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LAKE POWELL
RESEARCH PROJECT
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THE EXCELLENT BUT DETERIORATING AIR QUALITY IN THE LAKE POWELL REGION

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NATIONAL SCIENCE FOUNDATION
RESEARCH APPLIED TO NATIONAL NEEDS

LAKE POWELL RESEARCH PROJECT

The Lake Powell Research Project (formally known as Collaborative Research on Assessment of Man's Activities in the Lake Powell Region) is a consortium of university groups funded by the Division of Environmental Systems and Resources in RANN (Research Applied to National Needs) in the National Science Foundation.

Researchers in the consortium bring a wide range of expertise in natural and social sciences to bear on the general problem of the effects and ramifications of water resource management in the Lake Powell region. The region currently is experiencing converging demands for water and energy resource development, preservation of nationally unique scenic features, expansion of recreation facilities, and economic growth and modernization in previously isolated rural areas.

The Project comprises interdisciplinary studies centered on the following topics: (1) level and distribution of income and wealth generated by resources development; (2) institutional framework for environmental assessment and planning; (3) institutional decision-making and resource allocation; (4) implications for federal Indian policies of accelerated economic development of the Navajo Indian Reservation; (5) impact of development on demographic structure; (6) consumptive water use in the Upper Colorado River Basin; (7) prediction of future significant changes in the Lake Powell ecosystem; (8) recreational carrying capacity and utilization of the Glen Canyon National Recreational Area; (9) impact of energy development around Lake Powell; and (10) consequences of variability in the lake level of Lake Powell.

One of the major missions of RANN projects is to communicate research results directly to user groups of the region, which include government agencies, Native American Tribes, legislative bodies, and interested civic groups. The Lake Powell Research Project Bulletins are intended to make timely research results readily accessible to user groups. The Bulletins supplement technical articles published by Project members in scholarly journals.

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ABSTRACT

This Bulletin presents the findings, conclusions, and recommendations made during 4-1/2 years of measuring air quality in the Lake Powell region and collecting the data from other measurement programs. This Bulletin builds on the earlier results presented in Bulletin 3 ("Air Quality in the Lake Powell Region," out of print) of the Lake Powell Research Project.

Although the air quality in the Lake Powell region is still excellent (as of 1977), several variables indicate it is deteriorating. This deterioration shows up in the data for visual range, turbidity, sulfur dioxide, sulfates, sulfation rate, and aerosol mass concentration. The timing of these changes does not clearly indicate that the Navajo Generating Station is the cause of the deterioration.

Methane and ethane concentrations downwind of Page are anomalously lower than the concentrations in Page and at remote sites.

The turbidity coefficients at 380 nanometers are anomalously lower than those at 500 nanometers during 1973, most of 1974, and occasionally during 1975 and 1976.

It is important to continue selected measurements in the future in order to monitor important trends and to learn which sources are causing deterioration. Measurements of visual range, turbidity, some hydrocarbons, oxidant, nitrogen oxides, sulfur dioxide, sulfates, and sulfation rate should continue to be made.

INTRODUCTION

The purpose of this Bulletin is to present and interpret air quality data collected in the Lake Powell region. These data may be used in developing air quality models and in making decisions on future energy projects that will emit significant air pollution in this same region. Some of these air quality data were measured by the Background Air Quality Subproject of the Lake Powell Research Project (LPRP); the rest of the data were collected from other agencies.

This research results from concern over the possible degradation of the clear air in the Lake Powell Region. The concern developed after the construction of Glen Canyon Dam on the Colorado River, which led not only to the birth of Lake Powell but also to the creation of the nearby construction towns of Page, Arizona, and Glen Canyon City, Utah (Figure 1). The rise in the level of Lake Powell since its creation in 1964 has been accompanied by an increase in recreation, involving both automobiles and motorboats. The assured supply of cooling water available in Lake Powell allowed the construction of the 2,310-megawatt (MW) Navajo Generating Station near Page, Arizona. This powerplant, the local municipalities, automobiles, and motorboats are superimposing their effluents on the background air quality of the region. The background air quality also changes with the natural variation of wind-blown dust, emission of terpenes by vegetation, and weather.

Visibility is probably the most important air quality variable with respect to the recreation in the Lake Powell region. Legally, however, there are no regulations for visibility. There are emission regulations for particulates (aerosol) and sulfur dioxide (SO_2). There are ambient air quality standards for particulates, sulfur dioxide (SO_2) nitrogen dioxide (NO_2), oxidant (O_x), hydrocarbons (HC), and carbon monoxide (CO). Air pollution sources like the Navajo Generating Station are legally required to prevent their emissions from causing ground-level concentrations above the ambient air quality standards.

DEFINITION OF AIR QUALITY

Air quality is determined by visibility, turbidity, noise, aerosol, pollutant gases, and radioactivity. The variables for which data are presented in this Bulletin are listed in Table 1.

The constituents of air comprise aerosol and gases. Aerosol consists of all those solid particles and liquid

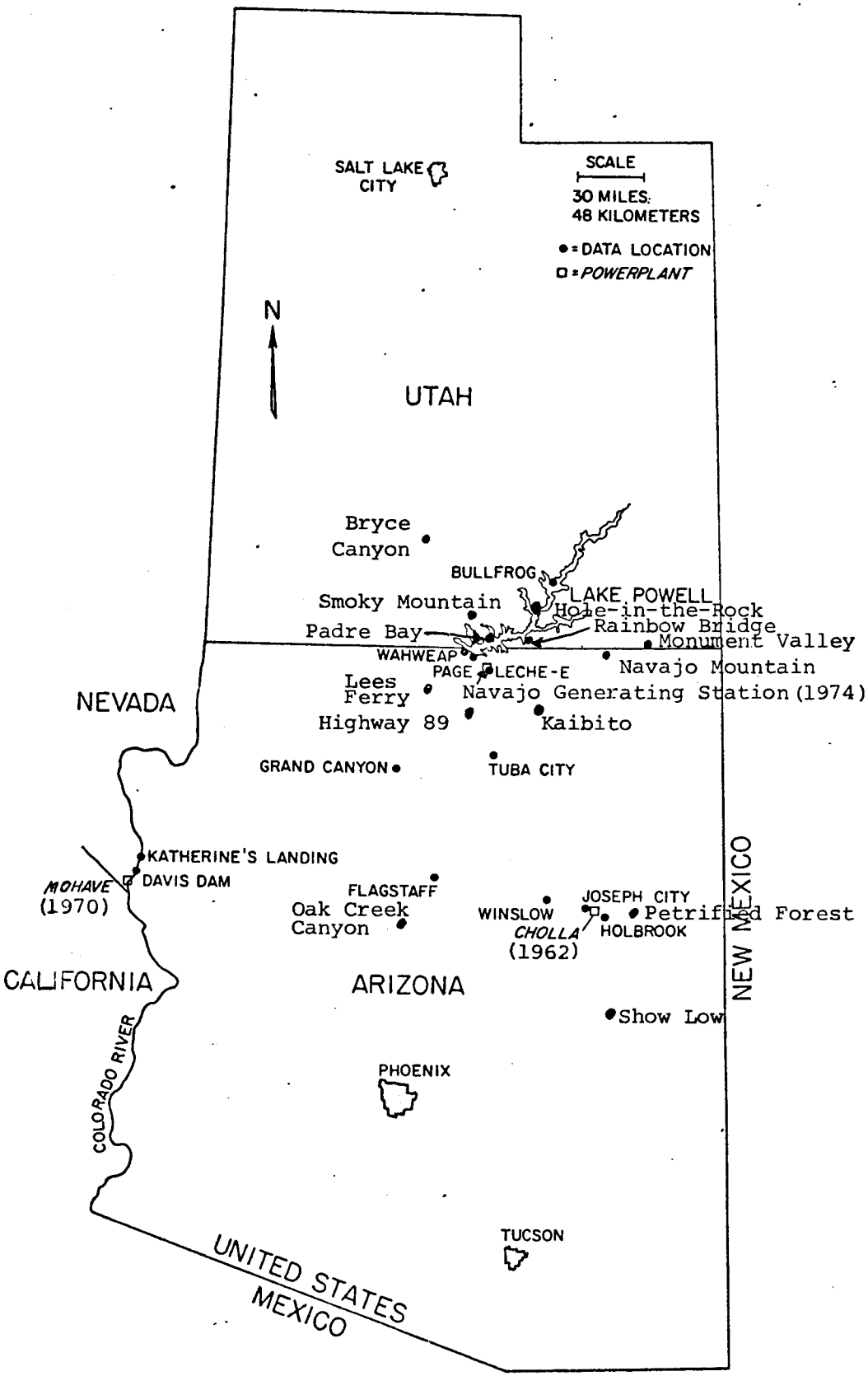


Figure 1: Index Map of Locations for Air Quality Data

Table 1: Air quality variables

Aerosol

- Composition
- Concentration, mass or number
- Size Distribution, mass or number

Gas Concentration

- Carbon Monoxide (CO)
- Hydrocarbons (HC)
  - Methane
  - Ethane
  - Propane
  - Butane
  - Pentane
  - Hexane
  - Ethene (ethylene)
  - Propene
  - Butene
  - Pentene
  - Hexene
  - Acetylene
- Nitrogen Dioxide (NO_2)
- Oxidant (e.g., ozone)
- Sulfur Dioxide (SO_2)
- Sulfation

Noise

Turbidity

Visibility

droplets that range in diameter from 0.002 to 100 microns (μ). There are three important aerosol variables: chemical composition, size distribution, and concentration. Chemical composition usually varies with the aerosol size. The size distribution is important to the health effects of aerosol, determining the deoosition of aerosol along the respiratory tract, while the chemical composition of aerosol determines the health effect of a particle once it deposits on the wall of the respiratory tract.

The Arizona Department of Health Services (ADHS) (]976) included the following constituents in its analysis of aerosol composition: benzene-soluble component, nitrate, sulfate, arsenic, busmuth, cadmium, chromium, cobalt, copper, iron, lead, manganese, mercury, nickel, tin, titanium, vanadium, and zinc. We believe this list also should include phosphorus, selenium, and beryllium. Phosphorus is important to the eutrophication of Lake Powell while selenium and beryllium are important toxic metals in both aquatic and terrestrial ecosystems.

The aerosol concentration may be measured in terms of either number or mass per unit volume of air. Additional information relevant to visibility variations is contained in the size distribution, which is the number or mass concentration in several size intervals.

Nitric oxide (NO) is listed because it is the important precursor of NO_2. Around Lake Powell, automobiles, motorboats, cities, and the Navajo Generating Station are the most important sources of NO. Hydrocarbons are important because they react with NO and NO_2 to form ozone and other photochemical oxidants.

Although noise is not usually considered as an air quality parameter, it is included here because (1) it is so important to the aesthetic quality of the environment around Lake Powell; (2) it will increase with increasing population, industry, and recreation (motorboats); and (3) it is transmitted through the air medium.

Radioactivity in the atmosphere is carried by gases and aerosol. Total beta-activity in the aerosol collected on a filter with a high-volume sampler at Page in 1969 was low enough to indicate to the then Arizona Department of Health Services that there was no threat to health and that such measurements could be suspended. Neither we nor any other program made any measurements of radioactivity.

Turbidity is the atmospheric aerosol loading that attenuates incident solar radiation by scattering and

absorption. Turbidity is quantified by a coefficient, defined as

$$B_\lambda = \{[\log(I_{o\lambda}/I_\lambda S)]/M_h\} - b_{h\lambda} - k_\lambda - W_\lambda$$

from the transmission equation

$$I_\lambda = (I_{o\lambda}/S)10^{-(B_\lambda + k_\lambda + b_{h\lambda} + W_\lambda)M_h}$$

where I_λ = irradiance at observing point and wavelength λ
$I_{o\lambda}$ = extraterrestrial irradiance at wavelength λ
S = correction factor for actual solar distance compared to mean solar distance
$B\lambda$ = turbidity coefficient per unit optical air mass at wavelength λ
k_λ = absorption coefficient per unit optical air mass for ozone at wavelength λ
$b_{h\lambda}$ = Rayleigh scattering of air molecules per unit optical air mass at height h and wavelength λ
$W\lambda$ = water vapor absorption coefficient at wavelength λ per unit optical air mass
M_h = relative optical air mass

Visibility is the quality that allows one to see distant objects, and it is called visual range for quantitative purposes. This air quality variable, probably the one most obvious to the layman, can be estimated objectively, without instruments. Instruments are used to indirectly measure the visual range by measuring related variables. Visibility is limited by light scattered out of the observing path by gas molecules and aerosol between the object and the observer's eye, and by light absorbed in the path by gas molecules and aerosol. This scattering and absorption reduces the contrast between the object and its background surroundings. Visibility is considered in the horizontal while turbidity is the roughly analogous variable in the vertical. All aerosol sources mentioned above potentially can affect visibility. Also, sources of NO, NO_2, and SO_2 can affect visibility after these gases have converted to aerosol in the atmosphere.

Six of the air quality variables just described have ambient air quality standards which define legally clean air. These standards were promulgated by the federal government as primary standards chosen to protect public health and secondary standards chosen to protect public welfare. Arizona promulgated a single set of ambient air quality standards chosen to protect both public health and welfare,

without distinguishing differences between them. Utah has formally adopted only particulate standards. All of these ambient air quality standards are presented in Table 2. They provide concentrations against which the data presented in this report may be compared.

Measurements

The measurements of air quality that have been made by others are listed in Table 3. The measurements shown in Table 3 cover the variables in Table 4. The remaining variables measured in this project are listed in Table 5.

The variables listed in Table 5 were measured at specific locations near Lake Powell. The sampling intervals for these measurements are listed in Table 6. The instrumentation for the measurements initially was housed in a trailer owned by the Desert Research Institute of the University of Nevada at Reno and then in a surplus radar trailer owned by Northern Arizona University. Both trailers were stationed next to the technician's mobile home in Vermillion Court, south of Page, Arizona.

LPRP Measurement Methods

o Aerosol Number Concentration

The aerosol number concentration was measured with two instruments called condensation nuclei counters or detectors. One instrument is portable, allowing manual measurement every minute or so. The other instrument automatically makes a measurement every fifth of a second. Both instruments humidify an air sample to saturation and then subject the saturated air to an adiabatic expansion. The resulting super-saturation (over 300 percent) causes the water vapor to condense on all aerosol down to a minimum radius of about 0.003μ. In less than one-tenth of a second the aerosol grows to at least 0.1μ radius and is therefore capable of attenuating the light beam between a lamp and a photocell. The size distribution of background aerosol is such that most of the particles are smaller than 0.1μ radius. These small particles do not significantly attenuate visible light and hence allow a reference light signal to be measured before expansion. Greatest attenuation per particle is achieved by particles with radii between 0.1μ and 1.0μ, the size achieved by the expansion.

Table 2: Ambient air quality standards (in micrograms of pollutant per cubic meter of air)

Pollutant	Time Period	Arizona[a]	National[b] Primary	and Utah Secondary
Total Suspended Particulate (Aerosol)	1 day (24 hours)	150	260	150
	1 year	60	75	60
Oxidant (Ozone)	1 hour	160	160	160
	4 hours	-	-	-
	1 day	-	-	-
Hydrocarbons (non-methane)	3 hours (6-9 AM)	160	160	160
	1 day	-	-	-
Sulfur dioxide	3 hours	1,300	-	1,300
	1 day	260	365	-
	1 year	50	80	-
Nitrogen dioxide	1 year	100	100	100
	1 day	-	250	250
Carbon Monoxide	1 hour	-	40,000	40,000
	8 hours	10,000	10,000	10,000

[a]Arizona Department of Health Services (1976)

[b]U.S. Environmental Protection Agency (1971)

[c]U.S. Bureau of Land Management (1976)

[d]National standards are quoted in the Utah regulations, but have not been formally adopted by the state.

Table 3: Air quality measurements

Variable	Agency	Station Location	Sampling Frequency	Sampling Duration	Method
1. Aerosol composition Benzene-soluble component Nitrate Sulfate	ADHS[a]	Clarkdale Davis Dam Flagstaff Holbrook Joseph City Leche-e Page[c] Tuba City	Every 6 days	1 day	Various methods
2. Aerosol composition Arsenic Bismuth Cadmium Chromium Cobalt Copper Iron Lead Manganese Mercury Nickel Tin Titanium Vanadium Zinc	ADHS	Clarkdale Davis Dam Flagstaff Holbrook Joseph City Leche-e Page[c] Tuba City	Every month	1 day	Various methods
3. Aerosol mass concentration	ADHS	Clarkdale Davis Dam Flagstaff Holbrook Joseph City Leche-e Page[c] Tuba City	Every 6 days	1 day	High-volume gravimetric
4. Aerosol mass concentration	D&M[b]	Page Airport	Every day	1 day	High-volume gravimetric
5. Aerosol mass concentration	D&M	Page Airport	Every day	2 hours	Tape Sampler
6. Aerosol mass	USDH[d]	Wahweap	Every day	1 day	High-volume gravimetric
7. Aerosol mass concentration	USDH	Bull Frog Basin	Every day	1 day	High-volume gravimetric
8. Aerosol mass/size	D&M	Page Airport	Twice per week	24 hours	Anderson cascade impactor and high-volume segregator
9. Aerosol dustfall	D&M	19 Sites around Northern Arizona and Southern Utah	Every 2 months	2 months	Sticky foil
10. Nitrogen dioxide	ADHS	Grand Canyon Village	Every 6 days	1 day	Saltzman bubbler

[a]ADHS = Arizona Department of Health Services

[b]D&M = Dames & Moore

[c]Only 50 meters (150 feet) from jet aircraft fueling facility

[d]USDA = Utah State Department of Health

Table 3 (continued)

Varible	Agency	Station Location	Sampling Frequency	Sampling Duration	Method
11. Nitrogen dioxide	ADHS	Davis Dam	Every 6 days	1 day	Saltzman bubbler
12. Nitrogen dioxide	D&M	Page Airport	Twice per week	1 hour	Saltzman bubbler
13. Oxidant	D&M	Page Airport	Twice per day	10 minutes	Haagen-Smit bubbler
14. Oxidant	ADHS	Grand Canyon Village	Every 6 days	1 day	Bubbler
15. Ozone	USDH	Cedar City	Every month	1 month	Rubber strip
16. Ozone	USDH	Bull Frog Basin	Every month	1 month	Rubber strip
17. Ozone	USDH	Padre Bay	Every month	1 month	Rubber strip
18. Ozone	USDH	Wahweap Bay	Every month	1 month	Rubber strip
19. Ozone	USDH	Cedar City	Every month	1 month	Rubber strip
20. Sulphur dioxide	D&M	Page Airport	Continuous	--	Conductimetry
21. Sulphur dioxide (sulfation rate)	D&M	Page Airport	Twice per week	1 day	West-Gaeke bubbler
22. Sulphur dioxide	D&M	19 sites	Every 2 months	2 months	Lead peroxide candle
23. Sulphur dioxide	ADHS	Grand Canyon Village	Every 6 days	1 day	Bubbler
24. Sulphur dioxide	ADHS	Davis Dam	Every 6 days	1 day	Bubbler
25. Sulphur dioxide (sulfation rate)	USDH	Wahweap Bay	Every month	1 month	Lead peroxide candle
26. Sulphur dioxide (sulfation rate)	USDH	Padre Bay	Every month	1 month	Lead peroxide candle
27. Sulphur dioxide (sulfation rate)	USDH	Bull Frog Basin	Every month	1 month	Lead peroxide candle
28. Sulphur dioxide (sulfation rate)	USDH	Cedar City	Every month	1 month	Lead peroxide candle
29. Water (relative humidity)	BR[e]	Page Airport	Continuous	--	Hair hygrometer[f]
30. Visibility	D&M	Page Airport	Every day	--	Integrating nephelometer (measures local air)
31. Visibility	D&M	Page Airport	Every day	Few minutes	Observer and distant points
32. Visibility	D&M	Page Airport	6 times	< 1 second	Camera and Questar telescope

[e]BR = Bureau of Reclamation

[f]Unknown if calibrated for altitude of Page

Table 4: Air quality variables measured by other projects

1. Aerosol
   a. Composition
      - benzene-soluble component
      - nitrate
      - sulfate
      - arsenic
      - bismuth
      - cadmium
      - chromium
      - cobalt
      - copper
      - iron
      - lead
      - manganese
      - mercury
      - nickel
      - tin
      - titanium
      - vanadium
      - zinc
   b. Concentration, mass
   c. Size distribution, mass
   d. Dustfall
2. Gas Concentration
   a. Nitrogen dioxide
   b. Oxidant
   c. Ozone
   d. Sulfur dioxide
   e. Water vapor
3. Visibility

Table 5: Air quality variables measured by Lake Powell Research Project

1. Aerosol
   a. Concentration, number
   b. Size distribution, number

2. Gas Concentration
   a. Carbon monoxide
   b. Hydrocarbons
      - Methane
      - Ethane
      - Propane
      - Butane
      - Pentane
      - Hexane
      - Ethene
      - Propene
      - Butene
      - Pentene
      - Hexene
      - Acetylene

3. Noise

4. Turbidity

Table 6: Sampling intervals for air quality measurements

Air Quality Parameter	Sampling Interval
Aerosol number concentration	Daily
Aerosol number/size distribution	Monthly at ground level and at various altitudes above ground
Carbon monoxide and hydrocarbons	On at least 1 weekday and 1 day of weekend each week
Noise	Occasionally
Turbidity	At 0900, 1200, and 1500 MST[a] on at least 1 clear day of each week

[a]MST = Mountain Standard Time

Aerosol Size Distribution, Number

A cascade impactor, with a vacuum pump to draw ambient air through it, was used to measure aerosol size distributions. Each stage in the impactor funnels the air down a channel with decreasing cross-sectional area until the air exits through a slit. Directly below each slit is a collecting stage, and a filter collects any aerosol small enough to escape all the impactor stages. Aerosol large enough to cross the airflow streamlines, which turn abruptly just above the collecting surface, impact on and attach to the collector. Each successive stage has a slit with smaller cross-sectional area and higher air velocity. Hence, smaller aerosol is collected on later stages.

After the ambient air has been sampled of its aerosol, the particles on each stage are sized and counted under a light microscope. The numbers of particles in each size sub-range give the size distribution.

- Gases

Remote air samples are collected in special Saran plastic bags that are designed to minimize gas transmission through their walls and sorption or reaction at the wall surface. The gas concentrations are all measured with a gas chromatograph. Column packings include Poropak N. silica gel and molecular sieve (Cudney et al., 1977). Although the measurement procedure for hydrocarbons that are not heavier than hexene has been standardized, the measurement of carbon monoxide is more difficult. The approach is to separate it from other gases with a molecular sieve, convert it to methane on a nickel catalyst in a hydrogen-augmented carrier, and measure the resulting methane pulse in a flame ionization detector at a longer retention time than that for the natural methane in the air sample.

- Noise

To measure this parameter, a portable sound-level meter is placed at various locations. The sound level, weighted on the A-scale to most closely represent human hearing, is recorded for several hours. The duration of the recording process is limited by the battery energy supply.

- Turbidity

An Eppley Sun Photometer is aimed directly at the sun at roughly 0900, 1200, and 1500 Mountain Standard Time (MST)

to obtain I_{380} and I_{500}. The subscripts are the mean wavelengths of the two transmitted radiation bands measured in nanometers. The local elevation is used to determine $b_{h\lambda}$ from tables (Elterman, 1968). The diopter on the instrument yields M_h. The date of observation and a table of solar distance correction factors yields S. The above information allows the final calculation of B_{380} and B_{500} (Malm et al., 1977).

LPRP Measurement Instrumentation

The important characteristics of the equipment used in this background air quality measurement program are listed in Table 7.

Table 7: Instrumentation for Lake Powell Research Project measurements

Parameter	Instrument	Manufacturer	Model	Power	Sensitivity	Recorder
Aerosol number concentration	1. Small particle detector	Gardner Associates	Type CN	Battery	$100/cm^3$	None
	2. Continuous condesation nuceli counter	General Electric	---	100 v. AC	$30/cm^3$	Esterline Angus strip chart
Aerosol number/size distribution	Cascade impactor	C.F. Casella & Co., Ltd.	MkIIa	Battery	---	None
Gases	Gas chromatograph	Hewlett-Packard	5711	100 v. AC (1.8KW)	---	Linear Instruments 252
Noise	Sound level meter	General Radio Company	1551-C	Battery	22 dbA	Linear Instruments 212
	Calibrator	General Radio Company	1562-A	Battery	---	None
Turbidity	Sun photometer	Eppley Labs	---	Battery	---	None

DATA ANALYSIS, RESULTS, AND DISCUSSION

The available data for each of the air quality parameters listed in Table 1 were collected and, where sufficient data existed, were analyzed for annual, seasonal, and monthly weekday and weekend/holiday means, maxima, minima, 90-percent confidence limits and frequency distributions. In the discussion, we indicate cases in which results may be skewed by problems of instrument location. Some of the air quality data may be expected to vary with the population of Page (Figure 2 and Table 8 (Makuch, personal communication, 1977)). As might be expected, the total population of Page is strongly determined by the construction force at the nearby Navajo Generating Station. The months when the three units at the generating station began operation are shown in Figure 2.

Where possible the data were separated into those from weekdays and weekends (including holidays). In addition, seasons were divided into the following months: winter, December through February; spring, March through May; summer, June through August; and fall, September through November. Three central measures or averages were used: the median, arithmetic mean, and geometric mean. The median is the middle number of a monotonically ordered series of numbers; the arithmetic mean is the sum of the numbers in a series divided by the number of numbers (n) in the series; and the geometric mean is the nth root of the product of the numbers.

The geometric mean is a more appropriate measure of central tendency or average for variables with logarithmic-normal distributions. One important characteristic of the geometric mean is that its calculation suppresses the exaggerating effect of especially large values. Another important characteristic of the two different means is that the arithmetic mean is always greater than or equal to the geometric mean. This is shown by the mathematical relationship between them: $AM = GM \exp [0.5 (\ln SGD)^2]$ where AM = arithmetic mean, GM = geometric mean, and SGD = standard geometric deviation.

Most air quality variables have logarithmic-normal (log-normal) distributions. The logarithms of the data, not the data themselves, have a normal statistical frequency distribution. It is convenient to plot such log-normal distributions as cumulative frequency graphs. These plots are straight lines from which approximate geometric means and standard deviations can be determined, and the plots are convenient for comparing different groups of data.

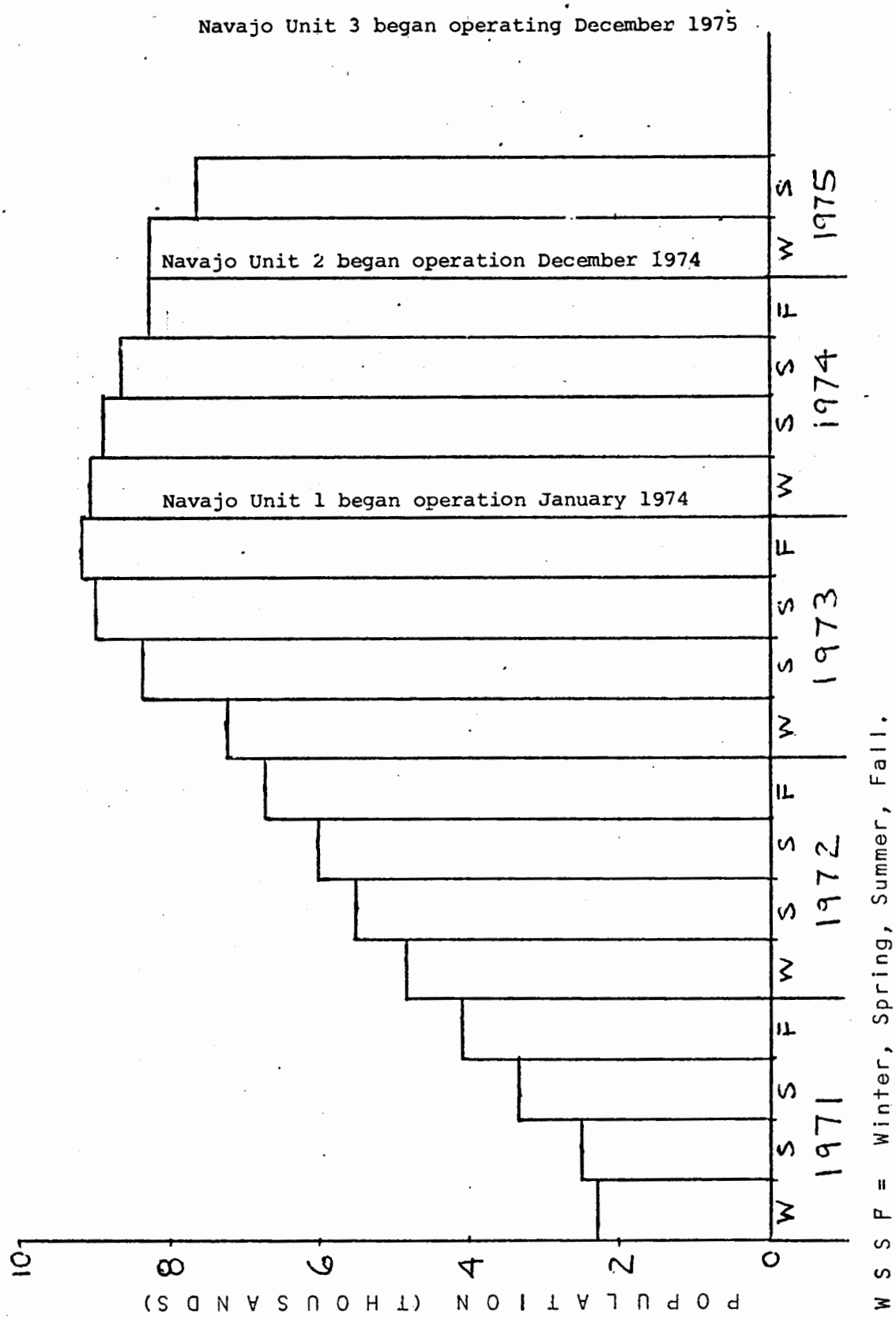


Figure 2: Seasonal population of Page, Arizona, from 1971 through 1975

Table 8: Population of Page, Arizona (1969-1975)

	Year						
	1969	1970	1971	1972	1973	1974	1975
Monthly Means							
January	(est) 1750	1815	2257	4845	7381	9065	8252
February			2303	5025	7240	8958	8342
March			2356	5302	7494	8978	7529
April			2374	5584	8664	8846	7481
May			2734	5601	8868	8757	7799
June			3108	5807	8861	8671	
July			3317	6007	8955	8622	
August			3680	6243	9071	8570	
September			3913	6578	9188	8543	
October			4047	6676	9138	8113	
November			4326	6945	9187	8086	
December		2257	4610	7053	9036	8045	
Quarterly Means							
First Quarter	--	--	2305	5057	7372	9000	8041
Second Quarter	--	--	2739	5664	8798	8758	--
Third Quarter	--	--	3637	6276	9071	8578	--
Fourth Quarter	--	2257	4328	6891	9120	8081	--
Seasonal Means							
Winter (Dec-Feb)	--	--	2272	4827	7225	9020	8213
Spring (Mar-May)	--	--	2488	5496	8342	8860	7603
Summer (Jun-Aug)	--	--	3368	6019	8962	8621	--
Fall (Sept-Dec)	--	--	4095	6733	9171	8257	--
Annual Average (Means)	--	--	3252	5972 ±350	8590	8604 ±167	--

Most recent: January 1977: 4500
1975 Census: 5892

The approximate geometric mean concentration for each location can be read off each line at the 50-percent cumulative frequency. The approximate geometric standard deviation is the ratio of the concentrations at 84- and 50-percent cumulative frequencies (or the ratio of the concentrations at 50- and 16-percent cumulative frequencies). Therefore, the steepness of the slope of the straight line plot is a measure of the variation of the measurements, with a steeper slope indicating more variation within the data.

When two means are being compared in order to see if there is a significant difference lower and upper 90-percent confidence limits are given. These limits bound the 90-percent confidence interval around a mean, in which there is a 90-percent chance the real mean actually exists. The confidence interval is proportional to the more familiar standard deviation, but is easier to understand. A frequency distribution gives the proportion or percentage of data in specified intervals in order to give a more complete picture of the variation of the data. Some results were compared to those of other locations, including those results from particularly clean and particularly polluted areas.

Aerosol Composition

More can be learned about the nature and sources of aerosol, if it is collected and analyzed for its chemical composition, than by just measuring its mass or number concentration in a unit volume of air. Different sources have different ratios of specific elements and compounds. ADHS (1976) collected aerosol for 24 hours per sample with high-volume samplers at numerous locations throughout Arizona. These samples were analyzed for both total mass concentration and for individual chemical constituents. These components ranged from specific elements like lead to compounds like sulfates and to groups of compounds like benzene-soluble organics.

Benzene-Soluble Organics

The arithmetic mean concentrations of benzene-soluble organics over the 4-year period from 1969 through 1972 are shown in Figure 3, while the arithmetic means over the later period of 1971 through 1975 are shown in Figure 4. Note the change of scale because of the inclusion of Phoenix in Figure 4. Those cities with significantly more automobile traffic show up clearly in data for this aerosol constituent. There does not seem to be a significant change in the concentrations at the locations shown in both Figures 3 and 4.

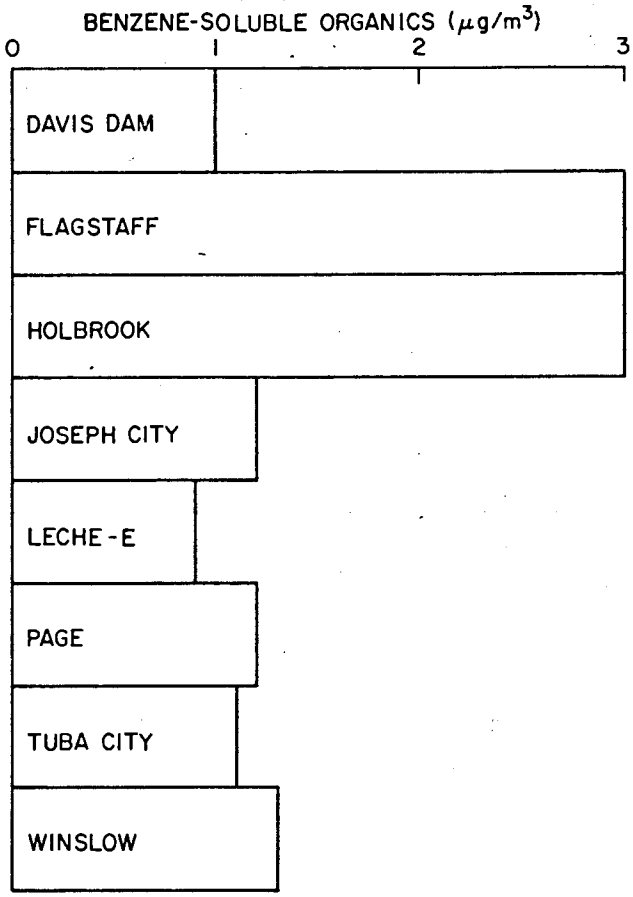


Figure 3: Benzene-soluble organics (1969-1972)

Source: ADHS (1969, 1970, 1971, and 1972)

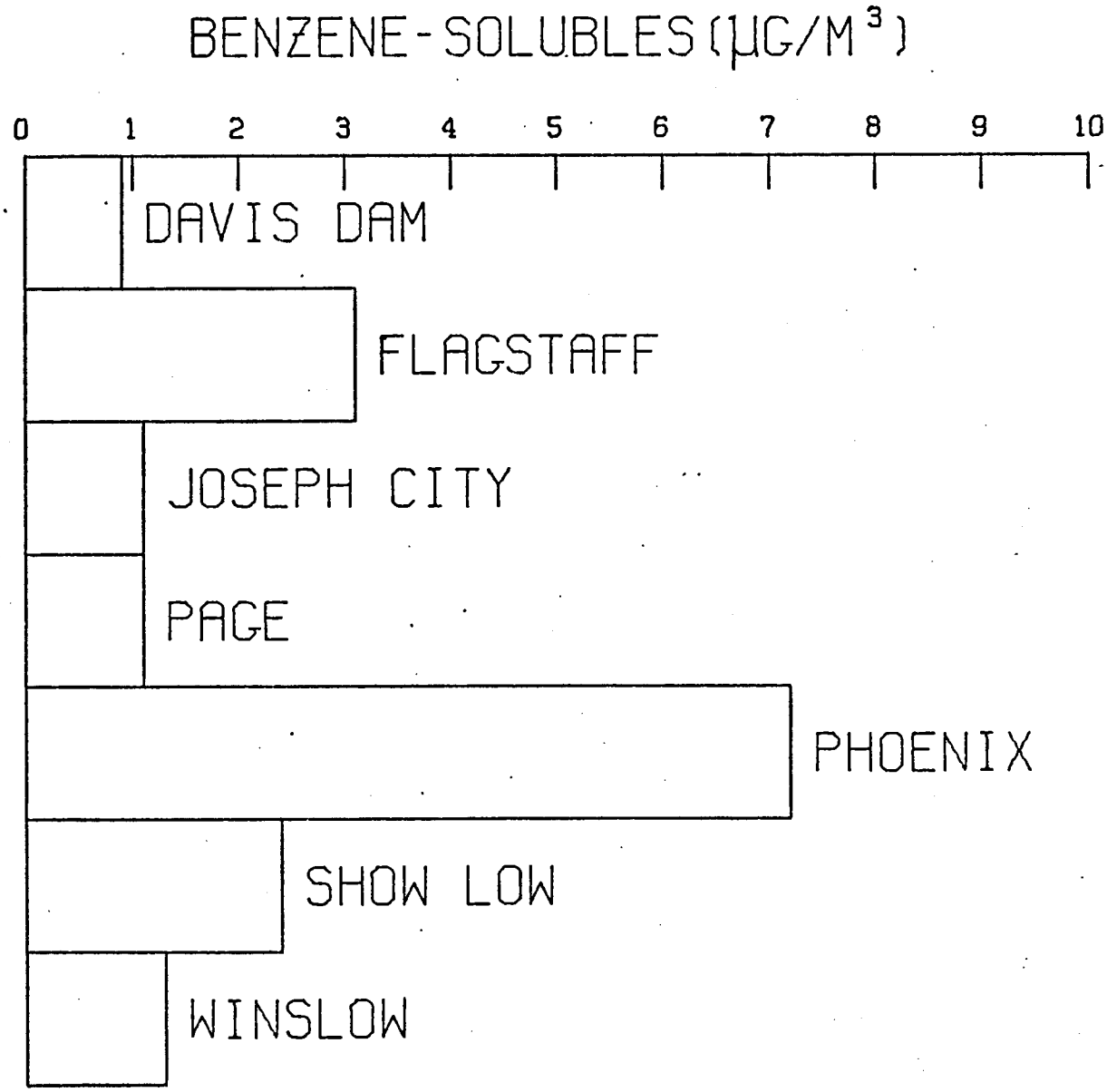


Figure 4: Benzene-soluble organics (1971-1975)

Source: ADHS (1971, 1972, 1973, 1974 and 1975)

The annual arithmetic mean concentrations of benzene-soluble organics collected in the aerosol of Page for each year from 1971 through 1975 are presented in Figure 5. The yar with the highest concentration (1974) is also the year with the highest population in Page.

Lead

The arithmetic mean concentrations of lead in the aerosols of eight locations over the 4-year period (1969 through 1972) are shown in Figures 6, while the arithmetic means over the later period of 1972 through 1975 are shown in Figure 7. The higher concentrations in the cities with greater vehicle traffic can be easily seen, as with the benzene-soluble organics presented earlier. Note the extremely low concentration in the Grand Canyon, which commonly has the lowest concentrations. This characteristic makes the Grand Canyon a good reference location in air quality comparisons.

The annual arithmetic mean concentrations of lead in the aerosol of Page for each year from 1972 through 1975 are presented in Figure 8. The peak concentration in 1974 is simultaneous with the peak population in Page. This result was expected because the population of cars, which emit lead, probably is closely correlated with the population of humans.

Nitrates

The arithmetic mean nitrate concentrations in the aerosols at the same eight locations in Figure 6 are presented in Figure 9. The data cover the 4-year period from 1969 through 1972. The arithmetic means of the later period (1971 to 1975) for six locations do not differ much from those shown in Figure 10.

The annual arithmetic mean nitrate concentrations in the aerosol measurements in Page, Arizona, for 1972, 1973, and 1974 are shown in Figure 11. Although the differences among the 3 years are small compared to the accuracy of the measurement technique, the highest value in 1974 and the highest concentrations at Davis Dam (near the Mahave Generating Station) suggest that nitrates should be monitored carefully in the future as a potential indicator of power-plant impact on air quality.

Sulfates

The arithmetic mean sulfate concentrations in the aerosols of eight locations over the 4-year period from 1969

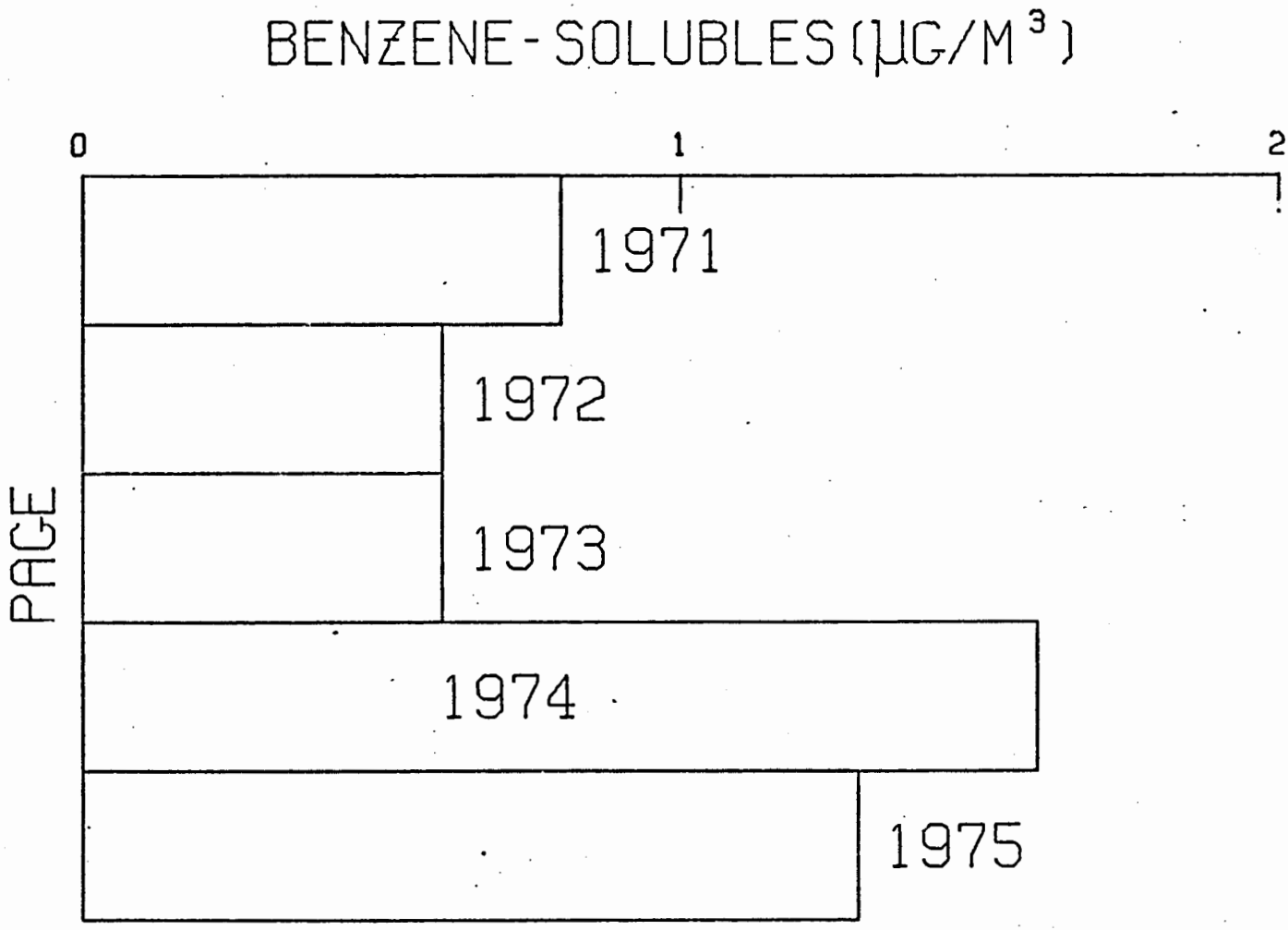


Figure 5: Annual arithmetic mean concentrations of benzene-soluble organics in Page, Arizona

Source: ADHS (1971, 1972, 1973, 1974, and 1975)

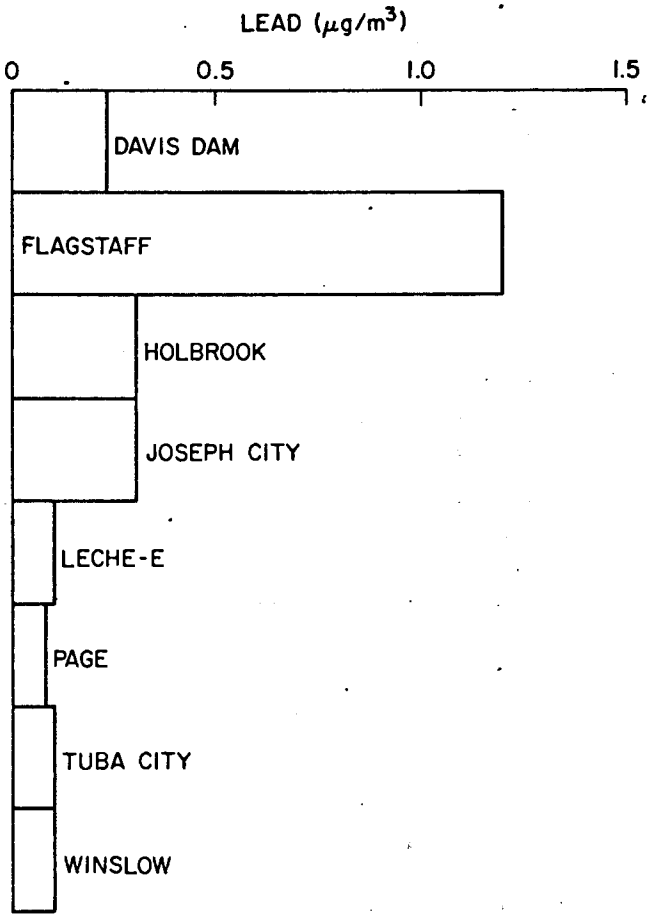


Figure 6: Lead (1969-1972)

Source: ADHS (1969, 1970, 1971, and 1972)

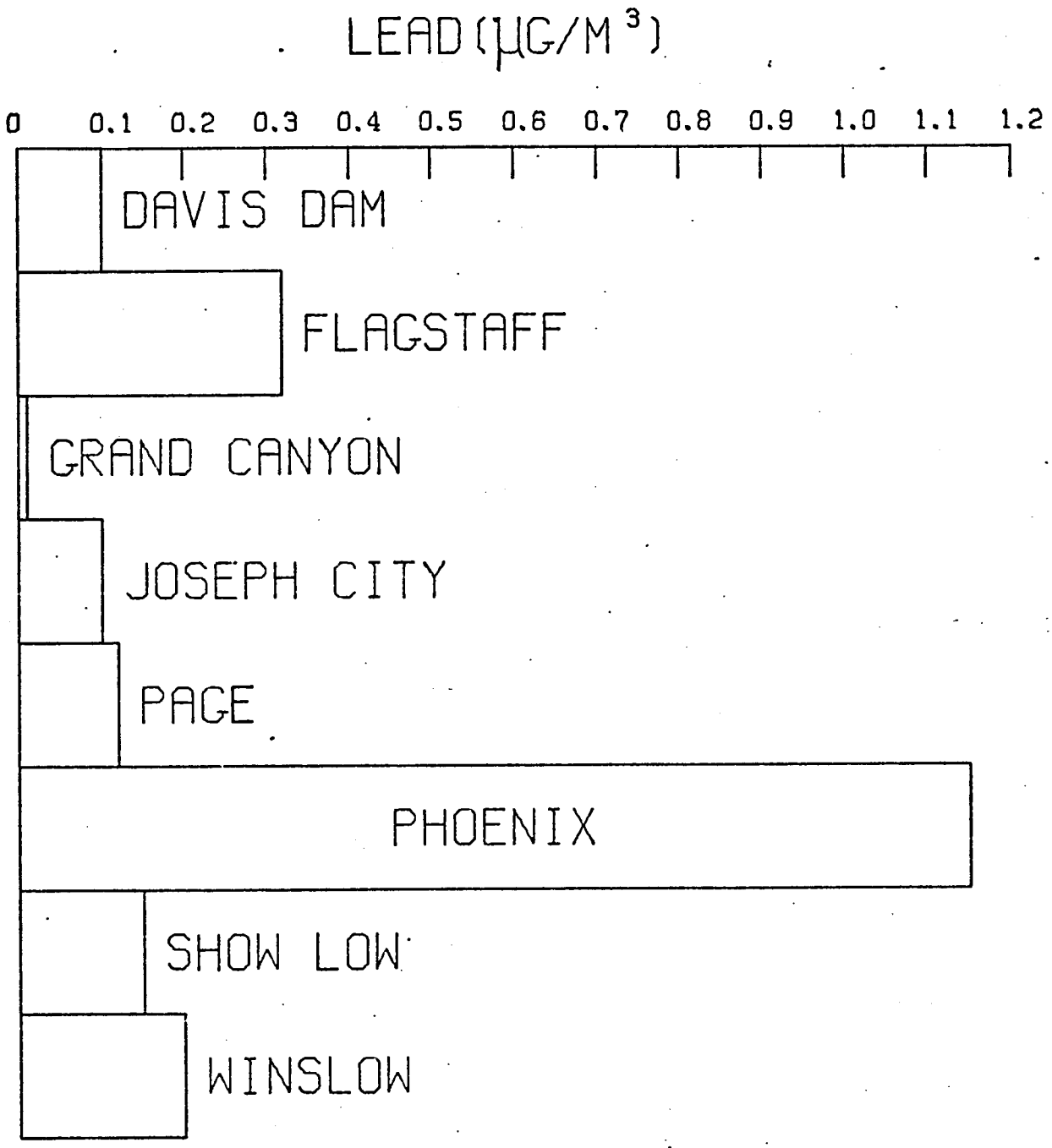


Figure 7: Lead (1972-1975)

Source: ADHS (1972, 1973, 1974 and 1975)

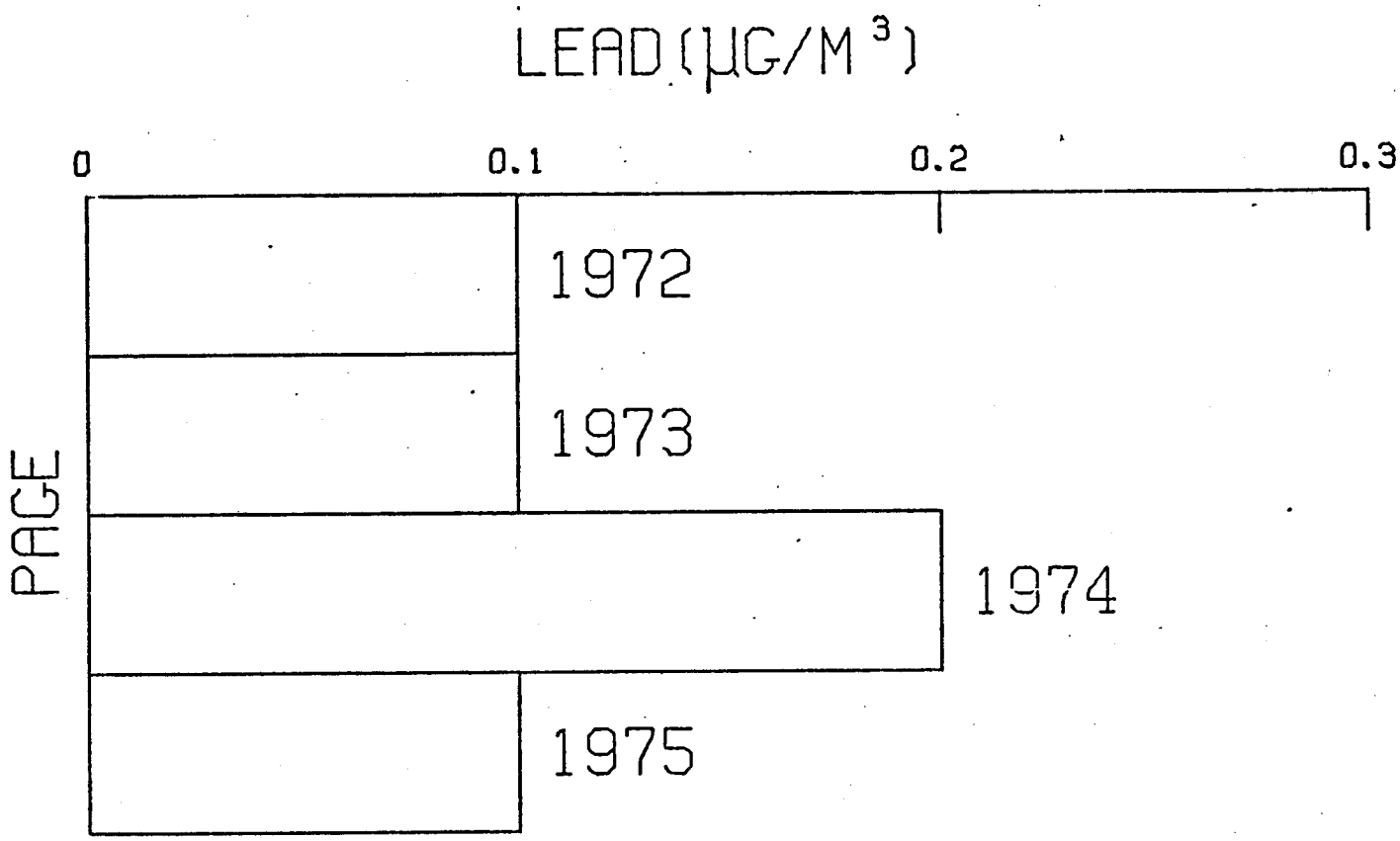


Figure 8: Annual arithmetic mean concentrations of lead in Page, Arizona

Source: ADHS (1972, 1973, 1974, and 1975)

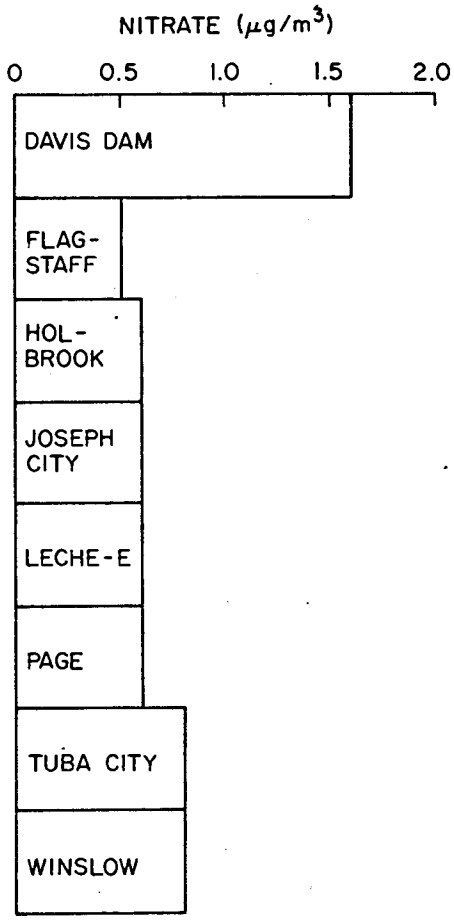


Figure 9: Nitrate (1969-1972)

Source: ADHS (1969, 1970, 1971, and 1972)

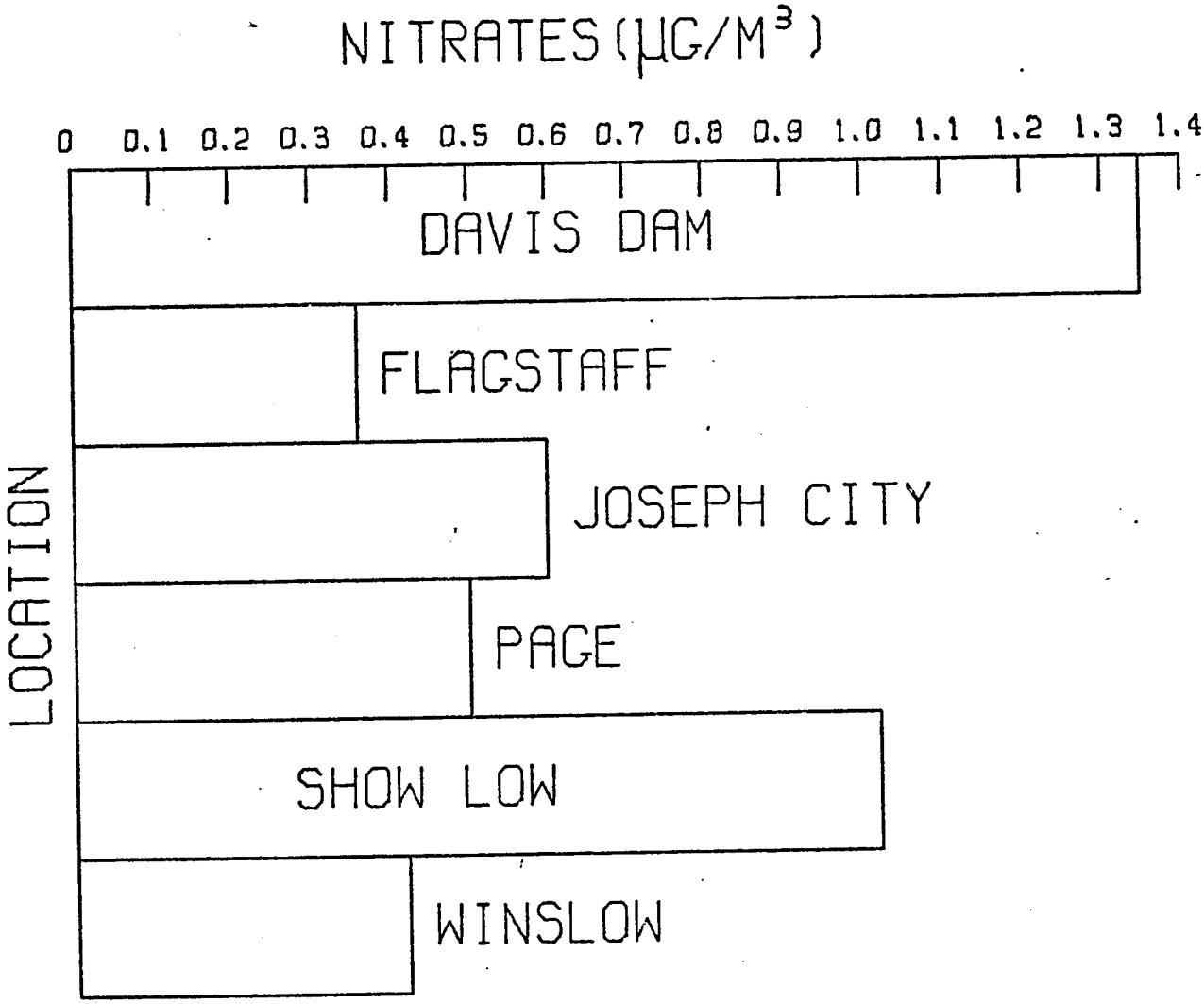


Figure 10: Nitrate (1971-1975)

Source: ADHS (1971, 1972, 1973, 1974, and 1975)

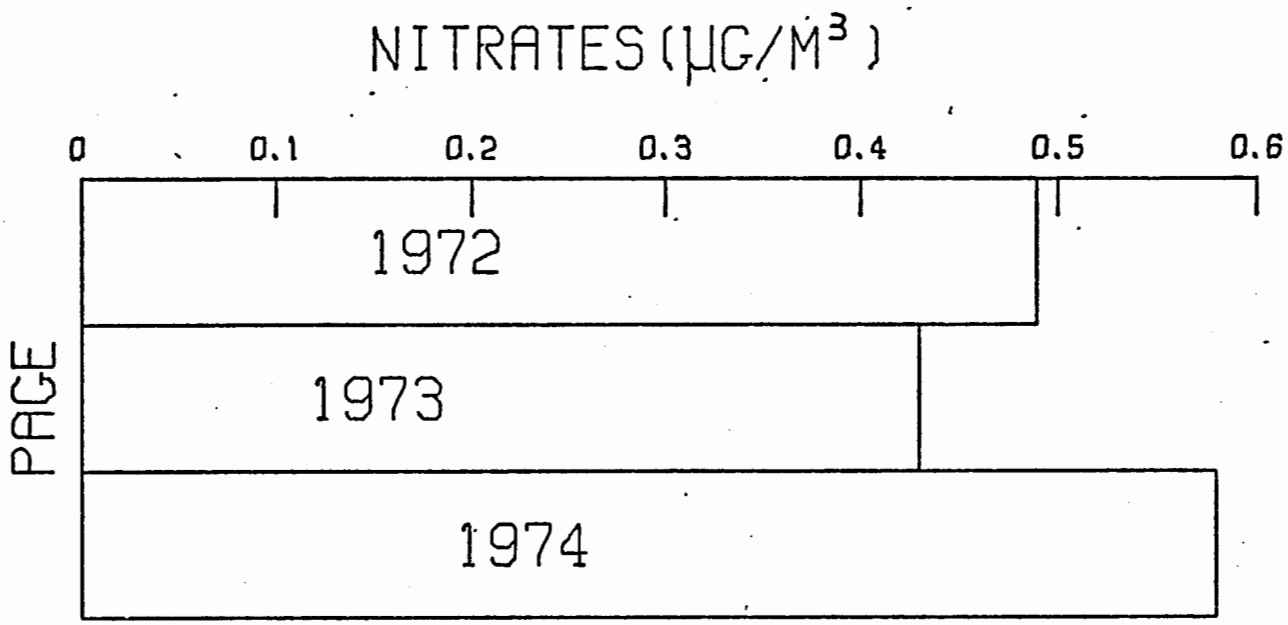


Figure 11: Annual arithmetic mean concentrations of nitrate in Page, Arizona

Source: ADHS (1972, 1973, and 1974)

through 1972 are presented in Figure 12, while the arithmetic means over the later period (1971 through 1975) at nine locations are presented in Figure 13. Note again the change in scale between Figures 12 and 13 because of the higher concentration in Phoenix. None of these sulfate concentrations is especially high when compared to concentrations elsewhere in the nation when compared to the 10 micrograms per cubic meter (μg/m3) being discussed as a possible future ambient air quality standard for sulfates. Here again the Grand Canyon has the lowest sulfate concentration.

The annual arithmetic mean sulfate concentrations in the aerosol of Page are presented in Figure 14. The apparent increase from 1971 through 1975 is important, even though none of these annual concentrations is high enough to cause alarm about potential health effects.

The increases from 1971 to 1973 cannot be attributed to the Navajo Generating Station, because the first unit did not begin operation until 1974.

Three locations (Davis Dam, Joseph City, and Holbrook) are located within 16 kilometers (km) (10 miles) of some coal-fired thermal-electric generating station. Joseph City is located the closest to a generating station, being about 3 km (2 miles) northwest of the 110-MW Cholla Power Plant. Davis Dam is about 5 km (3 miles) north of the 1,600-MW Mohave Generating Station in the Colorado River valley between Arizona and Nevada. Holbrook is about 16 km (10 miles) east-southeast of the Cholla Power Plant. Coal contains small proportions of a large number of elements (U.S. Department of the Interior, 1972), while coal combustion produces high concentrations of nitric oxide, sulfur dioxide, and aerosol. Oxidation of nitric oxide produced nitrogen dioxide which can then be further oxidized to nitrate. Similarly, the oxidation of sulfur dioxide yields sulfate. The other large sources of aerosol at these locations are automobiles and blowing dust. The latter contains mostly silica, which was not measured by the ADHS. Automobiles are significant sources of lead (Martens et al., 1973), nitrogen oxides, and carbon monoxide (benzene-soluble organics).

Aerosol Mass Concentration

The geometric mean aerosol mass concentration over the 4-year interval from 1969 through 1972 at eight locations in northern Arizona is shown in Figure 15. The federal secondary

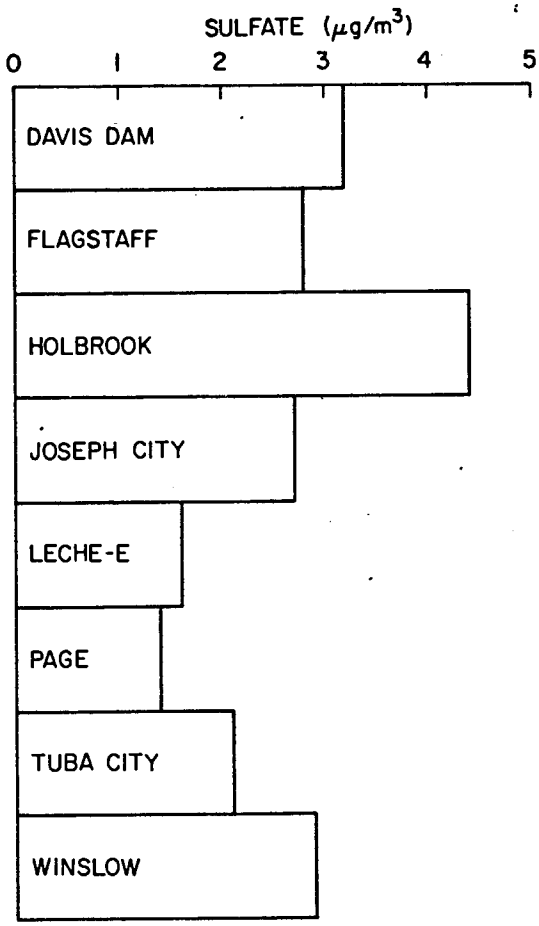


Figure 12: Sulfate (1969-1972)

Source: ADHS (1969, 1970, 1971, and 1972)

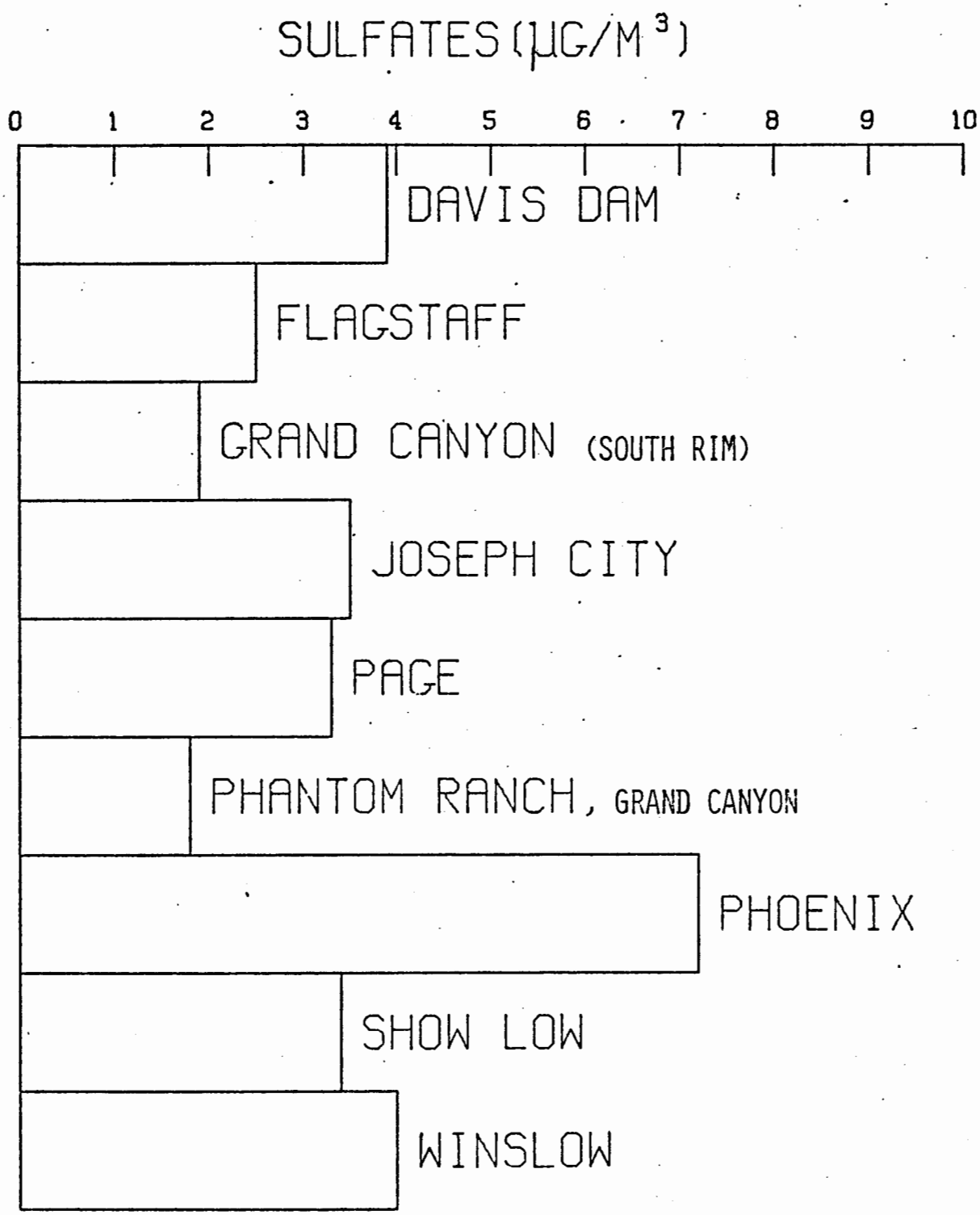


Figure 13: Sulfate (1971-1975)

Source: ADHS (1971, 1972, 1973, 1974, and 1975)

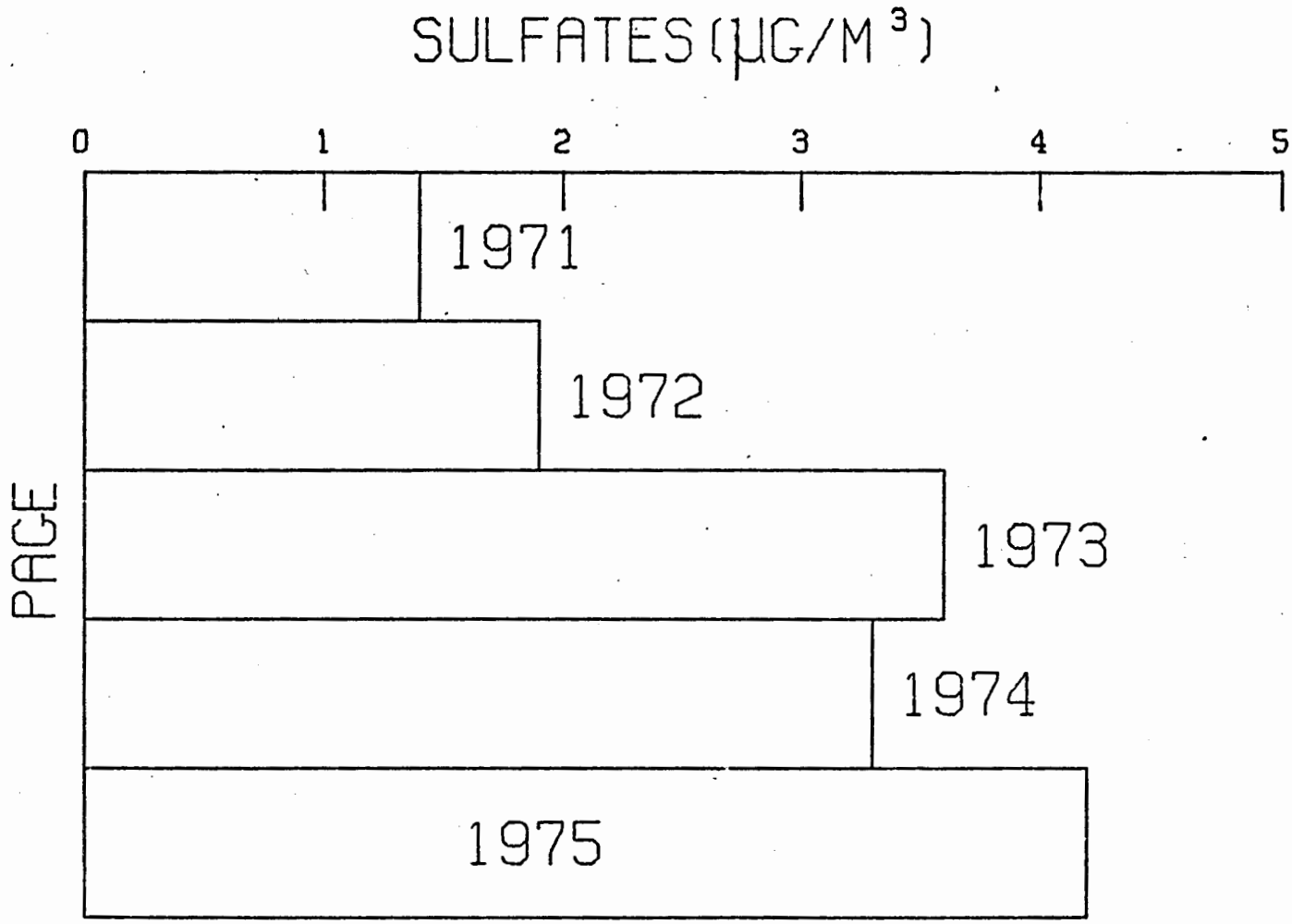


Figure 14: Annual arithmetic mean concentrations of sulfate in Page, Arizona

Source: ADHS (1971, 1972, 1973, 1974, and 1975)

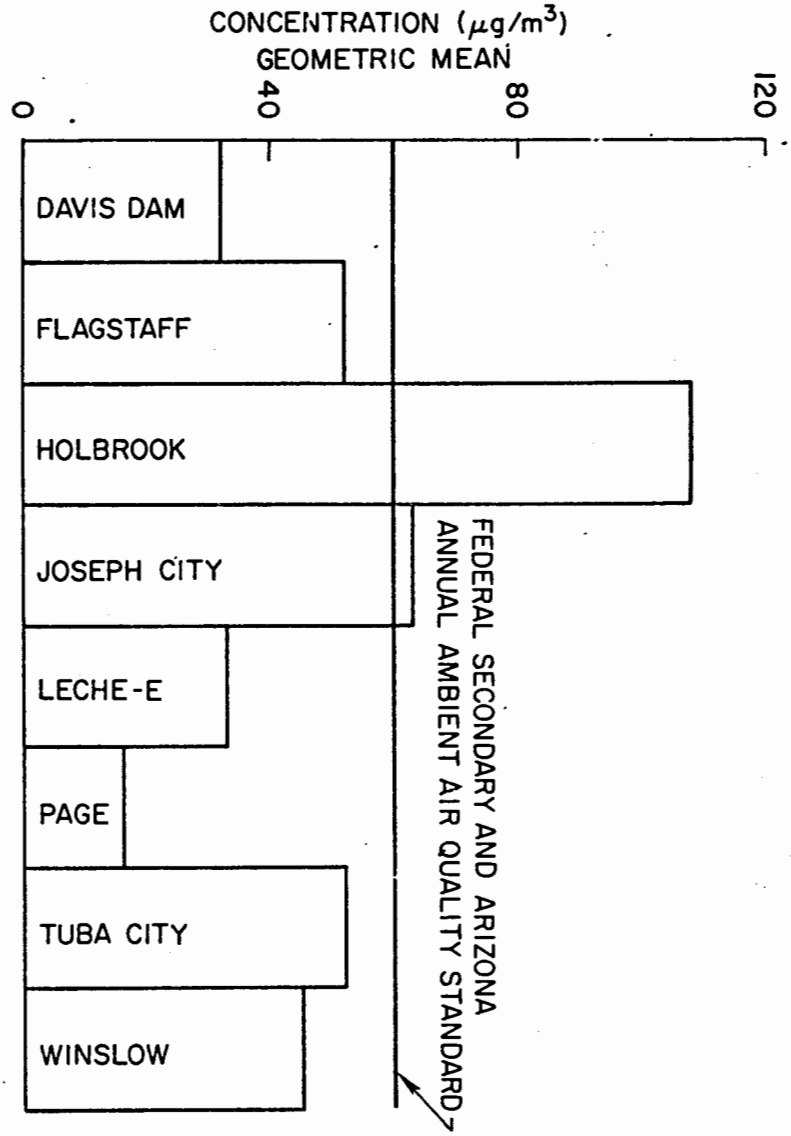


Figure 15: Aerosol mass concentration (1969-1972)

Source: ADHS (1969, 1970, 1971, and 1972)

and Arizona annual ambient air quality standard of 60μg per cubic meter geometric mean is shown for purposes of comparison. This value was chosen as appropriate for the protection of human welfare and health.

The geometric mean aerosol mass concentrations for the various locations in Figure 15 should be compared not only with each other but also with those in Figure 16, covering the 5-year period from 1971 through 1975. This comparison indicates the increase in the aerosol mass concentration at Page Airport and the decrease at Joseph City. We hypothesize that increasing human activity at and near the Page Airport caused the increase, and that the phasing out of sawdust burners near Joseph City may have caused the decrease there.

In comparison, the aerosol mass concentration at Davis Dam and Winslow did not change much. The lowest mean concentration in Figure 16 occurred at Phantom Ranch at the bottom of the Grand Canyon near the confluence of Bright Angel Creek and the Colorado River.

The aerosol mass concentrations at Flagstaff and at Lowell Observatory (located on a hill on the western boundary of the city) indicate the difference found below and above the inversion layer commonty formed in Flagstaff during the cold clear nights. Aerosol emissions from combustion and other sources during the night cannot easily rise above the inversion layer, which is below Lowell Observatory.

The aerosol mass concentration for Phoenix is included for comparison, showing how much higher it is than the Arizona and federal secondary ambient air quality standard of 60$\mu g/m^3$. The two highest concentrations, at Holbrook and Joseph City, both exceeded the standard during 1969 through 1972 and may show the influence of blowing soil or the nearby Cholla Power Plant which emitted 13,000 kilograms (kg) (14 tons) of fly ash aerosol per day. During this 4-year period, sawdust burners were other industrial sources in Holbrook, Winslow, and Flagstaff which may have contributed significantly to the amount of observed aerosol. Detailed study of the individual particles is necessary to separate the different sources from each other.

One such study (Hill et al., 1973) conducted around the Mohave Generating Station collected aerosol on both glass fiber and Nuclepore filters. The total mass concentration was obtained and individual particles were viewed with the scanning electron microscope. The particles were sized down to 0.4μ diameter and separated into four general classes:

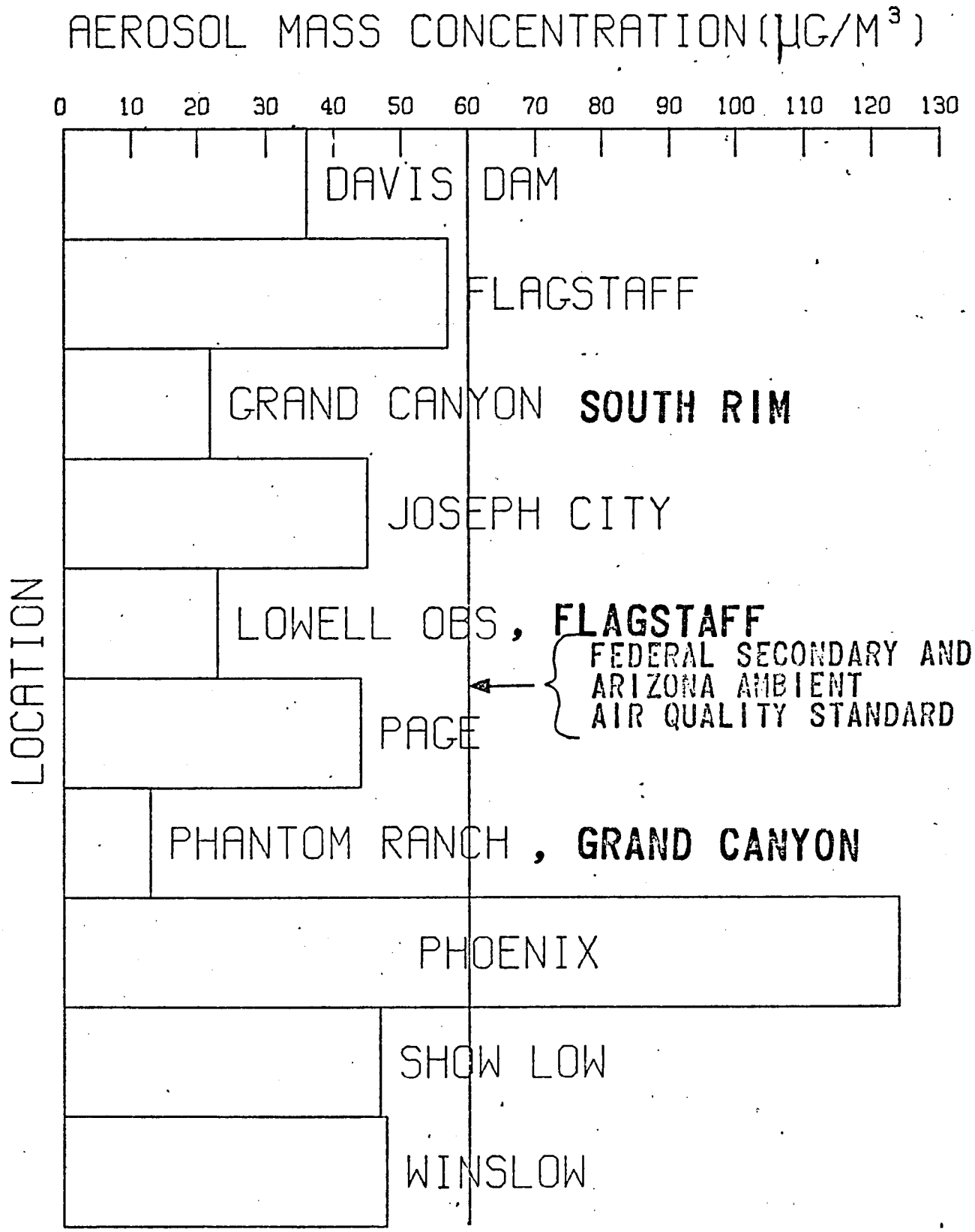


Figure 16: Aerosol mass concentration (1971-1975)

Source: ADHS (1971, 1972, 1973, 1974, and 1975)

fly ash, soil dust, soot, and sulfate/nitrate-type particles. The study concluded that soil dust contributed between 93 and 96 percent of the aerosol mass concentration; soot and ammonium sulfate/nitrate-type particles contributed less than 1 percent; and fly ash contributed between 0.8 and 2.5 $\mu g/m^3$.

Blowing dust and sand are contributors to the aerosol at all of these locations. Unpaved roads expose soil to the wind, and passing vehicles thrust it high enough above ground to allow its entrainment in the wind.

The aerosol mass concentrations measured at Page Airport by Dames & Moore (1975) were separated into the annual means for the 5 years from 1971 through 1975 as shown in Figure 17. The histogram seems to indicate a slight upward trend over the 5 years, probably the result of increasing human activities in the Page area, but especially those at the airport and in the adjacent housing development.

The Dames & Moore aerosol mass concentrations in Figure 17 must be compared with the significantly different aerosol mass concentrations measured by the ADHS (1976), also at Page, Airport (Figure 18). Since the instruments were located at different parts of the airport, we do not have a controlled common location in order to attribute the different results to analytical techniques. The Dames & Moore instrument was located 150 meters (490 feet) north of the airport buildings along a sandy road. The ADHS in strument was located just south of the airport buildings at the edge of the asphalt parking area.

The ADHS aerosol mass concentration data show 1973 to be the "dirtiest" year, while the Dames & Moore data show exactly the opposite. Except for the conflicting position of 1973 in the two sets of data, there seems to be some upward trend common to both sets.

Aerosol Number Concentration

Single measurements have been made of aerosol number concentrations at remote sites near Page since September 3, 1972, and in downtown Page and downwind of Page since March 5, 1973. Continuous measurement was made at the Wahweap Marina April 18 to May 6, 1973, June 7-26, 1973, and October 27, 1975, to March 11, 1976, and at the Lake Pumping Station of the Navajo Generating Station, May 15-31, 1974.

From Figure 19 we can see that the aerosol number concentration is lowest at the remote sites, higher downwind

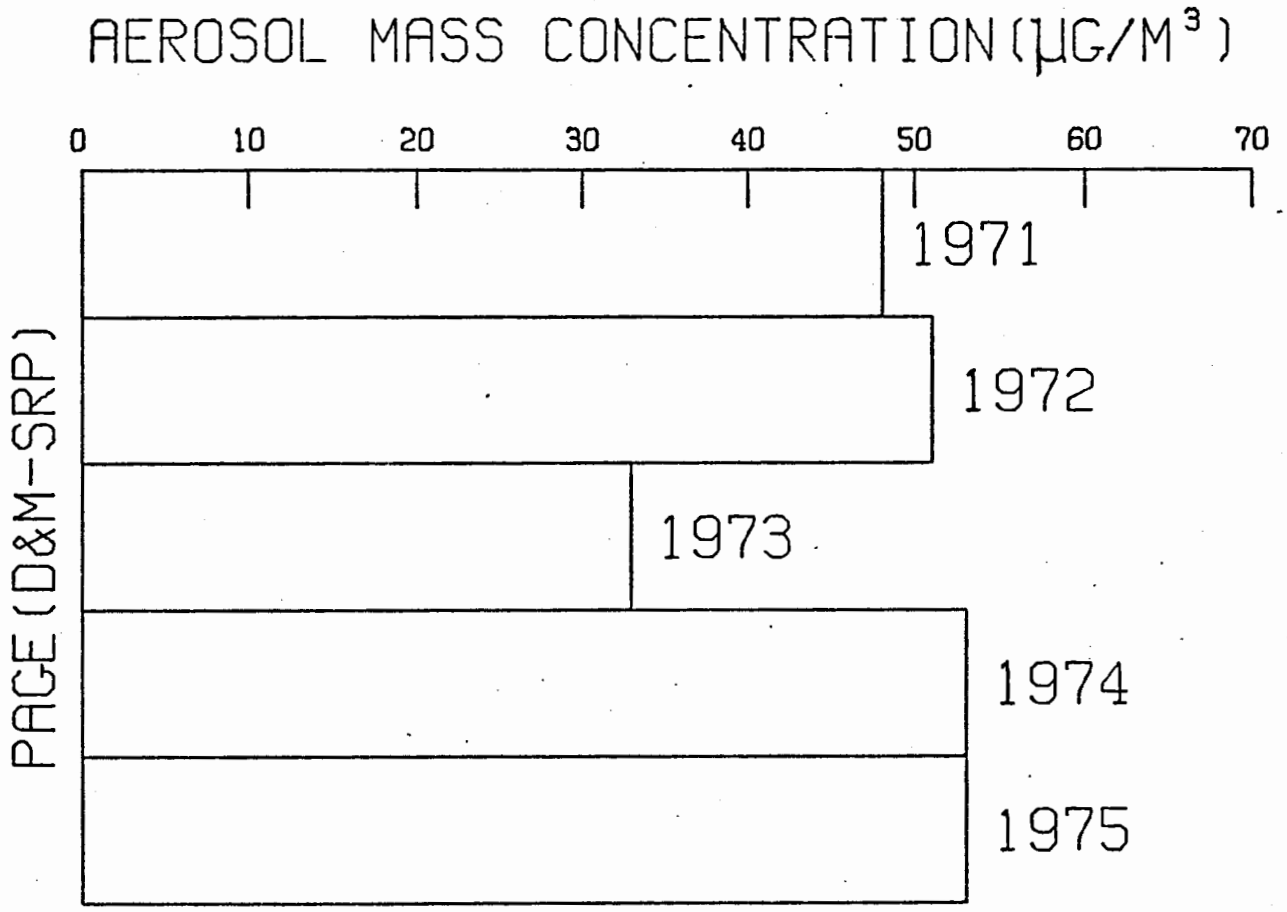


Figure 17: Annual geometric mean aerosol mass concentrations at Page Airport, Arizona

Sources: Dames & Moore (1975) and Salt River Project (1976)

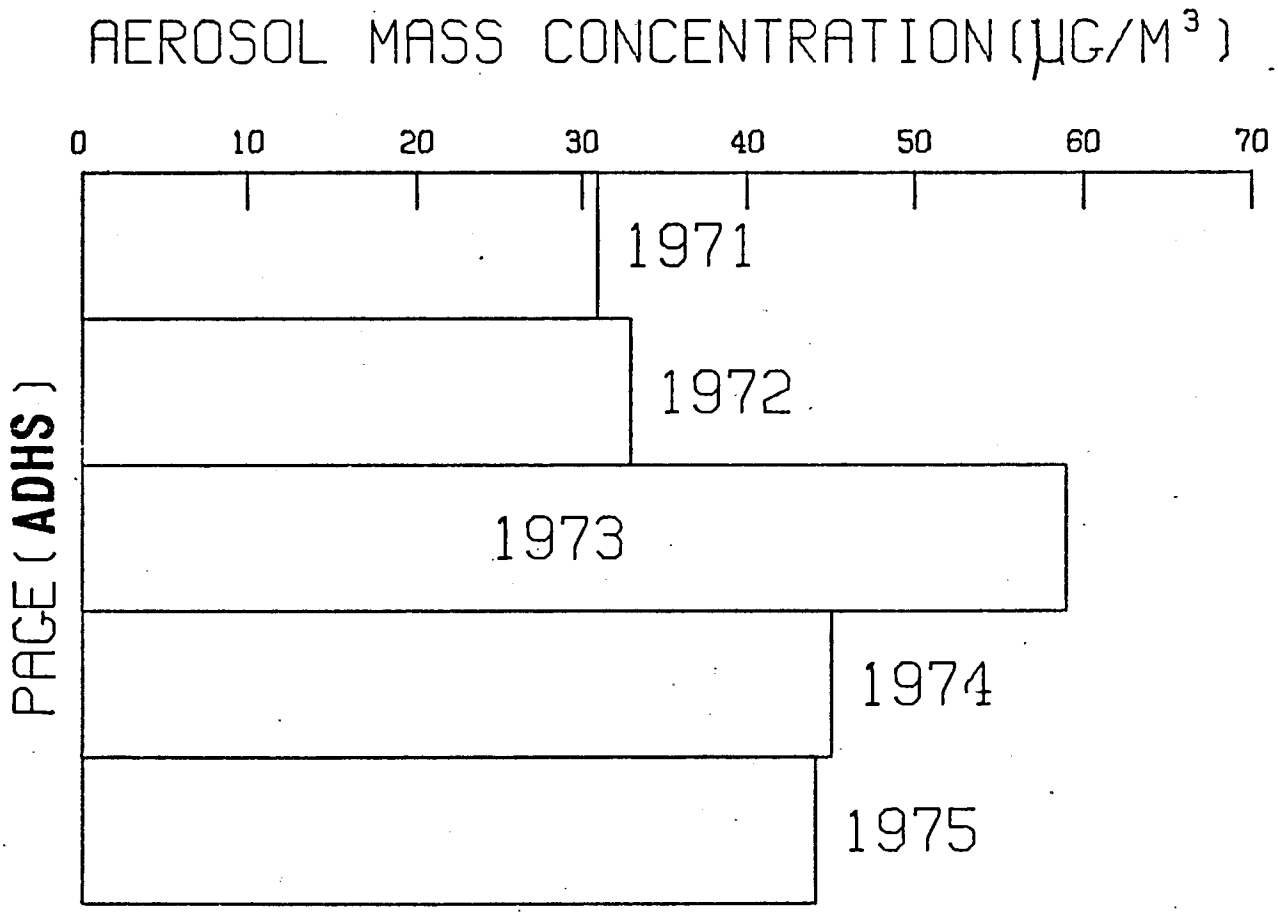


Figure 18: Annual geometric mean aerosol mass concentration at Page Airport, Arizona

Source: ADHS (1971, 1972, 1973, 1974, and 1975)

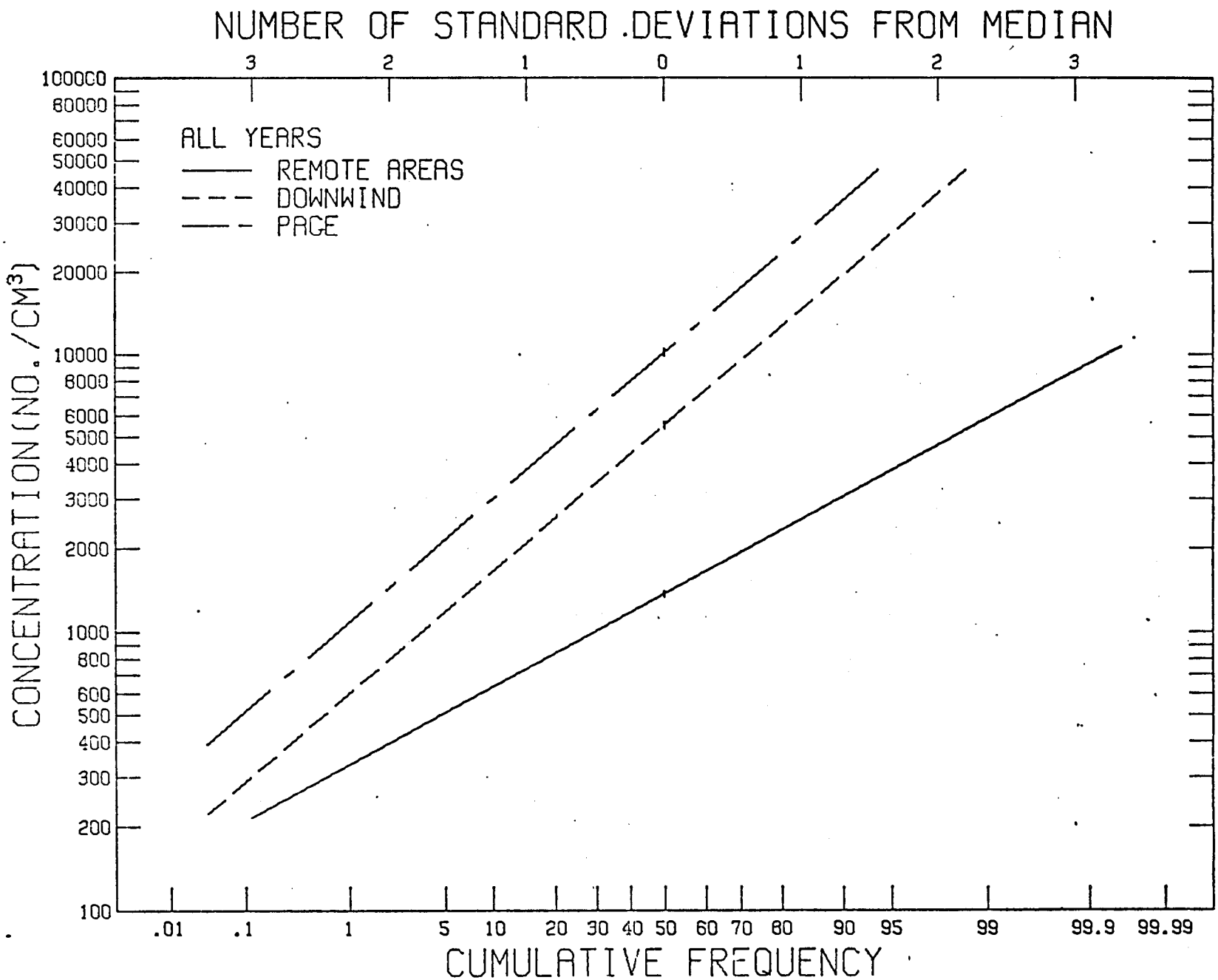


Figure 19: Aerosol number concentrations in Page, downwind of Page, and at remote sites

of Page, and highest in Page. This finding is consistent with Page having so many of the local engines and other combustion sources that produce large numbers of small particles. It can also be seen from Figure 19 that the geometric mean aerosol number concentration in Page is about ten times higher than that at the remote sites.

The slope and variability of the aerosol number concentration is least at the remote sites because of the lack of combustion sources which produce such high concentrations of aerosol. Page and areas downwind of it have steeper slopes because some measurements there can be very low during quiet parts of the night, while very high concentrations are measured during the use of nearby engines and other combustion sources. Under appropriate conditions of wind direction and atmospheric stability, the lowest concentrations in Page can approach the concentrations measured at remote sites.

The seasonal arithmetic mean aerosol number concentrations in Page and at remote sites are presented in Figure 20. The seasonal means at the remote sites remained far more constant than those in Page during 1973-1975. The seasonal data are presented numerically in Table A-1 of the Appendix.

One question asked from the beginning was: Do weekend recreation activities lead to different remote air quality than weekday work patterns? In order to answer this, the data were stratified into weekends and weekdays. The resulting cumulative frequency distributions for aerosol number concentration at remote sites are shown in Figure 21. The closeness of the two lines near the 50-percent cumulative frequency indicates that the two geometric means are not significantly different. Their arithmetic means have 90-percent confidence intervals that slightly overlap, again indicating no statistically significant difference. The difference in slope of the two lines is the result of the greater number of measurements taken during the 5 weekdays than during the 2-day weekends. For the remote sites near Page, no "weekend effect" of recreation is observed.

Another question was asked at the beginning of this study: Does the air quality have a seasonal pattern caused by the seasonal recreation pattern? The discrete aerosol number concentration measurements were stratified into the four seasons, defining winter as December through February, with each succeeding season being 3 months long. The cumulative frequency distributions for the aerosol number concentration in the four seasons are shown in Figure 22,

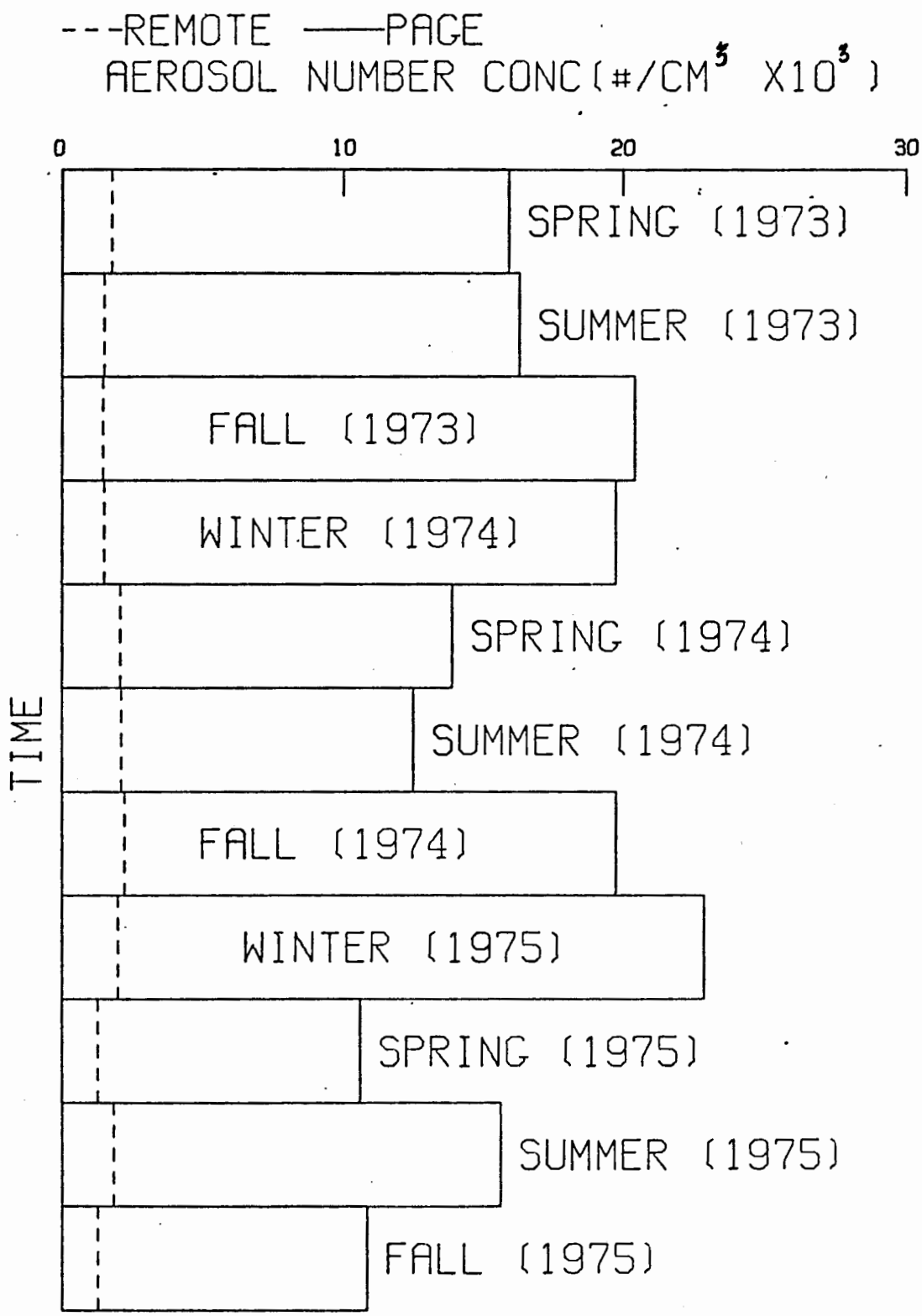


Figure 20: Seasonal arithmetic mean aerosol number concentrations in Page and at remote sites

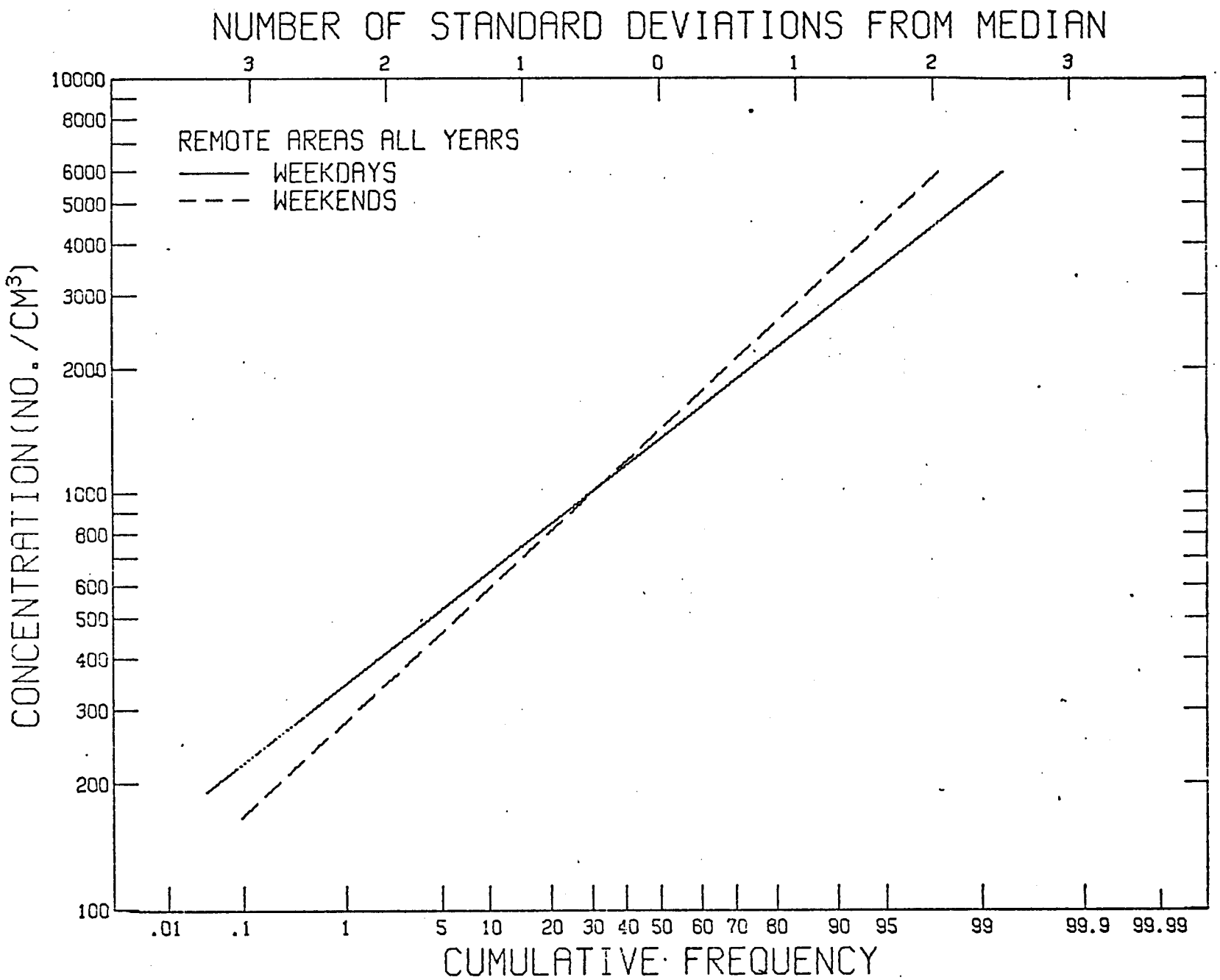


Figure 21: Aerosol number concentrations at the remote sites on weekdays and weekends

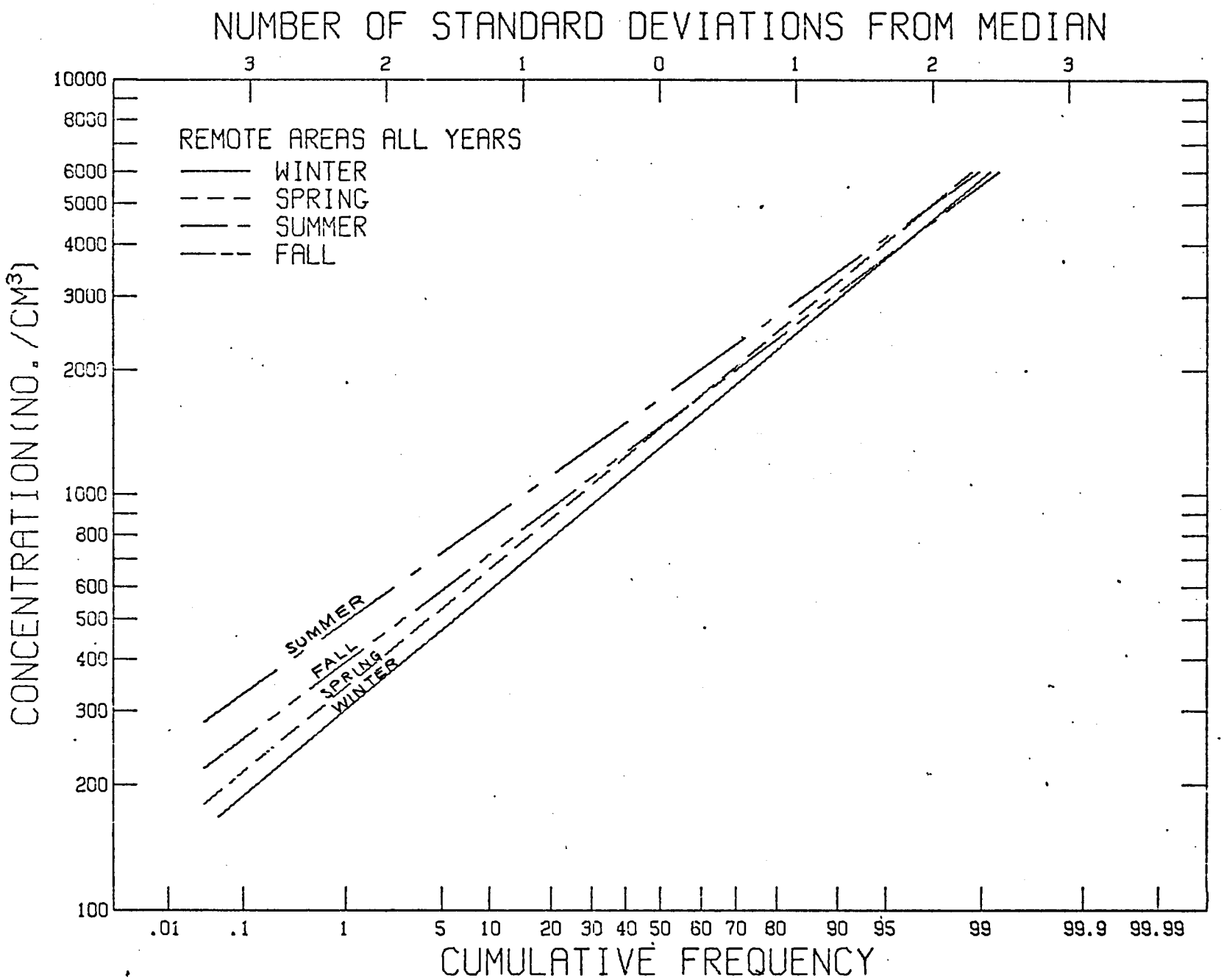


Figure 22: Aerosol number concentrations at the remote sites during winter, spring, summer; and fall

but the slight departures of the lines from each other are statistically insignificant. At least in remote areas we can see no seasonal pattern in the aerosol number concentration, an air quality variable that is very sensitive to such sources of combustion as off-road vehicles.

Another obvious question from the beginning was that of the possibility of a trend in air quality over the years. In a way this question was important to the funding of the LPRP Background Air Quality Subproject because there were some accusations that the new coalfired generating stations were ruining the air quality around Lake Powell. The cumulative frequency distributions of aerosol number concentrations measured at remote sites over the 4 years from 1973 through 1976 are presented in Figure 23. Although there is some overlap of the 90-percent confidence intervals around the means, the 1974 data are significantly higher than they are for 1976. Unfortunately, we had to terminate these measurements May 31, 1976, so the plot for 1976 does not represent an entire year. If any trend in aerosol number concentration can be inferred from this figure, then it is a slightly downward trend for 1974-1976.

Our aerosol number concentration data can be compared to some similar discrete aerosol number concentration data obtained at the bottom of the Grand Canyon. These data were obtained during the Grand Canyon Air Quality Study organized by faculty in the Department of Physics at Northern Arizona University (Layton et al., 1976). For this study a Gardner Small Particle Detector was used. The cumulative frequency distributions for 4 years of data taken at Phantom Ranch are shown in Figure 24. Here again, as in Figure 23, there is no clear trend from year to year, but the geometric mean for 1976 is statistically higher than the mean for 1973. Unfortunately, an instrument difficulty caused the data for 1974 to be discarded as unreliable.

The seasonal variation at Phantom Ranch, at the bottom of Grand Canyon, is shown in Figure 25. Only the fall season is significantly different from the other almost identical seasons.

The aerosol number concentration was monitored continuously during arbitrary periods of days in order to measure the means and extrema that may occur at odd hours when we did not make our standard discrete measurements. The General Electric Condensation Nuclei Counter was well suited to this task because it could be operated unattended, with

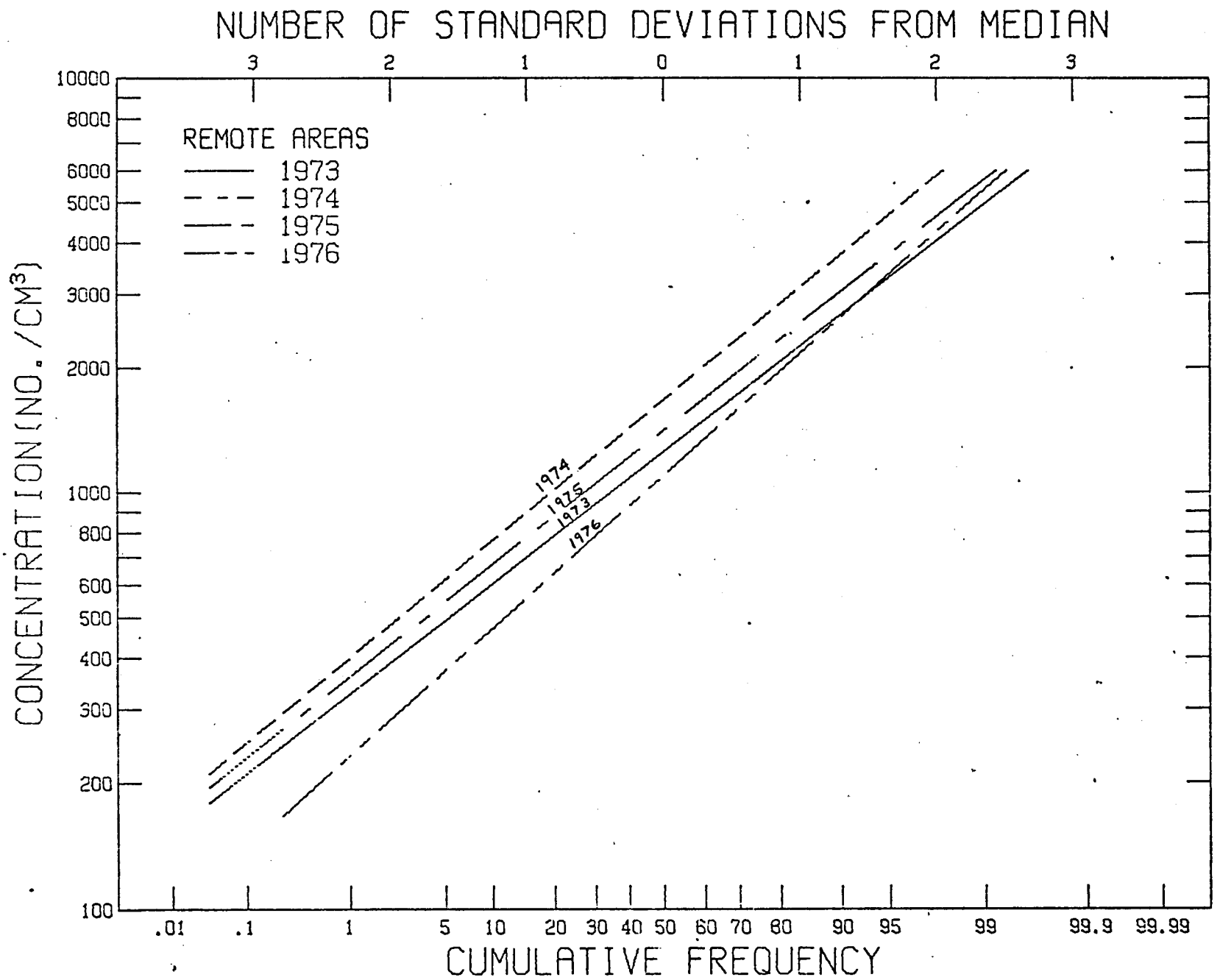


Figure 23: Aerosol number concentrations at the remote sites during 1973, 1974, 1975, and 1976

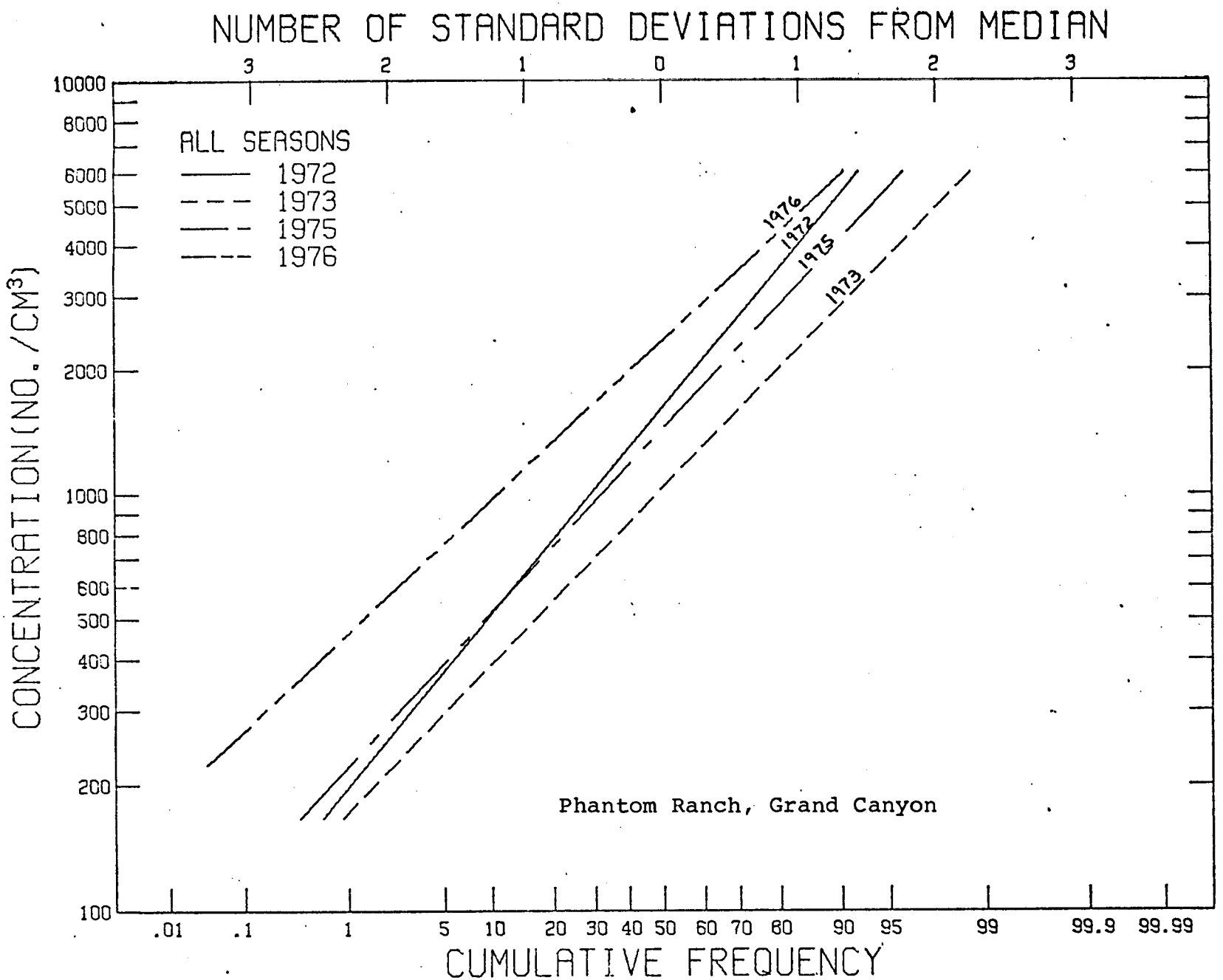


Figure 24: Aerosol number concentrations at Phantom Ranch at the bottom of Grand Canyon during 1972, 1973, 1975, and 1976

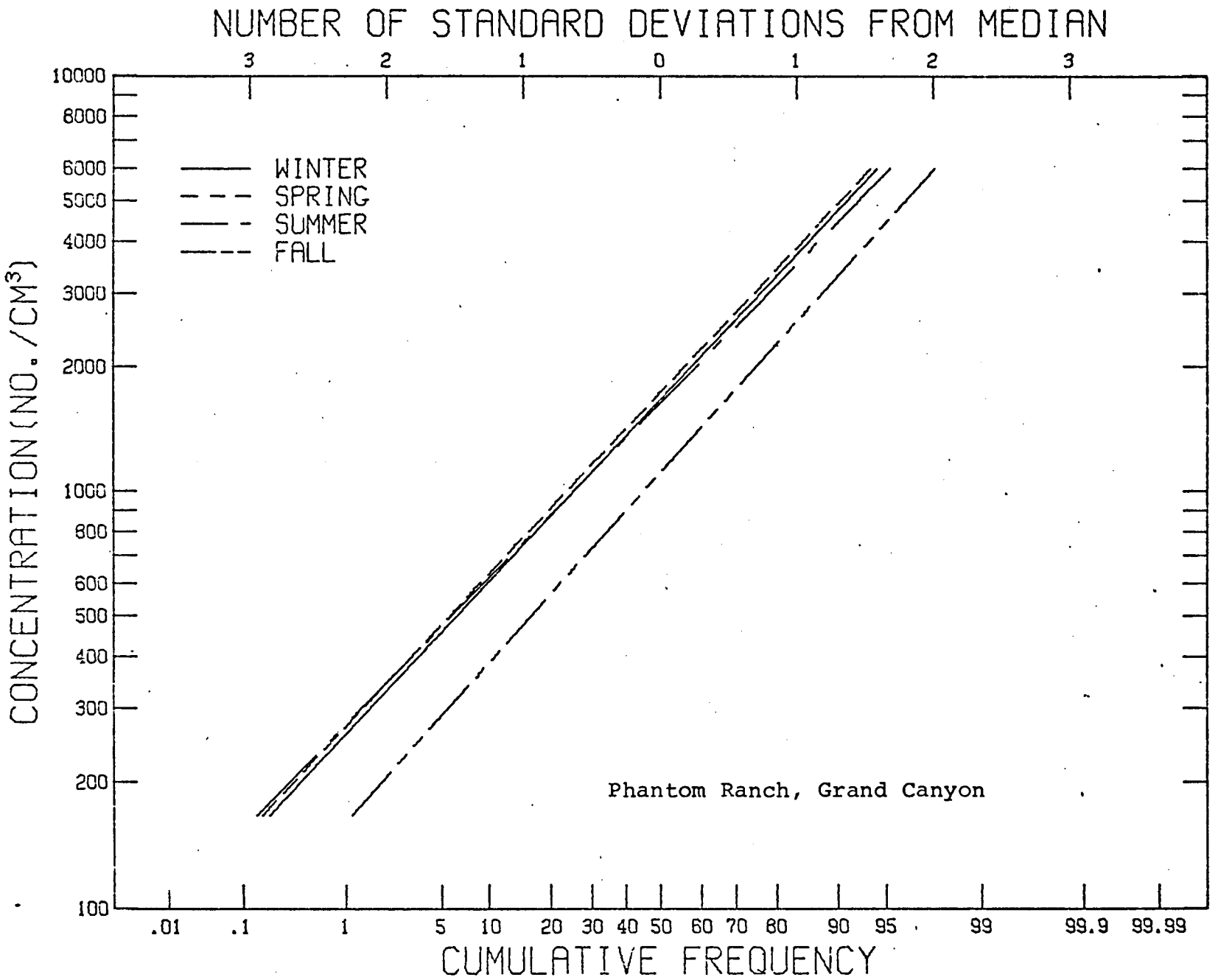


Figure 25: Aerosol number concentrations at Phantom Ranch at the bottom of the Grand Canyon during winter, spring, summer, and fall

the continuous data being recorded on a strip chart, and it was located in a special instrument room.

The results of four such arbitrary periods are presented in Table 9 for three locations--Wahweap Marina, Wahweap Trailer Court, and the Lake Pumping Station near the Navajo Generating Station. The means at these locations are all understandably less than the mean for Page and greater than the mean for the remote sites shown in Figure 19. Rarely do automobiles and other combustion sources visit the remote sites, while rarely is Page free from such sources of aerosol. All three locations selected for continuous measurement of aerosol number concentration encounter some automobile traffic.

The minimum of 100 particles per cubic centimeter at Wahweap Marina indicates how clean the air can become when no traffic comes near the instrument.

The General Electric Condensation Nuclei Counter measured the aerosol number concentration on the west side of Wahweap Trailer Court. The data from the 137 days between 27 October 1975 and 11 March 1976 were simplified by averaging the continuous data into 2-hour means. The means of these daily 2-hour means are presente in Figure 26.

The daily maximum concentration occurred during the hours of 1800-2000, and the daily minimum concentration occurred during the hours of 0200-0600. The minimum occurred during the time of minimum human activity, assuming the human activity pattern in and around this trailer court is the same as that in most places in the nation. However, independent measurements of the traffic or other activities in and around the trailer court were not made to test this hypothesis scientifically.

The 0200-to-0600 time interval may also be coincident with minimum atmospheric turbulence, which would slow down the horizontal transport of aerosol from any nearby combustion sources to the instrument. Again, independent measurements of atmospheric stability to study this possible coincidence were not made.

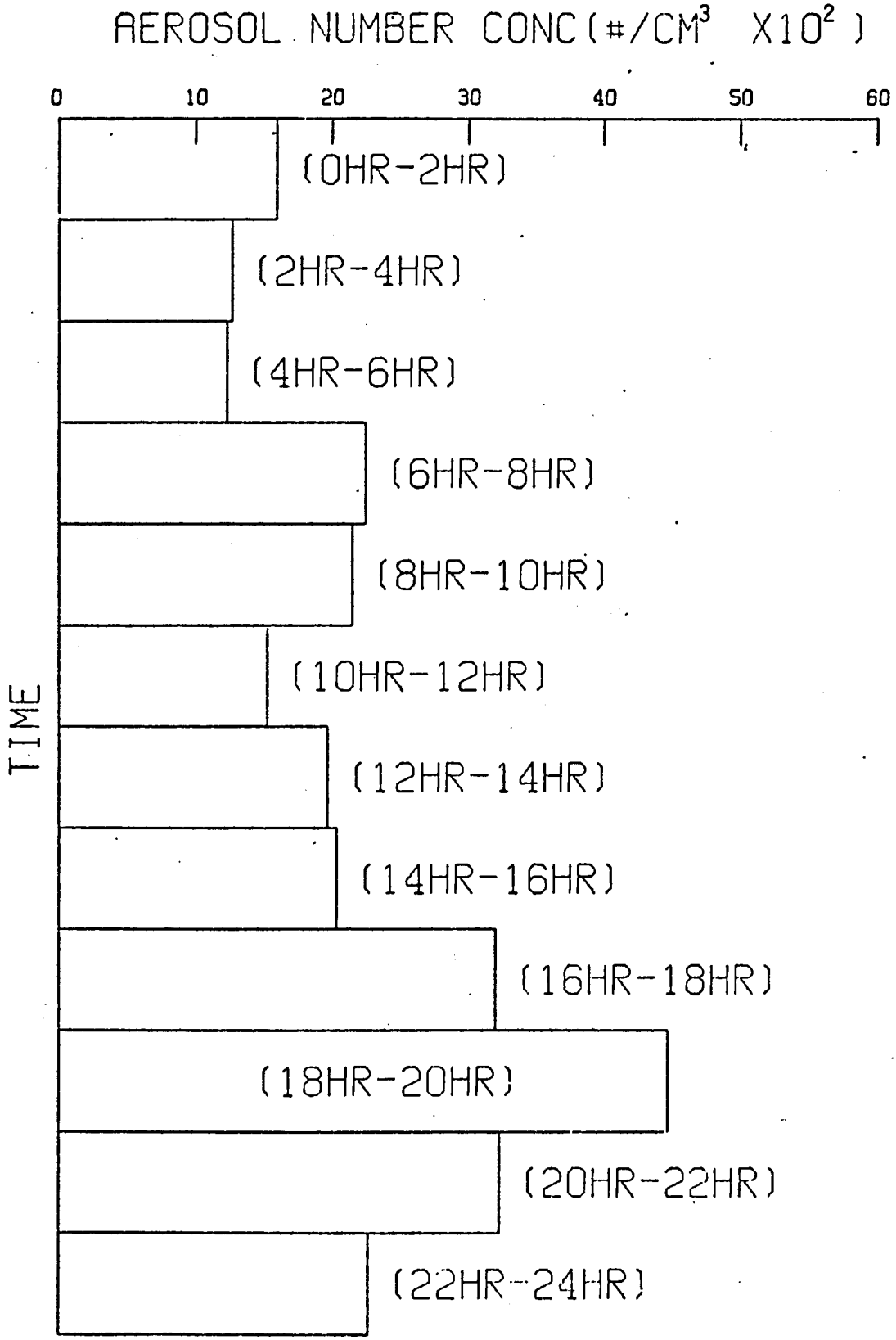
We believe that human activity in the usual daily pattern also explains the maximum, which is broader than just the hours of 1800-2000. The full maximum peak starts at 1600 and ends at 2200. This time span agrees with the normal human activity pattern at the end of the workday.

Table 9: Aerosol number concentrations at Wahweap Marina, Wahweap Trailer Court, and the Lake Pumping Station for the Navajo Generating Station (particles per cubic centimeter)

Location	Dates	Mean[a]	Minimum	Maximum
Wahweap Marina	18 Apr 1973-6 May 1973	5,300±350	100	29,000
Wahweap Marina	7-26 Jun 1973	7,200±650	600	30,000
Wahweap Trailer Court	27 Oct 1975-11 Mar 1976	2,300±450	200	10,000
Lake Pumping Station	15-31 May 1974	4,400±350	200	10,000

[a]Mean ± ½ 90 percent confidence interval

Figure 26: Aerosol number concentrations near the Wahweap Trailer Court as a function of time of day during the period 27 October 1975 to 11 March 1976



There is the traffic of people going home from work and engaging in typical evening activities of shopping and recreation. Here recreation also includes boating from Wahweap Marina which is located near the instrument.

Aerosol Size Distribution

Aerosol has a varied chemical composition as well as the number per unit volume found in specified size intervals. We can also refer to the mass per unit volume of air found in specified size intervals. Some examples of this latter mass distribution were presented in LPRP BUlletin 3 (walther et al., 1974) and others are presented here in Figures 27 and 28 (Dames & Moore, 1976).

On April 25, 1975, we collected an aerosol sample at Lake Powell with a Casella Cascade Impactor. The particles sampled on the various stages were counted in 11 size subranges from about 0.4μ radius up to 10μ radius, using an optical microscope. The number found in the size intervals is shown in Figure 29.

The curve in Figure 29 indicates the large majority of the aerosol is in the size range between a few tenths of a micron and 1μ radius. This size range is where a particle can cause the greatest effect on visibility through the scattering of light (Malm et al., 1977).

The slope of the curve in Figure 29 is a measure of the ratio of small to large particles. As the ratio increases, so does the slope. We collected ten different aerosol samples with the cascade impactor, including one at a height of 150 meters (490 feet) above ground and another at 4 km (13,100 feet) above ground. These measurements showed the ratio of small to large particles to increase when the aerosol number concentration increased.

Carbon Monoxide (CO)

Measuring carbon monoxide by gas chromatography proved to be difficult. The approach was to convert the carbon monoxide (CO) to methane over a heated nickel catalyst. The methane from the CO was measured with the flame ionization detector, using appropriate columns to separate it from ambient methane and other gases in the air sample. Instrument difficulties led to the retrieval of very few CO data.

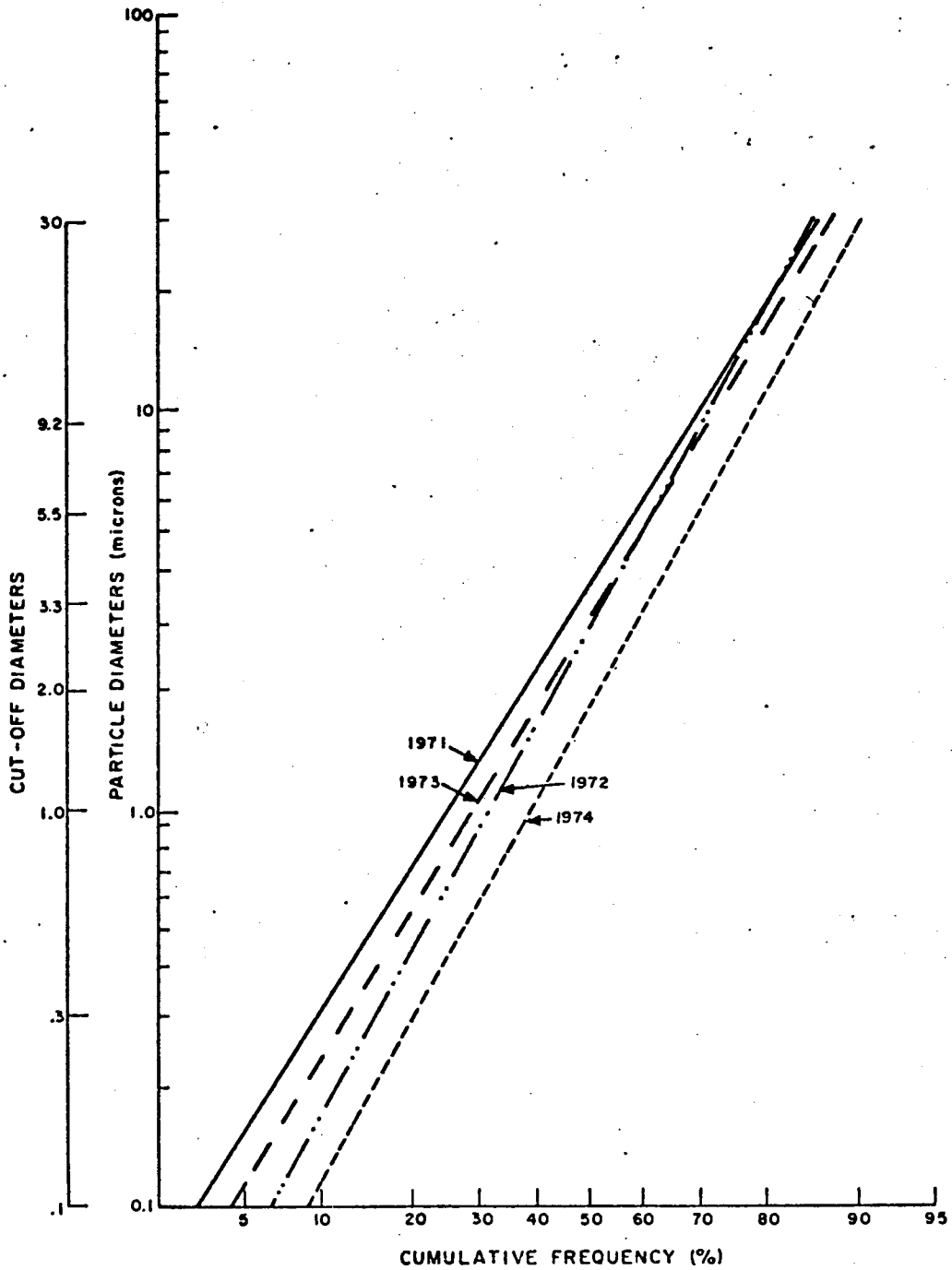


Figure 27: Cumulative frequency distribution of particle sizes as collected by the Cascade impactor

Source: Dames & Moore (1976)

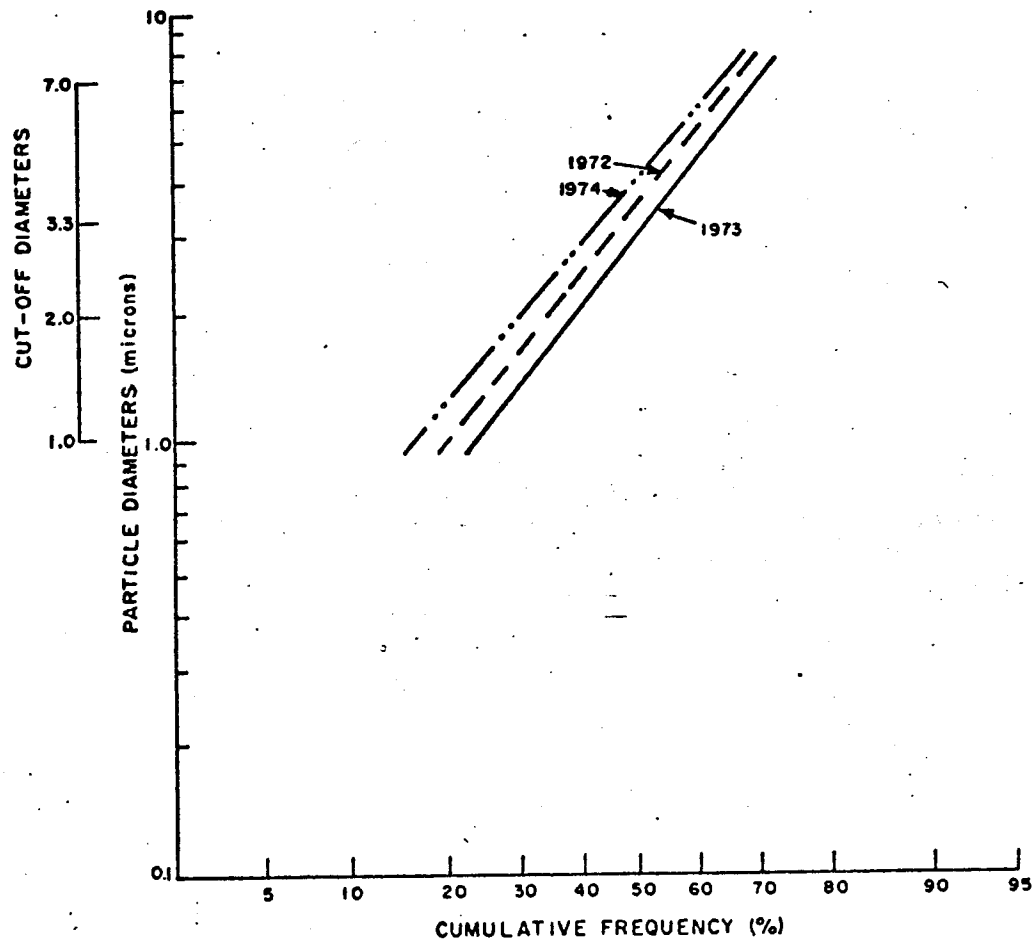


Figure 28: Cumulative frequency distribution of particle sizes as collected by the high-volume segregator

Source: Dames & Moore (1976)

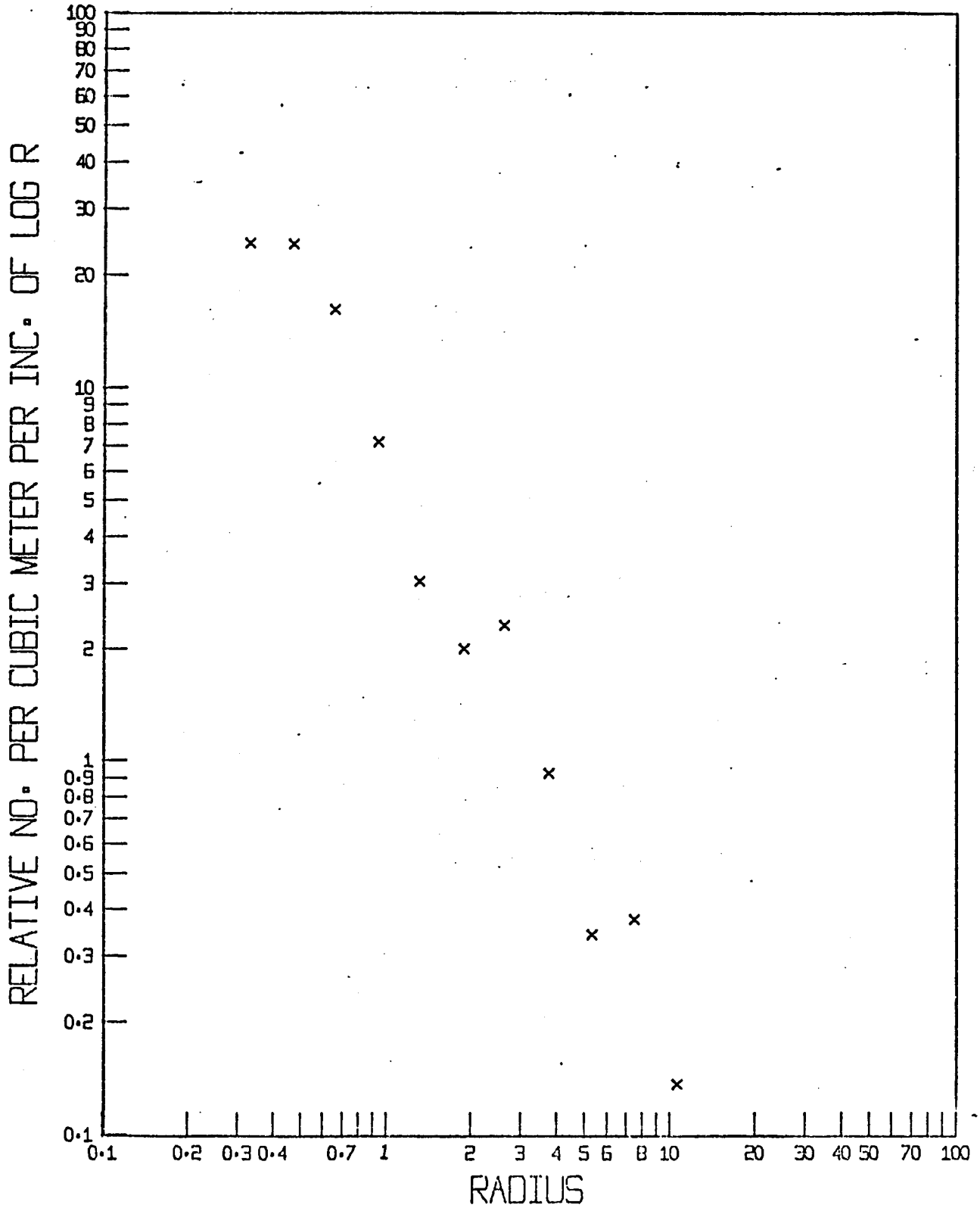


Figure 29: Aerosol size distribution taken at Lake Powell with a Casella Cascade impactor on 25 April 1975

Yet, enough CO data were obtained from Page and remote sites to almost support with 90-percent confidence the expectation that the CO concentration is higher in Page than at the remote sites (see Figure 30). The mean CO concentration in Page was 1.0 parts per million (ppm) with a 90-percent confidence interval of 0.3 to 1.7 ppm, while the mean concentration at the remote sites was 0.2 ppm with a 90-percent confidence interval of 0.1 to 0.4 ppm.

The CO concentrations were separated into the three seasons of measurement, and the seasonal arithmetic means in Page and at the remote sites are shown in Figure 31. The steady decrease for these three seasons may be caused by the decreased population in the Page area in combination with a seasonal change in atmospheric mixing. The seasonal data are presented in Appendix Table A-2.

Hydrocarbons

Hydrocarbons are a set of gases that often are neglected in studies of background air quality and in studies of generating station emissions. Hydrocarbon emissions are mostly from land vehicles and industry (Walther, 1977). Hydrocarbons are emitted in small amounts by a generating station running at design operating conditions, but far greater amounts can be emitted during either shut-down or start-up conditions.

In the Lake Powell region, Page is a continuous source of hydrocarbons from automobiles and residential heating with bottled gas (mostly propane).

Early in our study the decision was made to measure specific hydrocarbons and not to measure the total amount or all nonmethane hydrocarbons. It was felt this might allow separation of the hydrocarbons by their various sources, and specific hydrocarbon data could be used more precisely in photochemical reaction models for which the reaction rates vary greatly between different hydrocarbons. Hydrocarbons can react with nitrogen oxides and oxidants in complex ways, and the complexity is unraveled only with specific data.

A Hewlett-Packard 5711 Gas Chromatograph, equipped with a flame ionization detector and concentrating column cooled to -50°C, was used to measure individual alkanes and alkenes (from methane through hexene), and acetylene. More details are provided on the instrument, columns, and methodology in Cudney et al. (1977). This instrumentation was capable of

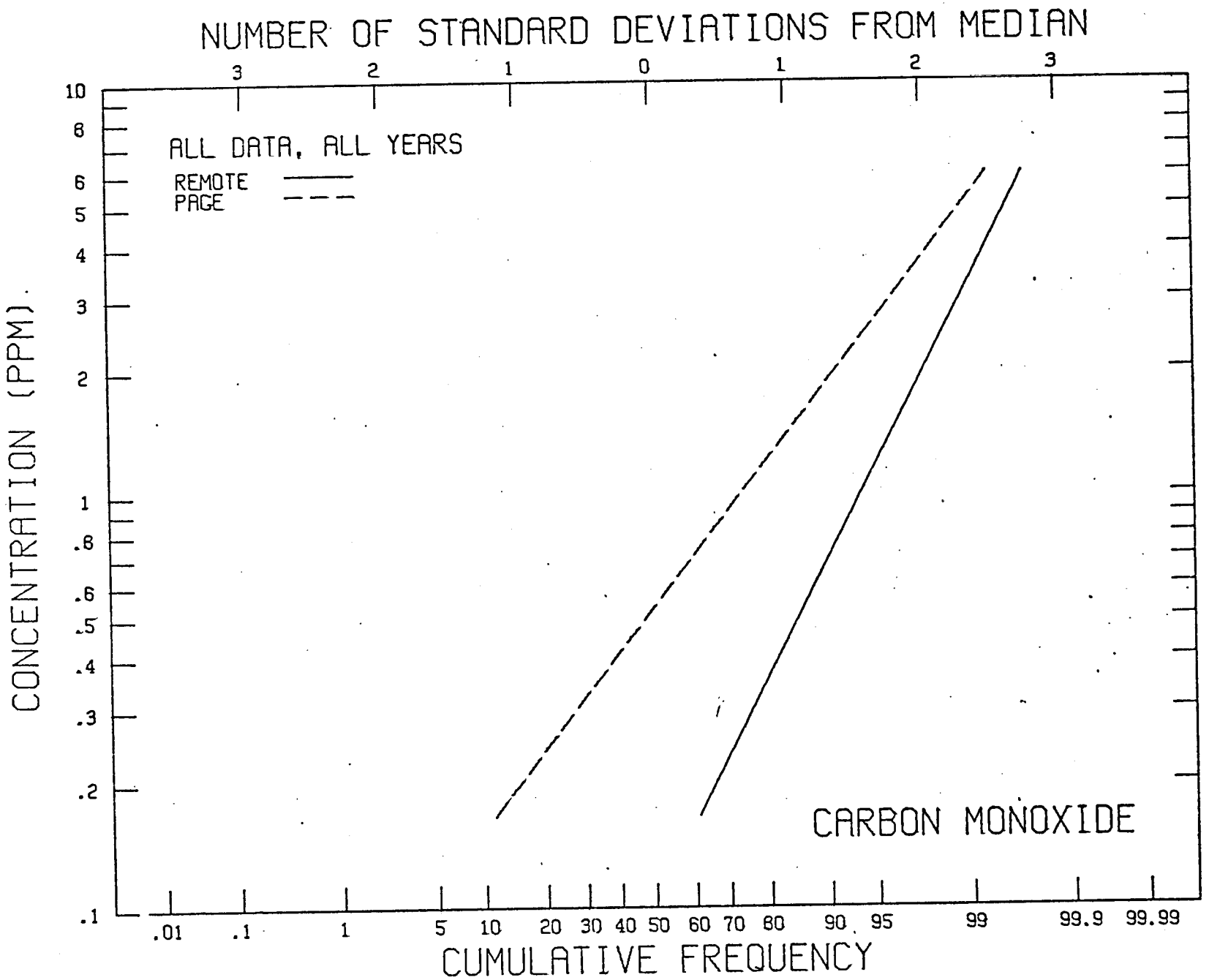


Figure 30: Carbon monoxide concentrations measured in Page and at remote sites

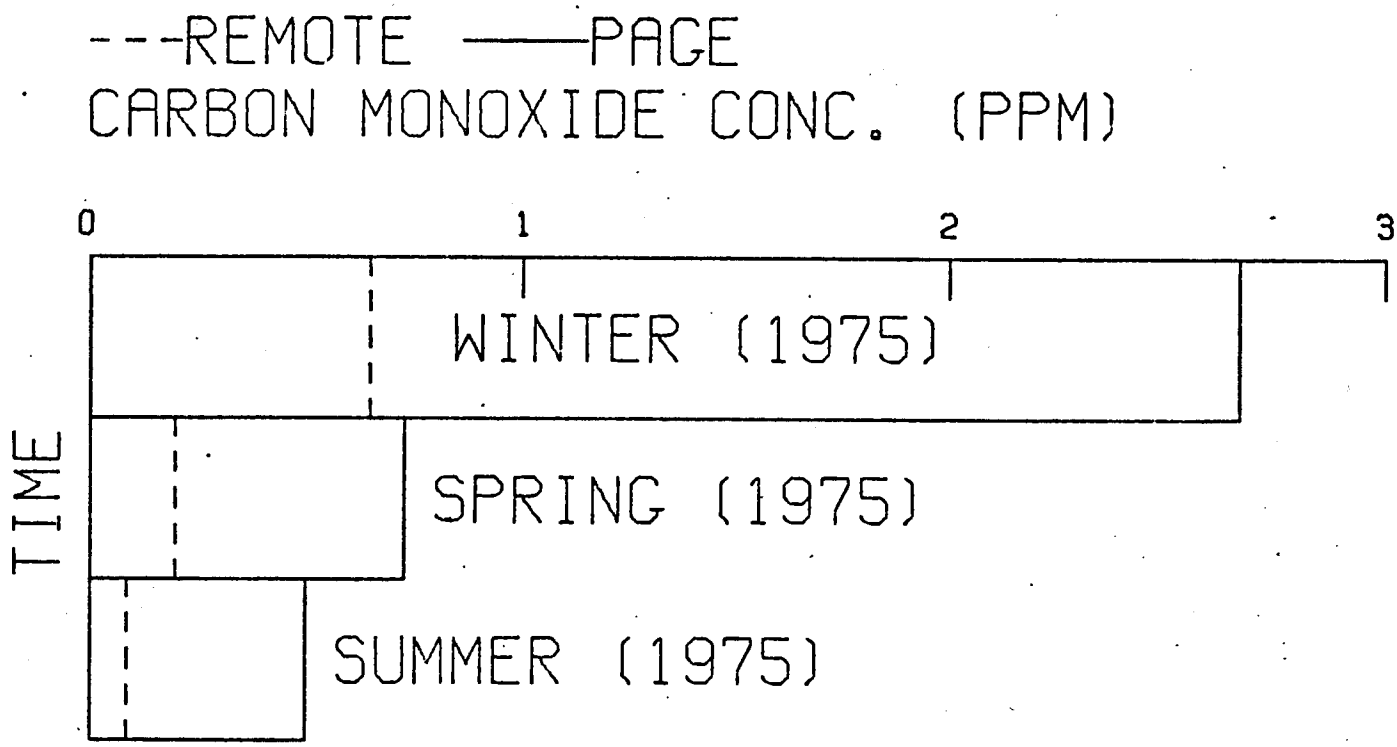


Figure 31: Seasonal arithmetic mean concentrations of carbon monoxide measured in Page and at remote sites

measuring concentrations of each hydrocarbon down to 1 part per billion (ppb). The detector would often respond to even lower concentrations, but we could not calibrate lower values because of the small size of the peak on the strip chart.

Each of the hydrocarbons was examined for significant differences in the concentrations among locations, seasons, years, and part of the week (the week is divided into two parts: 5 workdays and a 2-day weekend, including holidays). Findings of positive differences are emphasized in the figures presented here, but negative findings are also presented. The discussion is separated into sections for every hydrocarbon for which a sufficient number of concentration data exist to allow meaningful statistical analysis. The alkanes are discussed before the alkenes. Alkanes are singly bonded hydrocarbons while alkenes have one doublebond in each molecule. It is this doublebond that accounts for the higher reactivity of alkenes compared to alkanes. Alkanes have the general formula C_nH_{2n+2} while alkenes have the general formula C_nH_{2n}, where C=carbon, H=hydrogen, and n=a positive integer (1, 2, ----).

A summary of the findings from the analysis of all the hydrocarbon measurements is presented in Table 10. This table is supported by more detailed data for many, but not all, of its entries. Entries stating no trend or difference usually will not be followed by more detailed discussion or figures. The locations are listed in order of increasing mean concentration for each hydrocarbon. Where the differences between the mean concentrations are not completely separated by the 90-percent confidence intervals around the means, a note is added to the entry saying "less than 90-percent confidence." The seasonal hydrocarbon data are presented in Tables A-3 through A-14 in the Appendix.

Methane

Methane is the simplest of the hydrocarbons, containing one carbon atom surrounded by four singly bonded hydrogen atoms. Methane has the formula CH_4, and is the main c onstituent of natural gas. It is emitted by anaerobic biological decomposition, especially in swampy areas. Because the assumed methane would not be emitted by sources in Page, we expected to see the lack of a yearly trend (Figure 32), the lack of seasonal differences (Figure 33), and the lack of a difference between weekdays and weekends (Figure 34).

Table 10: Summary of hydrocarbon measurement results

	Analysis of Concentrations				
Hydrocarbon	Location	Season	Weekday/ Weekend	Year	Remarks
Methane	D<R<P*	No significant difference	Identical	No trend	Page not a source. Unknown substance reacting with methane?
Ethane	D<R<P	(Winter highest in Page)	Weekdays higher	No trend	May come from bottled gas. Unknown substance reacting with ethane?
Propane	D<R<P	(Winter highest)	Weekdays higher in Page; no significant difference at remote sites	No trend	Main hydrocarbon in bottled gas used for space heating
Butane	D<R<P	Winter highest	(Weekdays higher)	No trend	Second most concentrated hydrocarbon in bottled gas
Pentane	D<R<P	(Winter highest and spring lowest)	Weekdays higher	No trend	--
Hexane	D<R<P	(Winter highest)	Weekdays higher	No trend	--

*D = Downwind of Page; R = Remote sites; P = Page; < means 'less than'; ( ) means findings have statistical confidence less than 90 percent.

Table 10: Summary of hydrocarbon measurement results (continued)

	Analysis of Concentrations				
Hydrocarbon	Location	Season	Weekday/ weekend	Year	Remarks
Ethene (ethylene)	R<D<P	No significant differences	No significant differences at remote sites; weekdays higher in Page.	No significant differences	--
Propene	R<D<P	(Winter highest)	Weekdays higher in Page; no difference at remote sites.	No trend	Lower concentration than propane
Butene	(R<D<P)	(Winter highest)	(Weekdays higher in Page); weekdays higher at remote sites.	No trend	Lower concentration than butane
Pentene	(R<D<P)	Winter highest	(Weekdays higher)	No trend at remote sites	Lower concentration than pentane
Hexene	(R<D<P)	No significant differences	Identical	Downward trend	Lower concentration than hexane
Acetylene	R<D?	No significant differences	Not enough data	No trend	--

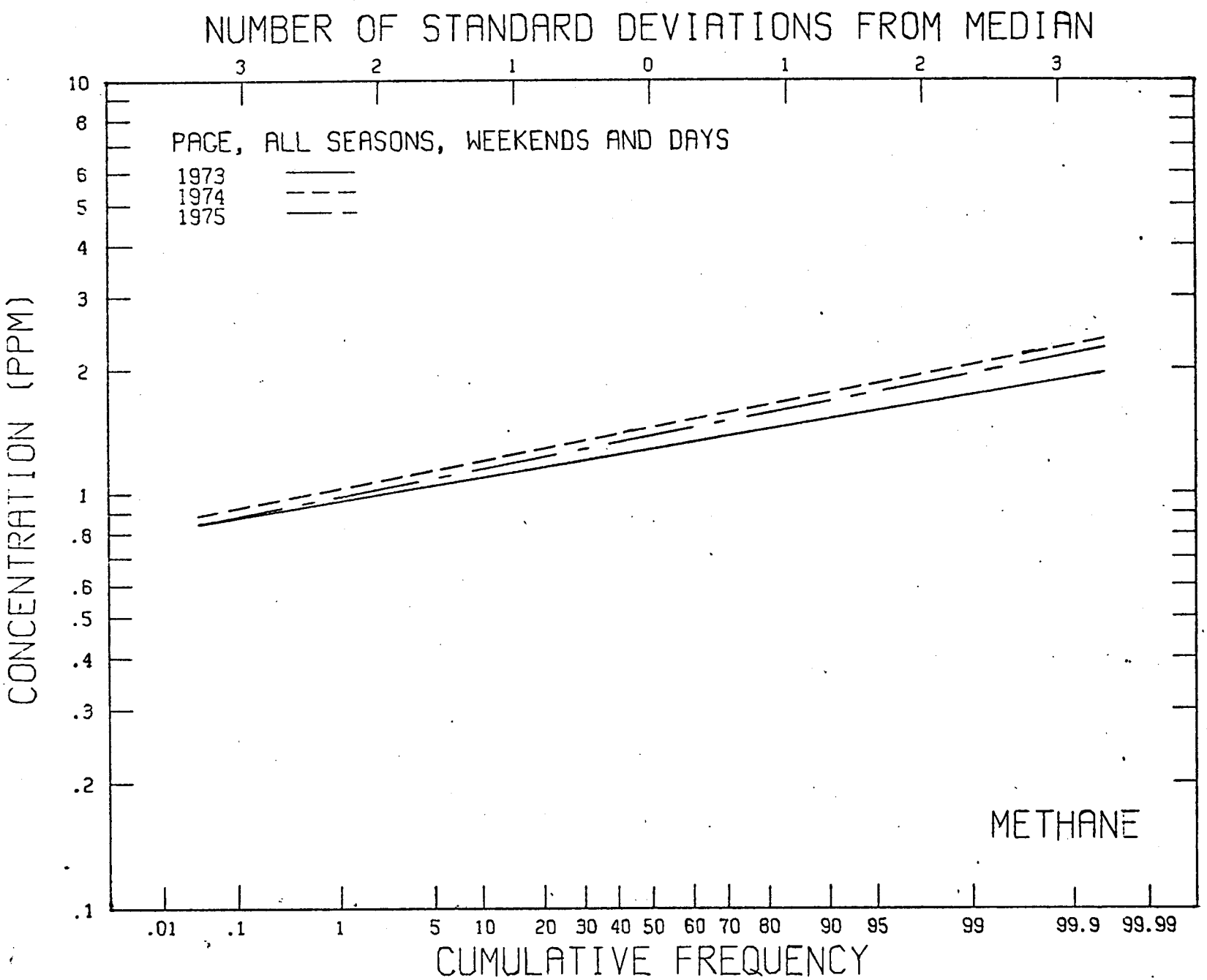


Figure 32: Methane concentrations measured in Page during 1973, 1974, and 1975

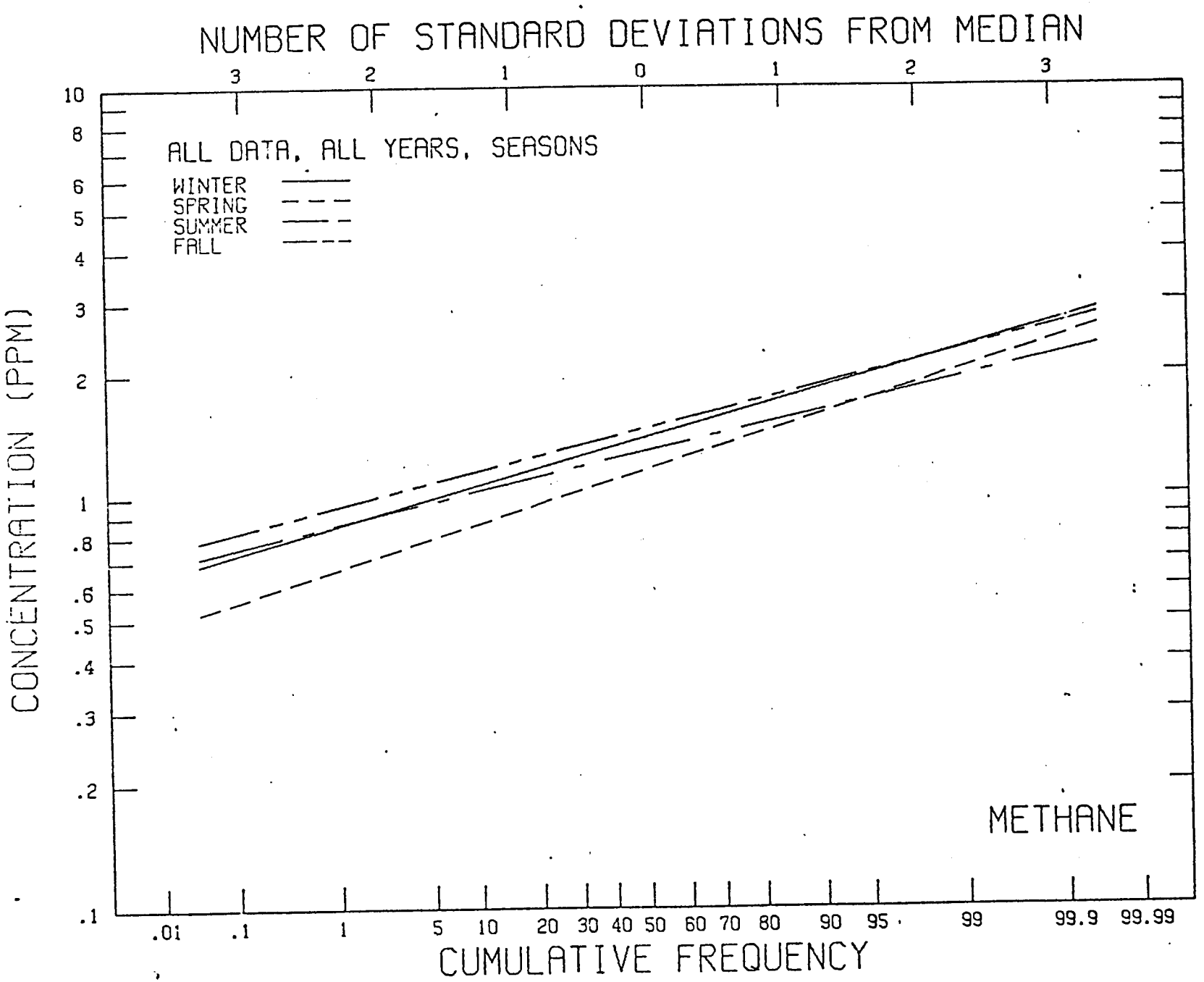


Figure 33: Methane concentrations measured at all locations during each of the four seasons

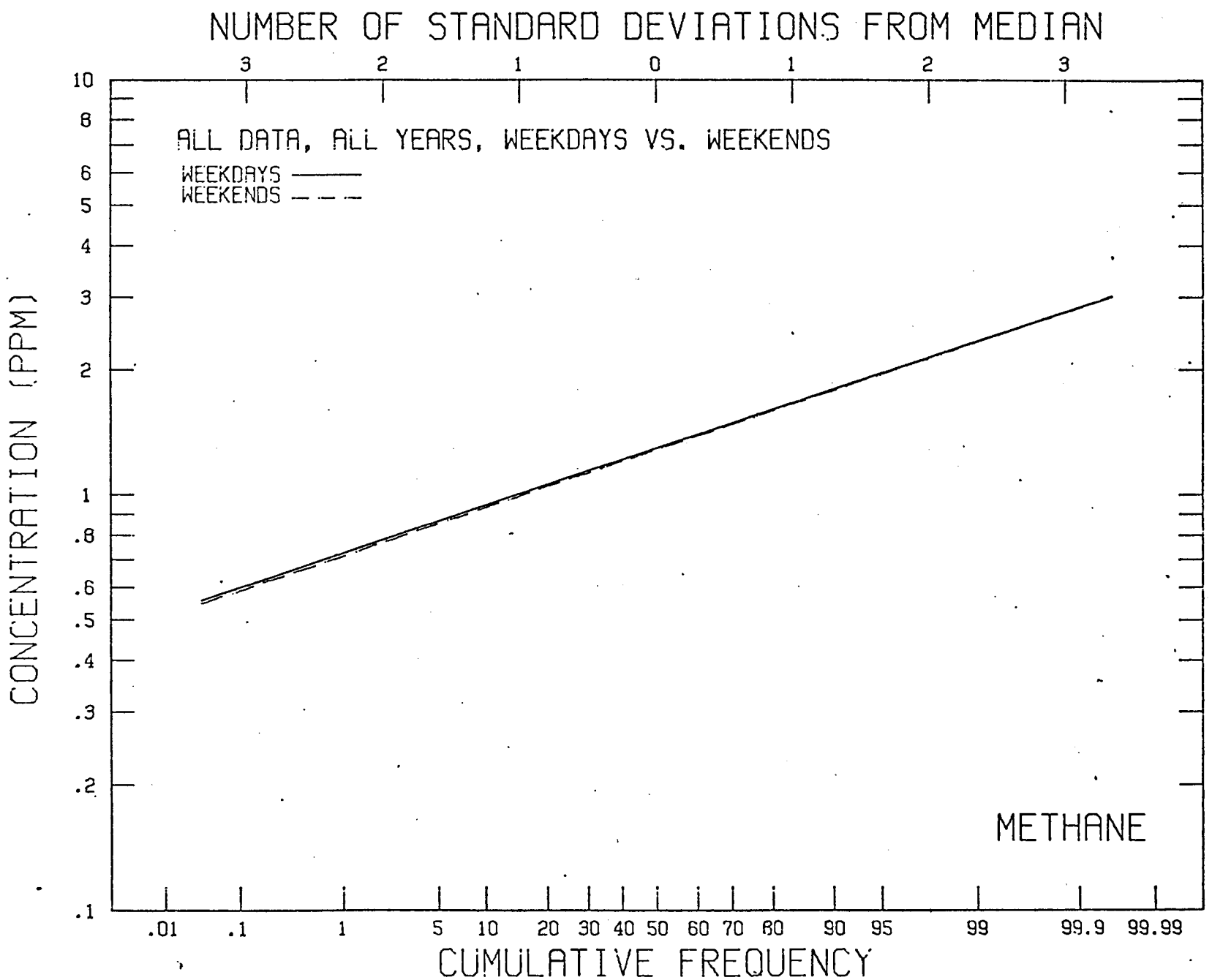


Figure 34: Methane concentrations measured at all locations during weekdays and weekends

These indications of constancy caused a temporary suspension of the methane measurements for a few months in mid-1973. The cumulative frequency distributions for the methane concentrations measured in Page, downwind of Page, and at the remote sites are presented in Figure 35. Note that the concentrations downwind of Page are lower than those at the remote sites, something that was not expected. The arithmetic means for Page and the remote sites are 1.42 $\pm$ 0.05 ppm and 1.41 $\pm$ 0.035 ppm, respectively. The numbers after $\pm$ are one-half the 90-percent confidence intervals around the means. The arithmetic mean for downwind of Page is 1.05 $\pm$ 0.10 ppm, showing that the difference between this location and the other locations is statistically significant.

Presently, there is no satisfactory explanation for less methane downwind of Page than at the remote sites. Possibly methane being transported through Page may be reacting with other atmospheric constituents like nitrogen oxides emitted by sources in Page.

Ethane

A similar finding for ethane has shown that downwind of Page concentrations were lower than either the concentrations in Page or those at remote sites (Figure 36). The ethane case differs from that for methane because the concentrations in Page are significantly higher than those at remote sites. This higher cumulative frequency distribution indicates Page is a significant source of ethane, while Page does not seem to be a source of methane. There is no satisfactory explanation for the ethane downwind of Page being lower than that at remote sites. There exists the possibility that ethane is reacting with unknown constituents.

The seasonal arithmetic mean ethane concentration in Page and at the remote sites from fall 1973 through fall 1975 are shown in Figure 37. The winter peaks in Page are apparent, suggesting ethane may be generated by the combustion of bottled propane, which also peaks in winter.

The ethane concentrations on weekdays are somewhat higher than those on weekends as shown by the arithmetic means of 2.7 $\pm$ 0.6 ppb for weekdays and 1.3 $\pm$ 0.4 ppb for weekends.

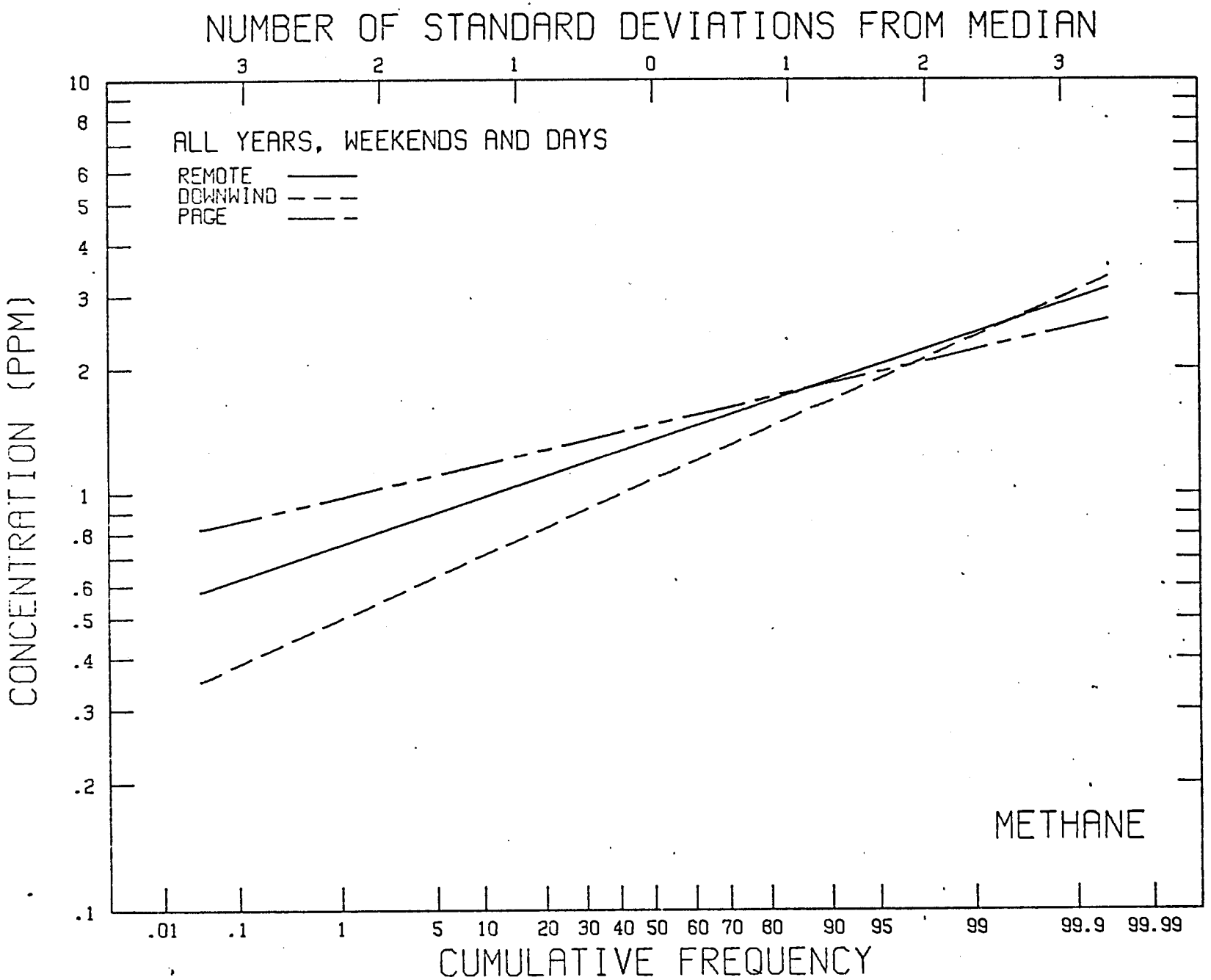


Figure 35: Methane concentrations measured in Page, downwind of Page, and at remote sites

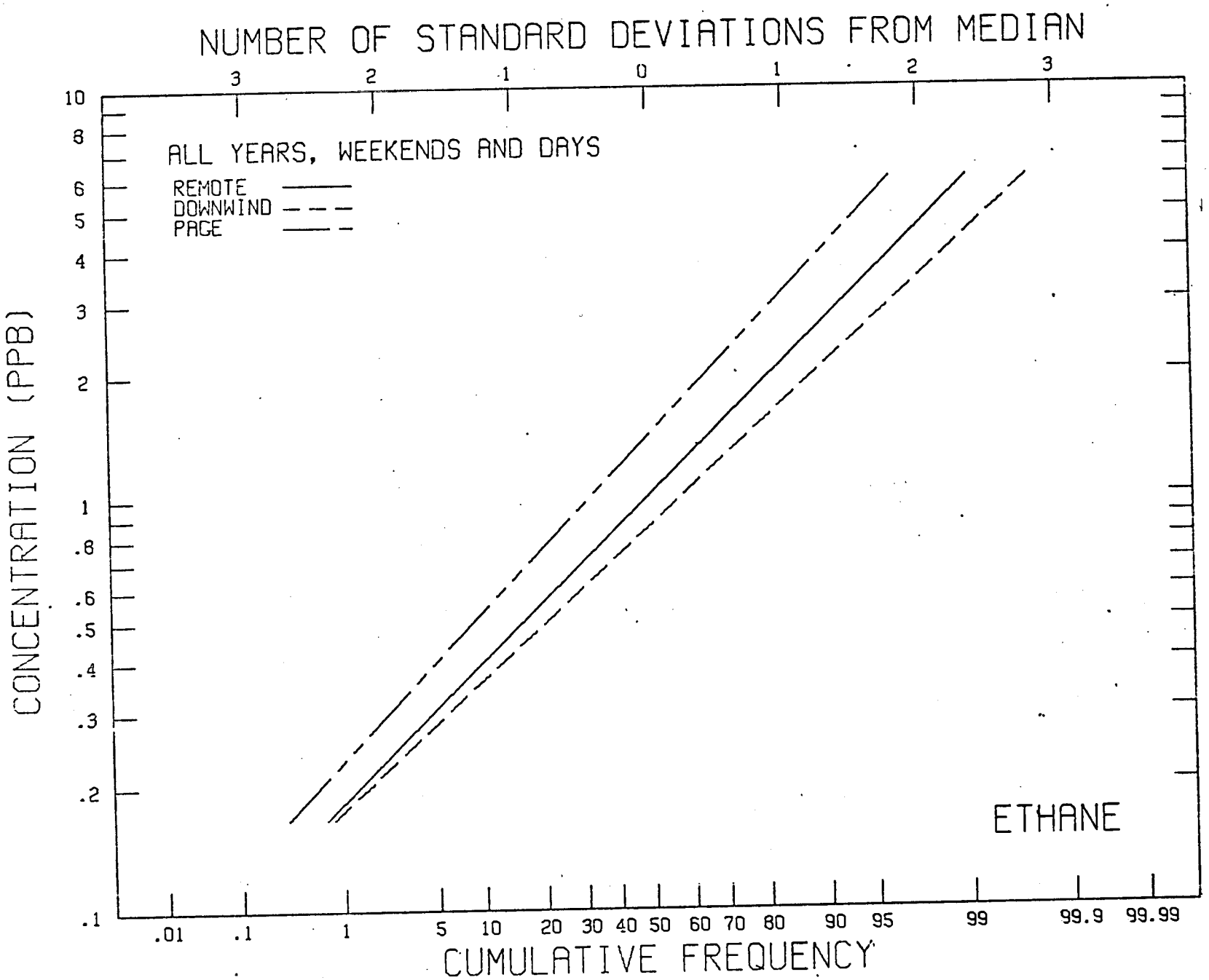


Figure 36: Ethane concentrations in Page, downwind of Page, and at remote sites

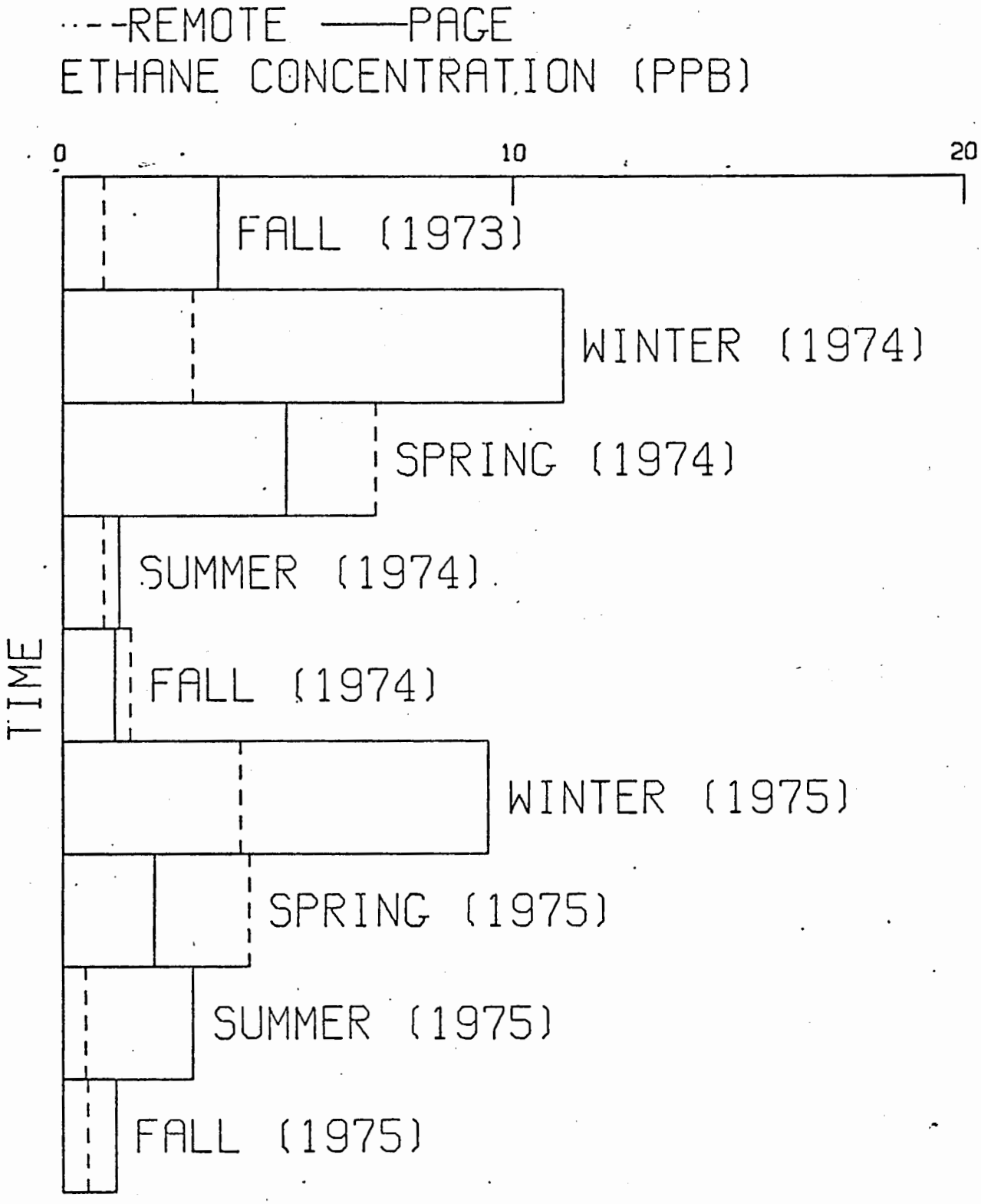


Figure 37: Seasonal arithmetic mean ethane concentrations in Page and at the remote sites

Propane

The cumulative frequency distributions for propane presented in Figure 38 do not show concentrations downwind of Page as being lower than those at remote sites.

Propane and the higher alkanes do not show the same unexplained order of concentrations as is found with methane and ethane. Yet, if methane and ethane are reacting with some unknown constituent. all the alkanes may be reacting with the same constituent. One would expect all alkanes to react in a similar way. It is possible that the ratio of concentrations of these higher alkanes in Page to the concentrations at the remote sites was too high for the chemical reactions to reduce the downwind-of-Page concentrations below those at the remote sites. This ratio of concentrations in Page to those at the remote sites was about 1.0 for methane and 1.3 for ethane. Both of these ratios are close enough to 1.0 that any appreciable chemical reaction could lower the downwind-of-Page concentrations below those at the remote sites. The ratio was 10 for propane, 2.7 for butane, 1.5 for pentane, and 2.2 for hexane. All of these ratios, but especially that for propane, would make it more difficult for reasonable chemical reaction rates to lower the downwind-of-Page concentrations below those at the remote sites.

Again, as with ethane, the analysis of seasonal data showed winter to have higher concentrations, but the difference from the other seasons does not have clear statistical significance (Figure 39). Clear statistical significance for the difference of two means only exists if there is no overlap of the 90-percent confidence intervals around the means. This interval tends to be larger when the data are more variable and when there are fewer data. We expected the concentrations of propane and butane to be higher in winter because propane is the main hydrocarbon and butane is the next most concentrated hydrocarbon in the bottled gas used for residential space heating.

The weekday/weekend separation of propane concentrations indicates higher concentrations on weekdays as shown by the cumulative frequency districutions in Figure 40. The arithmetic means of 37.8 $\pm$ 7.2 ppb for weekdays and 12.2 $\pm$ 3.6 ppb for weekends are clearly separated.

Butane

Butane is the major hydrocarbon impurity in the bottled propane available to local residents for space heating.

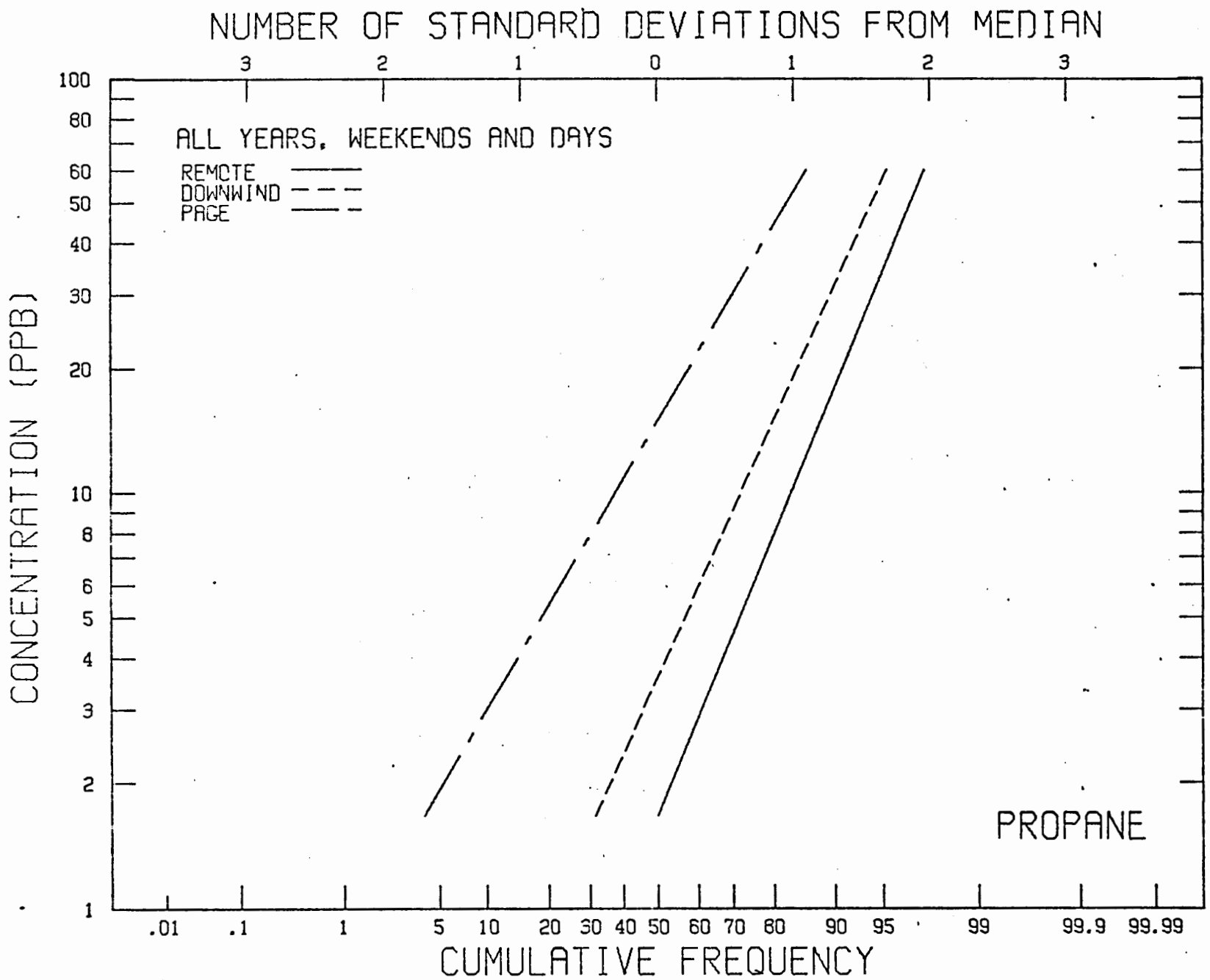


Figure 38: Propane concentrations in Page, downwind of Page, and at the remote sites

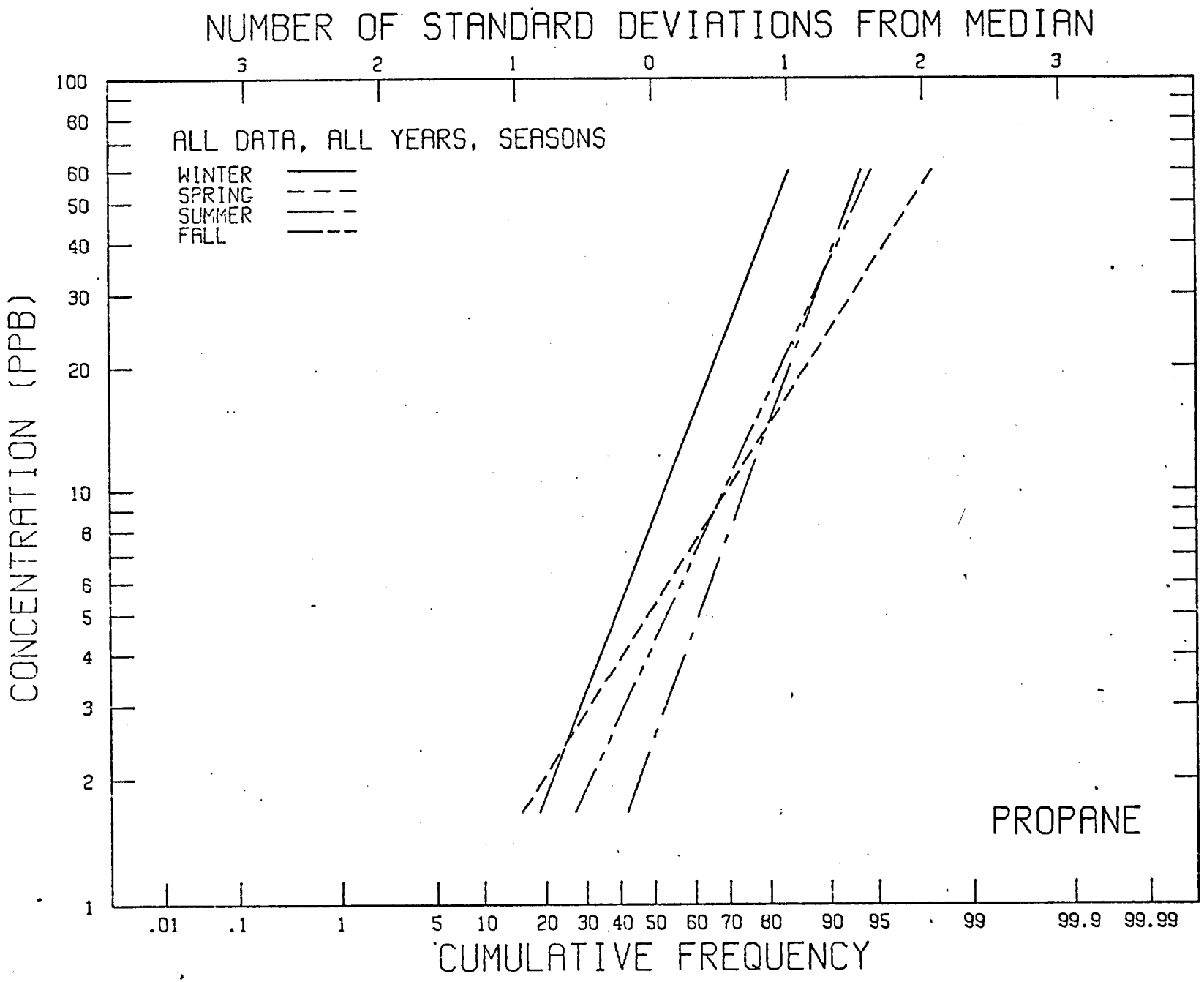


Figure 39: Propane concentrations at all locations during each of the four seasons

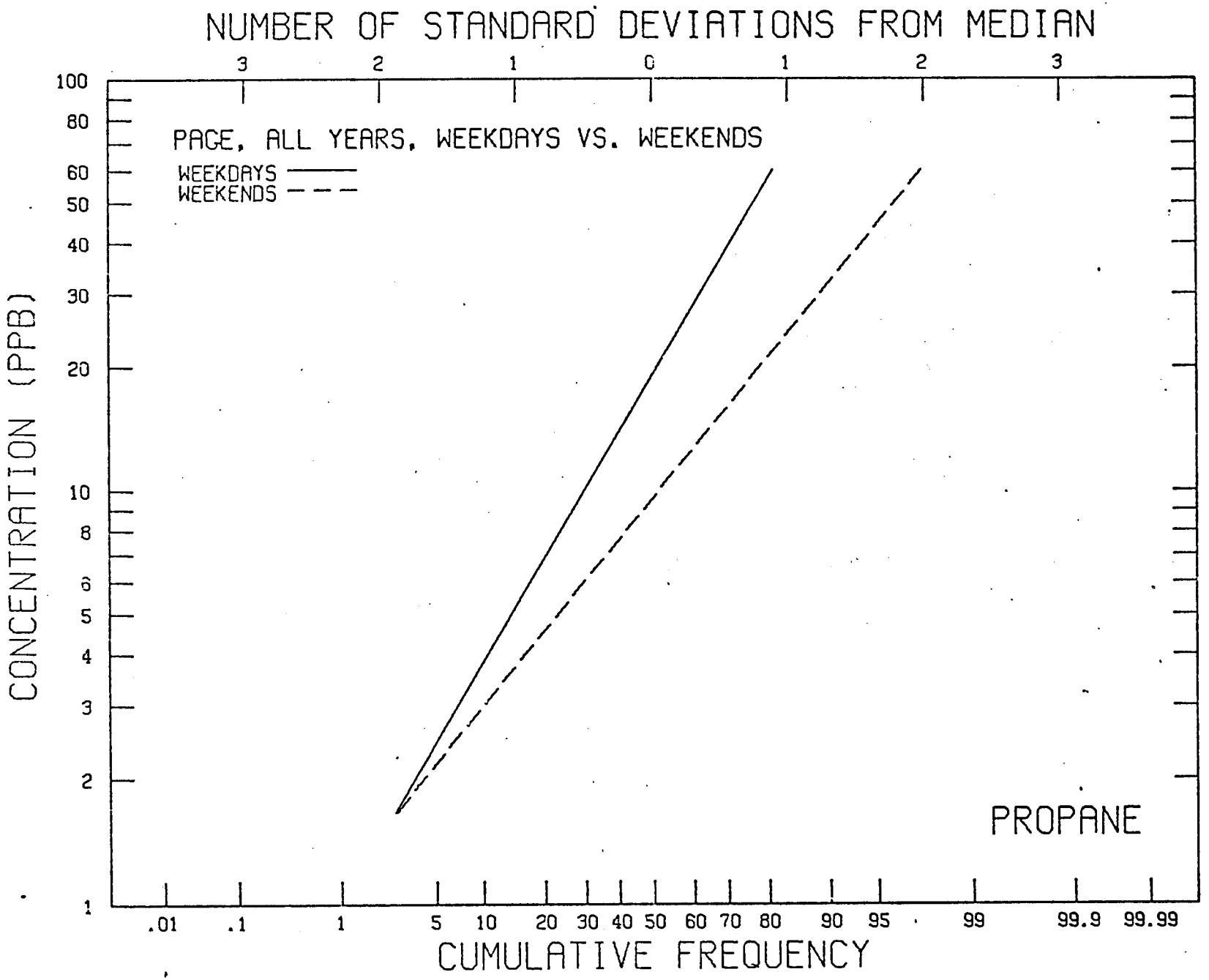


Figure 40: Propane concentrations in Page during weekdays and weekends

When the butane concentrations are separated by location, the cumulative frequency distributions for Page and at remote sites appear as shown in Figure 41. The higher concentrations in Page are evident, as expected, because the sources of butane are in Page.

The seasonal arithmetic means of butane in Page and at the remote sites are shown in Figure 42. The winters have the highest concentrations in Page, as expected. The greatest use of butane (in bottled propane) occurs during winter months.

The higher butane concentration in winter compared to the other three seasons is corroborated further by the cumulative frequency distributions shown in Figure 43.

All butane concentration measurements are separated into weekdays and weekends (Figure 44). Weekday concentrations are higher, but not quite enough to keep the 90-percent confidence intervals around the means from overlapping.

Pentane

Pentane concentrations in Page appear to be higher than those downwind of Page and at remote sites. Apparent differences cannot be accepted with 90-percent confidence because the following arithmetic means are not completely separated by 90-percent confidence intervals around the means:

Page	18.6 ± 5.4 ppb
Downwind of Page	14.8 ± 6.0 ppb
Remote	12.4 ± 4.0 ppb

Pentane concentrations at all locations were separated into seasons in order to produce the cumulative frequency distributions shown in Figure 45. Winter has the highest values and spring the lowest, but the differences are not enough to separate the 90-percent confidence intervals around the arithmetic means. This lack of separation can be understood by looking at the seasonal arithmetic means from winter 1974 to spring 1976 in Figure 46.

In order to look for any year-to-year trend, the 1974 and 1975 pentane concentration measurements in Page were separated. The concentrations in 1974 were clearly less than those in 1975, shown by the arithmetic means of 7.7 ± 14.0 ppb for 1974 and 28.2 ± 9.6 ppb for 1975.

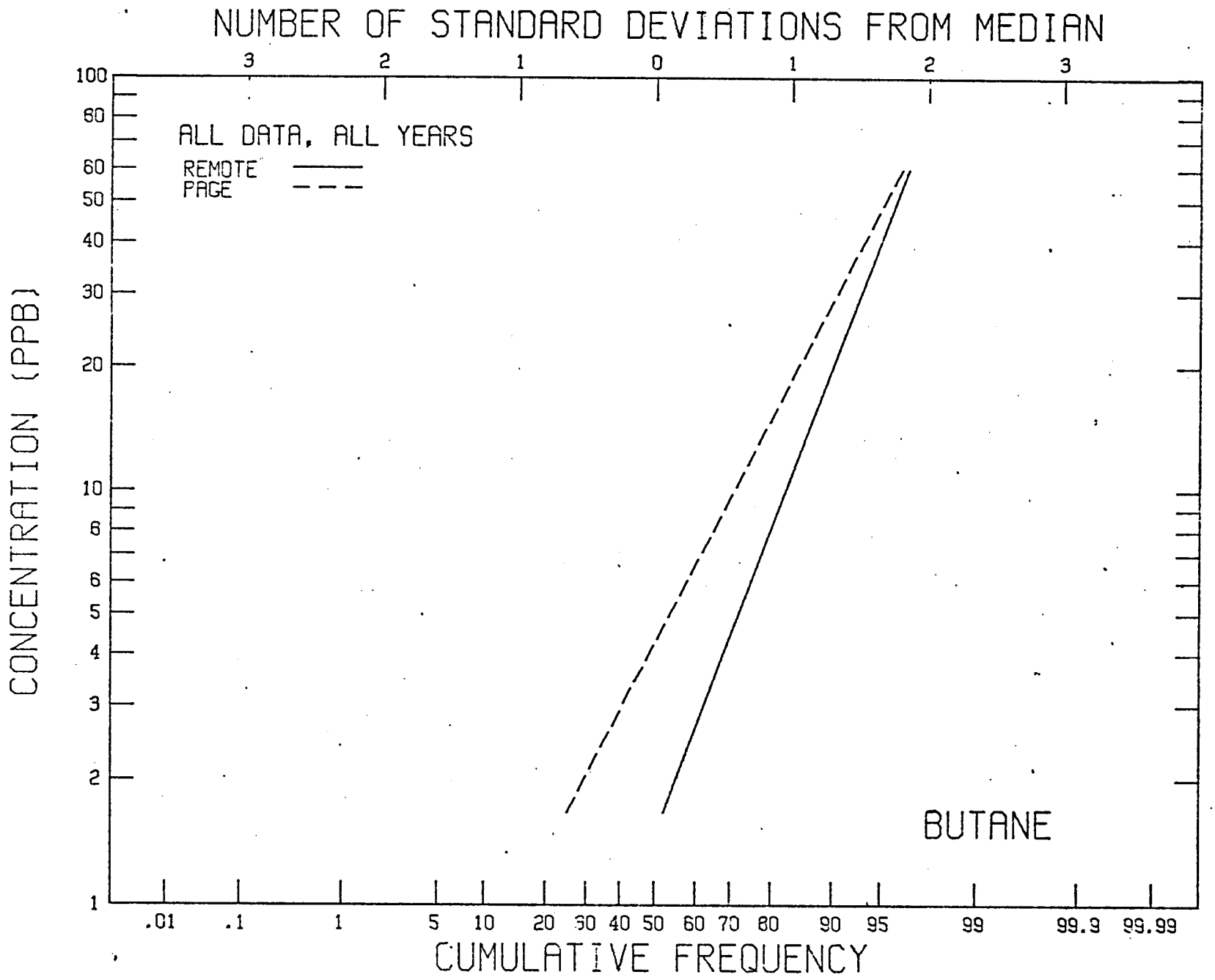


Figure 41: Butane concentrations in Page and at remote sites

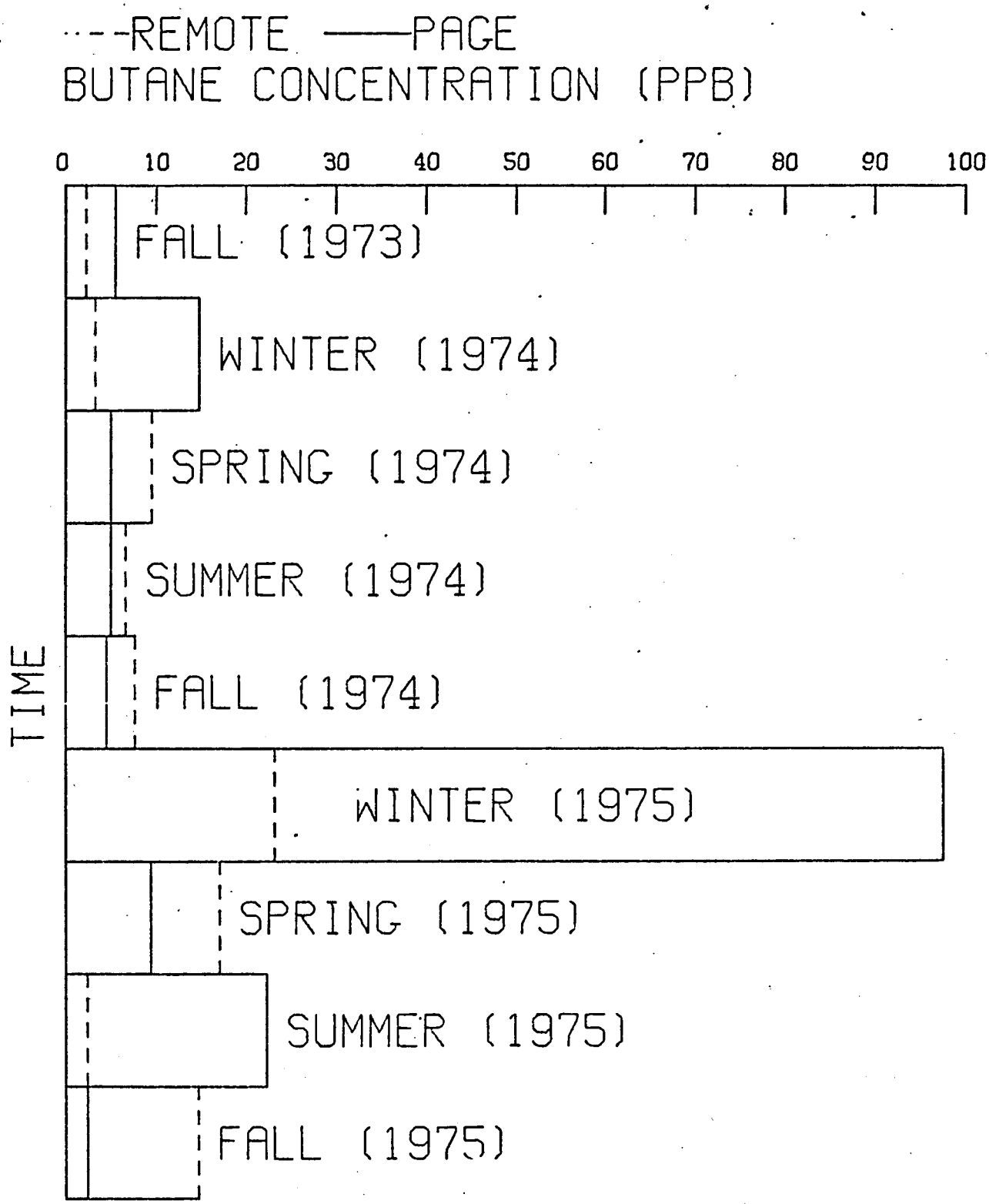


Figure 42: Seasonal arithmetic mean butane concentrations in Page and at the remote sites

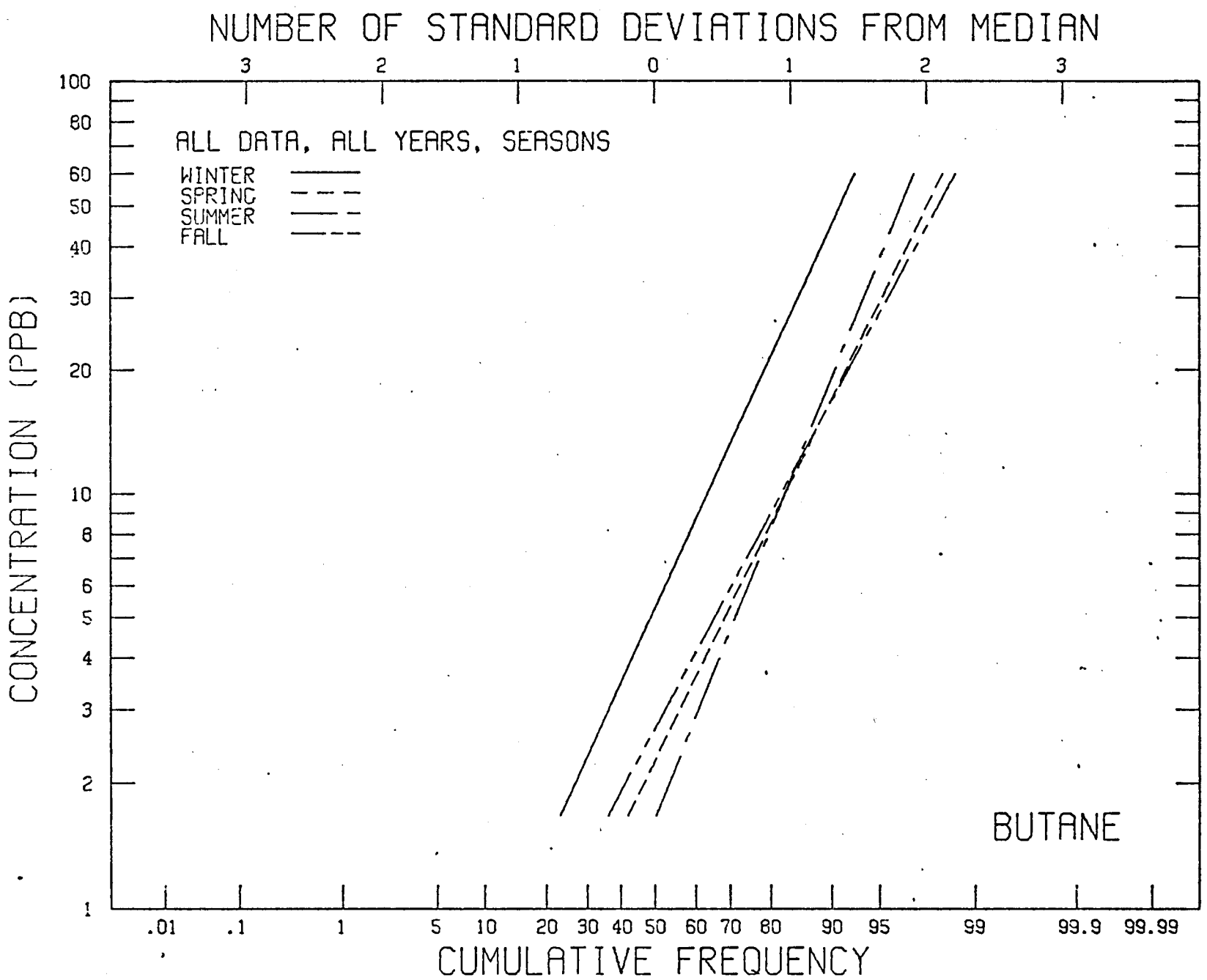


Figure 43: Butane concentrations at all locations during the four seasons

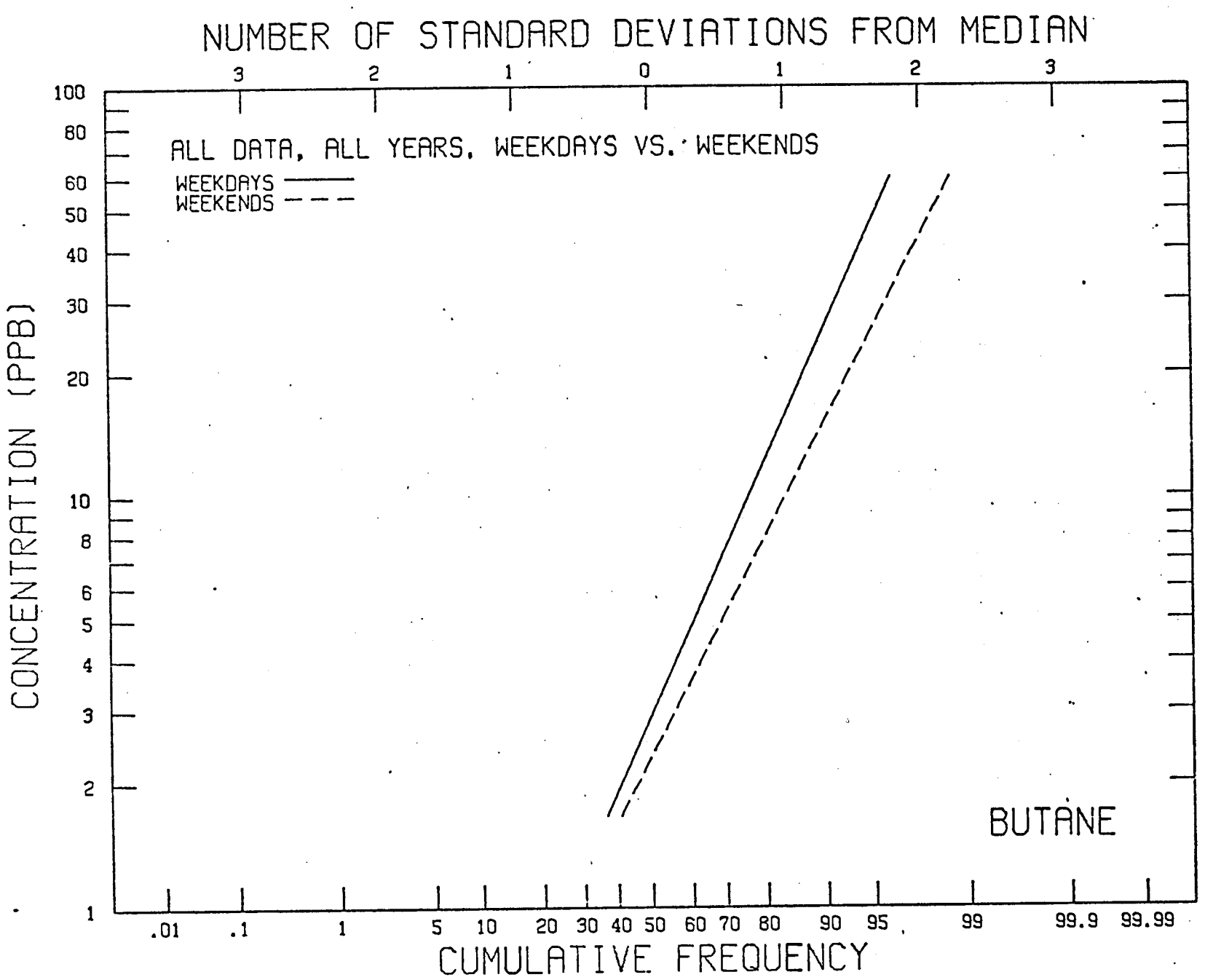


Figure 44: Butane concentrations at all locations on weekdays and weekends

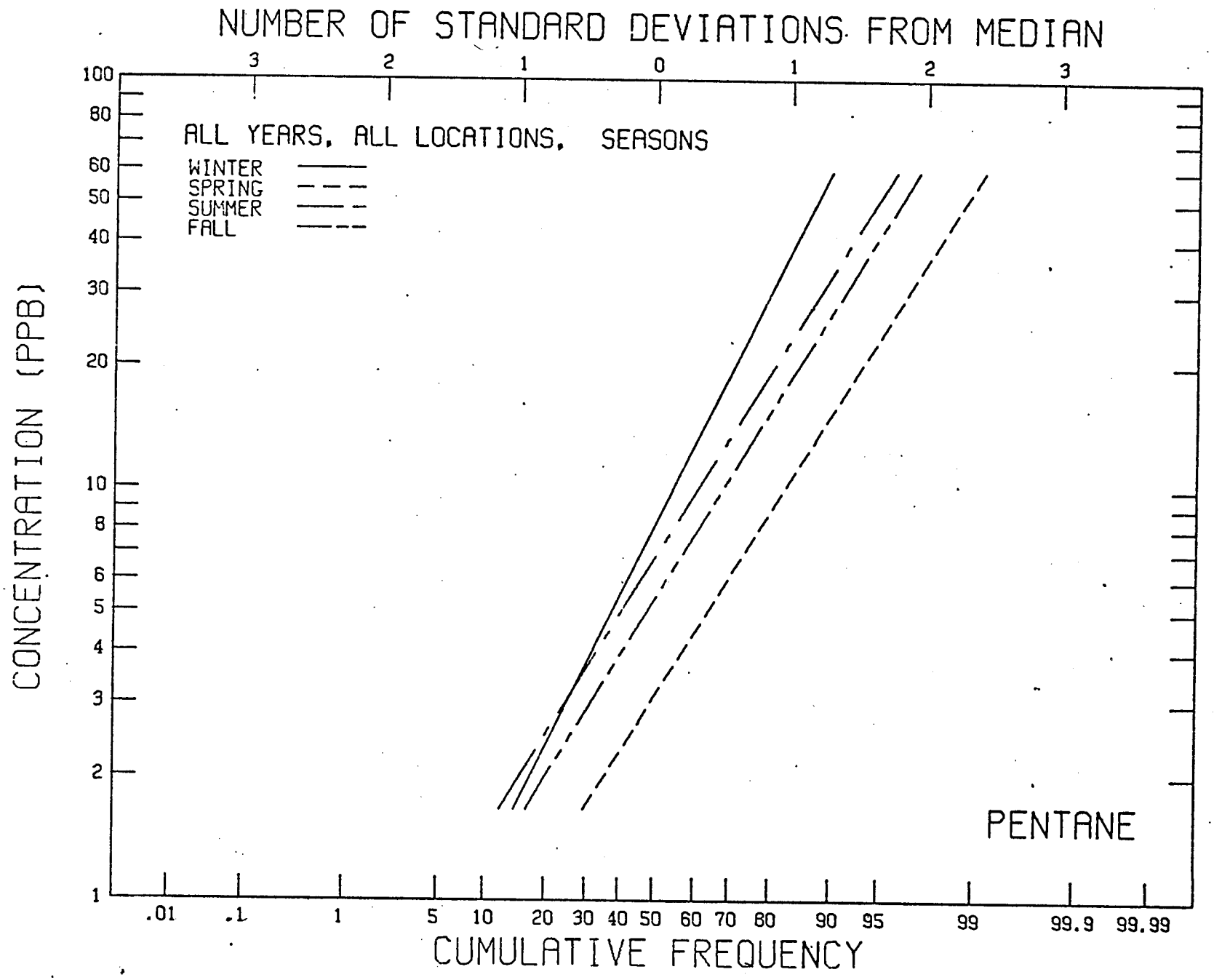


Figure 45: Pentane concentrations at all locations during the four seasons

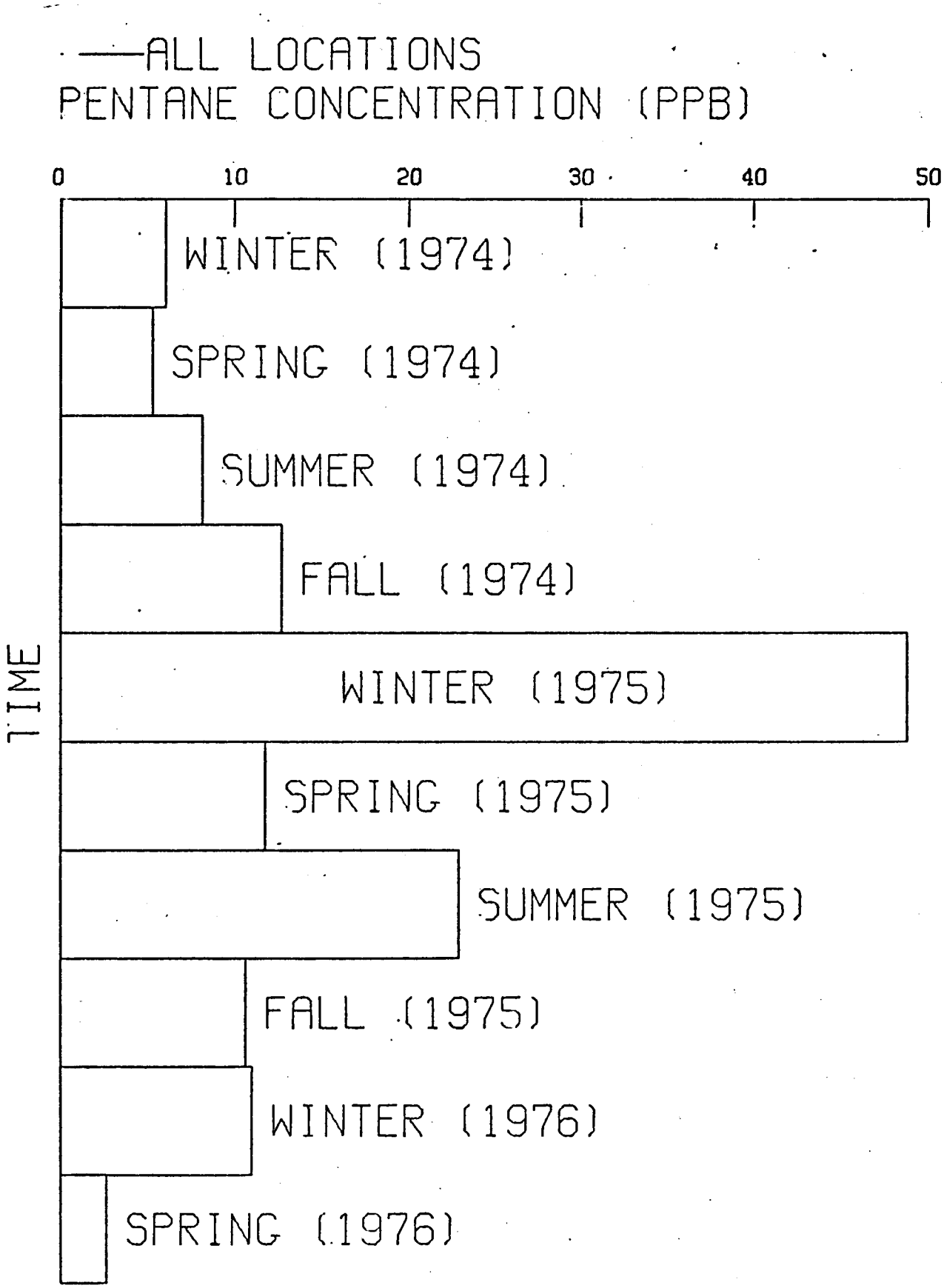


Figure 46: Seasonal arithmetic mean pentane concentrations at all locations

Separating the pentane concentrations between weekdays and weekends produced the cumulative frequency distributions shown in Figure 47. The weekdays had higher concentrations as shown in the figure and by the arithmetic means of 15.6 ± 2.8 ppb for weekdays and 7.7 ± 2.2 ppb for weekends.

At the remote sites, we also measured pentane concentrations in 1976. Here no lasting trend is apparent. The arithmetic means were:

1974	8.2 ± 3.6 ppb
1975	22.0 ± 10.0 ppb
1976	5.8 ± 3.0 ppb

Hexane

Hexane is the longest alkane we measured, simply because of the elution time required for different hydrocarbons. For a specified column, temperature, and gas chromatograph design, it takes more time to detect longer hydrocarbons. If one changes columns, then heavier hydrocarbons start being detected together without the separation necessary for individual analysis. Therefore, a system compromise was necessary, and we established a technique that yielded all alkanes through hexane, all the alkenes through hexene, and acetylene. Combined with all other steps in the detection procedure, the total analysis time was about 30 minutes per sample.

The cumulative frequency distributions for hexane measured in Page, downwind of Page, and at remote sites are presented in Figure 48. The hexane emitted by cars and any other sources in Page seems to dilute (and possibly react) enough to make the concentrations downwind of Page approximately equal to those at the remote sites.

A look at seasonal changes of hexane is provided by Figure 49, which shows the seasonal arithmetic mean concentrations in Page and at the remote sites. The range of seasonal means is greater for Page than for the remote sites, as would be expected because Page contains the sources of the hexane.

All hexane concentrations were separated into weekdays and weekends to produce the cumulative frequency distributions shown in Figure 50. Weekdays had higher concentrations. Overall arithmetic means were 15.0 ± 2.7 ppb for weekdays and 6.7 ± 5.8 ppb for weekends.

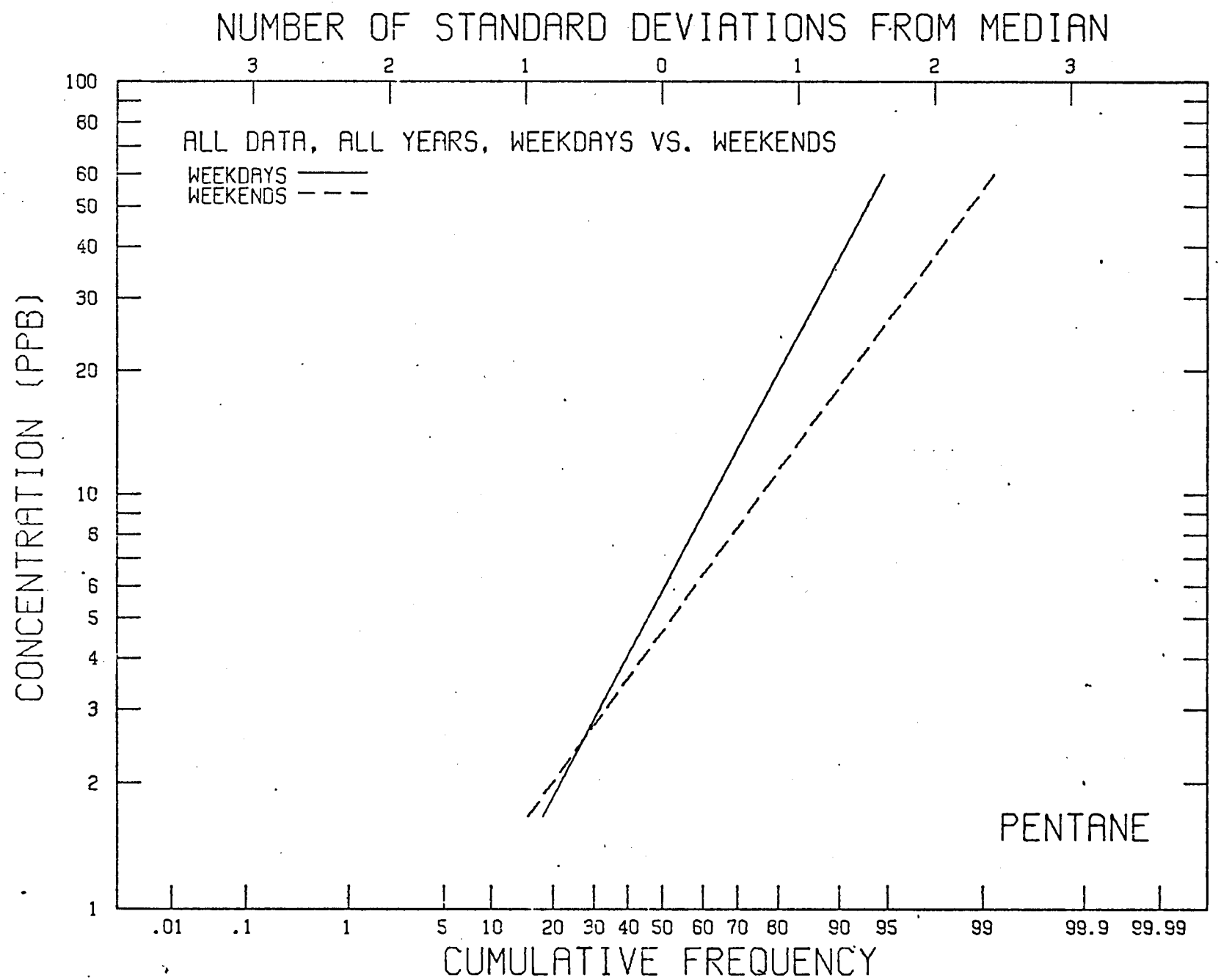


Figure 47: Pentane concentrations at all locations on weekdays and weekends

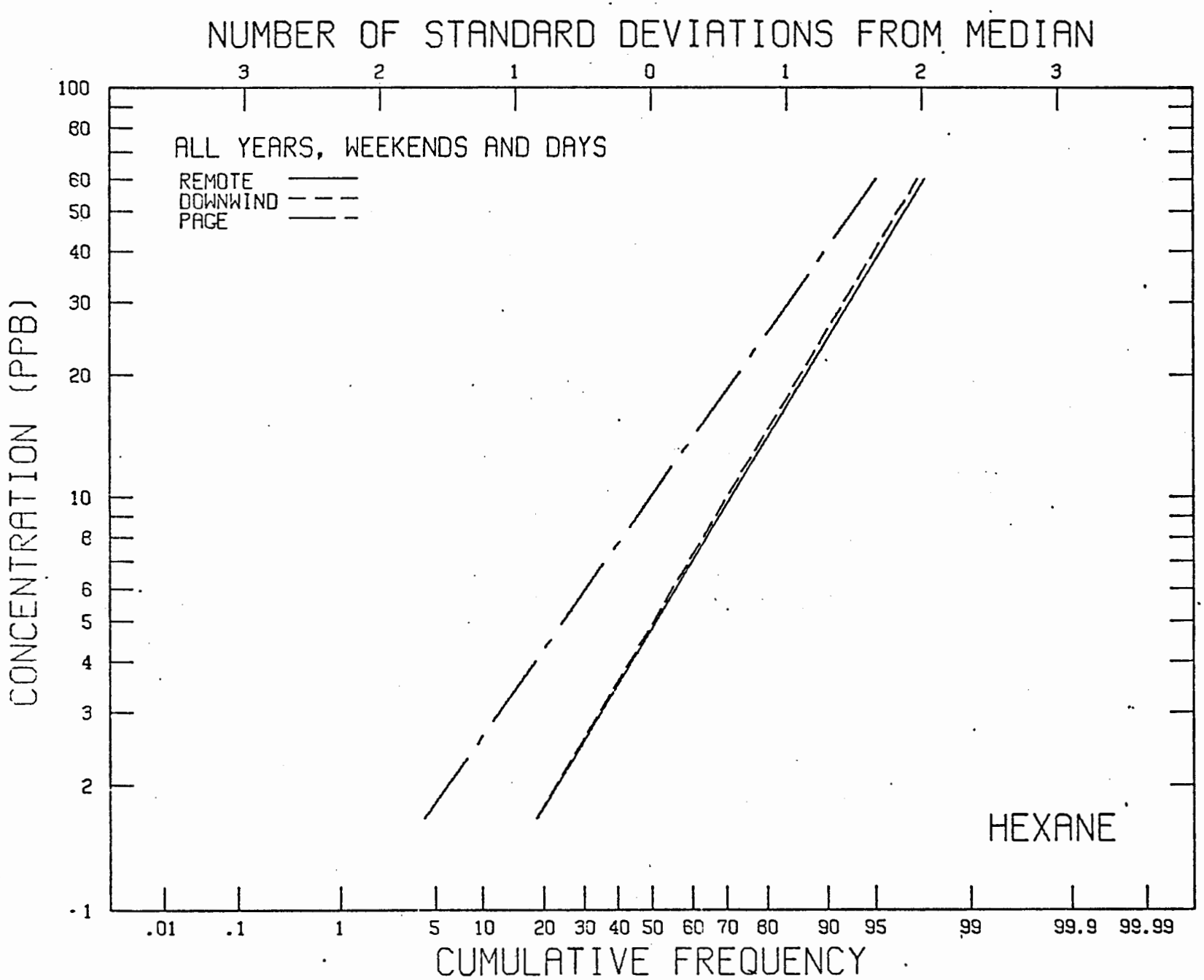


Figure 48: Hexane concentrations in Page, downwind of Page, and at the remote sites

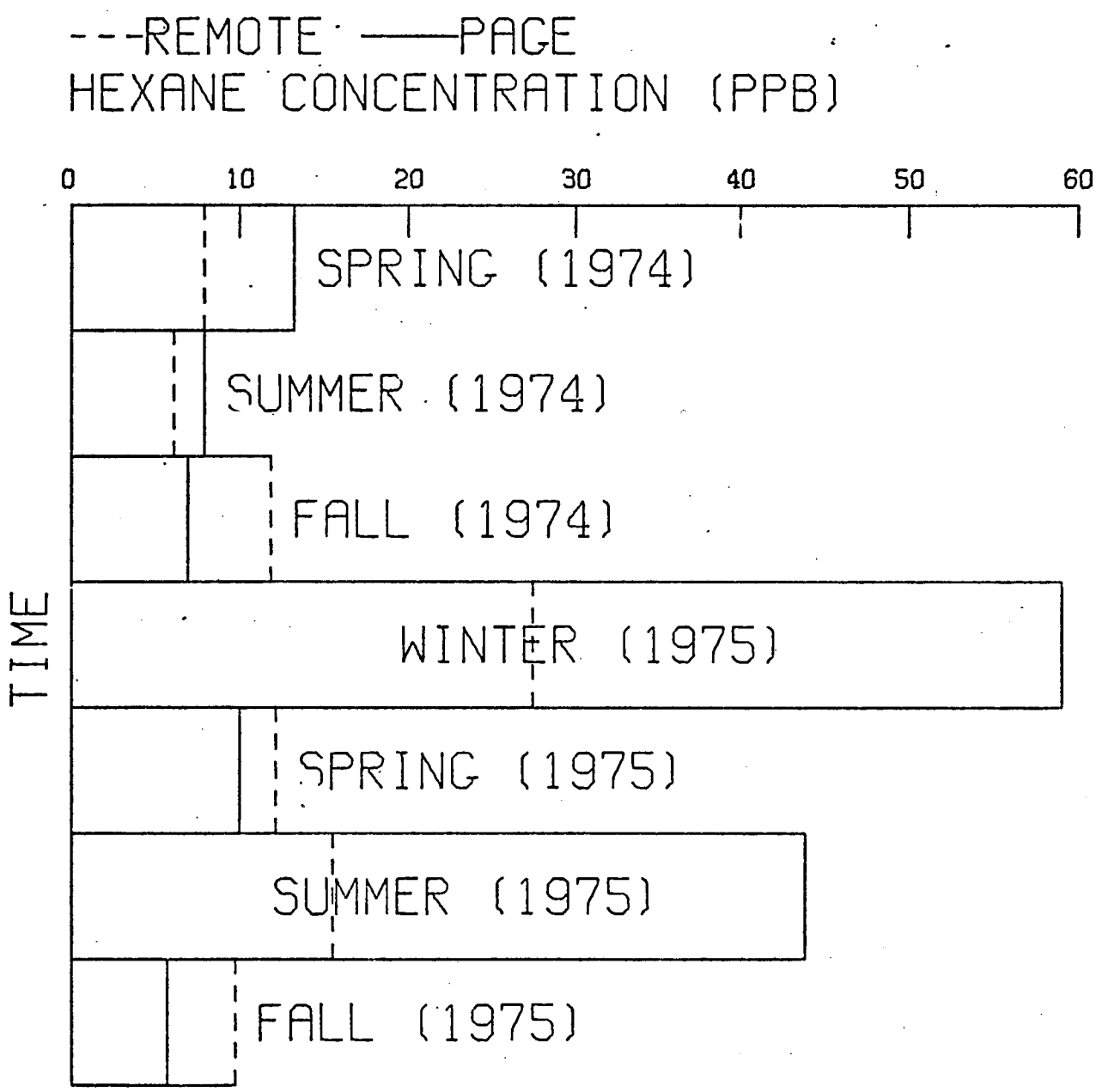


Figure 49: Seasonal arithmetic mean hexane concentrations in Page and at the remote sites

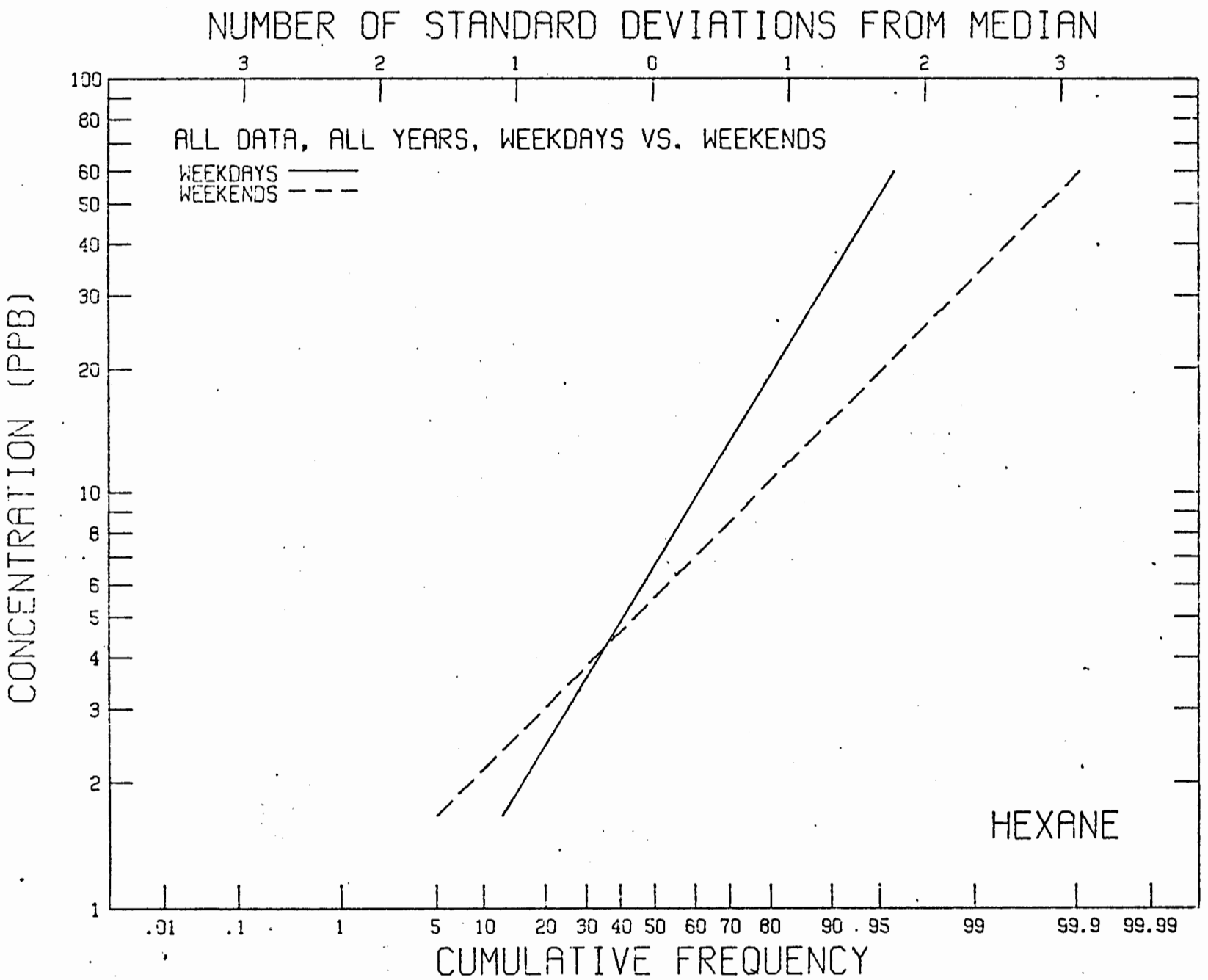


Figure 50: Hexane concentrations at all locations on weekdays and weekends

Ethene (Ethylene)

Each alkene has one doublebond between two carbon atoms; therefore, methane has no alkene relative because it has only one carbon atom. The nomenclature of organic chemistry has been improved over the years to minimize confusion in naming closely related organic compounds, including hydrocarbons. The alkene relative of the alkane ethane is now called ethene, but it was once called ethylene and many people still use this name. The same situation exists for propene, previously called propylene, the three-carbon alkene analog of the three-carbon alkane propane, and butene, previously called butylene.

The cumulative frequency distributions for ethene measured in Page, downwind of Page, and at the remote sites are presented in Figure 51. The concentrations generated in Page are significantly higher than those measured downwind of Page and at the remote sites, but the latter two locations are not statistically different. Here is a case where the distributions are totally separated in graphical form, but the 90-percent confidence intervals overlap for the arithmetic means downwind of Page and at the remote sites. The arithmetic means are 8.3 $\pm$ 4.2 ppb for Page, 1.9 $\pm$ 1.4 ppb downwind of Page, and 1.7 $\pm$ 1.2 ppb at the remote sites. The 90-percent confidence intervals are almost as large as the arithmetic means because of a combination of too few data and too little uniformity in the concentrations.

Note in Figure 51 that all three cumulative frequency distributions are to the right of 50 percent, the point on the horizontal axis at which the crossing of the line would give the geometric mean concentration on the vertical axis. Here is an example where most of the measurements were at the sensitivity limit of the gas chromatograph. The peaks generated by the flame ionization detector were not large enough to measure, just large enough to see. These barely detectable peaks were assumed to be caused by a hydrocarbon concentration of 0.5 ppb. The ethylene distributions are to the right of 50 percent because over half of the ethylene responses were 0.5 ppb. The vertical axis in Figure 51 is not continued downward to 0.1 ppb because no concentrations under 1.0 ppb can be quantitatively measured.

It should also be noted that the cumulative frequency distributions in Figure 51 and other similar figures can be extended downward to the left to the 50 percent line, if the

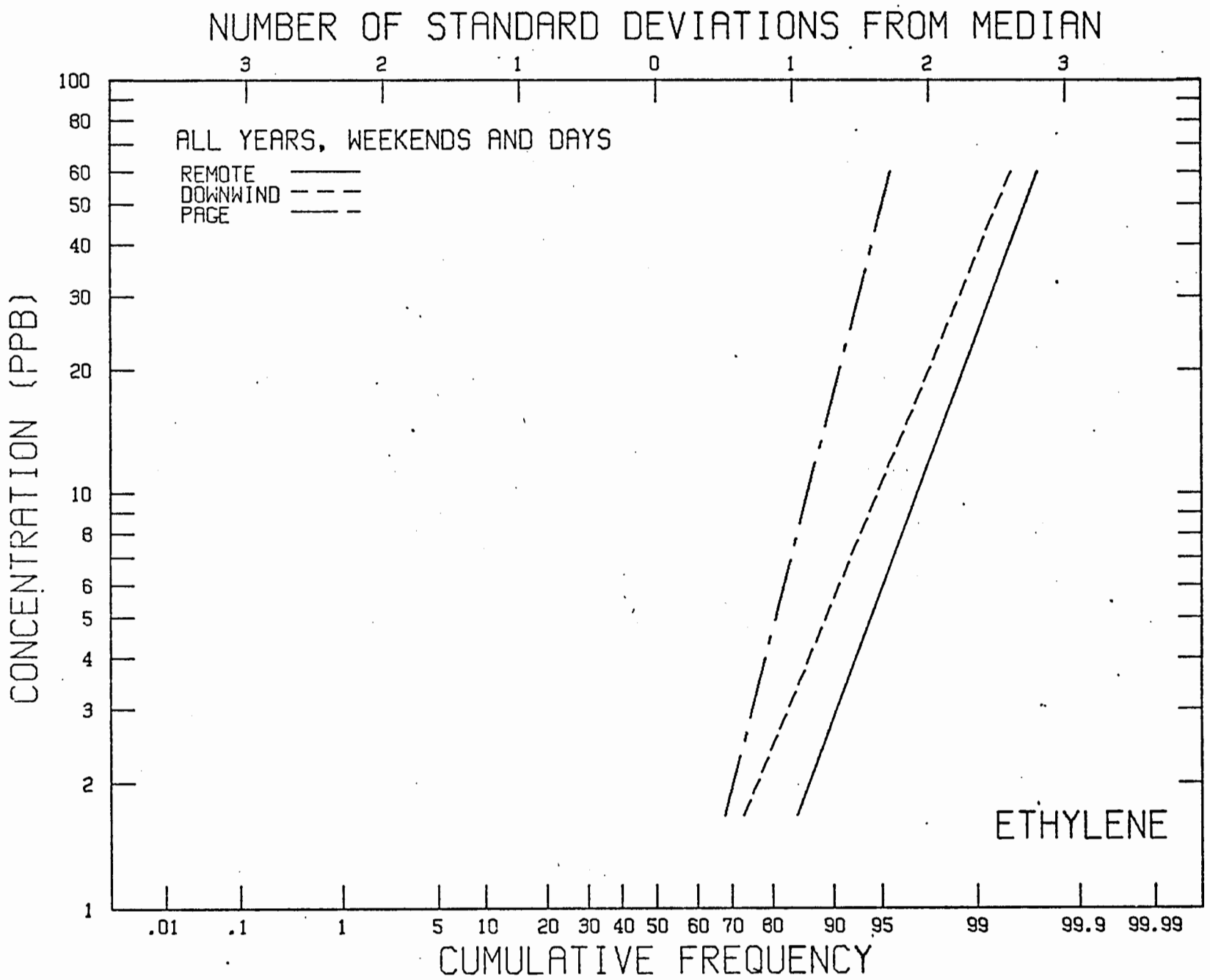


Figure 51: Ethene concentrations in Page, downwind of Page, and at the remote sites

distribution of concentrations is accepted as being log-normal. The geometric mean obtained by this graphical extrapolation will be more valid than the geometric mean obtained from the algebraic equation that takes the nth root of the product of the n concentrations, because of the bias introduced into the equation by the large number of trace values set arbitrarily at 0.5 ppb.

The seasonal arithmetic mean ethene concentrations in Page and at the remote sites from fall 1973 through fall 1975 are shown in Figure 52. There is no seasonal cycle apparent in the large variations from season to season.

The weekday ethene concentrations in Page were higher than those on the weekends, as shown by the arithmetic means of 10.6 $\pm$ 5.6 ppb on weekdays and 2.1 $\pm$ 1.8 ppb on weekends.

Propene

The cumulative frequency distributions for propene presented in Figure 53 show the same pattern as hexane. The propene generated by cars and other sources in Page is diluted or reacted downwind of Page to the background concentrations measured at the remote sites. The arithmetic mean concentration measured in Page (3.2 $\pm$ 0.7 ppb) is statistically different from the almost identical arithmetic means downwind of Page (1.5 $\pm$ 0.7 ppb) and at the remote sites (1.5 $\pm$ 0.4 ppb).

The seasonal arithmetic mean concentrations of propene in Page and at the remote sites are shown in Figure 54. The higher means in winter are not separated from the other seasonal means by the 90-percent confidence intervals around the means. Winter peaks would not be surprising in light of the peak propane combustion in winter, from which propene is probably a reaction product. The large increase of the winter means in Page over those at the remote sites seems to confirm Page as the source of propene.

The propene concentrations in Page are significantly higher on weekdays than those on weekends as shown in Figure 55 and by the arithmetic means of 3.6 $\pm$ 0.9 ppb on weekdays and 1.9 $\pm$ 0.6 ppb on weekends. No such difference between weekdays and weekends appeared in the propene concentrations from the remote sites.

Butene

The seasonal arithmetic mean butene concentrations at all locations from fall 1973 through spring 1976 are shown

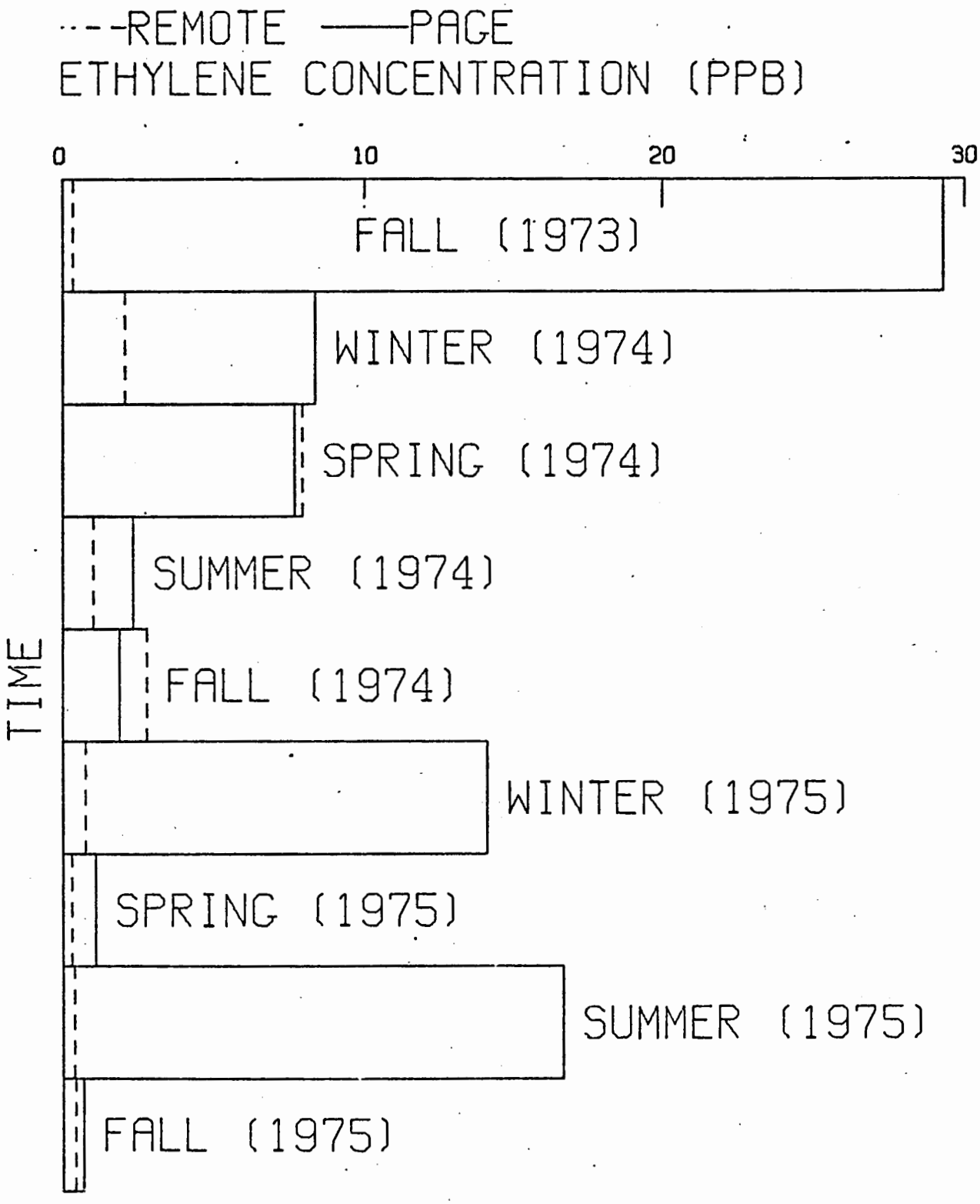


Figure 52: Seasonal arithmetic mean ethene (ethylene) concentrations measured in Page and at the remote sites

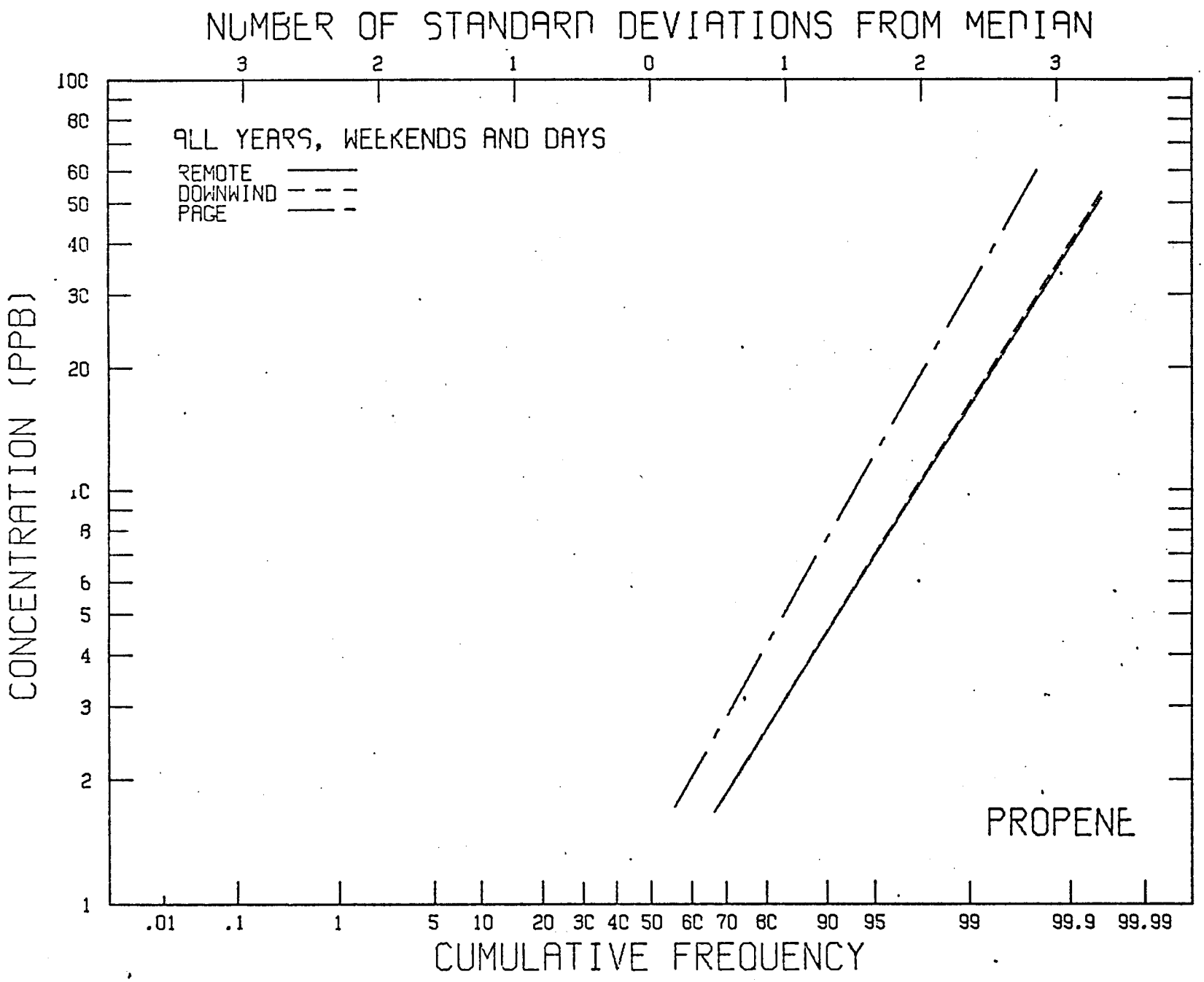


Figure 53: Propene concentrations measured in Page, downwind of Page, and at the remote sites

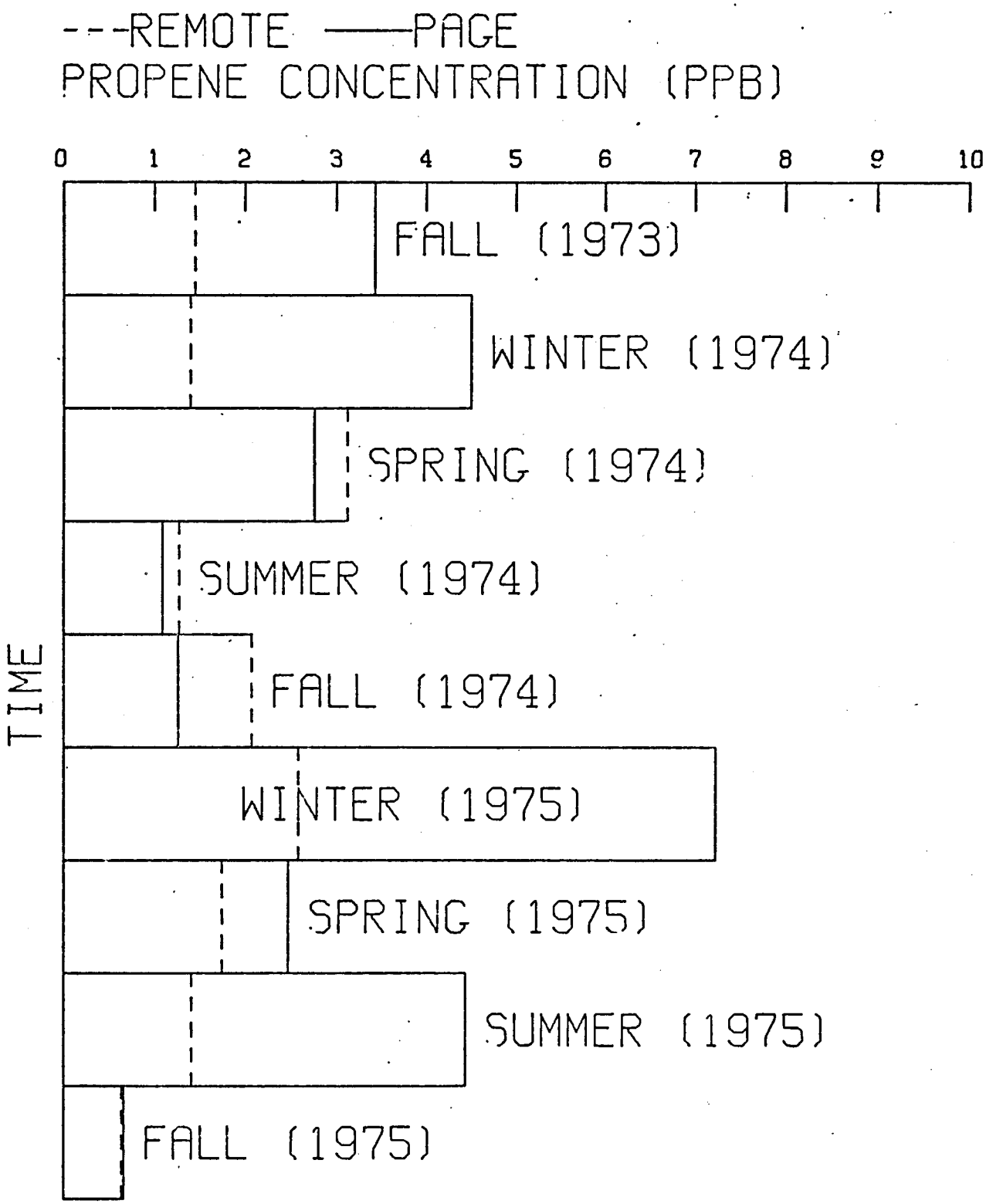


Figure 54: Seasonal arithmetic mean propene concentrations in Page and at the remote sites

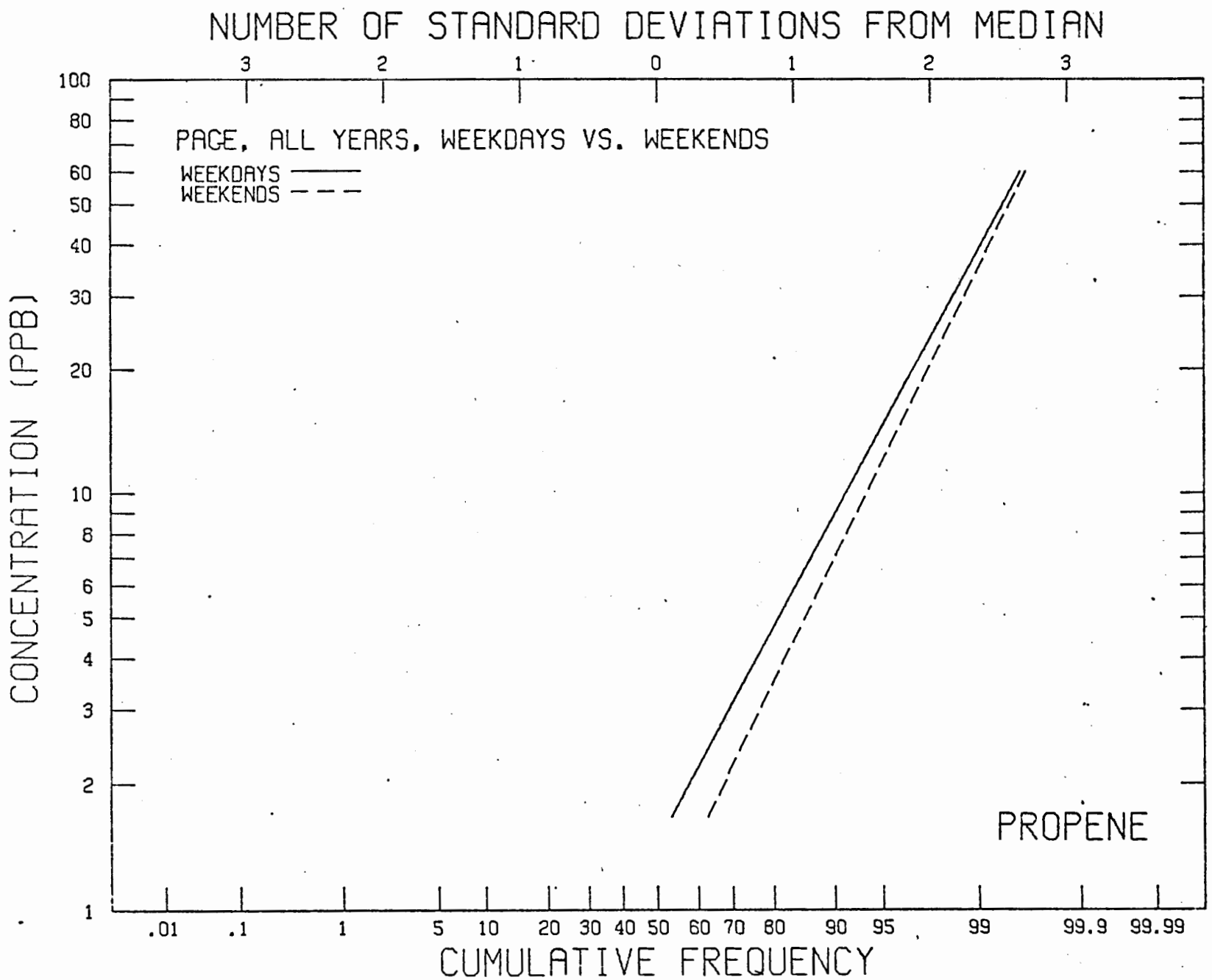


Figure 55: Propene concentrations in Page on weekdays and weekends

in Figure 56. No clear trend or seasonal cycle is apparent.

The cumulative frequency distribution for all butene concentrations is compared with the distribution for butane in Figure 57. The butane concentration is higher, as expected from the fact that butane is the major hydrocarbon impurity in the bottled propane used for residential space heating. Similar comparisons for each alkane/alkene pair show the alkane always to have a higher concentration, with the possible exception of some measurements of the ethane/ethene pair. Butene and other alkenes are produced in the combustion of gasoline and maybe also bottled gas, where the temperature of combustion is high enough to produce reactive doublybonded carbon atoms found in alkenes (U.S. Department of Health, Education, and Welfare, 1970; Seizinger, 1967).

Pentene

Pentene concentrations are much smaller than those of pentane, similar to the case of butene and butane. Here though, pentane is not used as a bottled fuel for any local use. Both pentane and pentene are probably produced in the combustion of gasoline and maybe other fuels. Comulative frequency distributions presented in Figure 58 are well separated, and arithmetic means are 13.7 $\pm$ 2.2 ppb for pentant and 3.4 $\pm$ 0.6 ppb for pentene.

Some seasonal differnece was indicated by distributions presented in Figure 59, but only the top and bottom lines for winter and spring are different enough to separate 90-percent confidence intervals aroung the means.

Pentene shows no significant trend at the remote sites between 1974 and 1976 (Figure 60).

Separating all pentene concentrations into seasonal arithmetic means from winter of 1974 through spring of 1976 (Figure 61) shows the erratic variations that would prevent a clear seasonal cycle from appearing in Figure 59. Also, the record seasonal low concentration for spring of 1976 indicates that the increase of 1975 over 1974 (Figure 60) may not be a trend over a longer time span.

Hexene

The seasonal arithmetic mean concentrations of hexene at all locations from spring 1974 through spring 1976 are shown in Figure 62. There appears to be some decrease in

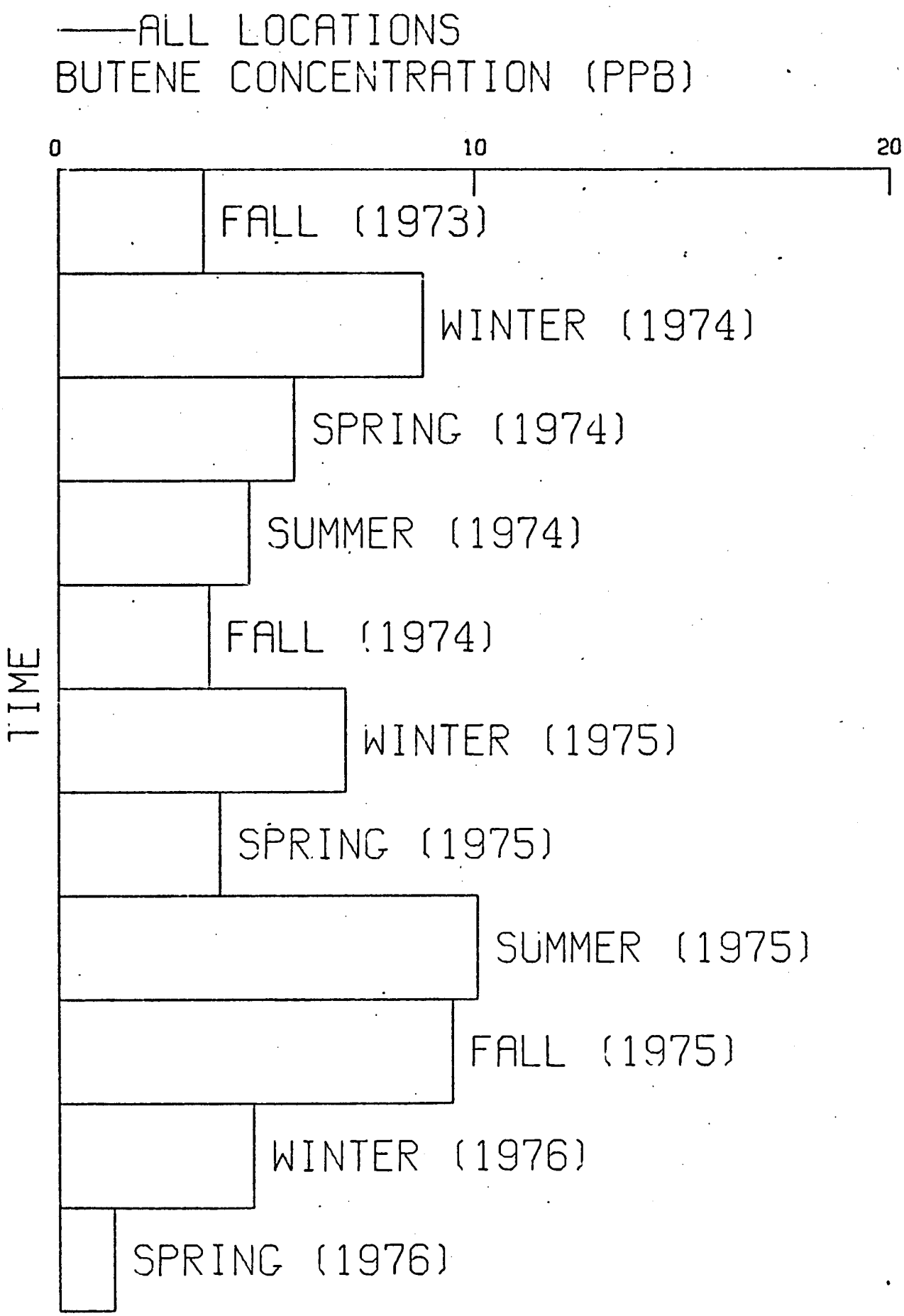


Figure 56: Seasonal arithmetic mean butene concentrations at all locations

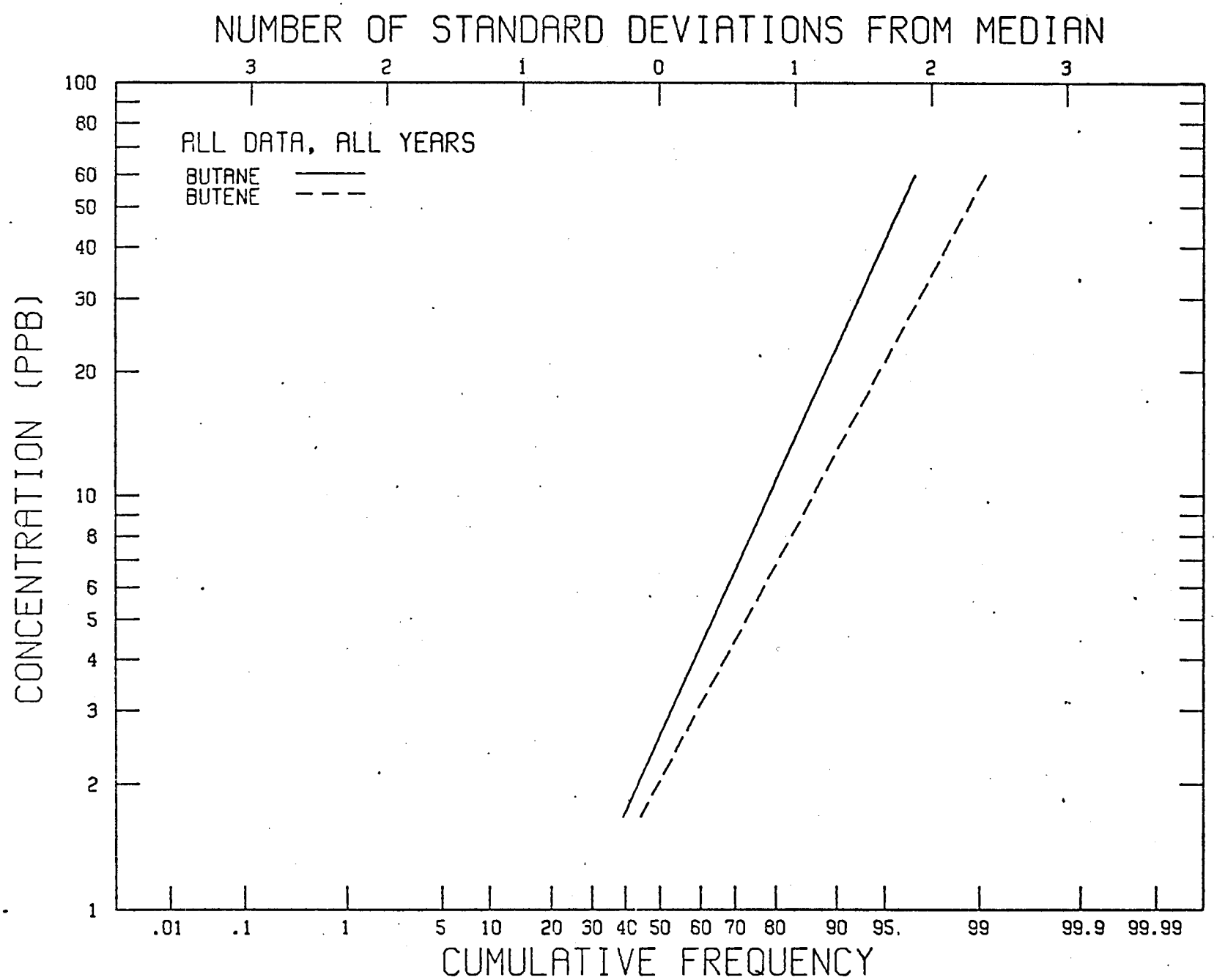


Figure 57: Butane and butene concentrations

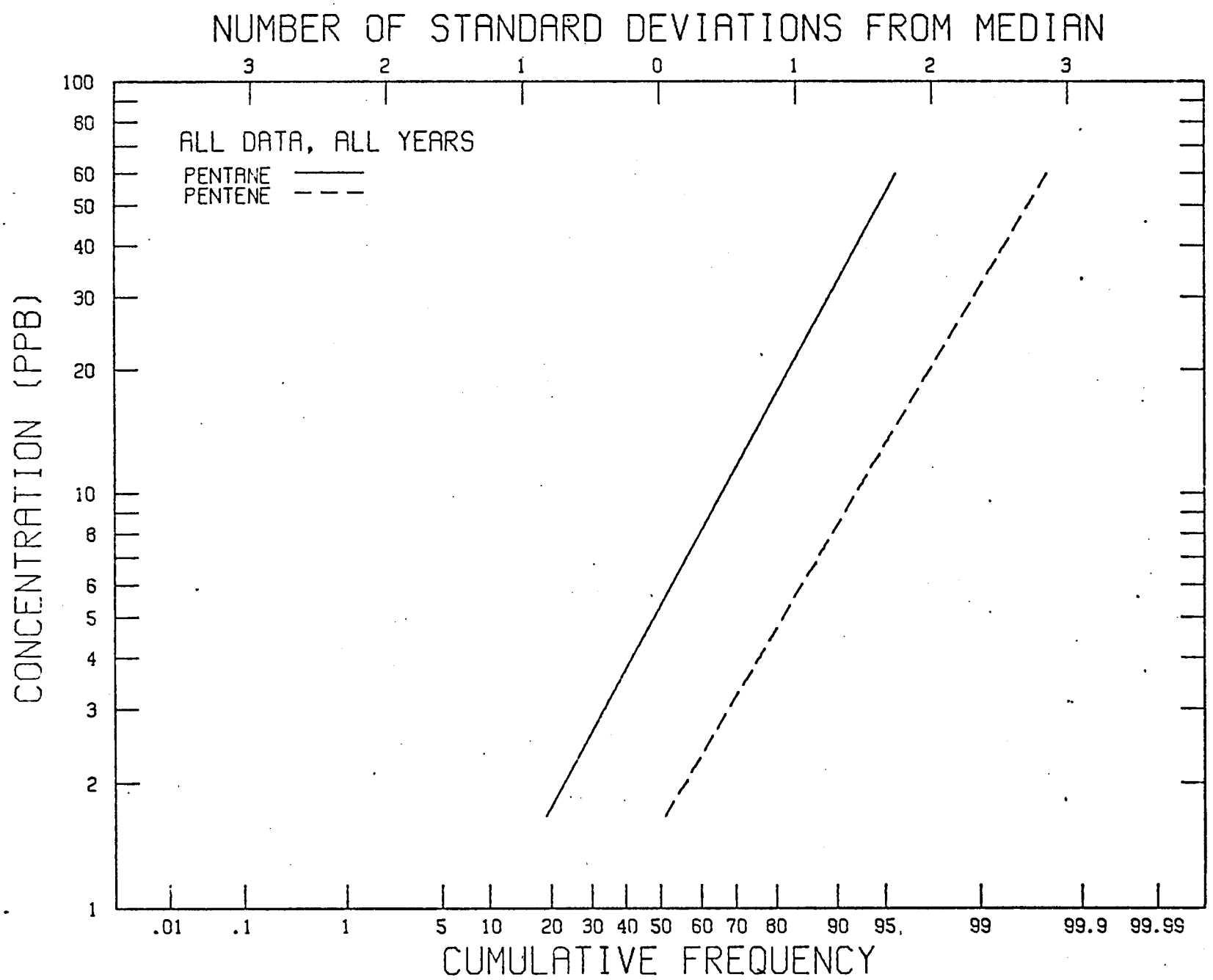


Figure 58: Pentane and pentene concentrations

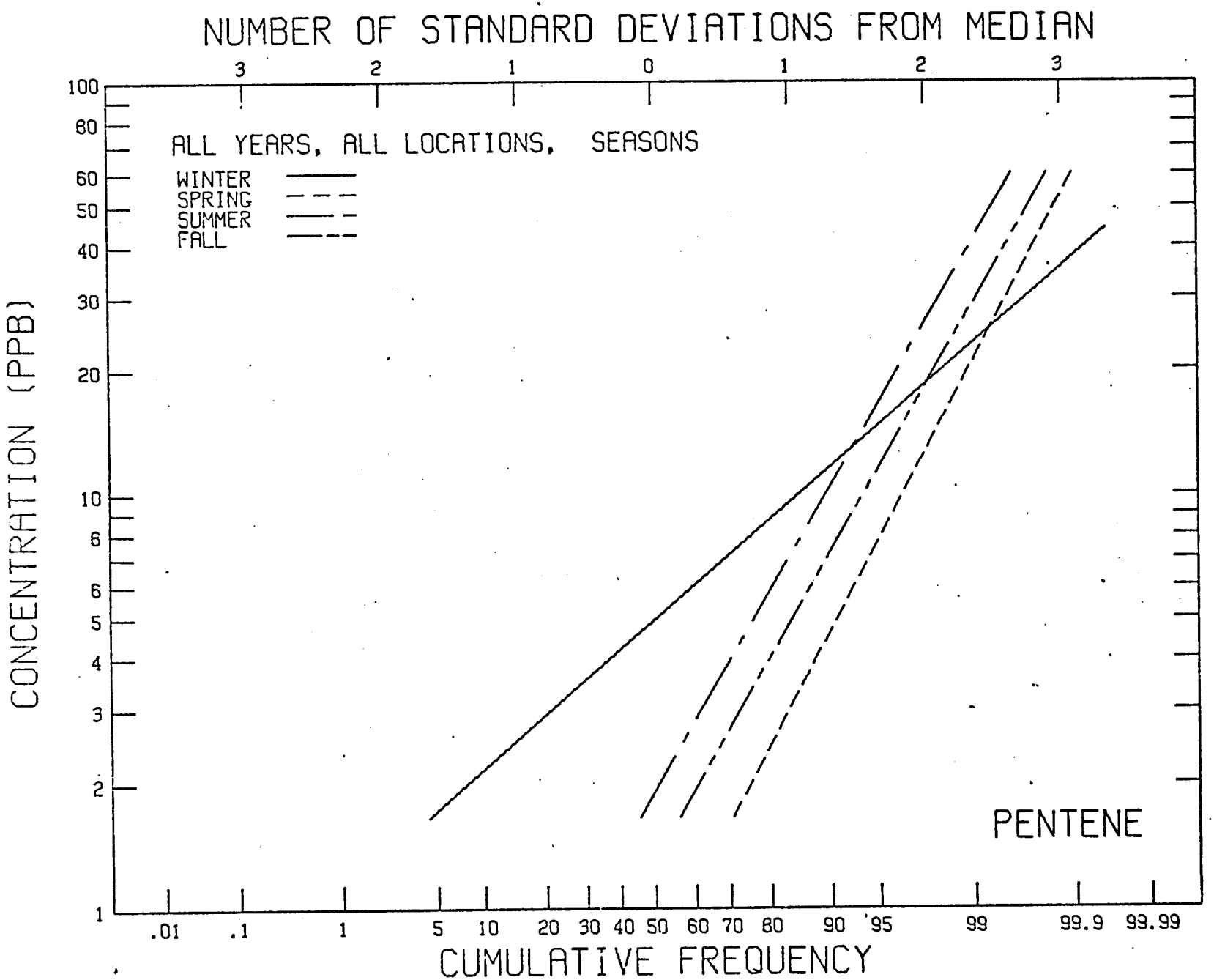


Figure 59: Pentene concentrations at all locations during the four seasons

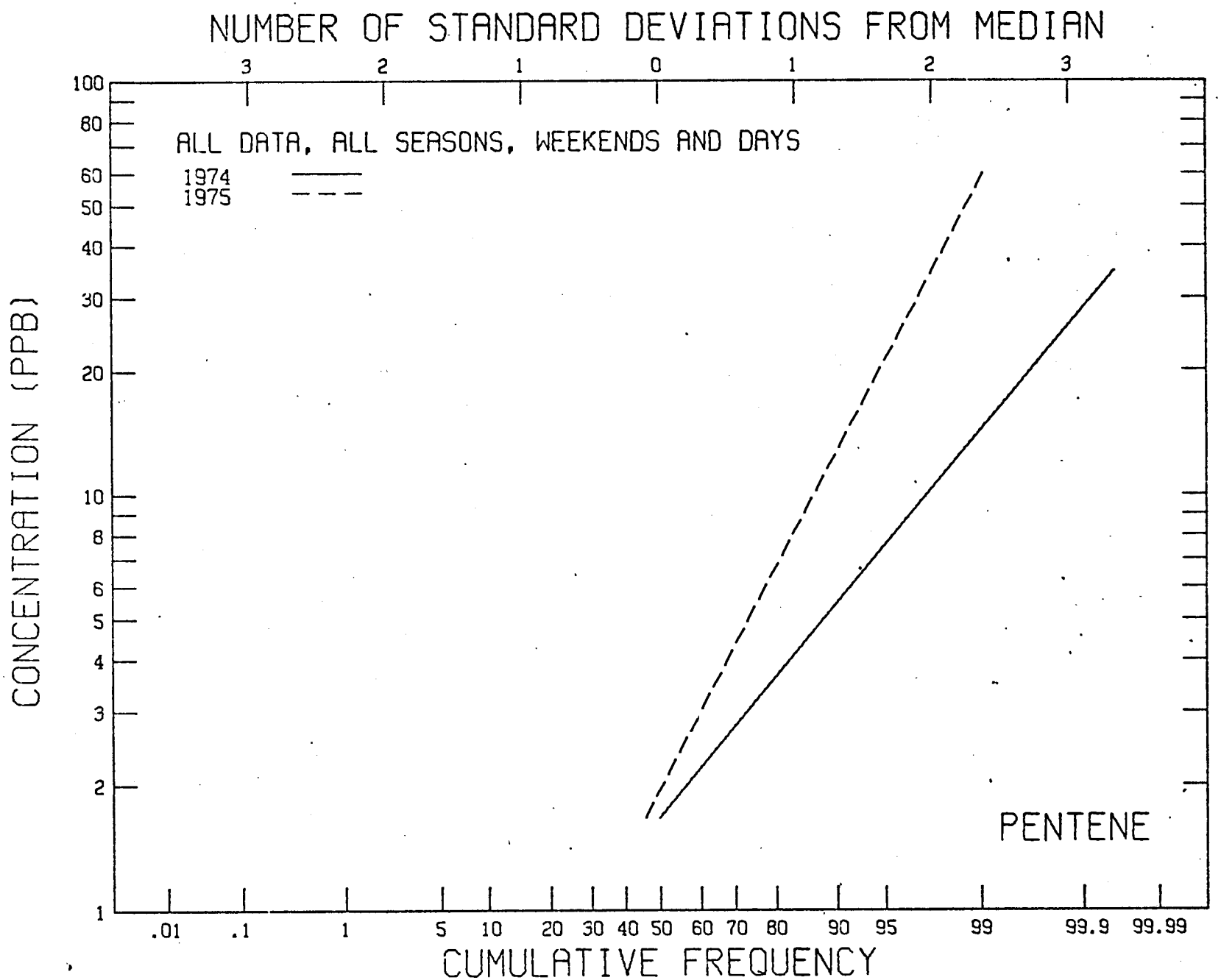
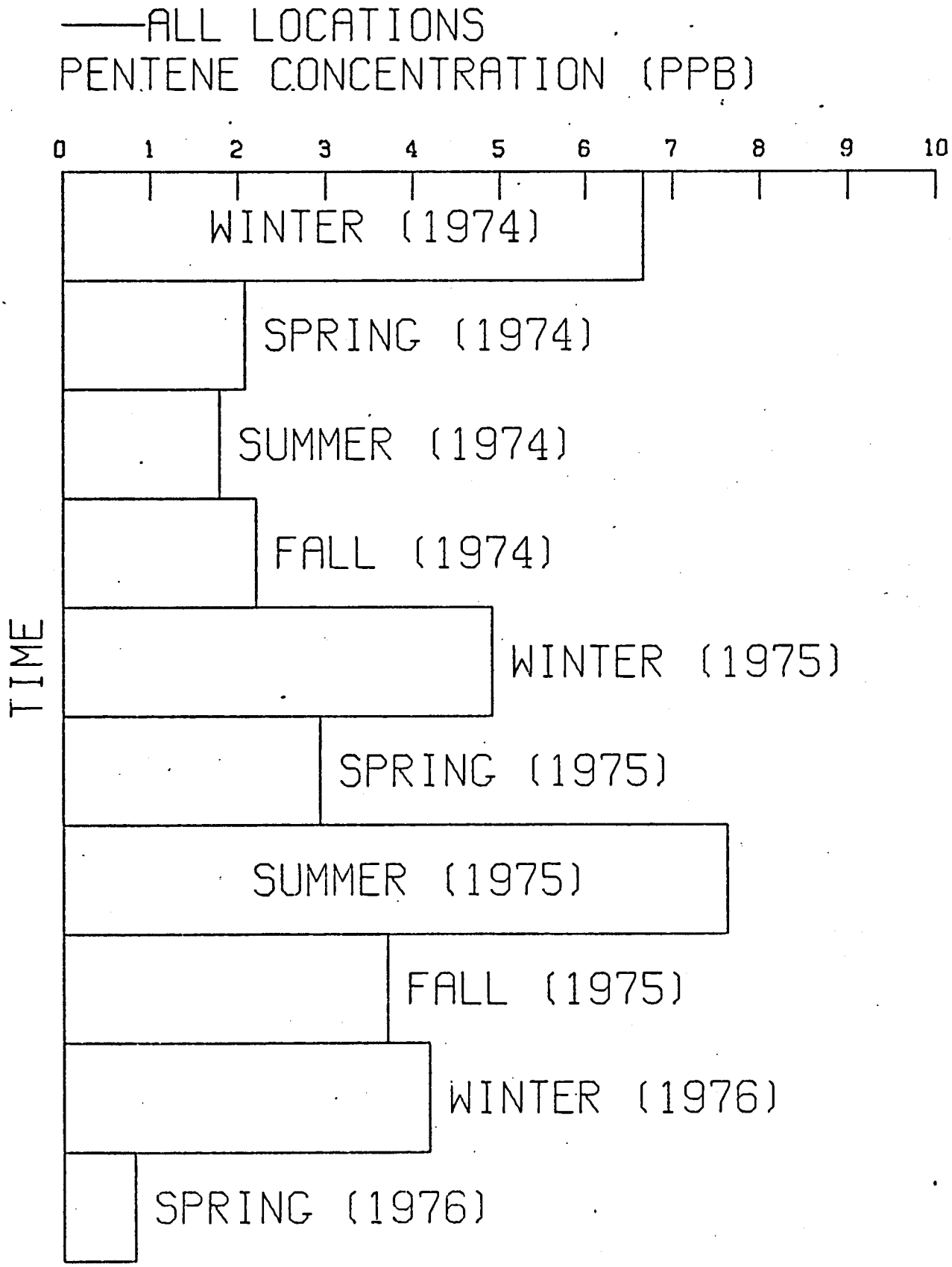


Figure 60: Pentene concentrations at all locations during 1974 and 1975

Figure 61: Seasonal arithmetic mean pentene concentrations at all locations



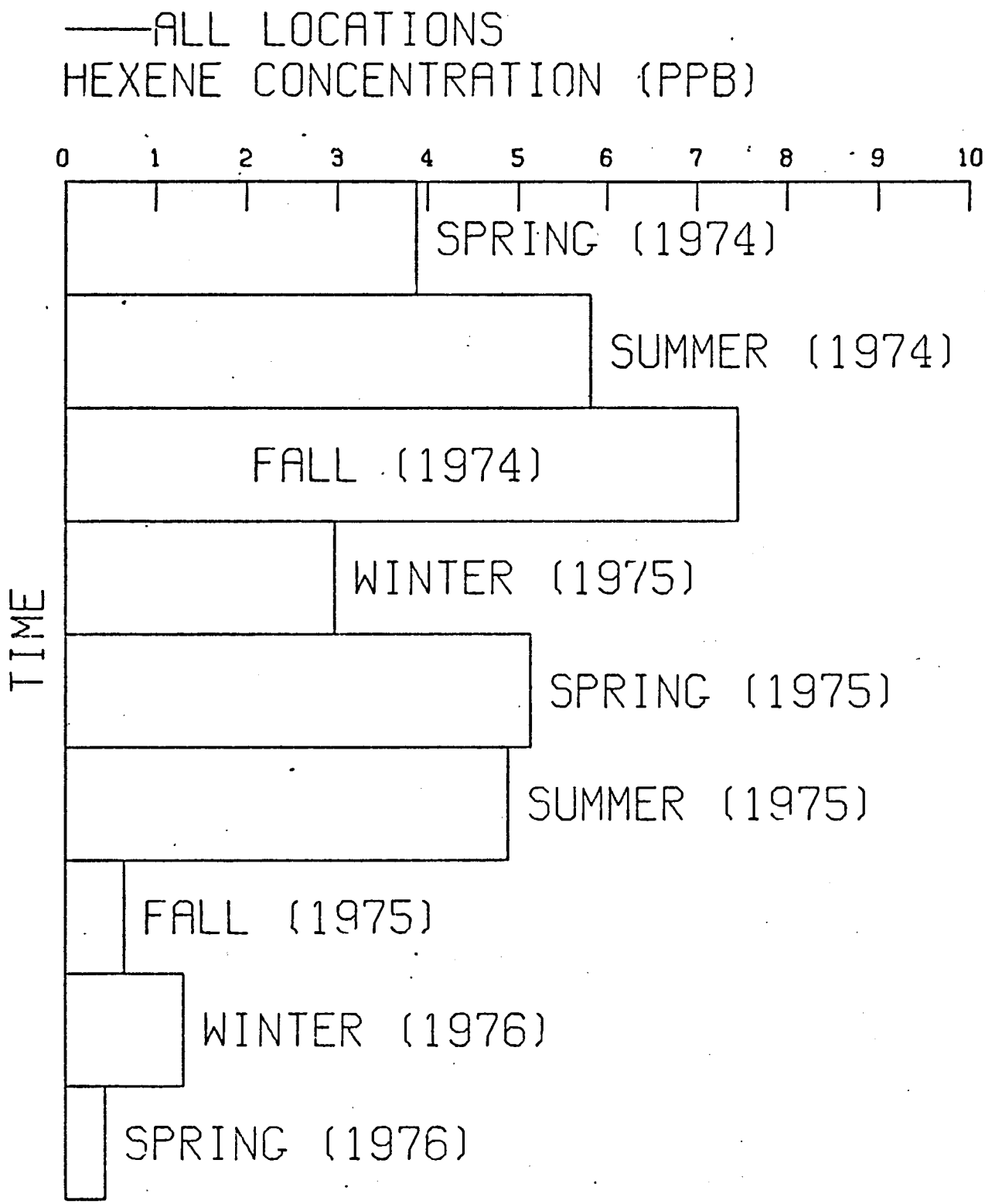


Figure 62: Seasonal arithmetic mean hexene concentrations at all locations

concentration over this period of time. This apparent downward trend is clearer in Figure 63 and in arithmetic means:

1974	6.5 ± 2.6 ppb
1975	3.5 ± 1.1 ppb
1976	0.8 ± 0.5 ppb

The cumulative frequency distributions for all the hexene concentrations are compared with the same for hexane in Figure 64. Hexane was higher in concentration than its alkene relative, hexene. This situation was the same for pentane, butane, and propane. The arithmetic mean for hexane was 13.0 ± 2.1 ppb and 3.7 ± 0.9 ppb for hexene.

Acetylene

Acetylene is the only hydrocarbon we measured in the Lake Powell region that is neither an alkane nor an alkene. It is an alkyne, characterized by the triplebond between its two carbon atoms. The seasonal arithmetic mean acetylene concentrations in Page and at the remote sites from fall 1973 to summer 1974 are shown in Figure 65. All of the means are at the limit of detectability except for fall 1973 in Page. The difference between the other means cannot be accepted as significant.

Nitrogen Dioxide (NO_2)

Nitrogen oxides refers to the combination of nitric oxide (NO) and nitrogen dioxide (NO_2). Automobiles, generating stations, and other machines that burn a hydrocarbon fuel and air at high temperature produce these oxides. The primary combustion produces mostly NO, which then reacts with oxygen in air to form NO_2. The methods used by ADHS (1976) and Dames & Moore (1975) are designed to measure NO_2 because NO_2, not NO, has the ambient air quality standard of 100 g/m^3 for an annual average. The annual arithmetic mean concentrations of NO_2 as measured at seven locations in 1975 are presented in Figure 66. None of the annual arithmetic means exceed the ambient air quality standard. The concentrations in Flagstaff and Phoenix are much higher than at the other locations because of the intensity of automobile traffic in these two cities. Lowell Observatory is located on a hill at the west side of Flagstaff. Its position on the upwind side of the city, its elevation above the inversion layer, and its low volume of traffic all help to keep down the concentration of NO_2. Forty-one percent of NO_2 is emitted by land vehicles (Walther, 1977), most of which are automobiles.

The measurement of NO_2 has proven difficult in recent years because one method was sanctioned for use by the Environmental Protection Agency (EPA) and then it was

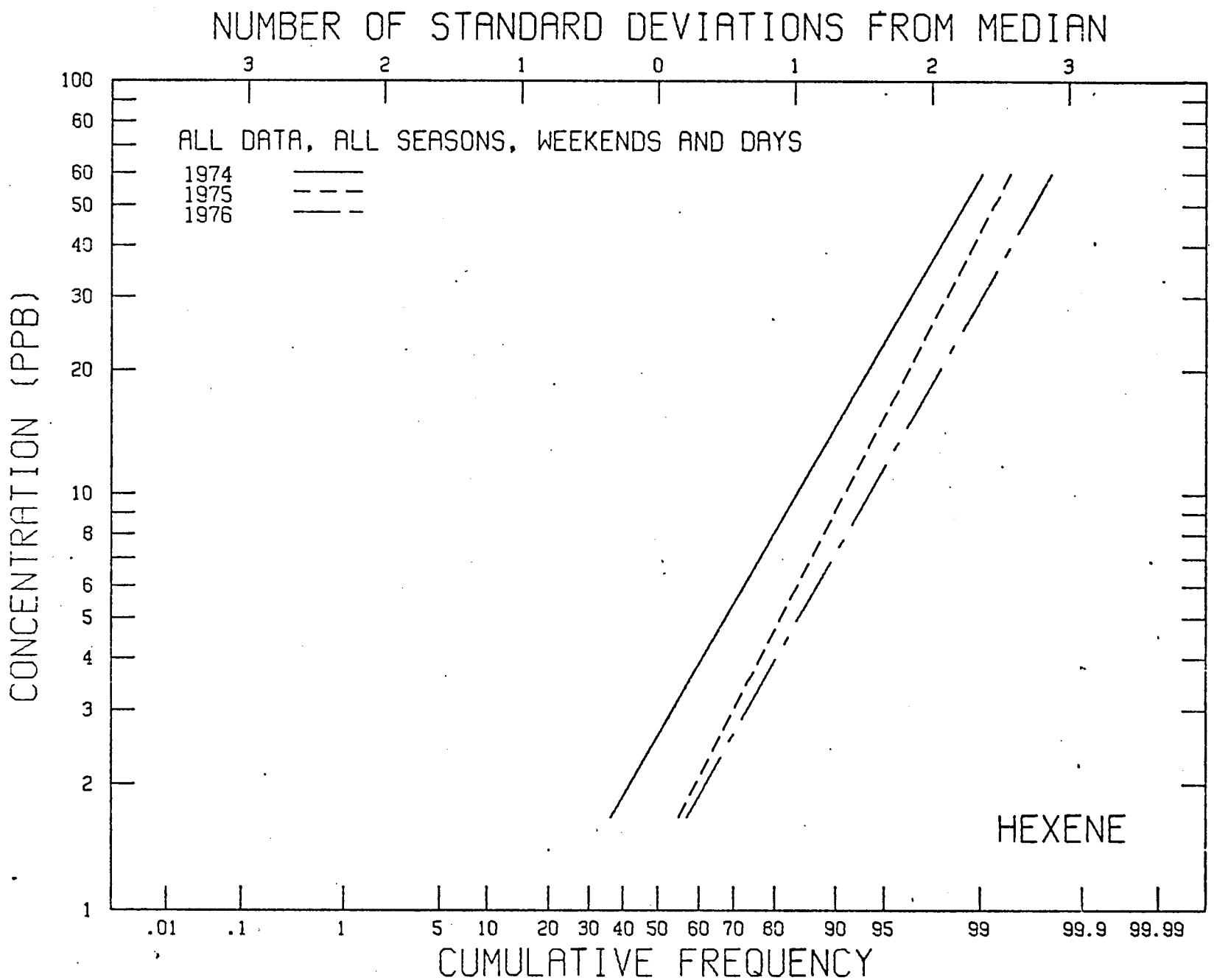


Figure 63: Hexene concentrations at all locations during 1974, 1975, and 1976

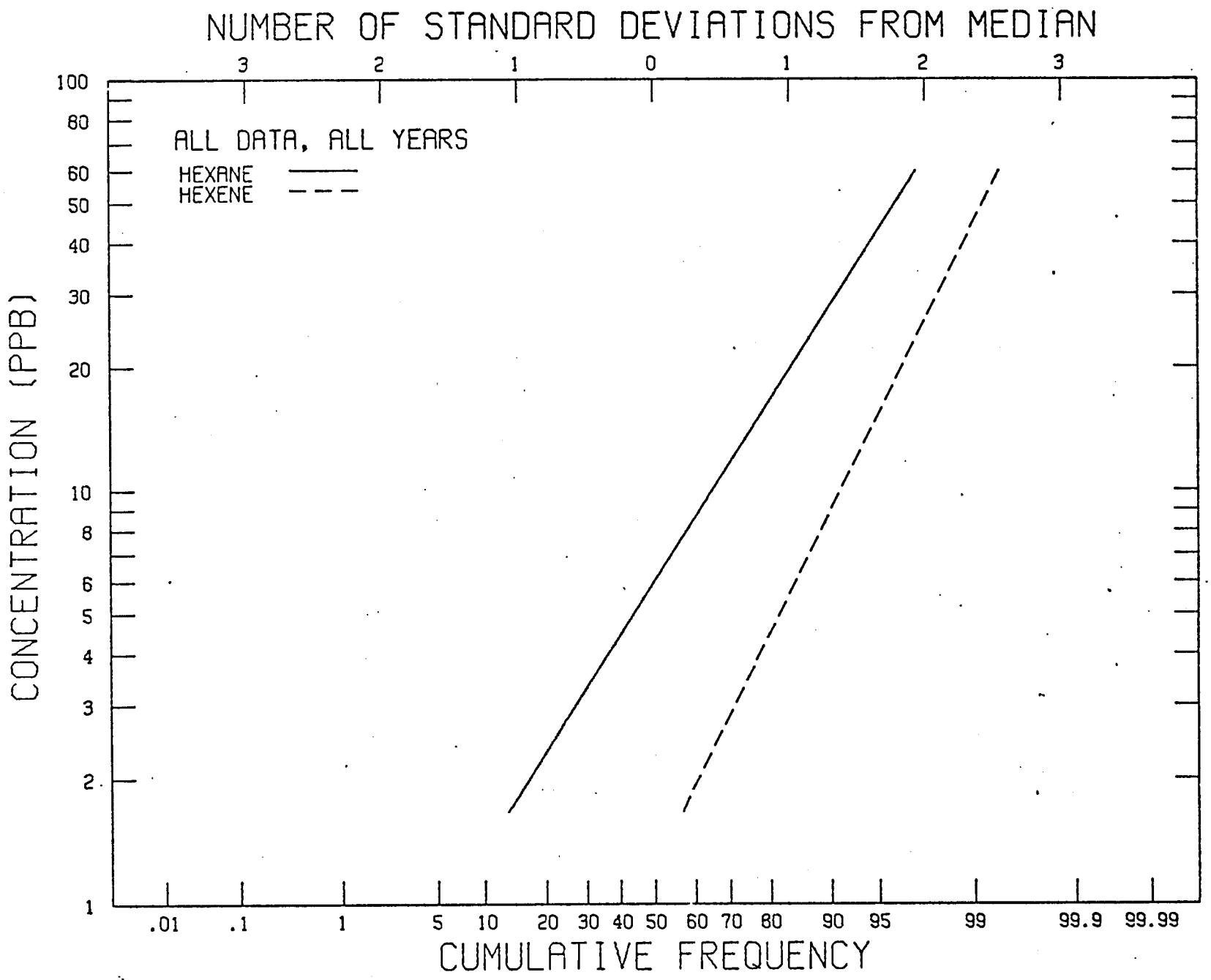


Figure 64: Hexane and hexene concentrations

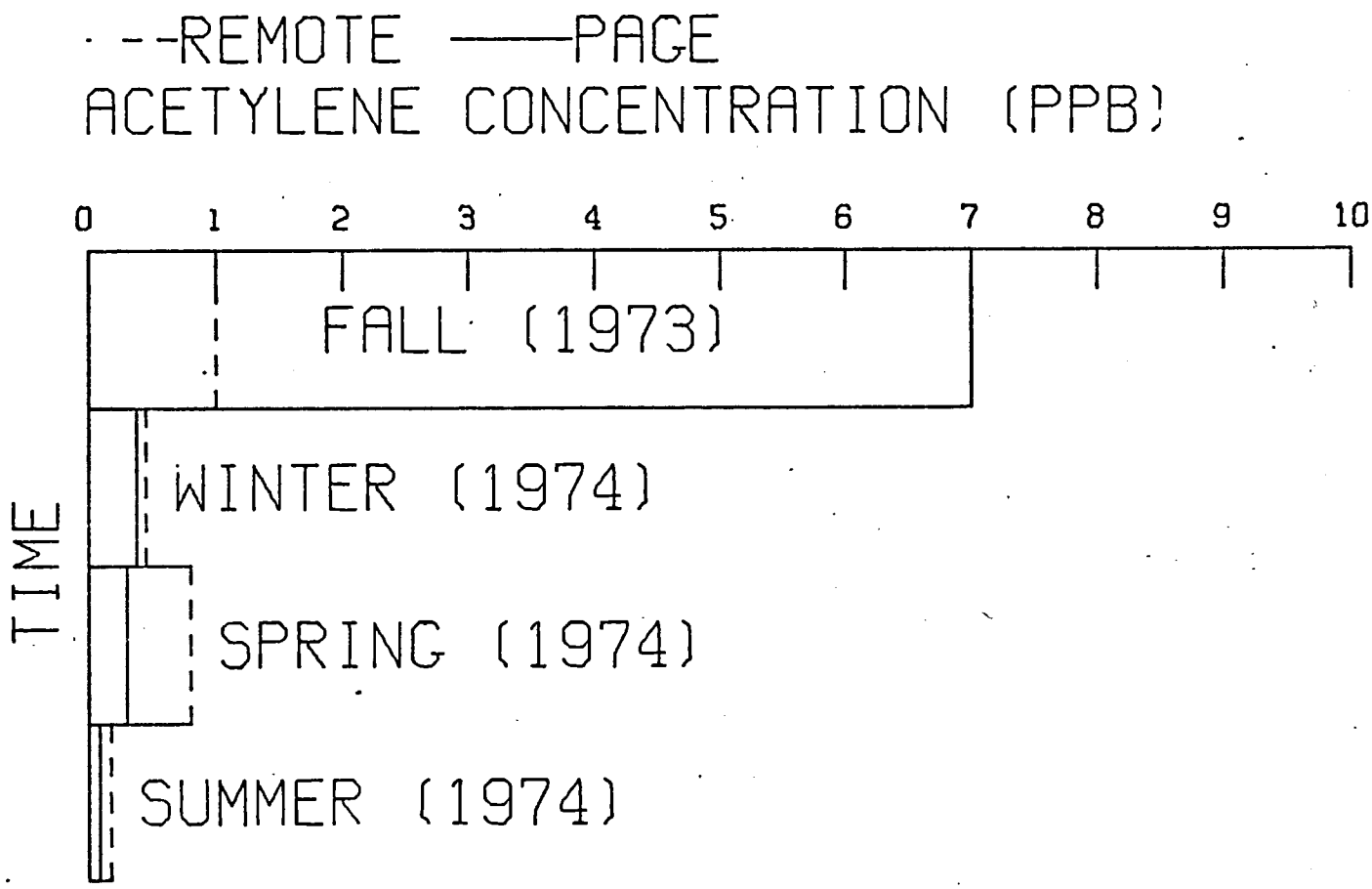


Figure 65: Seasonal arithmetic mean acetylene concentrations in Page and at the remote sites

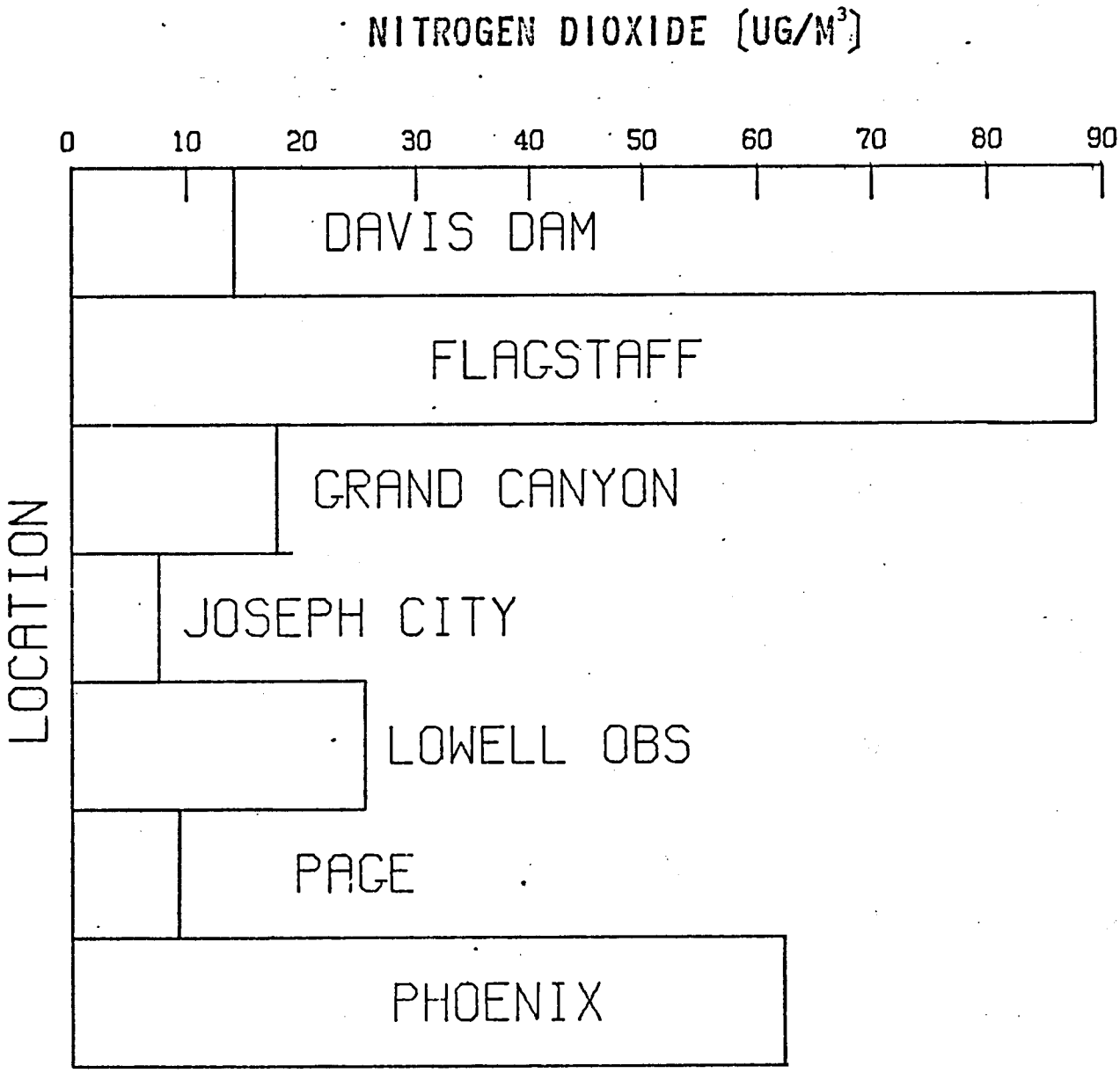


Figure 66: Nitrogen dioxide concentrations at seven locations during 1975

declared unacceptable. This change in approved methods forced us to discard at least 2 years of NO_2 measurements made at Page Airport by Dames & Moore. Even the more recent years of 1974 and 1975 have shown significant differences in the annual arithmetic means measured by Dames & Moore and ADHS, as shown in Figure 67. Despite the differences in the absolute annual arithmetic means, both sources of data show a decrease from 1974 to 1975. We hypothesize the decrease was caused by the decrease in automobile traffic after the 1973 peak in construction activity at the Navajo Generating Station. Thereafter, employment dropped, followed by a drop in the population of Page and the associated traffic.

Oxidant

Oxidant near Lake Powell has been measured by Dames & Moore (1975) at Page Airport since July 1970. They have used three methods at different times, starting with the Haagen-Smit method, adding an automatic coulometric method on April 25, 1972, and adding the EPA-approved reference method on May 4, 1972. Ozone is the major component of oxidant, especially in relatively clean air. Ozone is generated in the stratosphere by solar radiation and in urban air by photochemical reactions involving the hydrocarbons and nitrogen oxides emitted by human activities.

The cumulative frequency distributions of oxidants measured at Page Airport during 1972, 1973, and 1974 are presented in Table 11 (taken from Dames & Moore, 1976). The 1975 data from the Salt River Project (1976) is based on different increments of oxidant, but the annual geometric means for all 4 years are given at the bottom of Table 11 and shown in Figure 68. These means indicate a decreasing trend, but we think more oxidant measurements must be made at remote locations before this trend should be used to develop conclusions about the oxidant concentration in the Lake Powell region.

Monthly mean oxidant concentrations at Page during 1971 and 1972 are presented in Figure 69 in order to show the seasonal variation. The maximum in spring is consistent with other measurements made at latitudes higher than 20°N (Johnson, 1954).

Sulfur Dioxide (SO_2) and Sulfation Rate

SO_2 has been measured at Page Airport by Dames & Moore and ADHS, using three different methods before 1974 and then

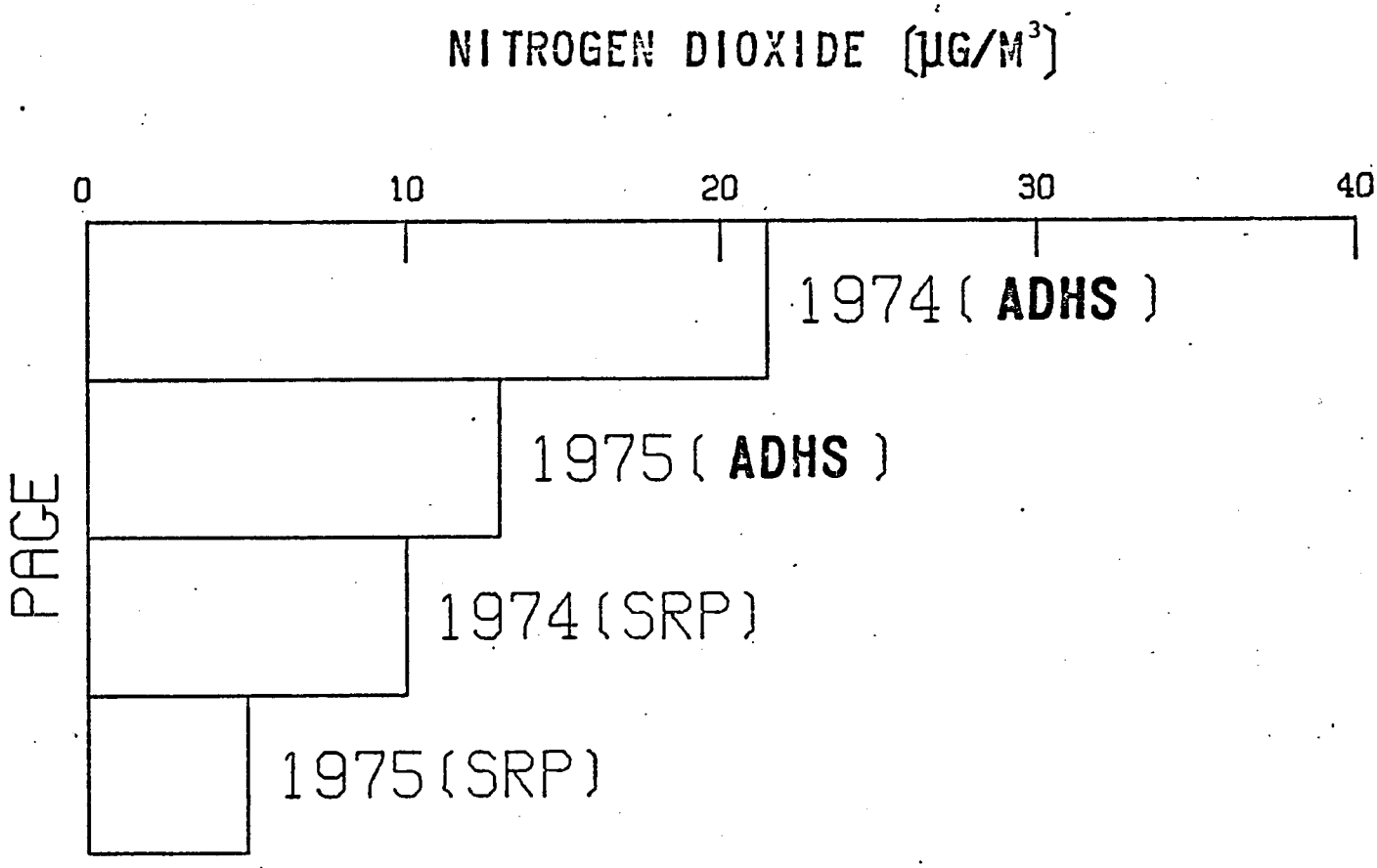


Figure 67: Annual arithmetic mean nitrogen dioxide concentrations at Page Airport in 1974 and 1975 as measured by either the Arizona Department of Health Services (ADHS) or the Salt River Project (SRP)

Table 11: Daily 1-hour maximum oxidant concentrations

Concentration (PPM)	Cumulative Percentage Less Than Indicated Concentration(%) 1972[a]	1973[a]	1974[a]	1975[b]
.005				1.69
.010	.54	.28	0.00	11.9
.012	1.08	1.12	0.00	
.014	2.69	1.96	1.33	
.015				37.3
.016	7.53	5.87	5.67	
.018	15.0	13.1	13.7	
.020	26.9	22.9	32.3	62.7
.022	43.6	34.1	47.3	
.024	60.8	46.7	62.3	
.025				83.0
.026	75.8	60.9	70.3	
.028	84.4	76.3	74.0	
.030	91.4	85.5	78.3	93.2
.032	95.7	92.5	82.3	
.034	97.3	96.6	84.7	
.035				98.3
.036	98.4	98.0	90.3	
.038	99.5	98.6	95.0	
.040	99.5	99.7	96.0	100.0
.042	99.5	100.0	97.7	
.044	100.0		98.7	
.046			99.0	
.048			100.0	
.080 Federal and Arizona standard				
Annual Geometric Mean (ppm)	.023	.024	.022	.018

[a]Dames & Moore (1975)
[b]Salt River Project (1967)

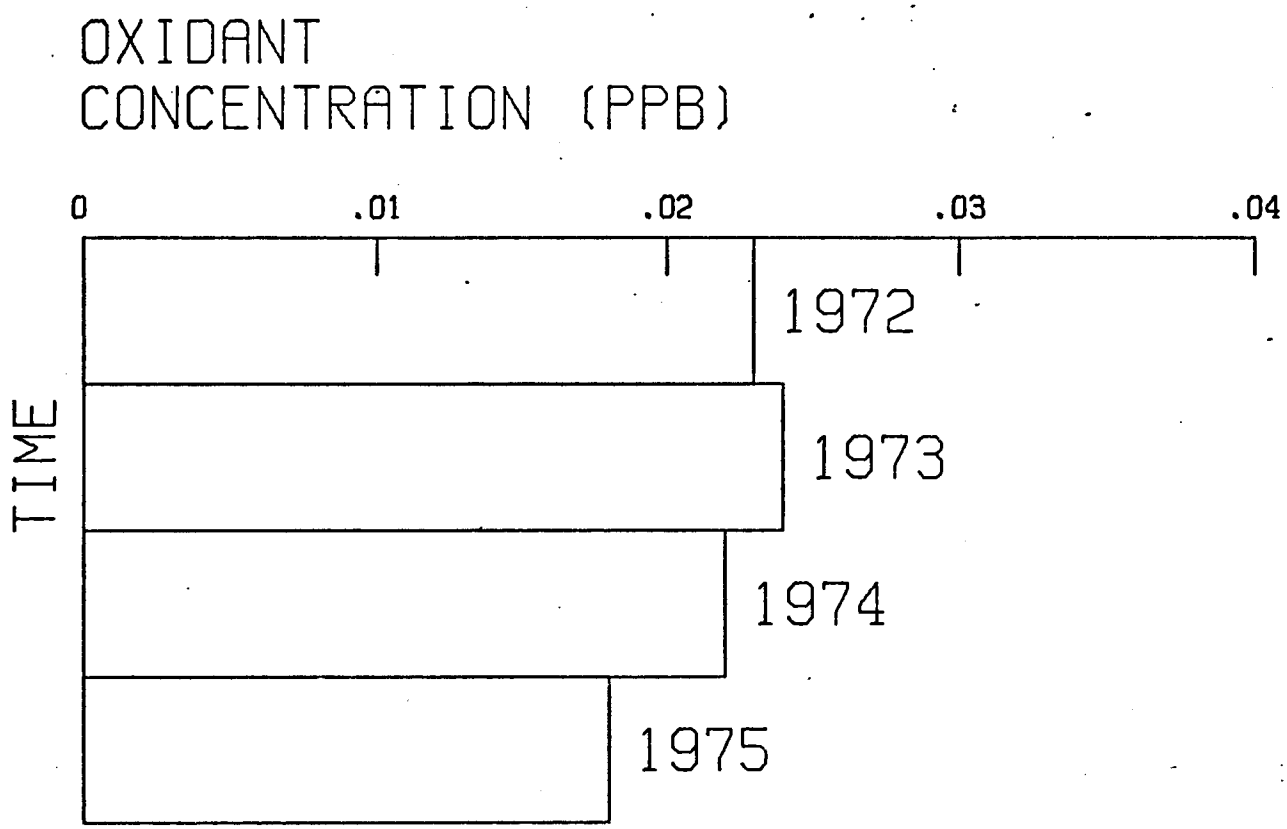


Figure 68: Oxidant concentrations (annual geometric mean) at Page Airport during 1972, 1973, 1974, and 1975

Sources: Dames & Moore (1965) and Salt River Project (1976)

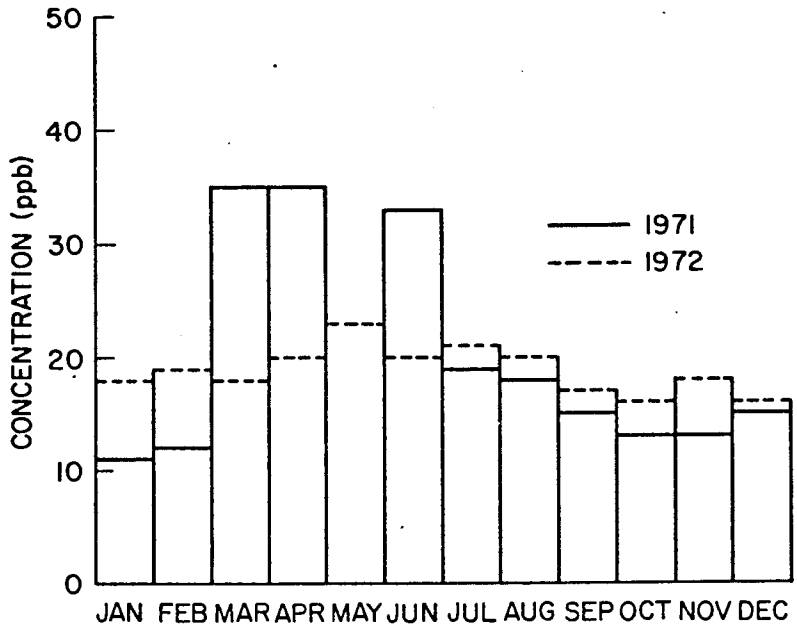


Figure 69: Oxidant concentrations (monthly means) at Page Airport during 1971 and 1972

Source: Dames & Moore (1973)

adding a fourth. The three earlier methods involved bubbling the air sample through West-Gaeke reagent, conductimetry, and the use of a Lear-Siegler automatic instrument. Later, flame photometry was added as a newer method. The West-Gaeke method was the only early method capable of sensing the extremely low concentrations of SO_2 in the background air of the Lake Powell region, but even this method produced only barely acceptable data at concentrations below 5 ppb (12.5 μg/m3).

Arithmetic means were calculated from the available data from 1972 through 1975 and are presented in Figure 70. These differences may be acceptable even though all the concentrations are below 12.5 $\mu g/m^3$ (5 ppb), the minimum concentration that the West-Gaeke bubbler method can sense without very special techniques of analysis.

The arithmetic mean concentrations shown in Figure 70 were the result of averaging concentrations above the detection limits of the measurement methods along with zero concentrations. Therefore, the differences shown in Figure 70 result from the mathematical averaging of higher concentrations and zero values.

A similar problem of credibility arises when looking at the annual arithmetic means of sulfur dioxide concentrations measured at Page Airport by ADHS (1976) and presented in Figure 71. All of these concentrations are below 7.5 $\mu g/m^3$ (3 ppb), a range where the West-Gaeke bubbler method is at least suspect if not totally unacceptable. Therefore, the apparent increase of SO_2 between 1973 and 1974 cannot be accepted scientifically.

SO_2 was also measured at Page Airport by Dames & Moore (1975) using the conductimetric method. The frequency distributions in Table 12 indicate that the SO_2 concentration was usually below 10 ppb (25 $\mu g/m^3$).

A special network of sulfur dioxide monitors was operated around the Navajo Generating Station during 1974 and 1975. The first, second, and 24-hour average concentrations are presented in Table 13. Note the great variation of these concentrations with the different directions and distances from the generating station. Wind direction, atmospheric stability, and topography all greatly affect the groundlevel concentrations.

SO_2 was measured indirectly by its reaction with lead peroxide. The measurement is called sulfation rate and it

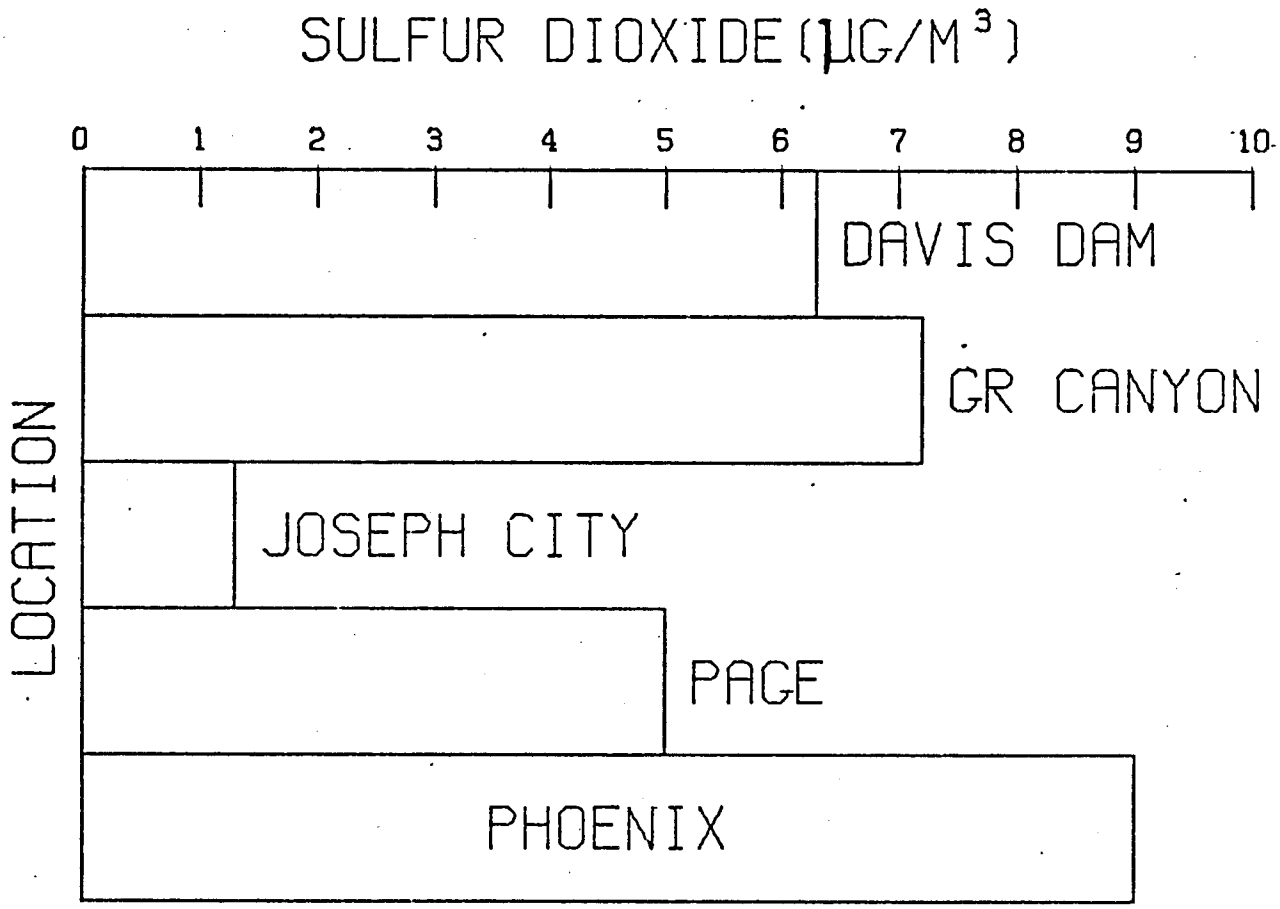


Figure 70: Sulfur dioxide concentrations at five locations during 1972-1975

Source: ADHS (1976)

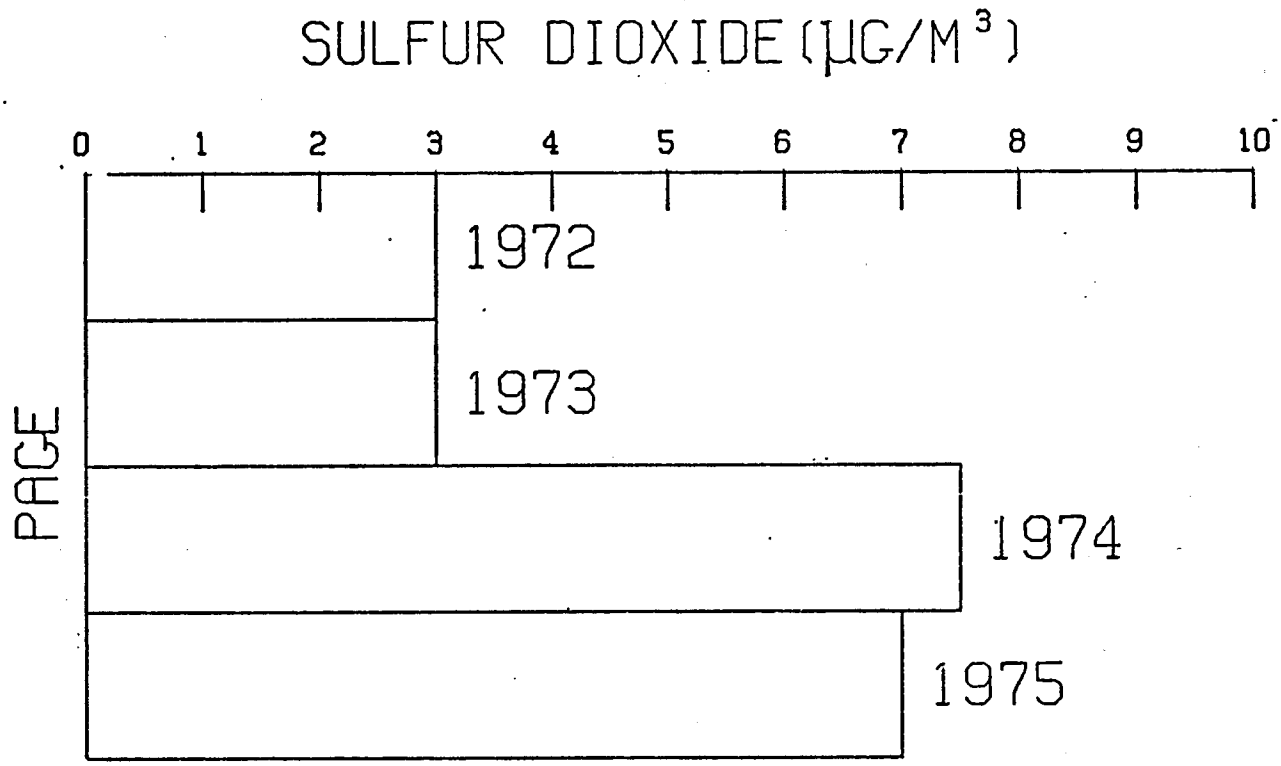


Figure 71: Annual arithmetic mean sulfur dioxide concentrations at Page Airport during 1972, 1973, 1974, and 1975.

Sources: Dames & Moore (1975) and Salt River Project (1976).

Table 12: Sulfur dioxide cumulative frequency distributions at Page Airport[a]

Concentration (parts per billion)	Daily Maximum 1-hour		Daily Maximum 3-hour	
	1971	1972	1973	1974
10	41.8	61.0	97.7	81.5
11			97.9	83.1
12	59.1	72.5	98.8	89.7
13			98.8	91.3
14	76.1	82.9	99.7	92.3
15			100.0	92.3
16	82.8	89.4		95.9
17				96.4
18	86.5	92.7		96.4
19				96.4
20	94.0	93.4		96.9
21				96.9
22	96.0	94.1		97.9
23				99.0
24	97.5	94.6		99.0
25				99.5
26	98.5	95.2		100.0
28	99.5	95.2		
30	100.0	99.4		
32		100.0		

[a]Arizona annual ambient air quality standard is 23 ppb.

Source: Dames & Moore (1975)

Table 13: Sulfur dioxide concentrations near the Navajo Generating Station in 1974 and 1975 ($\mu g/m^3$)

Location	Operator	Method	Ann. Avg.	3-Hr. Avgs. Max.	3-Hr. Avgs. 2nd High.	24-Hr. Avgs. Max.	24-Hr. Avgs. 2nd High.
Page Airport	SRP[a]	Bubbler/ Cond[m]	<1	117	94	13	8
105°, 3.6 km from Navajo Generating Station	SRP	Flame	NR[b]	105	42	26	13
256°, 3.2 km from Navajo Generating Station	SRP	Flame	NR	39	26	16	11
186°, 7.6 km from Navajo Generating Station	SRP	Flame	NR	18	13	8	5
174°, 23.3 km from Navajo Generating Station	SRP	Flame	NR	24	8	8	3
265°, 23.6 km from Navajo Generating Station	SRP	Flame	NR	68	68	18	16
269°, 24.6 km from Navajo Generating Station	SRP	Flame	NR	189	52	31	18
257°, 25.1 km from Navajo Generating Station	SRP	Color	NR	107	68	29	16
123°, 8.7 km from Navajo Generating Station	SRP	Flame	NR	84	55	26	24
218°, 7.4 km from Navajo Generating Station	SRP	Flame	NR	47	34	13	5
170°, 6.6 km from Navajo Generating Station	SRP	Color	NR	21	8	11	8
246°, 11.3 km from Navajo Generating Station	SRP	Color	NR	42	18	13	11
135°, 3.5 km from Navajo Generating Station	SRP	Color	NR	21	8	13	8
204°, 4.5 km from Navajo Generating Station	SRP	Color	NR	45	18	13	11
283°, 24.4 km from Navajo Generating Station	SRP	Color	NR	13	11	8	8
194°, 19.3 km from Navajo Generating Station	SRP	Color	NR	16	11	8	8

Table 13 (continued)

Location	Operator	Method	Ann. Avg.	3-Hr. Avgs. Max.	3-Hr. Avgs. 2nd High.	24-Hr. Avgs. Max.	24-Hr. Avgs. 2nd High.
252°, 28.1 km from Navajo Generating Station	SRP	Color	NR	100	55	24	21
192°, 15.7 km from Navajo Generating Station	SRP	Flame	NR	21	16	5	3
172°, 9.8 km from Navajo Generating Station	SRP	Color	NR	18	11	11	8
168°, 9.1 km from Navajo Generating Station	SRP	Color	NR	16	0	8	0
158°, 11.4 km from Navajo Generating Station	SRP	Flame	NR	29	0	11	0
144°, 8.7 km from Navajo Generating Station	SRP	Color	NR	21	18	11	11
Page Airport	State	Bubbler	8	NA[c]	NA	22	20

[a]SRP = Salt River Project (utility that operates the Navajo Generating Station)

Source: ADHS (1975)

b = not recorded

c = not applicable

Table 13 (continued)

Year: 1975

Location	Operator	Method	Ann. Avg.	3-Hr. Avgs. Max.	3-Hr. Avgs. 2nd High.	24-Hr. Avgs. Max.	24-Hr. Avgs. 2nd High.
Page Airport	SRP	Bubbler	<1	NA	NA	16	11
Page Airport	SRP	Flame	NR	100	88	18	18
Page Airport	SRP	Spec	1	138	128	24	24
NW, 14.3 km from Navajo Generating Station	SRP	Flame	NR	43	37	5	5
W, 5.8 km from Navajo Generating Station	SRP	Flame	NR	69	67	15	15
WSW, 3.2 km from Navajo Generating Station	SRP	Flame	NR	176	170	36	36
SW, 7.4 km from Navajo Generating Station	SRP	Flame	NR	94	77	18	18
Page Airport	State	Bubbler	7	NA	NA	22	22
Page Airport	State	Coul	0	40	0	5	0

Source: Arizona Department of Health Services (1976)

has the advantages of simplicity and low cost. A lead peroxide candle or disc can be placed anywhere because it requires no electrical power. The lead peroxide reacts with adsorbed SO_2 to form lead sulfate. The amount of lead sulfate was measured every 2 months.

The annual arithmetic mean sulfaction rates at 19 locations in northern Arizona and southern Utah during 1971, 1972, 1973, and 1974 are presented in Table 14. There is no clear trend easily seen in this table. A comparison of nine of these locations is given by the overall arithmetic mean sulfation rates for 1971 to 1974 presented in Figure 72. The differences are quite small, especially at these low rates of sulfation.

Any trend over these years would be very important to our understanding of the regional impact of coal-fired generating stations in this region. Therefore, we produced Figure 73 to present the average of the annual arithmetic mean sulfation rates at the eight locations nearest the Navajo Generating Station. The increasing trend from 1971 to 1974 is interesting, especially because the Navajo Generating Station did not commence operation until January 1974. Some other source must have caused the increases from 1971 to 1973.

The measurement of SO_2 and sulfation rate should be continued and made more sensitive in order to monitor these important changes.

Noise

Increasingly, in recent years, noise is becoming recognized as a special form of air pollution, requiring air as the medium for transmitting a purely mechanical vibration. To our knowledge, noise is only being measured in the Lake Powell region by the Lake Powell Research Project. Some minima, maxima, and means are listed in Table 15 when noise was measured continuously at various locations. It is so quiet at these locations that the actual minima may be less than the tabulated values, which are at or close to the lowest noise level measurable with the instrument we used. The lower limit of the instrument is determined by the amount of the internal electrical noise level within it. All the values in Table 15 are expressed in the accepted unit of decible (db), and the noise frequence (pitch) spectrum is weighted to represent the hearing response of the average normal human ear (the A-scale). The tabulated

Table 14: Sulfation Rates

Annual Arithmetic Mean Sulfation Rates

(milligrams SO_3 per 100 square centimeters per day)

Location	1971	1972	1973	1974
Grand Canyon, Arizona	0.029	0.014	0.015	0.024
Flagstaff, Arizona	0.016	0.021	0.019	0.022
Kaibito, Arizona	0.010	0.013	0.016	0.024
Monument Valley, Arizona	0.018	0.025	0.032	0.040
Bullfrog, Utah	0.006	0.010	0.016	0.016
Navajo Mountain, Arizona	0.021	0.009	0.016	0.014
Page Airport, Arizona	0.022	0.014	0.017	0.026
Leche-e Rock, Arizona	0.008	0.008	0.015	0.031
Lees Ferry, Arizona	0.028	0.008	0.017	0.019
Wahweap, Arizona	0.030	0.012	0.017	0.025
Padre Bay, Utah	0.008	0.010	0.016	0.020
Rainbow Bridge, Utah	0.016	0.018	0.024	0.034
Hole-in-the-Rock, Utah	0.010	0.008	0.016	0.017
Oak Creek Canyon, Arizona	0.059	0.025	0.028	0.030
Smoky Mountain	0.024	0.013	0.013	0.018
Bryce Canyon	--	0.014	0.014	0.016
Highway 89 South	--	0.012	0.016	0.025
Petrified Forest	0.079	0.033	0.043	0.048
Church Wells	0.027	0.011	0.015	0.018
Annual arithmetic mean of eight locations nearest the Navajo Generating Station	0.009	0.010	0.015	0.022

Source: Dames & Moore (1975)

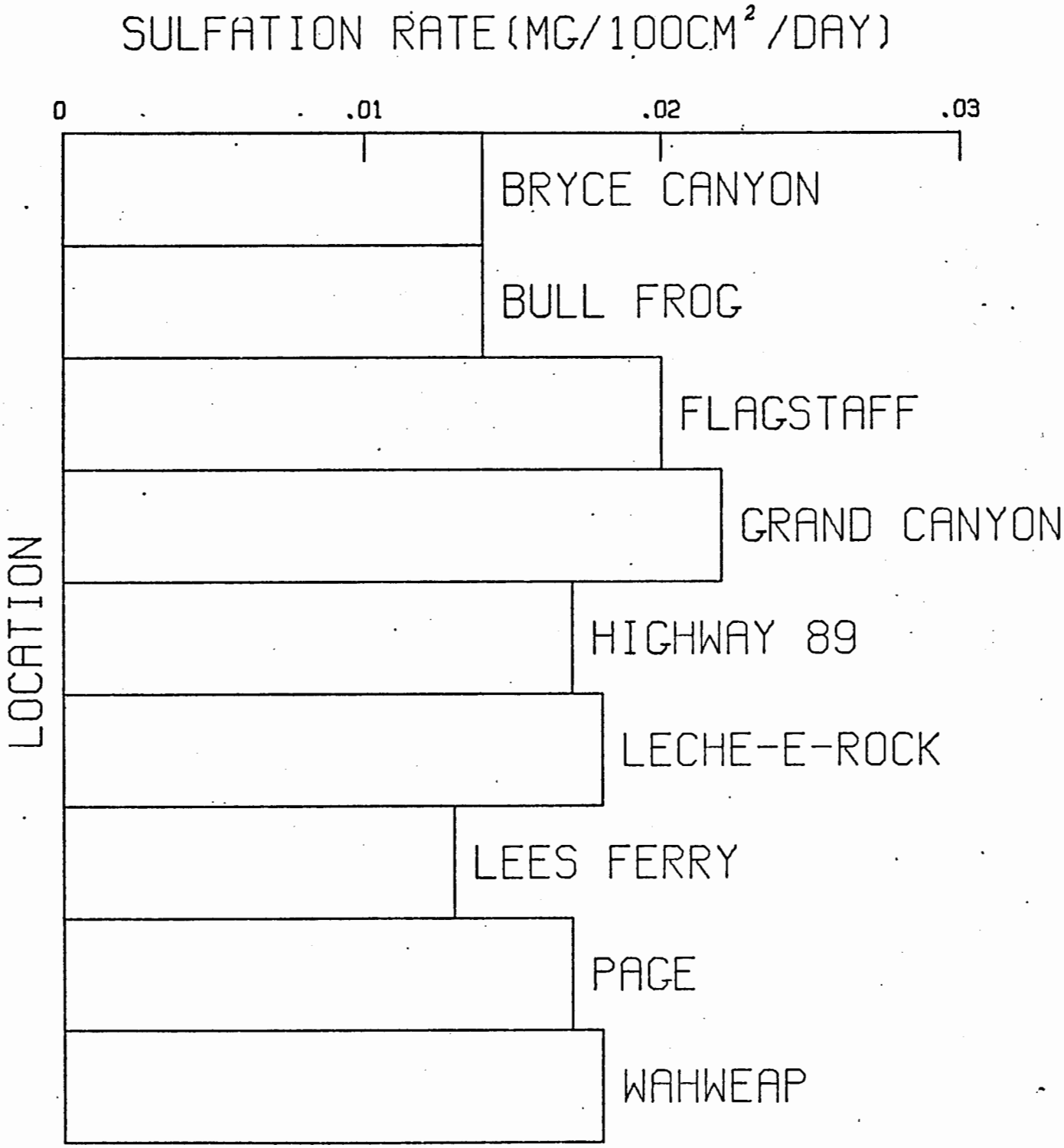


Figure 72: Sulfation rates at nine locations during 1971-1974

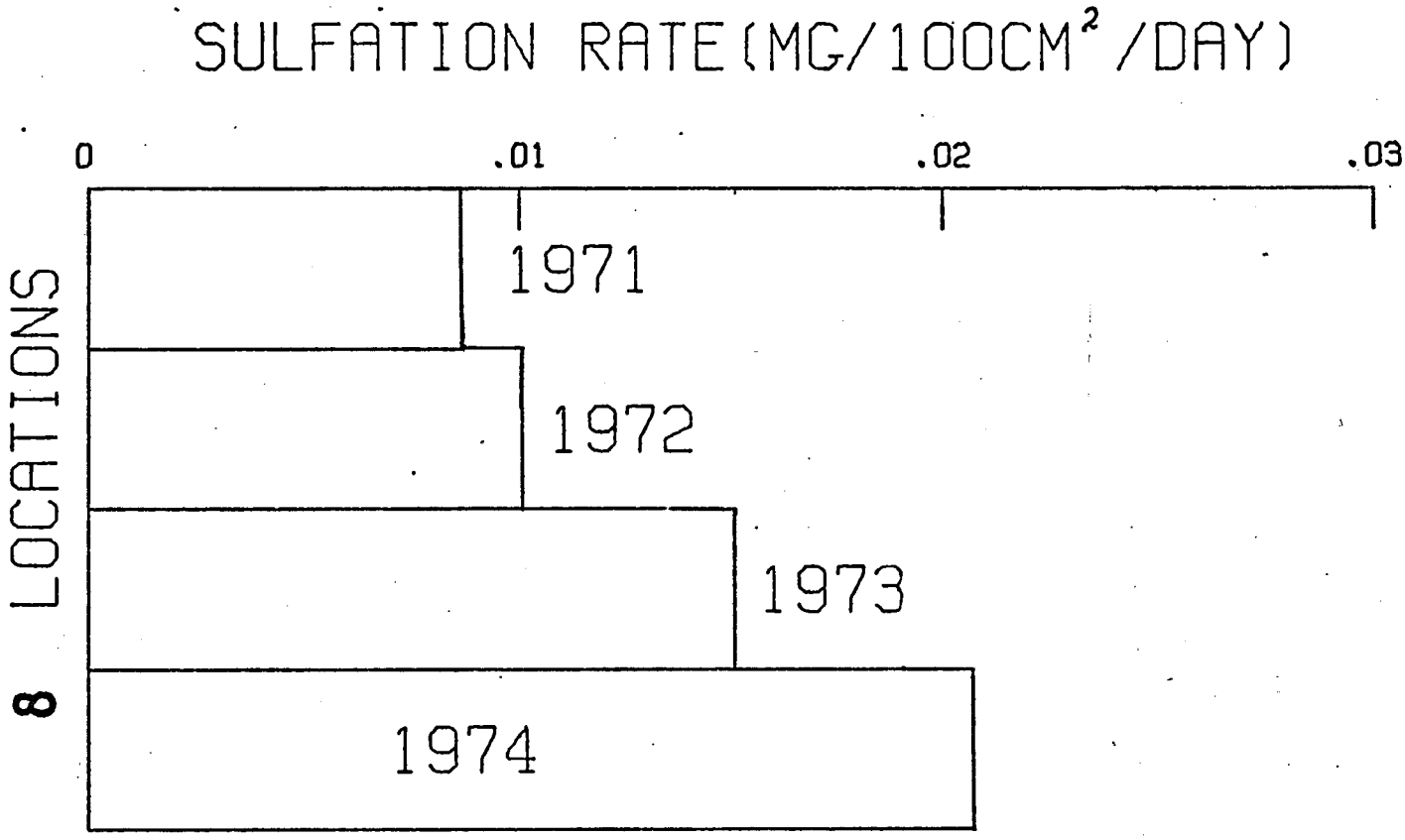


Figure 73: Annual arithmetic mean sulfation rates at eight locations nearest the Navajo Generating Station, which commenced operation January 1974.

Table 15: Noise measurements in the Lake Powell region

Date (1973)	Location	Minimum (dbA)[a]	Time (MST)[b]	Maximum (dbA)	Time (MST)	Mean (dbA)
24 Jan	Tower 16, near NGS[c]	24.5	1700	40	2345	--
1 Feb	Antelope Rock, near NGS	25	1045	46	1100	--
8 Feb	Leche-e Rock	27	0100	31	1130	--
10 Feb	Leche-e Rock	27.5	1730	65	1745	--
13 Feb	Leche-e Rock	22.3	1500	53	1400	--
17 Feb	Leche-e Rock	23.5	1230	58	1245	--
20 Feb	Utah Fish and Game Head-quarters at Wahweap Bay	26	1430	63	2030	--
27 Feb	North side, Wahweap Bay	22.5	1700	64.8	1415	--
3 Mar	North side, Wahweap Bay	23	1515	70	1530	--
4 Apr	Wahweap sew-age lagoon	24	1830-1930	70	1300-1430	--
16 Apr	Wahweap Bay	24	1300	70	1845	--

[a]dbA = decibels on the A-scale

[b]MST = Mountain Standard Time

[c]NGS = Navajo Generating Station

Table 15 (continued)

Date	Location	Minimum (dbA)	Time (MST)	Maximum (dbA)	Time (MST)	Mean (dbA)
28 Aug. 1973	Wahweap Bay	25	1730	60	1630	37.3 ± 0.3
5 Sept. 1973	Wahweap Basin	26	1630	68	2330	41.4 ± 0.4
12 Sept. 1973	Tower 16	25.5	0930	35	0930	30.3 ± 0.4
14 Sept. 1973	Vermillion Court, Page	38	0930	50	0900	47.0 ± 0.2
15 Sept. 1973	Vermillion Court, Page	37.5	2030	52	1100	46.5 ± 0.2
20 Sept. 1973	Wahweap Sewage Lagoon	22	1130	60	2300	42.7 ± 0.6
18 Oct. 1973	Antelope Rock	20	0945	48	0830	24.7 ± 0.3
24 Oct. 1973	Leche-e Rock	21.5	1200	50	1630	26.1 ± 0.2
27 Oct. 1973	Leche-e Rock	22	1930	42	0730	26.5 ± 0.3
15 Nov. 1973	Leche-e Rock	21	1000	42.5	0830	27.8 ± 0.5
23 Nov. 1973	Leche-e Rock	24	1800	40	1630	28.3 ± 0.3
28 Feb. 1974	Antelope Rock	25	0815	55	0830	34.4 ± 0.3
21 Mar. 1974	Antelope Rock	24	1230	54	1630	39.5 ± 0.4

maxima give some measure of the occasional noisiness of locations. Because the noise level is recorded automatically and the recorder is unattended, no record is available of the sources of the noise maxima. The very low maximum of 31 dbA which was recorded on February 8, 1973, indicates an exceptionally quiet day.

For reference, these sound levels should be compared with the sound level of normal conversation, which is 50 dbA. The lowest noise level ever successfully measured was 20 dbA, as shown in Table 15 for October 18, 1973.

The General Radio instrument we purchased for this project could only detect background noise levels of 20 dbA, even with the addition of a 10-to-1 amplifier on the microphone. The electrical noise within the amplifier of the General Radio instrument was not low enough to allow more sensitive measurement.

The mean noise levels at seven sites near Page are presented in Figure 74. The three quietest locations are also the most remote (Leche-e Rock, Antelope Rock, and Tower 16). Vermillion Court is a mobile home area, making it the noisiest of the seven sites.

Turbidity

Turbidity is a measure of the total aerosol in a vertical column of atmosphere. It is measured only on clear days because the measurement method is based on the solar radiation reaching the earth's surface at the two wavelengths of 380 and 500 nm (nm = 10^{-9} meter).

The instrument used to measure turbidity was a sun photometer manufactured by Eppley Laboratories. The hand-held instrument is small and portable, which facilitated making the turbidity measurements three times a day when weather permitted.

One of the important findings from the early data taken between February 1973 and April 1974 was that the turbidity coefficient at 380 nm (B_{380}) was lower than B_{500} most of the time, as shown in Figure 75. The arithmetic means of all the data from 1973 through 1976 are $B_{380} = 0.068 \pm 0.004$ and $B500 = 0.079 \pm 0.003$, where the numbers after the $\pm$ are one-half the 90-percent confidence intervals around these means. The means are statistically different, but in the opposite order of what is found at most locations. As discussed in Malm et al. (1977), we believe that the combination of water

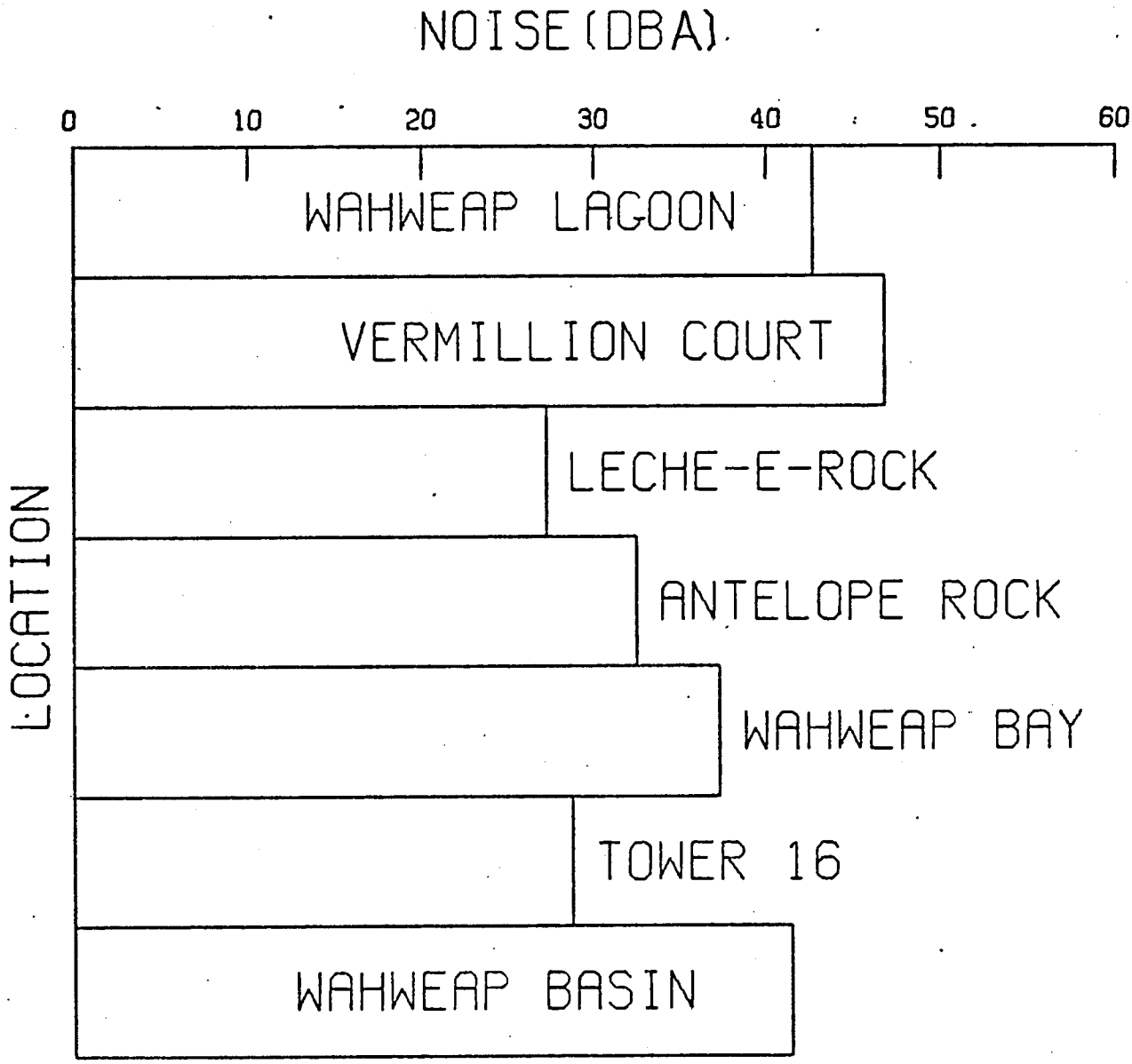


Figure 74: Mean noise levels at seven locations near Page during dates given in Table 15

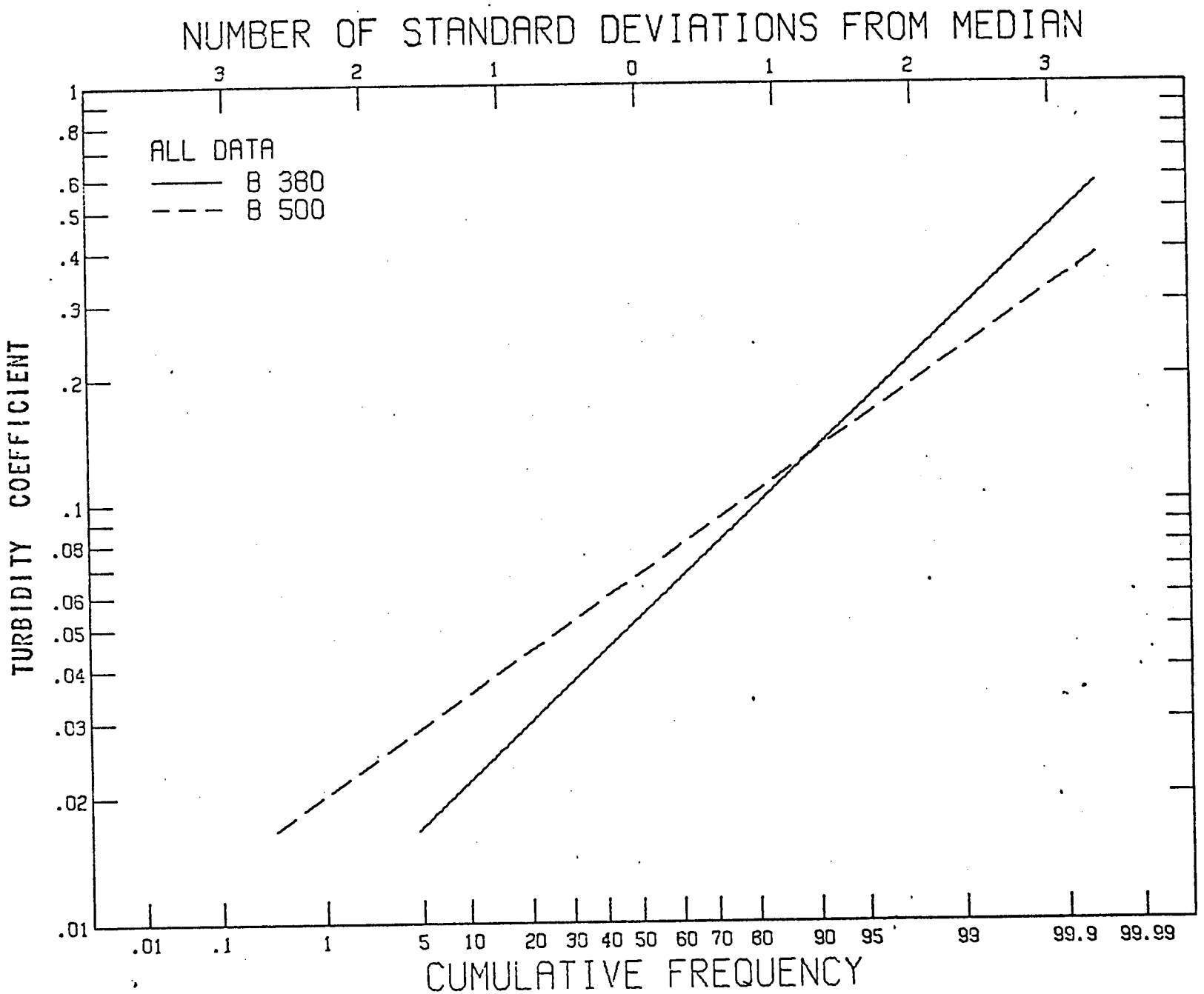


Figure 75: Turbidity coefficients at 380 and 500 nm measured at Vermillion Court near Page from 1973 through 1976

vapor in very clean air and a near monodisperse aerosol layer in the stratosphere accounts for this unusual condition of B_{380} B_{500}.

The crossing of the two lines in Figure 75 indicates that less than 10 percent of the measurements showed the usual B_{500} B_{380}. We believe these few data were taken on days for which the air was not as clean as it usually is in the Lake Powell region. This condition is quite reasonable because a dirtier atmosphere is associated with a shift in the aerosol size distribution that causes more light to be scattered at 380 nm that at 500 nm. Also, the greater sensitivity of light at 380 nm to the presence of aerosol probably explains the steeper slope of the 380 line in Figure 75, because the resulting B_{380} ranged more than B_{500}.

When all the turbidity coefficients from 1973 through 1976 are separated into seasons, there appears a trend in the ration of B_{500} and B_{380} as shown in Figure 76. The seasonal maxima, minima, means, and one-half 90-percent confidence intervals are presented in Appendix Table A-15. After winter 1975 all the next five seasons have $B_{500} < B_{380}$ (equivalent to $B_{500}/B_{380} < 1$). This changeover in the relative magnitudes of B_{380} and B_{500} is indicative of the more polluted locations at which turbidity is measured (National Oceanic and Atmospheric Administration, 1975).

We believe these data indicate a trend towards increasing air pollution in the Lake Powell region, similar to the indications inferred from the visual range and sulfation rate data. Yet, this trend is not universally indicated, by all of our air quality variables, as shown by the decreasing aerosol number concentrations measured at remote sites near Page and presented in Figure 22.

A seasonal pattern is indicated by the cumulative frequency distributions plotted for B_{380} and B_{500} in Figures 77 and 78. Summer has the highest turbidity and winter has the lowest. The only statistical insignificance is the difference between the means for B_{500} in fall and spring. Otherwise all the means are well separated.

The higher turbidity in summer is probably caused by a combination of more water vapor in the atmosphere around Lake Powell during the summer than during the winter and the entrainment of desert soil through the deep mixing depth of summer. In summer, there is strong convection over dry soil. Occasional dust storms and dust devils in spring and

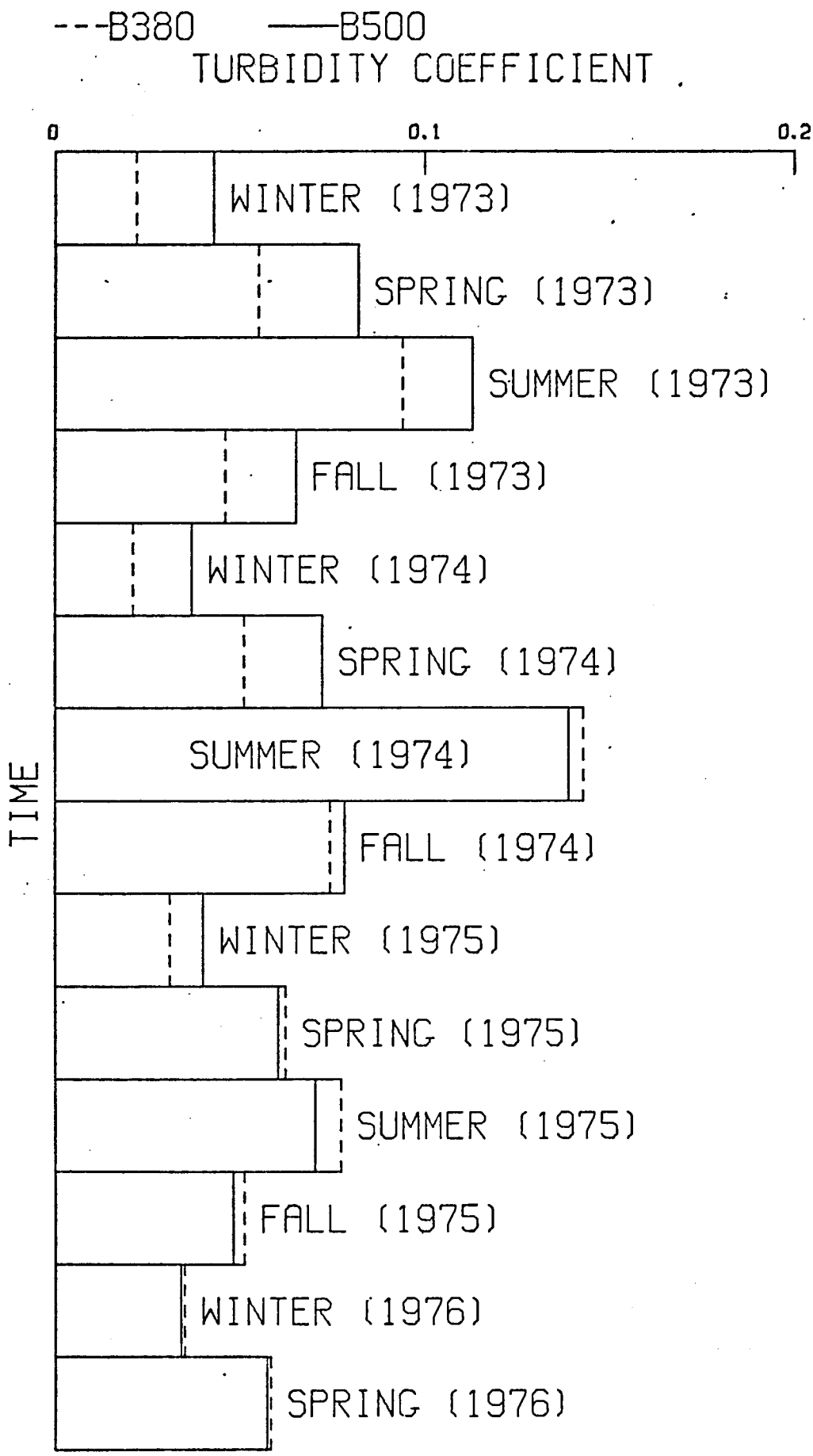


Figure 76: Seasonal mean turbidity coefficients at 380 and 500 nm measured at Vermillion Court near Page

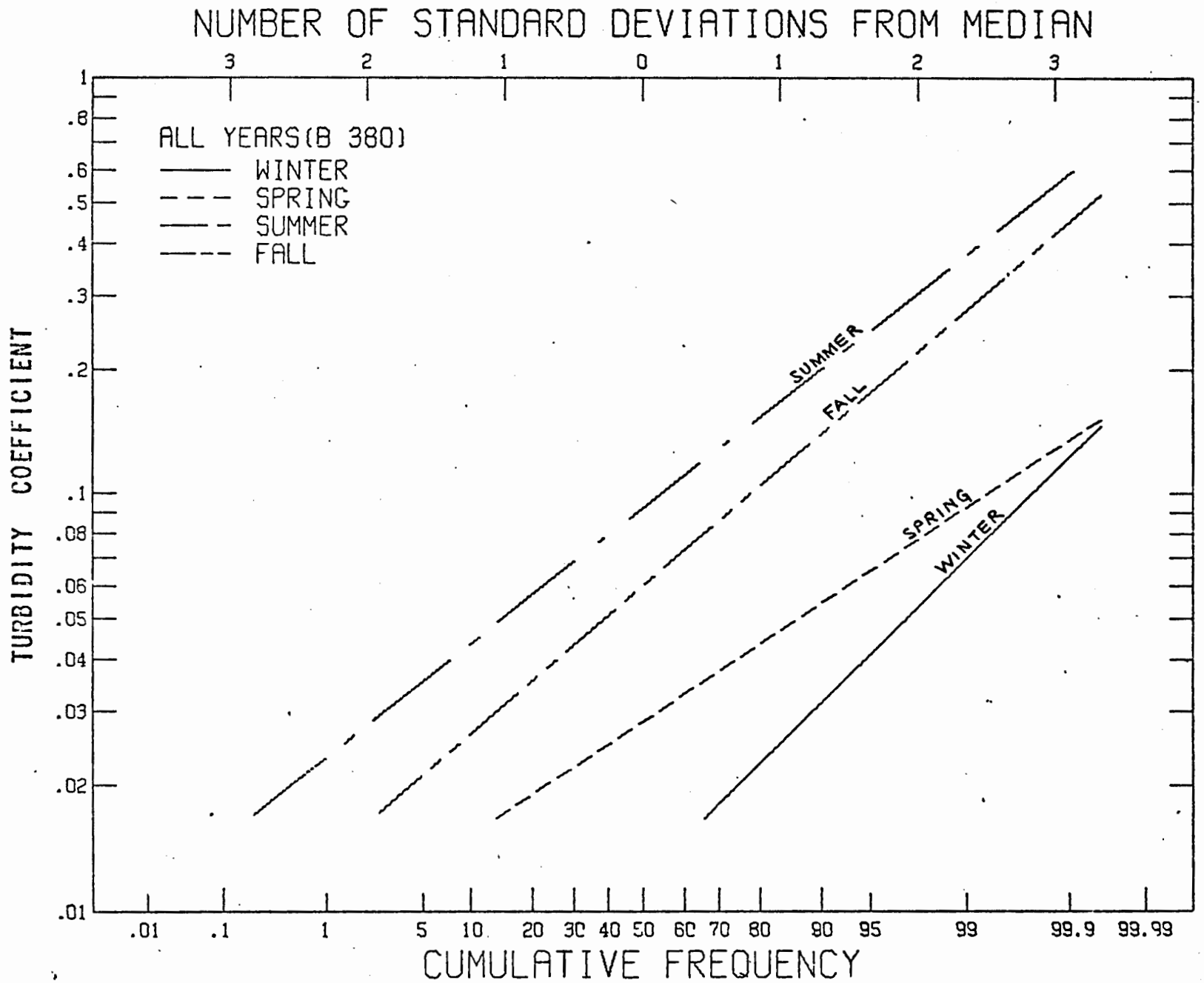


Figure 77: Turbidity Coefficients at 380 nm during the four seasons

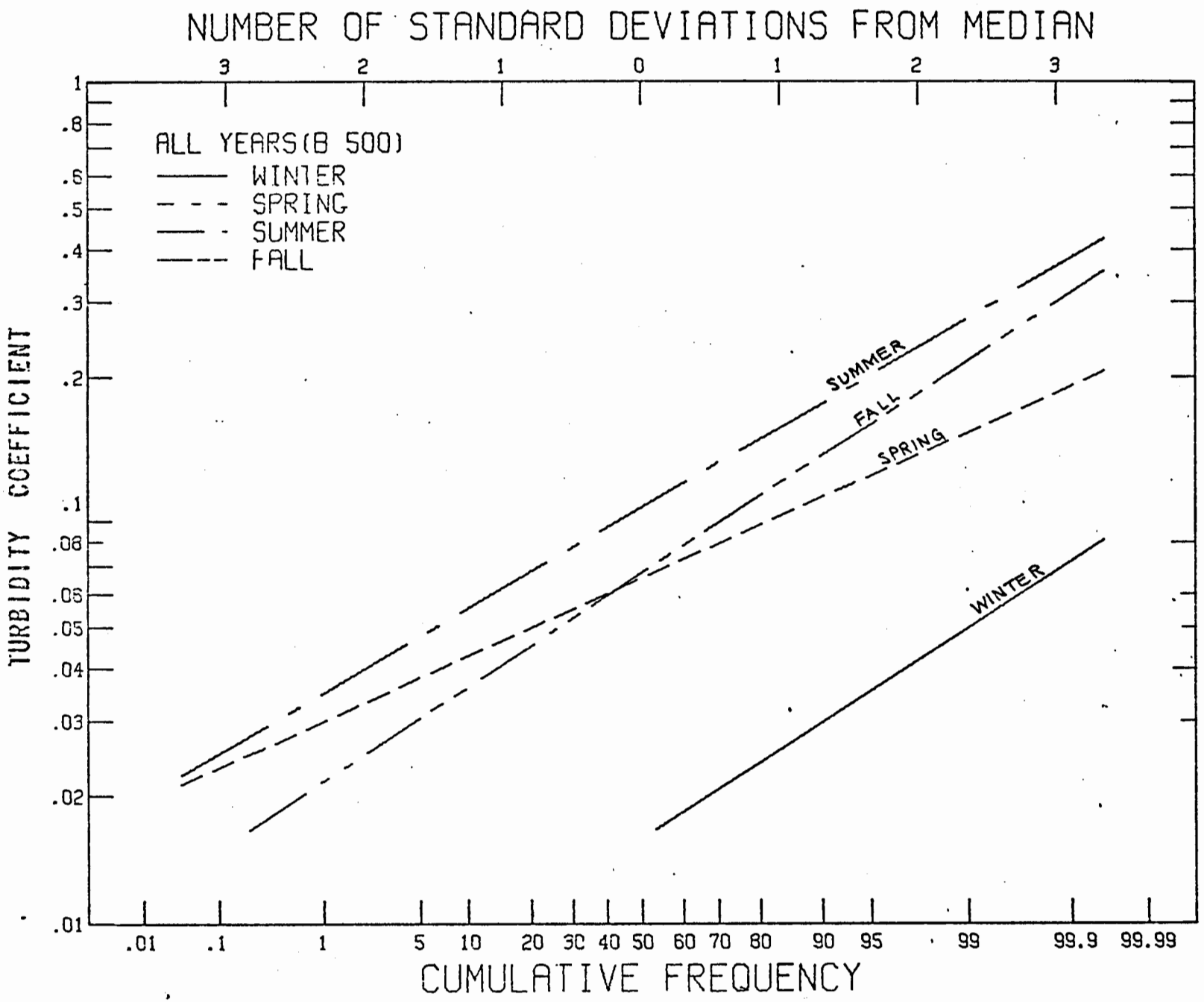


Figure 78: Turbidity coefficients at 500 nm during the four seasons

summer indicate how much dust can be elevated thousands of meters above these desert areas. In winter, snow often retards the entrainment of the desert soil in winds of equal soil-lifting speeds.

It is important to distinguish between the aerosol measured by turbidity and the aerosol measured by number concentration. Turbidity is measured with the use of the sun as a light source. Hence, it is a measure of the total aerosol in the path between the observer and the sun. This aerosol is mostly in the mixing layer of the troposphere, which may be several thousand meters deept, and in the stratosphere. This aerosol must be larger than about 0.1μ in size in order to scatter enough sunlight to be detected.

In contrast, aerosol number concentration is measured in a small volume of air near the observer's instrument, and the instrument works on a principle of condensing cloud droplets around the aerosol. As a result, this approach measures aerosol as small as 0.005μ. These small particles greatly outnumber the particles larger than 0.1μ, especially in combustion aerosol produced by cars and other vehicles.

The above differences in turbidity and aerosol number concentration make it easier to understand how turbidity can have a clear seasonal cycle not also shown by aerosol number concentration.

When the turbidity coefficients were stratified into the 4 years, no trend was clearly indicated by the cumulative frequency distributions for B_{380} and B_{500} presented in Figures 79 and 80. Despite the statistical indifference between the means for the separate years, 1974 still stands out as having more of the dirtiest measurements, shown by the steepest slope and the highest right side in Figures 79 and 80.

Visibility

In the Lake Powell region, three methods have been used to measure visibility. The best method for the long path measurement of regional visual range utilized a camera and telescope. The photographic contrast of chosen objects allowed the determination of the visual range, which is the quantitative measure of visibility.

The annual arithmetic means of this contrast-type visibility data for the years of 1972, 1973, and 1974 are shown in Figure 81, derived from data in Dames & Moore (1975). This

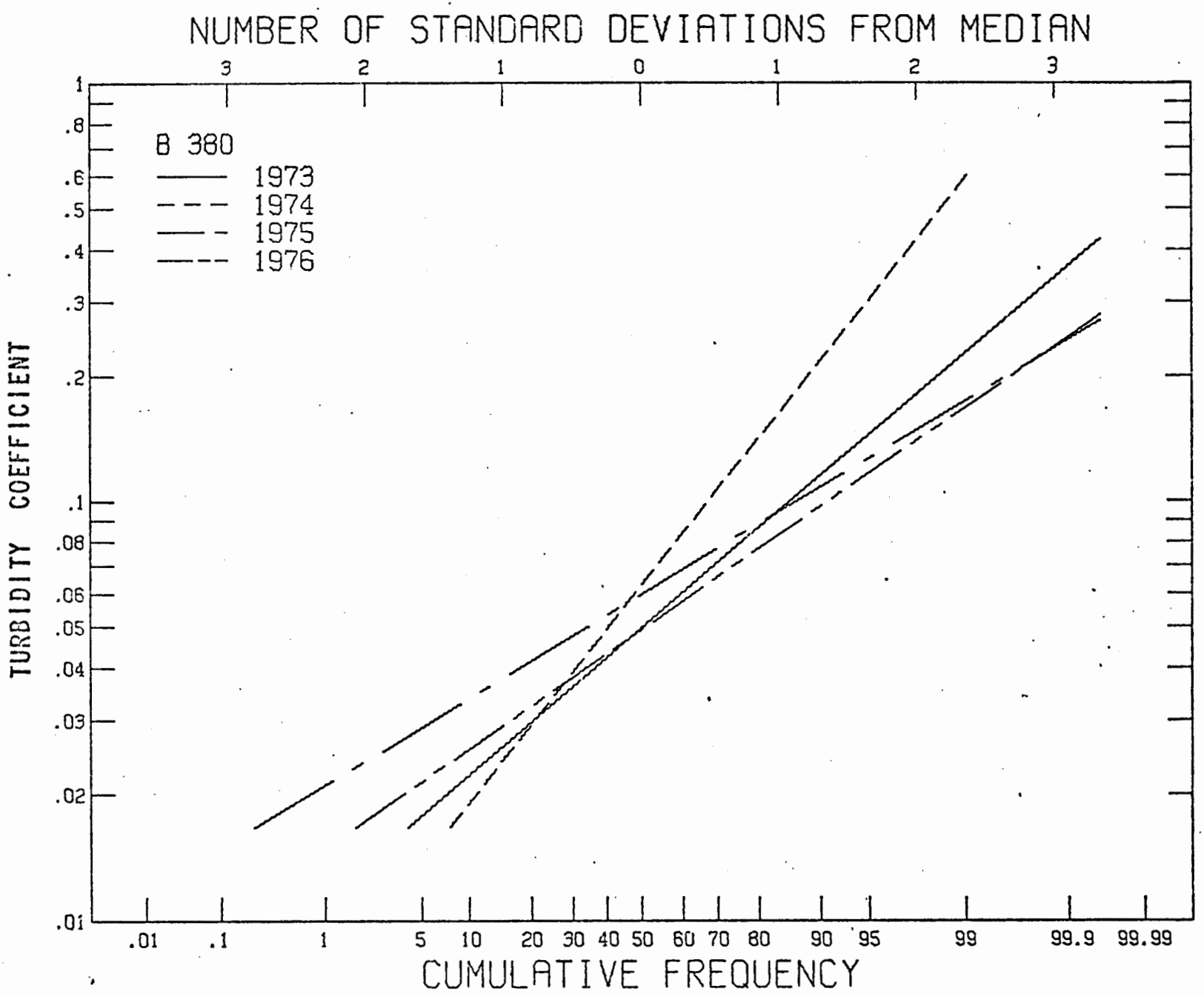


Figure 79: Turbidity coefficients at 380 nm measured at Vermillion Court near Page during 1973, 1974, 1975, and 1976

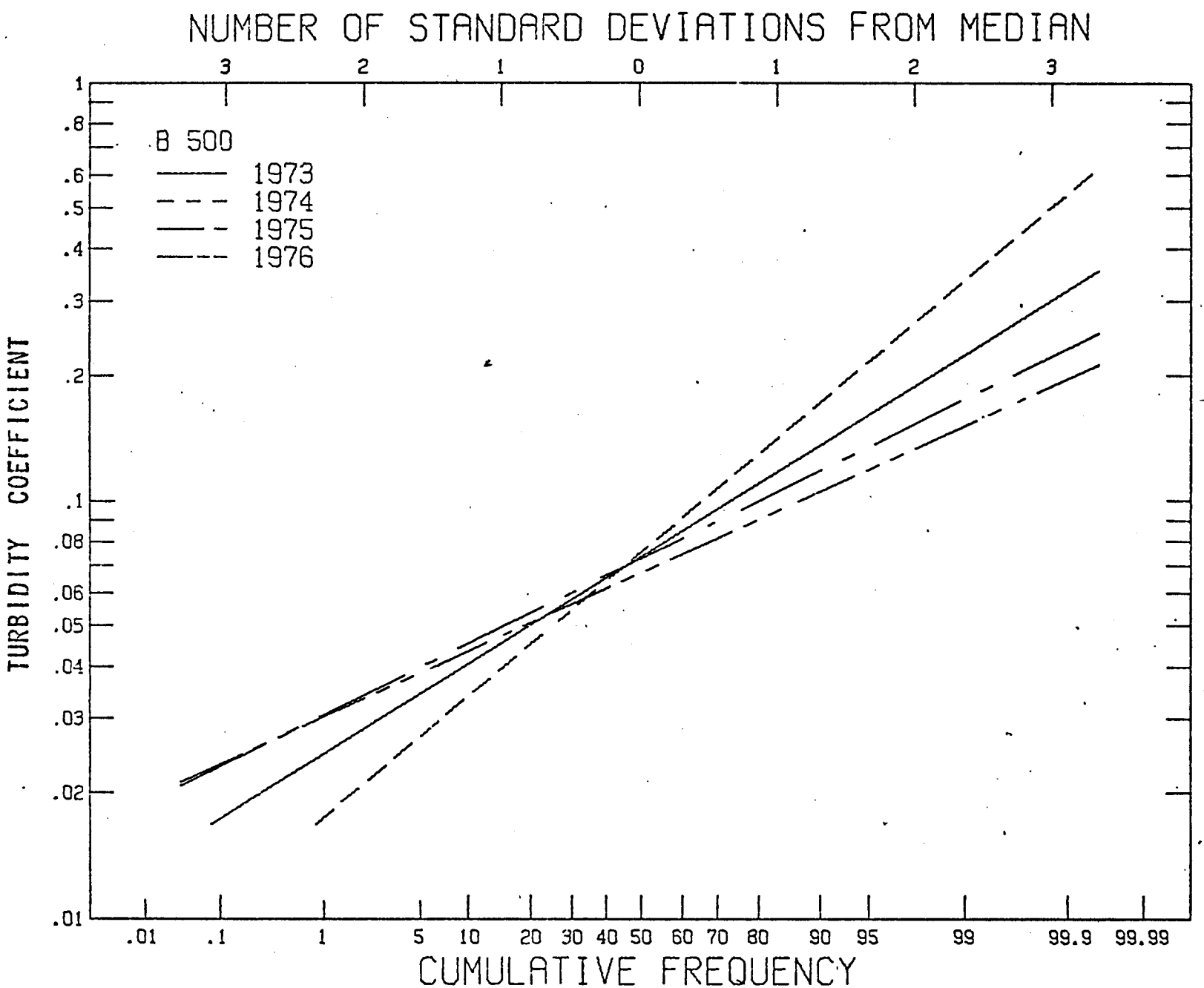


Figure 80: Turbidity coefficients at 500 nm measured at Vermillion Court near Page during 1973, 1974, 1975, and 1976

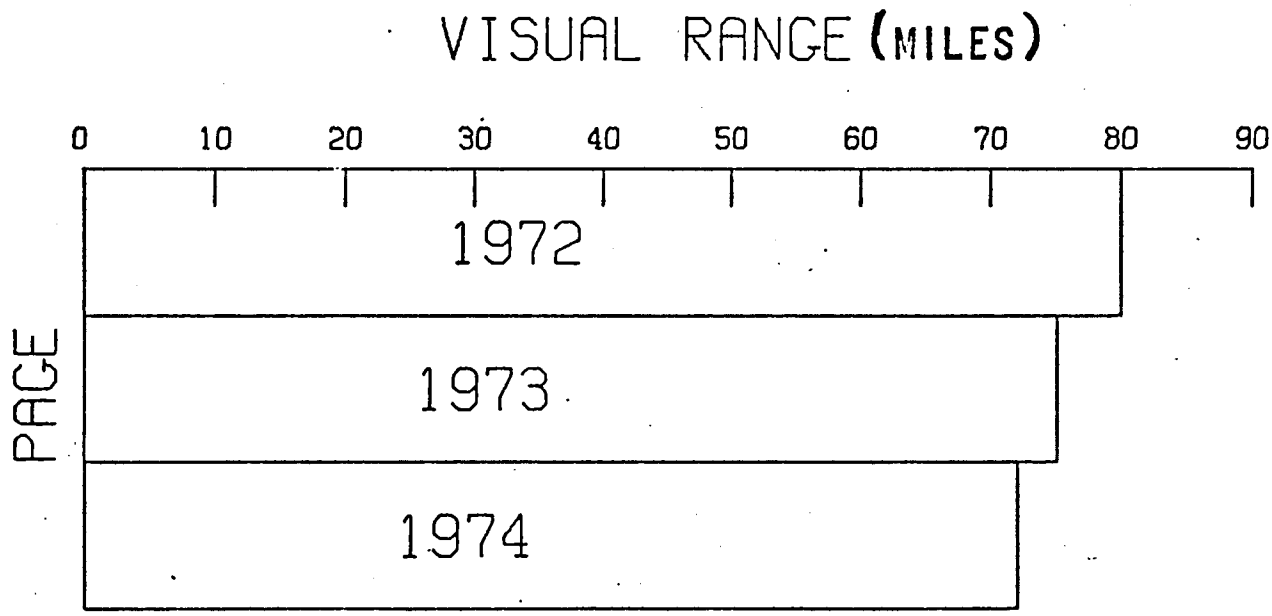


Figure 81: Visual range (annual arithmetic means) measured from Page Airport by the contrast method

Source: Dames & Moore (1975)

downward trend in visual range is so important in the Lake Powell region and any other recreation area potentially to be degraded by coalfired generating stations that we have proposed continuing air quality research in order to clearly identify the causes of this degradation and the geographical range of the degradation around a point source. Again, it must be understood that the Navajo Generating Station did not commence operation until January 1974. Hence, it could not have caused the decrease from 1972 to 1973 except through the addition of construction personnel to the local population and the associated increase in human activities.

These same contrast-type visibility data are shown in more detail by the frequency distributions for each of the 3 years in Figure 82, taken from Dames & Moore (1975). In each of the years, at least a few observations of visibility ranged all the way up to 260 km (160 miles).

The second method used by Dames & Moore (1975) to study visibility utilized the integrating nephelometer. This instrument measures the light scattered by the aerosol in a small volume of air. Those who developed the instrument compared the resulting scattering coefficient with independent measures of the visual range to yield the conversion scale. Therefore, the user of the instrument reads off a visual range that is based on an aerosol light-scattering measurement made at the site of the instrument. The conversion works quite well in contaminated air having relatively short visual range and in relatively uniform air. The conversion is less accurate in the Lake Powell region where the visual range is very long and the small scattering coefficient is difficult to measure. Also, the conversion from the aerosol light scattering to visual range is inaccurate if the aerosol concentration in the air is not uniform between the observer and distant points, because the instrument can only measure the air near the observer.

The cumulative frequency distributions for the visual range measured with the integrating nephelometer at Page Airport in 1972, 1973, and 1974 are shown in Figure 83. These data support the finding shown in Figure 81 that visibility has been degraded in the Lake Powell region.

In an attempt to analyze the local visual ranges measured by the integrating nephelometer for seasonal and time-of-week differences, we present the data for 1972 in Figure 84. There is no obvious difference between weekdays and weekends.

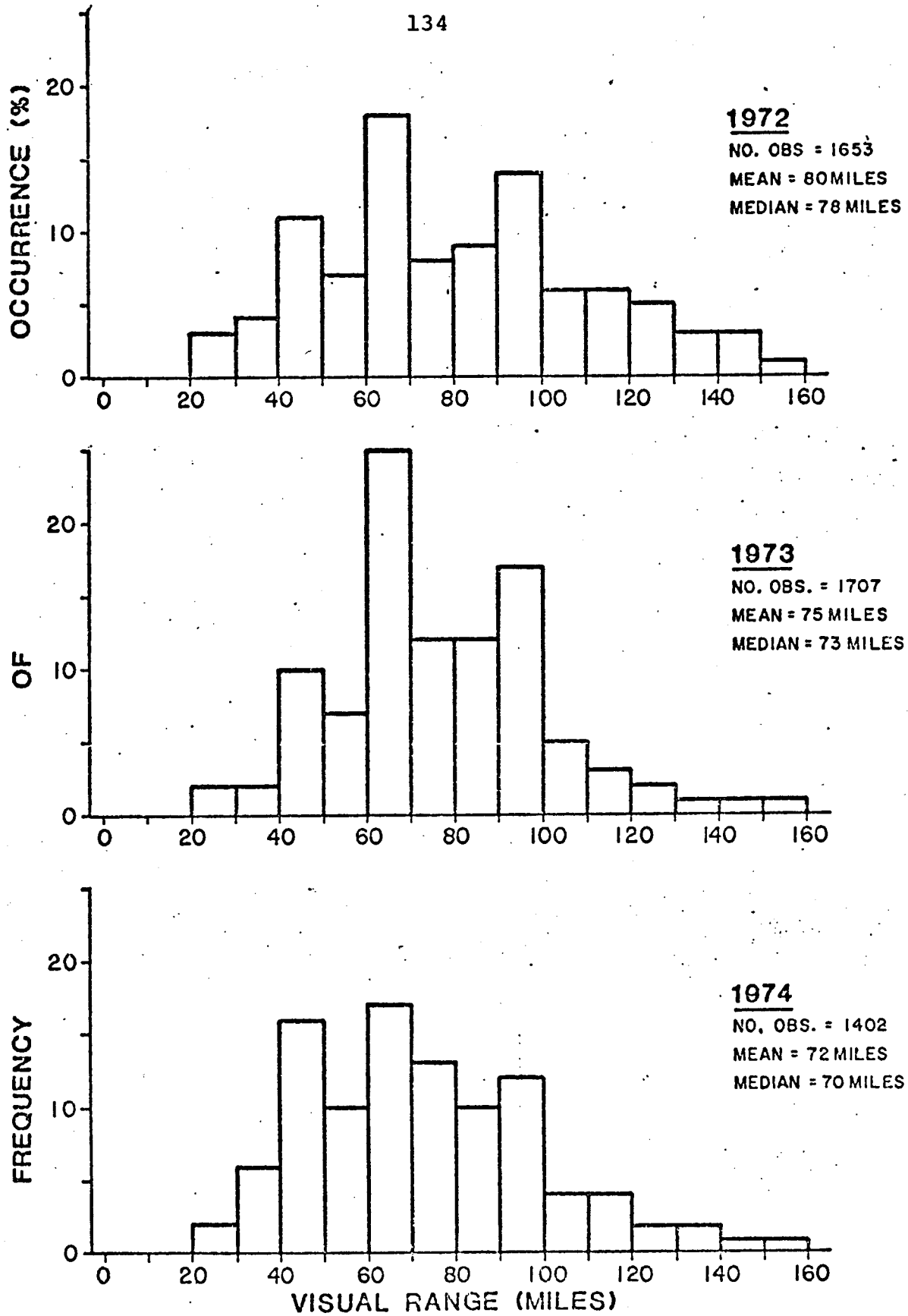


Figure 82: Distribution of visual range at Page, Arizona, 1972-1974 as measured by the contrast method

Source: Dames & Moore (1975)

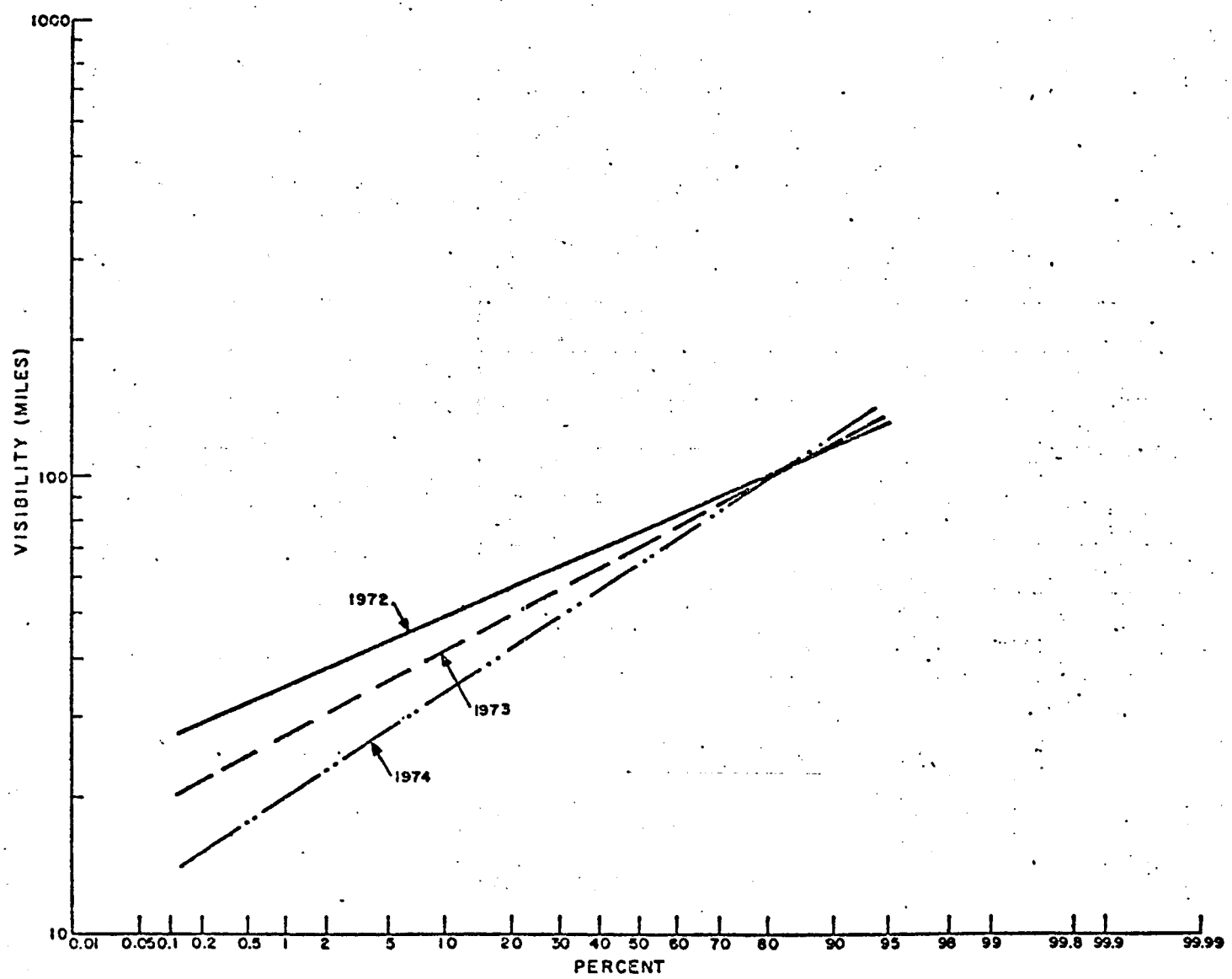


Figure 83: Cumulative frequency distribution of 2-hour average values of visual range as measured by integrating nephelometer at Page Airport during 1972, 1973, and 1974

Source: Dames & Moore (1975)

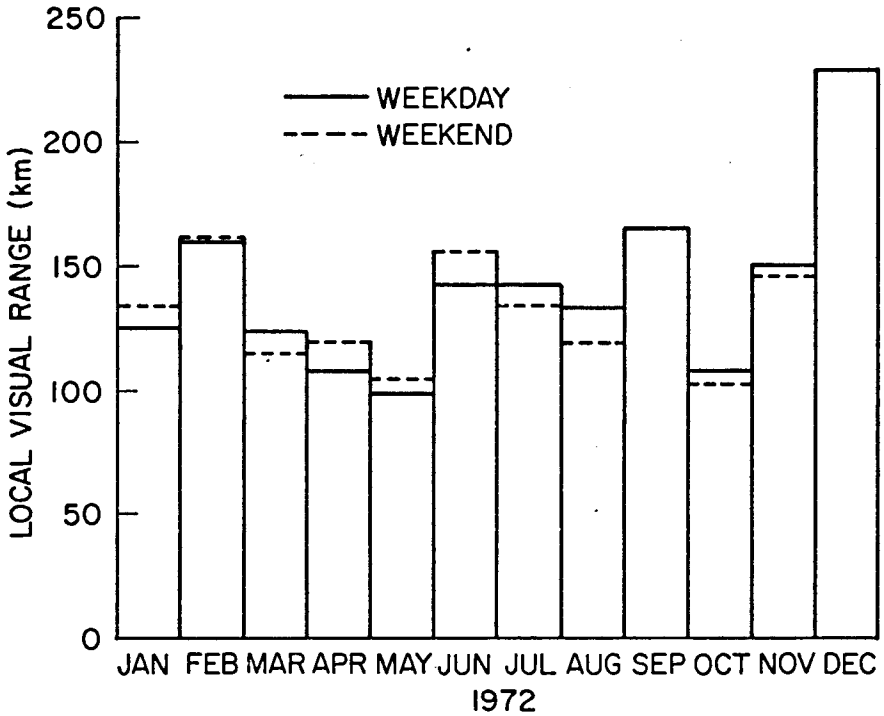


Figure 84: Local visual range as measured by an integrating nephelometer at Page Airport in 1972.

Source: Dames & Moore (1973)

Although Figure 84 does not clearly show a seasonal cycle, the minimum is seen in May and the maximum in December. The timings of these extrema may agree with the seasonal cycle of human activity, but we have no independent data on human activity in order to test this possibility. Also, the duststorms that are common in spring may help account for the May minimum. Unfortunately, we do not have duststorm data to check for an independent check.

We tested visual range data obtained with an integrating nephelometer by checking for its correlation with relative humidity data during the time period 1973 to 1974. The correlation coefficient was less than 0.1, indicating that relative humidity has no observable effect on the visual range in the Lake Powell area. This finding is supported by the experimental work of Covert et al. (1972), who found that specific aerosols increased their light scattering with increasing humidity, but the effect was significant only at relative humidities above 70 percent. The relative humidity in the Lake Powell region rarely exceeds 70 percent (Walther et al., 1974). Although relative humidity did not correlate with visual range, the turbidity and visual range correlated well, having a significant correlation coefficient of -0.63.

The third method used by Dames & Moore (1975) to estimate regional visual range is the viewing of distant objects by observers. Unfortunately, this type of measurement is very subjective and the tabulated form of the results is difficult to interpret; hence, the results are not included in this document. Yet, subjective observations of the viewing of distant objects by people is the method we all use in enjoying the recreational and aesthetic values of the Lake Powell region. Some better way must be found to analyze and communicate subjective observations.

Visibility is perhaps the most important air quality variable for all of us in our enjoyment of scenic America. This importance should be reinforced by a new ambient air quality standard for visual range, applicable in our federal recreation areas. Each region may need an individualized standard, much as our states have their different air quality standards.

Based on the data presented here, we suggest that an annual arithmetic mean visual range of 100 km (60 miles) would provide the Lake Powell region with reasonable protection and would allow some further degradation that will accompany additional development.

CONCLUSIONS AND RECOMMENDATIONS

This report presents a great number of findings about air quality in the Lake Powell region, especially about the air quality variables measured by the LPRP Background Air Quality Subproject: aerosol number concentration, carbon monoxide, hydrocarbons, noise, and turbidity.

In general, the absolute values of all these variables demonstrate the excellent air quality in this region.

Despite this excellent air quality, there is evidence it is deteriorating. The deterioration is shown most vividly by the downward trend in visual range; the reversal of $B_{380} < B_{500}$ to $B_{500} < B_{380}$; the upward trends in SO_2, sulfates, and aerosol mass concentrations at Page; and in the sulfation rates at the eight locations nearest the Navajo Generating Station.

The timing of these aerosol mass concentrations, sulfate, sulfation, and visual range trends precedes the operation of the Navajo Generating Station, while the turbidity and SO_2 changes follow the start-up date of Unit 1. Therefore, the potential cause-and-effect relationship of the powerplant operation and these air quality changes is unclear. The changes reported here do not precede the existence of Page or some other powerplants in the region, including the Four Corners Powerplant near Farmington, New Mexico, and the Mohave Generating Station near Davis Dam. Therefore, the changes may be showing regional scale deterioration of air quality caused by the cumulative impacts of these facilities.

Although the lowest air quality value in the various years differed among the air quality variables, 1974 had the lowest air quality based on lead, aerosol number concentration at remote sites, and visual range. This same year was the time of highest population in Page, as shown in Table 8.

The amounts of benzene-soluble organics and lead were greater in those locations with more land vehicle traffic, as expected if the land vehicles are the major sources of these contaminants.

The aerosol number and all hydrocarbons except methane and ethane had higher concentrations in Page than downwind of Page, and the concentrations downwind of Page were higher than at the remote sites. These findings demonstrate the

dilution of the initial emissions in Page by atmospheric dispersion as the contaminants move downwind. Methane and ethane concentrations were also higher in Page than at the remote sites, but the concentrations downwind of Page were lower than those at the remote sites. This surprising finding leads us to hypothesize that methane and ethane are reacting with nitrogen oxides or other pollutants, causing the resulting concentrations downwind of Page to be lower than those at the remote sites. Methane and ethane have their concentrations decreased by the combination of dispersion and chemical reaction. These reactions may also be producing oxidant, but the variables necessary to test this possibility were not measured.

The continuous measurement of aerosol number concentration appears to give a good indication of the daily pattern of human activities that use automobiles.

Most of the hydrocarbons indicated no yearly trend. They usually had higher concentrations in winter, most likely because of their use for space heating. They usually had higher concentrations on weekdays than on weekends.

Remote sites near Lake Powell are extremely quiet, so much so as to challenge accurate measurement by the best available commercial sound-level meters.

Based on our study, we make the following recommendations:

(1) There needs to be installed a monitoring network for several variables at several locations that will be operated on a regular basis until 1985, 10 years or so after the Navajo Generating Station began operation.

This network should measure SO_2, sulfates, sulfation rate, ozone, visual range, turbidity, nitrogen dioxide, and nitrates. The network should comprise at least six monitoring stations located at various distances and directions from the Navajo Generating Station and Page.

The network should be designed and operated under a mutual agreement among the EPA, the ADHS, and the Salt River Project, the utility operating the Navajo Generating Station.

(2) A research project should be designed and implemented to study the hydrocarbon reactions occurring in the air pollution plume of Page. These reactions seem to be able to deplete methane and ethane appreciably faster than turbulent dispersion and these reactions may also generate oxidant.

ACKNOWLEDGMENT

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GLOSSARY

A-scale	the magnitude scaling of sound or noise of different frequencies that represents the hearing response of a typical human ear
adiabatic	denotes a process (such as a parcel of air undergoing expansion or compression) in which there is no transfer of heat energy into or out of the system
alkanes	the class of hydrocarbons (organic compounds of hydrogen and carbon) in which the atoms are joined by simple single bonds
alkenes	the class of hydrocarbons in which at least two of the atoms are joined by a double bond
ambient air quality standard	a concentration of an air pollutant in the air for a specified time period designated to be the allowable maximum to protect public health (primary) or welfare (secondary)
anthropogenic	caused by humans
aromatic	having an aroma or smell
background air quality	the quality of air without significant local sources of man-made air pollution
beta-activity	a form of radioactive nuclear change that emits electrons
blue (and red) ends of scale	the wavelengths of light that correspond to these colors (roughly 350 and 500 nanometers respectively)
carcinogenic	cancer-causing
conductimetry	an electrical method of measurement based on the ability of a substance to conduct electricity
confidence limit (90%)	a statistical measure of the scatter of data; it is the upper

	or lower end of the confidence interval in which the mean exists with a specified probability (90%)
DAPC; ADHS	Division of Air Pollution Control; Arizona Department of Health Services
deposition	the set of physical processes that transfer a substance from the atmosphere to the Earth's surface
diopter	a device that uses a beam of light through a small hole to measure the elevation angle of the sun
dispersion	the physical process of diluting the concentration of a substance in a fluid by molecular and turbulent motion; e.g., smoke in air
entrainment	a process of transferring by turbulence a substance into a moving fluid; in this case, the transfer of dust and sand into the atmosphere by wind
fly ash	the solid particles that are carried out of a combustion furnace in the exhaust gas flow
flux	the transfer of something across a unit area during a unit time
gravimetric	a physical method of measuring mass or weight based on the force of gravitation
hygroscopic	readily attracting and retaining water
megawatt	one million watts, a unit of power or energy per unit time
nanometer	one billionth (10^{-9}) of a meter
oxidant	a gas that oxidizes; usually ozone
photochemical	referring to chemical reactions that require light
photometry	a physical method of measurement based on the transmission of light
picocurie	one trillionth (millionth millionth or 10^{-12}) of a curie, a measure of radioactivity
respiratory tract	the set of tubes and sacs which comprise the human-breathing system
stratosphere	the second major layer of the atmosphere, just above the troposphere, roughly

	between altitudes of 10 and 50 kilometers		which are emitted by vegetation
supersaturation	the state of air containing more than the saturated concentration of water vapor at a specified temperature	turbidity	the light-reducing characteristic of a fluid; in this case the light-reducing ability of the atmospheric particles along a vertical path through the atmosphere
terpenes	members of a subset of the alkene class		

APPENDIX

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Table A-1: Aerosol number concentration
(particles per cubic centimeter)

Remote Sites

Year	Season	Maximum	Minimum	Arithmetic Mean	1/2 90% Confidence Interval
1972	All	5,200	580	1,424	149
	Fall	5,200	580	1,424	149
1973	All	19,600	200	1,488	138
	Winter	3,450	200	1,222	129
	Spring	19,600	470	1,778	421
	Summer	6,900	690	1,513	188
	Fall	4,750	470	1,472	176
1974	All	12,000	370	1,974	160
	Winter	6,900	370	1,504	229
	Spring	12,000	580	2,051	400
	Summer	8,350	470	2,107	281
	Fall	6,900	470	2,179	314
1975	All	9,200	280	1,616	142
	Winter	9,200	470	2,002	367
	Spring	3,850	470	1,285	170
	Summer	6,900	690	1,837	302
	Fall	3,850	280	1,276	169
1976	All	4,250	280	1,275	136
	Winter	3,850	370	1,215	176
	Spring	4,250	280	1,341	212

Table A-1 (continued)

Aerosol Number Concentration

Year	Season	Maximum	Minimum	Arithmetic Mean	1/2 90% Confidence Interval
1973	All	265,000	1,140	17,790	4,024
	Spring	265,000	1,140	15,934	11,570
	Summer	91,000	1,720	16,300	4,041
	Fall	119,000	2,750	20,400	5,374
1974	All	145,000	305	16,310	2,055
	Winter	102,000	305	19,720	4,733
	Spring	145,000	1,720	13,900	4,730
	Summer	80,000	2,200	12,510	2,731
	Fall	91,000	2,460	19,720	3,930
1975	All	185,000	1,140	15,920	2,106
	Winter	80,000	3,850	22,830	3,194
	Spring	62,000	1,140	10,620	2,257
	Summer	185,000	1,140	15,630	4,851
	Fall	43,000	1,950	10,890	5,705

Table A-2: Carbon Monoxide
(parts per million)

Remote Sites

Year	Season	Maximum	Minimum	Arithmetic Mean	1/2 90% Confidence Interval
1975	All	1.3	0	0.26	0.16
	Winter	1.3	0.1	0.65	0.43
	Spring	0.4	0.1	0.20	0.16
	Summer	0.5	0	0.09	0.10

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Year	Season	Maximum	Minimum	Arithmetic Mean	1/2 90% Confidence Interval
1975	All	7	0	0.98	0.69
	Winter	7	0	2.67	3.60
	Spring	1.7	0.1	0.73	0.37
	Summer	1.3	0.1	0.50	0.47
	Fall	0.6	0	0.30	0.44

Table A-3: Methane
(parts per million)

Remote Sites

Year	Season	Maximum	Minimum	Arithmetic Mean	1/2 90% Confidence Interval
1972	All	2.7	0.9	1.59	0.11
	Fall	2.7	0.9	1.59	0.11
1973	All	2.4	0.8	1.44	0.04
	Winter	2.4	0.8	1.51	0.06
	Spring	2.1	1.0	1.37	0.05
	Summer	1.6	0.9	1.27	0.07
	Fall	1.4	1.2	1.30	0.09
1974	All	2.1	1.0	1.52	0.11
	Winter	2.1	1.1	1.67	0.20
	Spring	1.8	1.0	1.39	0.13
	Summer	-	-	-	-
	Fall	1.7	1.5	1.60	1.64
1975	All	1.7	0.8	1.41	0.12
	Winter	1.7	1.4	1.58	0.12
	Spring	1.6	1.2	1.48	0.16
	Summer	1.6	0.8	1.22	0.27
	Fall	1.6	1.1	1.35	0.41
1976	All	1.7	0.5	0.97	0.10
	Winter	1.7	0.8	1.21	0.14
	Spring	1.0	0.5	0.81	0.05

Table A-3 (continued)

Methane

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Year	Season	Maximum	Minimum	Arithmetic Mean	1/2 90% Confidence Interval
1973	All	1.7	1.0	1.33	0.04
	Spring	1.7	1.1	1.35	0.05
	Summer	1.4	1.0	1.28	0.09
	Fall	1.5	1.2	1.35	0.13
1974	All	2.1	1.0	1.60	0.11
	Winter	2.1	1.5	1.77	0.18
	Spring	1.9	1.0	1.48	0.15
	Summer	-	-	-	-
	Fall	1.7	1.5	1.60	0.10
1975	All	2.0	1.0	1.37	0.10
	Winter	2.0	1.2	1.50	0.24
	Spring	1.6	1.2	1.39	0.08
	Summer	1.3	1.0	1.12	0.12
	Fall	1.6	1.6	1.60	0.00

Table A-4: Ethane
(parts per billion)

Remote Sites

Year	Season	Maximum	Minimum	Arithmetic Mean	1/2 90% Confidence Interval
1973	All	1	0	0.9	0.2
	Fall	1	0	0.9	0.2
1974	All	45	0	2.9	1.3
	Winter	13	1	2.9	1.5
	Spring	45	0	6.9	5.0
	Summer	3	0	0.9	0.2
	Fall	9	0	1.5	1.0
1975	All	27	1	2.2	1.5
	Winter	25	1	3.9	3.6
	Spring	27	1	4.1	5.4
	Summer	1	1	1.0	0.0
	Fall	1	1	0.6	0.1
1976	All	13	0	1.3	0.8
	Winter	1	0	0.6	0.2
	Spring	13	0	1.8	1.3

Table A-4 (continued)

Ethane

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Year	Season	Maximum	Minimum	Arithmetic Mean	1/2 90% Confidence Interval
1973	All	20	0	3.4	4.6
	Fall	20	0	3.4	4.6
1974	All	55	0	4.9	2.0
	Winter	55	0	11.1	5.9
	Spring	27	1	4.9	3.4
	Summer	3	1	1.2	0.3
	Fall	3	1	1.1	0.2
1975	All	40	0	3.7	1.8
	Winter	40	1	9.4	8.2
	Spring	10	0	2.0	1.0
	Summer	19	1	2.9	2.1
	Fall	2	1	1.2	0.7

Table A-5: Propane
(parts per billion)

Remote Sites

Year	Season	Maximum	Minimum	Arithmetic Mean	1/2 90% Confidence Interval
1973	All	100	1	27.8	22.5
	Fall	100	1	27.8	22.5
1974	All	100	0	8.0	4.3
	Winter	100	0	19.5	14.7
	Spring	18	1	4.6	1.9
	Summer	8	1	1.9	0.6
	Fall	100	1	8.4	11.6
1975	All	100	1	10.0	6.3
	Winter	100	1	21.8	17.5
	Spring	100	1	15.7	20.0
	Summer	10	1	1.9	1.3
	Fall	5	1	1.8	0.7
1976	All	12	1	4.6	1.0
	Winter	12	1	4.6	1.3
	Spring	12	1	4.5	1.6

Table A-5 (continued)

Propane

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Year	Season	Maximum	Minimum	Arithmetic Mean	1/2 90% Confidence Interval
1973	All	100	2	24.7	25.1
	Fall	100	2	24.7	25.1
1974	All	100	1	29.7	8.0
	Winter	100	1	47.0	17.7
	Spring	100	2	18.4	12.5
	Summer	100	2	24.2	17.0
	Fall	100	3	28.4	16.0
1975	All	138	2	33.6	8.4
	Winter	138	7	65.4	27.5
	Spring	100	3	25.4	8.1
	Summer	100	2	30.2	13.7
	Fall	17	3	10.3	6.7

Table A-6: Butane
(parts per billion)

Remote Sites

Year	Season	Maximum	Minimum	Arithmetic Mean	1/2 90% Confidence Interval
1973	All	6	1	2.2	1.0
	Fall	6	1	2.2	1.0
1974	All	100	1	6.8	3.5
	Winter	8	1	3.2	1.1
	Spring	100	1	9.5	10.0
	Summer	100	1	6.6	7.0
	Fall	37	1	7.6	4.3
1975	All	100	1	14.0	6.8
	Winter	100	1	23.1	16.8
	Spring	100	1	16.9	19.6
	Summer	6	1	2.4	1.0
	Fall	77	1	14.6	12.6
1976	All	48	1	5.5	3.3
	Winter	48	1	9.2	6.6
	Spring	11	1	2.2	1.1

Table A-6 (continued)

Butane

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Year	Season	Maximum	Minimum	Arithmetic Mean	1/2 90% Confidence Interval
1973	All	12	1	5.5	2.7
	Fall	12	1	5.5	2.7
1974	All	100	1	7.3	2.8
	Winter	100	1	14.8	11.1
	Spring	13	1	5.1	1.6
	Summer	8	2	5.0	1.0
	Fall	12	1	4.5	1.8
1975	All	535	1	29.7	19.4
	Winter	535	1	97.3	94.0
	Spring	56	1	9.3	4.2
	Summer	127	1	22.3	15.8
	Fall	4	1	2.3	1.5

Table A-7: Pentane
(parts per billion)

All Locations

Year	Season	Maximum	Minimum	Arithmetic Mean	1/2 90% Confidence Interval
1974	All	100	1	9.1	2.2
	Winter	14	1	6.0	2.6
	Spring	13	1	5.3	1.2
	Summer	46	1	8.2	2.4
	Fall	100	1	12.7	5.3
1975	All	166	1	20.8	4.5
	Winter	166	1	48.7	16.5
	Spring	128	1	11.7	5.4
	Summer	147	1	22.9	8.5
	Fall	91	1	10.6	4.8
1976	All	49	0	6.5	1.7
	Winter	49	1	11.0	3.2
	Spring	13	0	2.6	0.8

Table A-8: Hexane
(parts per billion)

Remote Sites

Year	Season	Maximum	Minimum	Arithmetic Mean	1/2 90% Confidence Interval
1974	All	100	0	8.4	3.9
	Spring	27	0	7.9	5.2
	Summer	16	1	6.1	1.5
	Fall	100	1	11.9	11.3
1975	All	103	1	16.6	5.4
	Winter	103	1	27.4	17.4
	Spring	40	1	12.1	9.4
	Summer	29	4	15.5	3.5
	Fall	34	1	9.7	4.8
1976	All	145	1	9.2	7.8
	Winter	145	1	16.5	16.4
	Spring	6	1	2.8	0.7

Table A-8 (continued)

Hexane

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Year	Season	Maximum	Minimum	Arithmetic Mean	1/2 90% Confidence Interval
1974	All	38	0	8.9	2.2
	Spring	38	0	13.2	7.0
	Summer	16	3	7.9	1.8
	Fall	20	1	6.9	2.4
1975	All	166	1	29.9	10.3
	Winter	140	1	59.0	29.8
	Spring	28	2	9.9	3.2
	Summer	166	4	43.9	21.3
	Fall	9	1	5.7	4.0

Table A-9: Ethene (Ethylene)
(parts per billion)

Remote Sites

Year	Season	Maximum	Minimum	Arithmetic Mean	1/2 90% Confidence Interval
1973	All	1.0	0	0.3	0.3
	Fall	1.0	0	0.3	0.3
1974	All	98.0	0	3.2	2.5
	Winter	13.0	0	2.1	1.7
	Spring	98.0	0	7.9	10.7
	Summer	6.0	0	1.0	0.5
	Fall	23.0	0	2.8	2.8
1975	All	2.0	0	0.5	0.1
	Winter	2.0	0	0.8	0.3
	Spring	0.5	0	0.3	0.2
	Summer	0.5	0	0.4	0.1
	Fall	0.5	0	0.4	0.1
1976	All	1.0	0	0.2	0.1
	Winter	0.5	0	0.2	0.1
	Spring	1.0	0	0.2	0.1

Table A-9 (continued)

Ethene (Ethylene)

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Year	Season	Maximum	Minimum	Arithmetic Mean	1/2 90% Confidence Interval
1973	All	200	0	29.3	46.8
	Fall	200	0	29.3	46.8
1974	All	58	0	5.3	2.7
	Winter	58	0	8.4	7.0
	Spring	54	0	7.7	6.5
	Summer	10	0	2.3	1.4
	Fall	17	0	1.9	1.9
1975	All	128	0	8.9	6.4
	Winter	80	0	14.1	14.7
	Spring	10	0	1.1	0.8
	Summer	128	1	16.7	16.4
	Fall	1	1	0.7	0.3

Table A-10: Propene
(parts per billion)

Remote Sites

Year	Season	Maximum	Minimum	Arithmetic Mean	1/2 90% Confidence Interval
1973	All	4	1	1.4	0.6
	Fall	4	1	1.4	0.6
1974	All	20	0	1.9	0.6
	Winter	8	0	1.4	0.8
	Spring	20	0	3.1	2.3
	Summer	6	0	1.2	0.4
	Fall	7	0	2.1	1.0
1975	All	18	0	1.6	0.8
	Winter	18	0	2.6	2.3
	Spring	5	1	1.8	1.0
	Summer	10	0	1.4	1.3
	Fall	1	1	0.6	0.1
1976	All	2	0	0.6	0.1
	Winter	1	0	0.5	0.1
	Spring	2	0	0.6	0.2

Table A-10 (continued)

Propene

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Year	Season	Maximum	Minimum	Arithmetic Mean	1/2 90% Confidence Interval
1973	All	7	1	3.4	1.4
	Fall	7	1	3.4	1.4
1974	All	16	0	2.5	0.7
	Winter	16	0	4.5	2.1
	Spring	9	0	2.8	1.2
	Summer	2	1	1.1	0.1
	Fall	4	1	1.3	0.3
1975	All	29	0	3.9	1.4
	Winter	28	0	7.2	5.0
	Spring	10	1	2.5	0.9
	Summer	29	1	4.4	3.0
	Fall	1	1	0.7	0.3

Table A-11: Butene
(parts per billion)

All Locations

Year	Season	Maximum	Minimum	Arithmetic Mean	1/2 90% Confidence Interval
1973	All	6	1	3.5	4.1
	Fall	6	1	3.5	4.1
1974	All	100	0	5.3	1.3
	Winter	100	1	8.8	5.8
	Spring	53	0	5.7	2.6
	Summer	24	1	4.6	1.2
	Fall	14	1	3.6	0.8
1975	All	138	0	7.4	2.4
	Winter	40	0	6.9	3.4
	Spring	37	1	3.9	1.8
	Summer	138	1	10.1	5.7
	Fall	109	1	9.5	6.6
1976	All	32	0	2.9	5.1
	Winter	32	1	4.7	2.0
	Spring	8	0	1.3	0.4

Table A-12: Pentene
(parts per billion)

All Locations

Year	Season	Maximum	Minimum	Arithmetic Mean	1/2 90% Confidence Interval
1974	All	15	0	2.1	0.4
	Winter	15	1	6.7	7.0
	Spring	5	0	2.1	0.4
	Summer	14	0	1.8	0.5
	Fall	14	0	2.2	0.6
1975	All	87	0	4.8	1.3
	Winter	17	0	4.9	1.8
	Spring	30	0	2.9	1.4
	Summer	87	1	7.6	3.8
	Fall	38	1	3.7	2.0
1976	All	26	0	2.4	0.8
	Winter	26	0	4.2	1.6
	Spring	4	0	0.8	0.2

Table A-13: Hexene
(parts per billion)

All Locations

Year	Season	Maximum	Minimum	Arithmetic Mean	1/2 90% Confidence Interval
1974	All	100	2	6.5	2.6
	Spring	20	0	3.9	4.1
	Summer	57	0	5.8	4.4
	Fall	100	0	7.5	3.8
1975	All	50	0	3.5	1.1
	Winter	17	0	3.0	1.4
	Spring	43	0	5.1	1.9
	Summer	50	1	4.9	3.8
	Fall	3	0	0.7	0.2
1976	All	18	0	0.8	0.5
	Winter	18	0	1.3	1.3
	Spring	1	0	0.4	0.1

Table A-14: Acetylene
(parts per billion)

Remote Sites

Year	Season	Maximum	Minimum	Arithmetic Mean	1/2 90% Confidence Interval
1973	All	1	1	1.0	0.0
	Fall	1	1	1.0	0.0
1974	All	6	0	0.4	0.2
	Winter	1	0	0.4	0.3
	Spring	6	0	0.8	0.6
	Summer	3	0	0.2	0.2

Acetylene

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Year	Season	Maximum	Minimum	Arithmetic Mean	1/2 90% Confidence Interval
1973	All	7	7	7.0	0.0
	Fall	7	7	7.0	0.0
1974	All	2	0	0.2	0.1
	Winter	1	0	0.4	0.3
	Spring	2	0	0.3	0.2
	Summer	1	0	0.1	0.1

Table A-15: Turbidity coefficient
B_{380} All Locations

Year	Season	Maximum	Minimum	Arithmetic Mean	1/2 90% Confidence Interval
1973	All	0.220	0.001	0.062	0.005
	Winter	0.038	0.012	0.022	0.004
	Spring	0.158	0.013	0.055	0.005
	Summer	0.220	0.005	0.094	0.010
	Fall	0.118	0.001	0.046	0.006
1974	All	0.248	0.004	0.086	0.009
	Winter	0.079	0.004	0.021	0.005
	Spring	0.109	0.018	0.051	0.011
	Summer	0.248	0.021	0.143	0.014
	Fall	0.123	0.026	0.074	0.007
1975	All	0.182	0.002	0.063	0.005
	Winter	0.037	0.022	0.031	0.004
	Spring	0.089	0.026	0.062	0.006
	Summer	0.182	0.033	0.077	0.008
	Fall	0.121	0.002	0.051	0.007
1976	All	0.064	0.019	0.040	0.004
	Winter	0.061	0.019	0.035	0.004
	Spring	0.064	0.054	0.058	0.003

Table A-15 (continued)

B_{500} All Locations

Year	Season	Maximum	Minimum	Arithmetic Mean	1/2 90% Confidence Interval
1973	All	0.221	0.019	0.084	0.004
	Winter	0.061	0.026	0.043	0.005
	Spring	0.205	0.036	0.082	0.005
	Summer	0.220	0.041	0.114	0.008
	Fall	0.128	0.019	0.065	0.006
1974	All	0.335	0.017	0.092	0.008
	Winter	0.089	0.017	0.037	0.004
	Spring	0.136	0.038	0.072	0.001
	Summer	0.335	0.049	0.139	0.011
	Fall	0.124	0.035	0.078	0.006
1975	All	0.130	0.025	0.059	0.003
	Winter	0.052	0.029	0.040	0.007
	Spring	0.085	0.027	0.060	0.001
	Summer	0.130	0.035	0.070	0.005
	Fall	0.092	0.025	0.048	0.005
1976	All	0.068	0.020	0.038	0.004
	Winter	0.068	0.020	0.034	0.004
	Spring	0.067	0.047	0.058	0.005

THE AUTHORS

Dr. Eric G. Walther has been the Principal Investigator of the Air Quality Subproject since 1972. He has been conducting air quality research in association with the Museum of Northern Arizona, in Flagstaff, Arizona, and the Atmospheric Sciences Research Center of the State University of New York at Albany since 1967. The research has included the study of gas-to-aerosol conversions, the analysis of air pollutants and their source by effect rather than by mass, and the analysis of air quality and ecosystem impact, as well as field measurement of air quality in the southwestern United States and over Greenland. In addition, Dr. Walther is Manager of the Food Production/Climate Mission at the Charles F. Kettering Foundation, in Dayton, Ohio, where he is supporting studies of the interrelationships between world food production and climate. While Executive Director of the Colorado Plateau Environmental Advisory Council (1970-1973), Dr. Walther participated in the National Academy of Sciences study of the rehabilitation potential of western coal lands.

Robert A. Cudney has been a research associate on the Air Quality Subproject since 1972. He operates the Page, Arizona, field station of the subproject, collecting air samples in the Lake Powell region and measuring various air quality parameters.

In addition, he continues his development of electronic instrumentation for the measurement of atmospheric electrification, a subject on which he worked for several years at the Atmospheric Sciences Research Center of the State University of New York at Albany. He is now employed by the Public Service Company of New Mexico.

Dr. William C. Malm is Associate Professor of Environmental Science at Northern Arizona University in Flagstaff, where he teaches courses in air pollution and conducts research in air quality, both at Lake Powell with the Air Quality Subproject and in the Grand Canyon with the National Park Service. He is also continuing some of his physics research in ellipsometry and water absorption on silver iodide films which is related to cloud physics and weather modification.