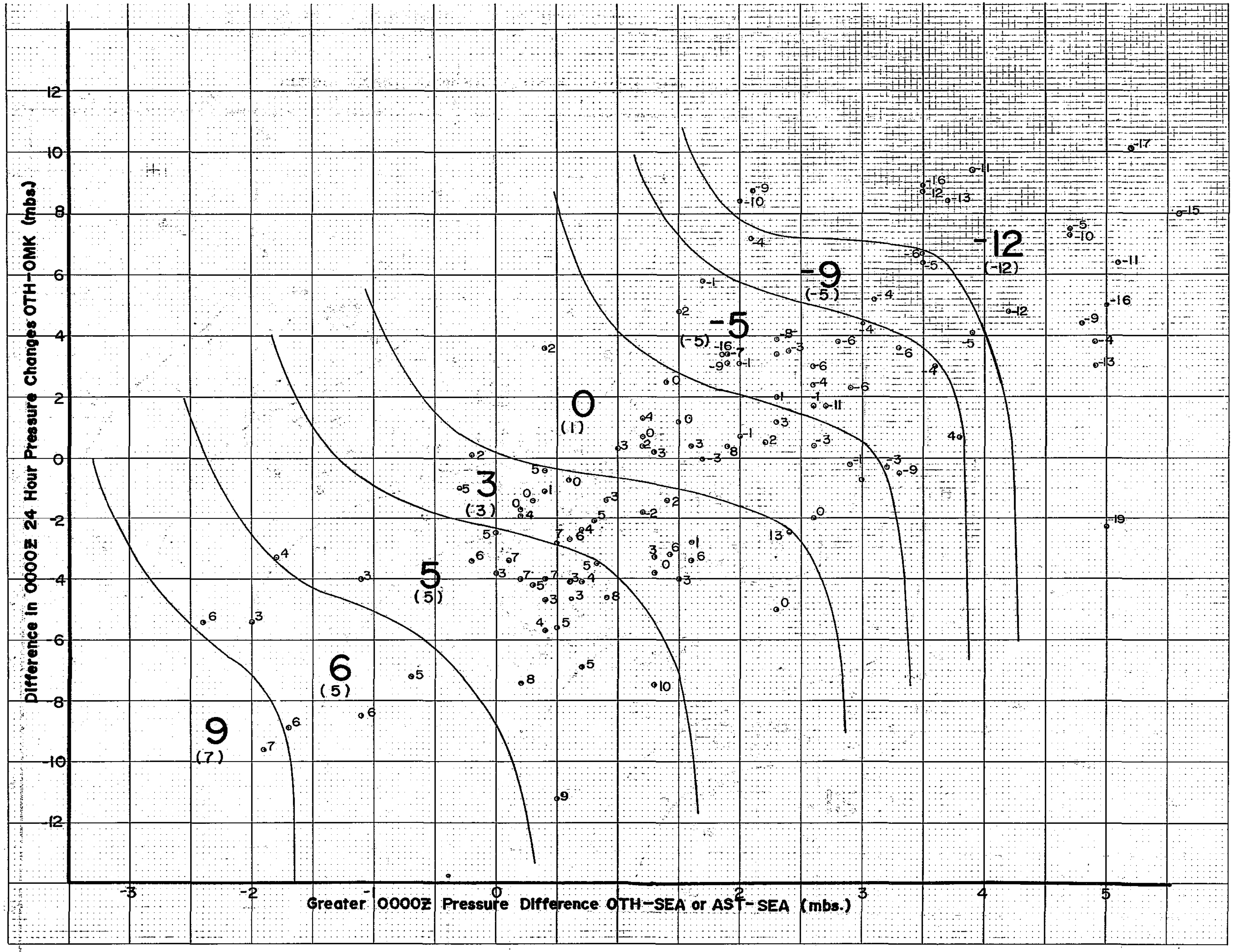

FIGURE 4. SCATTER DIAGRAM SIMILAR TO FIGURE 3 FOR TEST DATA, EXCEPT THAT ANALYSIS FROM FIGURE 3 BASED ON DEVELOPMENTAL DATA IS SUPERIMPOSED UPON THE PLOTTED TEST DATA.

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