AIR QUALITY

One of a series of background papers for the Planning Policy Committee Baylands Subcommittee. This paper was prepared by Francis Ludwig, Meteorologist, Stanford Research Institute. (8/14/70)

POSSIBLE EFFECTS OF BAY FILL ON AIR QUALITY

by

F. L. Ludwig

I INTRODUCTION

The Baylands Subcommittee is seeking background information on the effects and ramifications of developing those parts of San Francisco Bay that lie in Santa Clara County. This report covers some of the potential changes in air quality that may accompany the filling and development of Bay lands. In the following discussions, the term "air quality" has been interpreted broadly to include meteorological and climatological factors such as wind, temperature, clouds, fog, and rainfall, as well as air pollution.

Before proceeding, it should be understood that many of the consequences of Bay fill are uncertain. The atmosphere is extremely complex and its behavior involves many feedbacks. A small change in one element may result in sympathetic changes in several others, and these changes in turn affect the original element. The atmosphere may be likened to the national economy, another system that is filled with complex feedbacks and interactions. You wouldn't expect an economist to be able to tell you the precise results of a change in the tax rates of New Jersey, and you shouldn't expect a meteorologist to supply you with the precise consequences of certain levels of bay fill. However, I think that the gross effects are predictable, and this paper is directed toward predicting those gross effects.

Before going on to the specific problem, I would like to discuss some of the factors that determine climatological conditions in general and how they combine to give the Bay Area its special climate.

II BACKGROUND:

A. Factors Affecting Climate

1. General

Climates are the product of large scale motions in the atmosphere, the locations of continents and oceans, and, finally, the effects of local topography. The last item, local topography, is most important to the prediction of the effects of bay fill. It is very unlikely that changes in the Bay will affect the large scale motions of the atmosphere or the general arrangement of continents. Thus, the Bay Area will still have the same general climate that is found in the western parts of continents at latitudes of about 35° to 40° north or south of the equator. Experience shows that there can be considerable difference between the coastal and inland parts of such areas. These differences are, in large part, the result of local topography.

2. Wind

The general direction of the winds in an area are determined by the global circulations of the atmosphere and by the large weather systems. However, the local winds may vary considerably from these larger scale air motions. For example, the general motion of the air into the Bay Area may be from the west and air may leave the area and move across the central valley from west to east, but the wind direction at a given location may be quite different from this general wind direction. The wind may blow from the northwest* in the Santa Clara Valley and at the same time the wind at Point Richmond might blow from the south. The topography produces preferred channels for the wind. It can also introduce eddies downwind of obstructions.

Differential heating also plays a part in determining the wind. If low level air is heated in one area, it will rise and air will flow in from surrounding areas to replace the rising air. This influx of air contributes to the local winds.

3. <u>Temperature</u>

The air temperature near the ground is very strongly influenced by the nature of the underlying surface. Air is not directly heated by sunlight. Most sunlight passes unabsorbed through the air; it is absorbed in large amounts only when it strikes the surface. This surface, in turn, heats or cools the air. If the surface is warmer than the air above, then the air is warmed; if the surface is cooler than the air above, the air is cooled.

How the underlying surface affects air temperature depends on how that surface heats and cools. Here, there is a great difference between a water surface and a solid surface. A water surface is partly transparent to the sunlight, so that most of the sun's rays penetrate and heat the water to some depth. This solar heating effect is spread through a large volume of water, which means that the temperature of the water will rise

*Wind directions are specified according to the direction from which the wind comes.

only slightly. Another factor is the fluidity of water so heat is transferred by motions of the water. Thus the heat available from the sunlight is spread through a large volume of water and results in a smaller temperature rise than would be the case for a smaller volume. It is also a physical fact that, for a given amount of added heat and a given weight, the temperature of water rises less than most other materials.

For typical ground surfaces, the reverse of almost everything said about water surfaces is true. Sunlight is absorbed in the topmost ground layers only and its transfer to lower layers is not aided by convection. In fact, most soils are relatively poor conductors of heat so that most of the heat added by one day's incoming sunlight is generally confined to the top foot or so of ground. However, a given amount of heat will raise the temperature of soil more than it will the temperature of the same amount of water. All this means that ground surface temperatures rise higher when exposed to the sun than do water surface temperatures.

Arguments similar to those given in the preceding paragraphs can be applied to heat storage and heat losses. Water will store a lot of heat and can transfer it to the air without much lowering of temperature. On the other hand, ground surfaces will lose their heat relatively quickly at night and the lowering of the surface temperature will be large.

All these factors contribute to the commonly observed fact that locations near large bodies of water have smaller day-to-night and season-to-season temperature changes than do those locations farther from such bodies of water.

4. Fog and Clouds

Clouds are generally formed by air cooling to the point where it becomes saturated and cannot retain all the moisture present in gaseous form--so condensation takes place. The cooling can be initiated in several different ways such as passage over a cold surface, nighttime cooling, or by elevation to higher levels in the atmosphere.

The "high" fog that forms along the northern California coast is an example of moist air passing over a cold surface, in this case the very cold coastal waters. The Central Valley fogs in the winter illustrate the types of fog that accompany nighttime cooling processes. The summer thunderclouds in the Sierra form because the air is lifted to higher levels, partly by the flow over the mountains and partly by heat-produced buoyancy.

5. Rainfall

Rainfall is very heavily influenced by local topography. The general occurrence of rainfall is governed by the large scale air motions and weather systems, but the amount of rainfall can be greatly altered by local topography, especially mountains. As saturated storm clouds move over the mountains, they are forced to rise; they cool, and more moisture is converted to rain. As the clouds pass to the downwind side of the mountains the air goes to lower levels, is warmed, and the further removal of moisture is inhibited.

If most rainfall occurs with winds from the same general direction, then there will be larger amounts of yearly rainfall on the upwind slopes of the mountains than on the downwind. The Bay Area has some examples of this effect, as will be seen in a later section.

6. Air Pollution

Three factors affect the concentrations of air pollutants that arise from sources in a given area: (1) the rate at which they are released, (2) the volume of air into which they are mixed, and (3) the chemical reactions and removal processes that subsequently change the nature of the pollutants found in the air. I do not plan to discuss the third item since it is not principally a meteorological effect. The first two effects are largely responsible for the amounts of air pollution; the first and third items determine the nature of the chemical constituents that make up that pollution.

The reason why the concentrations of pollutants are affected by the rate at which the pollutants are generated is easy to see. If the amount of pollutants generated in a minute is doubled but everything else remains the same, then there will be twice the amount of pollutants added to the same amount of air. This means twice the concentration of pollutants. Similar reasoning tells us that if we halve the volume of air into which a certain amount of pollution is added, then we also double the concentration. There are at least two ways that this volume of air can be changed. These are illustrated in Figure 1. This figure shows schematically the same amounts of pollutants being added to different amounts of air. The changes in air volume are caused by changes in wind speed and in the depth through which the pollutants

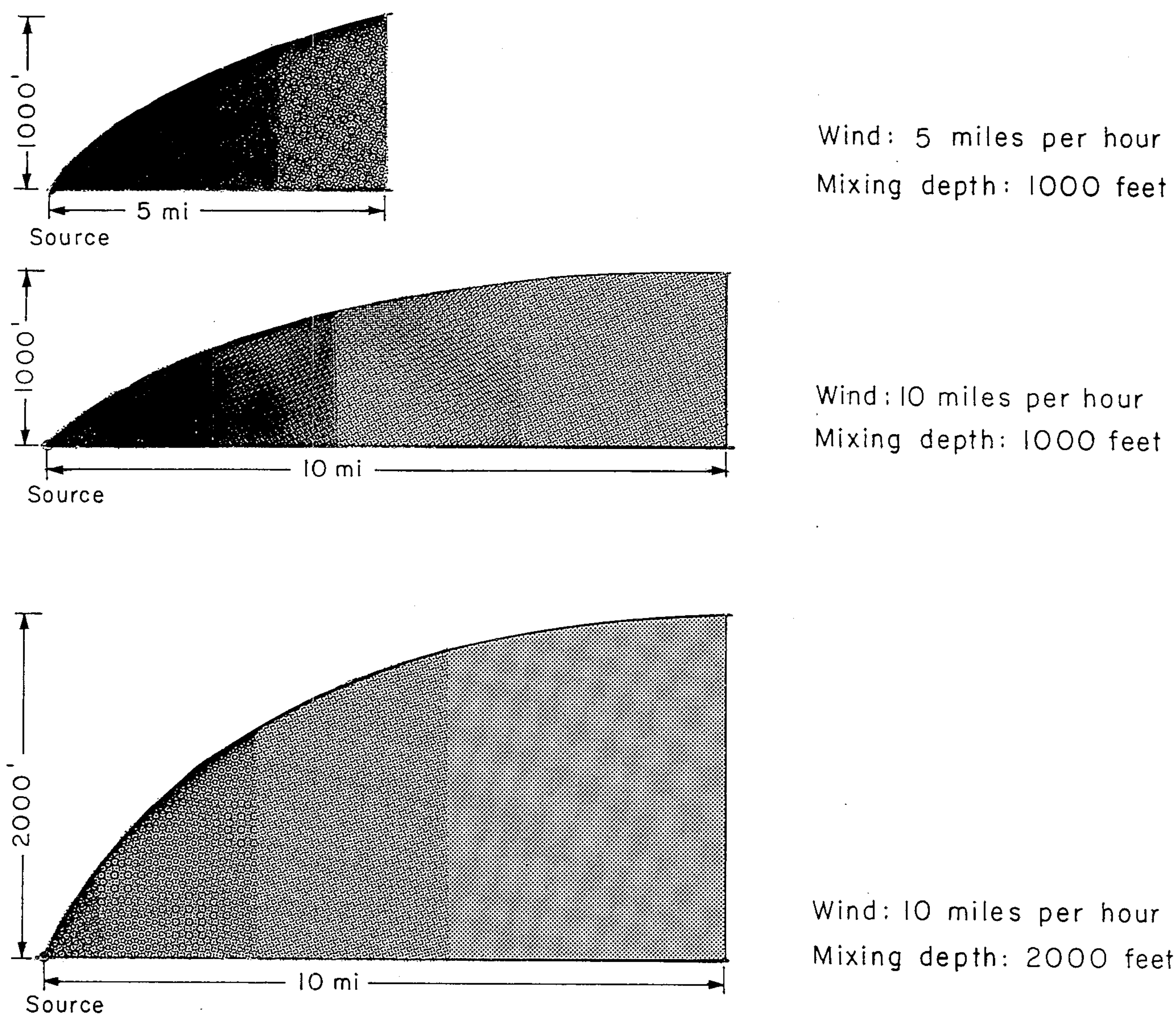

FIG. I SCHEMATIC DRAWING OF THE VOLUME INTO WHICH ONE HOUR'S POLLUTANTS ARE MIXED are mixed. The figure shows that doubling the wind speed also doubles the volume into which one hour's pollutants are mixed. Similarly, the altitude to which they are mixed affects the concentration by changing the volume.

Thus, the meteorological factors that influence air pollution are principally the wind speed and the depth through which the pollution is mixed. This latter factor is influenced by the difference between surface air temperatures and those at the higher levels. If it is warmer at higher levels than at lower levels, the height to which the pollutants are mixed is effectively limited. This condition, where temperature increases with height, is called an "inversion."

To summarize, the topographical features that most affect air pollution are those that affect wind speed and the distribution of temperature in the vertical. Topographically induced changes in the vertical distribution of air temperature are most likely to be accomplished through changes in the surface temperature. Therefore, in considering the effects of topography on air pollution, the effects on wind speed and temperature should be first considered. Finally, it should be emphasized that although topographically induced changes in pollutant concentrations can be appreciable, the rate at which the pollutants are generated is usually the most important factor.

B. Urban Effects

The physical principles that govern the effects that a city has on the atmosphere are the same as those discussed for topographical features, so the entire discussion does not need to be repeated. Table 1 (adapted from Landsberg, 1962) illustrates the typical magnitudes of effects produced by cities. It should be recognized that the city effects are likely to be superimposed on those produced by the topographical features. Thus, those listed in the table are more appropriate to a city located on flat, featureless terrain than they are to a place like San Jose with its complex surrounding geography.

Table 1

CLIMATIC CHANGES PRODUCED BY CITIES

Element	Comparison of City with Surrounding Rural Areas
Average wind	City 20 to 30% less
Average temperature	City 1 to 1.5°F warmer
Winter minimum temperature	City 2 to 3°F warmer
Clouds	City 5 to 10% more
Winter fog	City twice as much
Summer fog	City 30% more
Dust	City 10 times as much
Average relative humidity	
Winter	City 8% lower
Summer	City 2% lower

Source: Landsberg, 1962.

III THE CLIMATE OF THE BAY AREA

A. General

The atmospheric feature that most dominates the climate of the Bay Area is the Pacific High Pressure Cell.* This feature is thousands of miles across and is generally centered in the eastern Pacific Ocean. Winds blow clockwise around its center and its position is most often such that this clockwise motion results in winds from the northwest in this area. The Pacific High generally migrates toward the north in the summer and very effectively shields the San Francisco Bay from storms; its more southerly winter position allows storms to pass through the area more frequently.

The air circulating around the high pressure cell passes over many miles of ocean and becomes relatively moist. Along the coast, the ocean is particularly cold and as the moist air passes, it is cooled from below, often to the point where fog forms. Thus, the Pacific High usually provides the Bay Area with a supply of moist cool air moving in from the northwest. This is particularly typical of summer conditions. The interaction of this air with the local topography is the principal determinant of the climate of any particular region around the Bay.

B. Winds

The coastal mountains are a very effective barrier that generally prevent the winds from entering the Santa Clara Valley directly from the Pacific. Most of the air reaching San Jose has come through one

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*For other discussions of Bay Area climate, the author recommends those of Gilliam, 1966, or Miller, 1967.

of the several gaps in the mountains, for example the Golden Gate, the San Bruno Gap, or the Crystal Springs Gap. Once in the Bay or its geographical extension, the Santa Clara Valley, the winds tend to be constrained to move in a direction parallel to the axis of the valleys and by far the most common direction is down the Bay from the northwest. A typical flow pattern for the region is shown in Figure 2 (adapted from Smalley, 1957).

C. Temperature

On most days during the warmer half of the year, the coastal waters are cooler than those of the Bay so that the air is warmed as it moves in from the coast through the gaps and down the Bay toward San Jose. Figure 3 (adapted from Williams and DeMandel, 1966) shows the average maximum temperatures for the month of July. The influence of the Bay is quite obvious in this figure. It can be seen that the air warms much less rapidly during its passage over the Bay than it does over the warmer land surfaces. For instance, between the Oakland Bay Bridge and the southeastern end of the Bay (a distance of about 35 miles) the average maximum temperature changes from about 63° to about 75° F. This is an average temperature increase of about 0.34°F per mile. In the next 18 miles the average rises from 75 to 90°F, or 0.83°F per mile. Finally, as we reach Morgan Hill the air has been heated to the point where it is nearly in equilibrium with the underlying surface so the average temperatures do not rise much more as we proceed further to the southeast.

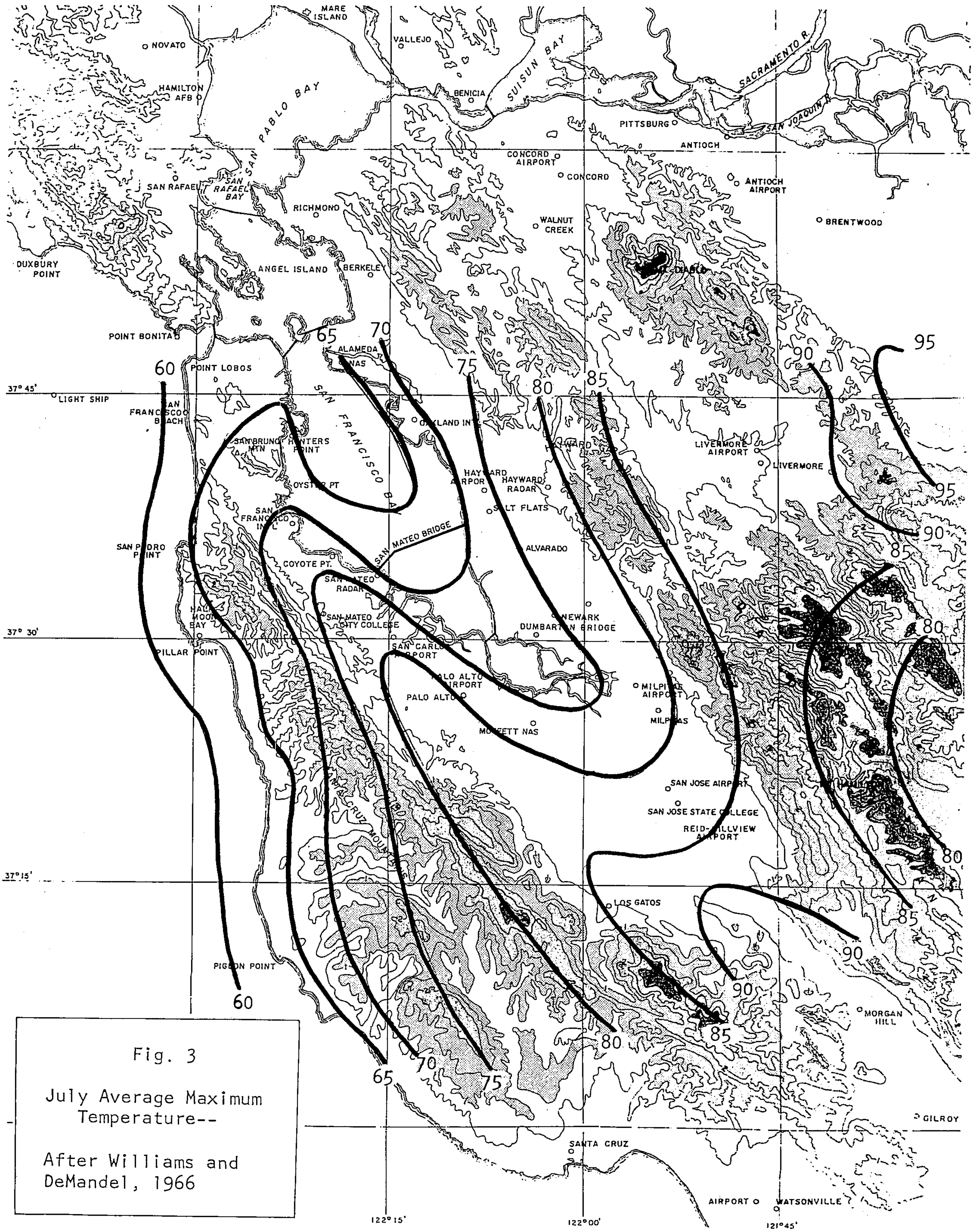

Fig. 3

July Average Maximum Temperature--

After Williams and DeMandel, 1966

During periods when the land, Bay, and coastal water temperatures are all much the same, then the effects of the Bay are not nearly so pronounced as those shown in Figure 3. For example, in January the average maximum temperature at the climatological stations within the area covered by the map vary only from 55° to 58° F (U. S. Weather Bureau). Mount Hamilton, with an average January maximum of 46°F, is the only station in the map area reporting an average temperature outside that range.

The average July minimum temperatures shown in Figure 4 (based on Williams and DeMandel, 1966) do not indicate the very pronounced Bay effects that the maximum temperatures do. The Bay apparently has some slight warming effect, with slightly higher temperatures at the eastern edge of the Bay than at the western. Another interesting feature of the analysis is the apparent warming caused by the San Jose urban area. The center of town is slightly warmer than 56°F while the immediate surroundings average about 55°F for the July minimum temperature. The warmer nighttime temperatures in a city are often referred to as the "urban heat island," and it is a commonly observed effect of urbanization (for an example, see Ludwig, 1968).

As was noted earlier, the greatest bay effects are found when the temperature differences are greatest between the offshore waters and the inland and bay surfaces. This suggests that bay effects may be most pronounced for extreme temperature situations, such as those occasions when the temperature falls below freezing or rises above 90°F.

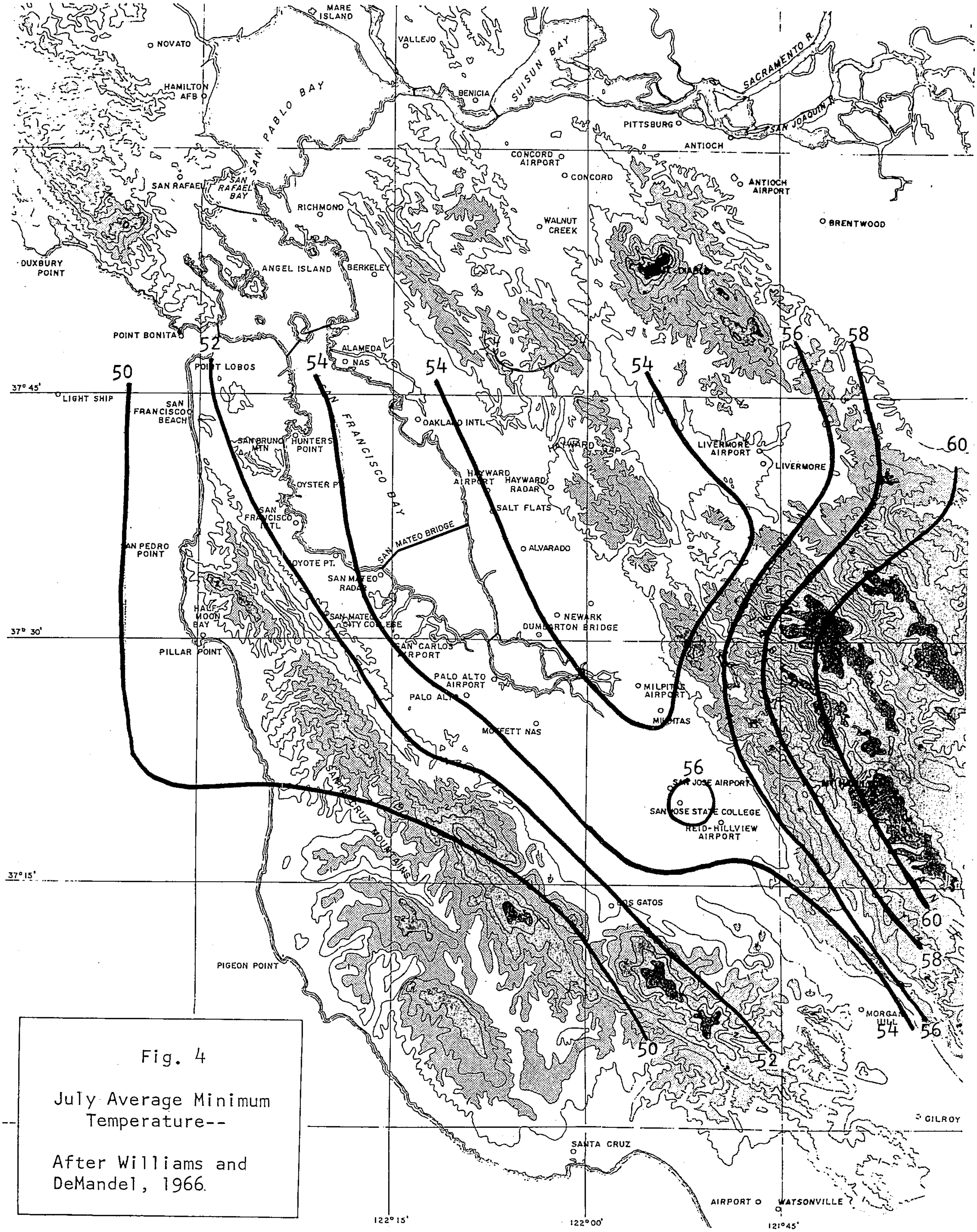

Fig. 4

July Average Minimum Temperature--

After Williams and DeMandel, 1966.

Figures 5 and 6 show the average number of days during a year when such temperatures occur. These figures (based on data from the U.S. Weather Bureau, 1964) do show the expected strong bay effects. There is a pronounced and rapid increase in the number of occasions on which the temperature exceeds 90°F as we go inland from the edges of the Bay. The number of times that the temperature falls below freezing seems influenced less by the Bay than by elevation differences, with the frequencies rising in the hills surrounding the Bay. There appears to be a slight bay effect though, with the frequency of freezing temperatures beginning to increase at the southern tip of the Bay but then falling again, reflecting the San Jose urban heat island.

D. Fog and Clouds

This discussion will be confined to fog and stratus because these are the only types of cloud that seem likely to be affected by the changes in the bay fill. Stratus are those extensive, low, flat layers of cloud common to this area during the summer and fall. Figure 7 shows the percentage of the time that such clouds were observed at mid-morning during the summer of 1952 (based on Patton, 1956). The figure shows that on about one-third of the occasions the stratus covered virtually the entire South Bay. The reference for this figure also shows that the stratus covered the Bay about 60 percent of the predawn hours and about 10 percent of the afternoon hours. At all times the stratus was more prevalent over the Bay than over its littorals. This probably reflects two causes. The first is the topography and channeling; it

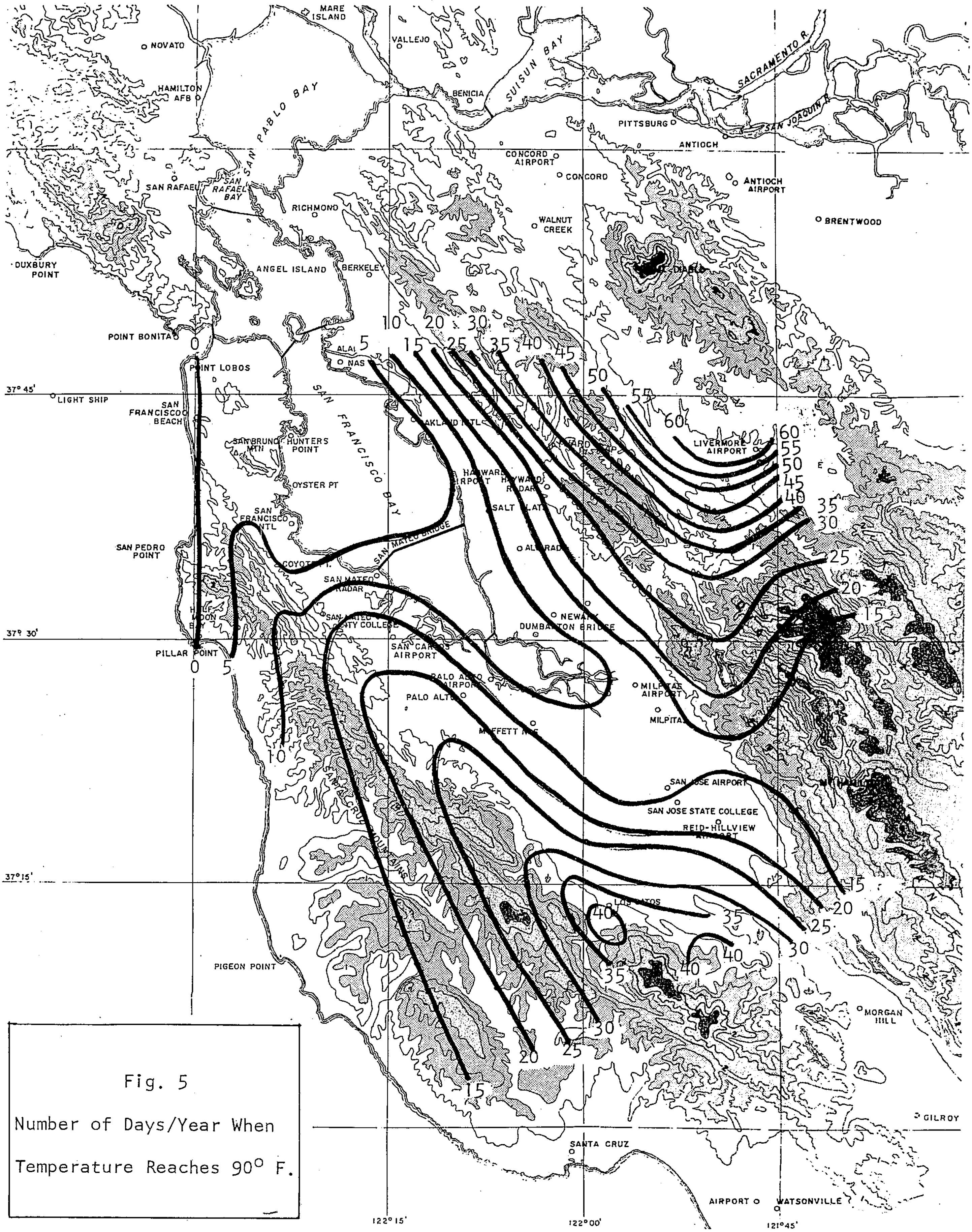

Fig. 5

Number of Days/Year When Temperature Reaches 90° F.

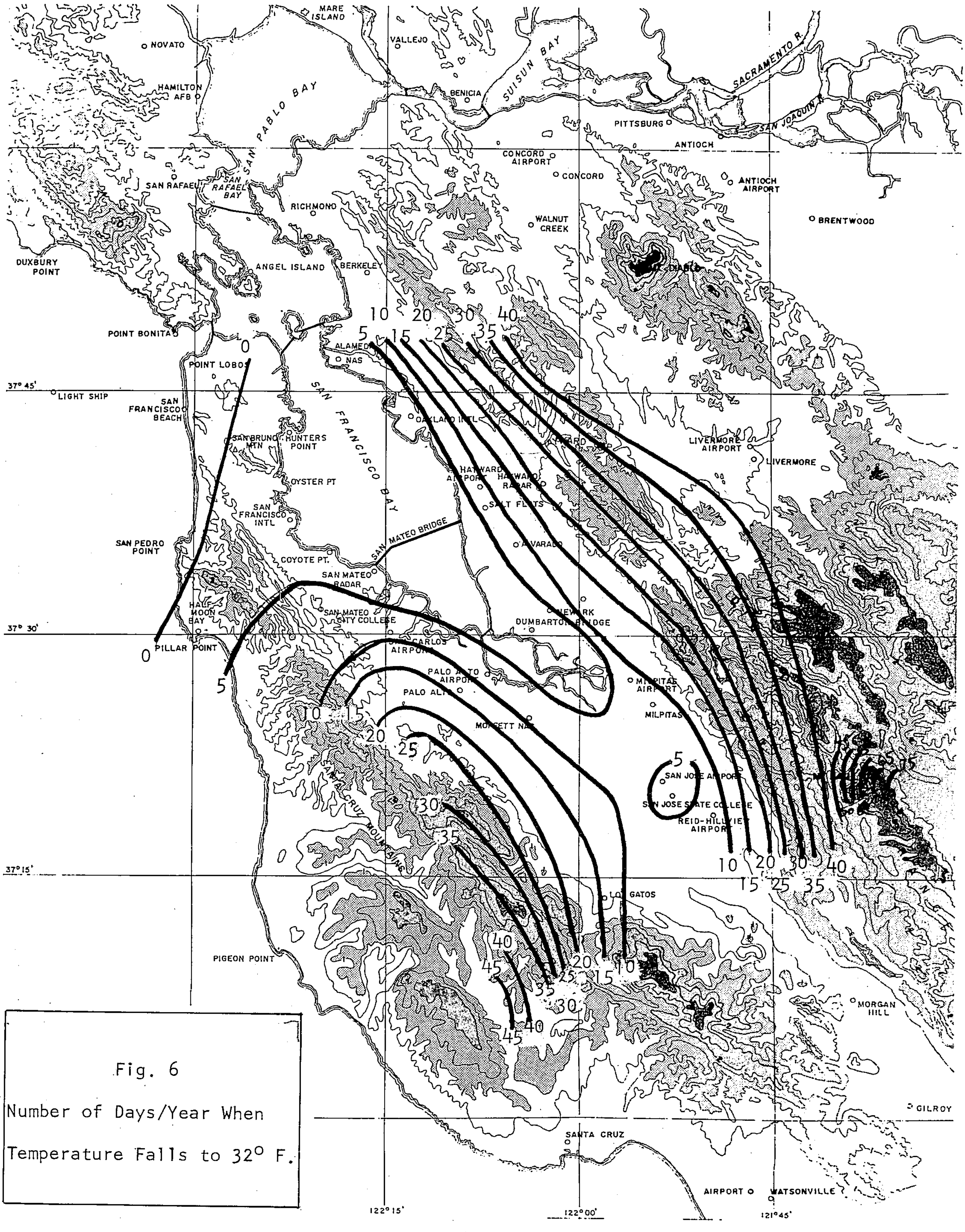

Fig. 6

Number of Days/Year When Temperature Falls to 32° F.

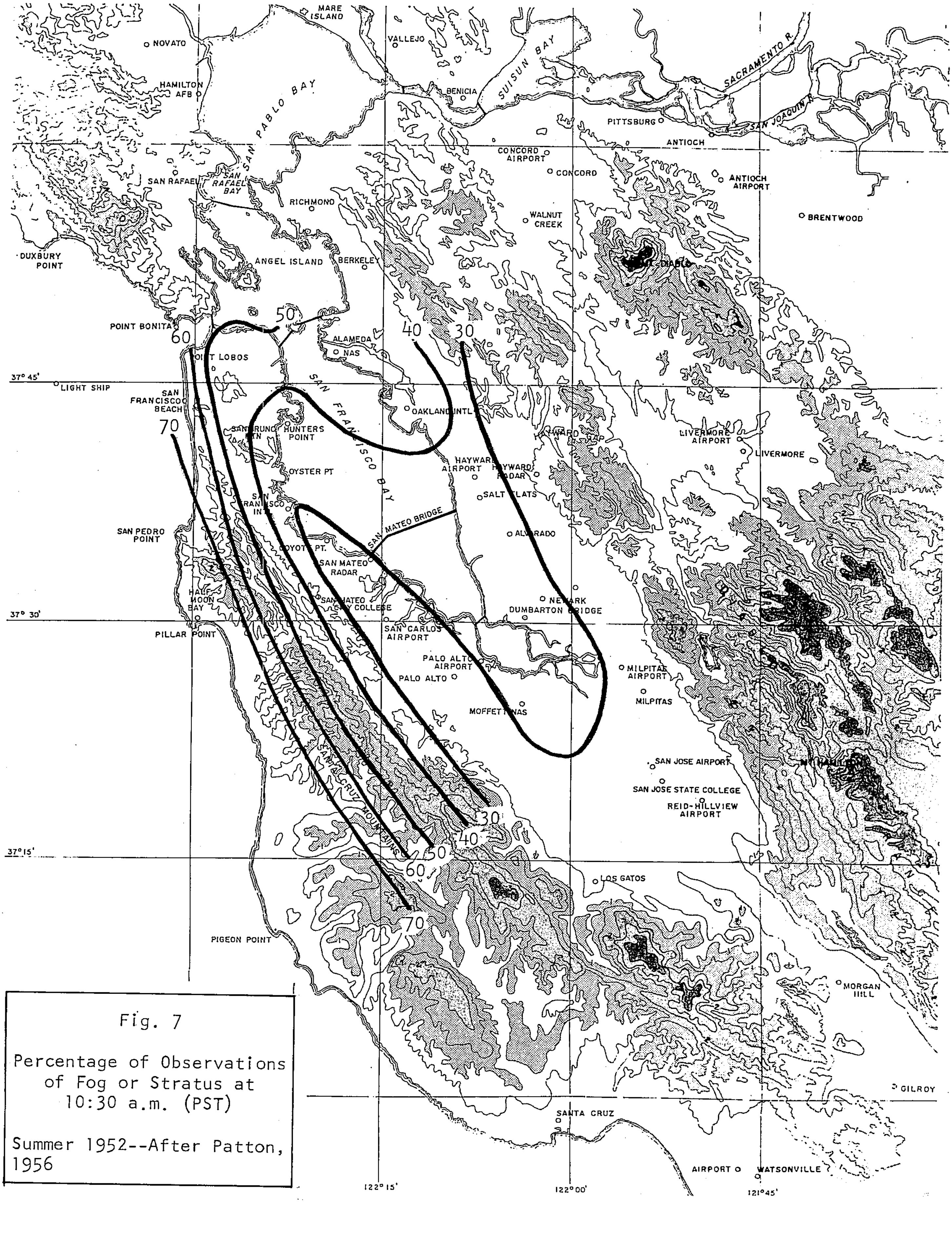

Fig. 7

Percentage of Observations of Fog or Stratus at 10:30 a.m. (PST)

Summer 1952--After Patton, 1956

is easier for the fog to penetrate the gaps in the coastal mountains and spread over the Bay than to move directly inland from its spawning ground over the cold coastal waters. The other reason for the prevalence of the stratus may be that the Bay waters, which are cooler than the land surfaces, allow the clouds to persist.

The stratus provides an example of the interaction of two meteorological elements. Although the cooler Bay may allow the longer duration of stratus, that longer duration restricts the solar heating of the underlying surface. Thus the two effects tend to reinforce each other.

E. Precipitation

Figure 8 (based on U.S. Weather Bureau data) shows the average annual distribution of precipitation in the South Bay area. The previously discussed mountain effects are quite visible. Most Bay area rain occurs during southwest winds. As these winds are forced to rise over the Santa Cruz mountains, the air is cooled and the large rainfalls occur just upwind of the crest. As the air descends into the Santa Clara Valley, the amount of rainfall quickly decreases. The mountains on the northeast side of the Valley produce a second rainfall maximum, but not so large a one as in the coastal mountains, because much of the moisture has already been removed before the air reaches this second mountain range.

F. Air Pollution

As was noted earlier, the concentrations of air pollutants in an area depend primarily on the source strengths, the wind speeds, and the depth through which the pollutants are mixed. In the Bay area, the

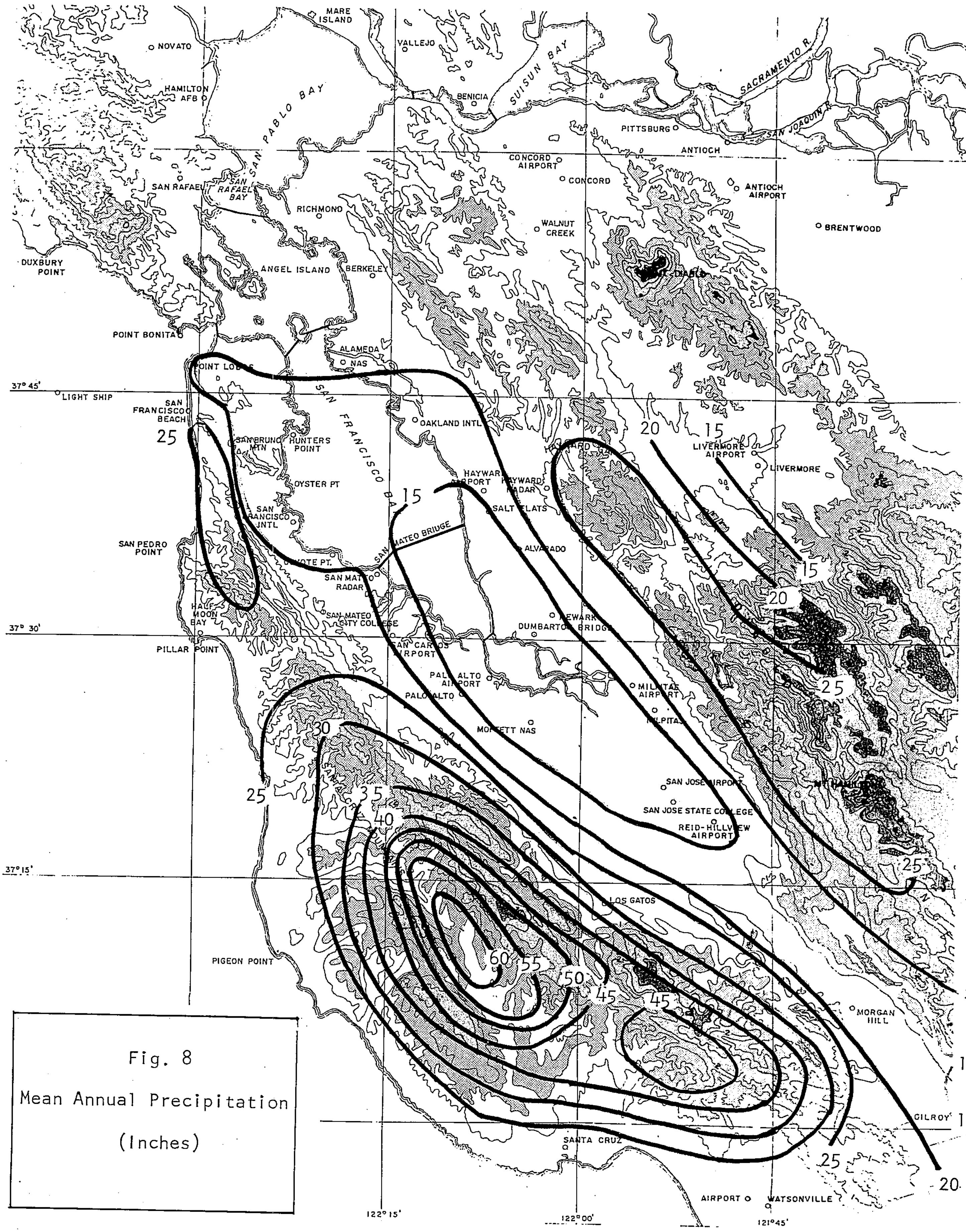

Fig. 8
Mean Annual Precipitation
(Inches)

maximum depth through which the pollutants can be mixed is generally determined by the height of the inversion. During the high smog months of the summer and fall this height averages about 1500 feet (Neiburger, et al., 1961). The average wind speed at the San Francisco airport during these months is 10 mph (Environmental Science Services Administration, 1968).

Table 2 illustrates the number or occurrences of various degrees of air pollution in the South Bay district (based on data from San Jose and Redwood City). In general, the South Bay has more days with heavy pollution than other parts of the Bay Area, so additional pollution in that district would be particularly undesirable.

IV POSSIBLE EFFECTS OF BAY FILL

A. General

The potential effects of Bay fill are likely to be the resultant of two factors. The first of these is the changing of the nature of the surface from one that is smooth and has a high capacity for absorbing heat without concomitant large temperature rises to one that is rough and heats rapidly. The second factor is really an extension of the first in that it is anticipated that the filling of the Bay would be followed by an urbanization that would extend the roughness and further change the surface heating. Urbanization also adds sources of air pollution that would not otherwise be there.

B. Wind

The best estimate that we can make of the effects that Bay filling would have on the winds in Santa Clara County is based on Landsberg's (1962) table presented earlier. It is reasonable to take the larger end of his range of effects because the current unfilled Bay represents a particularly smooth area uncluttered by obstructions to the wind. Thus, we would expect wind speeds to be about 30 percent lower in the area after filling than they are now. In other parts of the county the effects would be much less. For example, the winds in the San Jose metropolitan area might be slightly weaker than they are now, but no appreciable change is anticipated for areas farther to the southeast or in the northwest part of the county.

Since the wind directions in the area are dominated by the orientation of the mountains and the valleys, the filling of the marshlands and evaporation ponds at the south end of the bay is unlikely to affect them appreciably.

C. Temperatures

The following discussion is based on two premises: (1) that the areas that are proposed for filling, i.e., the marshes and the evaporation ponds, behave very nearly the same as the Bay,and (2) that the rates at which the air is heated as it travels over the Bay and over the northwest part of the Santa Clara Valley can be deduced from existing climatological data (such as those presented in Figure 3) or from other studies of the area (e.g., Ludwig, 1967).

As was mentioned earlier, the average July maximum temperature increases at a rate of about 0.3°F per mile as we proceed southeast along the axis of the Bay, and then the rate increases to about 0.8°F per mile over the northwestern end of the Santa Clara Valley. Farther to the southeast the rate of increase drops to nearly zero. In this area of reasonably constant average maximum temperature, i.e., southeast of Coyote, the air appears to have been already fully affected by its passage over the land surface, so it seems unlikely that bay fill effects will be very important. The rest of the discussion will be confined to that part of the county likely to be affected: the northwest end of Santa Clara Valley around San Jose.

If all the marsh and evaporation ponds at the south end of the Bay in Santa Clara County are filled, there would be approximately three more miles of land surface (with possible urbanization) over which the air would travel. If the air temperature increases by about $0.3^{\circ}F$ per mile over the Bay, but $0.8^{\circ}F$ per mile over land, filling would lead to a rise of about $1.5^{\circ}F$ in the average maximum temperatures during the warmest month in most of the San Jose metropolitan area. Since the effects appear to be more pronounced under the more extreme conditions, we may expect the temperature increases caused by the filling to be greater than normal for those days when it is hottest.

The effects of bay fill on the warm season minimum temperatures are likely to be less than those predicted for the maximum temperatures. In fact, almost no effect is expected if the filled area is not urbanized. If the filled area becomes urbanized, then the heat island effect will be dominant and probably will result in a rise of a degree or two on the average in the newly filled area and of less in the already urbanized area.

The effects of bay fill on winter minimum temperatures will probably be similar to the effects on summer temperatures. The effects on winter maximum temperatures will probably be less than those expected for the warmer seasons. The exception would be those somewhat unusual warm or hot days that sometimes occur; then the situation would be similar to the warmer summer days.

If the area to be filled is made into parkland, heavily covered with lawn, trees, or other vegetation, then I would expect the effects on summer maximum temperatures to be much less. This is based on observations (Ludwig, 1967; Ludwig and Kealoha, 1968) that show parks and wooded areas in New Orleans, Albuquerque, and Dallas to be considerably cooler during the summer days than their more urban surroundings.

D. Fog and Clouds

I would expect that filling the marshes and ponds of the South Bay would cause only a very slight change in the amount of clouds. If the clouds dissipate primarily because of the heating of the air by the underlying surface, then we would expect the occurrence of stratus at the south end of the Bay to decrease slightly. If the dissipation is principally the result of other causes, then we cannot be certain what the effects would be. It is very unlikely that the bay fill would have any effect on clouds common to this area other than stratus or ground fog.

In the Santa Clara Valley, fogs caused by the cooling of the air near land surfaces during winter nights are more common than cases where the fog is advected from the ocean (Miller, 1967). Filling of the marshes and ponds would probably increase the latter type of fog somewhat because the solid surface of the fill would cool faster than the Bay. However, if the fill is urbanized, then the heat island effect would moderate this cooling somewhat. On the other hand, the additional air pollution caused by the urbanization would stimulate condensation and promote fog formation. The net effect of urbanized fill would probably be a slight increase in the frequency of occurrence of winter fogs.

E. Precipitation

The effects of the proposed bay fill on precipitation are not likely to be measurable. This does not mean, of course, that great amounts of bay fill would not affect this weather element, nor does it mean that the fill would not affect the runoff of the precipitation that falls. However, that is another, very large problem that will be covered in one of the other reports in this series.

F. Air Pollution

The two meteorological factors affecting air pollution, wind speed and mixing depth, would both be affected by the proposed bay fill but in counteracting directions. The wind speed would decrease and the mixing depth would increase because of the higher than normal surface temperatures during the smog season. Thus, the net effect of the fill would probably be slight if no new pollution sources are added. But it seems unlikely that the fill will not have some sources of pollution, and the increase of pollution in the downwind areas will be proportional to the strength of the sources allowed on the filled land.

V DISCUSSION

In the preceding section estimates were given for the likely effects of the proposed bay fill on the various climatic elements. In this concluding section, I have included an example to illustrate a consequence of one of the changes. The example focuses only on the economic consequences, but the effects on human comfort should not be forgotten. The hottest days will be even a few degrees hotter for a large fraction of residents of the San Jose area and there may also be a few more hot days. There are likely to be a few more nighttime winter fogs and a little less summer stratus. In total, it appears that no individual will have to suffer an enormous change in climate, but a large number of people will be subjected to a small change.

The warm season maximum temperature change has been selected to provide an estimate of the economics of the climatic change because it is the most amenable to this kind of analysis. The costs resulting from the temperature change would take two forms, equipment costs and operating costs.

Heating and air conditioning equipment is chosen so that it will have the capability to provide comfortable indoor temperatures during the extreme outdoor conditions that might be expected. Generally, local climatological information is consulted and the equipment purchased is adequate for some selected high percentage of the conditions historically encountered. Thus, if the temperature in an area is found to be below

85°F during 95 percent of the time in the summer--as it is in San Jose (Fluor, 1964)--then air conditioning equipment suitable for cooling the building when temperatures are less than 85°F will generally be considered adequate. To choose a larger system would be unnecessarily expensive; to choose a smaller system would leave the building occupants uncomfortable too often. If the average outdoor temperature is raised a few degrees during extreme periods, then equipment costs will increase. The installation costs for the air conditioning in a 100,000 square-foot building in the San Jose area is about $500,000.* Every added degree of temperature will increase that installation cost by about 2 percent, or $10,000. Thus, the bay fill effects represent additional costs for air conditioning equipment for a new 100,000-square-foot building of perhaps $10,000 to $30,000. The costs to alter already existing equipment to meet the changed climate will probably be substantially greater.

After the equipment is installed, the owner faces the operating costs. The qualitative nature of the relationship between the operating of cooling equipment and outdoor temperature is quite obvious. The warmer it is, the greater the power required to cool the buildings adequately. For a 100,000-square-foot building in the San Jose area, the approximate air conditioning costs are $0.02 per square foot per month, or about $2,000 per month. The effects of temperature change in operating costs have been estimated as about 2 percent per degree Fahrenheit,*

*Mrs. Eleanor Young, Santa Clara County Planning Department, personal communication, 1970.

or, for our hypothetical air-conditioned building, about $60,00 per month. This is not very much, but when we consider the fact that there is a very large amount of air-conditioned office and industrial space in the San Jose area, the number becomes more impressive.

The above discussion indicates that, although the climatic effects of the proposed bay fill may amount to only a few degrees change of temperature, the resulting change in building and operating costs may be substantial when the entire affected area is considered. These costs should be borne in mind and balanced against the other potential costs and benefits. Another factor should also be considered. Santa Clara County is only one of the counties around the Bay. Although the Santa Clara County Bay fill proposals are reasonably modest and are likely to result in relatively small changes to the climate, they might well be only one of many Bay fill plans. If the other Bay counties all fill their shallow Bay lands, the result may very well give San Jose a climate in the future that is like Gilroy's climate now--except smoggier.

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