NOAA Technical Memorandum NOS OMS 4

SYNTHESIS OF CURRENT MEASUREMENTS IN PUGET SOUND, WASHINGTON - VOLUME 2: INDICES OF MASS AND ENERGY INPUTS INTO PUGET SOUND: RUNOFF, AIR TEMPERATURE, WIND, AND SEA LEVEL

Carol A. Coomes, Curtis C. Ebbesmeyer,
Jeffrey M. Cox, Jonathan M. Helseth,
and Laurence R. Hinchey
Evans-Hamilton, Inc.
6306 21st Avenue, N.E.
Seattle, Washington 98115

Glenn A. Cannon
Pacific Marine Environmental Laboratory
National Oceanic and Atmospheric Administration
Seattle, Washington 98195

Clifford A. Barnes
Department of Oceanography
University of Washington
Seattle, Washington 98195

Rockville, Md.
May 1984

UNITED STATES
DEPARTMENT OF COMMERCE
Malcolm Baldrige, Secretary

National Oceanic and
Atmospheric Administration
John V. Byrne, Administrator

National Ocean Service
Paul M. Wolff,
Assistant Administrator

Submitted to
National Oceanic and Atmospheric Administration
National Ocean Services
Ocean Assessment Division

by

Evans-Hamilton, Inc.
Seattle, Washington 98115

Pacific Marine Environmental Laboratory, NOAA
Seattle, Washington 98115

Department of Oceanography
University of Washington
Seattle, Washington 98195

DISCLAIMER

CONTENTS

TABLES

FIGURES

LIST OF ABBREVIATIONS

ABBREVIATIONS

^{o}C	-- degrees Celsius
m	-- meter
mb	-- millibars
MISC	-- miscellaneous
NOS	-- National Ocean Survey
PMEL	-- Pacific Marine Environmental Laboratory
rms	-- root mean square
s	-- second
Sea-Tac	-- Seattle Tacoma International Airport
USGS	-- United States Geological Survey
UW	-- University of Washington

PREFACE

Puget Sound is an estuary in northwestern Washington consisting of three branches joined near their mouths to an entrance sill zone. In turn, this zone connects to the Pacific Ocean via the Strait of Juan de Fuca. The branches consist largely of basins embraced by sill zones; the largest or Main Basin accounts for half of Puget Sound's volume and the other half occurs mostly in three secondary basins. The estuarine flow is strongly modified by vertical mixing of surface and deep water over the sills as the water moves between the basins. As a result, the major portion of the surface flow is mixed downward and returned inland before exiting Puget Sound. This downwelling has raised concerns that primary fractions of municipal and industrial wastes are also refluxed inland and may be retained in the fjord complex for considerable periods.

To describe the characteristics of the circulation in Puget Sound, a synthesis of historical measurements of currents, water properties, and meteorological conditions has been undertaken. The results of this project are presented in three volumes:

Volume 1. Index to current measurements made in Puget Sound from 1908-1980, with daily and record averages for selected measurements.

Volume 2. Indices of mass and energy inputs into Puget Sound: runoff, air temperature, wind, and sea level.

Volume 3. Circulation in Puget Sound: an interpretation based on historical records of currents.

Volume 1 contains the locations and statistics of the recorded currents, and describes the types of equipment used to obtain the data.

This volume (Volume 2) examines indices of mass and energy inputs necessary to interpret changes in the currents and water properties. Freshwater additions, air temperature, and wind were analyzed for both daily and monthly periods. Using these data, long-term norms and anomalies of runoff, air temperature, and wind were determined.

The data are presented in three appendices. The first appendix contains monthly means of runoff, air temperature, and wind during 1930-1978. The second appendix contains daily averages of runoff, air temperature, and wind during 1949-1968, during which water properties were intensively sampled. In the third appendix are presented daily averages during 1969-

1978 for these variables plus supporting data of sea level, tidal range, and barometric pressure. The bulk of the current measurements were obtained during the latter interval.

Volume 3 contains an interpretation of the circulation based on the data contained in Volumes 1 and 2.

SYNTHESIS OF CURRENT MEASUREMENTS IN PUGET SOUND, WASHINGTON

VOLUME 2: INDICES OF MASS AND ENERGY INPUTS INTO PUGET SOUND: RUNOFF, AIR TEMPERATURE, WIND, AND SEA LEVEL

Jeffrey M. Cox, Curtis C. Ebbesmeyer, Carol A. Coomes, Jonathan M. Helseth, Laurence R. Hinchey, Glenn A. Cannon, and Clifford A. Barnes

1. INTRODUCTION

1.1 PROJECT OVERVIEW

Puget Sound is an estuary located in northwestern Washington (Fig. 1.1). The population near Puget Sound numbers several million people and a variety of wastes are discharged into the estuary. The dilution and distribution of these wastes is in part controlled by a complex circulation of water in Puget Sound.

In a gross perspective the estuary consists of a central or main basin, three secondary basins, and an entrance sill zone which connects to the Pacific Ocean via the Strait of Juan de Fuca (Fig. 1.2). The central axis is a chain of sills and basins. The prominent features of this chain are a seaward sill zone (Admiralty Inlet), a central basin (Main Basin), a secondary sill zone, and a terminal basin (Southern Basin). Appended to the central axis near its mouth are two other basins. One of these (Hood Canal) has a sill at its mouth; the other (Whidbey Basin) lacks an entrance sill, but contains an outlet to the Strait of Juan de Fuca at its head.

The circulation in the Main Basin is in part controlled by vigorous tidal mixing in the embracing sill zones (Ebbesmeyer and Barnes, 1980). As a consequence some of the water initially moving seaward in the estuary's upper layer is carried to depth within these zones, where it is then returned to the estuary's lower layer moving inland. This partial recycling of surface waters through Puget Sound has increased the concern regarding the fate of wastes discharged into the estuary. A common belief was that most of these wastes were rapidly removed from Puget Sound within the outflow of the upper layer. The recent study by Ebbesmeyer and Barnes (1980) suggests that these wastes will accumulate in the water column to some presently unknown

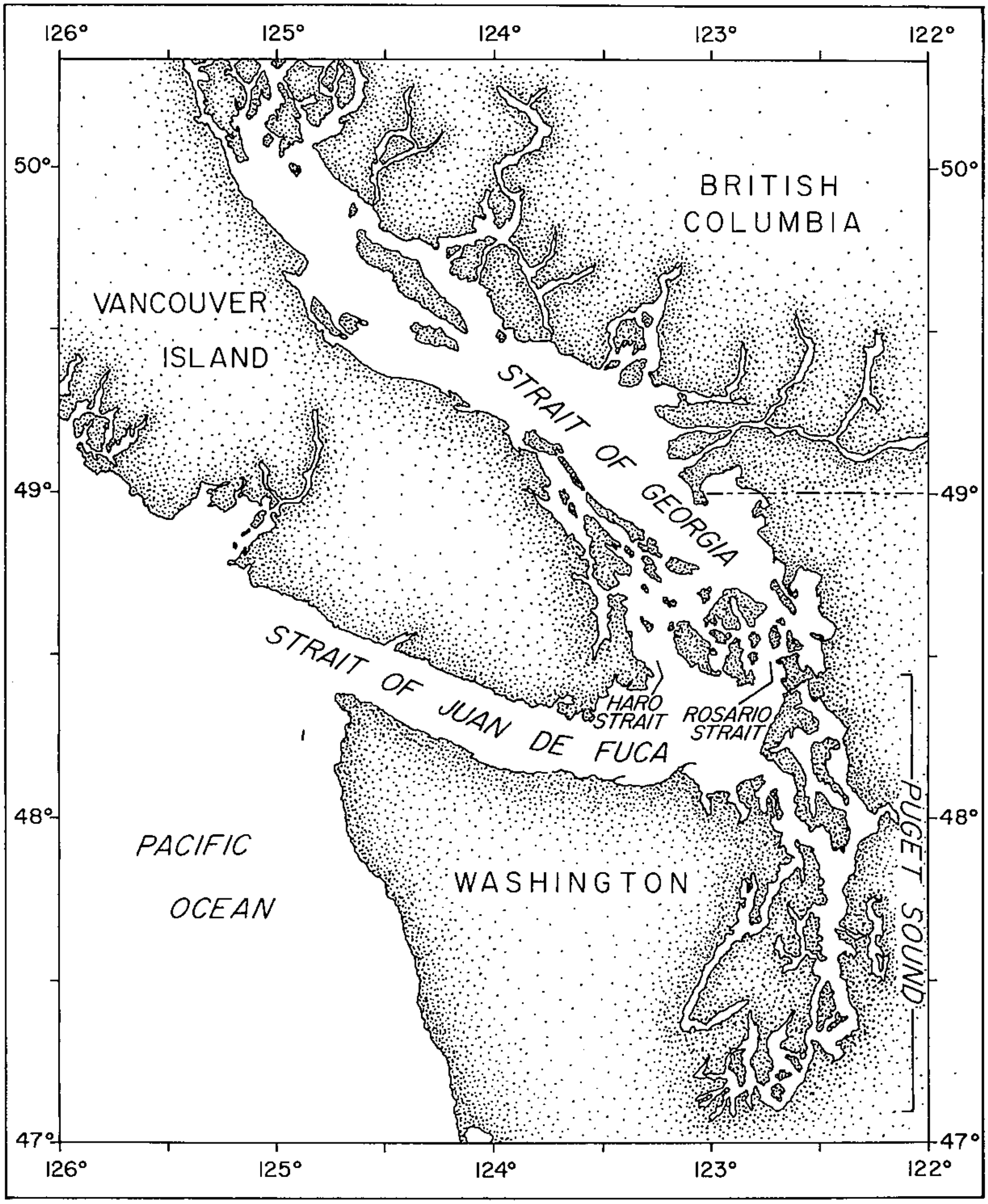

Figure 1.1. Inland marine waters of northwestern Washington and Canada.

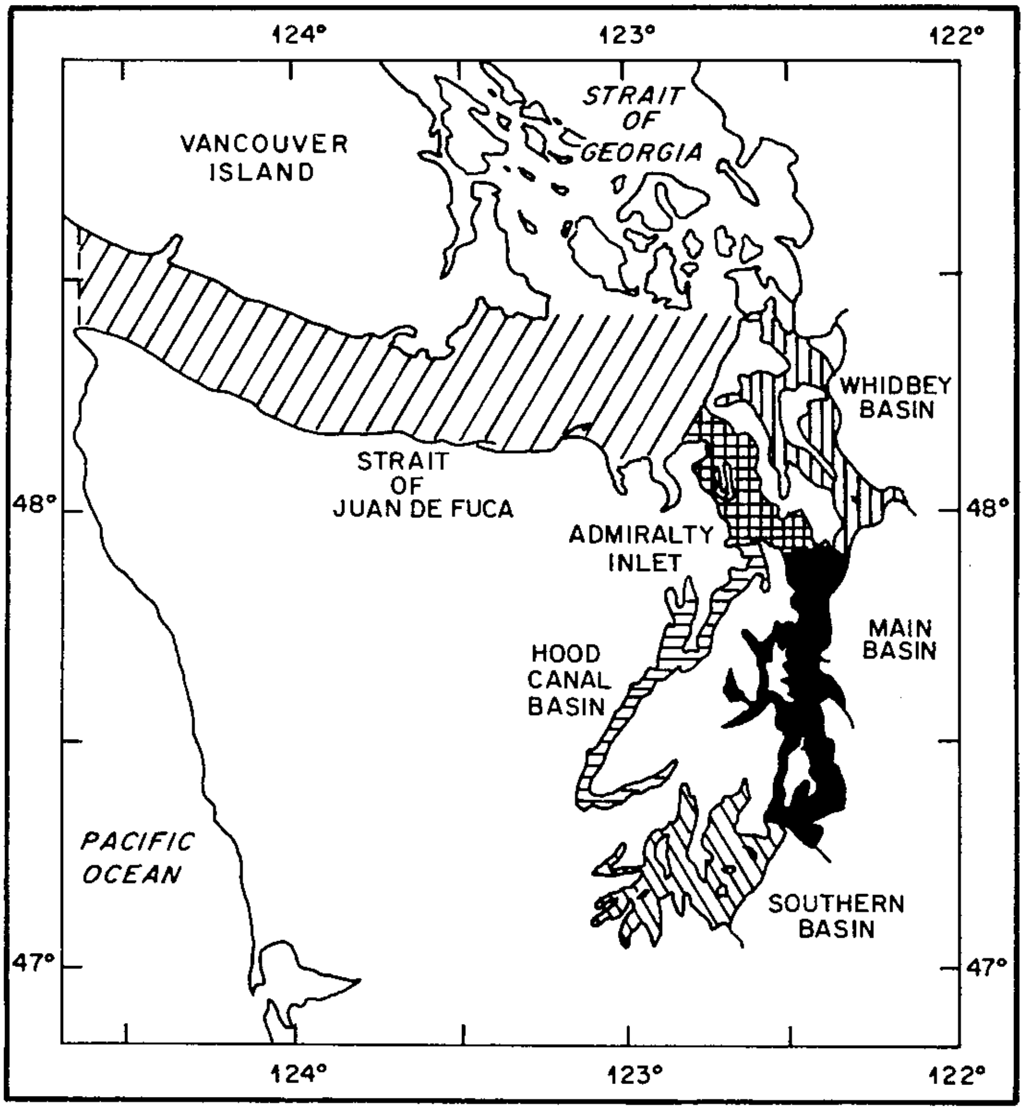

Figure 1.2. Puget Sound and approaches. The Sound consists of the Main Basin (darkened), three secondary basins (Whidbey Basin, Hood Canal Basin, and Southern Basin), and an entrance sill zone (cross-hatched) which are attached to the ocean via the Strait of Juan de Fuca.

background concentration depending upon the rate of their input to the estuary, and the rate of their removal by the combined effects of: escape to the Strait of Juan de Fuca; chemical and biological decomposition; and settling to the bottom.

To predict the background concentration of the wastes for particular rates of discharge, one needs to know the composition of the waste, its settling characteristics, and its biological and chemical removal rates. For some wastes these rates may be small compared to those associated with the physical removal of the waste from the estuary by circulatory features. Hence, an accurate estimate of the amount of surface water (and its waste content) recycled through the estuary is a primary concern.

For the Main Basin, a rough estimate of the recycled fraction is currently available; estimates for the secondary basins remain undetermined. Based upon hydrographic data taken from 1932-1975, Ebbesmeyer and Barnes (1980) estimated that approximately two-thirds of the surface water flowing seaward in Admiralty Inlet was mixed downward and returned landward within the Main Basin's lower layer.

To further describe this circulation, we have undertaken a synthesis of water property, current, and related measurements (runoff, air temperature, wind, and sea level) taken in and around Puget Sound. Observations of the water's physical characteristics (temperature, salinity, and nutrients) have been sampled at many locations and times since the 1930's. These data have been indexed by Collias (1970) and presented in atlas form by Collias, McGary and Barnes (1974). These data have also been combined and interpreted in order to deduce the quantities and patterns of water movement (Friebertshauser and Duxbury, 1972; Barnes and Ebbersmeyer, 1978; and Ebbesmeyer and Barnes, 1980). The full citations are given in the references in Volume 3.

Currents have been measured at various times and locations in Puget Sound since 1908, and although many observations were available, no systematic exploration of the various observations had been undertaken to complement the analysis of water properties. An analysis had not previously been performed because of the formidable amount of data, and because the data had been stored in various forms in scattered locations.

Specific objectives of the present synthesis are: 1) estimate the portion of surface water that is refluxed into Puget Sound; 2) examine the response of currents to inputs of mass and energy; and 3) describe seasonal variations of the circulation.

The data gathered for this project and the results of the synthesis have been organized into three volumes as follows:

Volume 1. Index to current measurements made in Puget Sound from 1908-1980, with daily and record averages computed for selected measurements.

Volume 2. Indices of mass and energy inputs into Puget Sound: runoff, air temperature, wind, and sea level.

Volume 3. Circulation in Puget Sound: an interpretation based on historical records of currents and water properties.

Volume 1 contains an index to current measurements made in Puget Sound from 1908-1980. Daily and record averages and standard deviations of net currents, and water properties where available, are presented for measurements spanning at least one tidal day (approximately 25 hours).

Volume 2 provides daily and monthly averages of runoff, air temperature, wind, and sea level.

Volume 3 describes selected aspects of Puget Sound's general circulation, but also examines the variability within the Main Basin.

This study was initiated by the Marine Ecosystems Analysis (MESA) Puget Sound Project within the Office of Marine Pollution Assessment (OMPA) of the National Oceanic and Atmospheric Administration (NOAA). The MESA Puget Sound Project was established to focus scientific research on environmental problems relating to Puget Sound. The primary objective of the Project is to document the occurrence and fluxes of contaminants of special concern, the dynamic processes influencing their physical and chemical transport and fate, and their biological and ecological effects.

1.2 VOLUME 2 OVERVIEW

To interpret the fluctuations of currents and water properties, we must know the accompanying inputs of mass and energy into the waters of Puget Sound. During much of the time in which currents and water properties have been observed, mass and energy inputs have also been measured.

Inputs of mass into Puget Sound in which we are interested include additions of freshwater and Pacific Ocean water. On the long-term average the overall volume of Puget Sound consists of approximately 10% freshwater and 90% ocean water. The river discharge into the Sound fluctuates, thus varying the amount of freshwater available for dilution with the oceanic salt which in turn primarily controls density in the Sound. The salinity distribution provides estimates of vertical mixing in and between the various segments of the Sound. Freshwater input has been calculated from flow measurements estimated from river gages; there is no satisfactory routine measure of the input of oceanic water.

Measures of factors pertinent to energy inputs include those of air temperature, tides, and wind. Tides affect the entire water column whereas inputs from air temperature and wind act at the water surface.

In the Sound the inputs and measured properties in the water column change continuously in time and space. The transient nature of the variables makes it difficult to relate changes in the water with specific changes in the inputs. However, in certain instances the fluctuations of the inputs are sufficiently abrupt, and the responses in the water so marked, that cause-and-effect can be clearly determined.

It is well known that the inputs exhibit fluctuations on long (order of months to years) and short (order of days) temporal scales. Barnes and Ebbesmeyer (1978), Cannon and Ebbesmeyer (1978), and Ebbesmeyer and Barnes (1980) have shown that on both scales the fluctuations have significant effects upon the circulation. To identify long-term fluctuations we computed anomalies taken of the mean value for a particular month minus the month's long-term average. Anomalies were computed for runoff and air temperature during 1930-1978, and wind speed and its variance during 1948-1978. To identify short-term fluctuations we searched for extremes of daily means of runoff, air temperature, and wind during 1948-1978. Also examined are supporting data of sea level, tide range, transport, and barometric pressure.

The report is arranged as follows. Data sources and computations are described in section 2; average yearly cycles of the inputs are discussed in section 3; long- and short-term fluctuations are described in sections 4 and 5, respectively; and finally, monthly and daily average values are given in the Appendices.

The Appendices are organized to correspond with the body of the report. Appendix A.1 shows monthly means of runoff and air temperature during 1930-1978 and wind parameters during 1948-1978, both periods superimposed on the long-term norms. Appendix A.2 lists the monthly means for data presented in Appendix A.1. Appendix B tabulates daily averages of runoff, air temperature, and wind during 1949-1968. Finally, Appendix C gives daily averages of runoff, air temperature, wind, barometric pressure, sea level, tides, and tidal ranges during 1969-1978. Appendix C is most extensive because the interval of 1969-1978 contains the majority of the current observations.

2. METHODS

Data presented in this report have been collected from various sources. The sources and analytic methods applied to the data are described below.

2.1 RUNOFF

Runoff into the Sound was estimated using a modification of the procedure developed by Lincoln (1977). His method gives freshwater inflow into the Sound's major subregions using discharge data from 22 United States Geological Survey (USGS) gaging stations in operation during 1970-1975. Ungaged freshwater entering the Sound (i.e., drainage areas downstream from gaging stations) is estimated by factoring gaged streams with similar characteristics. As runoff greatly exceeds both direct precipitation to the Sound and evaporation, direct precipitation has been ignored. Lincoln (1977) estimated that the ungaged runoff was about 18% of the Sound's total runoff.

The main body of current and water property observations was made during 1930-1978; however only a few of the 22 gaging stations used by Lincoln (1977) were in operation during this time. Therefore, his procedure has been modified so as to be based on seven gages which were in continuous operation during the entire 48-year period. The locations of the seven gages selected are shown in Figure 2.1.

The modified procedure was determined by comparing the discharge from the seven river gages with total runoff from the larger set of 22 gages (i.e., Lincoln's technique). To derive a relationship the total river runoff was expressed as a linear equation consisting of a constant plus coefficients modifying the discharge at the seven gages. An equation was written for each of 60 months between 1970-1975, and the coefficients were found using standard linear regression techniques. The set of equations is expressed as follows.

$$R_T(t_j) = a_o + a_1 R_1(t_j) + a_2 R_2(t_j) + a_3 R_3(t_j) + a_4 R_4(t_j) + a_5 R_5(t_j) + a_6 R_6(t_j) + a_7 R_7(t_j) + \Sigma(t_j) \quad (1)$$

where R_T is the total runoff from Lincoln's technique; R_{1-7} represents the runoff at the seven gages during month j; a_{1-7} are the constant coefficients to be determined; and $\Sigma(t_j)$ is the rms noise. In computing this equation 60%

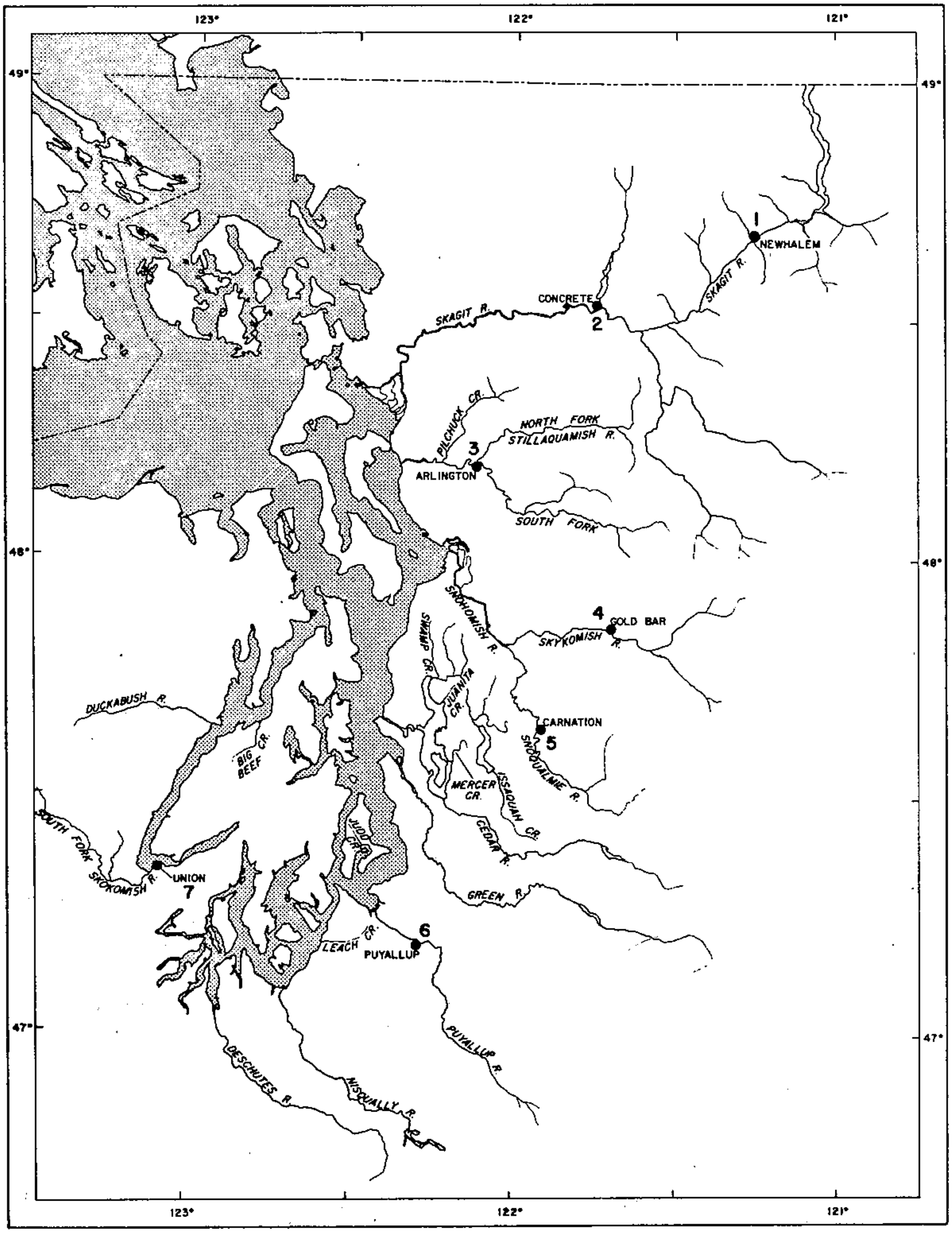

Figure 2.1. Locations (•) of the seven river gages (see Table 2.1) used to compute the total runoff. Additional rivers shown are all those used by Lincoln (1977).

of the Skagit River discharge was assumed to exit through Deception Pass and has therefore been excluded from R_T (see Collias et al., 1973). The resulting coefficients are given in Table 2.1 for the seven gaging stations.

Figure 2.2 shows R_T computed using Lincoln's (1977) technique compared with that computed from the reduced set of seven river gages. The rms difference between the two methods was 3.3% with a maximum difference of 10% in one month. It was concluded that the modified procedure provides a reasonably accurate estimate of total Sound runoff. Runoff into the Sound's subbasins has been computed only for 1971-1975 because rivers representative of all basins were not gaged in the early portions of 1930-1978.

Equation (1) was used to calculate daily and monthly average river runoff. The data were obtained from USGS Water Supply papers (for years 1930-1967) and USGS Water Resources Data for Washington (1968-1978).

2.2 AIR TEMPERATURE

Air temperatures were obtained at two locations. Monthly mean air temperatures at the Seattle Weather Bureau (Fig. 2.3) were obtained from publications of the U.S. Environmental Data Service (1930-1978). Hourly observations at the Seattle-Tacoma International Airport (Sea-Tac; Fig. 2.3) for 1949-1978 were obtained from the National Climatic Data Center.

2.3 WIND

Hourly wind speed and direction at West Point were obtained during 1968-1973 from the Washington State Air Pollution Control Agency, and during 1973-1978 at the U.S. Coast Guard station at West Point from the National Climatic Data Center. From 1948-1978 hourly wind speed and direction were also obtained at Sea-Tac from the National Climatic Data Center.

The equipment used at Sea-Tac was changed in November 1959. A comparison was made of data taken for 10 years prior to November 20, 1959 with data taken for the following 20 years. The result was that the wind speeds were smaller by a factor of 0.778 following the equipment change. Therefore, all wind speeds subsequent to November 20, 1959 were multiplied by 1.286.

The wind measurements were analyzed in two ways. First, daily and monthly net speed and direction were computed. However, since the water responds to wind stress which is proportional to the square of the wind speed, we also computed the daily total variance of the wind. The variance was computed as

$$\sigma_w^2 = \frac{1}{n} \sum_{i=1}^{24} (u_{wi}^2 + v_{wi}^2) \qquad (2)$$

TABLE 2.1. RIVER GAGES AND FACTORS USED IN EQUATION (1) TO COMPUTE TOTAL RUNOFF.

River	U.S. Geological Survey Gage No.	Factor a_i
Skagit at Newhalem	12178000	0.153
Skagit at Concrete	12194000	0.472
North Fork Stillaguamish	12167000	3.967
Skykomish	12134500	-1.812
Snoqualmie	12149000	3.969
Puyallup	12101500	3.481
South Fork Skokomish	12060500	11.233

$a^o = -63.4$ m/s.

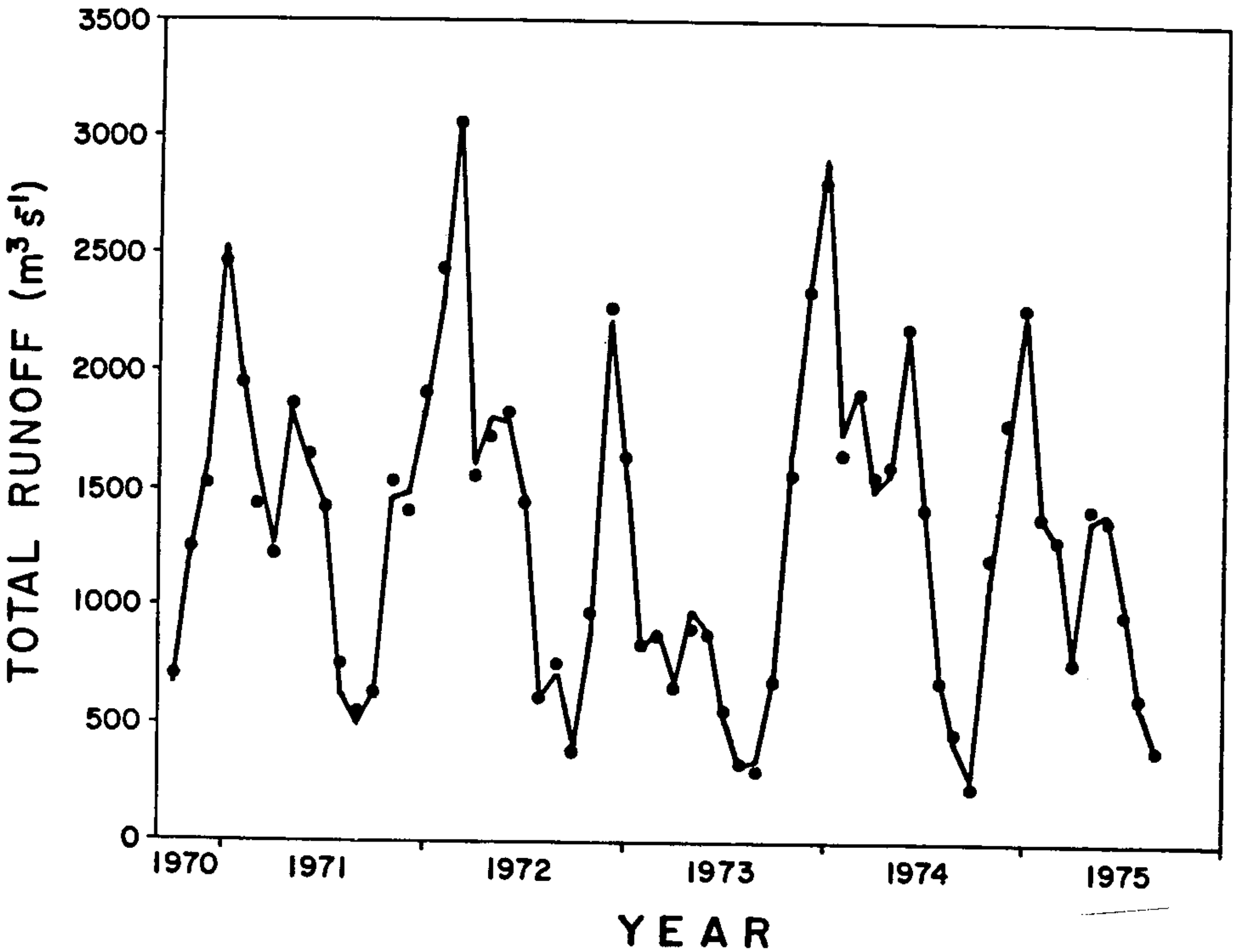

Figure 2.2. Total runoff for October 1970 through September 1975 using Lincoln's (1977) technique (solid line) and the present technique (dots).

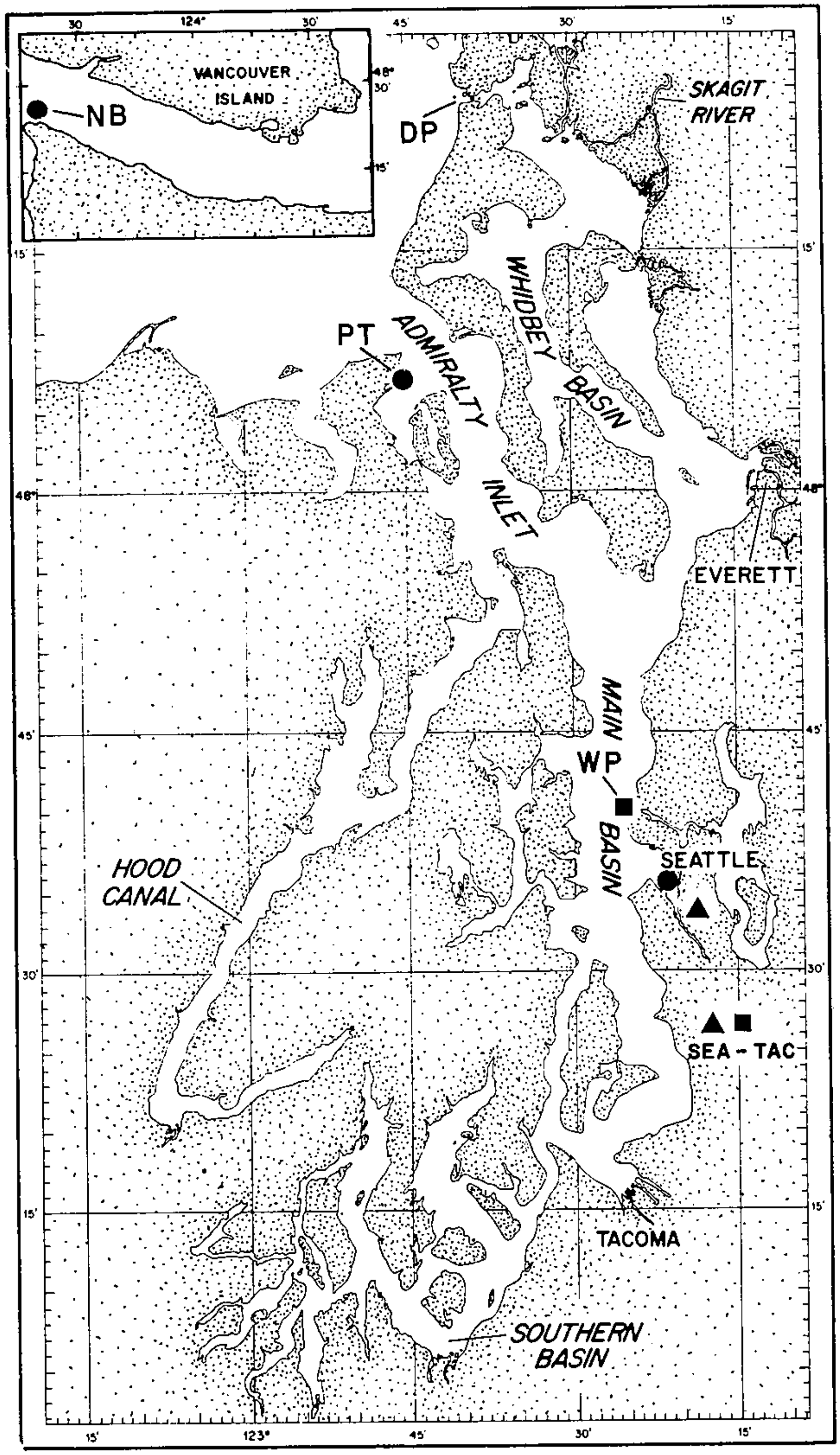

Figure 2.3. Locations of air temperature (▲), wind (■), and sea level (●) measurements. Notation: NB, Neah Bay; DP, Deception Pass; PT, Port Townsend; WP, West Point.

where u_w and v_w are the zonal and meridional components determined during the i-th hour.

2.4 SEA LEVEL

Hourly sea levels at three stations (Neah Bay, Port Townsend, and Seattle; Fig. 2.3) during 1968-1979, and monthly average sea levels at Seattle during 1930-1967, were obtained from the National Ocean Survey (NOS).

The increase of tidal range and phase lag going landward through the Sound has previously been described (University of Washington, 1953, Volume III). For purposes of interpretation we selected Seattle as the primary reference station in order to be consistent with previous syntheses by Barnes and Ebbesmeyer (1978) and Ebbesmeyer and Barnes (1980). The high and low sea levels were determined from the hourly sea levels at Seattle.

An estimate of the daily average transport of water into and out of the Sound (over the entire water column primarily via Admiralty Inlet) was calculated from the difference in daily average sea levels at Seattle. Transport was computed as $T = \frac{\delta h}{1 \text{ day}} \times \frac{\delta V}{\delta H}$, where δh is the change in daily average sea level between two consecutive days; $\delta V = 8.07\ km^3$ (from McLellan, 1954) is the volume between mean high and mean-lower-low water; and $\delta H = 3.22$ m (from McLellan, 1954) is the range between mean high and mean-lower-low water. This calculation assumes the sea level within Puget Sound (defined as inland from Admiralty Inlet and Deception Pass) changes uniformly.

2.5 BAROMETRIC PRESSURE

Hourly observations of barometric pressure at Sea-Tac during 1969-1978 were obtained from the National Climatic Data Center. These were measured simultaneously with air temperature and wind.

3. SEASONAL PROGRESSION OF LONG-TERM NORMS

In this section we describe the seasonal progression of the long-term norms of runoff, air temperature, and wind. Later we will subtract the long-term norms from the time series of monthly and daily averages in order to identify extreme deviations. The norms for runoff, air temperature, and wind are shown in Figure 3.1 and are listed in Table 3.1.

3.1 RUNOFF

The seasonal progression of the total runoff norm (1930-1978; Fig. 3.1.a) shows two periods of high runoff (May-June and November-February). The standard deviation of the monthly mean runoff follows for the most part the long-term norm.

Figure 3.2 shows the seasonal cycle of runoff into the Sound's major basins: Whidbey Basin, Main Basin, Southern Basin, and Hood Canal (Fig. 2.3). These cycles were computed for 1971-1975 using Lincoln's technique (i.e., when 22 river gages were in operation). Three of the basins (Whidbey Basin, Main Basin, and Hood Canal) have seasonal progressions similar to that for the Sound's total runoff. In contrast, the Southern Basin is similar with the exception it lacks the peak in early summer.

The percentages of total Sound runoff received monthly for each basin during 1971-1975 are shown in Figure 3.3. For the entire five-year period Whidbey Basin received an average of about 55%; Main Basin, 19%; Hood Canal, 14%; and Southern Basin, 12% of the total annual runoff (total for Sound). These amounts fluctuate throughout the year, Whidbey Basin receiving as much as 65% of the total runoff during July but as little as 48% during January.

The seasonal cycles for each basin differ according to the type of rivers discharging into them (Fig. 3.4). For our purposes we will distinguish between two types of rivers: those at high and low elevation. High elevation rivers (e.g., Skagit and Puyallup rivers) are fed both by rain and snowmelt and produce two periods of high runoff. The fall-winter period from about October through March is associated with heavier precipitation at lower elevations and an accumulation of snow at higher altitudes. Occasional snowmelt at lower mountain elevations aids runoff during this time. The spring period, April through June, is associated with melting snow at higher elevations. The second type of river, those of low elevation (e.g., Skokomish and Deschutes rivers), are primarily rain-fed and show a single high runoff period during October through March.

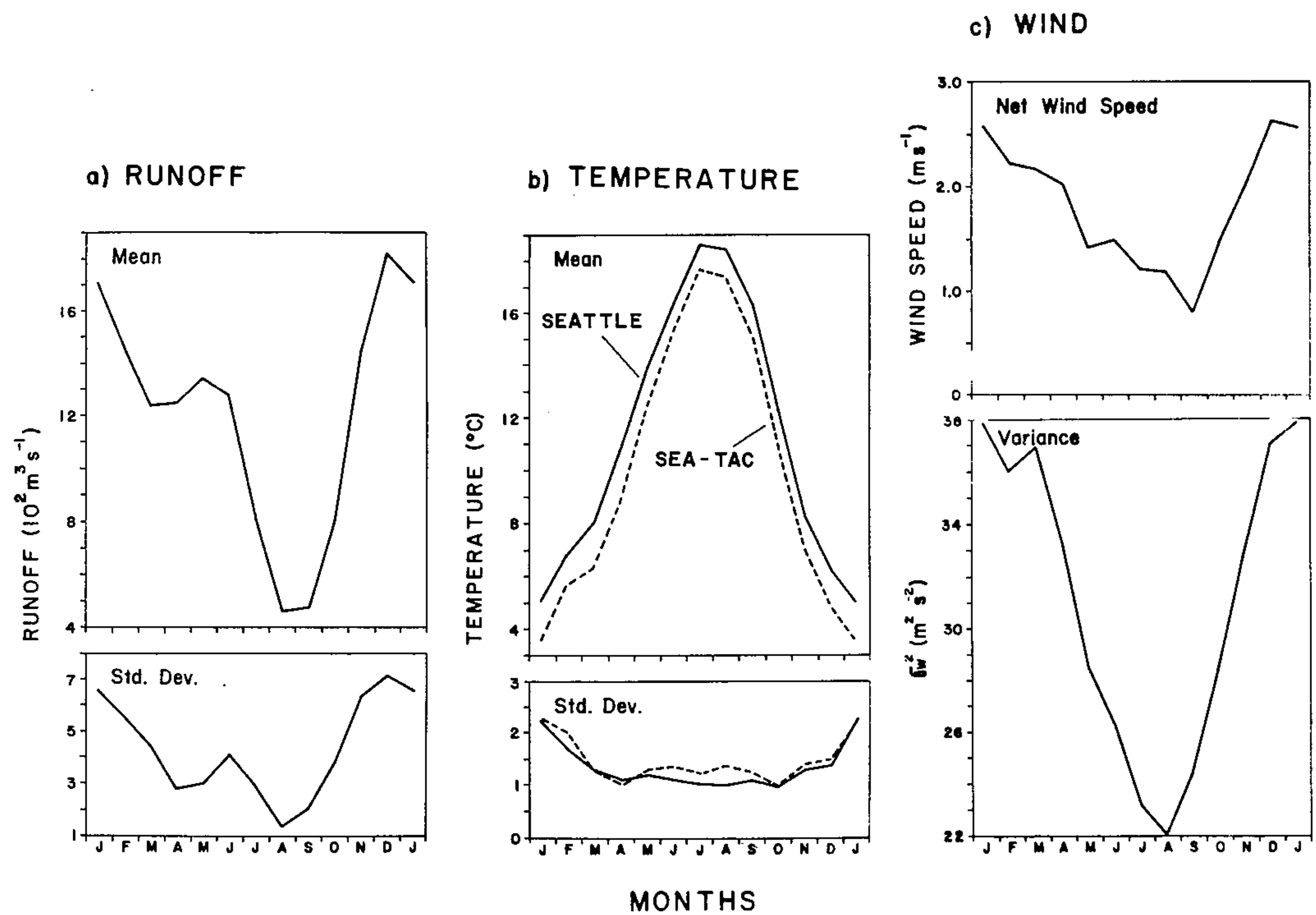

Figure 3.1. Long-term norms of runoff (a), air temperature (b), and wind (c). In (a) the mean (top) and standard deviation (bottom) of the monthl' averages are shown for the entire Puget Sound, 1930-1978. In (b) the means (top) and standard deviations (bottom) are shown for the monthly averages at Seattle (solid line) for 1930-1978 and at Sea-Tac (dashed line) for 1949-1978. In (c) the net wind speed (top) and mean variance (bottom) are shown of the monthly averages at Sea-Tac for 1949-1978.

TABLE 3.1. MONTHLY MEANS AND STANDARD DEVIATIONS FOR RUNOFF, AIR TEMPERATURE, AND WIND.

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
Runoff ($m^3 s^{-1}$) 1930-1978												
Mean	1710.69	1453.45	1237.68	1244.95	1339.87	1279.82	809.45	463.93	477.97	805.19	1445.10	1818.47
Std. dev.	659.46	559.29	445.71	280.34	300.22	412.83	293.13	134.58	203.32	379.23	635.15	714.43
Air Temperature (°C) at Sea-Tac 1949-1978												
Mean	3.58	5.64	6.36	8.83	12.40	15.29	17.68	17.39	15.03	10.88	7.03	4.83
Std. dev.	2.28	1.98	1.28	1.03	1.30	1.38	1.23	1.37	1.26	0.98	1.40	1.51
Air Temperature (°C) at Seattle 1930-1978												
Mean	5.11	6.81	8.07	10.75	13.88	16.34	18.64	18.47	16.25	12.27	8.23	6.25
Std. dev.	2.25	1.68	1.29	1.12	1.19	1.09	1.03	1.00	1.09	0.94	1.30	1.38
Wind at Sea-Tac 1949-1978												
Net speed ($m s^{-1}$)	2.57	2.22	2.18	2.04	1.43	1.49	1.23	1.20	0.81	1.48	2.03	2.63
Variance ($m^2 s^{-2}$)	37.87	35.99	36.88	33.32	28.52	26.24	23.18	22.03	24.36	28.40	32.90	37.06

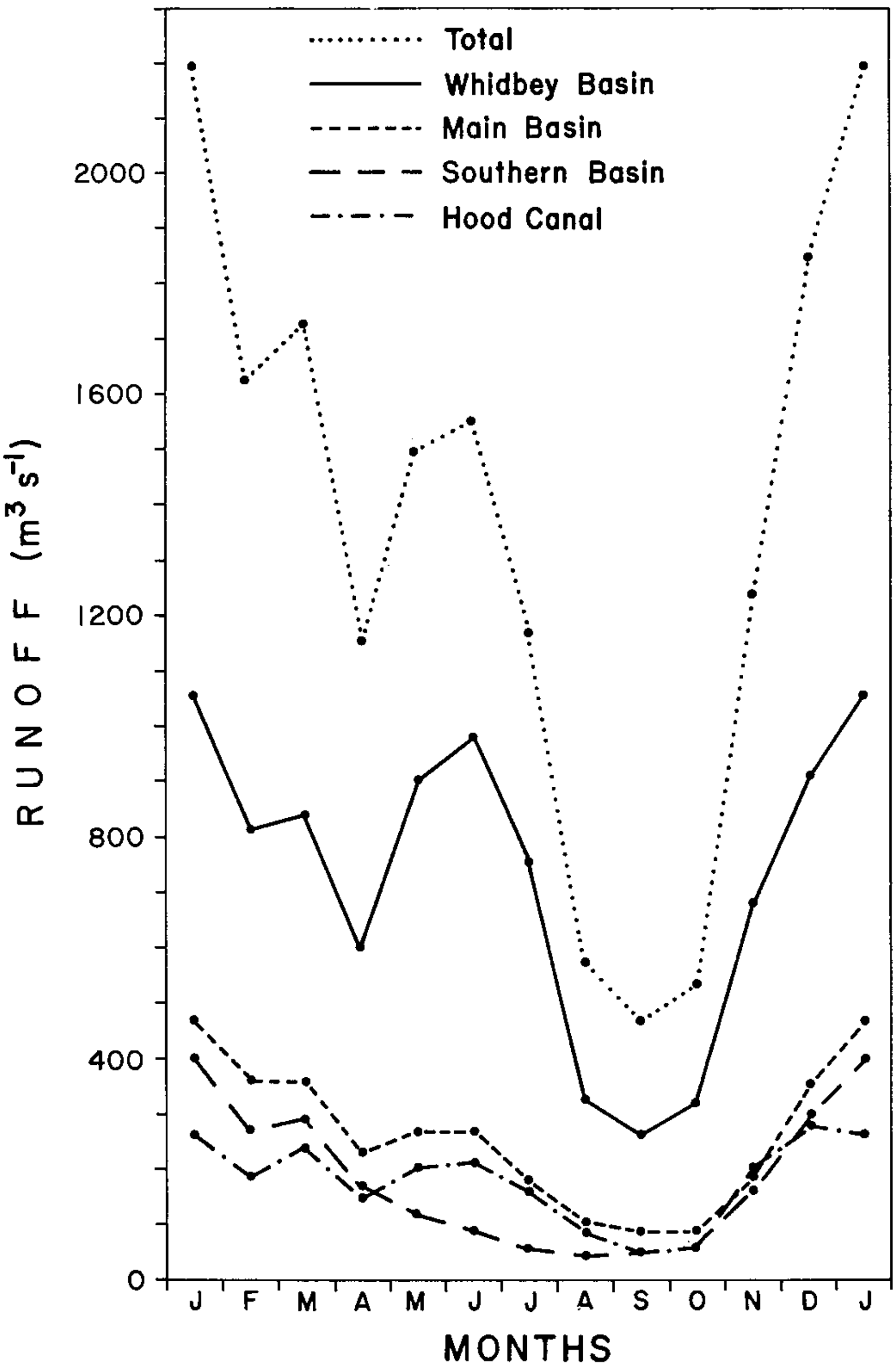

Figure 3.2. Seasonal cycles of runoff by basin compared to the total runoff entering Puget Sound for years 1971-1975 using Lincoln's (1977) technique.

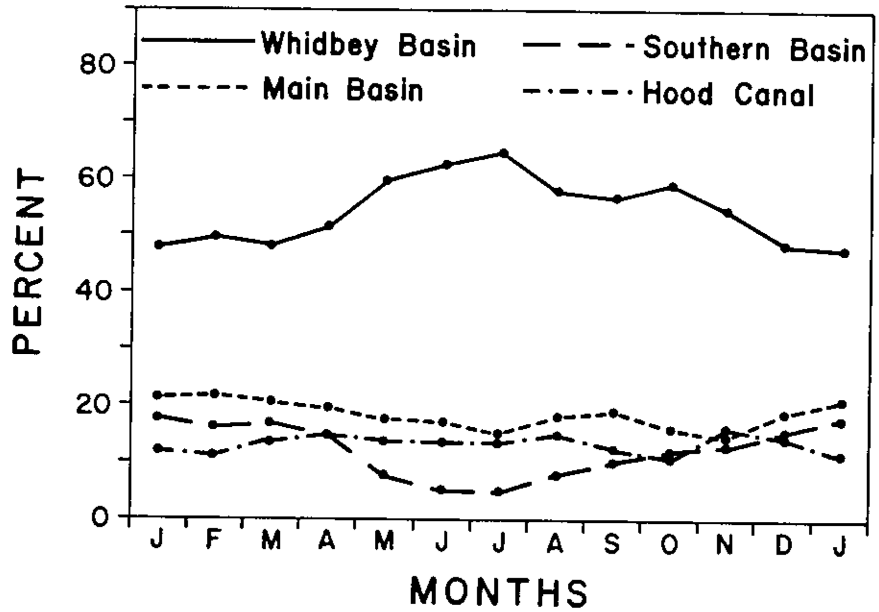

Figure 3.3. The percentage of total Puget Sound runoff received monthly for each basin for years 1971-1975.

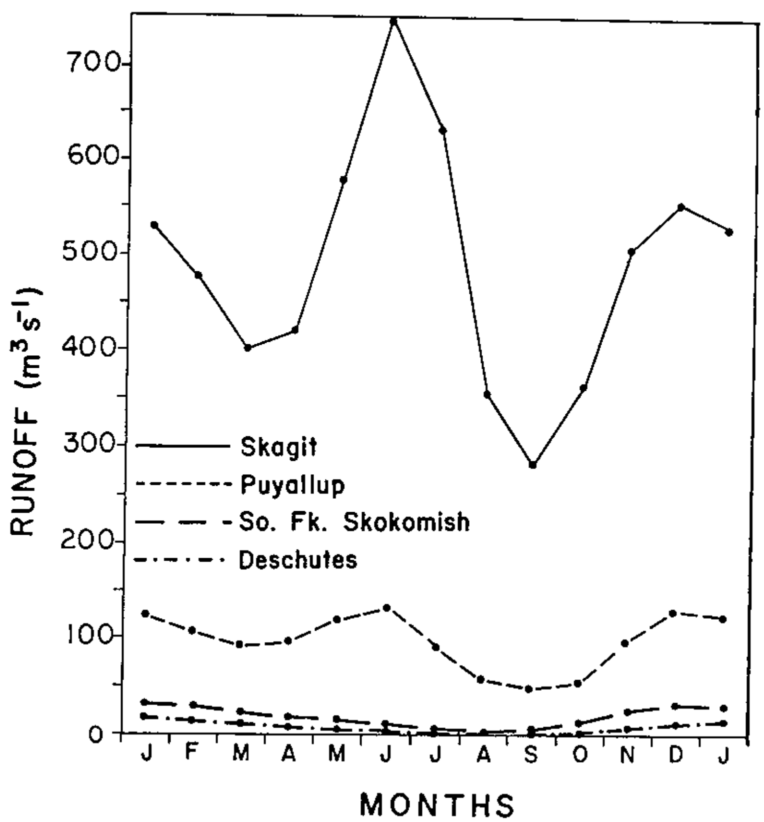

Figure 3.4. Seasonal cycles of runoff for four rivers (see Fig. 2.1) flowing into Puget Sound: the Skagit River (for years 1949-1978, including the 60% which exits through Deception Pass) entering Whidbey Basin; Puyallup River (1931-1978) entering the Main Basin; South Fork of the Skokomish (1931-1978) entering Hood Canal; and Deschutes River (1949-1975) entering the Southern Basin.

The majority of runoff into the Sound is derived from high-elevation rivers which accounts for the two distinct peaks seen in the seasonal cycle of total runoff (Fig. 3.2). It is striking that two high-elevation rivers (Skagit and Snohomish rivers), both discharging into Whidbey Basin, account for over half (51%) of the Sound's total runoff. The Main Basin, Southern Basin, and Hood Canal are primarily fed by low-elevation streams which peak when precipitation is highest (November-January). The moderate increase in runoff that occurs in the Main Basin and Hood Canal during the spring and early summer months is due to a few high-elevation streams that carry small quantities of snowmelt.

3.2 AIR TEMPERATURE

Air temperature for the area surrounding the Sound varies seasonally but remains a relatively moderate climate. The mean annual temperature for the region is approximately 10°C (National Oceanic and Atmospheric Administration, 1978). The reason is due in part to the topography surrounding Puget Sound and its proximity to the Pacific Ocean. The Cascade Mountains which parallel the Sound to the east effectively prevent warm summer and cold winter continental air from penetrating westward to the Sound.

Figure 3.1.b shows the mean and standard deviation of monthly mean temperatures for Seattle (1930-1978) and Sea-Tac (1949-1978). Monthly mean temperatures range from lows of 5.1°C and 3.6°C in January to highs of 18.6°C and 17.7°C in July at Seattle and Sea-Tac, respectively. The difference in mean temperatures is probably mostly due to the difference in elevation between the two stations. The Sea-Tac station is 113 m higher than the Seattle weather bureau station and mean temperatures at Sea-Tac are approximately 1.4°C cooler on the annual average than at Seattle. The standard deviation of the monthly mean temperature range from a low of 0.94°C in October to a high of 2.25°C in January at Seattle and 0.98°C in October to 2.28°C in January at Sea-Tac.

3.3 WIND

The winds prevailing over the Sound have been previously presented by season (Harris and Rattray, 1954; Fig. 3.5). An independent synopsis of the local climatology has been prepared by Overland and Walter (1980). The topography adjacent to the Sound constrains the wind within channels which are oriented primarily in the meridional direction. From October through March the flow is predominantly from the south-southwest. Through the spring this flow gradually reverses direction from predominantly northerly to southerly.

Winds measured at West Point clearly illustrate the channel flow in which the wind direction is either northerly or southerly (Fig. 3.6.a). At Sea-Tac (Fig. 3.6.b), also located near the Main Basin, the winds also show this pattern although it is not as marked. Highest monthly net wind speeds are in the range of 6-9 m s^{-1} and are from the south between September and May (Fig. 3.6.c-d). Highest net wind speeds from the north are lower

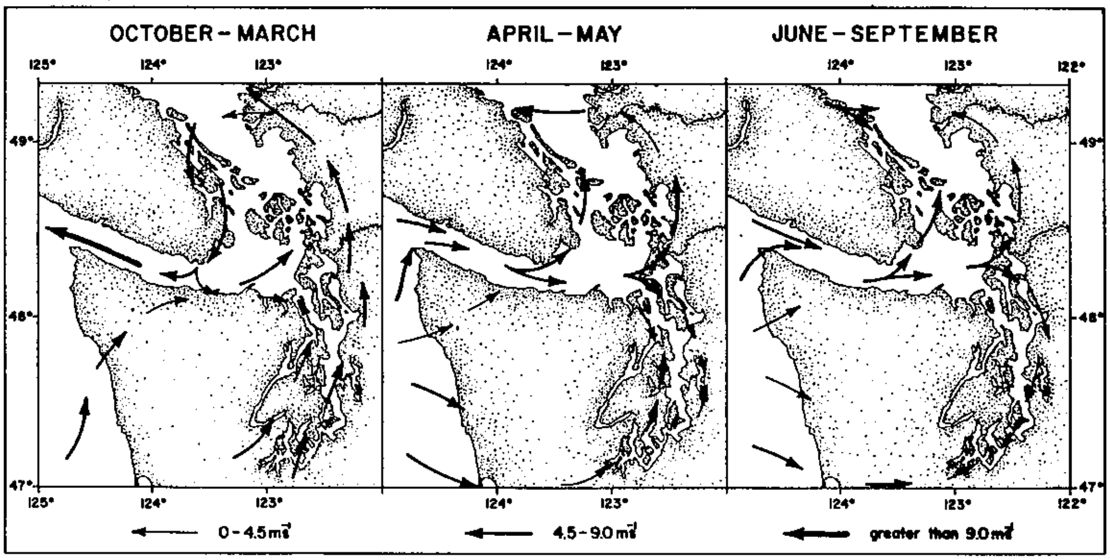

Figure 3.5. Seasonal progression of prevailing winds (adapted from Harris and Rattray, 1954).

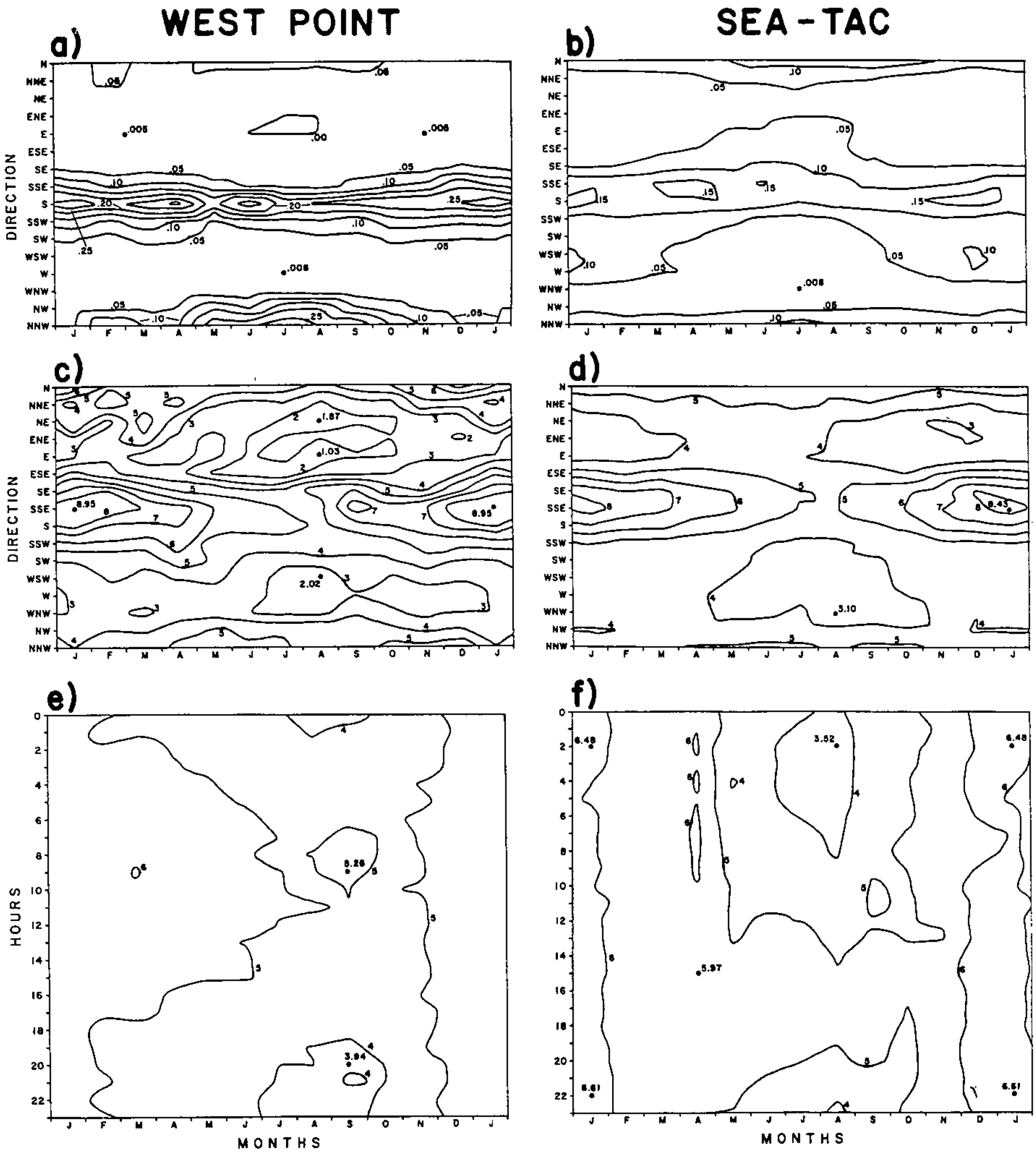

Figure 3.6. Seasonal cycles of winds measured at West Point (a,c,e) for years 1969-1978 and at Sea-Tac (b,d,f) for years 1948-1978 (a-b). Fraction of the time the wind blows from individual directions (16 directions total); (c-d) average wind speed (m s^{-1}) by direction; and (e-f) average wind speed (m s^{-1}) by hour of the day.

than those from the south and are in the range of 5-7 m s^{-1}. Hourly mean wind speeds (Fig. 3.6.e-f) do not show a significant sea breeze as is evident in the Strait of Juan de Fuca.

In order to detect extreme fluctuations the norms of net wind speed and variance will later be subtracted from the time series of their monthly values. Figure 3.1.c shows the norms. The seasonal progressions of both norms are similar. The net wind speeds and variance are lowest during August-September and highest during December-January.

4. FLUCTUATIONS OF MONTHLY MEANS

Now that the norms of the various inputs have been determined, we wish to identify pronounced fluctuations about the norms. To do this, monthly mean data from 1930-1978 for runoff and air temperature, and from 1948-1978 for net wind speed and variance, have been superimposed on the seasonal norms (Fig. 4.1). Fluctuations of the inputs can be either above or below the norm. The fluctuations have been partitioned according to their magnitude and duration.

4.1 GROSS VARIABILITY

To characterize the relative magnitude of the fluctuations a ratio (g) was computed for each input equal to the standard deviation of all the monthly means divided by the range of the norm. The results are as follows: runoff, g = 0.30; air temperature, g = 0.095; net wind speed, g = 0.42; and wind variance, g = 0.51. These results show that air temperature has little variability compared to the range of its norm, whereas the relative variability of runoff, net wind speed, and wind variance are three to fivefold higher. Of the two wind parameters variance is more sensitive in identifying fluctuations; therefore, henceforth we will use the variance to identify extreme fluctuations.

To examine the durations we found the intervals between points where the time series crossed their norms. Figure 4.1 shows these intervals coded according to whether the anomaly was greater than or less than the norm. These intervals were then grouped in a histogram of anomaly duration where the ordinate has been expressed in two ways (Fig. 4.2): as a fraction of the total record length rather than frequency, and as a fraction of the total number of anomalies.

Anomalies of two months or shorter account for the following fractions of the total record length: runoff, 0.15; air temperature, 0.20; and wind variance, 0.18. Durations of five months or longer are: runoff, 0.53; air temperature, 0.26; and wind variance, 0.59. The large increase in wind variance anomalies 17 months or longer is due to three anomalies of 23 and 24 months long (see Fig. 4.1).

The striking aspect of Figure 4.2.b. is that runoff, air temperature, and wind variance all show a similar gradation from short to extended duration. Anomalies of two months or shorter account for the following fractions of total number of anomalies: runoff, 0.49; air temperature, 0.67; and wind variance, 0.58. Similarly durations of five months or longer are: runoff, 0.29; air temperature, 0.16; and wind variance, 0.27.

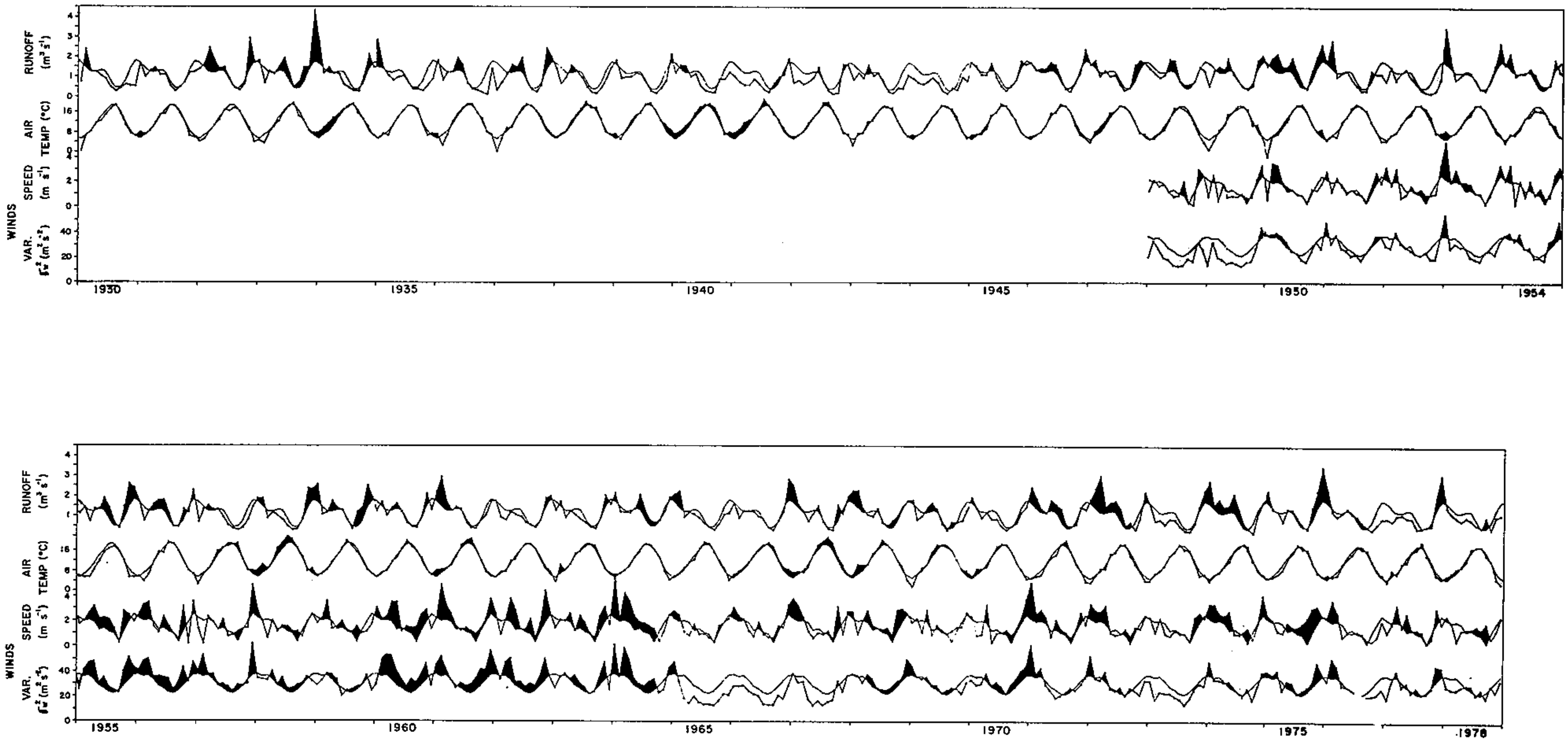

Figure 4.1. Time series of monthly means of runoff and air temperature during 1930-1978 and net wind speed and variance during 1948-1978 superimposed on the long term norms. Anomalies above the norm are shaded dark; anomalies below the norm are light. Note: expanded version in Appendix A.1.

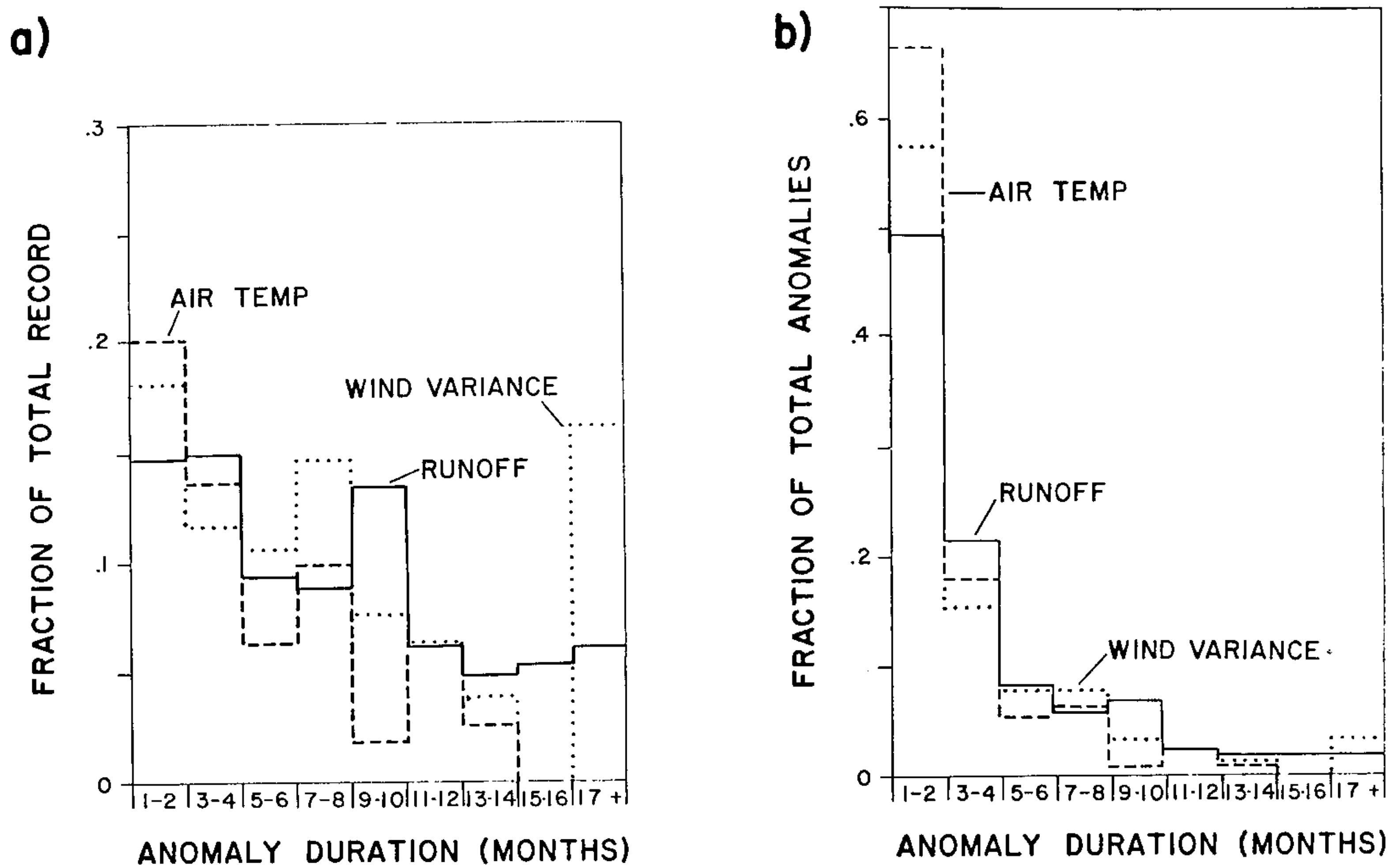

Figure 4.2. Fractions of the total record length (a) and total number of anomalies (b) constituted by runoff, air temperature, and wind variance anomalies of various durations.

4.2 EXTREME FLUCTUATIONS

Figure 4.1 shows a diversity of pronounced anomalies from the norm. The ones to be studied in detail from an oceanographic standpoint depend on the times when oceanographic data are available. However, it is worth pointing out two types of extreme anomalies which are readily apparent. Inspection of Figure 4.1 shows spikes for runoff, wind, but not air temperature and protracted anomalies for runoff, wind, and air temperature.

4.2.1 Extended Anomalies

It is well known that certain years are wetter or dryer, colder or warmer, and windier or calmer than normal. Nevertheless, it is worth pointing out in Figure 4.1 several of the more extreme departures.

The runoff record (Fig. 4.1) shows three particularly wet and dry years. The wet years (1949-1950; 1972; 1973-1974) have occurred since 1948. Two of the dry years (1940-1941; 1943-1944) occurred during a decade in which runoff was predominantly below normal (i.e., a dry decade, 1935-1944). The third dry year (1976-1977) occurred between two years in which there were pronounced runoff spikes. Although not an extended anomaly, the period of September-December 1951 is worth noting. This period of subnominal runoff precedes a major spike and has been described previously by Ebbesmeyer and Barnes (1980).

As was mentioned earlier, the variability for air temperature is less marked than for runoff and wind, therefore, air temperature anomalies are less apparent, but a few are noteworthy. Warm intervals include 1930-1931, 1957-1958, and 1966-1968; a cold interval occurred during 1955-1956.

The wind variance exhibits an overall variability similar to that for runoff. The years which are windier than normal include 1955-1957, 1960-1962, and 1963-1964. These three anomalies comprise a windier than normal decade (1955-1964). The calmer years include 1948-1949 and 1965-1967.

4.2.2 Runoff and Wind Spikes

Figure 4.1 shows that spikes for both runoff and wind are common. A closer inspection of Figure 4.1 shows that the larger spikes occur between November and March. For example, Figure 4.1 shows six runoff spikes which had peak values exceeding 3000 $m^3\ s^{-1}$ (November 1932; January 1934; January 1953; March 1972; December 1975; and December 1977). This threshold corresponds to the maximum value of the runoff norm plus two standard deviations.

Figure 4.1 shows five wind peaks which had values exceeding 56 $m^2\ s^{-2}$ (December 1957; December 1961; January 1964; March 1964; and January 1971). The wind variance threshold corresponds to the maximum value of the wind norm plus 1.52 standard deviations.

5. FLUCTUATIONS OF DAILY MEANS

In section 4 we noted the variability of monthly mean fluctuations about the long-term norms. To gain further insight as to the structure of these extended fluctuations we examined the daily variability from November to February of selected anomalies. For example, Figure 5.1 shows histograms and time series of daily runoff during a wet (1975-1976) and a dry (1976-1977) period. Similarly for air temperature, Figure 5.2 shows the effects of strong depressions of temperature on deviations from the long-term norm during 1949-1950. Finally, Figure 5.3 illustrates for wind, the variability of daily wind associated with spikes.

It is obvious that the presence or absence of these spikes, lasting on the order of days, greatly influences the variability during the extended anomalies. As a result, an objective of our project is to determine if similar fluctuations are evident in the current meter records which were primarily obtained during 1969-1978. Specifically, we wish to isolate floods, cold snaps, and storms. To determine if the sample from 1969-1978 is representative of the longer term, we will first consider these events isolated for the 30-year period 1949-1978.

5.1 PERSPECTIVE: 1949-1978

5.1.1 Floods

Figure 5.4 shows time series of daily average runoff between January 1949-December 1978 superimposed on the long-term norm mentioned earlier. The record contains numerous spikes, the largest of which occur from November through February.

To examine the occurrence of spikes we counted the number for which the peak value exceeded 6000 $m^3 s^{-1}$ as listed in Table 5.1. Henceforth we will refer to values which exceed this threshold as floods. Floods follow periods of heavier precipitation or a warming trend after a cold snap, producing snowmelt. These floods constitute general area floods and not those resulting from snowmelt in May-June which may influence individual high altitude river systems (e.g., the Skagit River).

The tally was as follows for the three decades: 1949-1958, 12 floods; 1959-1968, 12 floods; 1969-1978, 13 floods. Thus the number of floods occurring during the decade of extensive current observations (1969-1978) appears representative of the longer term record. On the average there are approximately 1.2 floods per winter; however, not every winter has floods, as during the winters of 1951-1952, 1957-1958, 1965-1966, 1969-1970, and 1976-1977. These intervals are about evenly distributed during 1949-1978.

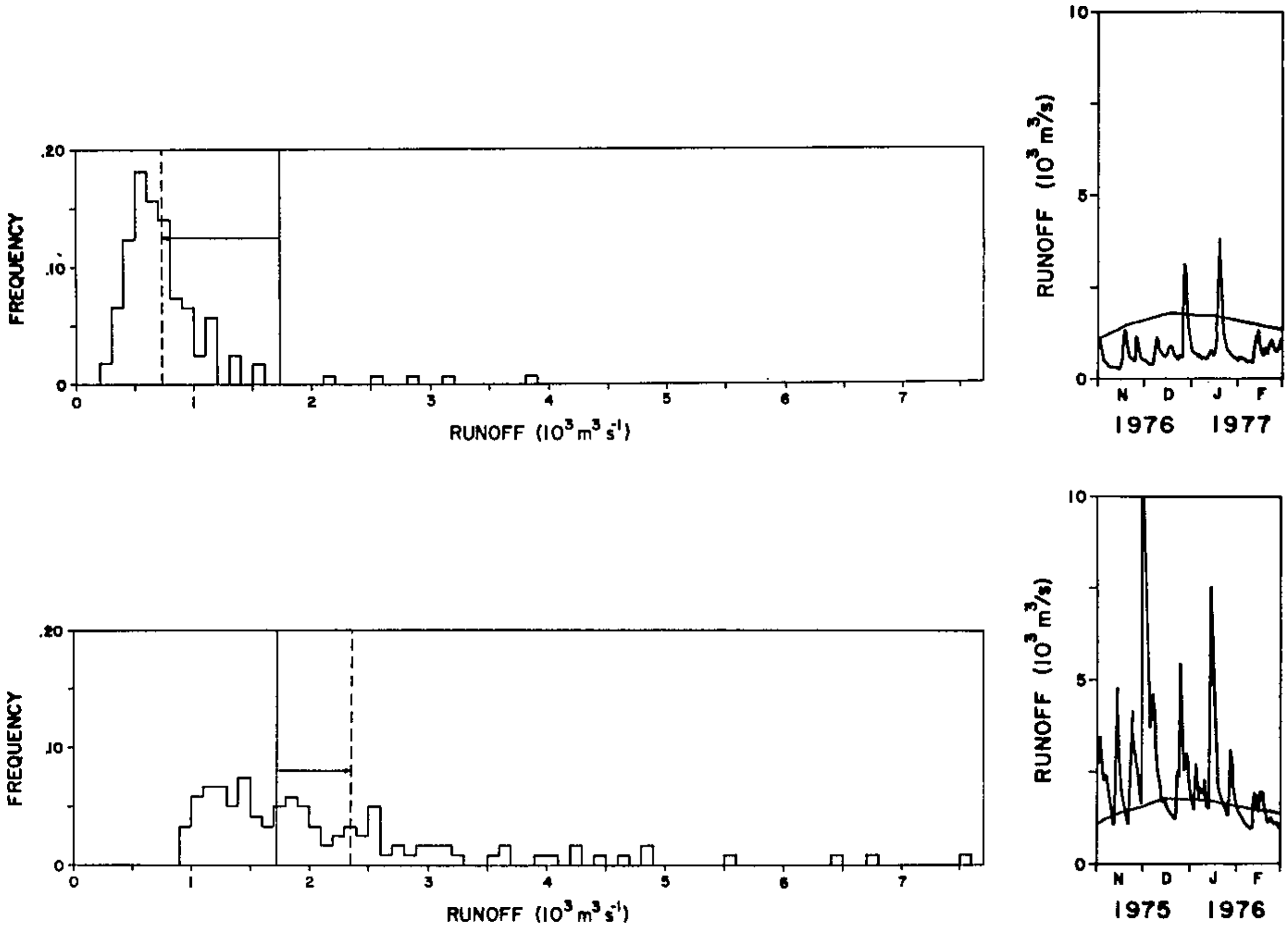

Figure 5.1. Histograms (at left) and time series (at right) of mean daily runoff during an abnormally low runoff winter (top; Nov. 1976-Feb. 1977), and an abnormally high runoff winter (bottom; Nov. 1975-Feb. 1976). Notation: solid lines, long term winter norms; dashed lines, winter means; lines with arrows, deviation of the winter mean from the norm.

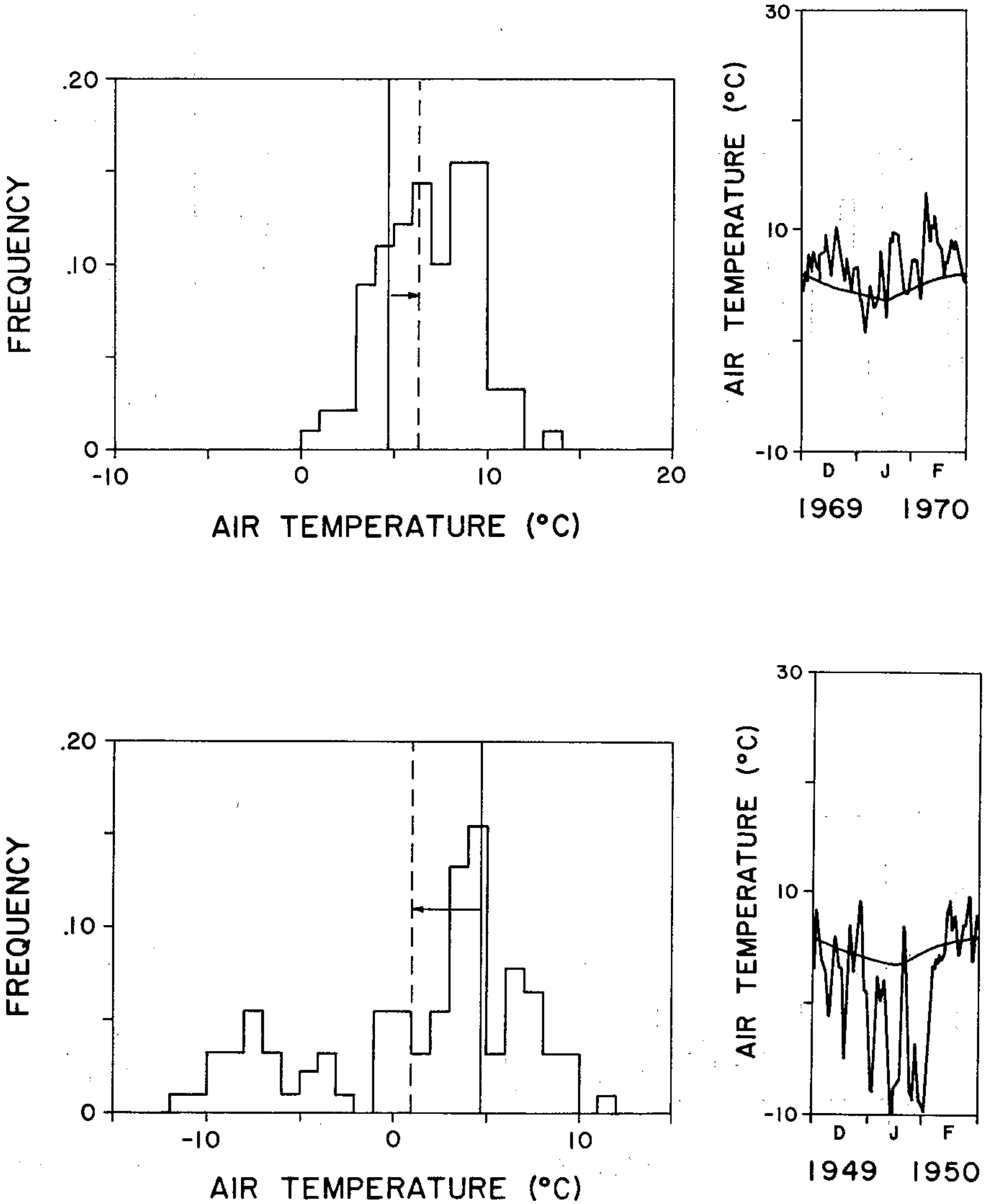

Figure 5.2. Histograms (at left) and time series (at right) of mean daily air temperature at Sea-Tac during a warm winter (top; Dec. 1969-Feb. 1970), and a cold winter (bottom; Dec. 1949-Feb. 1950). Notation: solid lines, long term winter norms; dashed lines, winter means; lines with arrows, deviation of the winter means from the norm.

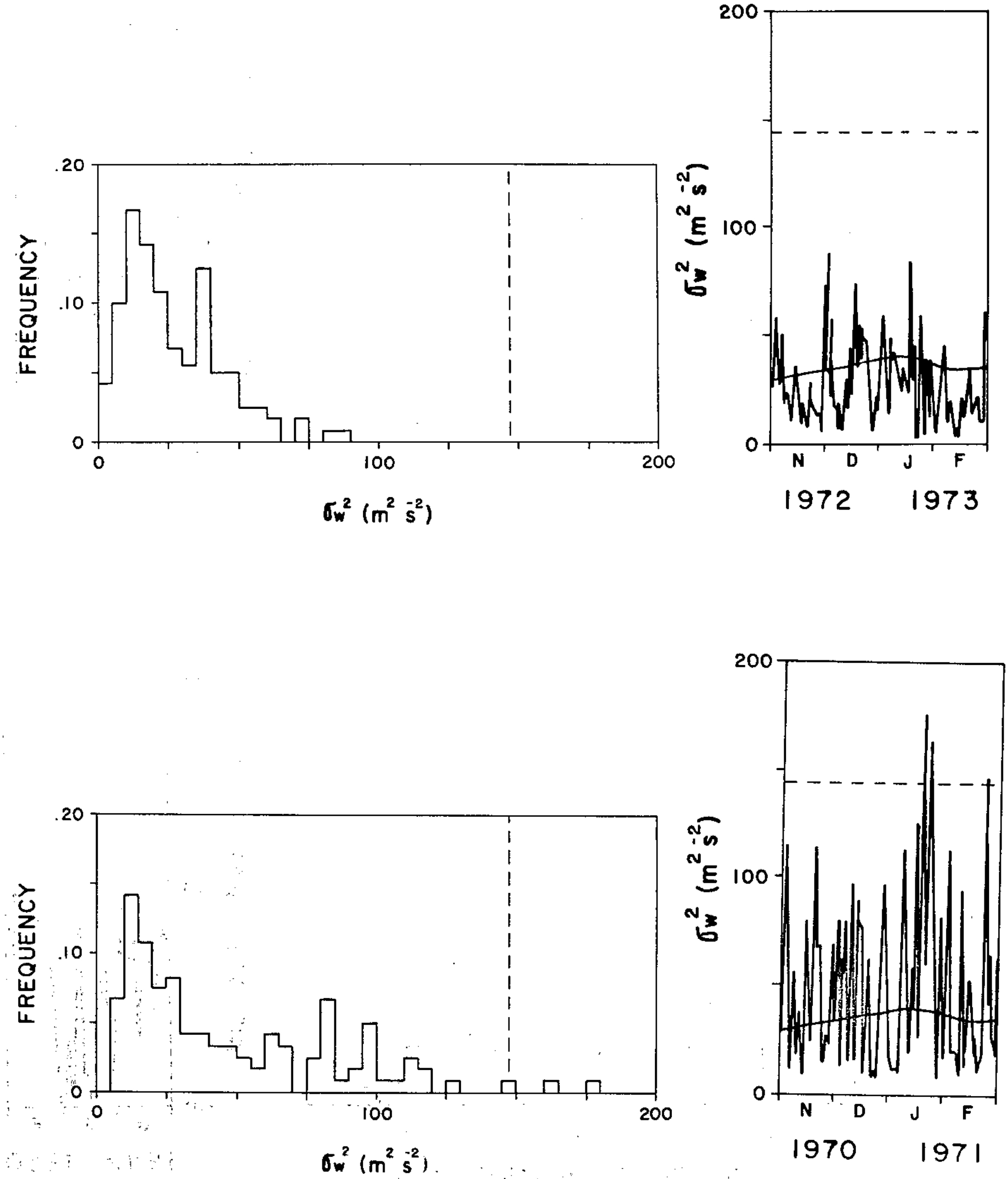

Figure 5.3. Histograms (at left) and time series (at right) of wind variance at Sea-Tac during a calm winter (top; Nov. 1972-Feb. 1973), and a windy winter (bottom; Nov. 1970-Feb. 1971). Notation: solid lines, long term winter norms; dashed lines, winter means, r mear

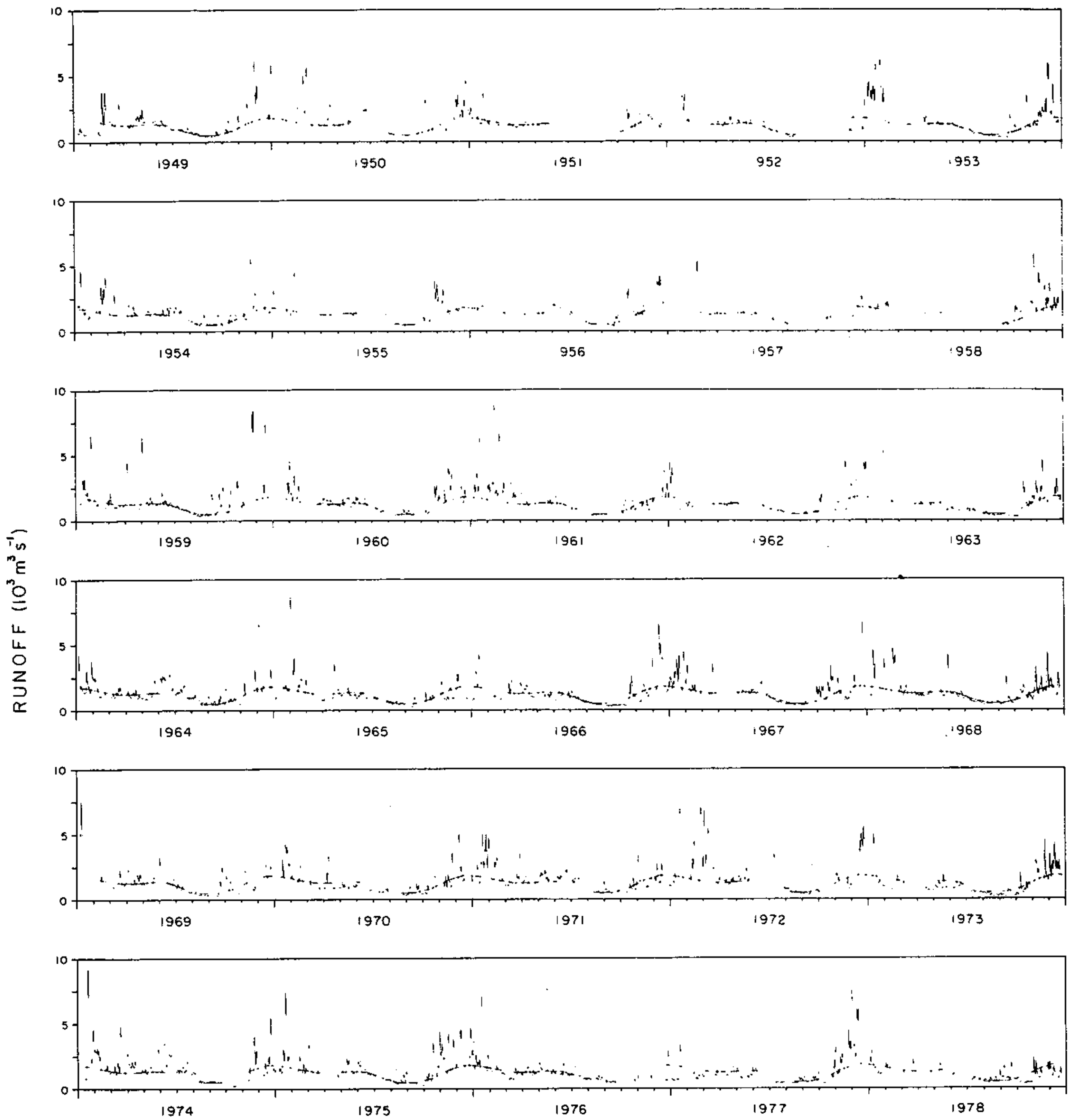

Figure 5.4. Time series of daily average total runoff during 1949-1978 superimposed on the seasonal norm.

TABLE 5.1. CHARACTERISTICS OF FLOODS SELECTED FROM DAILY RUNOFF COMPUTED FOR 1949-1978.

Decade	Date	Peak daily average runoff (m^3 s^{-1})
1. 1949-1958	11-27-49	7336
	12-28-49	7456
	3-4-50	6006
	2-10-51	12771
	1-12-53	6483
	1-23-53	6652
	2-1-53	6528
	12-10-53	6273
	11-3-55	9556
	12-12-55	8321
	12-10-56	6179
	11-12-58	6974
	Total - 12 floods	
2. 1959-1968	1-24-59	6855
	4-30-59	6877
	11-23-59	9878
	12-15-59	8074
	1-15-61	8020
	2-21-61	8240
	11-20-62	8173
	12-1-64	6708
	1-29-65	8932
	12-13-66	7708
	12-25-67	7165
	1-21-68	6773
	Total - 12 floods	
3. 1969-1978	1-5-69	7664
	12-7-70	6415
	1-21-72	8158
	2-29-72	7573
	3-6-72	7977
	12-26-72	6545
	1-16-74	10502
	12-21-74	6804
	1-18-75	9238
	12-3-75	11479
	1-16-76	7593
	12-2-77	9321
	12-11-77	6295
	Total - 13 floods	
	Mean	7824
	σ	1533

5.1.2 Cold Snaps

Figure 5.5 shows time series of daily average air temperature at Sea-Tac during 1949-1978 superimposed on the record's norm. The record shows numerous intervals when the temperature dropped below 0°C for several days. These intervals were usually associated with intrusions of cold, dry arctic air. For our purposes we will define a cold snap as an interval when the daily average temperature stays below 0°C for four days or longer.

Table 5.2 contains a tabulation of 26 cold snaps which occurred at Sea-Tac in the following decades: 1949-1958, 14 cold snaps; 1959-1968, 7 cold snaps; and 1969-1978, 5 cold snaps. It is striking that over half (14) of the cold snaps occurred during the first decade (1949-1958), whereas approximately a quarter (7,5) occurred in each of the following two decades. Thus during the decade of intensive current meter records (1969-1978) cold snaps were much less frequent than during 1949-1958.

Cold snaps, when they occur, have the following characteristics. The average duration is 6.9 days with the longest cold snaps lasting 12 days (January 23-February 3, 1950; January 18-29, 1957). The temperature during all cold snaps averaged -3.25°C; three cold snaps had an average temperature below -6.0°C (January 11-19, 1950; January 23-February 3, 1950; and December 27, 1968-January 1, 1969).

5.1.3 Storms

Figure 5.6 shows time series of daily average wind variance during 1949-1978. Their record is characterized by frequencies that are shorter than for runoff and air temperature. There are many days when the net wind speed exceeds 10 m s^{-1} (Fig. 5.7).

To gain some perspective we tabulated days when the wind variance exceeded 144 m^2 s^{-2} (Table 5.3): hereafter these occurrences will be referred to as storms. Table 5.3 shows that storms can occur any month between September and April, inclusively.

The result was the following number of storms per decade: 1949-1958, 4 storms; 1959-1968, 15 storms; and 1969-1978, 5 storms. The tabulation shows that over half (15) of the storms occurred during 1959-1968, whereas less than one quarter (4,5) of the storms occurred in each of the other two decades (1949-1958; 1969-1978).

5.2 DECADE OF INTENSIVE CURRENT MEASUREMENTS: 1969-1978

Figure 5.8 at bottom shows when current measurements were taken during 1969-1978. Figure 5.8 also shows supporting information for later interpretation of water properties and circulation (see Volume III).

Table 5.4 shows six floods, two cold snaps, and five storms which occurred when current observations were obtained. In Volume III the effects of these extreme anomalies on the water column are discussed.

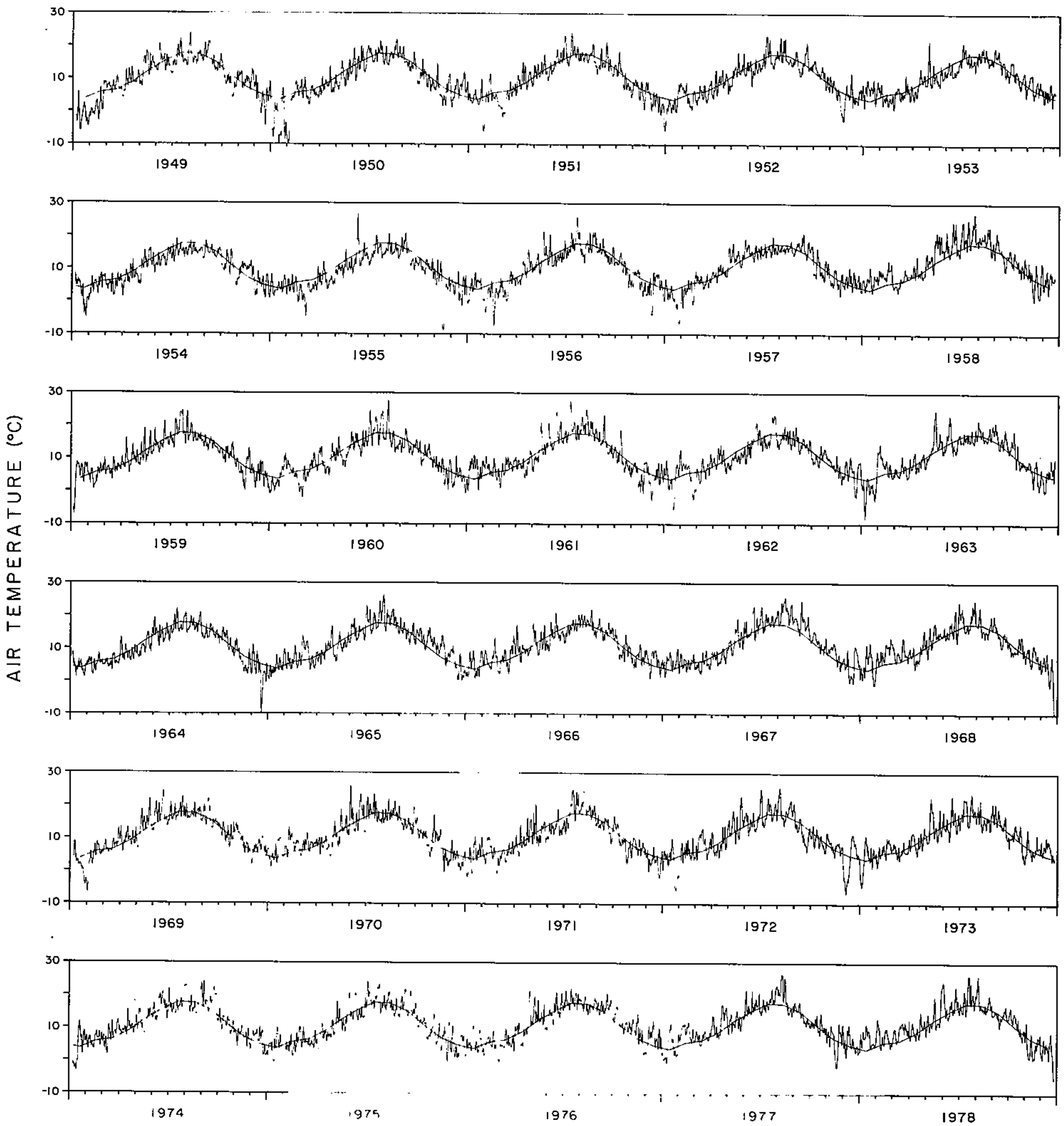

Figure 5.5. Time series of daily average air temperature at Sea-Tac during 1949-1978 superimposed on the seasonal norm.

TABLE 5.2. CHARACTERISTICS OF COLD SNAPS OCCURRING AT SEA-TAC DURING 1949-1978.

Decade	Date	Duration (days)	Coldest daily average temperature (°C)	Average temperature for total duration (°C)
1. 1949-1958	1/8-14/49	7	-6.2	-3.36
	1/19-28/49	10	-5.0	-2.58
	2/1-5/49	5	-1.4	-1.02
	1/1-5/50	5	-8.1	-4.86
	1/11-18/50	8	-11.1	-6.65
	1/23-2/3/50	12	-10.6	-6.64
	1/27-2/1/51	6	-6.4	-3.78
	3/5-9/51	5	-1.9	-0.86
	12/30/51-1/4/52	6	-5.9	-3.60
	11/26-29/52	4	-3.0	-1.67
	1/15-20/54	6	-5.1	-3.07
	11/11-17/55	7	-9.0	-5.96
	1/29-2/2/56	5	-3.3	-1.96
	1/18-29/57	12	-6.8	-2.95
	Total - 14 cold snaps			
2. 1959-1968	1/2-5/59	4	-7.3	-4.60
	1/18-23/62	6	-5.6	-3.27
	2/24-28/62	5	-2.6	-1.16
	1/10-13/63	4	-8.3	-5.27
	1/26-30/63	5	-2.9	-1.02
	12/15-18/64	4	-10.4	-1.44
	12/27/68-1/1/69	6	-10.9	-6.48
	Total - 7 cold snaps			
3. 1969-1978	1/21-31/69	11	-6.9	-3.64
	1/3-6/71	4	-1.9	-1.07
	1/25-2/3/72	10	-5.8	-2.87
	12/4-14/72	11	-6.7	-3.21
	1/1-11/74	11	-3.3	-1.46
	Total - 5 cold snaps			
	Mean	$\overline{6.9}$	$\overline{-3.25}$	
	σ	2.8	1.86	

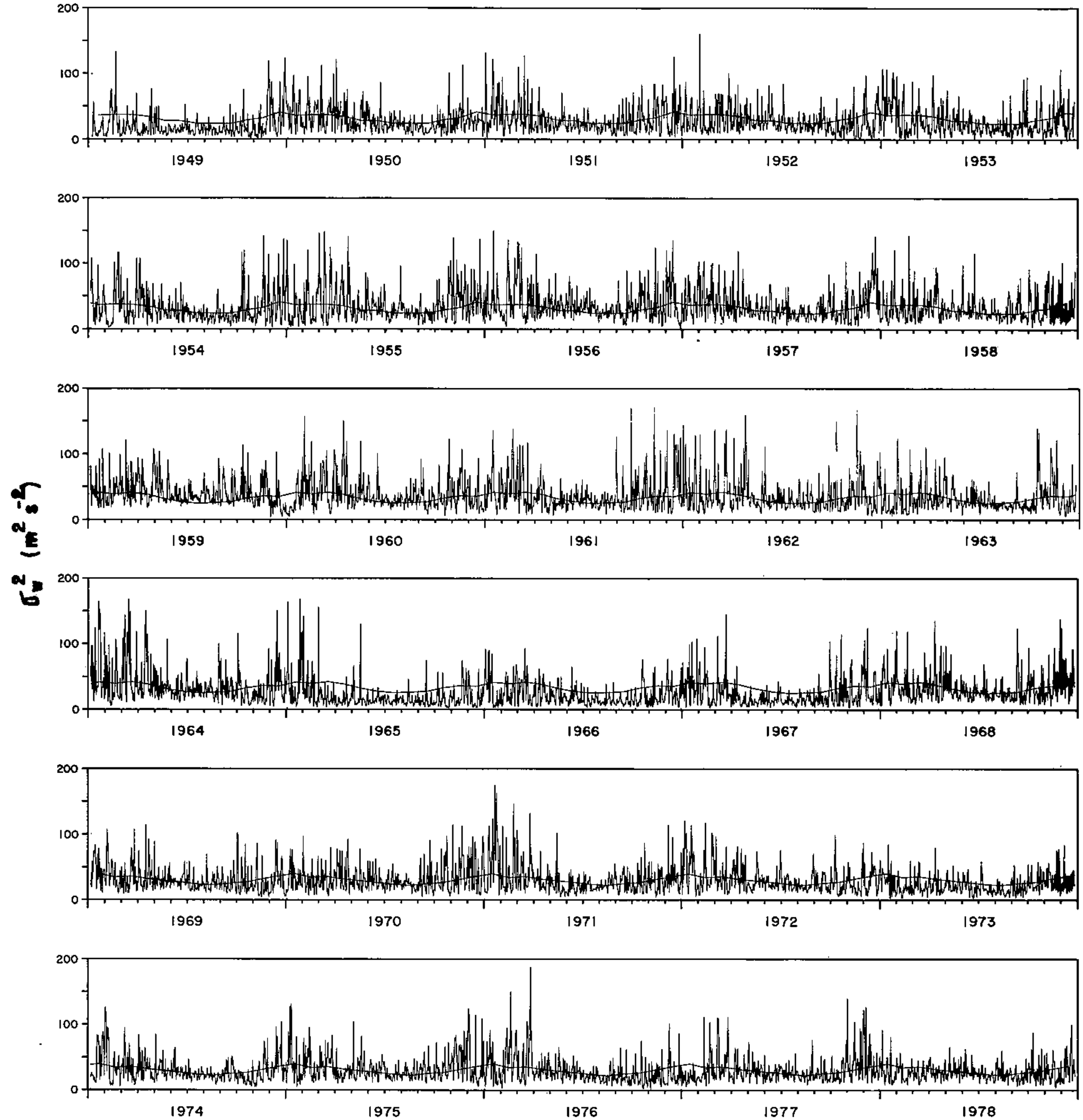

Figure 5.6. Time series of daily average wind variance at Sea-Tac during 1949-1978 superimposed on the seasonal norm.

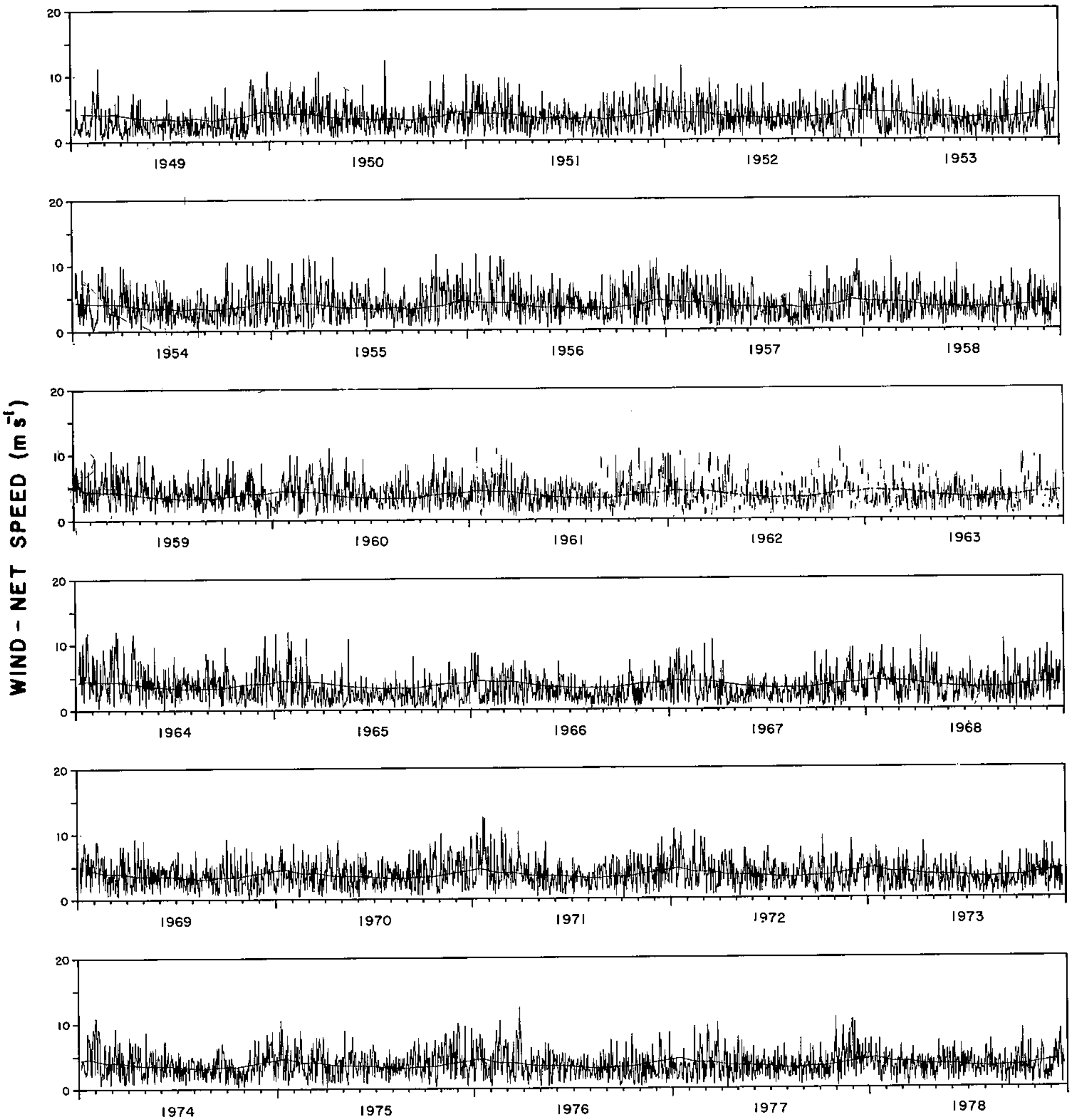

Figure 5.7. Time series of daily average net wind speed at Sea-Tac during 1949-1978 superimposed on the seasonal norm.

TABLE 5.3. CHARACTERISTICS OF STORMS BASED ON WINDS OBSERVED AT SEA-TAC DURING 1949-1978.

Decade	Date	Peak daily average variance (m^2 s^{-2})
1. 1949-1958	2-4-52	160.9
	2-28-55	146.7
	3-10-55	148.6
	1-16-56	150.6
	Total - 4 storms	
2. 1959-1968	2-2-60	157.8
	4-14-60	151.1
	9-28-61	181.0
	11-10-61	182.5
	11-19-62	179.0
	1-16-64	163.5
	1-18-64	151.8
	3-11-64	166.9
	3-14-64	148.6
	4-12-64	150.3
	12-12-64	150.1
	1-1-65	163.4
	1-24-65	167.5
	2-27-65	155.2
	3-23-67	144.7
	Total - 15 storms	
3. 1969-1978	1-21-71	176.2
	1-24-71	164.5
	2-25-71	147.7
	2-18-76	151.5
	3-25-76	189.4
	Total - 5 storms	
	Mean	160.4
	σ	12.4

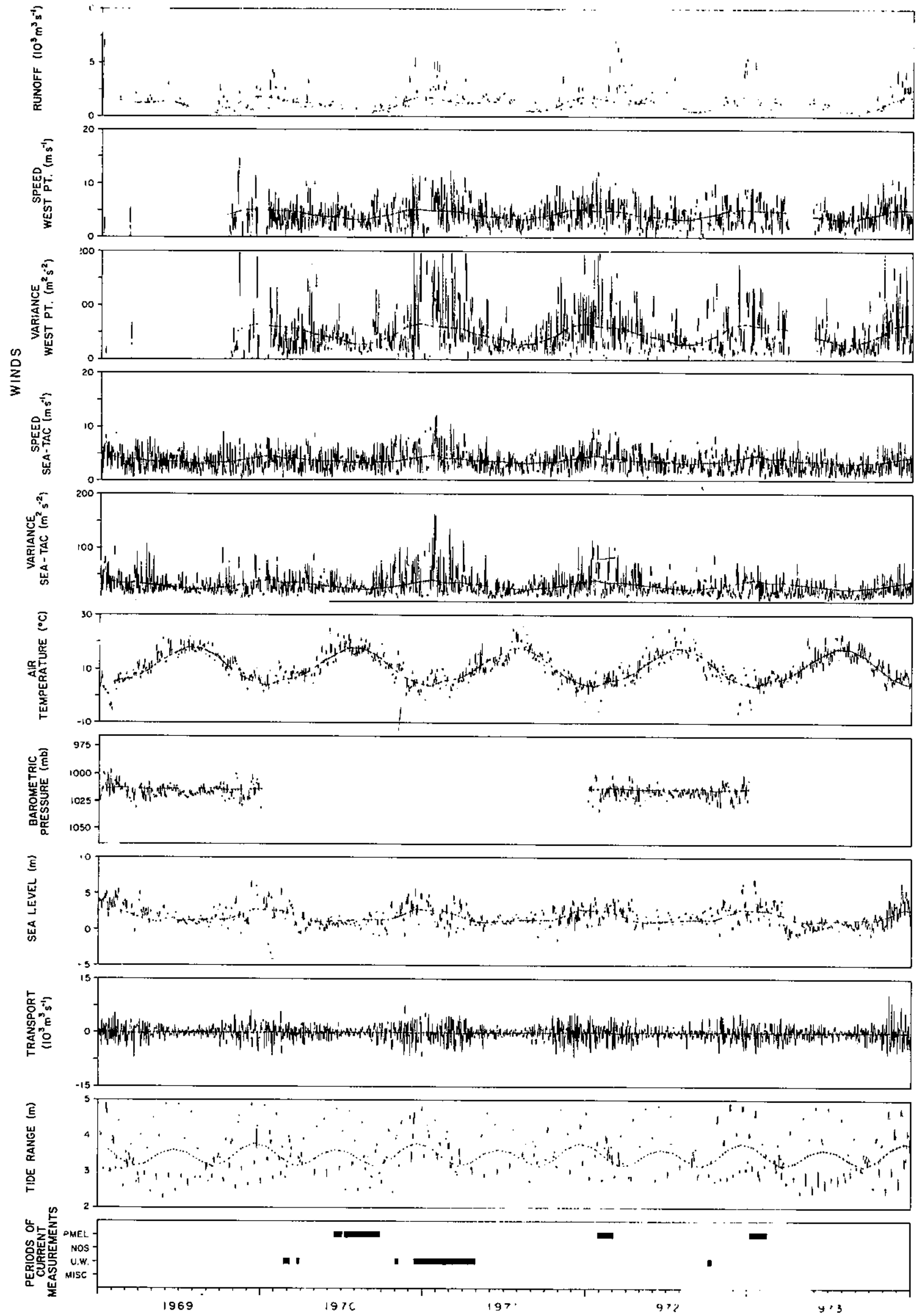

Figure 5.8. Time series during 1969-1978 of daily averages superimposed on norms for: runoff; net wind speed and variance at West Point and Sea-Tac; air temperature at Sea-Tac; barometric pressure at Sea-Tac; sea level, transport, and tidal range at Seattle. Bottom panel shows periods (solid rectangles) of current measurements taken by various agencies and individuals. Note that there are some periods of missing data of winds and barometric pressure.

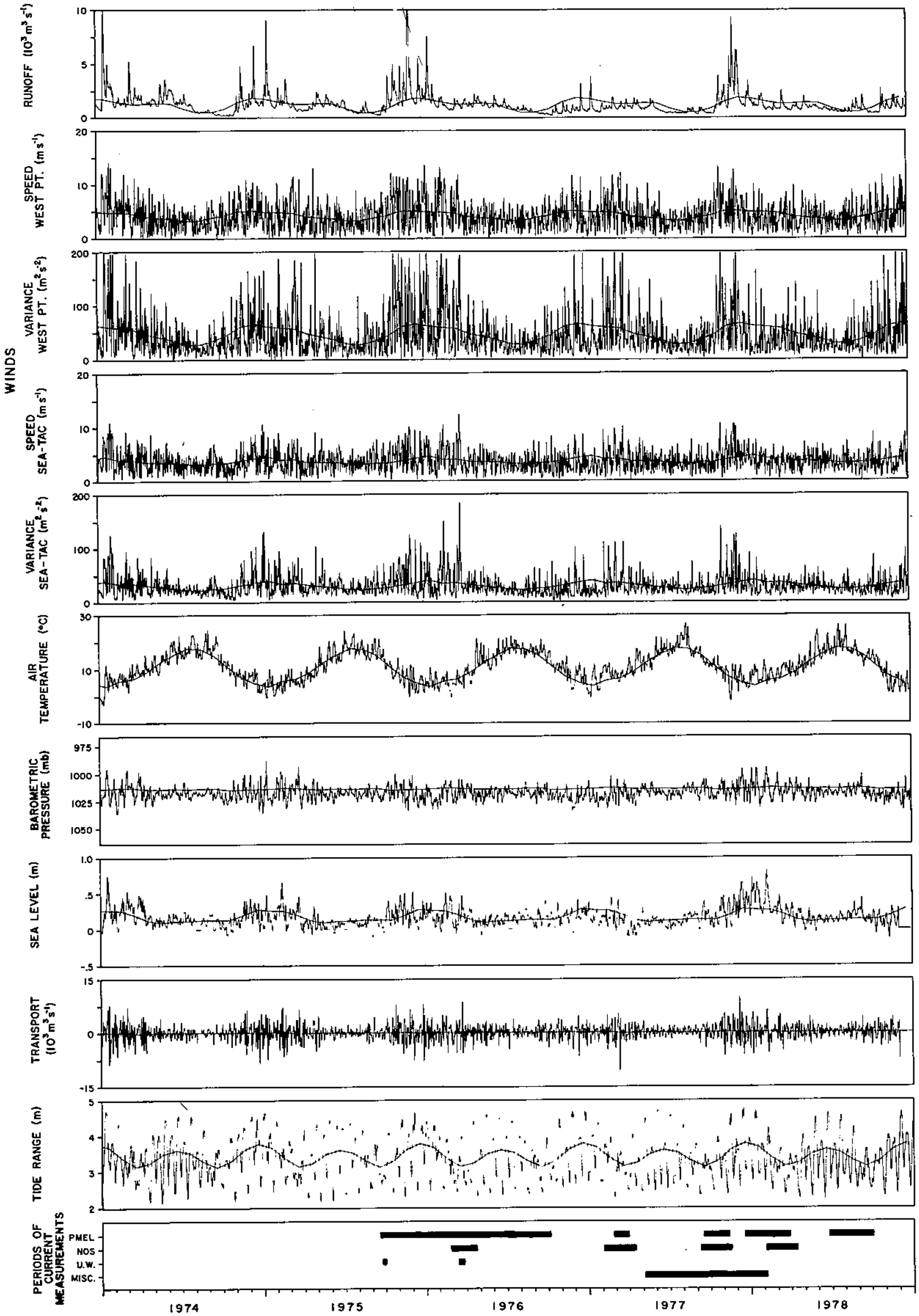

Figure 5.8 (continued)

TABLE 5.4. FLOODS, COLD SNAPS, AND STORMS WHICH OCCURRED FROM 1969-1978 DURING CURRENT MEASUREMENTS. EVENTS ARE ORDERED CHRONOLOGICALLY CORRESPONDING TO CURRENT MEASUREMENTS.

Dates of current measurements	Events (date)	Type of event	Mean for event
2/20-3/6/70			
3/21-26/70			
6/16-7/1/70			
7/7-9/25/70			
10/31-11/15/70			
12/11/70-4/28/71	12/7/70	Flood	6415 m^3 s^{-1}
	1/3-6/71	Cold Snap	-1.07°C
	1/21/71	Storm	176.2 m^2 s^{-2}
	1/24/71	Storm	164.5 m^2 s^{-2}
	2/25/71	Storm	147.7 m^2 s^{-2}
1/31-3/2/72	1/25-2/3/72	Cold Snap	-2.87°C
	2/29/72	Flood	7573 m^3 s^{-1}
10/4-13/72			
1/7-2/14/73			
9/16/75-9/28/76	12/3/75	Flood	11,479 m^3 s^{-1}
	1/16/76	Flood	7593 m^3 s^{-1}
	2/18/76	Storm	151.5 m^2 s^{-2}
	3/25/76	Storm	189.4 m^2 s^{-2}
2/2-4/20/77			
5/6/77-4/13/78	12/2/77	Flood	9321 m^3 s^{-1}
	12/11/77	Flood	6295 m^3 s^{-1}

6. CONCLUSION

The historical data from 1930-1978 show that, with respect to the annual norms, monthly means of runoff and wind variance are much more variable than those of air temperature. The long-term record also indicates that runoff and wind variance persistently exceed the norms for periods of years to decades, whereas a similar persistence for air temperature is not readily apparent.

On temporal scales from days to weeks three events are prominent: floods, cold snaps, and storms. During 1949-1978 there was considerable variability in the occurrence per decade of cold snaps and storms, but the number of floods remained nearly constant.

During 1969-1978 approximately 90% of all current observations were obtained. During this interval thirteen prominent events occurred, i.e., six floods, two cold snaps, and five storms.

ACKNOWLEDGEMENTS

We would like to express our appreciation to the personnel of the following agencies for supplying data: USGS Water Supply Division in Tacoma, Washington for river discharge statistics; Washington State Air Pollution Control Agency for wind data; Seattle Weather Bureau and the National Climatic Data Center for wind and air temperature data; and NOS for sea level measurements.

We are also grateful to Terry L. Storms for graphics and Ronald P. Kopenski for reviews.

This work was conducted for the NOAA/MESA Puget Sound Project under Contract No. NA80RAC00074 to Evans-Hamilton, Inc.

REFERENCES

Barnes, C.A., and C.C. Ebbesmeyer. 1978. Some aspects of Puget Sound's circulation and water properties. In: Estuarine Transport Processes (B. Kjerfve, ed.), University of South Carolina Press, Columbia, South Carolina. pp. 209-228.

Cannon, G.A., and C.C. Ebbesmeyer. 1978. Some observations of winter replacement of bottom water in Puget Sound. In: Estuarine Transport Processes (B. Kjerfve, ed.), University of South Carolina Press, Columbia, South Carolina, pp. 229-238.

Cannon, G.A., N.P. Laird, and T.L. Keefer. 1979. Puget Sound circulation: final report for FY 77-78. National Oceanic and Atmospheric Administration Technical Memorandum ERL MESA-40. 55 pp.

Collias, E.E. 1970. Index to physical and chemical oceanographic data of Puget Sound and its approaches, 1932-1966. University of Washington Department of Oceanography Special Report No. 43. 823 pp.

Collias, E.E., C.A. Barnes, and J.H. Lincoln. 1973. Skagit Bay study dynamical oceanography final report. University of Washington Department of Oceanography. 197 pp.

Collias, E.E., N. McGary, and C.A. Barnes. 1974. Atlas of physical and chemical properties of Puget Sound and its approaches. University of Washington Department of Oceanography. 235 pp.

Collias, E.E., and S.I. Andreeva. 1977. Puget Sound marine environment, an annotated bibliography. University of Washington Department of Oceanography Contribution 965. 392 pp.

Ebbesmeyer, C.C., and C.A. Barnes. 1980. Control of a fjord basin's dynamics by tidal mixing in embracing sill zones. Estuarine and Coastal Marine Science 10(11):311-330.

Harris, R.G., and M. Rattray. 1954. The surface winds over Puget Sound and the Strait of Juan de Fuca and their oceanographic effects. University of Washington Department of Oceanography Technical Report No. 37. 101 pp.

Lincoln, J.H. 1977. Derivation of freshwater inflow into Puget Sound. University of Washington Department of Oceanography Special Report No. 72. 20 pp.

National Oceanic and Atmospheric Administration. 1978. Climates of the States: narrative summaries, tables, and maps for each state with current tables of normals, 1941-1970, means and extremes to 1975, and overview of state climatologist programs. Volume 2. Gale Research Company, Book Tower, Detroit, Michigan. pp. 607-1185.

McLellan, P.M. 1954. An area and volume study of Puget Sound, Washington. Technical Report No. 21. University of Washington Department of Oceanography, Seattle, Washington. 39 pp.

Overland, J.E., and B.A. Walter. 1980. Marine climatology of western Washington. To be in: Puget Sound. Oceanography of the Inshore Waters of Washington (L.K. Coachman and D. Henry, eds.), University of Washington Press, Seattle (submitted).

U.S. Department of the Interior. Surface water supply of the U.S. Part 12, Pacific slope basins in Washington except Columbia River Basin. Geological Survey Water-Supply Paper.

U.S. Department of the Interior. 1967. Water management manual; a manual pertaining primarily to measurement of water for irrigation projects. Bureau of Reclamation U.S. Government Printing Office, Washington. 329 pp.

U.S. Environmental Data Service. 1930-1978. Climatological Data Washington, vol. 34-82. U.S. Weather Bureau, Seattle, Washington.

U.S. Geological Survey. 1945. Stream-gaging procedure, a manual describing methods and practices of the Geological Survey. Water Supply Paper No. 888.

University of Washington. 1953. Puget Sound and approaches, a literature survey. Volumes I and II. Department of Oceanography, Seattle, Washington.

University of Washington. 1954. Puget Sound and approaches, a literature survey. Volume III. Department of Oceanography, Seattle, Washington.

Water Resources Data for Washington Part 1., Surface water records. United States Department of the Interior, Geological Survey, Water Resources Division, Tacoma, Washington. Published yearly.