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NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION
National Weather Service

Relationship of Wind Velocity and Stability to SO_2 Concentrations at Salt Lake City, Utah

WERNER J. HECK

Western Region

SALT LAKE CITY,
UTAH

January 1971

WESTERN REGION TECHNICAL MEMORANDA

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A western Indian symbol for rain. It also symbolizes man's dependence on weather and environment in the West.

U. S. DEPARTMENT OF COMMERCE
NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION
NATIONAL WEATHER SERVICE

NOAA Technical Memorandum NWSTM WR-61

RELATIONSHIP OF WIND VELOCITY AND STABILITY TO SO_2 CONCENTRATIONS AT SALT LAKE CITY, UTAH

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Scientific Services Division
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WESTERN REGION
TECHNICAL MEMORANDUM NO. 61

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1. INTRODUCTION

Atmospheric pollution is becoming an increasingly critical problem to human health and welfare. Salt Lake City, like most other major U. S. cities, has long had an air pollution problem. Although the public is probably more concerned about air pollution now than in earlier years, Salt Lake City's air pollutants have decreased over the past thirty years [1]. This drop-off has largely been the result of conversion from coal to gas for heating and the use of diesel rather than steam locomotives on the railroads. Despite this marked drop-off, sulfur dioxide (SO_2) is still among pollutants that are of major concern in Salt Lake City. One of the largest emitters of SO_2 is the copper smelter located fifteen miles west of the city (Figure 1). Other continuous sources of SO_2 are oil refineries five miles to the north, steel refineries 30 miles to the south, and motor vehicles in the metropolitan area itself. Among the strong intermittent sources of SO_2 are the burning of tires, oil, and scrap automobiles in various dumps around the city.

Salt Lake City is located in a valley bounded by the Oquirrh Mountains on the west and the Wasatch Range on the east. During late fall and winter, stagnant high-pressure systems develop over the Great Basin, resulting in stable air masses with low wind speeds.

Under these stagnant conditions, a southeast drainage wind prevails at Salt Lake City from about 1900 MST until 1100 MST the following morning [2]. During the afternoon, northwesterly winds prevail. This constantly reversing pattern tends to trap air pollutants in the valley and build up SO_2 concentrations. It is the purpose of this paper to:

1) Study the relationship between wind velocities and SO_2 concentrations during late fall and winter, and

2) Study a high-pollution episode for the relationship between day-to-day SO_2 concentrations and mixing depth.

II. DATA

Meteorological conditions favoring the build-up of pollutants occur most frequently during late fall or winter, when the atmosphere is frequently stable and inversions are most prevalent and persistent. For this reason the colder half of the year (October - March) was studied. SO_2 concentrations for downtown Salt Lake City were obtained from the Utah State Division of Health. Their data were obtained from an SO_2 sampler presently located on the roof of a two-story building at 6th South and 4th East. The SO_2 sampler has been in this location since April 1967, prior to which time it was located on the roof of a one-story building at 2nd East and 6th South, two blocks from the present location. A thirty-foot smokestack was located 50 feet east of the sampler at its previous location. Although the stack emitted smoke from once-daily paper burnings, it is unknown what effect these emissions had on SO_2 concentrations near the sampler. The SO_2 sampler, accurate to .01 ppm SO_2, recorded hourly concentrations of SO_2, but this was refined to half-hourly concentrations in October 1969. These half-hourly values were converted to hourly values by summing, dividing by two, and rounding off to the nearest hundredth. Although hourly wind velocities were also recorded at the sampler location, it was decided to use hourly winds from the local Weather Service Forecast Office (WSFO) four miles west-northwest of the sampler site, because the WSFO wind records were much more complete, and also less subject to inner city turbulence. Winds at the WSFO were considered representative of the general flow in the Salt Lake Valley.

Five years of data consisting of six-month winter periods were studied beginning in October 1964 and ending March 1970. SO_2 data for the period October 1966 - March 1967 were not available since the SO_2 sampler became inoperative and was later moved to its present location. Despite the exclusion of the 1966 - 1967 year, gaps in SO_2 data ranging from days to months were still frequent. SO_2 data were unavailable 29% of the time for the overall five-year period.

Temperature inversion data required for the high-pollution episode were obtained from raobs taken at the WSFO.

III. PROCEDURE

SO_2 data were classified by hourly intervals from 0000 to 2300 MST for monthly periods. The following values were tabulated for each hour: (a) frequency of SO_2 concentrations $\geqslant$ .01 ppm, (b) sum of SO_2 concentrations $\geqslant$ .01 ppm, (c) frequency of zero SO_2, and (d) frequency of no record (NR). An average SO_2 concentration for hours having concentrations $\geqslant$ .01 ppm was determined by dividing (b) by (a). An overall average SO_2 concentration was obtained by dividing (b) by [(a) + (c)]. Hourly averages were computed for each of the six months studied for the entire five-year period. Daily averages of hourly SO_2 concentrations for a one-week period were also computed. Averages for adjacent months with similar hourly SO_2 concentrations were combined. As a result, the months of October and November, December and January, and February and March were paired (Figures 2, 3, 4). The same procedure was followed for a four-year period excluding the 1967-1968 year, and also for the 1967-1968 year alone, when the copper smelter was shut down (Figure 5).

Hourly wind speeds and directions were obtained only for hours with SO_2 data available. A wind rose was then computed for the hours 0000, 0400, 0800, 1100, 1200, 1300, 1400, 1700, 1800, 1900 MST for each of the three two-month periods (Figures 6, 7, and 8). Hourly wind roses were computed for the overall five-year period.

Mixing depths for the high-pollution episode were found by using plots of Salt Lake City soundings on a pseudo-adiabatic chart. Both morning and afternoon soundings were used. In each case the dry adiabat was followed up from the observed maximum temperature until it intersected the pressure-temperature curve. The height of the intersection above ground was considered the mixing depth. The average daily mixing depth was found by adding the morning and afternoon mixing depths and dividing by two.

IV. DISCUSSION

Figure 6 shows October-November wind roses for various hours between 0000 MST and 1900 MST. During morning hours (0000-0800 MST) the south-to-southeast drainage wind prevailed 65% of the time. By 1100 MST the frequency of south and southeast winds decreases to 40% and the frequency of the north and northwest winds increases from 10% at 0800 MST to 35% at 1100 MST. North-to-northwest winds increase until they reach a maximum frequency of 60% at 1400 MST. Also at this time, the south-to-southeast wind falls to a frequency of about 20%. These south-southeast winds result from the synoptic situation and are not part of the diurnal wind regime. At times the diurnal wind regime is masked by winds resulting from transitory synoptic features. Between 1700 MST and 1900 MST, the north-northwest component decreases and the westerly component increases, indicative of the transition from up-valley (north to northwest) to down-valley wind (south to southeast), which begins to occur at this time of day. By 2300 MST the south-to-southeast drainage wind prevails again.

Figure 7 shows wind roses for December - January. The diurnal wind regime for these months is still prominent, but not as pronounced as in October - November. Calm winds are also more prevalent throughout the day, indicative of weak pressure gradients associated with stagnant highs and inversions. During late morning, the frequency of the southeast drainage winds decreases, and the frequency of north-to-northwest winds increases. The north-to-northwest wind reaches its maximum frequency at 1400 MST; but unlike October - November, the south-to-southeast component is still quite prominent. This, along with the fairly prominent north-northwest component during the morning hours, is an indication of pre- and post-frontal winds which dominate the circulation at various times during these two months. By 1700 MST, the westerly component has increased slightly, and by 1800 MST the southeast component also has increased. At 1900 MST south-to-southeast winds again dominate the circulation.

Figure 8 shows wind roses for February - March. These wind roses are quite similar to the October - November roses, although small differences do exist. South-to-southeast winds during the morning hours of

February - March, for example, are less frequent than in October - November. Late afternoon north-to-northwest winds for February - March, however, are slightly more frequent and have higher speeds than late afternoon north-northwest winds for October - November. Also maximum frequency for north-northwest winds during February-March occurs at 1700 MST as opposed to 1400 MST for October - November. This is probably due to the more intense solar insolation and longer days in March, which permit stronger development of the up-valley wind.

A comparison of hourly winds for the various months (Figures 6, 7, and 8) and hourly SO_2 concentrations for the same months (Figure 4) yields some very interesting results. October - November SO_2 concentrations increase rapidly from 0800 MST to the peak at 1200 MST. This corresponds to the time when south-southeast winds decrease from their maximum frequency at 0800 MST, while north-northwest winds are increasing in frequency.

The December - January SO_2 curve is almost parallel to the October - November curve, but with much greater concentrations. The December - January increase of SO_2 during the morning hours also corresponds to the transition of south-southeast winds to north-northwest winds. February - March SO_2 concentrations are much lower than in fall and winter, and also show no well-defined peak, but rather a gradual increase to a fairly constant afternoon level. This is due to the greater mixing depths in late winter and spring.

Figure 5 shows average hourly SO_2 concentrations for October 1967 - March 1968, during which period the copper smelter located near the north end of the Oquirrh Mountains was shut down. With the exception of the December - January curve, which had one-third of the data missing, the shape and time of peak concentrations correspond to the five-year average, but with much lower concentrations. These curves indicate that there are other important sources of SO_2 besides the smelter. If we assume the five-year wind roses to be valid for 1967 - 1968, we can again say the onset of the up-valley winds corresponds to increasing SO_2 concentrations.

Although the data strongly indicate increasing SO_2 concentrations during the transition from south-southeast to north-northwest winds, we might wonder why these high concentrations are not sustained throughout the afternoon. Since the major sources of SO_2 lie to the north and west of the city, light south-southeast winds during the night would tend to move these pollutants toward the northwest end of the valley and allow them to accumulate. During the morning hours, as the south-southeast winds begin to slacken with the transition to a north-northwest wind regime, these pollutants gradually approach the city with the maximum concentration occurring during early afternoon. These pollutants are apparently sufficiently diffused throughout the valley during the afternoon so as not to produce another SO_2 maximum with the transition back to the southeast drainage wind. SO_2 concentrations are highest during December - January since strong inversions, which favor the build-up of pollutants, are most frequent during winter. The lack of a well-defined maximum for February - March is due, in part, to relatively strong insolation and strong winds which tend to diffuse pollutants throughout the atmosphere.

One factor not taken into consideration in the study is the half life of SO_2. Estimates on this half life vary from four to twelve hours. This undoubtedly is also a factor in decreasing SO_2 concentrations following the noon peak.

V. CASE STUDY

Synoptic conditions associated with high-pollution episodes typically begin several days after the passage of a cold front through northwestern Utah. The front is followed by a building surface high over the Great Basin, which becomes stationary as the ridge aloft slowly shifts eastward until surface high and upper ridge are nearly vertical. This leads to extremely stable conditions in the Salt Lake Valley. The breakdown of this ridge does not occur until a moderately strong frontal system or upper trough moves into the plateau from the Pacific Ocean. When this occurs, the pressure gradient increases and strong southerly winds may blow for as much as two to three days before passage of the next cold front at Salt Lake City. These strong winds are very effective in clearing the valley of pollutants.

A high-pollution episode (December 17 - 22, 1965) was studied in detail. Table 1 shows the relationship between day-to-day average hourly SO_2 concentrations and average of 0500 MST and 1700 MST mixing depths. On the initial day, December 17, the average mixing depth is high (Figure 9a) resulting in relatively low average hourly SO_2 concentrations. On the second day, December 18, the average mixing depth decreases by 50 meters (Figure 9b and Table 1) and SO_2 concentration increases threefold. The mixing depth decreases 200 meters on the third day, December 19 (Figure 10a), with an eightfold increase in SO_2. The decrease of mixing depth and increase of hourly SO_2 concentration continue until the fifth day, December 21 (Figures 10b and 11a). On the sixth day, December 22 (Figure 11b, Table 1), the mixing depth increases only 50 meters from the previous day's value, but the SO_2 concentration decreases to only one-sixth the previous day's value. The 50-meter increase in mixing depth is obviously not sufficient to explain the sharp decrease of SO_2. Surface winds, which remained relatively light throughout the day (Figure 11b), cannot completely account for the decrease. The sharp decrease most likely resulted from the scavenging effect of precipitation (2.2 inch of snow) which began falling shortly after 0800 MST. Thus precipitation, in addition to strong winds, is considered highly effective in cleansing the atmosphere of pollutants.

VI. CONCLUSIONS

The data strongly indicate rapidly increasing SO_2 concentrations in downtown Salt Lake City during morning hours with the transition from south-southeast drainage winds to north-northwest up-valley winds. Pollutants are apparently sufficiently diffused throughout the afternoon so as not to produce another SO_2 maximum with the transition back to the drainage wind in the early evening. Although the summarized data strongly indicate that the shift to north-northwest up-valley winds is responsible for a rapid increase in hourly SO_2 concentration during the morning hours, there are quite a number of individual cases in which SO_2 concentrations increased rapidly downtown with calm or light southeast winds at the Salt Lake City WSFO. A north-northwest wind at the Salt Lake City WSFO is, therefore, not necessary for a rapid increase of hourly SO_2 concentrations.

The detailed study of a high-pollution episode during December 17 - 22, 1965, indicates a marked increase in SO_2 concentrations under a stagnant high-pressure system with rapidly decreasing mixing depths. The overall study has shown winds to be an important factor in the increase of hourly SO_2 concentrations, while the mixing depth is the more important factor in the increase of average daily SO_2 concentrations. More knowledge could be gained by studying individual air-pollution episodes, taking into consideration more parameters, such as mean wind-speed through mixing depth, relative humidity, precipitation, etc. The greatest contribution to further understanding of pollution concentrations would be a detailed study of wind circulation in the lower levels of the atmosphere during stable conditions in the Salt Lake Valley, along with many more measurements of SO_2 at various locations in the valley.

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2. Hawkes, H. Bowman, "Mountain and Valley Winds with Reference to the Diurnal Mountain Winds of the Great Salt Lake Region", unpublished PhD Thesis, Ohio State University, 1947.

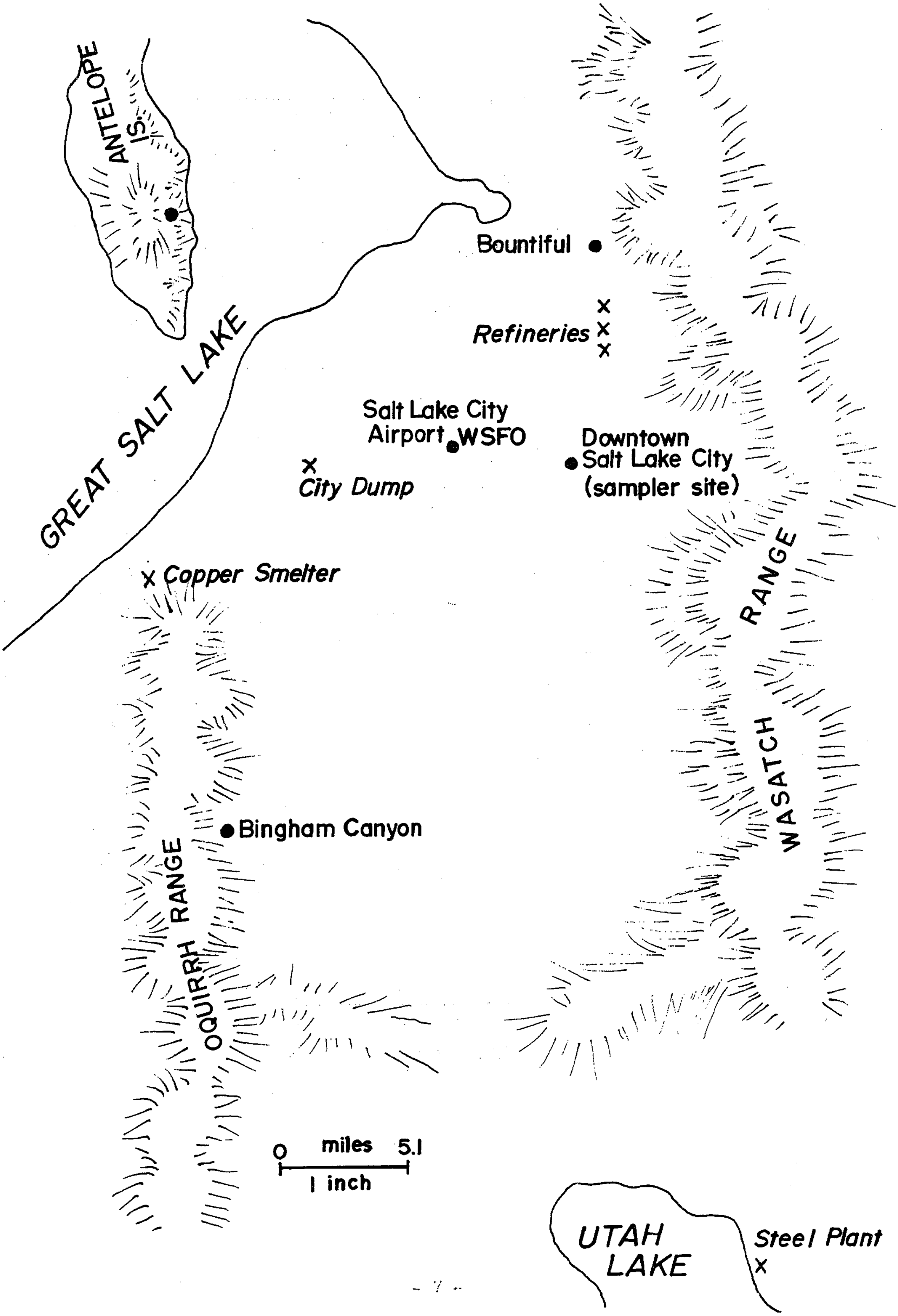

FIGURE 1. Map of Salt Lake City and Vicinity.

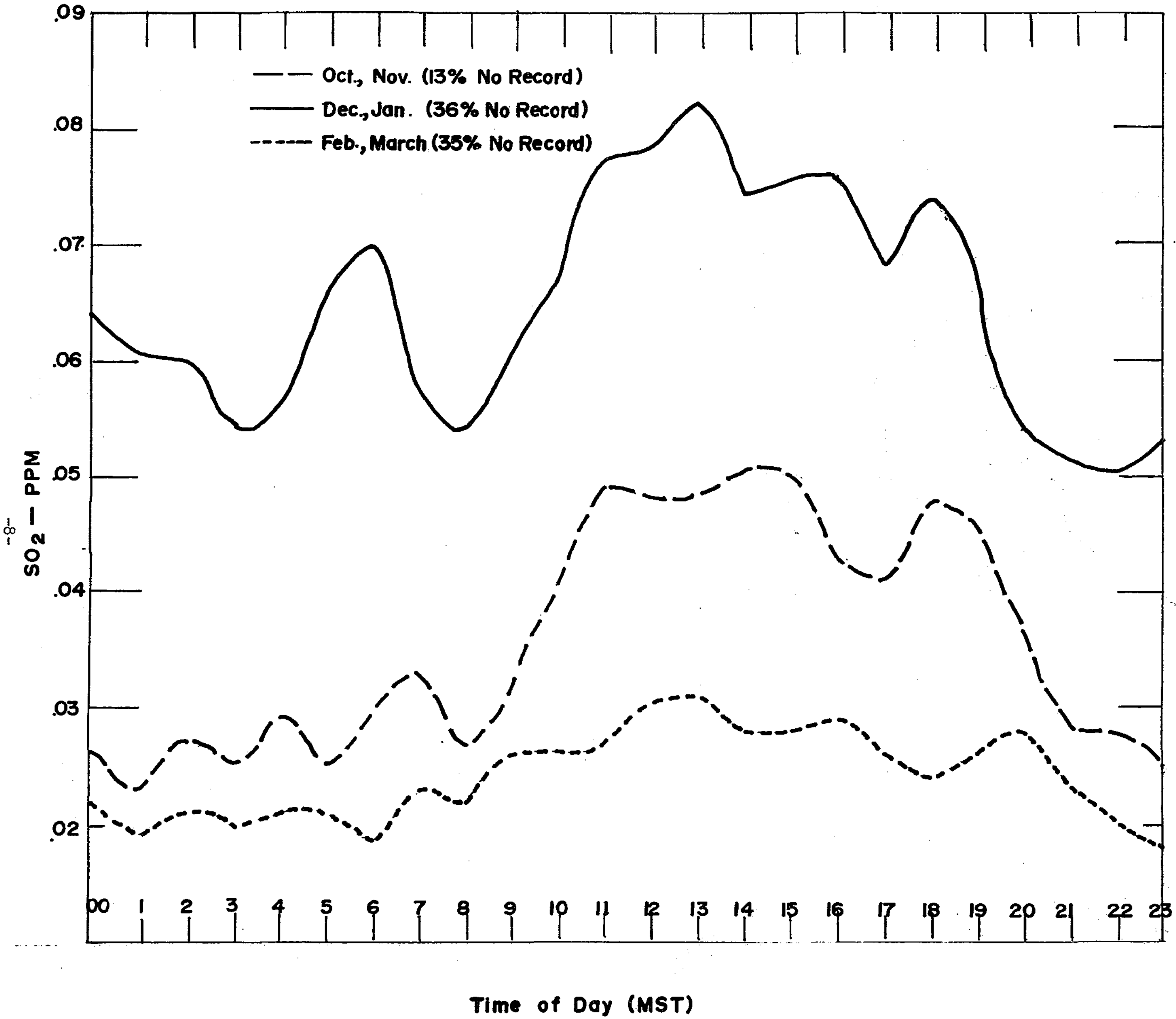

FIGURE 2. Average Hourly SO_2 Concentration at Salt Lake City for Hours with $SO_2 \geq .01$ PPM, October-March 1964-1969 except 1966-1967.

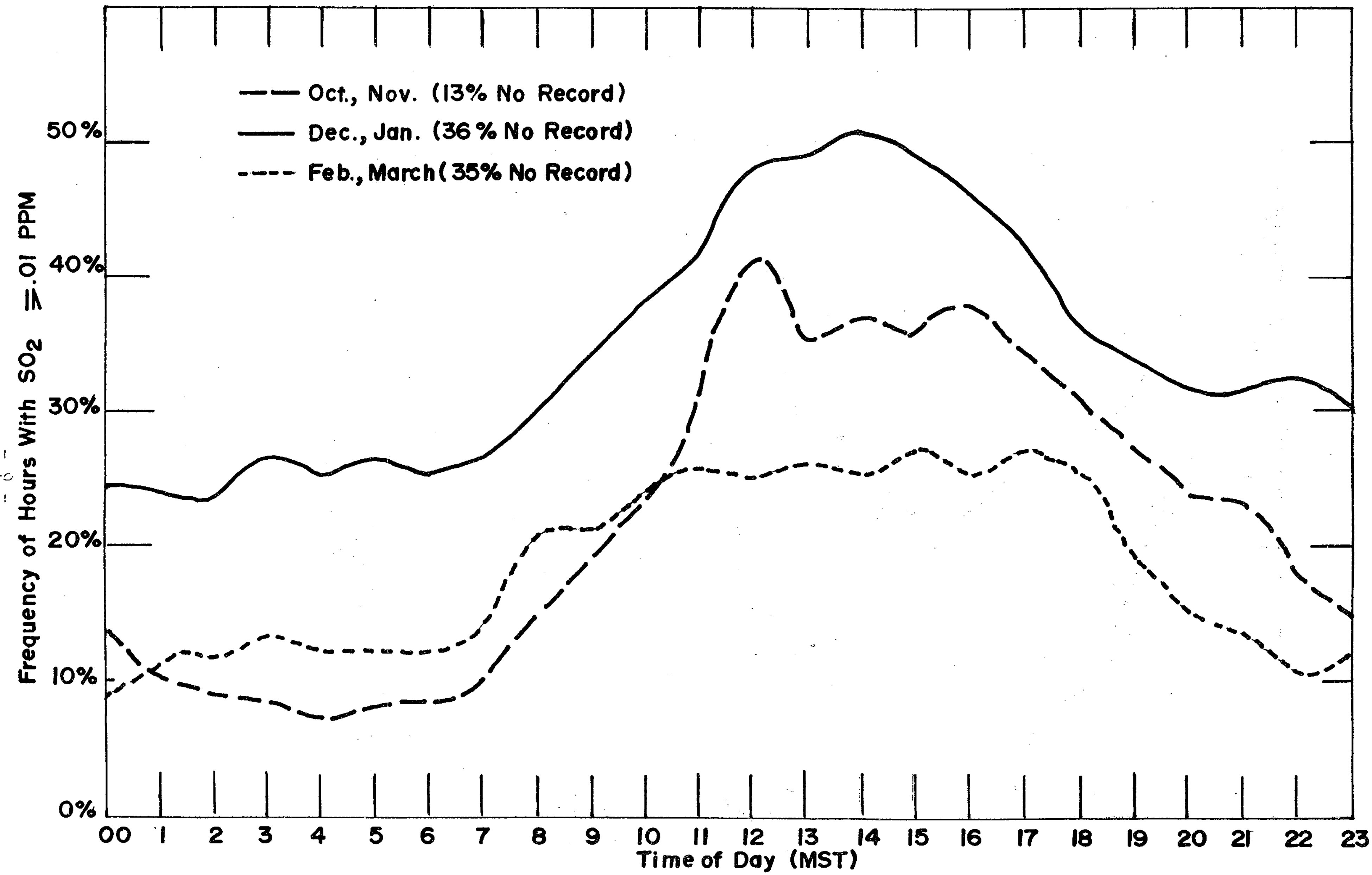

FIGURE 3. Frequency of Hours with SO_2 ≥.01 PPM at Salt Lake City, October-March 1964-1969 except 1966-1967.

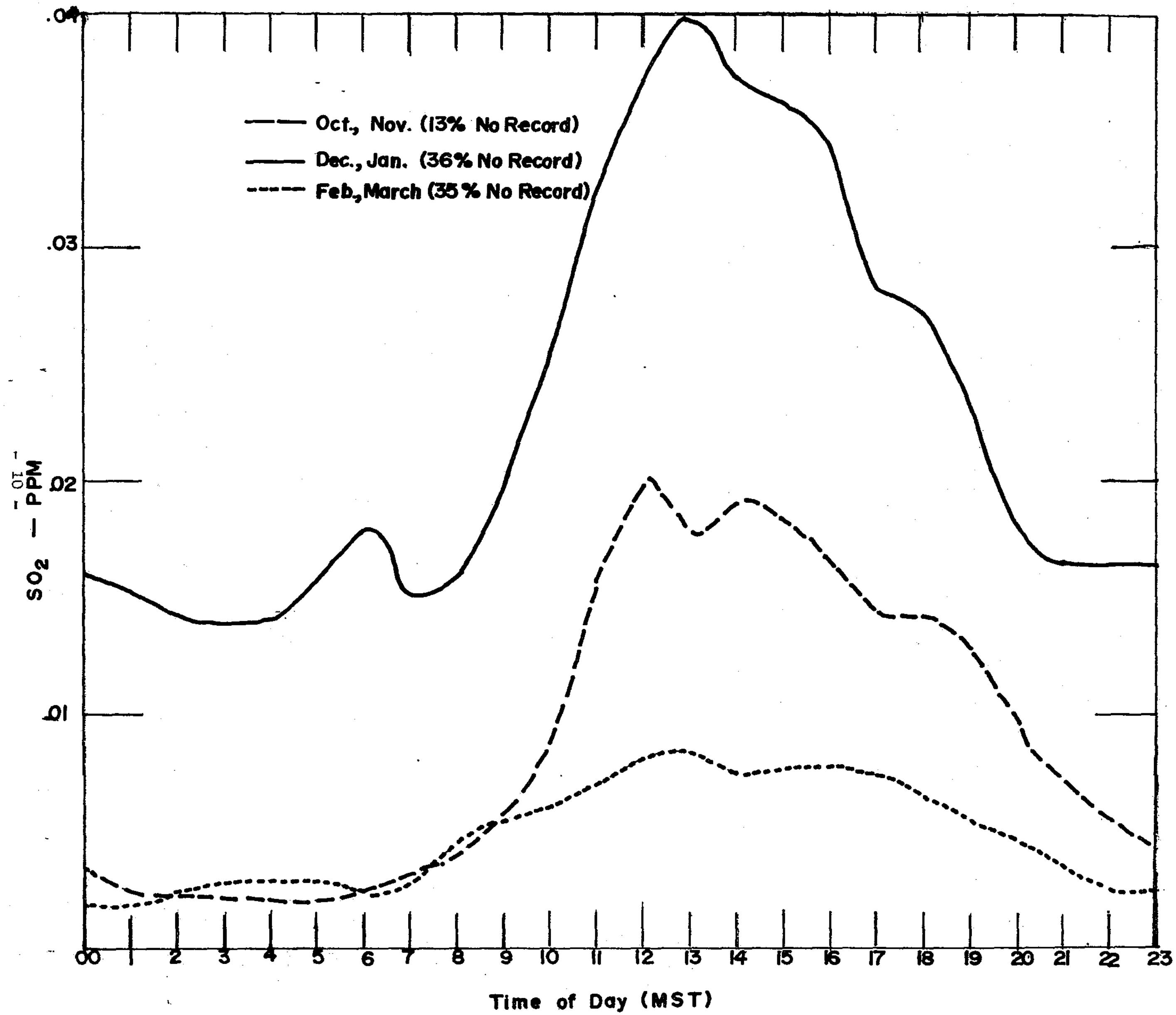

FIGURE 4. Average Hourly SO_2 Concentration at Salt Lake City for All Hours, October-March 1964-1969 except 1966-1967.

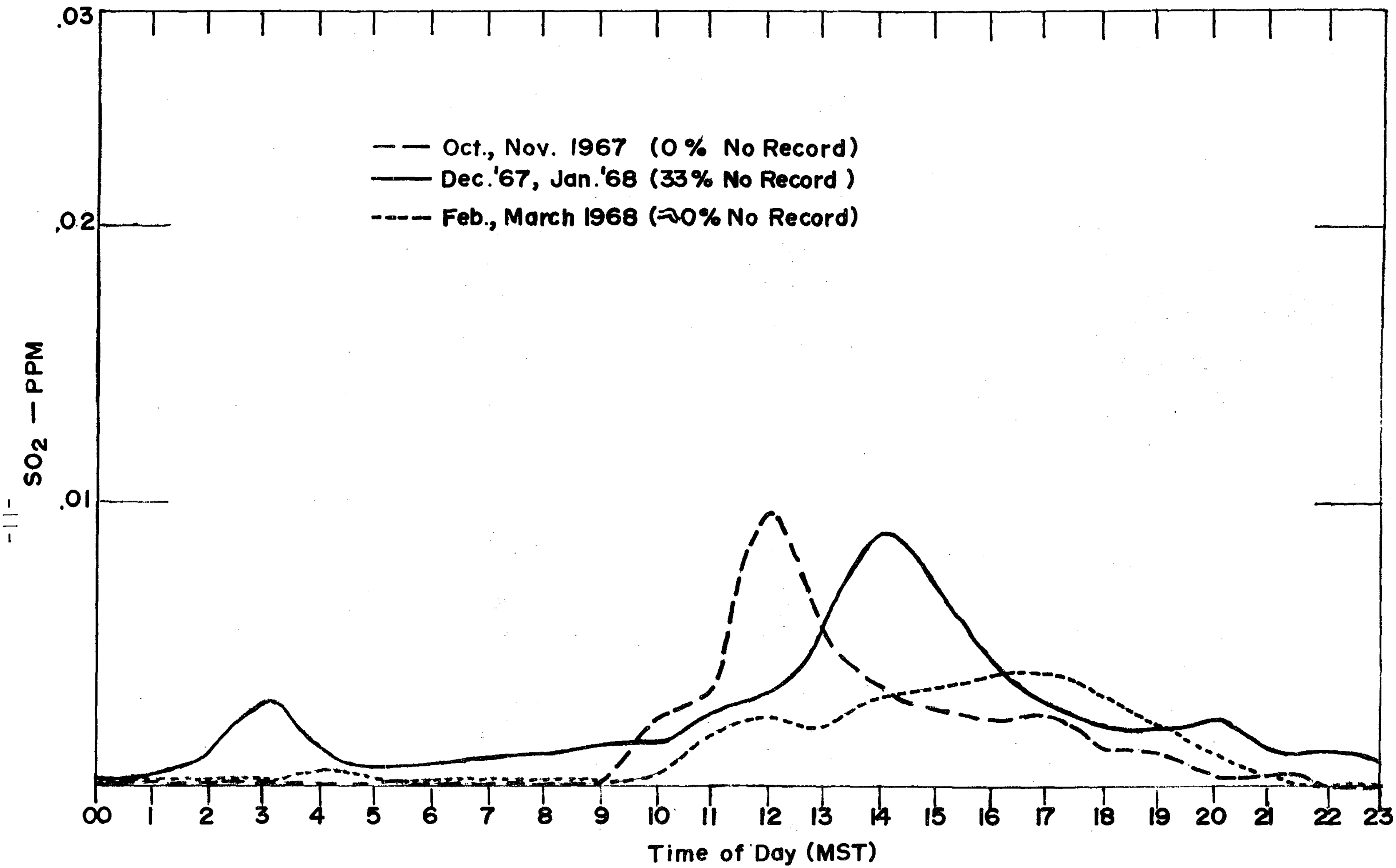

FIGURE 5. Average Hourly SO_2 Concentration at Salt Lake City for All Hours, October 1967 - March 1968.

OCTOBER– NOVEMBER

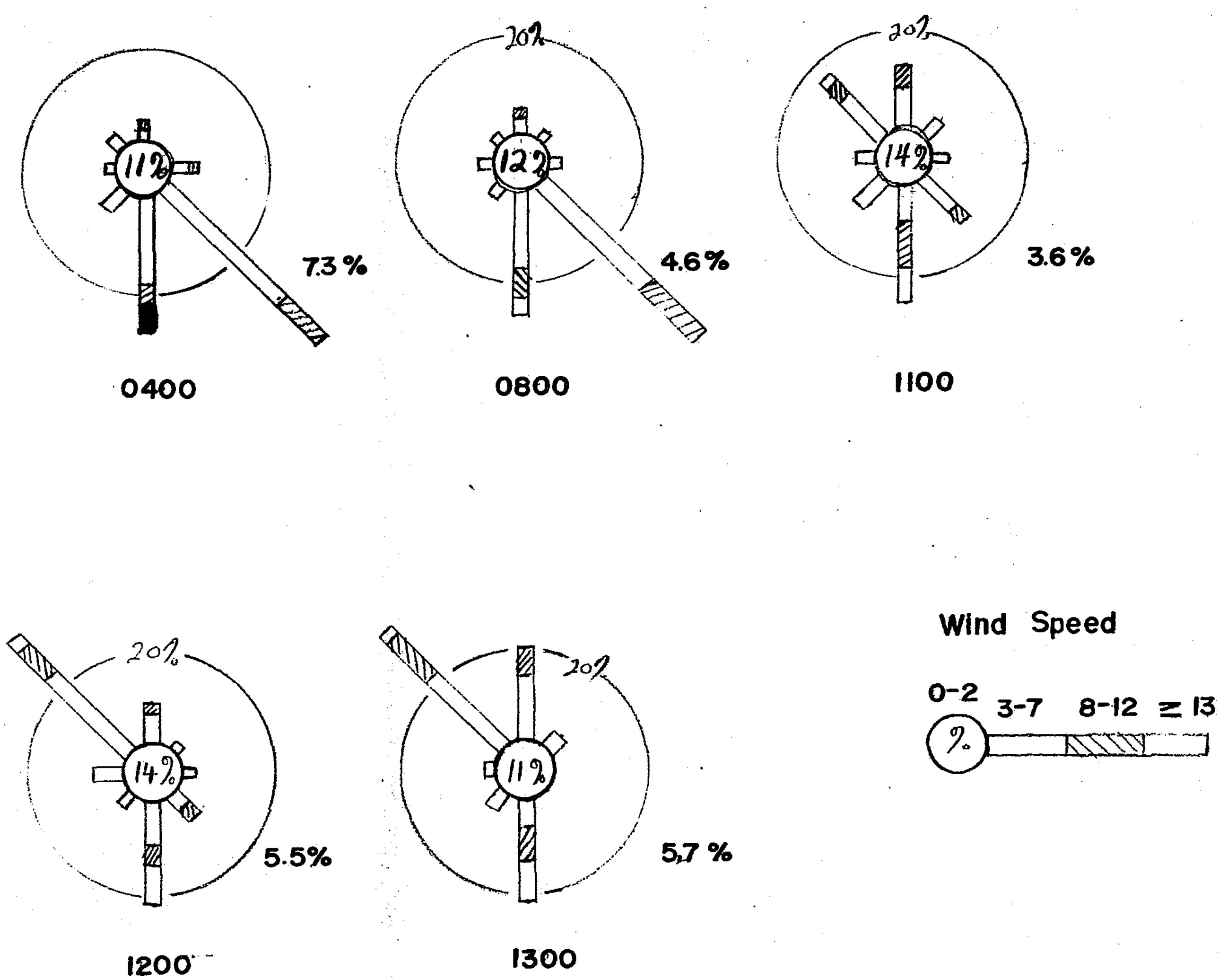

FIGURE 6. October-November (0400-1300 MST) Wind Roses for Salt Lake City 1964-1965, 1967-1969. Directional barbs proportional to wind speed. Percent calms in center of rose. Percentages to lower right of roses refer to winds not shown by directional barbs.

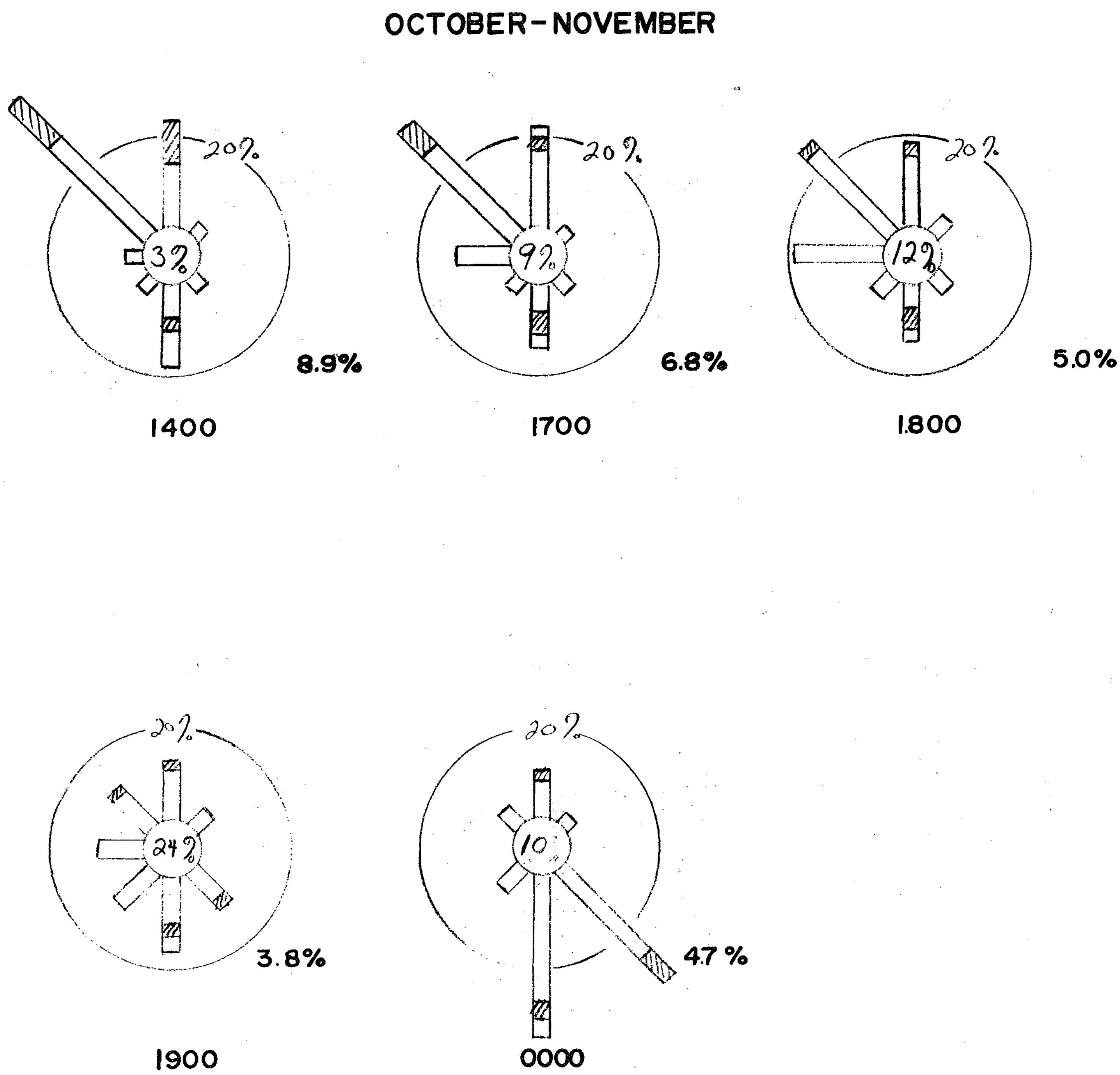

FIGURE 6a. Same as Figure 6, except for 1400 - 0000.

DECEMBER-JANUARY

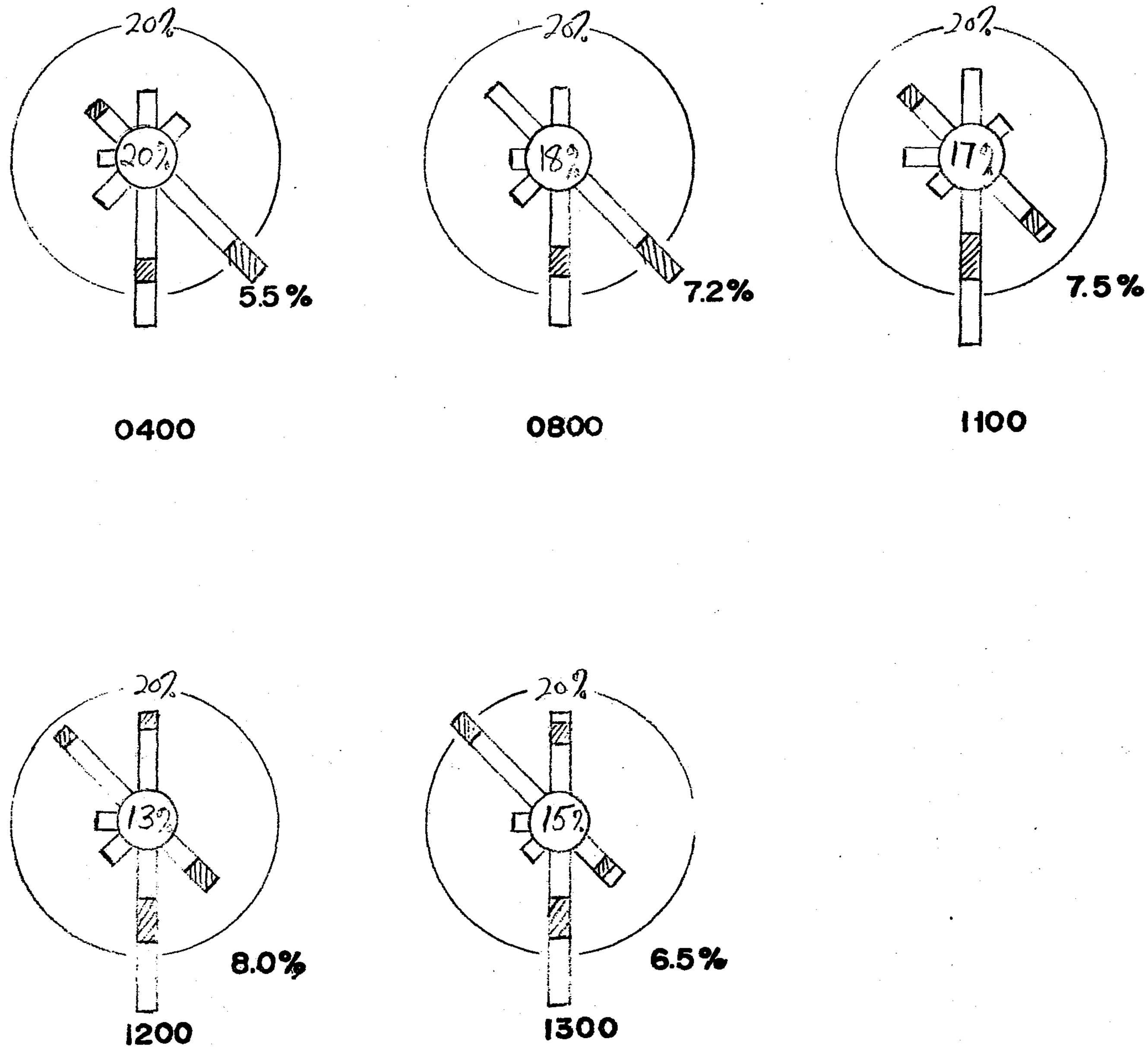

FIGURE 7. Same as Figure 6, except December - January (0400 - 1300).

DECEMBER — JANUARY

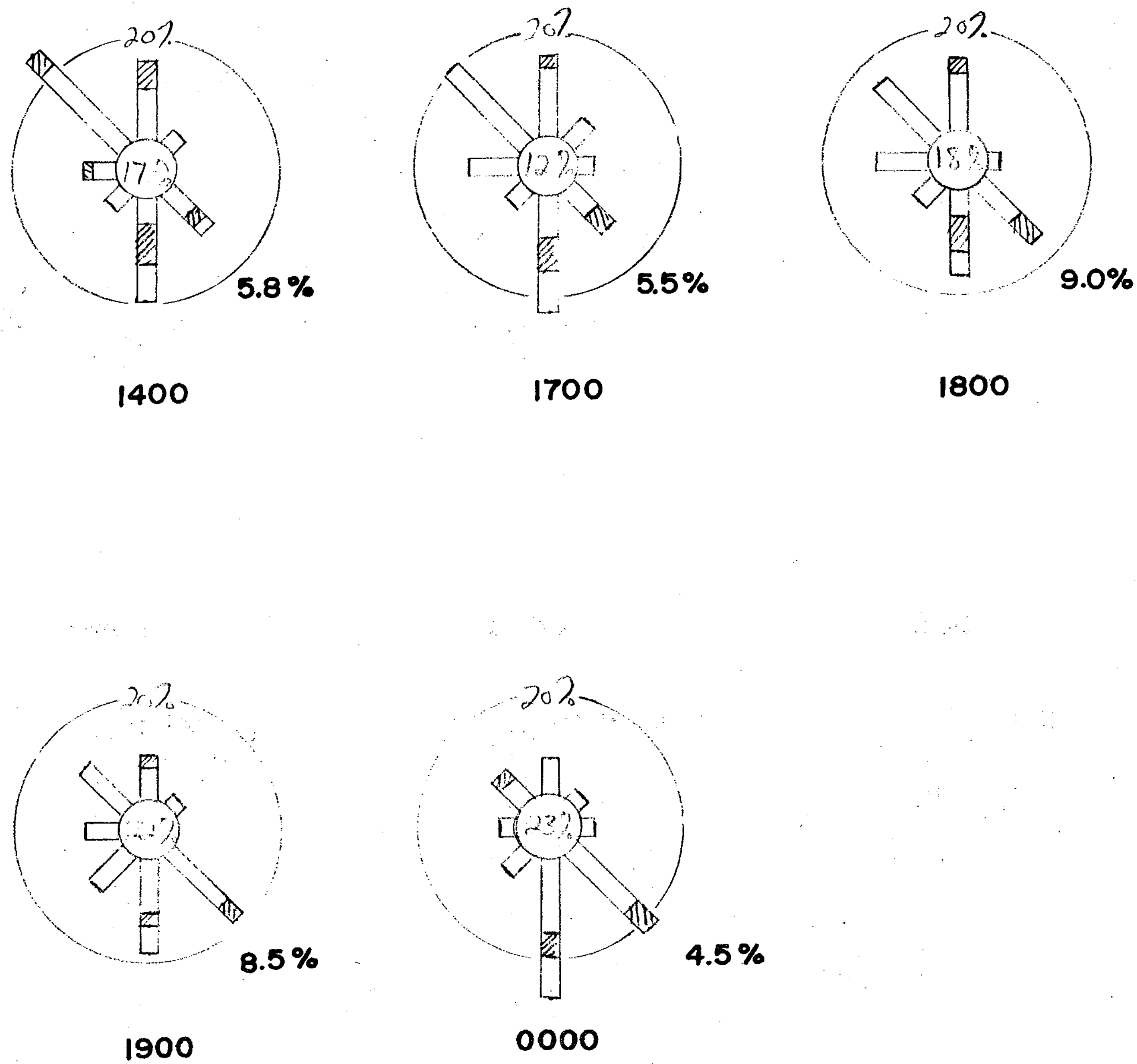

FIGURE 7a. Same as Figure 6, except December - January (1400 - 0000).

FEBRUARY—MARCH

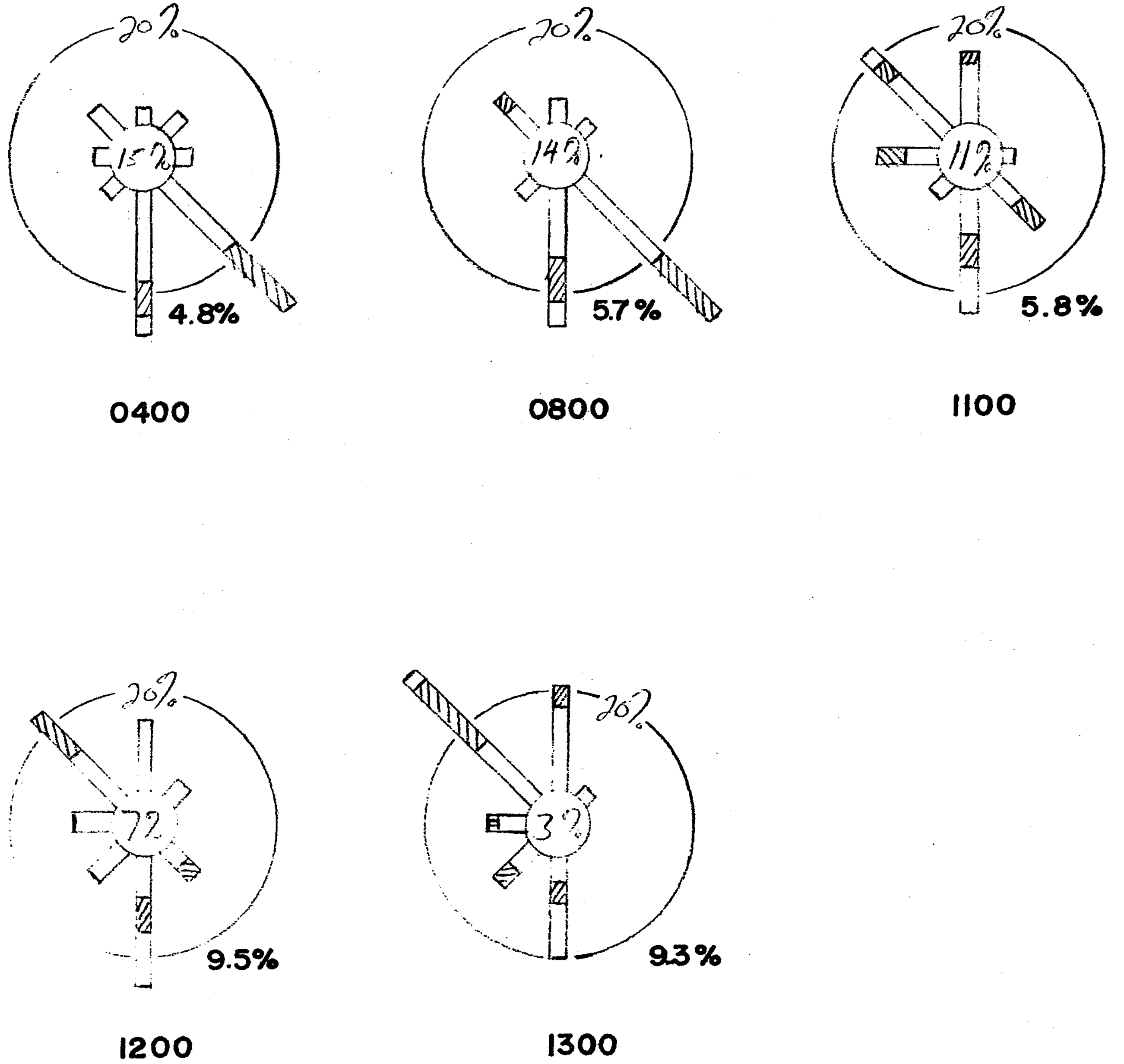

Figure 8. Same as Figure 6, except for February - March (0400 - 1300).

FEBRUARY—MARCH

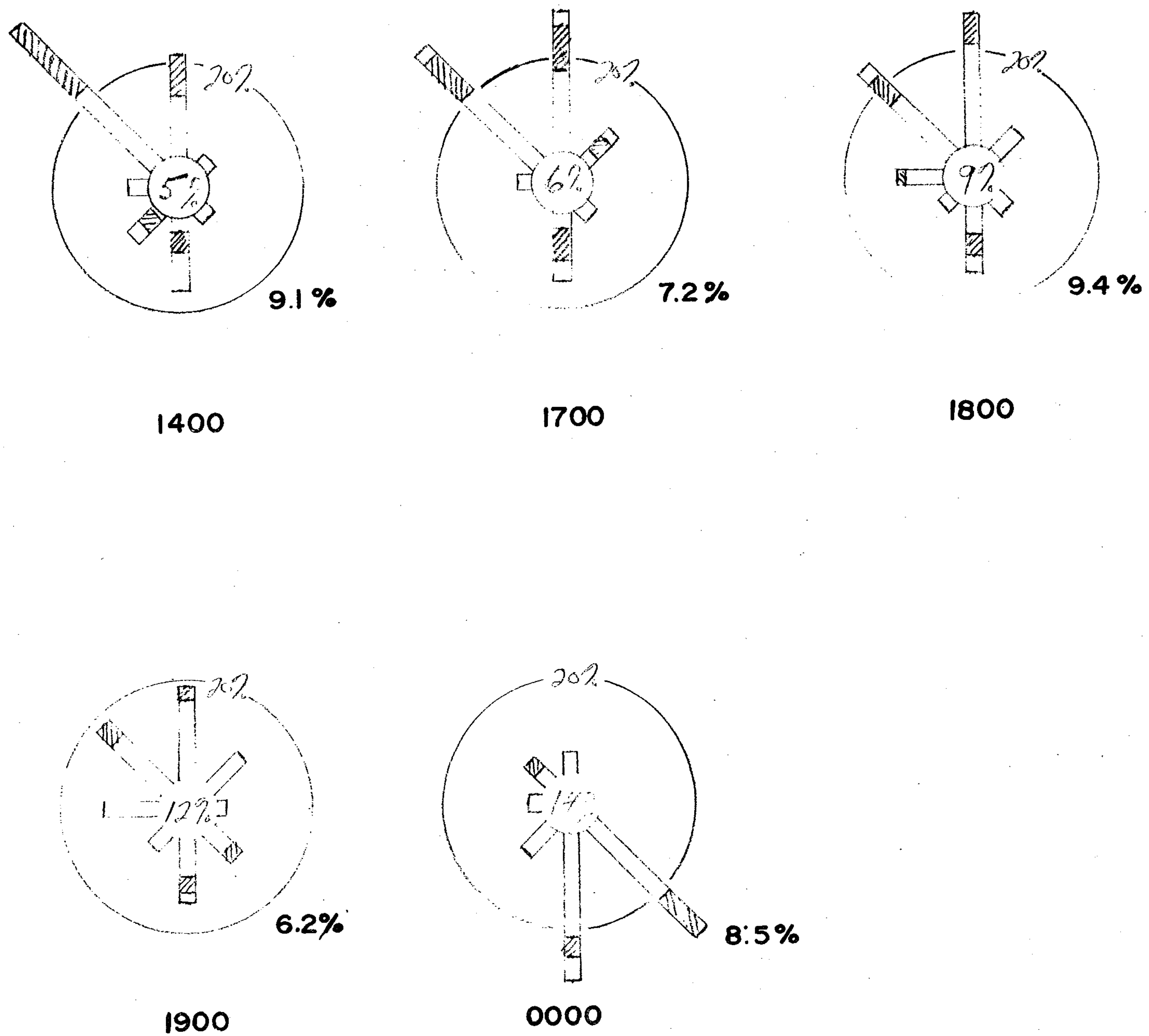

Figure 8a. Same as Figure 6, except for February - March (1400 - 0000).

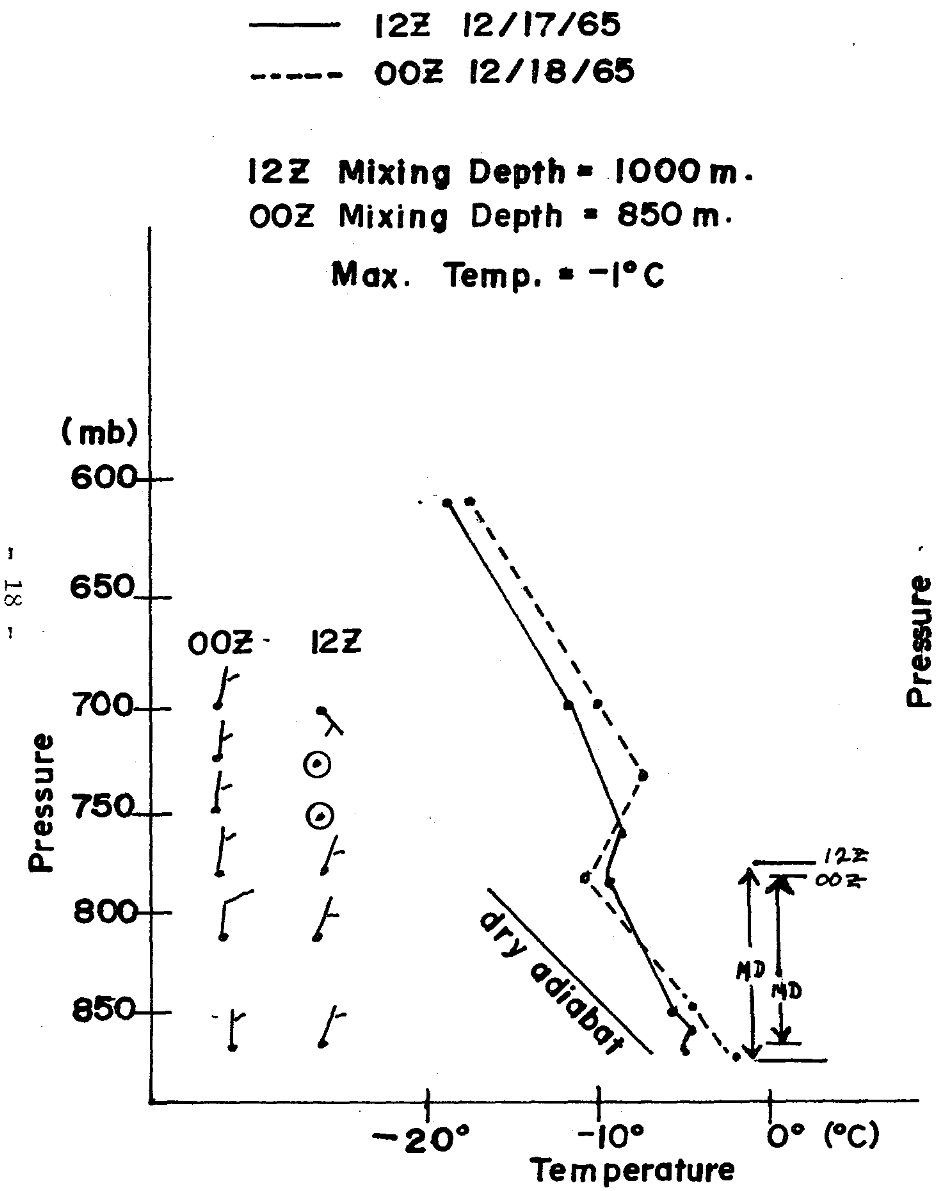

Figure 9a

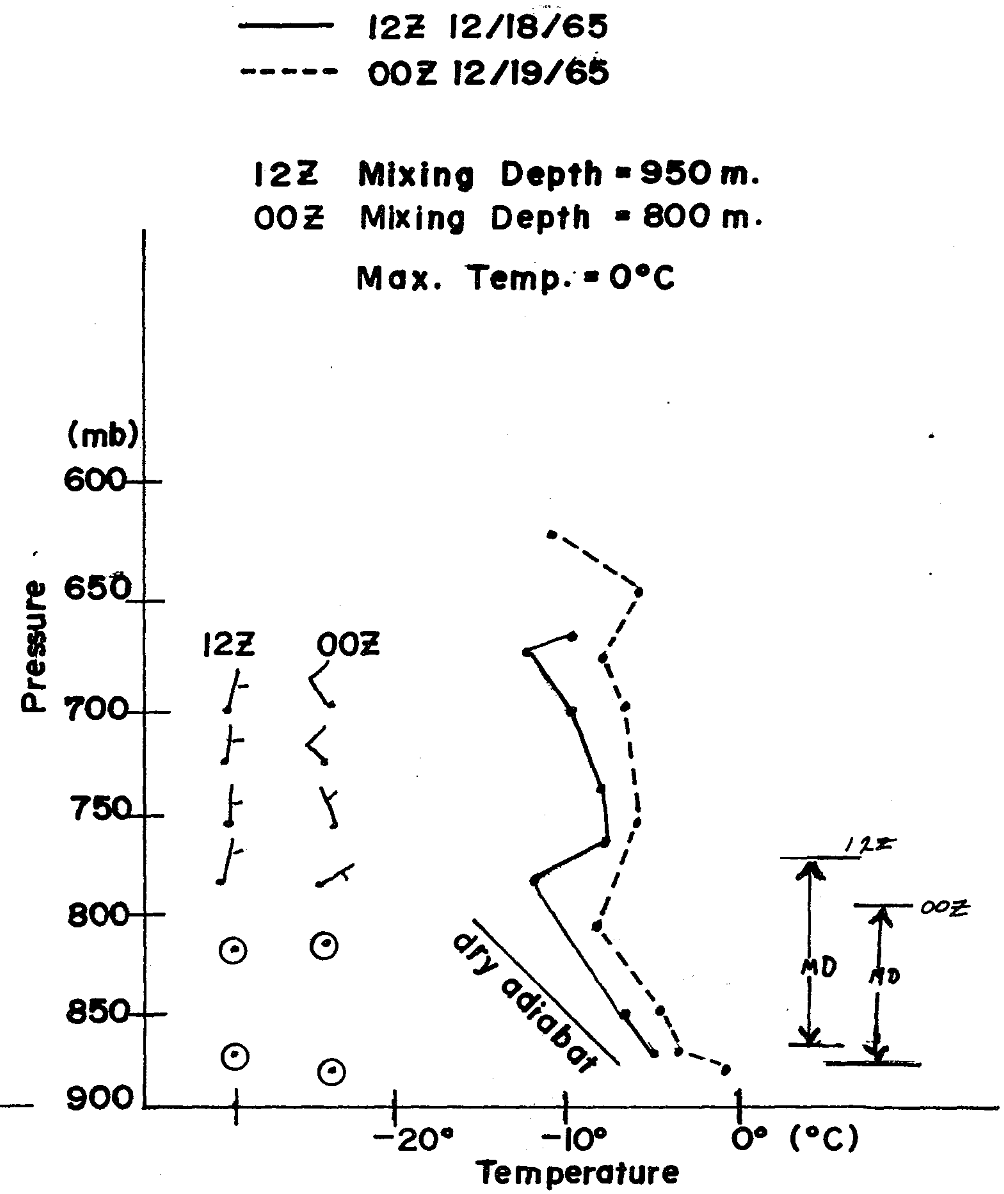

Figure 9b

FIGURE 9. Temperature Soundings, Winds Aloft and Mixing Depths for Salt Lake City, December 17 - 19, 1965.

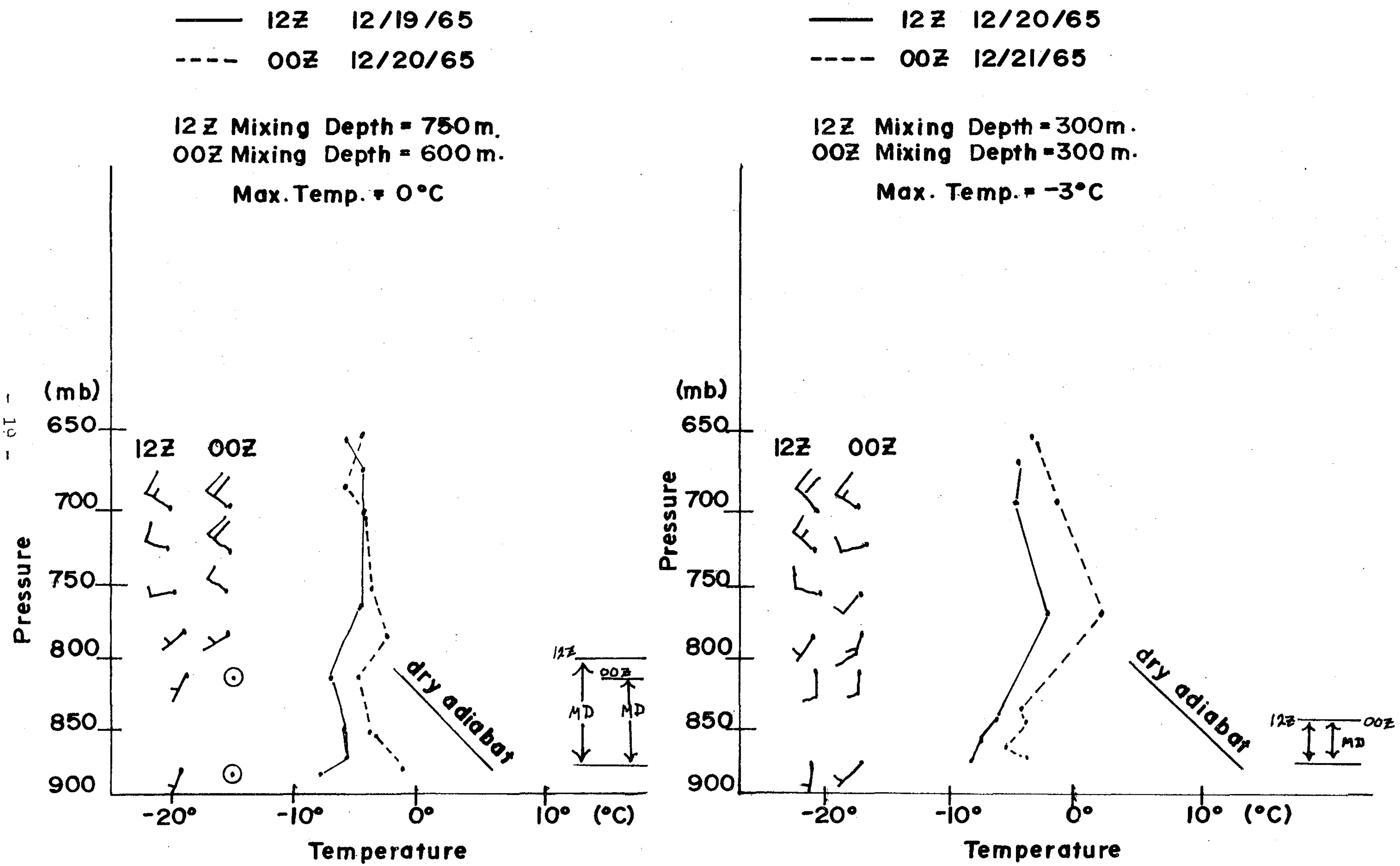

Figure 10a

Figure 10b

FIGURE 10. Temperature Soundings, Winds Aloft and Mixing Depths for Salt Lake City, December 19 - 21, 1965.

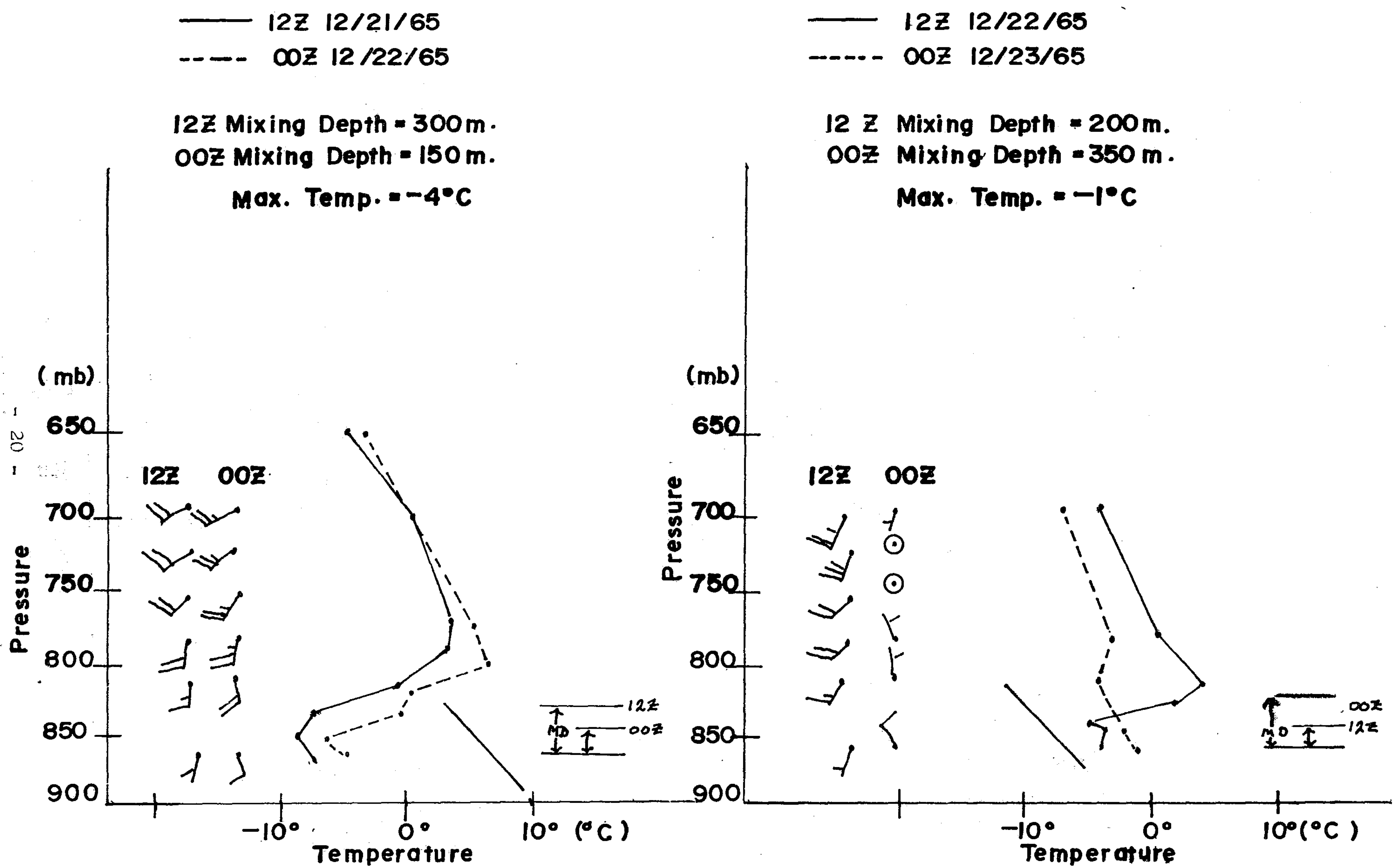

Figure 11a

Figure 11b

FIGURE 11. Temperature Soundings, Winds Aloft and Mixing Depths for Salt Lake City, December 21 - 23, 1965.

TABLE 1

HIGH POLLUTION EPISODE, DECEMBER 17 - 22, 1965

Date	Average Mixing Depth (Meters) (0500 & 1700)	Average Hourly SO_2 Concentrations (PPM) X 10^{-2}	Maximum Temperature (°C)
12/17/65	925	.0075	-1°
12/18	875	.023	0°
12/19	675	.058	0°
12/20	300	.215	-3°
12/21	225	.244	-4°
12/22	275	.036	-1°

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