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A TIDE CLIMATOLOGY FOR BOSTON, MASSACHUSETTS

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ABSTRACT. The Techniques Development Laboratory in cooperation with the Boston Weather Service Forecast Office has compiled a climatology of measured tide levels for Boston, Mass. Approximately 44 years (January 1936 through March 1980) of hourly tide levels were used to determine monthly and yearly frequencies of occurrence of tides above and below specified heights, at half-foot intervals by categories of duration. Also included are tabulations of heights and dates of highest and lowest annual tides and storm surges.

1. INTRODUCTION

Accurate tide measurements are needed for determining astronomical tides and storm surges, developing and tuning storm surge models, and compiling tide climatologies. Tides at Boston have been recorded by a National Ocean Survey (NOS) tide gage on a nearly continuous basis since 1922.

The Boston tide gage is located inside Boston Harbor on Appraisers Stores Wharf near a swing bridge (Fig. 1). The tide can vary from almost 15 ft above to nearly 4 ft below mean low water--a range of approximately 19 ft. High tides and associated wave action can cause tremendous destruction and damage; on the other hand, extreme low tides can make harbor navigation virtually impossible, resulting in lost revenue for the marine industry. Tidal considerations are important in the design of municipal sewage systems, power plants, and other structures having components along the coast. In addition, a knowledge of tidal frequencies helps the operational forecaster estimate the probability of specific tidal events. For these reasons, marine forecasters are often asked the expected frequencies and associated duration of extreme tide levels. This climatological study will provide some answers.

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2. DATUM PLANES

Tide levels are referenced to established surfaces (datum planes). The datum plane most frequently used on the east coast is mean low water (mlw). The mlw is the average height of all low waters recorded over a 19-year period. A period of 19 years (epoch) is generally considered as constituting a full tidal cycle, because the most important tidal variations go through complete cycles during this period of time.

In this study, all tide levels are referenced to mlw which has been adjusted for a 0.005-ft/yr rise in sea level. We refer to this datum as adjusted mlw (amlw). To convert from amlw to adjusted mean sea level or adjusted mean high water, add 4.9 ft or 9.5 ft respectively.

3. TIDE DATA

Tides are generated by the difference in gravitational attraction of the moon and the sun on the earth and the waters of the earth (astronomical tide), seasonal and longer period climatology (climatological tide), and day-to-day meteorology (meteorological tide). Short period disturbances such as wind-waves and swell are filtered from our tide level measurements. Extreme tides occur when high (low) astronomical tides coincide with high (low) meteorological tides.

3.1. Astronomical Tides

Astronomical tides at Boston are of the semidiurnal type--two high and two low waters occur each tidal day. Fig. 2 shows one tide cycle (approximately 24.8 h) of a tidal curve. The tidal range (difference in height between consecutive high and low water depicted in Fig. 2) is 9.5 ft. This is the mean range of the Boston tide (U.S. Dept. of Commerce, 1980). However, the range will change from day to day. Most of the variability in range is due to the moon's changing phase, its varying distance from earth, and its changing declination.

The most noticeable variation in range is related to the moon's changing phase. About 1 1/2 days after the earth, moon, and sun are in line, new and full moon, the range of the tide at Boston becomes greater. We call these tides spring tides. The mean range of the Boston spring tides is 11 ft (U.S. Dept. of Commerce, 1980). Tides which occur 1 1/2 days after the moon's first and third quarter, when the range is least, are called neap tides.

A second variation in the tidal range is associated with the moon's varying distance from earth. About 2 1/2 days after the moon is closest to the earth or in perigee, high tides at Boston rise higher and low tides fall lower than usual. The rise and fall of the tide is less than usual approximately 2 1/2 days after the moon is farthest from earth or in apogee. Tides occurring near the time of perigee are called perigean tides, while those occurring near the time of apogee are known as apogean tides.

The changing declination of the moon is also responsible for variations in the rise and fall of the tide. About a day after the moon is closest to the equator, the two high waters of a day and likewise the two low waters are very similar, and we have equatorial tides as shown in Fig. 2. With increasing declination, differences between morning and afternoon tides appear. About a day after the moon's maximum semimonthly declination, these differences are most pronounced at Boston. Tides occurring near the maximum declination are called tropical tides.

While we have discussed the moon's changing phase, its varying distance from earth, and it changing declination independently, the moon's position and distance relative to the earth and its position relative to the sun must be considered jointly for tide prediction. For example, greater than normal spring tides will occur when a new or a full moon occurs near the time that the moon is nearest the earth. At Boston, these perigean spring tides can have a range of approximately 14 ft (U.S. Dept. of Commerce, 1980).

3.2. Climatological Tide

The rise and fall of sea level over thousands of years has been attributed to climatic and geological changes. Over a time scale of 57 years (1922 through 1978), the period for which we had yearly mean sea level values, we calculated a 0.005-ft/yr rise in sea level at Boston.

When we look at Boston tide levels on a shorter time scale (Fig. 3), we see that the seasonal cycle is quite different from one year to the next. The monthly means of sea level, plotted in Fig. 3, have been adjusted for our calculated 0.005-ft/year rise in sea level. The annual cycle used in Boston's astronomical tide predictions is shown as a solid curve superimposed on the water level record for 1936.

3.3. Meteorological Tide

On a very short time scale, tidal fluctuations (measured tide levels minus astronomical tides) are generated by day-to-day weather. When these fluctuations are caused by storms they are called storm surges. The highest positive storm surge, for the period 1922 through 1979, was 4.9 ft; this was generated by an extratropical storm on November 30, 1945. The greatest negative surge, for the period which was examined (1936 through 1979), was -3.7 ft which occurred on February 2, 1976. Earlier data were not considered in searching for negative surges because they were not readily available on magnetic tape.

4. CALCULATED FREQUENCIES OF OCCURRENCE

We calculated monthly and yearly frequencies of occurrence of tide levels, at half-foot intervals, beginning with tides equal to or greater than a high water criterion of 10 ft above amlw. This level was selected by the Boston Weather Service Forecast Office as a critical level for high water situations. Monthly and yearly frequencies at half-foot intervals were also calculated for tides beginning with those which were less than or equal to amlw (our low water criterion). Fig. 4 shows the relationship of our high and low water criteria to one tide cycle. The tidal range is 9.5 ft, the mean range of the Boston tide. Tide level frequencies are based on approximately

44 years (January 1936 through March 1980) of measured hourly tide levels which have been stored on magnetic tape.

In addition to calculating monthly and yearly frequencies of heights, we also computed monthly and yearly frequencies of specific heights by durations, where duration is defined as the number of consecutive hours that specific heights were measured. For example, the frequency that a specific height was reached for 2 or more consecutive hours (≥ 2) is equal to the frequency associated with 2 consecutive hours plus the frequency associated with 3 consecutive hours, and so on, until the maximum duration is included. The frequency associated with each category is exclusive, a duration of 4 hours is not counted as two 2-h durations. When tide levels remained equal to or exceeded our high or low criterion, from one month into the next, the calculated duration was based on tide levels from the two months. However, the calculated duration was credited only to the month the duration began.

4.1. High Tide Levels

Tables 1 through 12 contain the monthly frequencies of high tide levels. Yearly frequencies are given in Table 13. Frequencies are tabulated for specified heights at half-foot intervals beginning with heights greater than or equal to 10 ft above amlw. Frequencies, based on the number of hours tide levels reached or exceeded specified heights are listed under column I (independent of duration). The frequencies at which tides reached or exceeded specified heights for specific duration times are listed in the remaining columns labeled ≥ 2, ≥ 3, ≥ 4, etc. Following each table is a graphic display of the table data (Fig. 5 through Fig. 17). In each figure, height categories are plotted as a function of duration and frequency of occurrence. The letter I or number (2, 3, 4, or 5) next to the bottom row of points denotes the duration category. Points associated with the same duration are connected. Consider Fig. 5. This figure depicts frequency data for January. During this month, a height of 10 ft above amlw, independent of duration, was reached or exceeded about 30 times. However, only once during approximately 40 Januarys (1/40) was a height of 13.5 ft above almw reached or exceeded. With regard to duration, there are about two events in January where tides reached or exceeded 11 ft above amlw for 2 or more consecutive hours.

All months averaged a few more than 30 hourly events where the tide level equaled or exceeded 10 ft above amlw. See column I of Tables 1 through 12. Tide levels greater than or equal to 12 ft above amlw occurred with a frequency of one or a little less than one a month, except during June, July, August, and September. During these months, a height 12 ft above amlw occurred less than once in 6 months. There were only three to five events a month where tides were greater than or equal to 10 ft above amlw for 3 or more consecutive hours. The number of events associated with this same height category but with the next duration category (≥ 4 consecutive hours) was very small. July, August, and September averaged less than one event every 10 months, while the remaining months averaged one event every 2 to 4 months.

4.2. Low Tide Levels

Monthly frequencies associated with low tides are shown in Tables 14 through 25. Table 26 contains yearly frequencies. Following each table is a graphic display of the table data (Figs. 18 through 30).

When duration is not considered, the frequency of tide levels less than or equal to amlw ranged between 46 and 63 events a month. These frequencies are about 1.6 times larger than the frequencies associated with high tidal events greater than or equal to 10 ft above amlw. See first height category of column I in Tables 13 and 26. After a closer look at Fig. 4, the large frequency of low tidal events comes as no surprise. Note that mean low tide coincides with the low water criterion while mean high tide is 0.5 ft below the high water criterion. If we had used 0.5 ft below amlw as our low water criterion the frequency of high and low water events would have been nearly the same.

Tide levels less than or equal to 2.0 ft below amlw occur between once every 2 months and four times a month. With regard to durations ≥ 3 there are generally four to eight events each month where waters equal or fall below amlw. The greatest number of these events occurred in January, February, March, and December.

5. ANNUAL MAXIMUM AND MINIMUM HEIGHTS

Heights and dates of maximum and minimum annual measured tide levels, referenced to amlw, are tabulated in Table 27. Also tabulated are heights and dates of maximum annual positive and negative storm surges. Datum plane values of the most recent tidal epoch (1960-1978) were used to calculate storm surge heights. Table 27 is a modified and updated version of a table presented by Peterson et al. (1964, Table 4 on page 31). We modified the table of Peterson et al. by adding minimum annual tide levels and maximum annual negative surges from 1936 through 1960. The table was also updated with data from 1961 through 1979.

In most cases, the maximum annual positive surge is greater than the magnitude of the maximum annual negative surge. A little more than 40 percent of the maximum annual positive surges are greater than 3 ft. Only about half of the maximum annual negative surges are less than -2 ft.

The highest tide level (14.7 ft above amlw) occurred on February 7, 1978. March 24, 1940 and February 2, 1976 accounted for the lowest tide level (3.7 ft below amlw). The meteorological settings and the astronomical tides associated with the February events are discussed in the following paragraphs.

5.1. February High Tide Event

The highest measured tide was associated with the record storm of early February 1978. This storm formed off the South Carolina coast during the evening of February 5 (Fig. 31). The storm intensified as it moved up the east coast. Cape Cod reported winds of 92 mph. The highest tide (14.7 ft above amlw) occurred February 7 when a 3.7-ft storm surge coincided with a high perigean spring tide. See Fig. 32. The tide remained higher than 10 ft above amlw for 6 consecutive hours.

5.2. February Low Tide Event

The lowest tide since 1940 also occurred in February. Fig. 33 shows the sea-level pressure charts associated with this event. A low pressure system formed over the Gulf of Mexico on the morning of February 1, 1976. Twenty-four hours later this system deepened to 964 mb and was located about 150 miles north-northeast of Boston. At Boston International Airport, westerly winds reached speeds in excess of 40 kts. On February 2, a 3.4-ft negative surge lowered the tide level to 3.7 ft below amlw (Fig. 34). Tide levels remained below amlw for 5 consecutive hours.

6. SUMMARY

Boston tide levels have varied from 14.7 ft above to 3.7 ft below amlw. Extreme high tide levels, greater than or equal to 14.5 ft above amlw, have occurred about once in 22 years. Extreme low tides, less than or equal to 3.5 ft below amlw, occurred about once in 7 years. High tides greater than or equal to 12 ft above amlw and low tides less than or equal to 2.5 ft below amlw occurred infrequently during June, July, August, and September. These months also accounted for the least number of maximum annual positive and negative surges (Table 27).

In general, high tides rise higher above our high water criterion than low tides fall below the low water criterion, even though our criteria favor the opposite. The maximum duration associated with high and low tides is 6 and 5 hours respectively. The lowest tide level since 1940, the highest tide level, and the maximum duration for both high and low tides occurred in February. However, future storms may set new records in different months.

ACKNOWLEDGMENTS

We thank Steve Lyles and Howard Kushner of NOS for hourly tide data and Milt Rutstein, also of NOS, for furnishing information on tidal datum planes. A special thanks to Judith Morrison for preparing all the figures for publication. We also thank Cheryl Shaw, Alice Baker, and Judith Morrison for typing the manuscript and tables.

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U. S. Dept. of Commerce, 1980: Tide Tables 1981, East Coast of North and South America including Greenland, 285 pp.

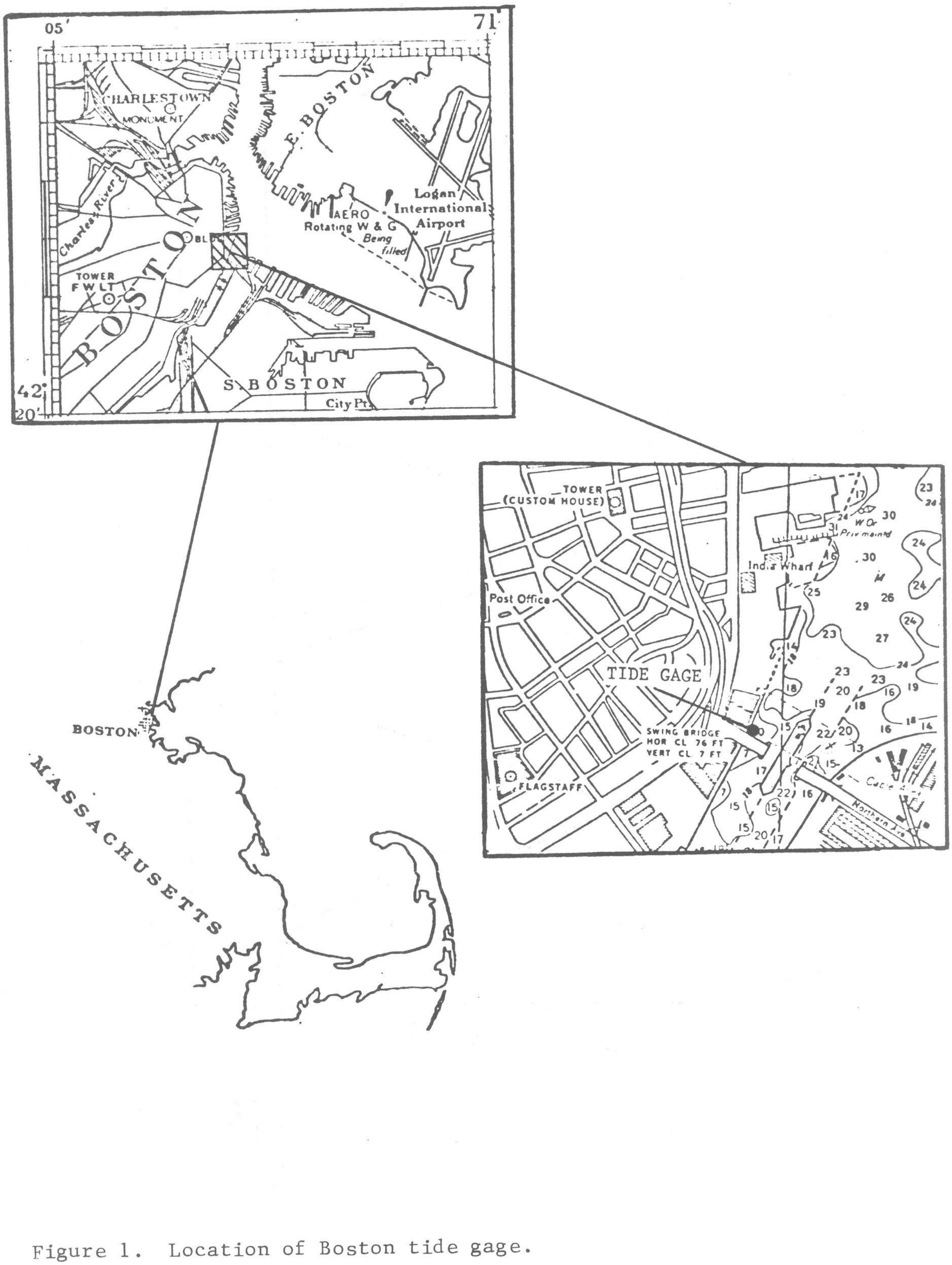

Figure 1. Location of Boston tide gage.

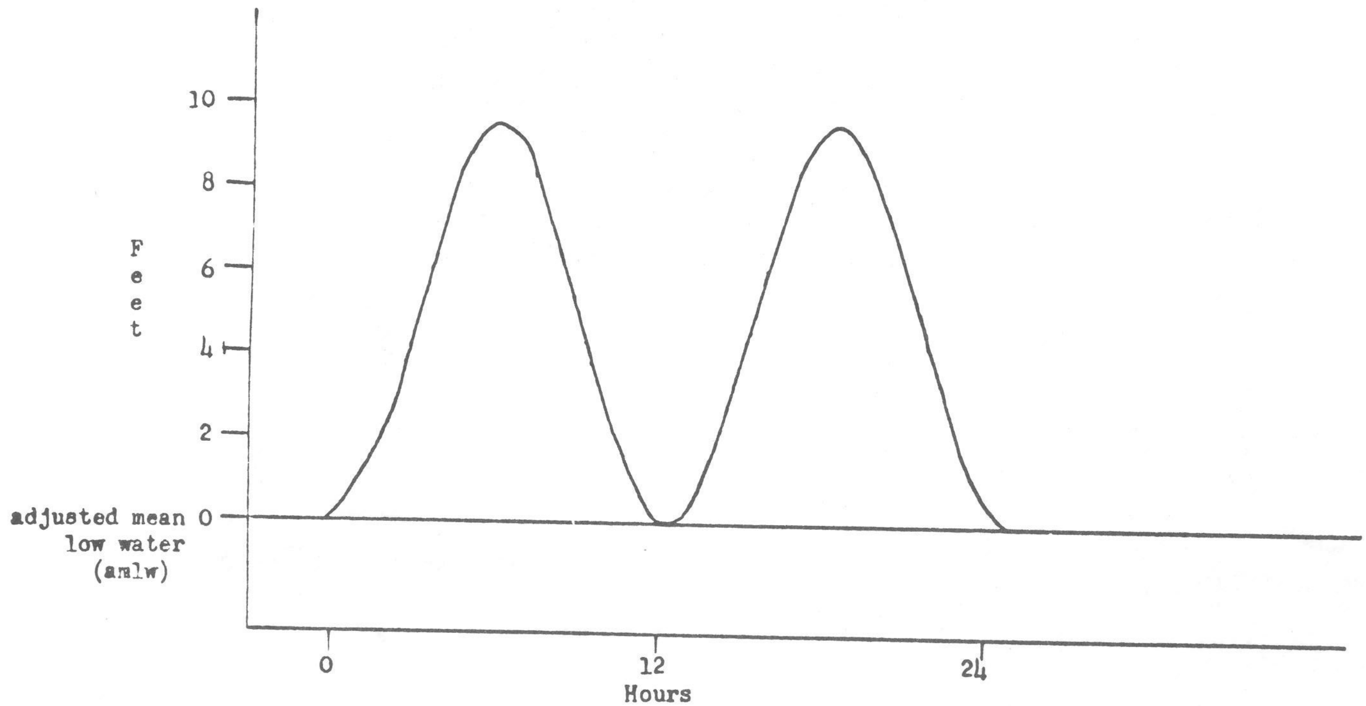

Figure 2. Tidal curve.

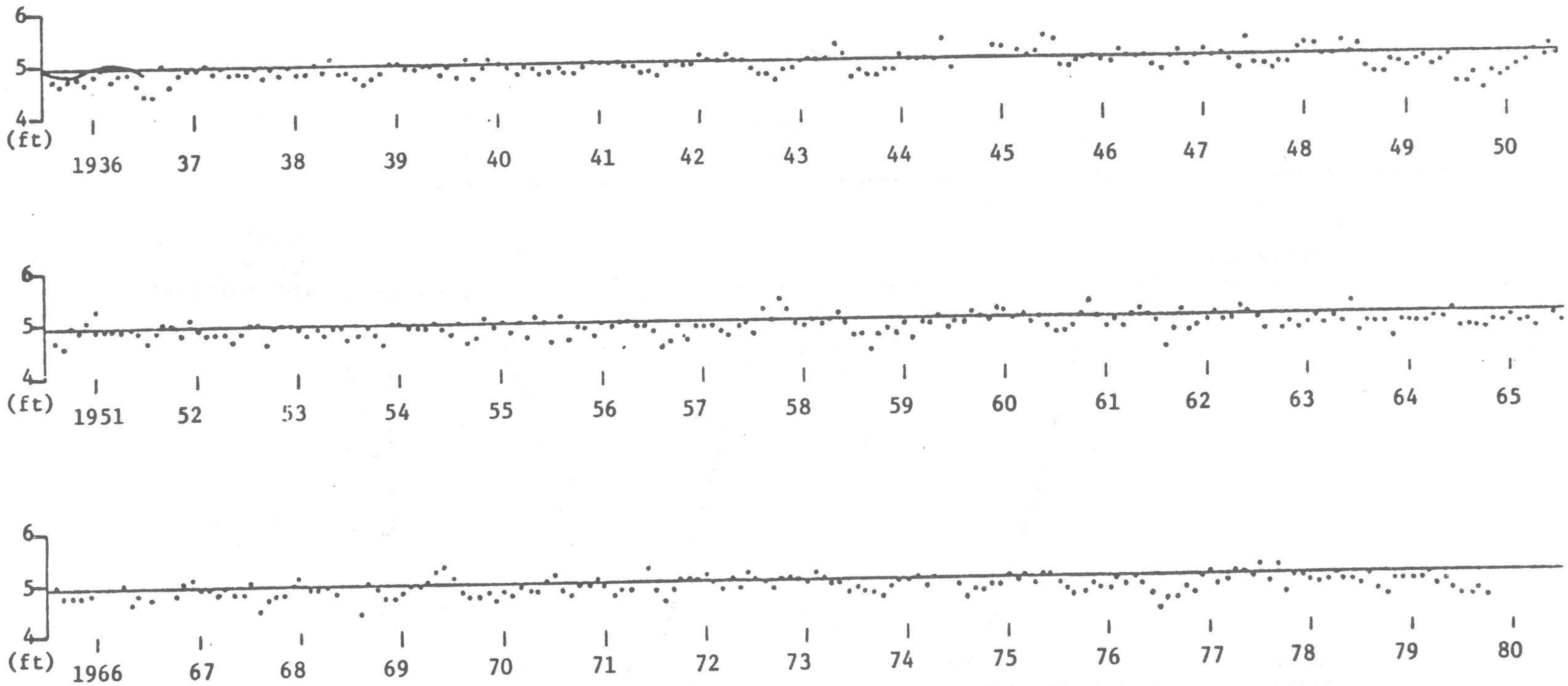

Figure 3. Monthly means plotted in ft above adjusted mean low water (amlw). The year is plotted in June. The solid curve superimposed on the tide record for 1936 is the annual cycle used in the Boston astronomical tide predictions.

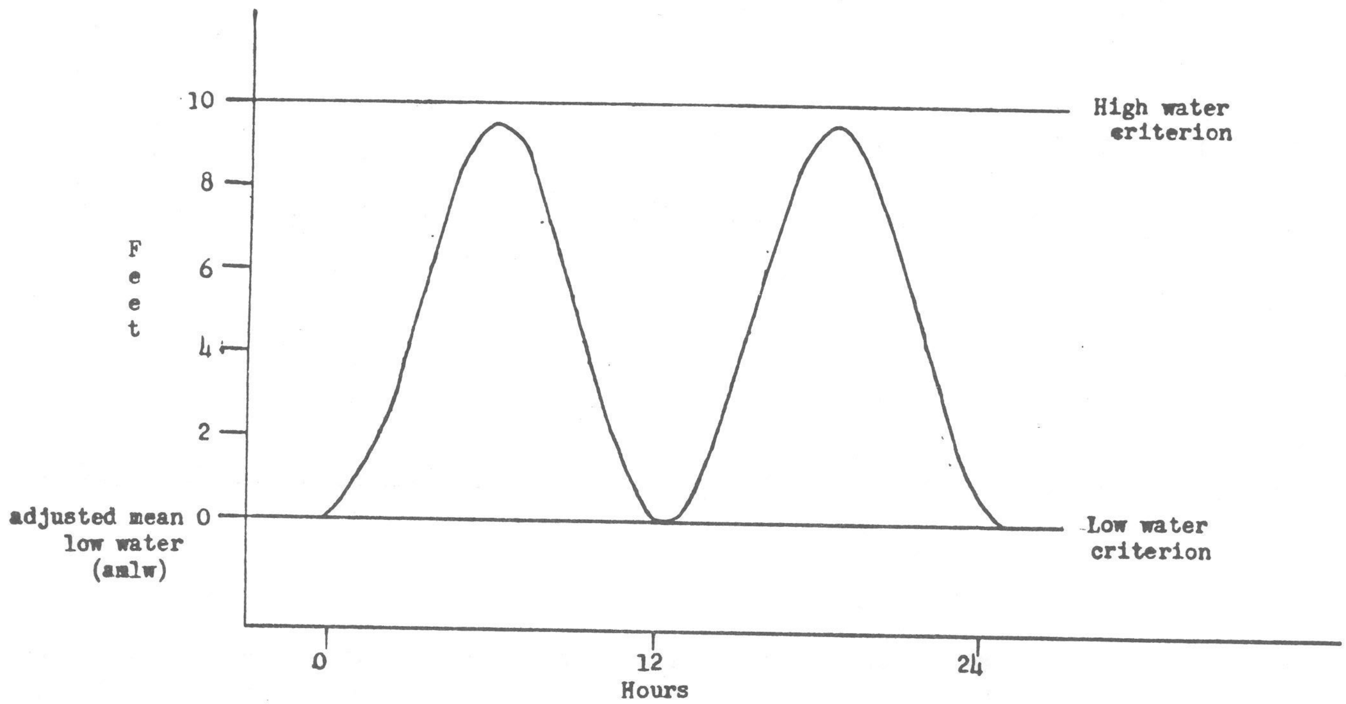

Figure 4. Relationship of high and low water criteria to one tide cycle.

Table 1. Averaged monthly frequencies of high tide levels by height and duration for January. Frequencies are tabulated for specified heights at half-foot intervals beginning with heights greater than or equal to 10 ft above amlw. Listed under column I are frequencies at which tides reached or exceeded specified heights, independent of duration. Frequencies listed in the remaining columns, for durations of ≥2h, ≥3h, ≥4h, and ≥5h, are the number of times that tides reached or exceeded specified heights for specified durations. January frequencies are based on 43.2 months.

Specified heights (Departures from amlw in ft)	I	Duration			
		≥2h	≥3h	≥4h	≥5h
≥ 10.0	31.3	10.7	3.8	1/2.2	1/43.2
≥ 10.5	15.7	5.1	1.7	1/8.6	
≥ 11.0	6.6	2.1	1/2.5	1/43.2	
≥ 11.5	2.8	1/1.4	1/7.2		
≥ 12.0	1/1.3	1/4.3	1/21.6		
≥ 12.5	1/3.1	1/10.8	1/43.2		
≥ 13.0	1/10.8	1/43.2			
≥ 13.5	1/43.2				

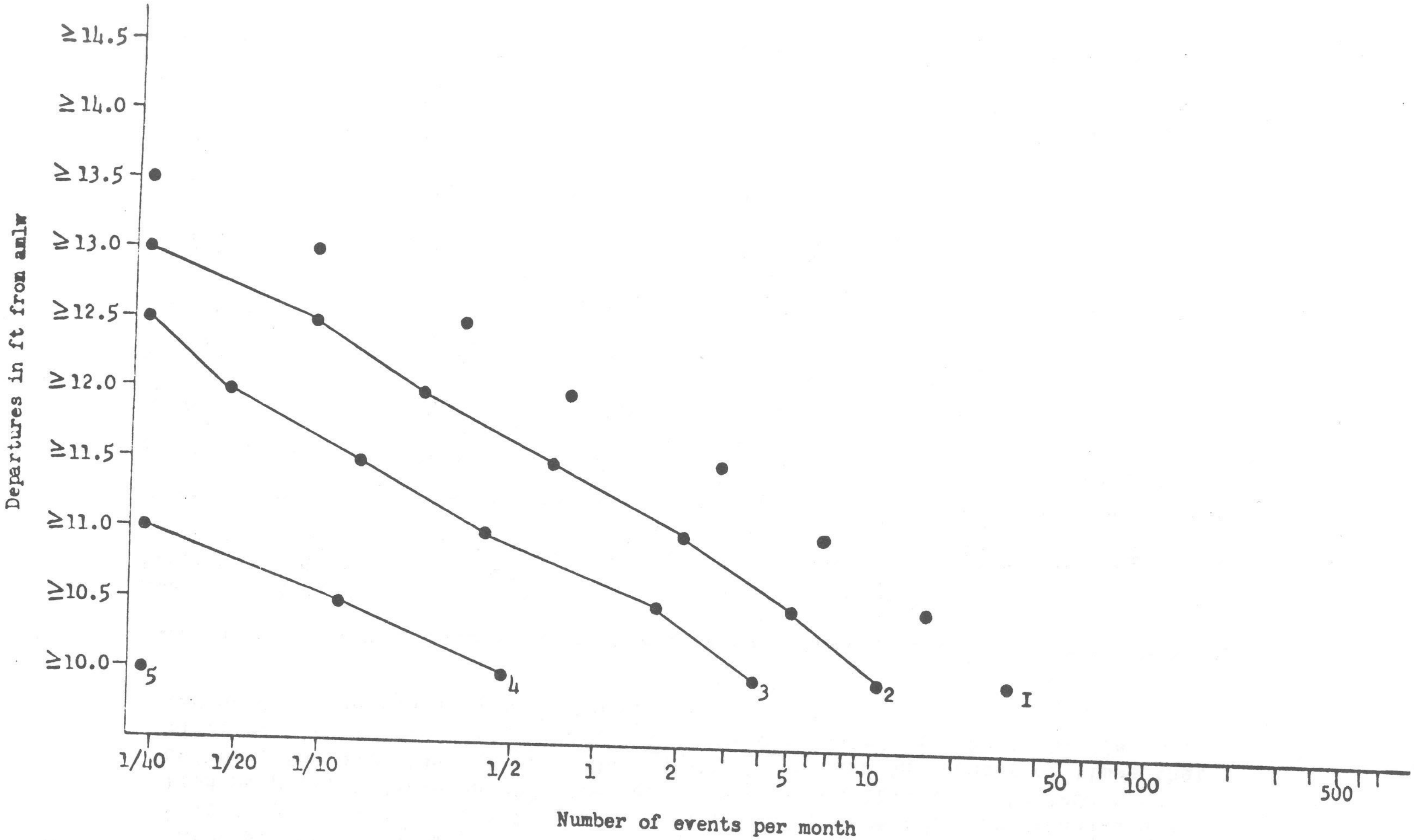

Figure 5. Graphic display of January data from table on previous page. Categories of height (vertical scale) are plotted as a function of duration and number of events per month (logarithmic horizontal scale). The letter I or number (2, 3, 4, or 5) next to the bottom row of points denotes the duration category. Points associated with I are independent of duration. The number N, denotes the duration greater than or equal to N consecutive hours. Points associated with the same duration are connected.

Table 2. Same as Table 1 except for February. Frequencies are based on 43 months.

Specified heights (Departures from amlw in ft)	I	Duration ≥2h	≥3h	≥4h	≥5h	≥6h
≥ 10.0	30.9	10.7	3.8	1/1.9	1/10.8	1/43.0
≥ 10.5	15.8	5.2	1.6	1/4.8	1/43.0	
≥ 11.0	7.4	2.6	1/1.8	1/10.8		
≥ 11.5	3.0	1/1.3	1/5.4	1/14.3		
≥ 12.0	1/1.1	1/5.4	1/14.3	1/43.0		
≥ 12.5	1/3.1	1/10.8	1/21.5	1/43.0		
≥ 13.0	1/4.8	1/14.3	1/21.5	1/43.0		
≥ 13.5	1/14.3	1/43.0				
≥ 14.0	1/14.3	1/43.0				
≥ 14.5	1/21.5	1/43.0				

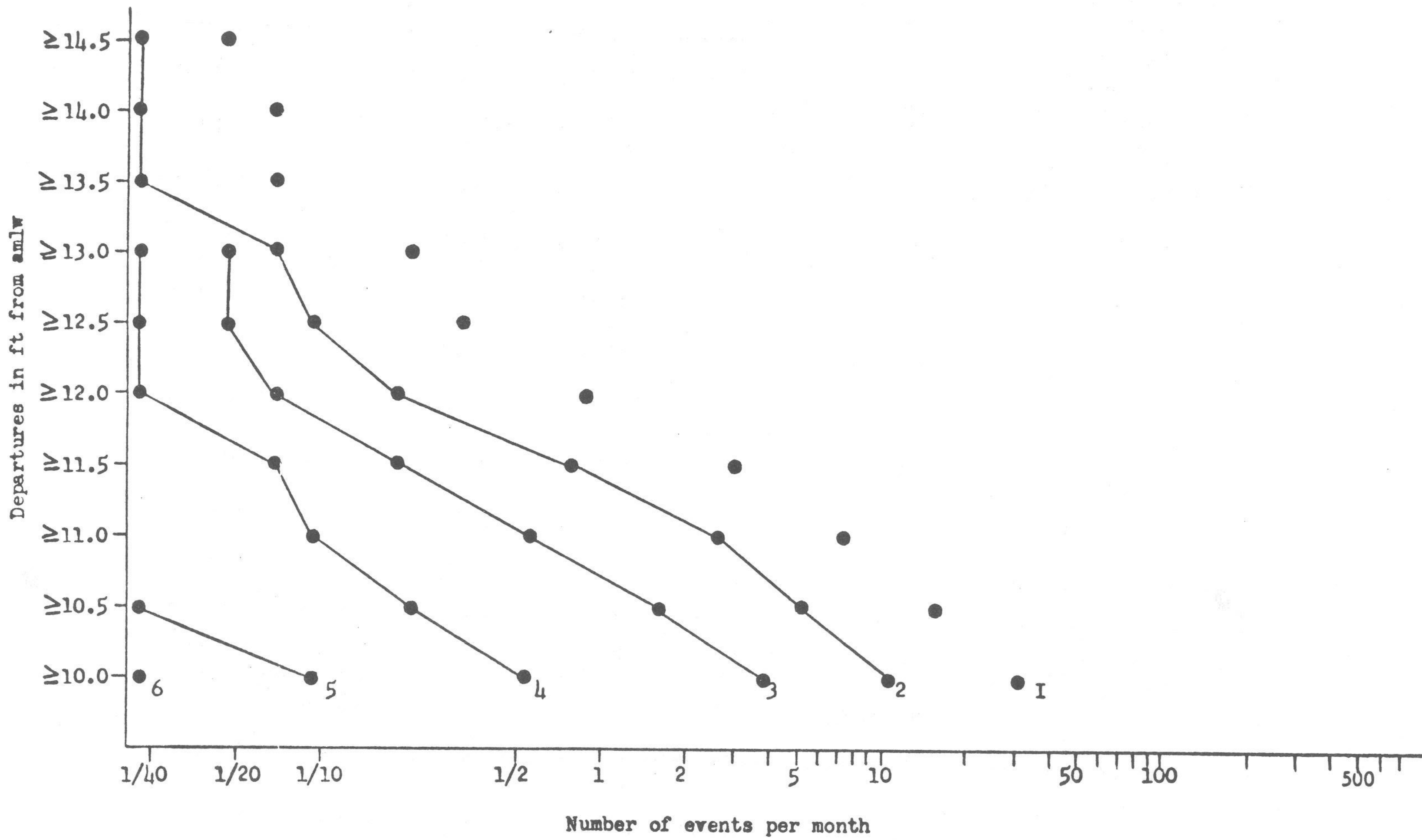

Figure 6. Same as Fig. 5 except for February.

Table 3. Same as Table 1 except for March. Frequencies are based on 43.5 months.

Specified heights (Departures from amlw in ft)	I	Duration ≥2h	≥3h	≥4h	≥5h
> 10.0	33.8	12.1	3.4	1/2.4	1/21.8
≥ 10.5	15.7	5.2	1.1	1/7.3	
≥ 11.0	5.7	1.6	1/5.4	1/43.5	
≥ 11.5	1.8	1/2.2	1/7.3		
≥ 12.0	1/2.0	1/6.2	1/43.5		
≥ 12.5	1/4.8	1/14.5	1/43.5		
≥ 13.0	1/21.8				

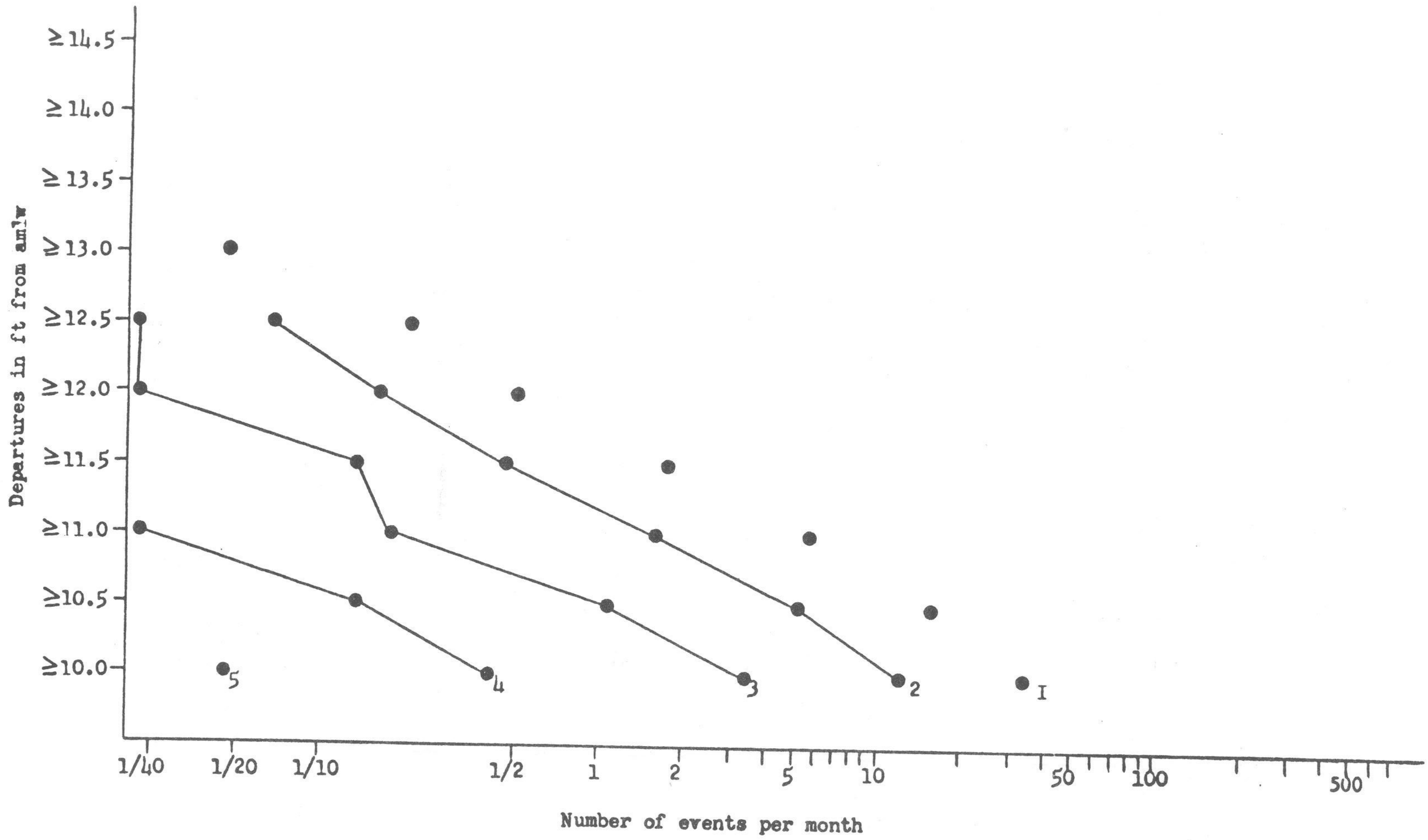

Figure 7. Same as Fig. 5 except for March.

Table 4. Same as Table 1 except for April. Frequencies are based on 43 months.

Specified heights (Departures from amlw in ft)	I	Duration ≥2h	≥3h	≥4h
≥ 10.0	33.4	12.0	3.6	1/2.0
≥ 10.5	15.6	5.1	1.6	1/5.4
≥ 11.0	6.4	2.0	1/1.8	1/21.5
≥ 11.5	2.7	1/1.3	1/5.4	1/43.0
≥ 12.0	1.0	1/3.3	1/14.3	
≥ 12.5	1/2.9	1/21.5		
≥ 13.0	1/14.3	1/43.0		

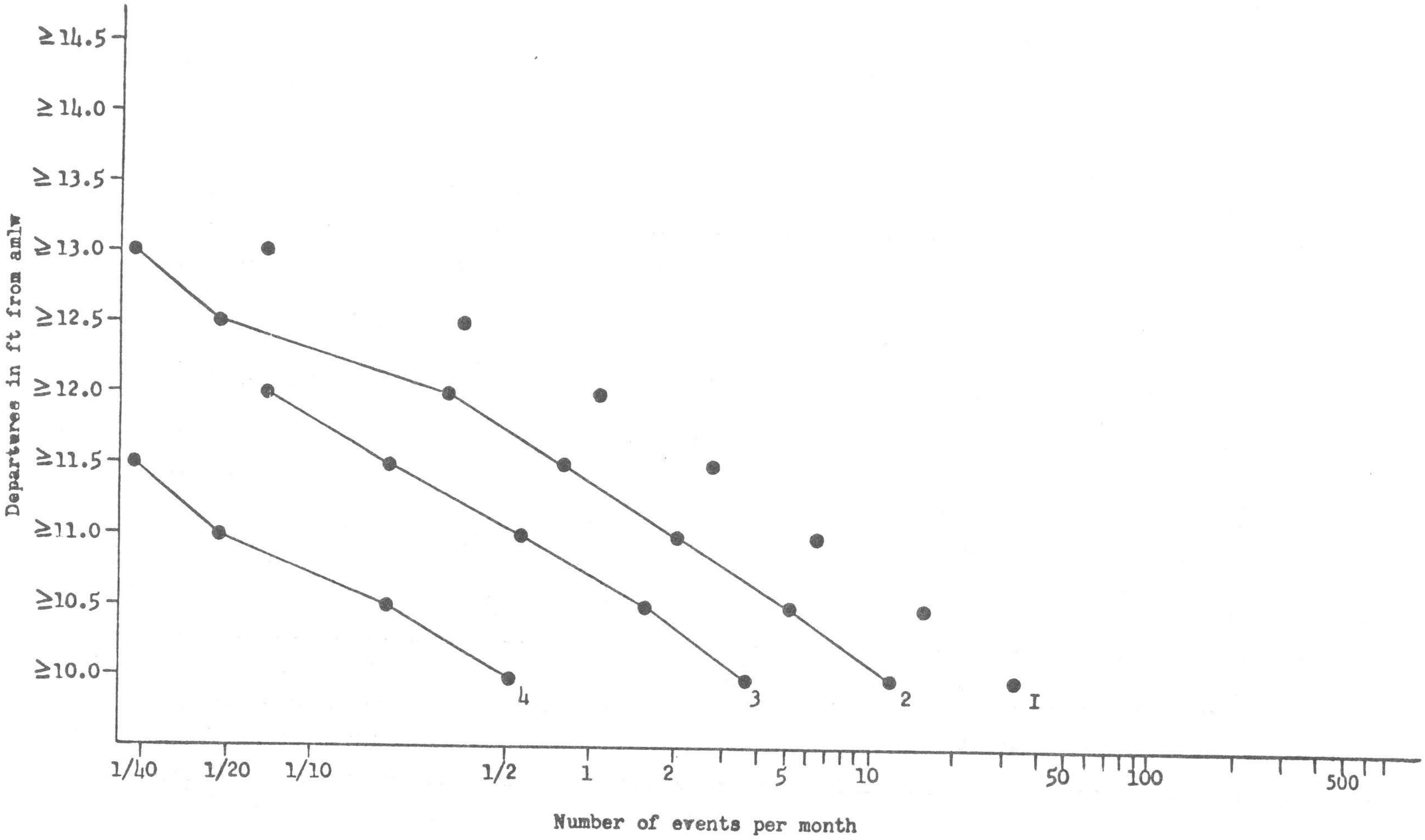

Figure 8. Same as Fig. 5 except for April.

Table 5. Same as Table 1 except for May. Frequencies are based on 43.6 months.

Specified heights (Departures from amlw in ft)	I	Duration ≥2h	Duration ≥3h	Duration ≥4h
≥ 10.0	31.6	10.8	3.8	1/3.4
≥ 10.5	15.7	5.6	1.4	1/21.8
≥ 11.0	7.2	2.4	1/4.4	1/43.6
≥ 11.5	2.0	1/2.3	1/43.6	1/43.6
≥ 12.0	1/2.9	1/21.8	1/43.6	
≥ 12.5	1/21.8	1/43.6		
≥ 13.0	1/43.6			

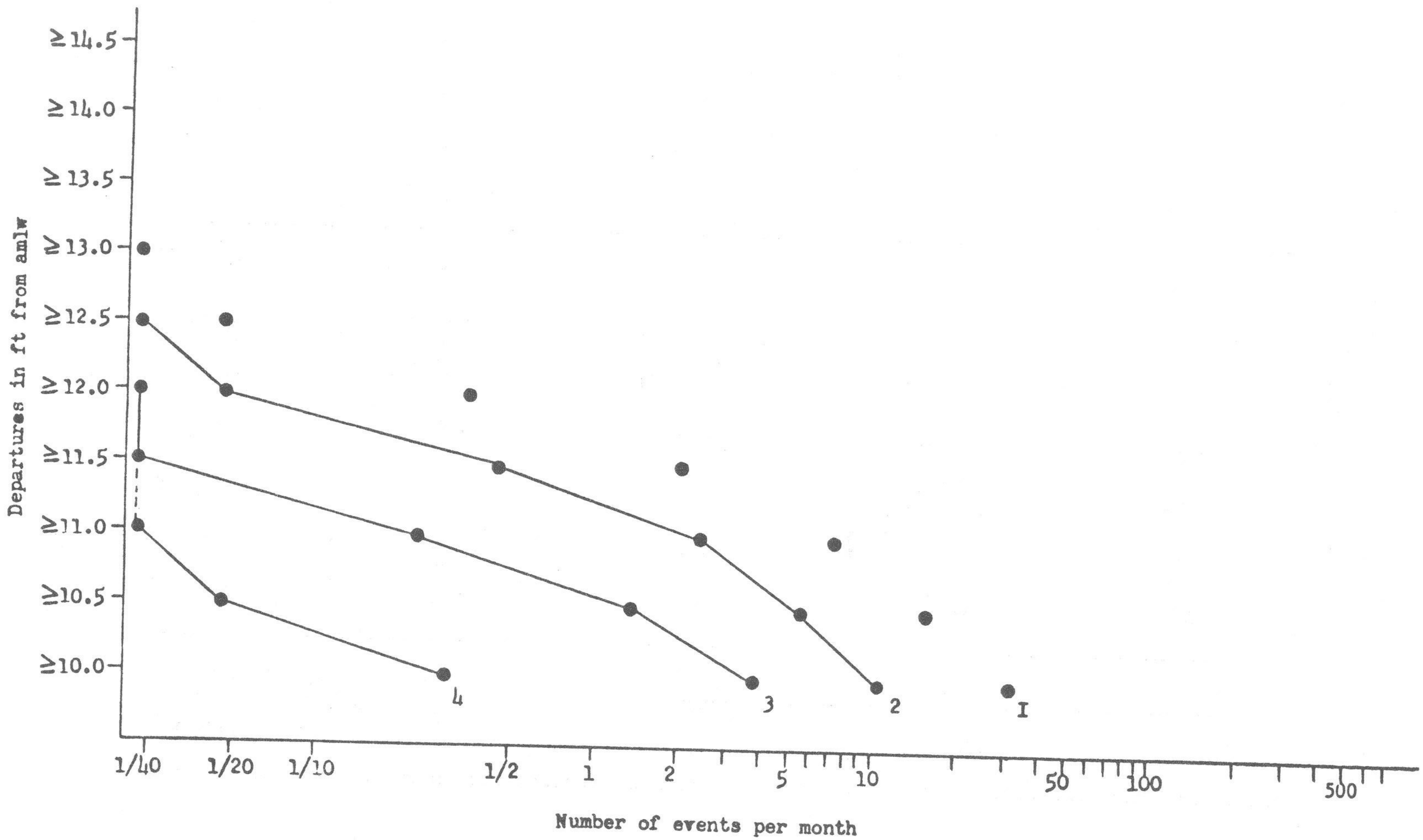

Figure 9. Same as Fig. 5 except for May.

Table 6. Same as Table 1 except for June. Frequencies are based on 42.9 months.

Specified heights (Departures from amlw in ft)	I	Duration		
		≥2h	≥3h	≥4h
≥ 10.0	32.2	10.6	4.4	1/3.1
≥ 10.5	15.6	5.5	1.6	
≥ 11.0	7.3	2.5	1/3.9	
≥ 11.5	2.4	1/2.0		
≥ 12.0	1/6.1			

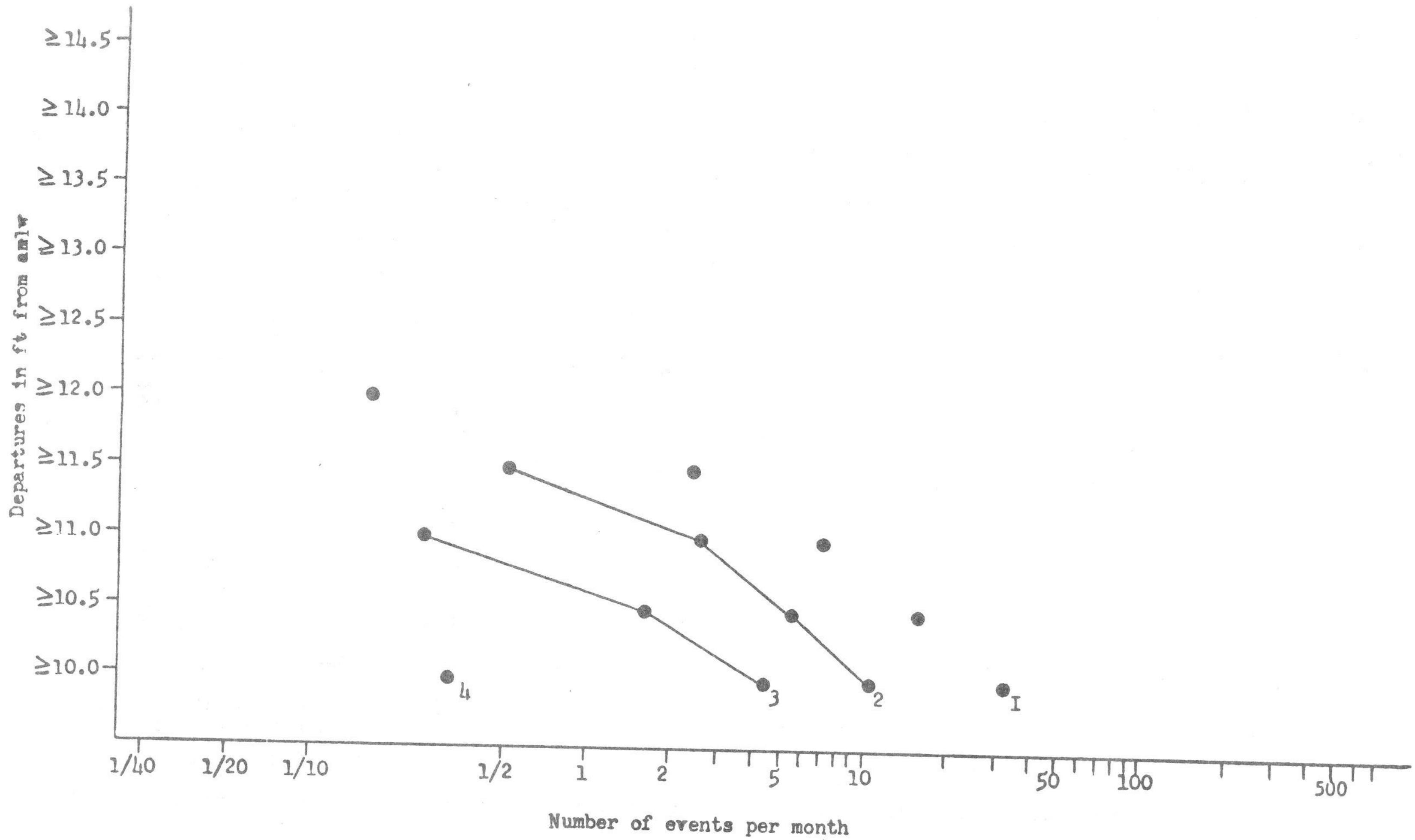

Figure 10. Same as Fig. 5 except for June.

Table 7. Same as Table 1 except for July. Frequencies are based on 43 months.

Specified heights (Departures from amlw in ft)	I	Duration		
		≥2h	≥3h	≥4h
≥ 10.0	32.9	11.4	3.5	1/21.5
≥ 10.5	14.7	5.0	1.0	
≥ 11.0	6.0	1.9	1/10.7	
≥ 11.5	1.7	1/3.3		
≥ 12.0	1/8.6			

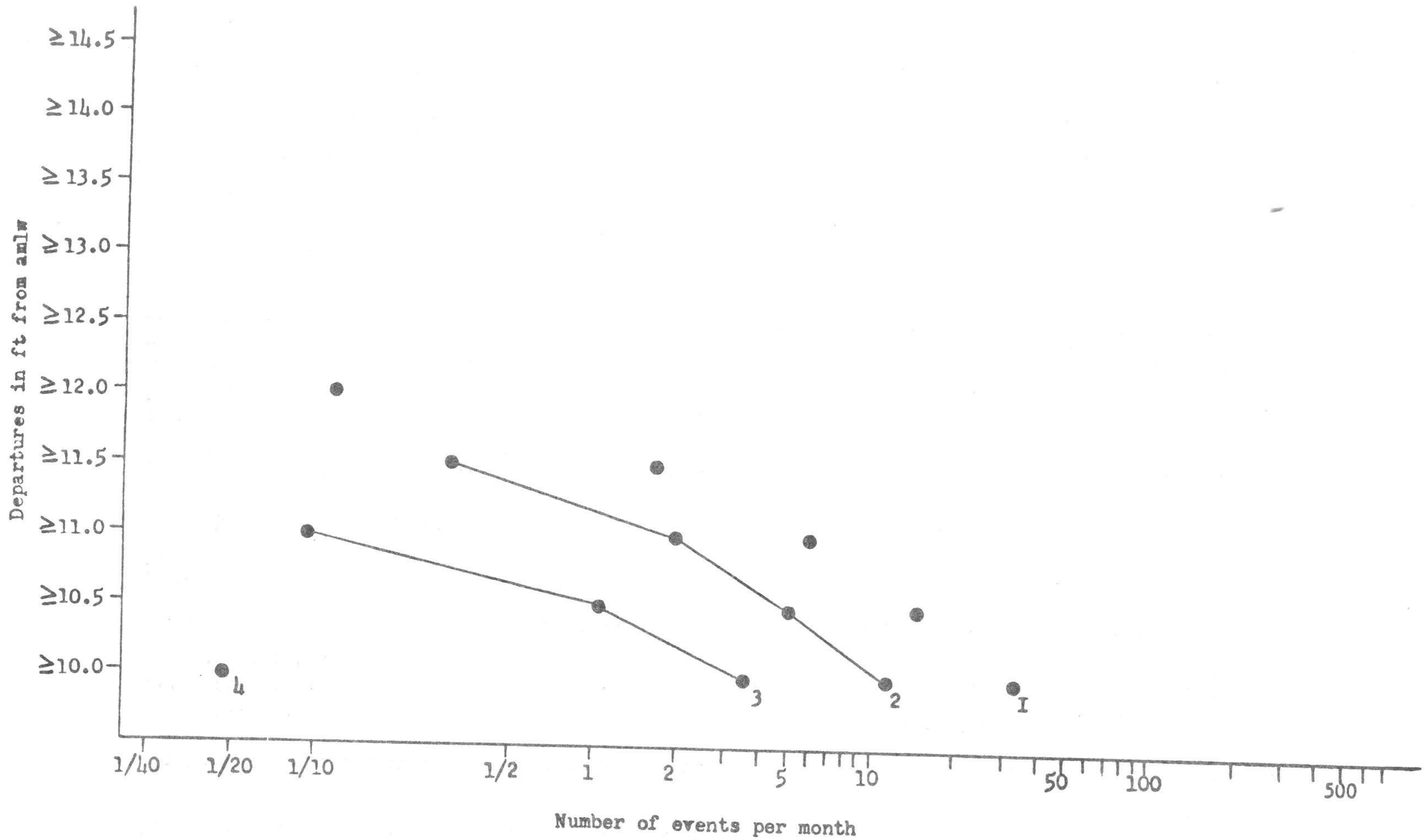

Figure 11. Same as Fig. 5 except for July.

Table 8. Same as Table 1 except for August. Frequencies are based on 43 months.

Specified heights (Departures from amlw in ft)	I	Duration		
		≥2h	≥3h	≥4h
≥ 10.0	32.2	11.3	3.2	1/10.7
≥ 10.5	14.5	4.7	1/1.2	
≥ 11.0	4.8	1.2	1/43.0	
≥ 11.5	1.0	1/6.1		
≥ 12.0	1/10.7			
≥ 12.5	1/43.0			

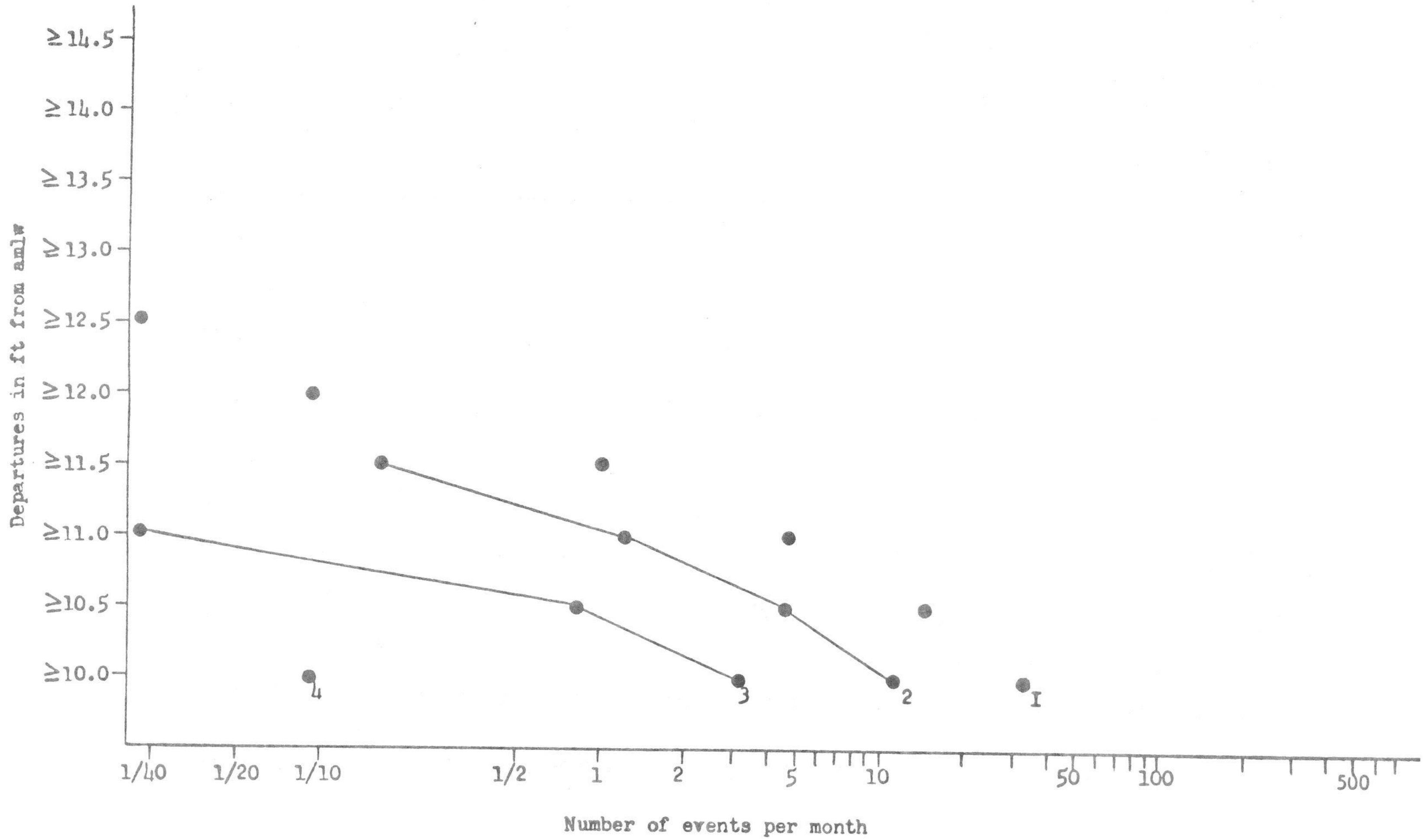

Figure 12. Same as Fig. 5 except for August.

Table 9. Same as Table 1 except for September. Frequencies are based on 43.1 months.

Specified heights (Departures from amlw in ft)	I	Duration ≥2h	≥3h	≥4h
≥ 10.0	33.5	11.9	3.2	1/21.5
≥ 10.5	15.1	5.1	1/2.0	1/43.1
≥ 11.0	5.0	1.3	1/43.1	
≥ 11.5	1/1.5	1/10.8		
≥ 12.0	1/21.5	1/43.1		

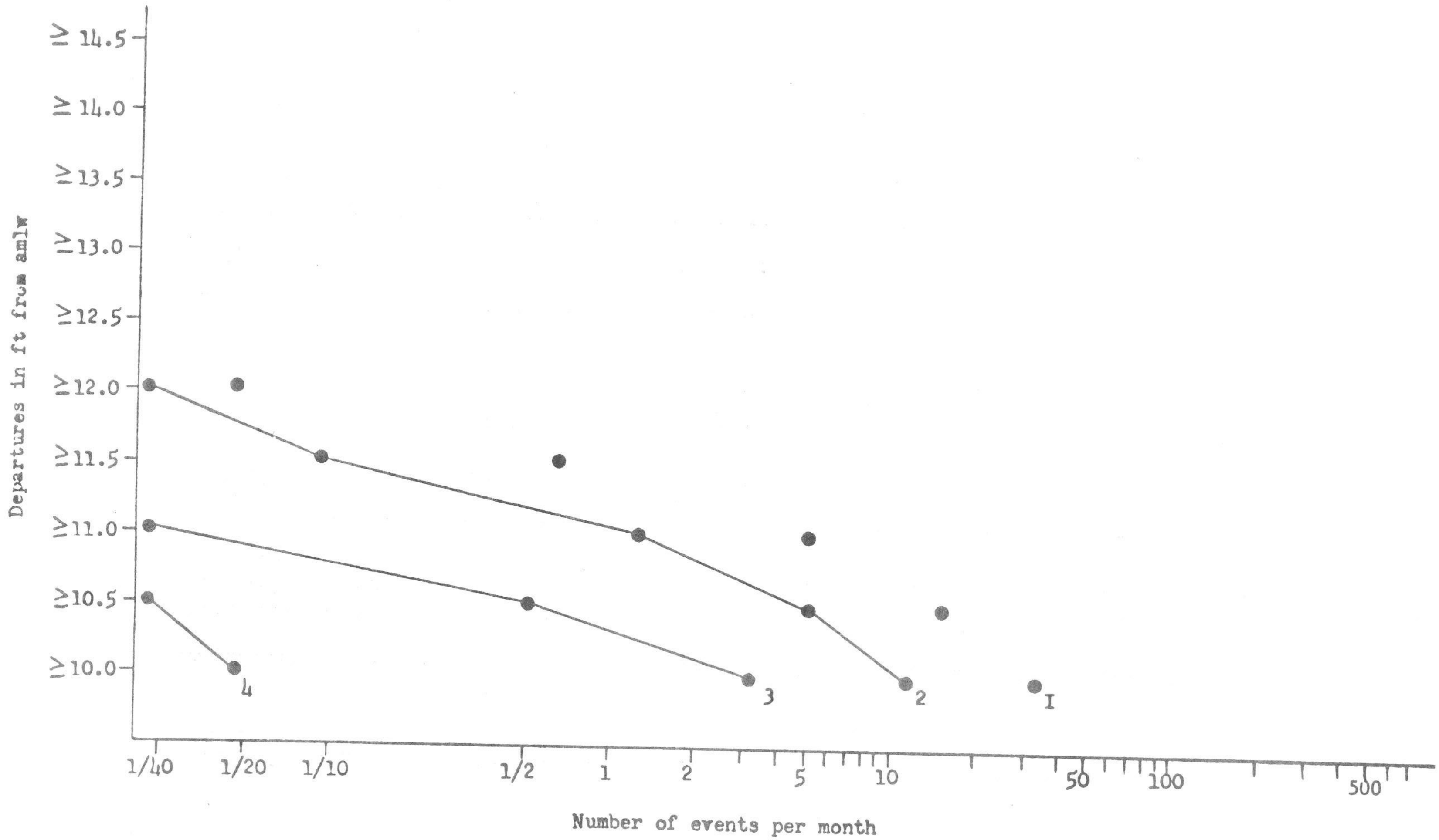

Figure 13. Same as Fig. 5 except for September.

Table 10. Same as Table 1 except for October. Frequencies are based on 41.4 months.

Specified heights (Departures from amlw in ft)	I	Duration		
		≥2h	≥3h	≥4h
≥ 10.0	36.1	12.8	4.0	1/3.8
≥ 10.5	18.1	6.2	1.5	1/20.7
≥ 11.0	7.4	2.3	1/2.3	
≥ 11.5	2.4	1/1.7	1/10.3	
≥ 12.0	1/2.0	1/13.8		
≥ 12.5	1/10.3			

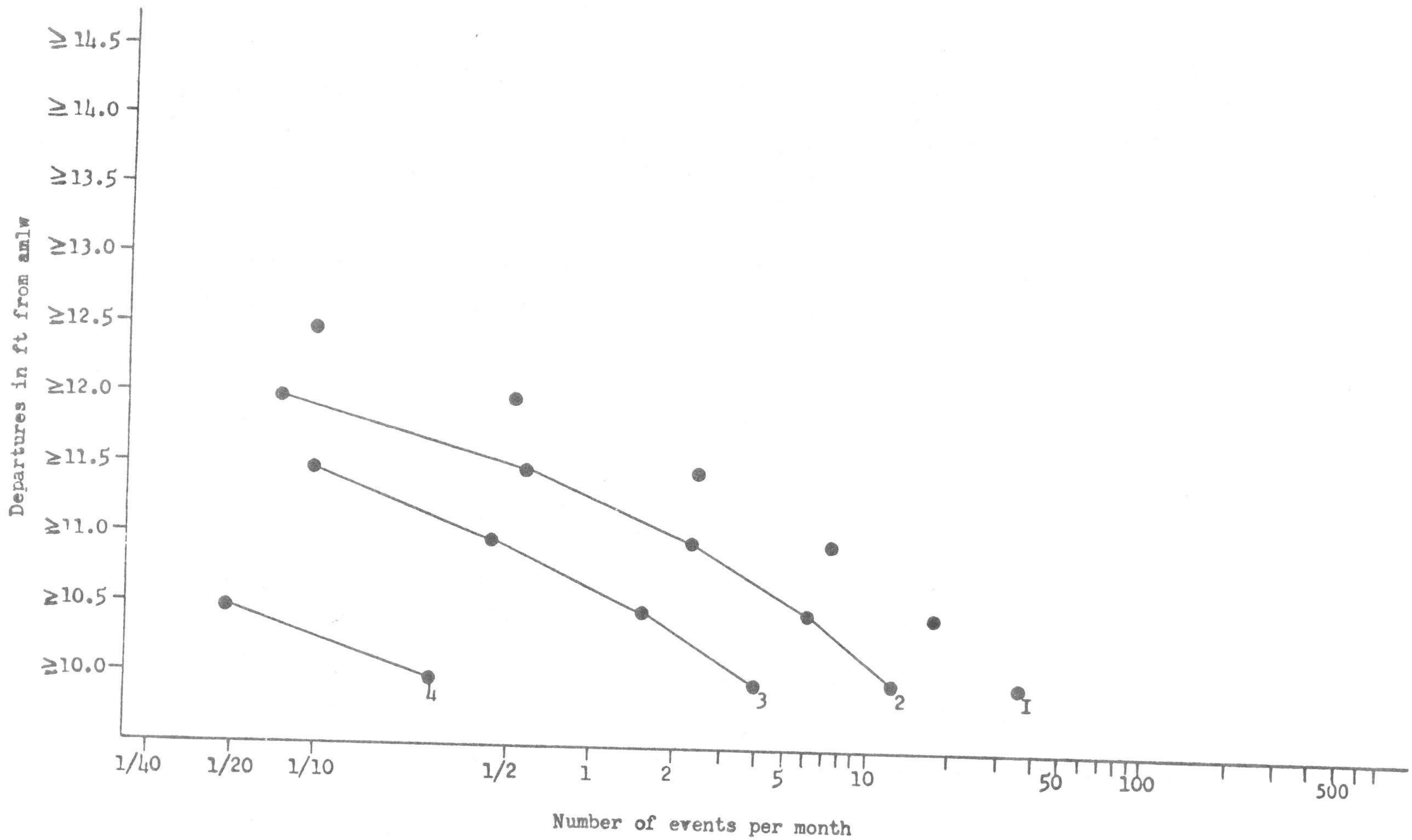

Figure 14. Same as Fig. 5 except for October.

Table 11. Same as Table 1 except for November. Frequencies are based on 42.8 months.

Specified heights (Departures from amlw in ft)	I	Duration			
		≥2h	≥3h	≥4h	≥5h
≥ 10.0	35.2	11.9	4.7	1/1.5	1/21.4
≥ 10.5	17.8	6.4	1.7	1/14.3	
≥ 11.0	8.6	2.9	1/1.9		
≥ 11.5	3.3	1.0	1/7.1		
≥ 12.0	1.0	1/4.8	1/42.8		
≥ 12.5	1/6.1	1/42.8			
≥ 13.0	1/42.8				

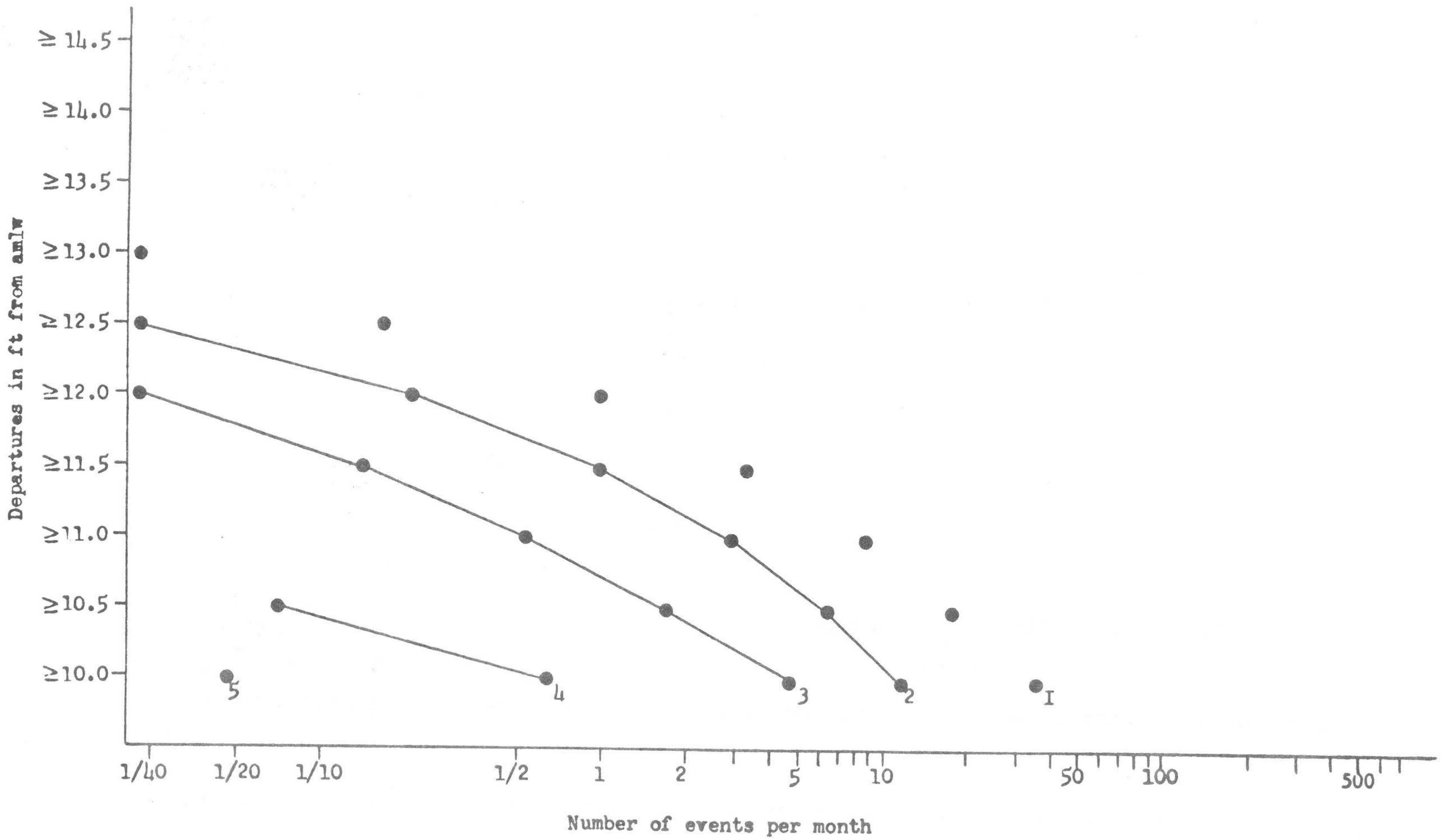

Figure 15. Same as Fig. 5 except for November.

Table 12. Same as Table 1 except for December. Frequencies are based on 43.3 months.

Specified heights (Departures from amlw in ft)	I	Duration			
		≥2h	≥3h	≥4h	≥5h
≥ 10.0	33.3	11.6	4.2	1/1.7	1/43.3
≥ 10.5	16.9	5.8	1.8	1/6.2	
≥ 11.0	8.3	2.8	1/1.4	1/21.7	
≥ 11.5	3.2	1/1.1	1/6.2		
≥ 12.0	1.0	1/5.4	1/43.3		
≥ 12.5	1/5.4	1/43.3			
≥ 13.0	1/21.7	1/43.3			
≥ 13.5	1/43.3				

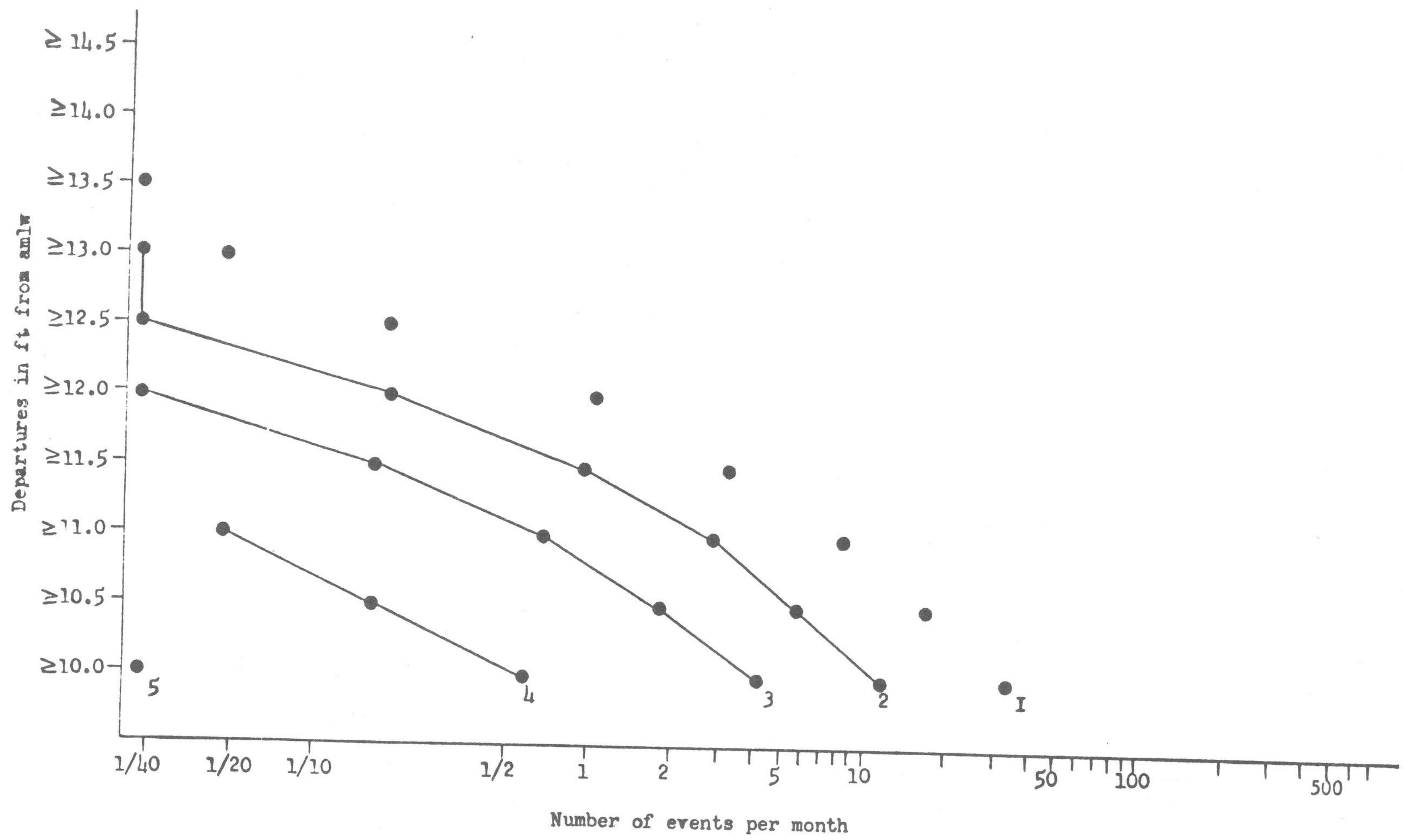

Figure 16. Same as Fig. 5 except for December.

Table 13. Same as Table 1 except for averaged yearly frequencies which are based on 43 years.

Specified heights (Departures from amlw in ft)	I	Duration $\geq$2h	$\geq$3h	$\geq$4h	$\geq$5h	$\geq$6h
$\geq$ 10.0	397.4	137.7	45.6	4.2	1/4.3	1/43.0
$\geq$ 10.5	191.3	64.9	16.3	1.0	1/43.0	
$\geq$ 11.0	80.6	25.7	4.0	1/3.9		
$\geq$ 11.5	26.8	6.8	1.1	1/8.6		
$\geq$ 12.0	6.5	1.4	1/3.6	1/43.0		
$\geq$ 12.5	1.7	1/2.7	1/10.8	1/43.0		
$\geq$ 13.0	1/2.0	1/7.2	1/21.5	1/43.0		
$\geq$ 13.5	1/8.6	1/43.0				
$\geq$ 14.0	1/14.3	1/43.0				
$\geq$ 14.5	1/21.5	1/43.0				

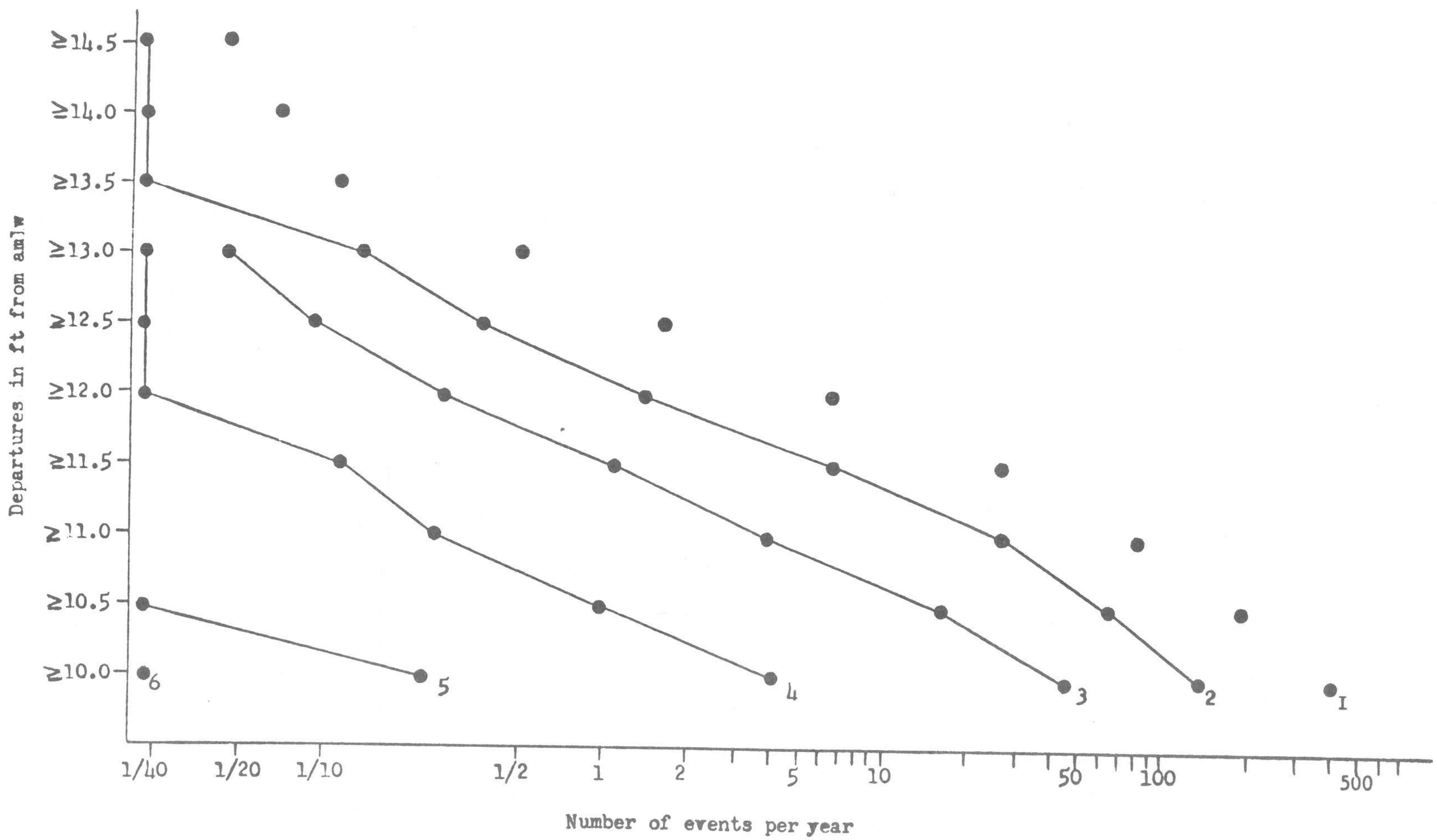

Figure 17. Same as Fig. 5 except for yearly frequencies.

Table 14. Averaged monthly frequencies of low tide levels by height and duration for January. Frequencies are tabulated for specified heights at half-foot intervals beginning with heights less than or equal to amlw. Listed under column I are frequencies at which tides were less than or equal to specified heights, independent of duration. Frequencies listed in the remaining columns, for durations of $\geq 2h$, $\geq 3h$, and $\geq 4h$, are the number of times that tides reached or fell below specified heights for specified durations. January frequencies are based on 43.2 months.

Specified heights (Departures from amlw in ft)	I	Duration		
		$\geq 2h$	$\geq 3h$	$\geq 4h$
$\leq$ 0.0	62.4	22.1	8.3	1/1.1
$\leq$ -0.5	36.6	12.4	3.3	1/6.2
$\leq$ -1.0	19.8	6.4	1.0	
$\leq$ -1.5	9.2	2.5	1/3.3	
$\leq$ -2.0	3.3	1/1.1	1/43.2	
$\leq$ -2.5	1.0	1/5.4		
$\leq$ -3.0	1/4.3	1/43.2		
$\leq$ -3.5	1/43.2			

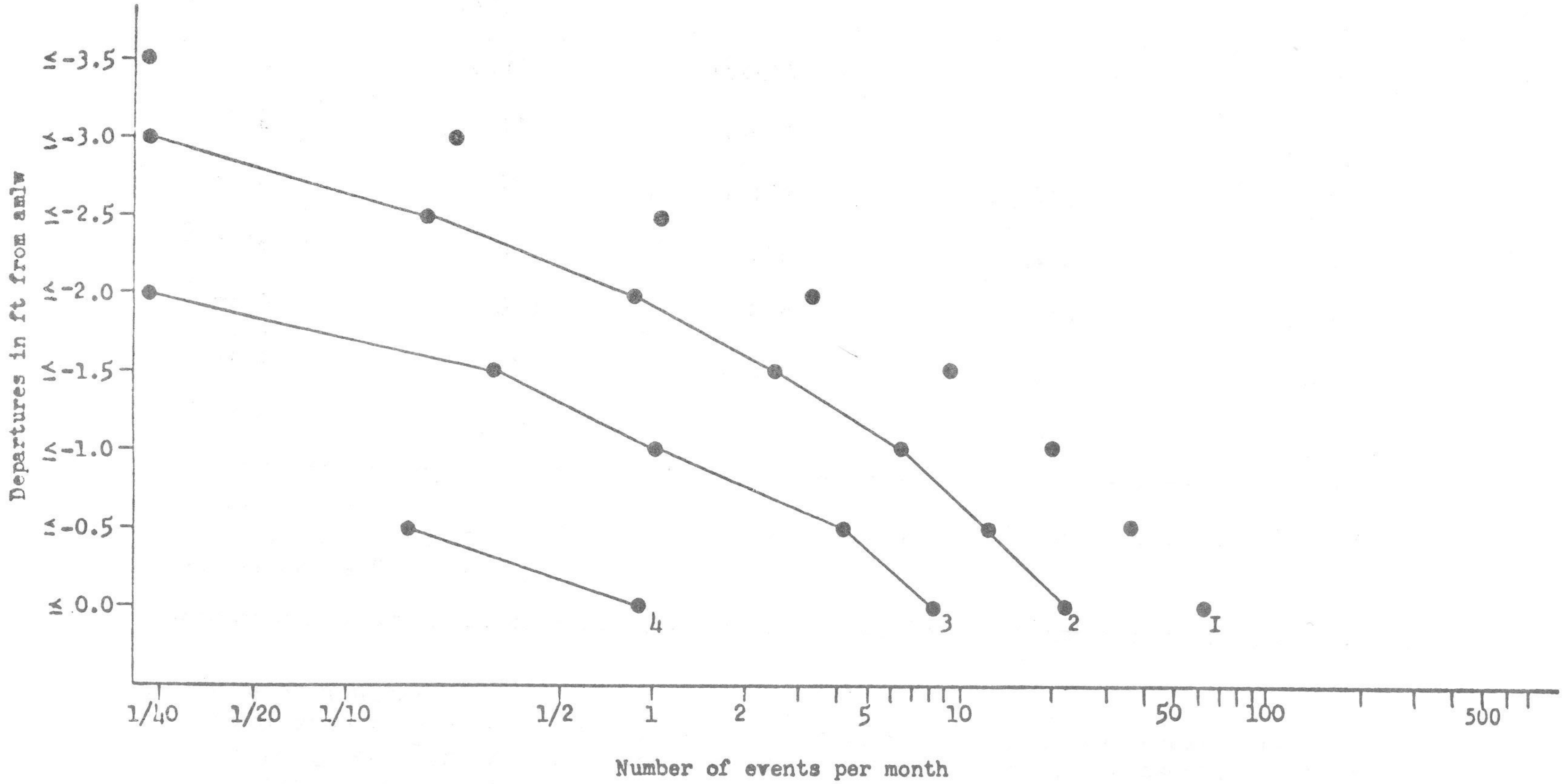

Figure 18. Same as Fig. 5 except for low water levels which occurred in January.

Table 15. Same as Table 14 except for February. Frequencies are based on 43 months.

Specified heights (Departures from amlw in ft)	I	Duration			
		$\geq$2h	$\geq$3h	$\geq$4h	$\geq$5h
$\leq$ 0.0	58.8	20.5	7.7	1/2.3	1/43.0
$\leq$ -0.5	33.4	11.5	2.8	1/14.3	
$\leq$ -1.0	18.0	5.7	1/1.2	1/43.0	
$\leq$ -1.5	8.3	2.2	1/4.3	1/43.0	
$\leq$ -2.0	2.7	1/2.0	1/43.0		
$\leq$ -2.5	1/1.5	1/14.3			
$\leq$ -3.0	1/8.6				
$\leq$ -3.5	1/43.0				

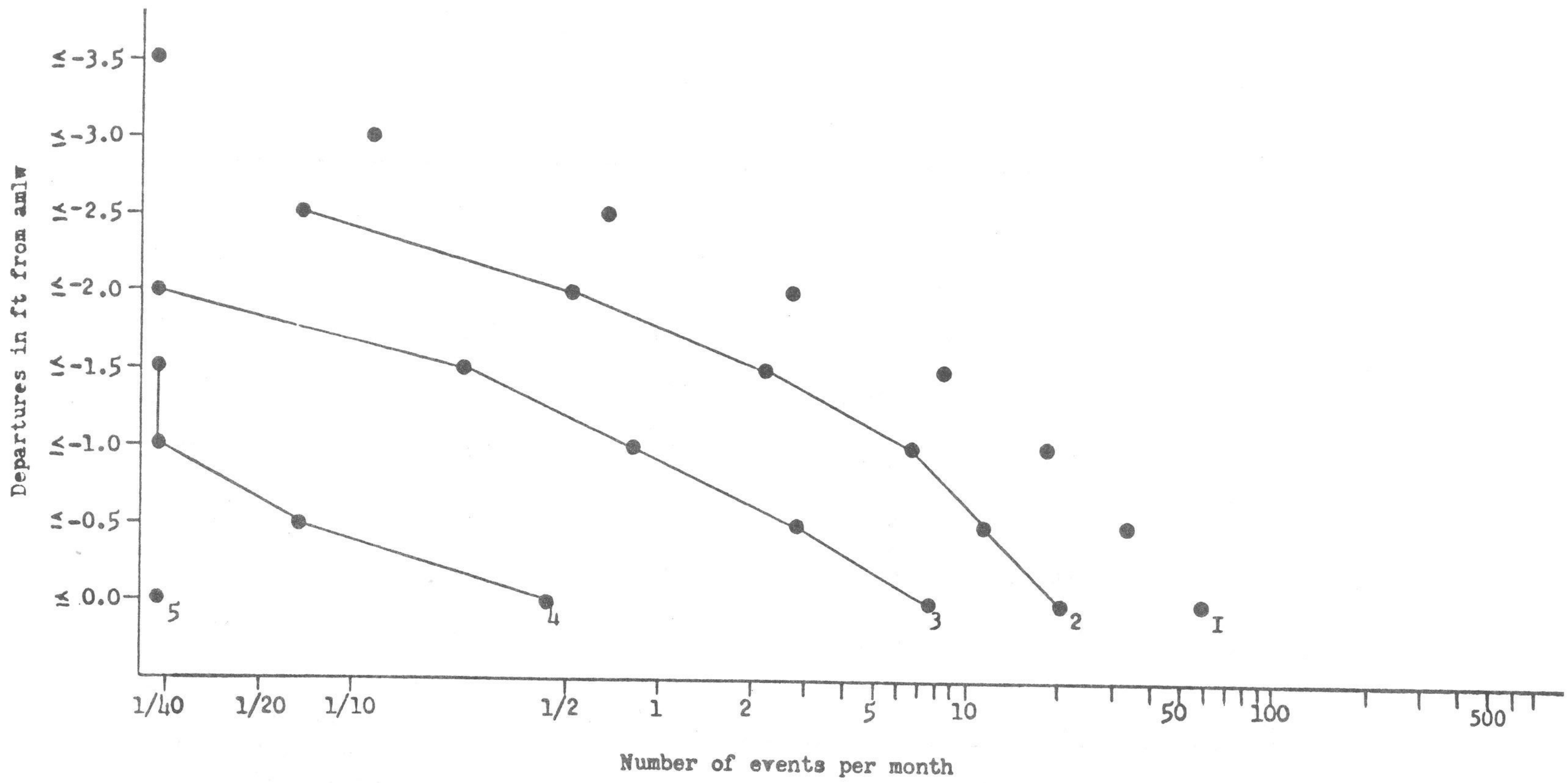

Figure 19. Same as Fig. 5 except for low water levels which occurred in February.

Table 16. Same as Table 14 except for March. Frequencies are based on 43.5 months.

Specified heights (Departures from amlw in ft)	I	Duration		
		$\geq$2h	$\geq$3h	$\geq$4h
$\leq$ 0.0	61.0	21.3	8.3	1/1.5
$\leq$ -0.5	36.4	12.4	3.5	1/6.2
$\leq$ -1.0	20.0	6.6	1/1.1	1/43.5
$\leq$ -1.5	10.2	2.9	1/4.0	
$\leq$ -2.0	4.0	1/1.3	1/10.9	
$\leq$ -2.5	1.1	1/4.8		
$\leq$ -3.0	1/3.6	1/21.8		
$\leq$ -3.5	1/21.8			

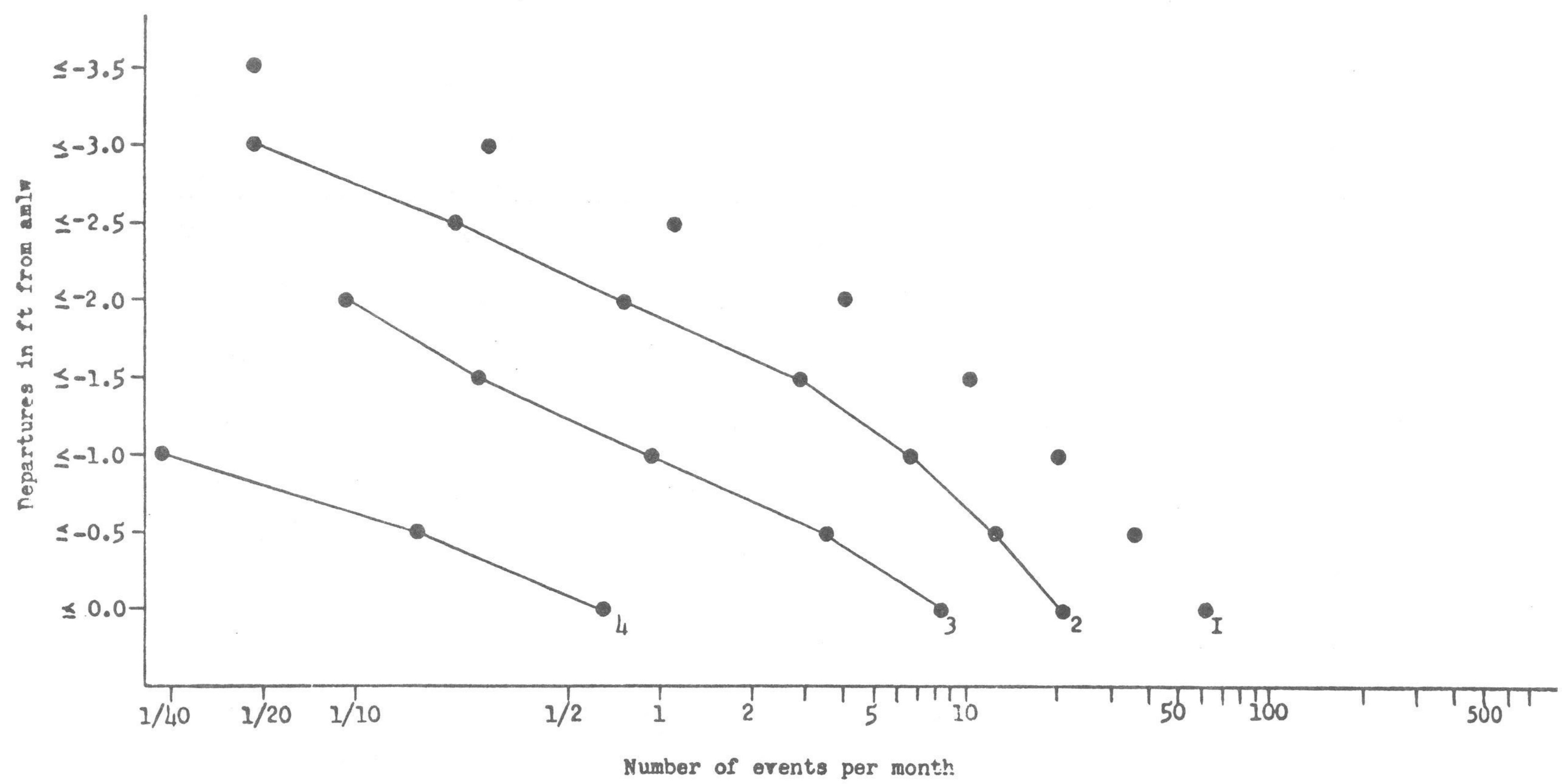

Figure 20. Same as Fig. 5 except for low water levels which occurred in March.

Table 17. Same as Table 14 except for April. Frequencies are based on 43 months.

Specified heights (Departures from amlw in ft)	I	Duration ≥2h	Duration ≥3h	Duration ≥4h
≤ 0.0	54.7	19.3	5.8	1/2.5
≤ -0.5	31.6	10.8	2.1	1/43.0
≤ -1.0	16.3	5.0	1/1.5	
≤ -1.5	6.7	1.8	1/10.7	
≤ -2.0	2.5	1/2.0		
≤ -2.5	1/1.5	1/21.5		
≤ -3.0	1/14.3			

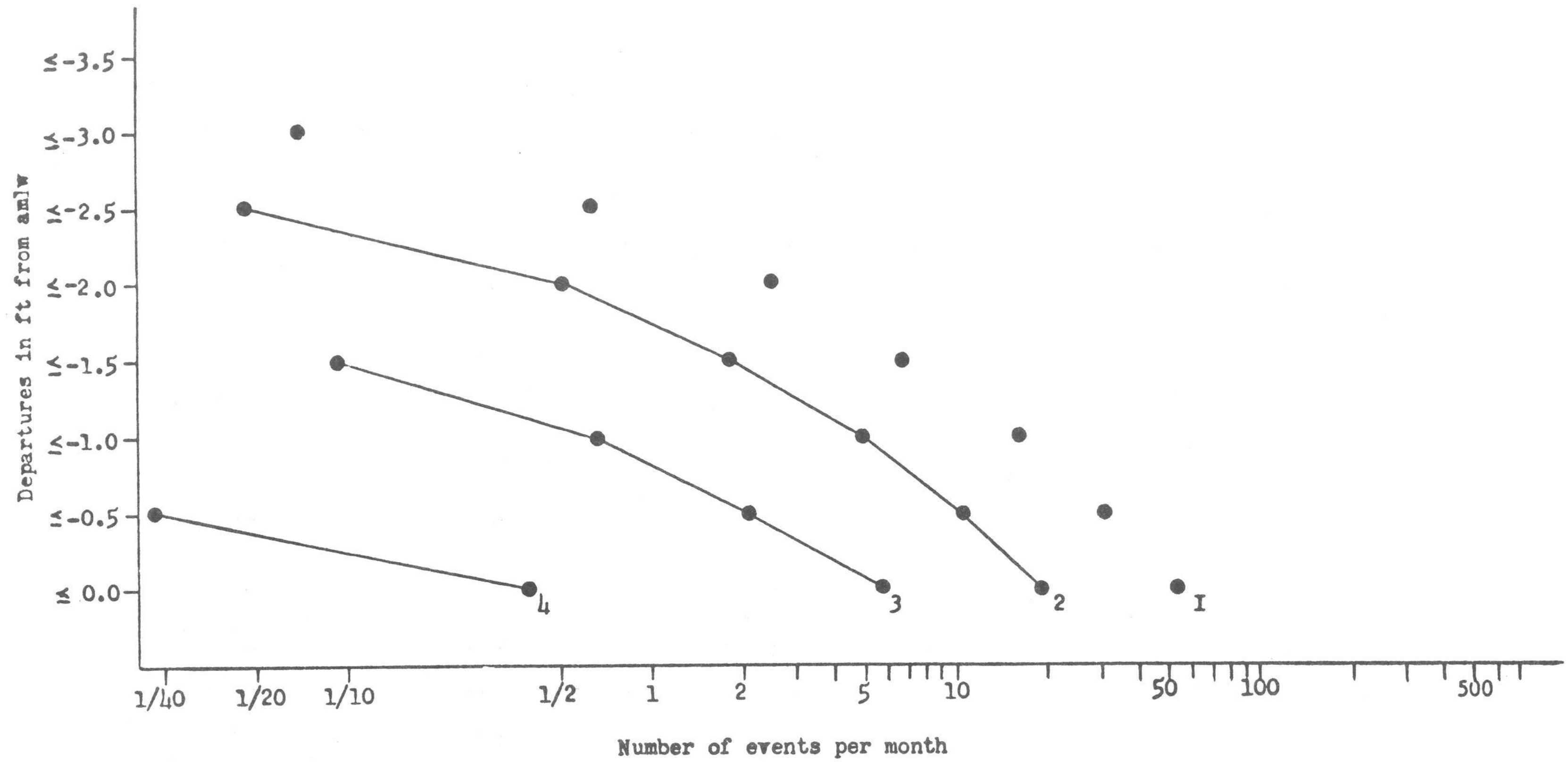

Figure 21. Same as Fig. 5 except for low water levels which occurred in April.

Table 18. Same as Table 14 except for May. Frequencies are based on 43.6 months.

Specified heights (Departures from amlw in ft)	I	Duration		
		≥2h	≥3h	≥4h
≤ 0.0	51.9	18.1	5.6	1/3.1
≤ -0.5	27.3	9.1	1.7	1/43.6
≤ -1.0	14.1	4.2	1/2.1	
≤ -1.5	6.1	1.6	1/14.5	
≤ -2.0	2.0	1/2.9		
≤ -2.5	1/1.9	1/14.5		
≤ -3.0	1/14.5			

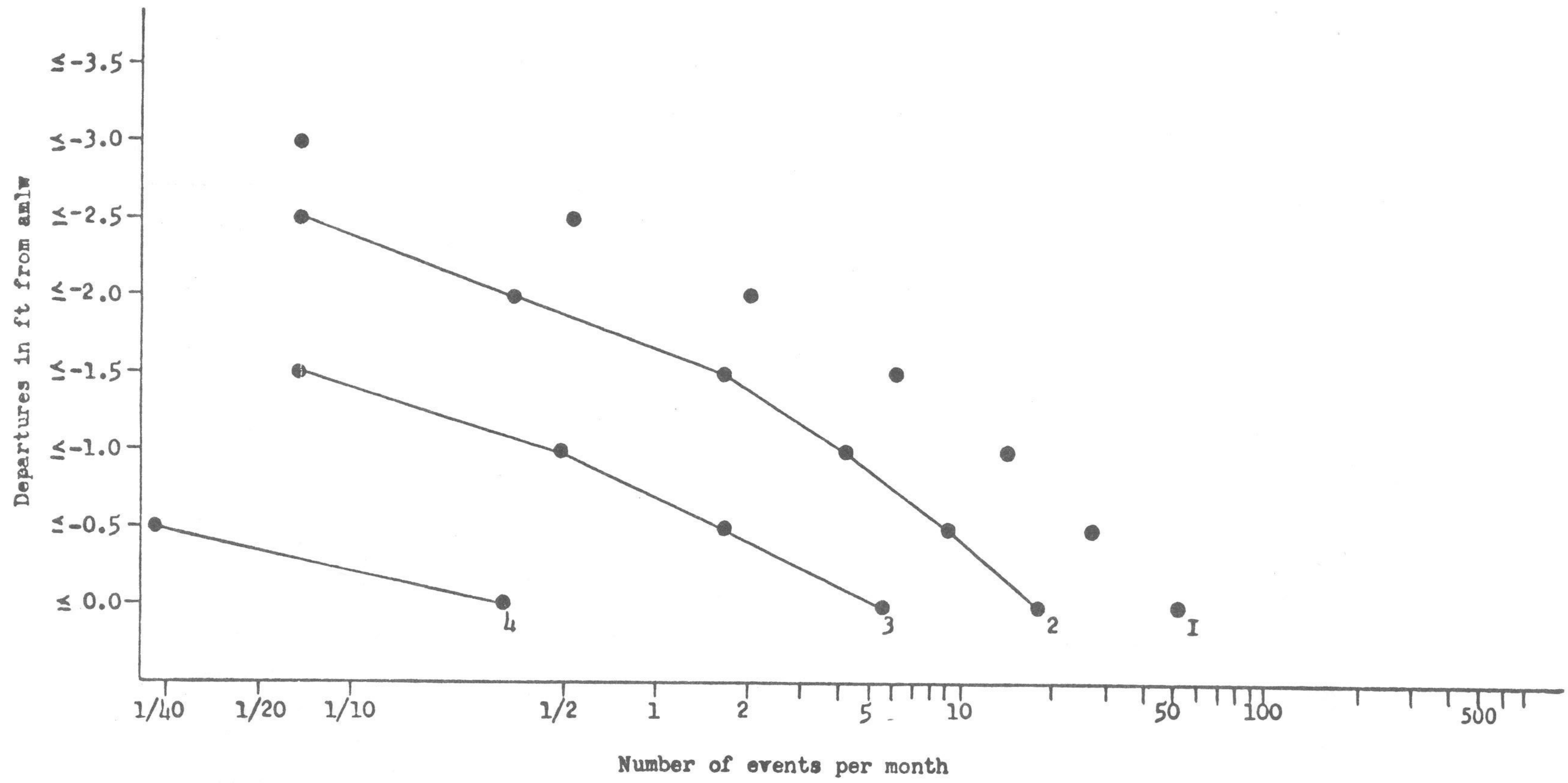

Figure 22. Same as Fig. 5 except for low water levels which occurred in May.

Table 19. Same as Table 14 except for June. Frequencies are based on 42.9 months.

Specified heights (Departures from amlw in ft)	I	Duration		
		≥2h	≥3h	≥4h
≤ 0.0	46.7	15.7	4.6	1/3.9
≤ -0.5	24.4	7.8	1.6	
≤ -1.0	11.6	3.8	1/4.3	
≤ -1.5	4.7	1.1		
≤ -2.0	1.3	1/7.2		
≤ -2.5	1/10.7			

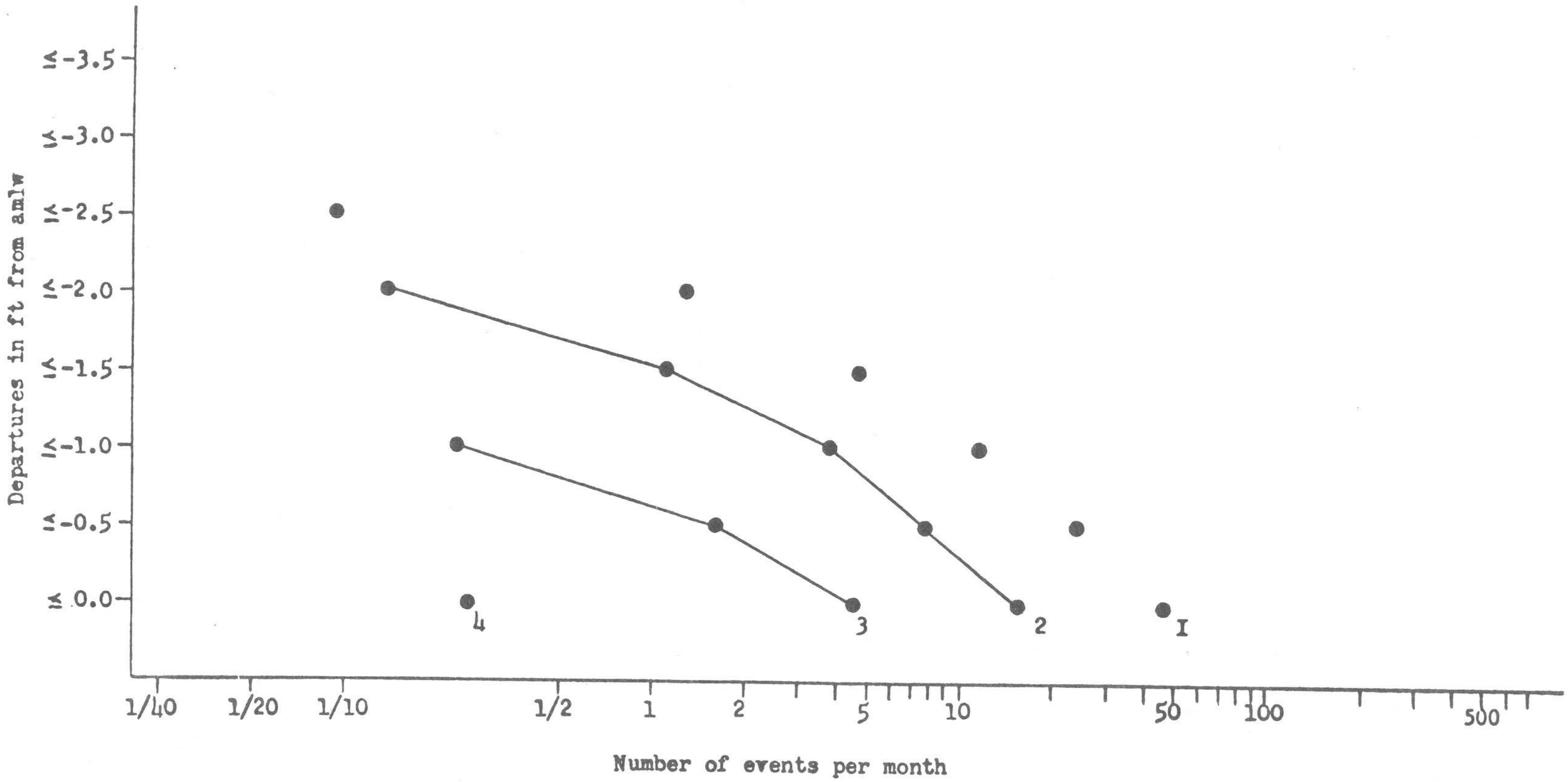

Figure 23. Same as Fig. 5 except for low water levels which occurred in June.

Table 20. Same as Table 14 except for July. Frequencies are based on 43 months.

Specified heights (Departures from amlw in ft)	I	Duration		
		≥2h	≥3h	≥4h
≤ 0.0	50.3	16.9	4.9	1/43.0
≤ -0.5	26.6	8.8	1.4	
≤ -1.0	12.3	3.7	1/4.8	
≤ -1.5	5.0	1.1		
≤ -2.0	1.1	1/21.5		
≤ -2.5	1/14.3			

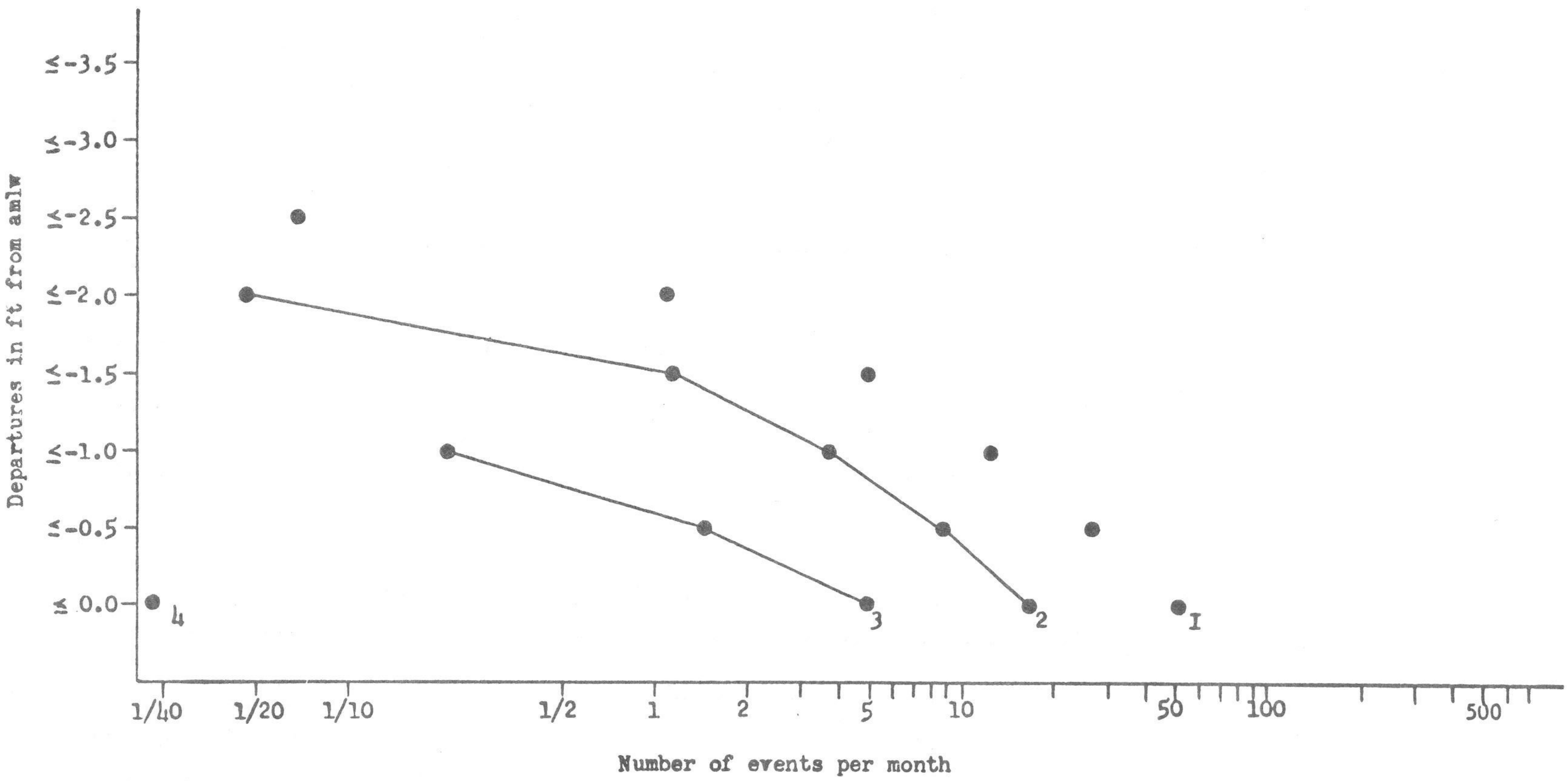

Figure 24. Same as Fig. 5 except for low water levels which occurred in July.

Table 21. Same as Table 14 except for August. Frequencies are based on 43 months.

Specified heights (Departures from amlw in ft)	I	Duration		
		≥2h	≥3h	≥4h
≤ 0.0	48.2	17.0	3.9	1/43.0
≤ -0.5	25.7	8.5	1/1.2	
≤ -1.0	11.5	3.1	1/14.3	
≤ -1.5	3.4	1/2.4		
≤ -2.0	1/1.7	1/43.0		
≤ -2.5	1/43.0			
≤ -3.0	1/43.0			

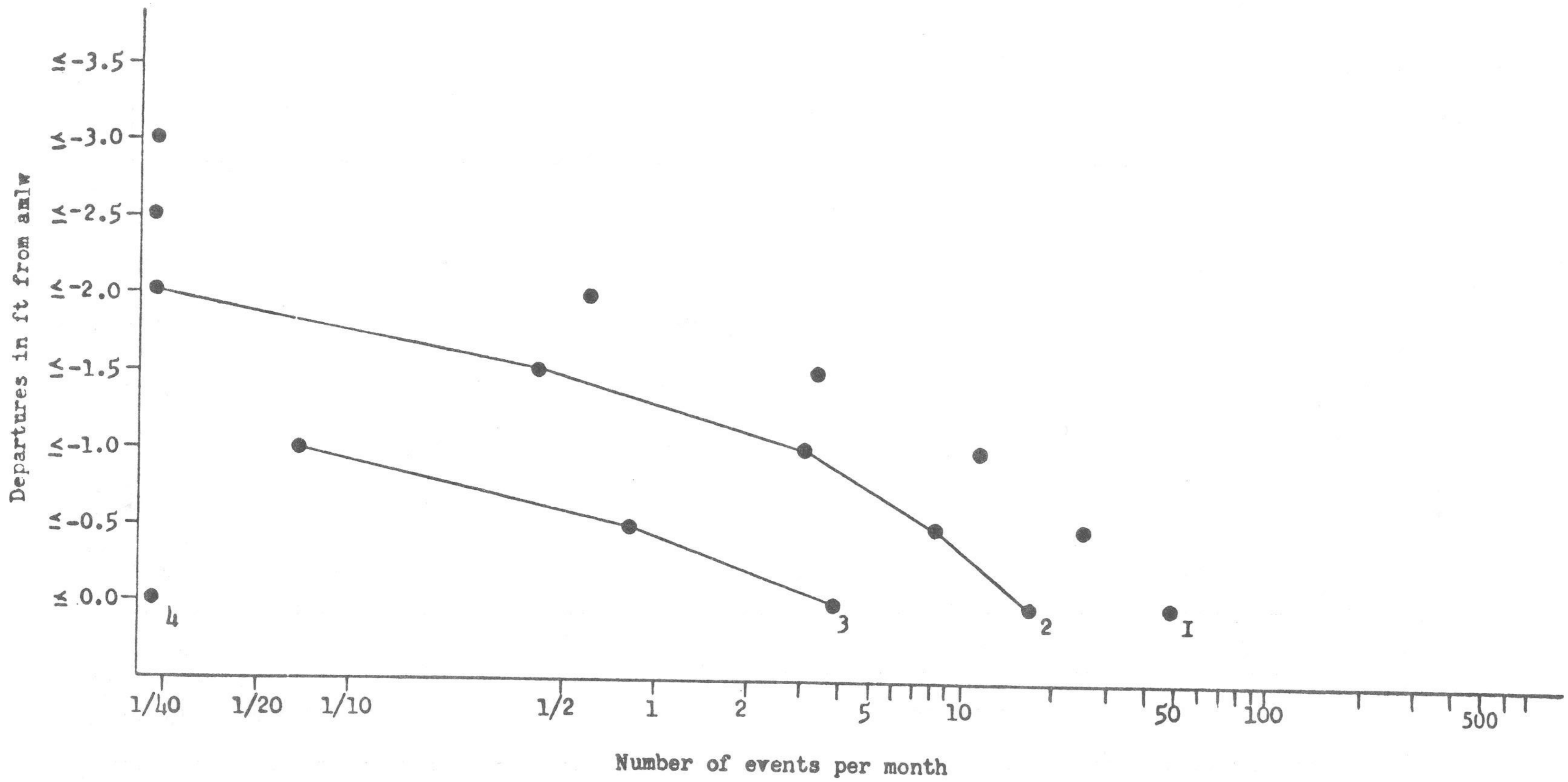

Figure 25. Same as Fig. 5 except for low water levels which occurred in August.

Table 22. Same as Table 14 except for September. Frequencies are based on 43.1 months.

Specified heights (Departures from amlw in ft)	I	Duration ≥2h	≥3h	≥4h
≤ 0.0	47.0	16.3	4.3	1/43.1
≤ -0.5	26.2	9.4	1.3	
≤ -1.0	13.2	4.0	1/14.4	
≤ -1.5	5.2	1/1.1		
≤ -2.0	1.0	1/14.4		
≤ -2.5	1/10.8			

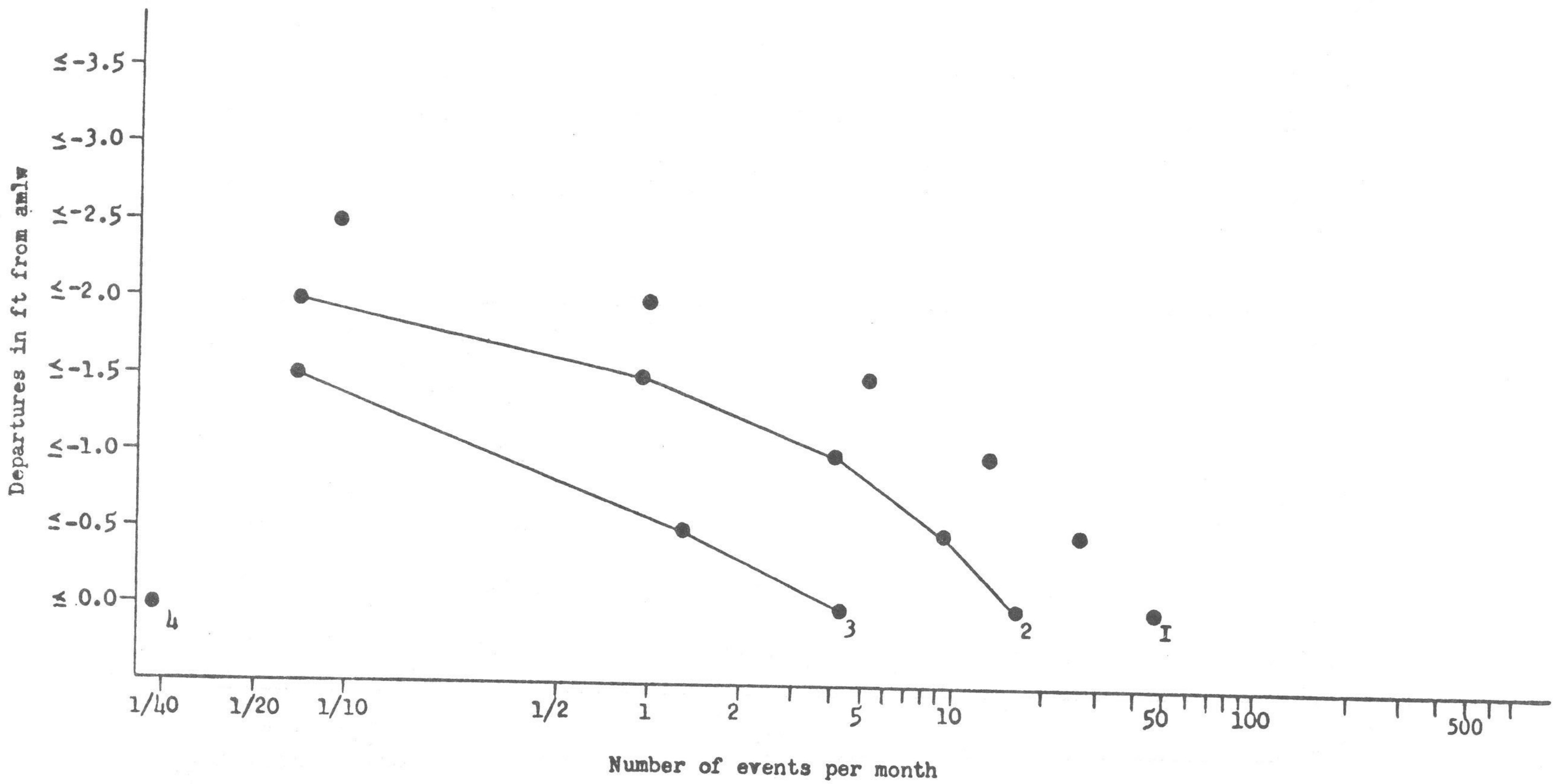

Figure 26. Same as Fig. 5 except for low water levels which occurred in September.

Table 23. Same as Table 14 except for October. Frequencies are based on 41.4 months.

Specified heights (Departures from amlw in ft)	I	Duration $\geq 2h$	Duration $\geq 3h$	Duration $\geq 4h$
$\leq$ 0.0	47.5	16.8	4.5	1/20.7
$\leq$ -0.5	25.9	8.6	1.5	
$\leq$ -1.0	12.1	3.5	1/3.0	
$\leq$ -1.5	5.0	1.2	1/41.4	
$\leq$ -2.0	1.5	1/5.2		
$\leq$ -2.5	1/4.6			
$\leq$ -3.0	1/41.4			

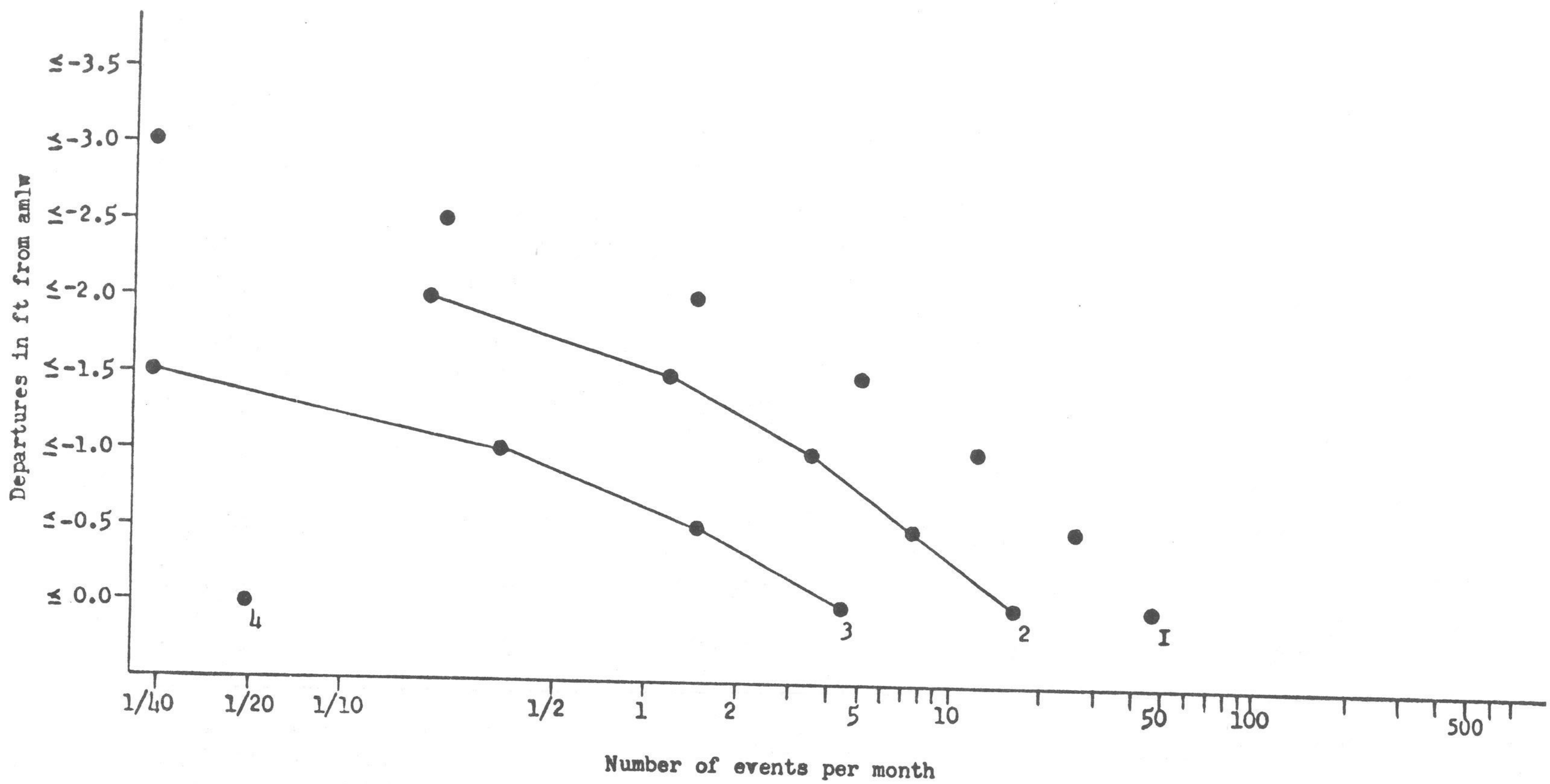

Figure 27. Same as Fig. 5 except for low water levels which occurred in October.

Table 24. Same as Table 14 except for November. Frequencies are based on 42.8 months.

Specified heights (Departures from amlw in ft)	I	Duration		
		≥2h	≥3h	≥4h
≤ 0.0	47.0	16.2	5.1	1/2.3
≤ -0.5	25.7	8.2	1.9	1/10.7
≤ -1.0	13.2	4.2	1/2.3	1/42.8
≤ -1.5	5.3	1.4	1/21.4	
≤ -2.0	2.0	1/2.5		
≤ -2.5	1/2.1	1/8.6		
≤ -3.0	1/14.3	1/42.8		
≤ -3.5	1/42.8			

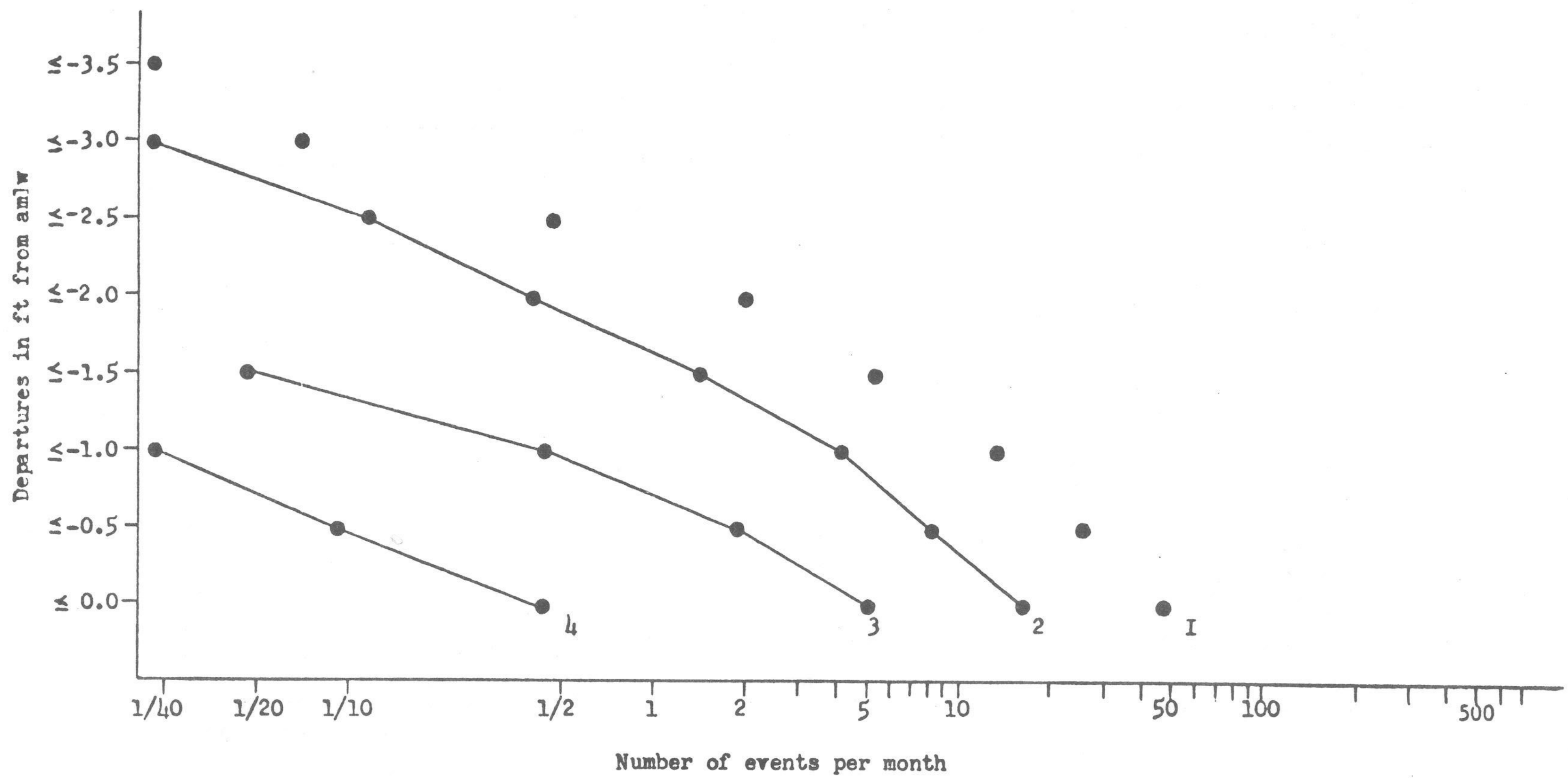

Figure 28. Same as Fig. 5 except for low water levels which occurred in November.

Table 25. Same as Table 14 except for December. Frequencies are based on 43.3 months.

Specified heights (Departures from amlw in ft)	I	Duration		
		≥2h	≥3h	≥4h
≤ 0.0	58.3	20.4	7.3	1/1.4
≤ -0.5	33.6	11.2	2.9	1/8.7
≤ -1.0	17.3	5.5	1/1.1	
≤ -1.5	8.0	2.4	1/7.2	
≤ -2.0	3.0	1/1.5	1/43.3	
≤ -2.5	1/1.3	1/10.8		
≤ -3.0	1/10.8			
≤ -3.5	1/43.3			

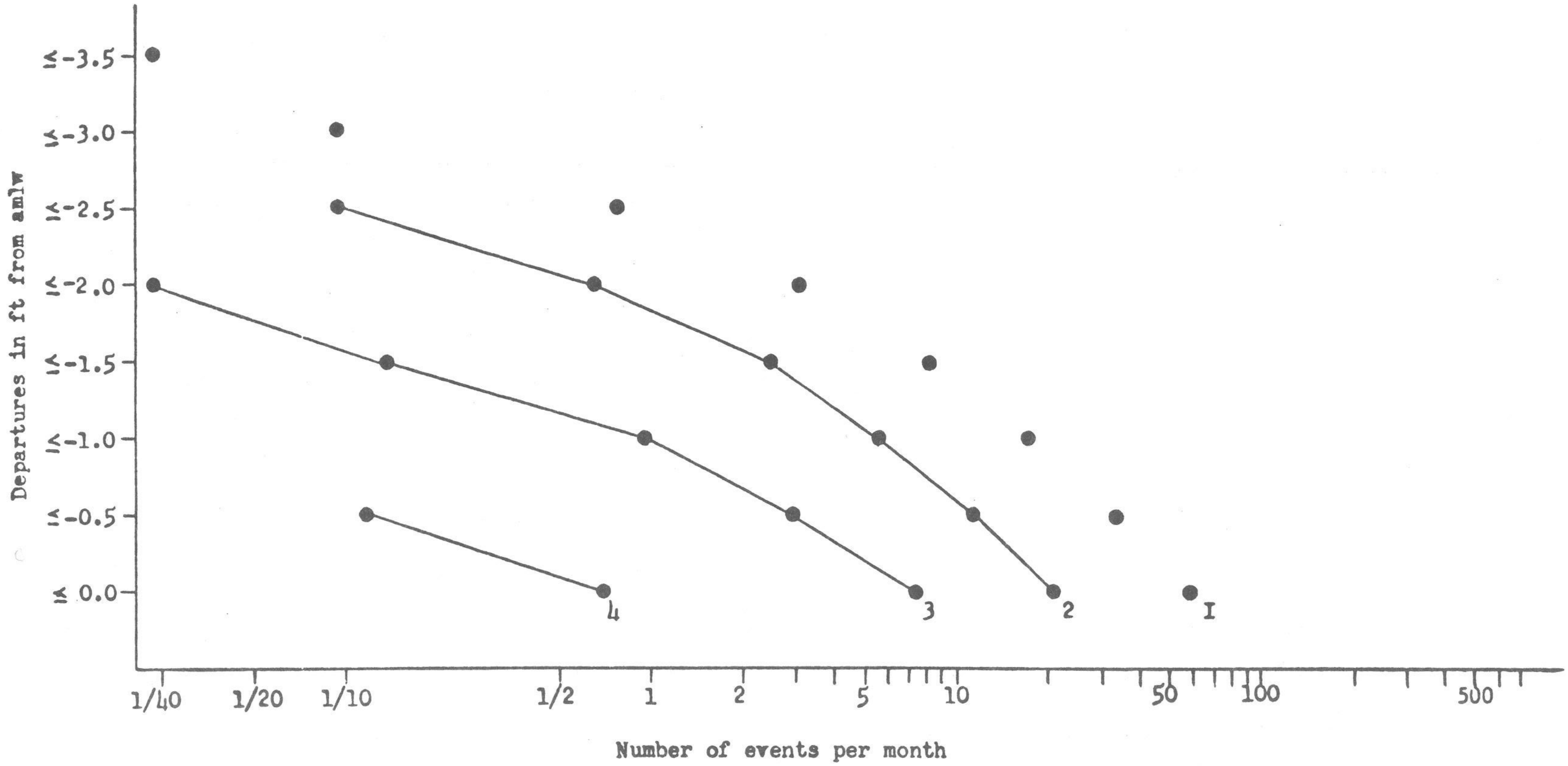

Figure 29. Same as Fig. 5 except for low water levels which occurred in December.

Table 26. Same as Table 14 except for averaged yearly frequencies which are based on 43 years.

Specified heights (Departures from amlw in ft)	I	Duration ≥2h	≥3h	≥4h	≥5h
≤ 0.0	633.7	220.8	70.3	4.2	1/43.0
≤ -0.5	353.5	118.7	24.9	1/1.5	
≤ -1.0	179.2	55.8	6.2	1/14.4	
≤ -1.5	77.1	19.8	1.2	1/43.0	
≤ -2.0	25.0	4.5	1/6.2		
≤ -2.5	5.7	1/1.3			
≤ -3.0	1.0	1/10.8			
≤ -3.5	1/7.2				

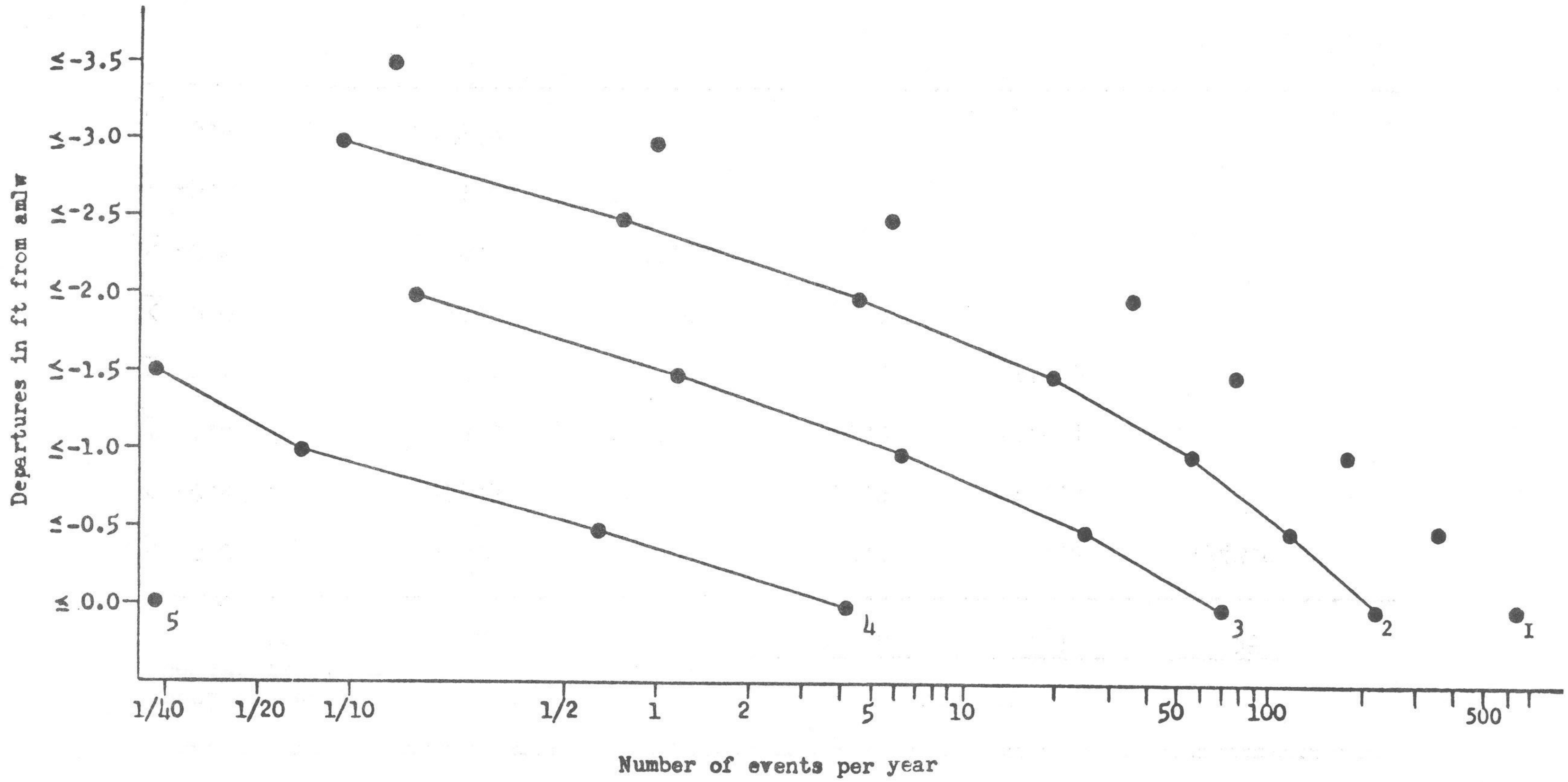

Figure 30. Same as Fig. 5 except for yearly frequencies associated with low water levels.

Table 27. Maximum and minimum annual tide levels and maximum annual positive and negative surges at Boston.

	MAXIMUM AND MINIMUM ANNUAL TIDE LEVELS (Departures from amlw in ft)				MAXIMUM ANNUAL POSITIVE AND NEGATIVE STORM SURGES (ft)			
Year	Max.	Date	Min.	Date	Positive	Date	Negative	Date
1922	12.1	4-11			2.7	12-29		
23	11.8	4-30			3.1	3-7		
24	11.9	2-6			3.2	3-11		
1925	11.6	6-9			1.7	1-20		
26	12.4	2-10			2.4	2-4		
27	12.1	3-3			3.1	2-20		
28	12.3	12-28			2.0	1-20		
29	12.2	4-13			2.8	4-16		
1930	11.9	2-15			2.3	10-25		
31	13.5	3-4			2.8	3-8		
32	12.4	11-30			2.3	3-7		
33	13.0	1-28			2.1	12-4		
34	11.8	10-23			2.0	2-20		
1935	12.0	12-9			4.1	11-17		
36	12.4	10-1	-3.3	12-28	3.1	1-19	-2.7	1-24
37	12.5	11-20	-2.6	6-10	1.9	2-17	-2.1	12-14
38	12.5	1-17	-2.5	12-10	2.3	9-21	-1.9	12-28
39	12.6	4-2	-3.0	3-8	3.2	1-31	-2.2	3-8
1940	13.4	4-21	-3.7	3-24	4.2	2-14	-2.8	3-24
41	12.1	5-11	-2.9	4-13	2.4	3-1	-1.6	1-14
42	11.9	5-31	-3.0	1-17	2.4	1-29	-2.1	12-19
43	12.1	8-17	-3.2	1-7	2.5	10-27	-3.2	1-21
44	13.4	11-30	-2.7	12-28	2.8	9-15	-2.2	2-15
1945	12.6	11-20	-2.4	12-18	4.9	11-30	-1.8	1-2
46	12.2	12-9	-2.2	6-29	2.5	2-20	-2.0	2-16
47	12.8	11-12	-2.7	12-29	3.8	3-3	-1.9	1-22
48	12.5	1-2	-2.9	1-26	2.7	12-31	-2.0	2-15
49	11.9	10-22	-2.5	3-17	2.4	3-1	-2.0	2-3
1950	12.4	12-11	-3.1	5-3	3.6	11-26	-2.5	6-13
51	12.2	5-24	-2.6	4-24	2.1	3-11	-2.1	12-19
52	12.8	2-28	-2.6	1-27	3.2	2-18	-1.5	2-29
53	12.6	4-13	-1.9	2-16	3.0	11-7	-2.0	2-16
54	12.8	8-31	-3.2	11-11	3.5	8-31	-3.0	4-3
1955	12.5	4-26	-3.5	11-30	2.0	10-17	-2.0	11-30
56	13.0	3-17	-3.2	2-26	3.4	3-16	-2.1	3-9
57	12.1	2-15	-3.1	1-19	2.3	12-5	-2.0	12-1
58	13.1	4-7	-2.8	12-10	3.5	2-16	-2.0	11-30
59	13.7	12-29	-2.7	12-1	2.9	3-12	-2.1	3-14
1960	12.6	3-4	-2.5	7-10	3.8	3-4	-2.8	2-23
61	13.2	1-20	-3.1	1-18	4.7	4-13	-1.9	11-13
62	12.9	3-7	-3.0	8-6	3.5	11-15	-2.7	7-20
63	12.8	11-2	-3.6	12-30	2.4	11-7	-2.4	12-20
64	12.2	2-16	-3.1	12-19	2.7	2-19	-2.6	12-2
1965	12.0	7-28	-3.0	1-19	2.5	2-25	-1.8	2-23
66	12.2	3-6	-2.6	2-6	3.8	1-30	-1.7	12-30
67	13.4	5-26	-2.4	5-24	2.3	5-25	-1.5	3-19
68	12.4	12-23	-2.7	5-14	3.7	11-12	-3.0	1-8
69	12.3	11-12	-2.7	1-20	3.3	12-27	-2.8	1-2
1970	12.2	1-8	-2.8	2-6	2.4	12-17	-1.8	2-23
71	12.3	10-6	-2.6	1-28	3.0	8-14	-3.3	8-14
72	13.4	2-19	-2.4	11-22	4.0	2-19	-2.8	1-26
73	12.8	4-5	-2.2	11-12	3.0	1-29	-1.8	11-2
74	12.6	12-2	-3.0	1-8	2.6	12-2	-2.4	2-23
1975	11.8	11-3	-3.1	2-27	2.7	4-3	-1.7	12-20
76	13.1	3-16	-3.7	2-2	2.5	3-16	-3.6	2-2
77	12.2	10-14	-2.8	4-4	3.6	3-22	-2.2	1-11
78	14.7	2-7	-3.6	1-10	4.6	2-6	-1.9	3-6
79	13.6	1-25	-2.8	3-28	3.7	1-25	-1.9	12-9

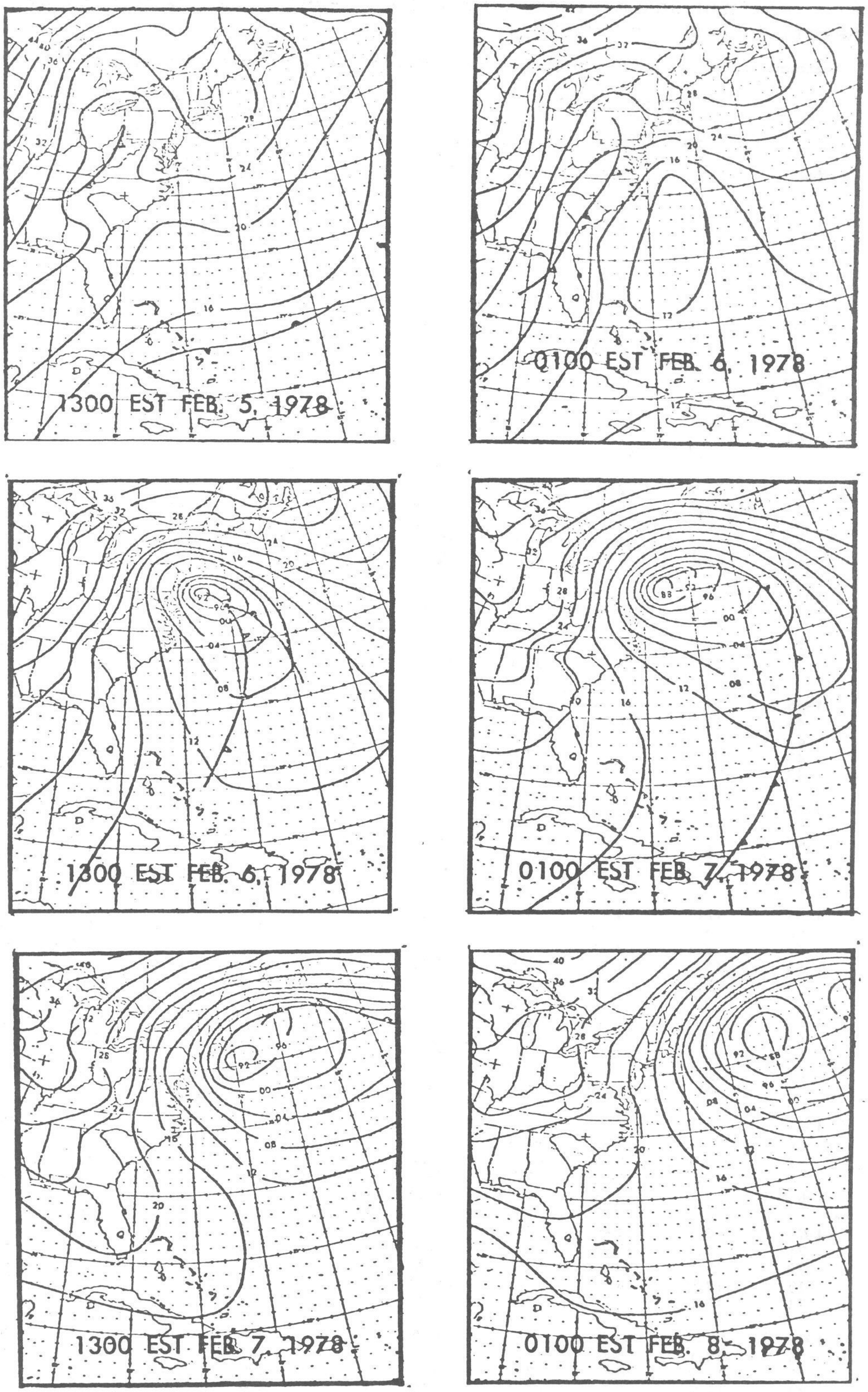

Figure 31. Sea-level pressure charts from 1300 EST February 5, 1978 to 0100 EST February 8, 1978.

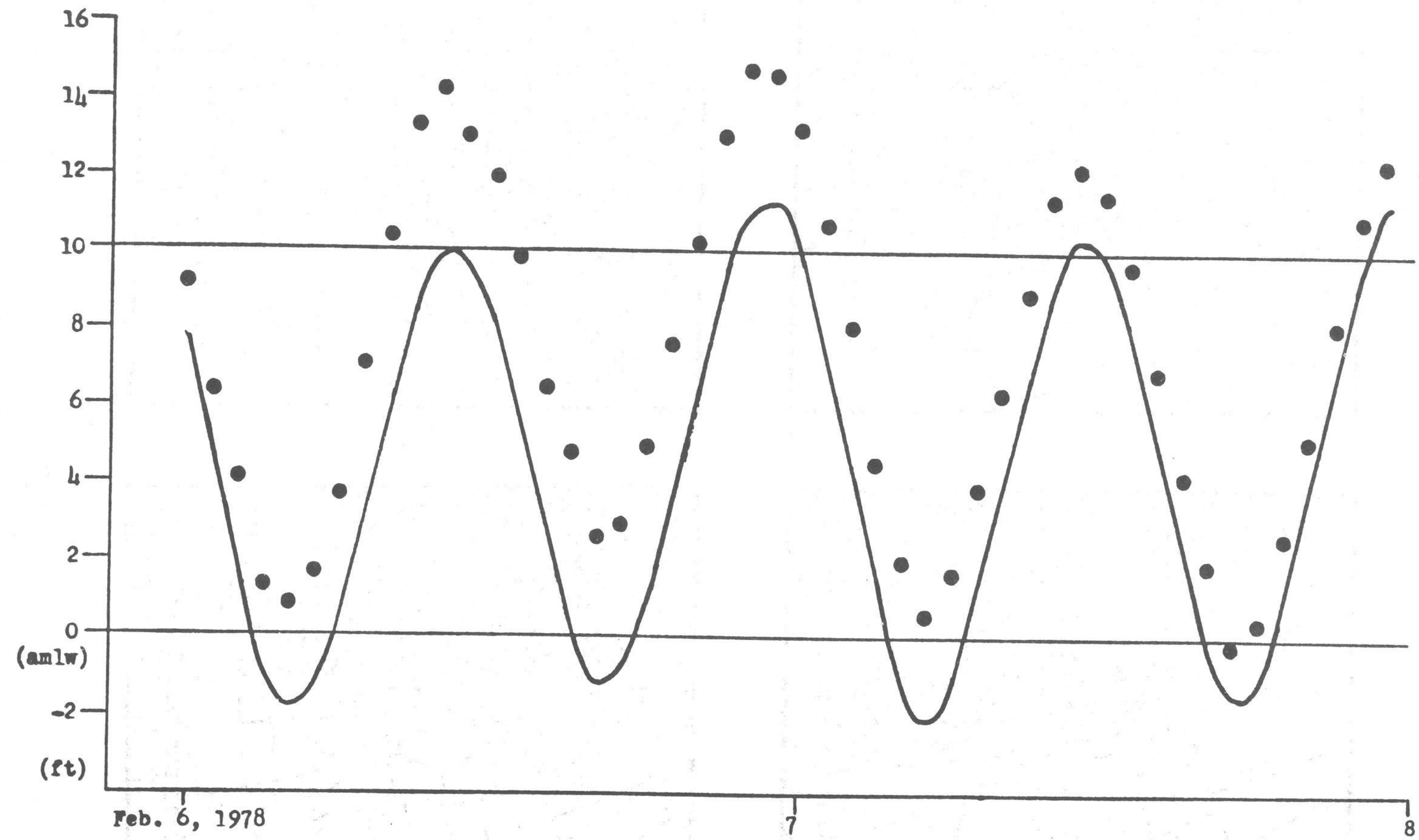

Figure 32. Astronomical tide (solid curve) and measured hourly tides (dots) for the February high tide event. Solid lines at amlw and 10 ft above amlw depict our low and high water criteria. Dates are shown at 1200 EST.

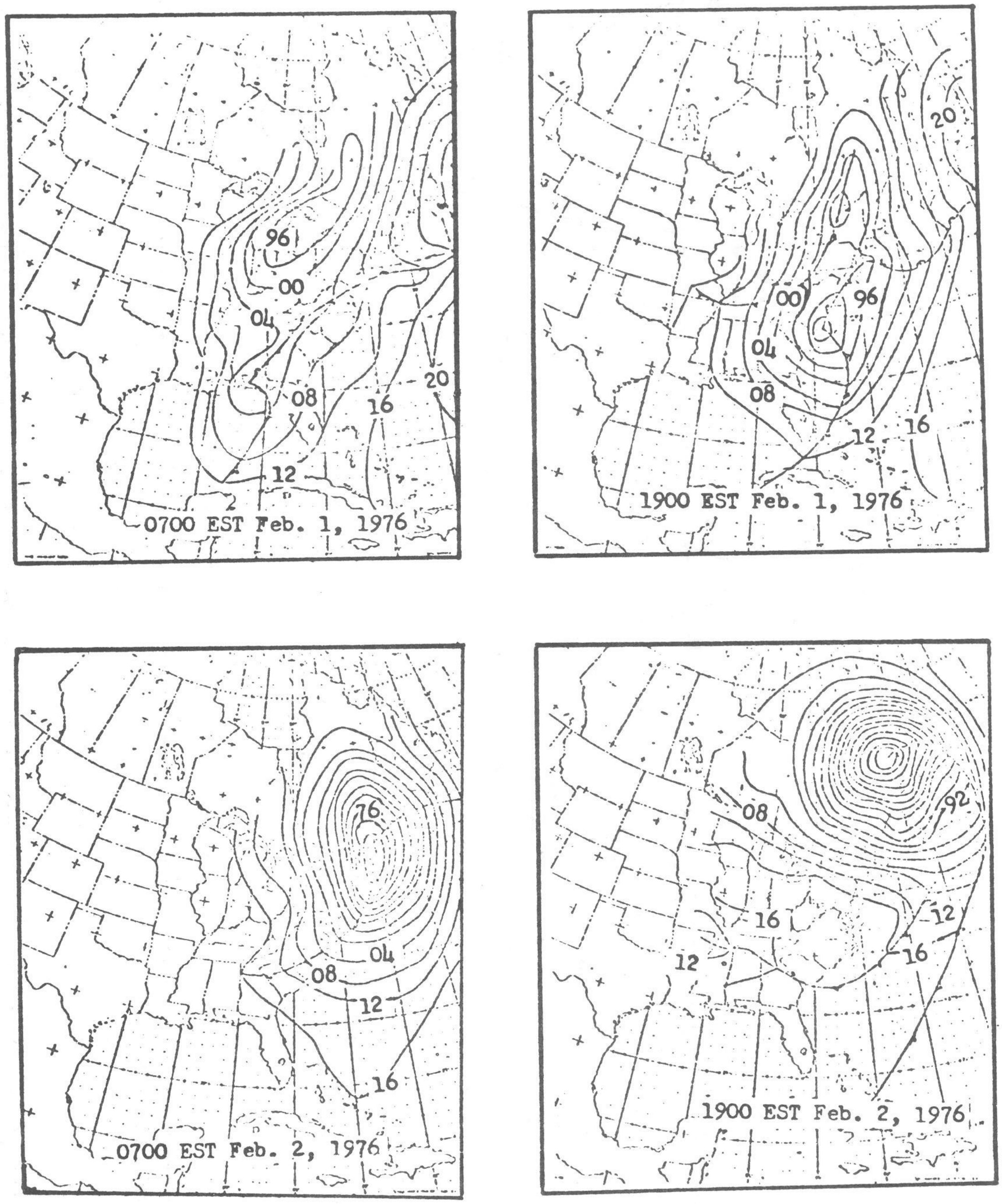

Figure 33. Sea-level pressure charts from 0700 EST February 1, 1976 to 1900 EST February 2, 1976.

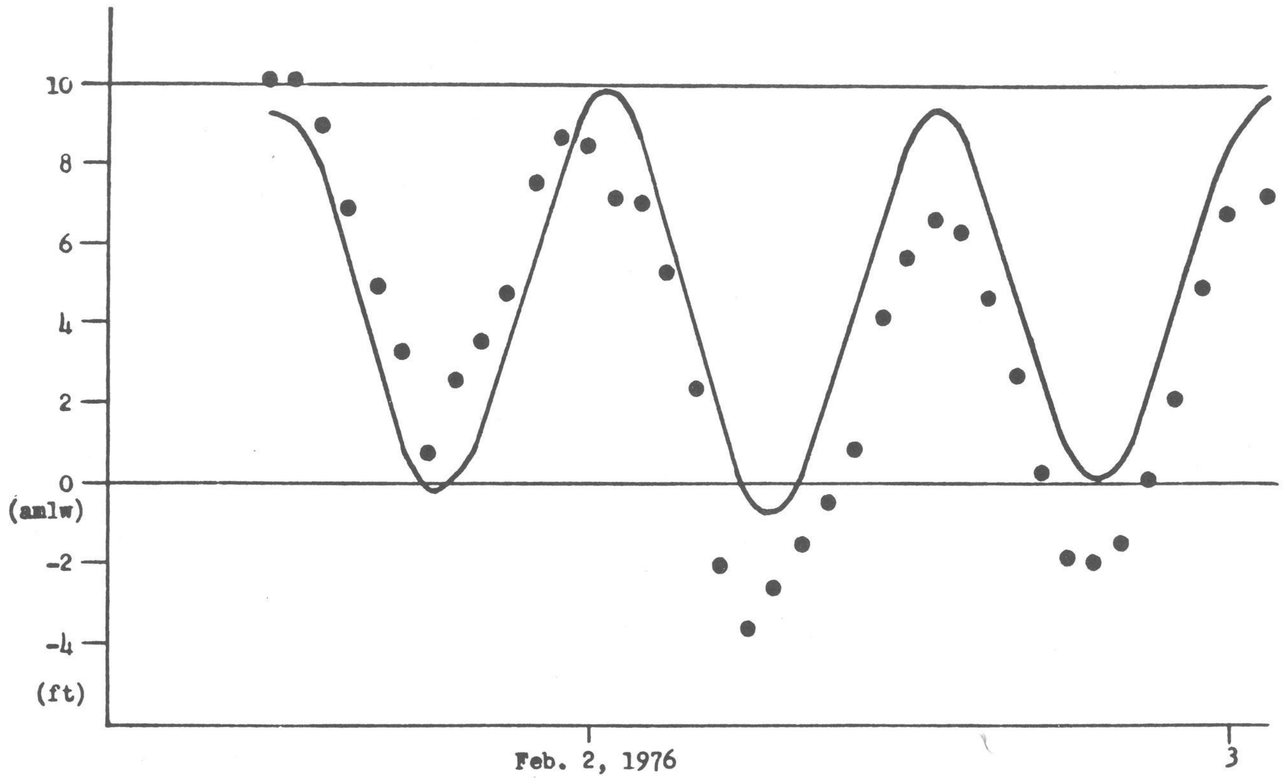

Figure 34. Astonomical tide (solid curve) and measured hourly tides (dots) for the February low tide event. Solid lines at amlw and 10 ft above amlw depict our low and high water criteria. Dates are shown at 1200 EST.

(Continued from inside front cover)

NOAA Technical Memorandums

NWS TDL 39 Computer Prediction of Precipitation Probability for 108 Cities in the United States. William H. Klein, February 1971, 32 pp. (COM-71-00249)

NWS TDL 40 Wave Climatology for the Great Lakes. N. A. Pore, J. M. McClelland, C. S. Barrientos, and W. E. Kennedy, February 1971, 61 pp. (COM-71-00368)

NWS TDL 41 Twice-Daily Mean Monthly Heights in the Troposphere Over North America and Vicinity. August F. Korte, June 1971, 31 pp. (COM-71-00826)

NWS TDL 42 Some Experiments With a Fine-Mesh 500-Millibar Barotropic Model. Robert J. Bermowitz, August 1971, 20 pp. (COM-71-00958)

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