

A UNITED STATES
DEPARTMENT OF
COMMERCE
PUBLICATION



NOAA Technical Report NMFS SSRF-671

U.S. DEPARTMENT OF COMMERCE
National Oceanic and Atmospheric Administration
National Marine Fisheries Service

LIBRARY

OCT 16 1973

Woods Hole, Mass.

Coastal Upwelling Indices, West Coast of North America, 1946-71

ANDREW BAKUN

NOAA TECHNICAL REPORTS

National Marine Fisheries Service, Special Scientific Report--Fisheries Series

The major responsibilities of the National Marine Fisheries Service (NMFS) are to monitor and assess the abundance and geographic distribution of fishery resources, to understand and predict fluctuations in the quantity and distribution of these resources, and to establish levels for optimum use of the resources. NMFS is also charged with the development and implementation of policies for managing national fishing grounds, development and enforcement of domestic fisheries regulations, surveillance of foreign fishing off United States coastal waters, and the development and enforcement of international fishery agreements and policies. NMFS also assists the fishing industry through marketing service and economic analysis programs, and mortgage insurance and vessel construction subsidies. It collects, analyzes, and publishes statistics on various phases of the industry.

The Special Scientific Report—Fisheries series was established in 1949. The series carries reports on scientific investigations that document long-term continuing programs of NMFS, or intensive scientific reports on studies of restricted scope. The reports may deal with applied fishery problems. The series is also used as a medium for the publication of bibliographies of a specialized scientific nature.

NOAA Technical Reports NMFS SSRF are available free in limited numbers to governmental agencies, both Federal and State. They are also available in exchange for other scientific and technical publications in the marine sciences. Individual copies may be obtained (unless otherwise noted) from NOAA Publications Section, Rockville, Md. 20852. Recent SSRF's are:

- 619 Macrozooplankton and small nekton in the coastal waters off Vancouver Island (Canada) and Washington, spring and fall of 1963. By Donald S. Day. January 1971, iii + 94 pp., 19 figs., 13 tables.
- 620 The Trade Wind Zone Oceanography Pilot Study. Part IX: The sea-level wind field and wind stress values, July 1963 to June 1965. By Gunter R. Seckel. June 1970, iii + 66 pp., 5 figs.
- 621 Predation by sculpins on fall chinook salmon, *Oncorhynchus tshawytscha*, fry of hatchery origin. By Benjamin G. Patten. February 1971, iii + 14 pp., 6 figs., 9 tables.
- 622 Number and lengths, by season, of fishes caught with an otter trawl near Woods Hole, Massachusetts, September 1961 to December 1962. By F. E. Lux and F. E. Nichy. February 1971, iii + 15 pp., 3 figs., 19 tables.
- 623 Apparent abundance, distribution, and migrations of albacore, *Thunnus alalunga*, on the North Pacific longline grounds. By Brian J. Rothschild and Marian Y. Y. Yong. September 1970, v + 37 pp., 19 figs., 5 tables.
- 624 Influence of mechanical processing on the quality and yield of bay scallop meats. By N. B. Webb and F. B. Thomas. April 1971, iii + 11 pp., 9 figs., 3 tables.
- 625 Distribution of salmon and related oceanographic features in the North Pacific Ocean, spring 1968. By Robert R. French, Richard G. Bakkala, Masanao Osako, and Jun Ito. March 1971, iii + 22 pp., 19 figs., 3 tables.
- 626 Commercial fishery and biology of the freshwater shrimp, *Macrobrachium*, in the Lower St. Paul River, Liberia, 1952-53. By George C. Miller. February 1971, iii + 13 pp., 8 figs., 7 tables.
- 627 Calico scallops of the Southeastern United States, 1959-69. By Robert Cummins, Jr. June 1971, iii + 22 pp., 23 figs., 3 tables.
- 628 Fur Seal Investigations, 1969. By NMFS, Marine Mammal Biological Laboratory. August 1971, 82 pp., 20 figs., 44 tables, 23 appendix A tables, 10 appendix B tables.
- 629 Analysis of the operations of seven Hawaiian skipjack tuna fishing vessels, June-August 1967. By Richard N. Uchida and Ray F. Sumida. March 1971, v + 25 pp., 14 figs., 21 tables. For sale by the Superintendent of Documents, U.S. Government Printing Office, Washington, D.C. 20402 - 35 cents.
- 630 Blue crab meat. I. Preservation by freezing. July 1971, iii + 13 pp., 5 figs., 2 tables. II. Effect of chemical treatments on acceptability. By Jurgen H. Strasser, Jean S. Lennon, and Frederick J. King. July 1971, iii + 12 pp., 1 fig., 9 tables.
- 631 Occurrence of thiaminase in some common aquatic animals of the United States and Canada. By R. A. Greig and R. H. Gnaedinger. July 1971, iii + 7 pp., 2 tables.
- 632 An annotated bibliography of attempts to rear the larvae of marine fishes in the laboratory. By Robert C. May. August 1971, iii + 24 pp., 1 appendix I table, 1 appendix II table. For sale by the Superintendent of Documents, U.S. Government Printing Office, Washington, D.C. 20402 - 35 cents.
- 633 Blueing of processed crab meat. II. Identification of some factors involved in the blue discoloration of canned crab meat *Callinectes sapidus*. By Melvin E. Waters. May 1971, iii + 7 pp., 1 fig., 3 tables.
- 634 Age composition, weight, length, and sex of herring, *Clupea pallasii*, used for reduction in Alaska, 1929-66. By Gerald M. Reid. July 1971, iii + 25 pp., 4 figs., 18 tables.
- 635 A bibliography of the blackfin tuna, *Thunnus atlanticus* (Lesson). By Grant L. Beardsley and David C. Simmons. August 1971, 10 pp. For sale by the Superintendent of Documents, U.S. Government Printing Office, Washington, D.C. 20402 - 25 cents.

Continued on inside back cover.



U.S. DEPARTMENT OF COMMERCE

Frederick B. Dent, Secretary

NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION

Robert M. White, Administrator

NATIONAL MARINE FISHERIES SERVICE

NOAA Technical Report NMFS SSRF-671

**Coastal Upwelling Indices,
West Coast of North America,
1946-71**

ANDREW BAKUN

SEATTLE, WA

June 1973

The National Marine Fisheries Service (NMFS) does not approve, recommend or endorse any proprietary product or proprietary material mentioned in this publication. No reference shall be made to NMFS, or to this publication furnished by NMFS, in any advertising or sales promotion which would indicate or imply that NMFS approves, recommends or endorses any proprietary product or proprietary material mentioned herein, or which has as its purpose an intent to cause directly or indirectly the advertised product to be used or purchased because of this NMFS publication.

CONTENTS

	Page
Introduction	1
Method	1
Calculations	2
Pressure data	3
Effects of monthly mean data on calculated results	5
An effect of coastal topography	8
Mean yearly cycle of indicated upwelling	8
Discussion	9
Acknowledgments	12
Literature cited	12
Appendix—Tabulations and plots of coastal upwelling indices	13
60°N, 149°W	14
60°N, 146°W	20
57°N, 137°W	26
54°N, 134°W	32
51°N, 131°W	38
48°N, 125°W	44
45°N, 125°W	50
42°N, 125°W	56
39°N, 125°W	62
36°N, 122°W	66
33°N, 119°W	72
30°N, 119°W	78
27°N, 116°W	84
24°N, 113°W	90
21°N, 107°W	96

Figures

1. A conceptual diagram of the coastal upwelling process	3
2. Data grid	4
3. (a) Configuration of data points used to form pressure derivatives. (b) Diagram showing the transformation of the geostrophic wind vector to form an estimate of the wind near the sea surface	5
4. (a) Long-term mean annual cycle of offshore Ekman transport composited from actual wind observations within the 1-degree squares indicated on the coastline drawing to the right. (b) Long-term mean annual cycle of offshore Ekman transport formed from upwelling indices computed from monthly mean atmospheric pressure data at points indicated by dots on the coastline drawing. (c) Values from Figure 4(a) after having been adjusted to the slopes of the regression lines in Table 2. Units are cubic per second per meter of coastline	7
5. Height of a constant pressure surface	8
6. Mean monthly values of the computed upwelling indices for the 20-yr period, 1948 through 1967 ($\text{m}^3 \text{ sec}^{-1}/100 \text{ m}$)	10

Tables

1. Sources of synoptic surface atmospheric pressure fields used by Fleet Nu- merical Weather Central in constructing monthly mean fields	5
2. Results of comparison of a 54-mo series of monthly means of offshore com- ponent of Ekman transport computed 6-hourly to the corresponding se- ries computed from monthly mean data at the selected coastal grid points .	6
3. Mean monthly values of the indices for the 20-yr period, 1948-67. Units are cubic meters per second per 100 m of coastline	9

Coastal Upwelling Indices, West Coast of North America, 1946-71

ANDREW BAKUN¹

ABSTRACT

A series of monthly indices of intensity of large-scale, wind-induced coastal upwelling at selected locations along the west coast of North America is presented for the period 1946 through 1971. The indices are based on calculations of offshore Ekman surface wind transport from monthly mean surface atmospheric pressure data. Summaries by quarter and by year are included.

The effect of using monthly mean pressure data is evaluated by comparison to a similar series of monthly means of transports computed 6-hourly over a 4½-yr period. The correlation between the two series at any particular location was found to be high. However, the slope of the regression line varies at different locations. Also values off southern California during summer may be amplified relative to other locations as a result of the discontinuity in the atmospheric pressure gradient caused by the coastal mountain range between the thermal low in the interior of southern California and the higher pressure offshore. The conclusion is that these series may be satisfactory indicators of temporal variations of upwelling at each location, but less satisfactory indicators of spatial distributions.

INTRODUCTION

Coastal upwelling can profoundly affect the physical environment of marine organisms. An extreme example is the "El Niño" of the Peru Current where high surface temperatures related to cessation of upwelling have apparently resulted in such dislocation of marine fauna as to have caused starvation of great numbers of guano-producing seabirds (Wooster, 1960). Perhaps even more important from a fishery standpoint is the role of upwelling in the cycle of organic production in the sea, both in transporting nutrient-rich deeper waters into the illuminated surface layers where they are available for production, and in providing virgin water which is sufficiently free from predators to allow accumulation of large phytoplankton blooms (Cushing, 1969). Estimates have run as high as Ryther's (1969) suggestion that upwelling areas com-

prising about one-tenth of 1% of the ocean surface may produce one-half of the world's harvestable fish supply. Evidently, some indication of fluctuations in the upwelling regime is extremely important to understanding fluctuations in marine populations. This report is an attempt to provide indices of intensity of coastal upwelling off western North America on time and space scales useful to fishery research in general, and to the MARMAP (Marine Resources Monitoring, Assessment and Prediction) program of the National Marine Fisheries Service in particular.

METHOD

It is generally recognized that coastal upwelling in broad, diffuse eastern boundary currents such as the California Current and the eastern portion of the Gulf of Alaska Gyre is largely due to replacement from below of surface water transported offshore by the stress of the wind on the sea surface (Sverdrup et al., 1942, p. 501). Other possible mechanisms producing coastal up-

¹ Pacific Environmental Group, National Marine Fisheries Service, NOAA, Monterey, CA 93940.

welling include upwarping of density surfaces within a geostrophic current (Stommel and Wooster, 1965) and cross-isobar onshore flow at the bottom due to bottom friction (Hsueh and O'Brien, 1971). However, these are more likely to be important in narrower, more intense flows than normally occur in the area covered by this report.

Our present understanding of surface wind transport is based on Ekman's (1905) theory. Under Ekman's assumptions of steady state motion, uniform wind, and infinite homogeneous ocean, the mass transport per unit width of ocean surface is directed 90 degrees to the right (in the Northern Hemisphere) of the direction toward which the wind is blowing and is related to the magnitude of the wind stress by the expression

$$M = \frac{\tau}{f} \quad (1)$$

where M is the mass transport resulting from a wind stress, τ , and f is the Coriolis parameter. This mass transport has come to be called the *Ekman transport*. The layer in which appreciable transport occurs is often referred to as the *Ekman layer* and extends from the surface to depths not exceeding 50 to 100 m. The bottom of the Ekman layer is sometimes identified with the bottom of the homogeneous wind-mixed zone.

Smith (1967) has shown that Yoshida's (1955) expression for the offshore transport in the early stage of coastal upwelling reduces to the Ekman transport expression if the stress is assumed constant. This leads to the conclusion that the Ekman theory gives a valid description of wind-driven offshore flow in the early nonequilibrium phase of upwelling as well as in the later steady-state phase.

The approach taken in generating the indices presented in this report has been to estimate the monthly mean wind stress on the sea surface at points near the coast, from this to compute the Ekman transport, and finally to resolve the component of Ekman transport perpendicular to the coast. The magnitude of the offshore component is considered an indication of the amount of water upwelled through the bottom of the Ekman layer to replace that driven offshore (Fig. 1). Negative values indicate onshore transport or convergence at the coast. Since accumulation of surface waters tends to cause downward displacement of the density structure in the coastal area, this sit-

uation is sometimes referred to as *downwelling*.

The basic input data is the wind field over the ocean. However, the distribution of sea-surface wind observations in the near coastal regions of the northeastern Pacific is uneven, both spatially and temporally. The number available for a given area during a given month is often insufficient to form a good estimate of the monthly mean stress on the sea surface. In order to construct a consistent series, use is made of the relationship in mid-latitude regions of wind to atmospheric pressure. Incorporating atmospheric pressure data increases the coverage in data-sparse areas and allows an understanding of the behavior of large-scale pressure systems to aid in providing continuity to the analysis of scattered observations. Therefore, winds derived from analyzed atmospheric pressure fields are used in the production of these indices.

Calculations

The computed values are based on monthly mean pressure fields prepared by Fleet Numerical Weather Central (FNWC). These data are available on a 63 by 63 point square grid which is superimposed on a polar stereographic projection of the Northern Hemisphere (Hughes, 1966). The mesh length is 200 nautical miles at lat. 60°N and decreases southward to about 144 nautical miles at lat. 20°N. The data were transferred to a 3-degree mesh length geographical (spherical coordinates) grid (Fig. 2) using Bessel's central difference formula.

First derivatives of the surface pressure at each grid point were estimated by taking the difference in pressure between the grid points to either side and dividing by the 6-degree angular mesh length. For example, the derivatives of the pressure at point "0" in Figure 3(a) would be approximated as

$$\frac{\partial P}{\partial \phi} \cong \frac{P_1 - P_2}{2h}; \quad \frac{\partial P}{\partial \lambda} \cong \frac{P_4 - P_3}{2h} \quad (2)$$

where ϕ and λ denote the northward and eastward angular coordinates, h is the 3-degree angular mesh length in radians and P_1 denotes the pressure at point "1", etc. The geostrophic wind was computed according to

$$u_g = -\frac{1}{f\rho_a R} \frac{\partial P}{\partial \phi}; \quad v_g = \frac{1}{f\rho_a R \cos \phi} \frac{\partial P}{\partial \lambda} \quad (3)$$

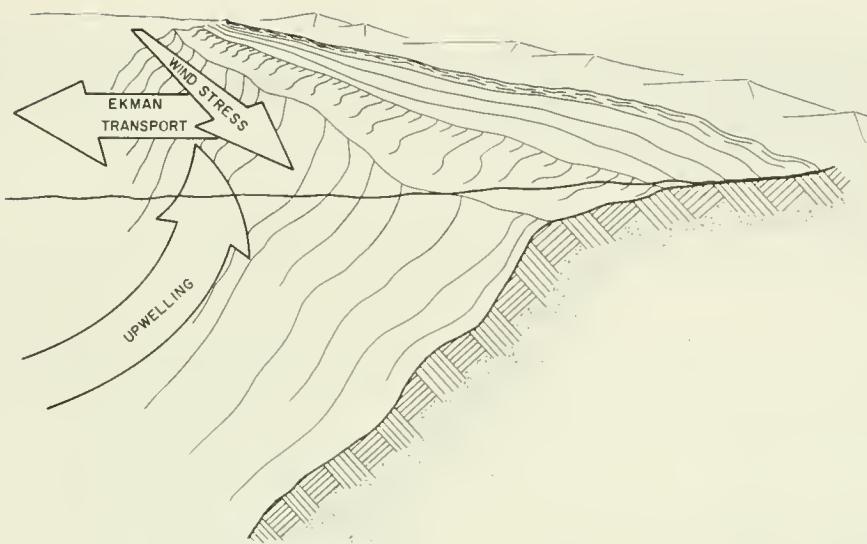


Figure 1.—A conceptual diagram of the coastal upwelling process. The coast of the continent is represented in cutaway view with the ocean to the left of the figure. Offshore transport in the surface Ekman layer due to stress of the wind parallel to the coast on the sea surface is replaced by upwelling from depth.

where v_g and u_g are the respective northward and eastward components of geostrophic wind velocity, f is the Coriolis parameter, ρ_a is the density of air and R is the mean radius of the earth. The density ρ_a was considered constant at $0.00122 \text{ g cm}^{-3}$. An estimate of the wind near the sea surface was formed by rotating the geostrophic wind vector 15 degrees to the left and reducing it by 30% as in Figure 3(b) to approximate frictional effects.

The sea-surface stress was then computed according to the classical square-law formula

$$\vec{\tau} = \rho_a C_d |\vec{v}| \vec{v} \quad (4)$$

where $\vec{\tau}$ is the stress vector, ρ_a is the density of air, C_d is an empirical drag coefficient, \vec{v} is the estimated wind vector near the sea surface with magnitude $|\vec{v}|$. A relatively high value, 0.0026, of the drag coefficient was used to partially offset the effect of using mean data. Finally, the Ekman transport was computed according to Equation (1). Except for the estimates of the pressure derivatives which necessarily differ because of the different grid format, this calculation procedure is the same as that used by Fofonoff (1960).² The offshore transport is determined by resolving the component perpendic-

ular to a line drawn by visual estimation on a bathymetric chart along the dominant trend of a 200-mile segment of coastline centered near the grid point in question.

The indices generated by this method must be considered as indicative of rather large-scale coastal upwelling. The 6-degree gap across which the derivatives are measured as well as the scale of coastline resolution indicates a 100- to 200-mile scale as being appropriate for interpretation of the indices. Certainly, smaller scale upwellings could occur within a larger scale downwelling just as short-term upwellings might occur during a monthly period of average downwelling.

Pressure Data

The number of synoptic surface atmospheric pressure fields available at FNWC for each month during the period 1946-71 is variable. Because of the nonlinear dependence of stress on wind velocity (Equation 4), use of a variable sampling interval destroys the internal consistency of the time-series. For this reason monthly mean

² Fofonoff, N. P. 1960. Transport computations for the North Pacific Ocean-1958. Fish Res. Board Can., Manuser. Rep. Ser. (Oceanogr. Limnol.) 80, 81 p. (Processed.)

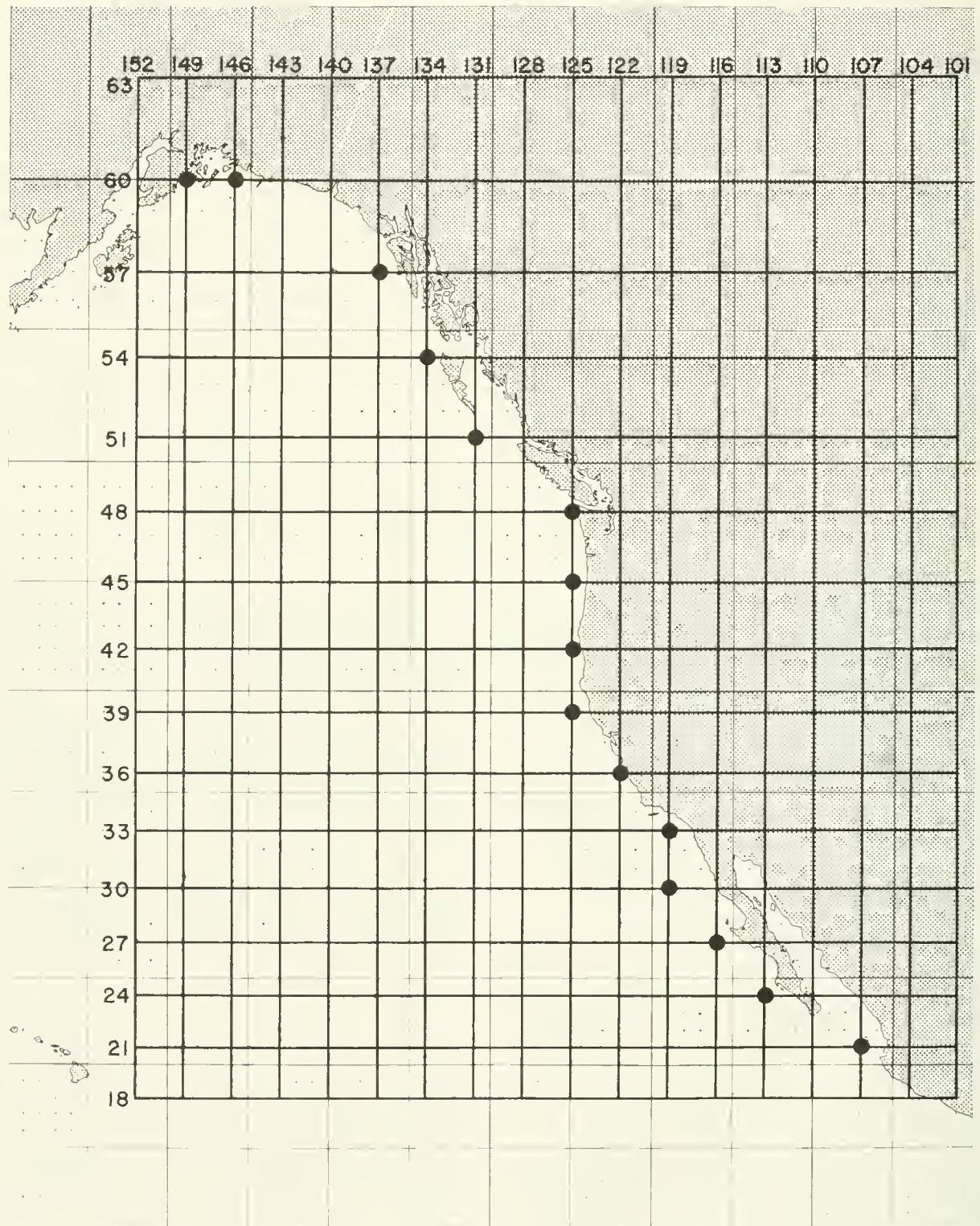
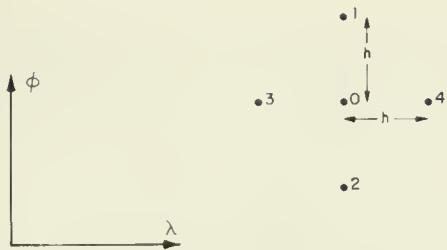
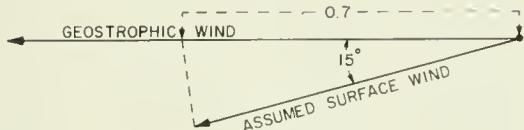


Figure 2.—Data grid. Intersections at which upwelling indices are computed are marked with large dots.



(a)



(b)

pressure fields were used as input data, thereby making best use of available data within each month while retaining a consistent sampling interval for computation of the stress. The effect of using monthly mean data on the absolute magnitude of the index at each location is discussed in the next section.

The monthly mean fields have been assembled by FNWC from, as far as was possible, 6-hourly (four per day) synoptic fields. Where this frequency was not available, twice per day where available or once per day fields were utilized. This decreased frequency occurs mainly in those years previous to 1963 when FNWC began to produce its own analysis. To extend the series back to 1946, FNWC has collected synoptic fields from the sources listed in Table 1.

Because of the different data sources and the expected trend toward increased detail in later pressure fields due to an expanded system of meteorological observations, care should be used in attempting to discern long-term trends in these upwelling indices. For example, it is difficult to determine how much of the decreased amplitude of the yearly cycle apparent at several of the locations during the earliest several years is real and how much is due to relative smoothing of the data in the earliest pressure fields. The intention has been to produce a series which will give a useful indication of the relative intensity

Figure 3.—(a) Configuration of data points used to form pressure derivatives. (b) Diagram showing the transformation of the geostrophic wind vector to form an estimate of the wind near the sea surface.

of upwelling by month within any group of fairly contemporaneous years.

Effects of Monthly Mean Data on Calculated Results

Due to the nonlinear linkage of wind to stress (Equation 4) the value of the Ekman transport computed from monthly mean data will be small-

Table 1.—Sources of synoptic surface atmospheric pressure fields used by Fleet Numerical Weather Central in constructing monthly mean fields.

Time period	Source agency	Remarks
Jan. 1946- Mar. 1955	National Climatic Center Ashville, N.C.	Hand analysis of available reports; once per day.
Apr. 1955- Dec. 1959	National Center for Atmospheric Research Boulder, Colo.	National Meteorological Center analysis digitized at alternate gridpoints; twice per day.
Jan. 1960- June 1962	National Climatic Center Asheville, N.C.	Once per day.
July 1962- Dec. 1971	Fleet Numerical Weather Central, Monterey, Calif.	FNWC objective machine analysis. Certain gaps filled with NCC data; four times per day.

er than the monthly mean of Ekman transport computed at synoptic intervals by an amount depending upon the variance of the wind vector within the month. In order to evaluate this effect, a 54-mo series (January 1967 through June 1971) of monthly means of 6-hourly computations of offshore component of Ekman transport was generated for comparison with the corresponding values computed from monthly mean data. The results of the comparison are summarized in Table 2.

The high values of the correlation coefficients indicate quite linear relationships between the two sets of series. Thus the distortion introduced into the series at any particular location due to use of monthly mean data is mainly one of absolute magnitude. The relationship of each monthly value to the other monthly values at the location is affected only slightly. This indicates that the series computed from monthly mean data gives an indication of the monthly variations in intensity of upwelling nearly equivalent to that given by the corresponding series of monthly means of values computed each 6 hr.

However, Table 2 shows the slope of the regression line for the two series to be variable from one location to the other. This indicates a change with location in the amount of variability of the wind vector within a month. Thus the use of monthly mean data in conjunction with the nonlinear stress law (Equation 4) gives an erroneous impression of the relative magnitudes of offshore Ekman drift when different locations are compared. For this reason the indices tabulated in this report which are designed to indicate temporal variations at a particular location, should be used with caution as indicators of spatial distributions.

This distortion of the spatial distributions introduced by designing the computational method to minimize distortion of the time-series at each particular location can be illustrated by examining the long-term mean annual cycle of offshore Ekman transport computed in two different ways. Figure 4(a) is a time-series isogram of offshore component of Ekman transport for a long-term composite year computed from actual wind observations taken from the National Climatic Center's file of marine surface observations. The figure summarizes over 75,000 individual wind observations taken by ships at sea

Table 2.—Results of comparison of a 54-mo series of monthly means of offshore component of Ekman transport computed 6-hourly to the corresponding series computed from monthly mean data at the selected coastal grid-points.

Location	Rank correlation coefficient	Product-moment correlation coefficient	Slope of least-squares regression line
60°N, 149°W	0.99	0.98	0.62
60°N, 146°W	0.99	0.98	0.66
57°N, 137°W	0.99	0.98	0.66
53°N, 134°W	0.97	0.94	0.54
51°N, 131°W	0.96	0.94	0.47
48°N, 125°W	0.99	0.97	0.48
45°N, 125°W	0.99	0.97	0.49
42°N, 125°W	0.99	0.96	0.57
39°N, 125°W	0.99	0.96	0.68
36°N, 122°W	0.99	0.98	0.83
33°N, 119°W	0.99	0.99	0.94
30°N, 119°W	0.99	0.99	0.98
27°N, 116°W	0.95	0.96	0.97
24°N, 113°W	0.96	0.96	0.83
21°N, 107°W	0.99	0.96	0.59

over the 20-yr period, 1948 through 1967, within the 1-degree squares shown in the accompanying coastline plot. The Ekman transport was computed for each wind observation and the offshore components were averaged by month for each coastal square. The drag coefficient used with these actual observed winds was 0.0013. Bakun (1971) demonstrated that the spatial distributions obtained in this manner agreed well with the mean annual cycle of sea-surface temperature distributions. Reference to the slopes of the regression lines in Table 2 indicates that since this drag coefficient is half that used with winds computed from monthly mean pressure fields to generate the indices tabulated in this report, rough numerical equivalence between the two transport sets should occur at about lat. 45°N.

Figure 4(b) is a similar isogram constructed from long-term mean monthly values for the same period of the indices derived from monthly mean pressure data. The locations at which the indices were calculated are marked on the accompanying coastline plot. Comparison with Figure 4(a) shows an extreme southward shift and intensification of the point of maximum indicated upwelling.

Figure 4(c) displays the data from Figure 4(b) after having been adjusted to the slopes of the re-

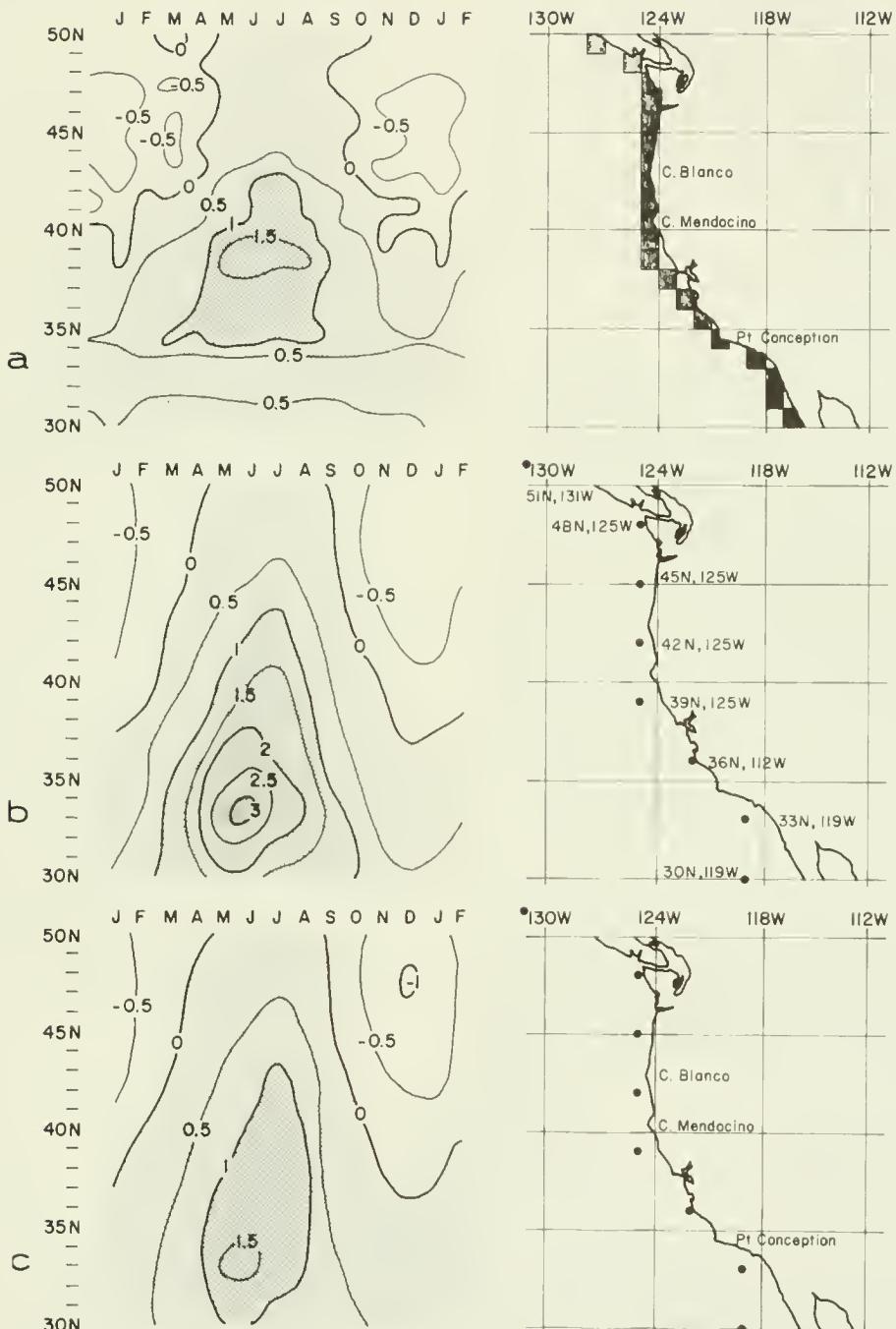


Figure 4.—(a) Long-term mean annual cycle of offshore Ekman transport composited from actual wind observations within the 1-degree squares indicated on the coastline drawing to the right. (b) Long-term mean annual cycle of offshore Ekman transport formed from upwelling indices computed from monthly mean atmospheric pressure data at points indicated by dots on the coastline drawing. (c) Values from Figure 4(a) after having been adjusted to the slopes of the regression lines in Table 2. Units are cubic meters per second per meter of coastline.

gression lines by multiplying each monthly value by 0.5 and by the reciprocal of the slope given in Table 2. The multiplication by 0.5 is necessary because the value of the drag coefficient used to construct Figure 4(a) is half that used for Figure 4(b) whereas the slopes in Table 2 were computed for two series with equal drag coefficients. Multiplication by the reciprocal of the slopes then serves to adjust the data so that the spatial variation in the underestimate of the monthly mean wind stress due to computation from monthly mean atmospheric pressure data as predicted in Table 2 is removed.

The magnitudes and spatial variations displayed in Figure 4(c) are more like those shown in Figure 4(a) than are those in Figure 4(b). Some smoothing of gradients in Figure 4(b) and (c) results from having data points at 3-degree intervals with each point incorporating data across a 6-degree area. This causes some loss in detail and displacement of contours relative to Figure 4(a) where data points are at 1-degree intervals and incorporate data restricted to a 1-degree square area. There remains however a definite shift of the maximum toward southern California in Figure 4(c) relative to Figure 4(a). A possible cause for this shift in maximum upwelling is described in the following section.

An Effect of Coastal Topography

During the summer an intense thermal low develops in the interior of southern California. Due to the 3-degree mesh length of the computation grid, the meridional component of the geostrophic wind at a coastal gridpoint is computed (Equation 2) from a continuous constant pressure gradient between an offshore gridpoint and one on the continent (dashed line in Fig. 5). However, the southern California coastal mountain range causes a discontinuity in this pressure gradient such that the gradient actually in equilibrium with the geostrophic wind (solid line in Fig. 5) may be less than that used in the computations. This leads to an overestimation of the geostrophic wind that in turn leads to an overestimation of the upwelling index. The assumption made in presenting these series as indicators of time variations of intensity of coastal upwelling is that the actual pressure gradient at the coast varies in rough proportion to the total onshore-offshore pressure difference which is used in the computations.

MEAN YEARLY CYCLE OF INDICATED UPWELLING

Having been designed to give a consistant indication of temporal variations at each particular

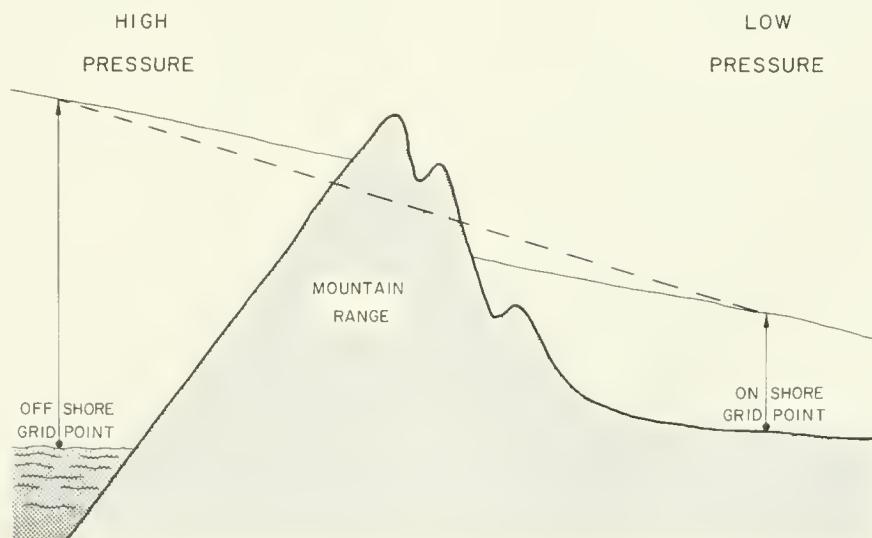


Figure 5.—Height of a constant pressure surface. The slope of the dashed line indicates the assumed gradient used in the calculations. The slope of the solid line indicates the lesser gradient which may exist in reality.

Table 3.—Mean monthly values of the indices for the 20-yr period, 1948-1967. Units are cubic meters per second per 100 m of coastline.

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
60°N, 149°W	-138	-86	-46	-11	0	6	6	6	-3	-26	-73	-109
60°N, 146°W	-180	-103	-48	-12	-2	6	5	3	-9	-34	-94	-129
57°N, 137°W	-212	-117	-51	-24	-11	0	1	-6	-29	-88	-140	-163
54°N, 134°W	-97	-68	-27	-20	-10	1	3	-1	-23	-82	-98	-91
51°N, 131°W	-64	-36	-12	-5	4	15	16	12	-3	-40	-58	-57
48°N, 125°W	-90	-47	-21	0	18	25	34	22	4	-39	-88	-100
45°N, 125°W	-94	-47	-15	9	34	48	74	50	16	-20	-73	-93
42°N, 125°W	-67	-28	3	33	79	103	132	91	36	0	-42	-57
39°N, 125°W	-13	9	36	69	124	168	182	139	63	20	-7	-12
36°N, 122°W	11	35	80	121	203	239	198	183	94	49	12	7
33°N, 119°W	19	48	120	178	282	312	231	212	137	76	22	10
30°N, 119°W	56	77	116	141	199	199	143	142	129	103	65	54
27°N, 116°W	71	93	119	148	202	195	114	105	110	106	74	63
24°N, 113°W	51	74	93	116	143	129	48	44	49	69	52	39
21°N, 107°W	18	39	97	100	87	39	3	5	-14	-15	8	8

location, this set of indices may be admirably suited for describing the spatial variations of timing and duration of upwelling. In Table 3 are listed the long-term monthly mean values of the indices for the 20-yr period, 1948-67. Figure 6 displays plots of these values.

The period of maximum values of the indices is earliest to the south, becoming progressively later in the year with distance to the north. At lat. 21°N the peak is in April. Off the coast of Baja California the peak is in May. A June peak occurs off southern and central California. North of San Francisco the peak is generally in July, with a slight shift back to June at the northern extremity of the Gulf of Alaska.

From the southern tip of Baja California northward to Monterey Bay the mean values of the indices indicate upwelling throughout the year. Northward from San Francisco the season of indicated upwelling becomes progressively restricted, lasting March through October off northern California, April through September off Oregon, May through August off northern Vancouver Island, finally narrowing at lat. 57°N to a scarcely significant positive value of the index during July.

Tabulations of the deviations from these long-term mean values accompany the tabulations of the values of the indices in the Appendix. Graphical plots of both the anomalies and the values of the indices are included.

DISCUSSION

Detailed analysis and interpretation of the time-series plots contained in the Appendix is beyond the scope of this report. However, it may be useful to point out several examples and to speculate briefly upon possible consequences.

Accompanying the plots of the monthly indices for each location are tables of quarterly and annual averages. The following three examples are each illustrative of phenomena occurring basically on one of these three different time-scales. As it happens, the first two concern negative values of the index. Negative values of the index indicate accumulation of wind-transported surface waters at the coast and resulting downwelling.

Short-Term Intense Convergences in the Northern Gulf of Alaska

A glance at the first chart in the Appendix reveals an extreme negative spike in the upwelling index at lat. 60°N, long. 149°W during February 1950. In this case, the indicated convergence is over 4½ times the 20-yr mean value for February. It is interesting to speculate upon the effect of such an anomaly on the density structure of the northern portion of the Alaskan Gyre.

If the given numerical value is accepted as an estimate, we find for February 1950 an anomalous onshore flow of nearly 300 m³/sec along each

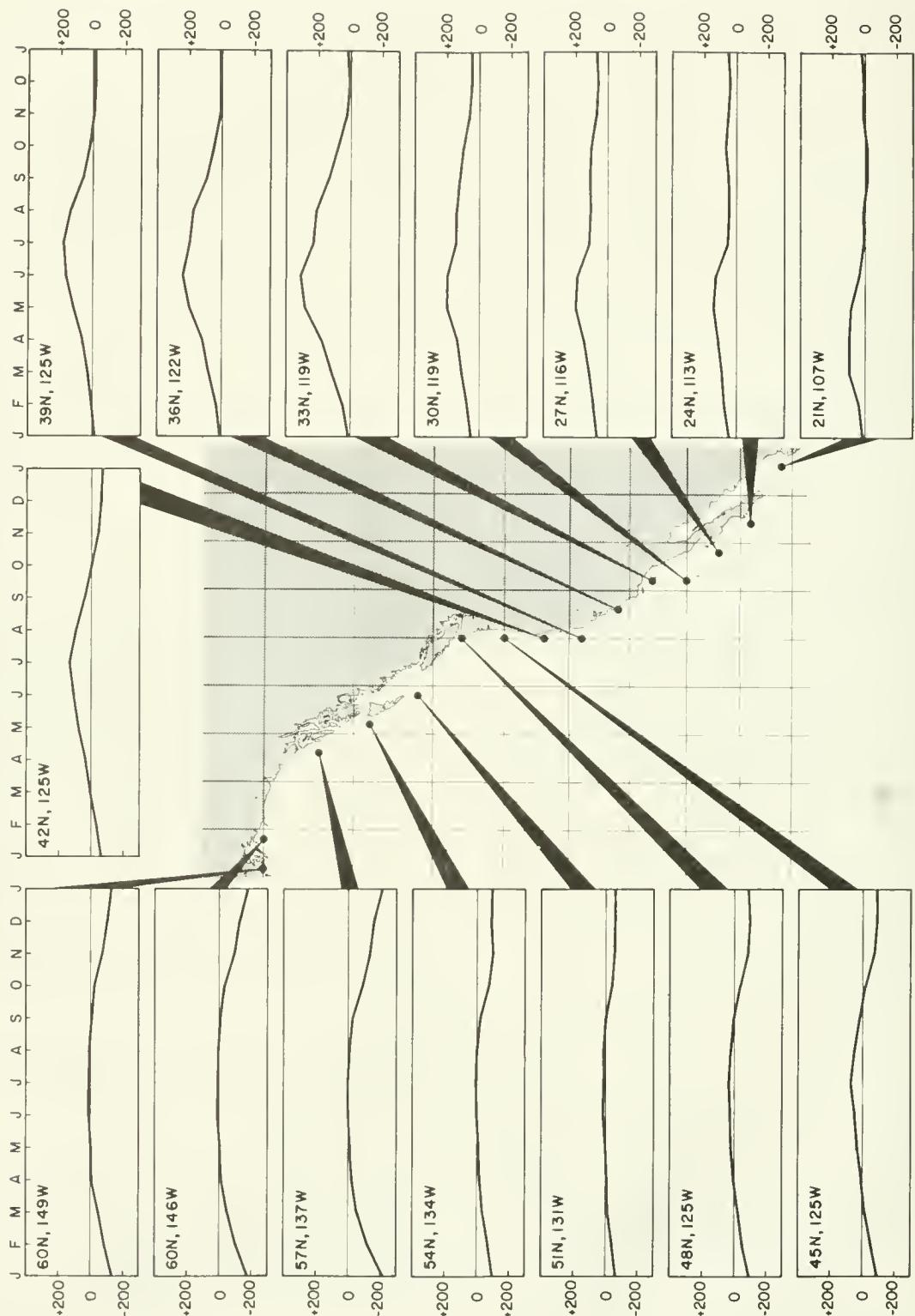


Figure 6.—Mean monthly values of the computed upwelling indices for the 20-yr period, 1948 through through 1967 ($\text{m}^3 \text{ sec}^{-1}$ /per 100 m).

100 m of coastline. Assuming this flow accumulates within a zone extending 300 km offshore, this represents for the 1-mo period a lens of excess surface water about 24 m thick. If the flow away from the coast which must balance this accumulation occurs below the pycnocline the result is a downward shift of the upper density structure an average of 24 m over the shoreward 300 km. Such a shift implies an extreme increase in baroclinicity in this already highly baroclinic area, tending to accelerate the westward geostrophic flow along the northern boundary of the Gulf of Alaska.

The striking negative anomalies for the same month in charts of the index at lat. 60°N, long. 146°W and at lat. 57°N, long. 137°W indicate that this feature existed over the major portion of the northern Gulf of Alaska coastline. This wide geographical extent justifies such a two-dimensional treatment as presented in the previous paragraph. It also indicates a possibly far-reaching effect on the marine environment of this region.

Several similar short-term intense negative values of the index appear in the charts at other times. In each case the major pulse is confined to only one monthly value but has spatial coherence in the Northern Gulf. Most impressive along with February 1950 just discussed are the months of January during the years 1959, 1966, and 1971. January 1971 differs from the others in that the absence of a strong anomaly at lat. 57°N, long. 135°W indicates a lesser eastward extent of the feature.

Periods of Intense Winter Convergence off Washington and Oregon

The monthly charts of the index at lat. 45°N, long. 125°W indicate the periods of December 1957 through February 1958 and January through March 1961 as having been intervals of extreme convergence of wind-drifted surface waters at the coast. Winter of 1958, in particular, exhibits a striking anomaly in the charts for locations extending from lat. 51°N to lat. 39°N. These periods differ from the intense convergences previously described for the more northerly region in containing several successive months of anomalously large negative values of the index rather than a single extreme month and are

highly evident in the charts of quarterly summaries presented in the appendix. The effect of this apparent downwelling at the coast upon the density structure would be to accelerate northward flow or to decelerate southward flow. Either situation would favor an anomalous warm advection.

Long-Term Groupings of Mean Yearly Values

In examining these data for long-term or regional trends it is sometimes helpful to filter out some of the shorter term variability by means of annual averages. For example the charts of mean yearly values indicate anomalously high mean annual upwelling throughout the most recent 8-yr period, 1964 through 1971, from Cape Blanco to San Diego (lat. 42°N to lat. 33°N). In contrast, along Baja California (lat. 30°N to lat. 24°N) strikingly low anomalies are indicated for the 4 successive years, 1965 through 1968.

The period 1955 through 1959 has anomalously high values from the Los Angeles Bight to the southernmost point covered by the grid (lat. 33°N to lat. 21°N). In fact, the anomalously high values during this period extend all the way north to the Straits of Juan de Fuca (lat. 48°N) if the year 1958 which is anomalously low in the more northern area is left out. The low yearly mean values for 1958 are largely due to the extremely low first quarter value previously discussed.

Low annual absolute values of the indices are found for the first 4 yr of the series (1946-49) at nearly all locations. As previously mentioned this may be due, at least in part, to relatively sparse data coverage in the early years leading to some smoothing of the gradients used in the computations.

Conclusion

Anomalies of the type discussed may have important marine biological consequences. Vertical displacements of the thermocline due to intense convergences or divergences such as that indicated for February 1950 may affect the depth on the continental shelf where groundfish are located. Anomalous upwellings and downwellings undoubtably affect productivity and the concentrations of primary producers and zooplankton.

They may also affect recruitment and distribution of fishery resources, particularly where the anomaly is of longer term or recurs in successive years.

In view of these possibilities it is hoped that biologists will find the indices presented here to be convenient and suitable for incorporation into studies of the dynamics of biological distributions, and that empirical associations may lead to ecological hypotheses and finally to experiments which can verify both the hypotheses and the indices presented in this report. Finally, although this work was directed primarily toward developing a tool for biological and fisheries research, it is suggested that these indices may find applications in such fields as coastal oceanography, fog research, and studies of climate and weather of coastal regions.

ACKNOWLEDGMENTS

Invaluable discussion and advice was provided by James H. Johnson, Gunter R. Seckel, and Douglas R. McLain of the Pacific Environmental Group, National Marine Fisheries Service, NOAA, throughout this project, from its conception through the completion of the manuscript.

Atmospheric pressure data and electronic computing and plotting facilities were provided by the U.S. Navy, Fleet Numerical Weather Central.

LITERATURE CITED

- BAKUN, A.
1971. Climatology of upwelling off California. (Abstract.) (030), AGU 1971 Fall Annu. Meet. EOS-Trans. Am. Geophys. Union 52(11):850.
- CUSHING, D. H.
1969. Upwelling and fish production. FAO Fish. Tech. Pap. 84, 40 p.
- EKMAN, V. W.
1905. On the influence of the earth's rotation on ocean currents. Ark. Mat. Astron. Fys. 2, 11:1-52.
- HSUEH, Y. and J. J. O'BRIEN.
1971. Steady coastal upwelling induced by an along-shore current. J. Phys. Ocean. 1:180-186.
- HUGHES, R. E.
1966. Computer products manual. Fleet Num. Weather Facil., Tech. Note 21, 301 p.
- RYTHER, J. H.
1969. Photosynthesis and fish production in the sea. Science (Wash., D.C.) 166:72-76.
- SMITH, R. L.
1967. Note on Yoshida's (1955) theory of coastal upwelling. J. Geophys. Res. 72:1396-1397.
- STOMMEL, H., and W. S. WOOSTER.
1965. Reconnaissance of the Somali Current during the southwest monsoon. Proc. Natl. Acad. Sci. 54:8-13.
- SVERDRUP, H. U., M. W. JOHNSON, and R. H. FLEMING.
1942. The oceans, their physics, chemistry, and general biology. Prentice-Hall, New York, 1087 p.
- WOOSTER, W. S.
1960. El Niño. Rep. Calif. Coop. Oceanic Fish. Invest. 7:43-45.
- YOSHIDA, K.
1955. Coastal upwelling of the California coast. Rec. Oceanogr. Works Jap. 2(2):8-20.

APPENDIX

Tabulations and plots of coastal upwelling indices

The following pages display the coastal upwelling indices by month, quarter, and year for 15 near-coastal points over the period 1946-71. The display for each location comprises six pages. The first four contain monthly values. The fifth contains quarterly values. The sixth contains the completion of the table of quarterly values and the table of yearly mean values.

The first column of figures on each page indicates the month, quarter, or year to which the information appearing on the same line pertains. In the tabulations by month, the first two digits refer to the year and the last two to the month. For example, 4601 refers to January 1946. In the tabulations by quarter the first two digits again refer to the year and the last two refer to the quarter. For example, 4601 in this case refers to first quarter (Jan., Feb., Mar.) 1946. In the tabulations by year the year is printed in full.

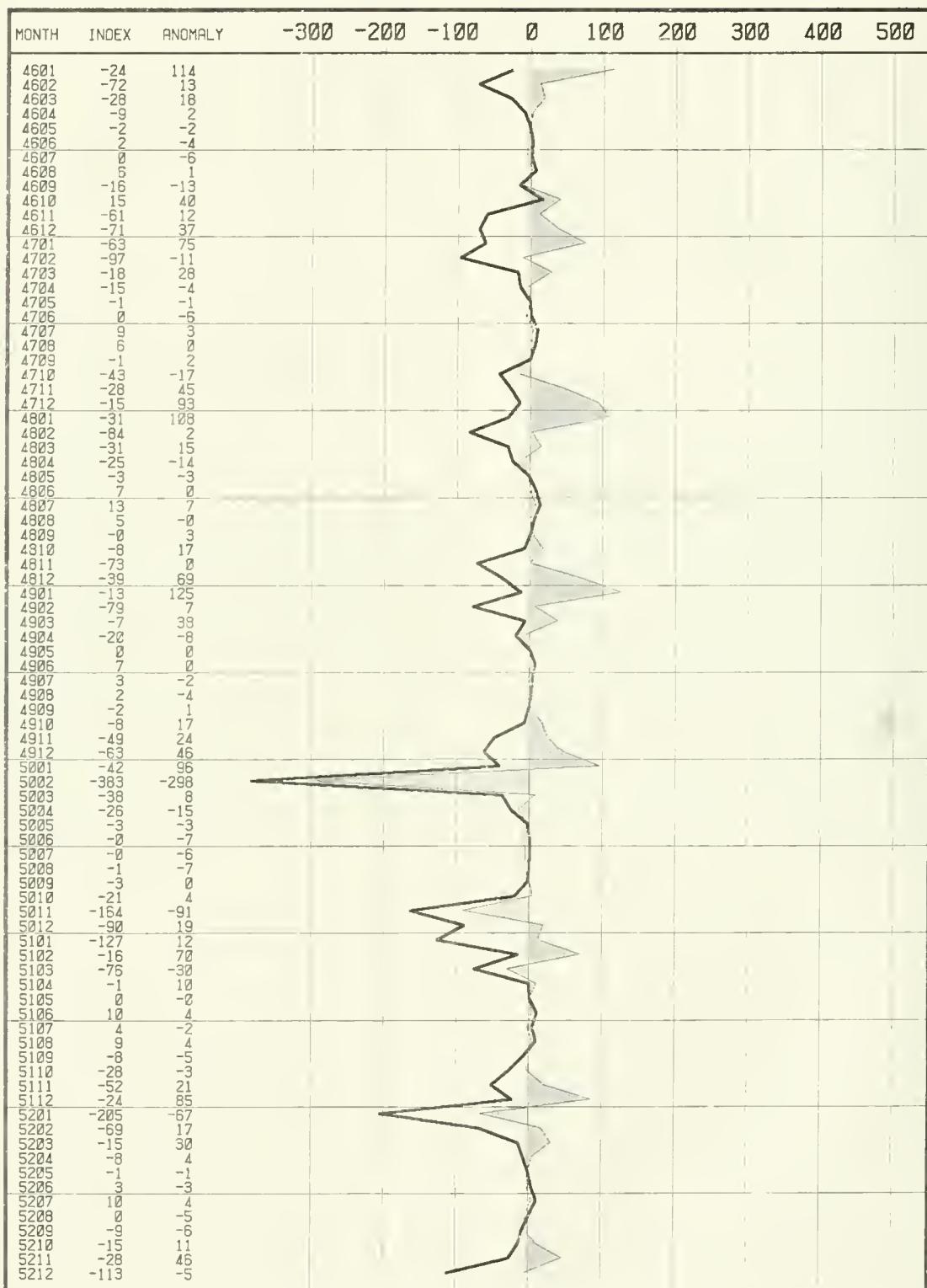
The second column contains the value of index for each period. The units are metric tons per second per 100 m of coastline. These units may be thought of as indicative of the average amount (metric tons or cubic meters) of water upwelled through the bottom of the Ekman layer each second along each 100 m of a straight line directed

along the dominant trend of the coast on a scale of about 200 miles. However, it must be remembered that because of uncertainty in exact values of some of the constants employed and for other reasons outlined in the section on "Method," these indices should be regarded more as indicative of relative fluctuations of upwelling intensity at each point than as quantitative measures of absolute magnitude. The quarterly and yearly values are averages of the monthly values weighted by the number of days in each month. An exception to this rule is February which is considered to always contain 28 days in order to avoid a different set of long-term means for leap years. Such refinement is well below the level of sensitivity of these indices.

The third column contains the anomalies or deviations from the long-term mean value of the index at the particular point for the particular month, quarter, or year over the 20-yr period, 1948-67.

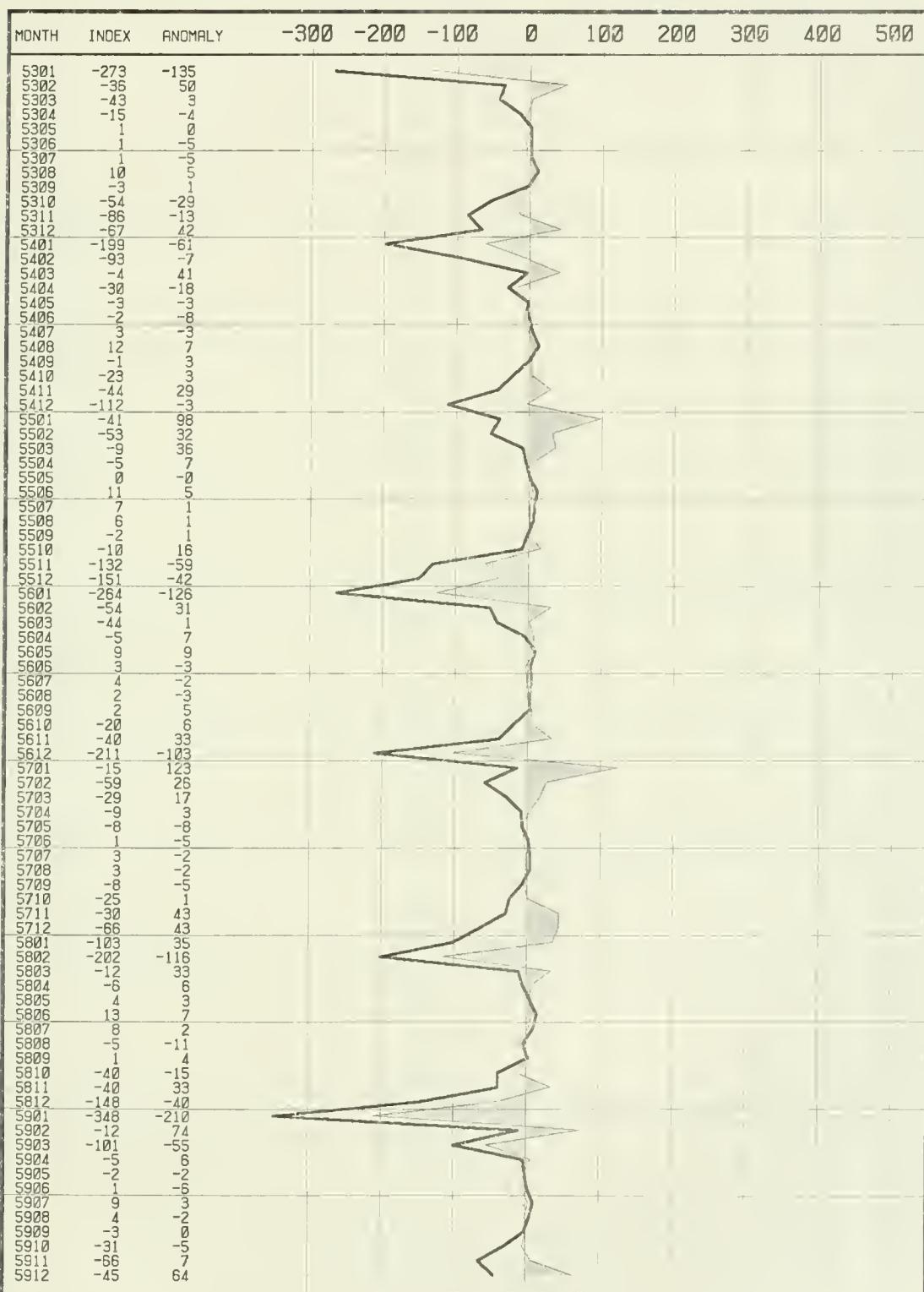
The values and anomalies are plotted to the right of each page. The heavy line indicates the values of the upwelling index while the lighter line indicates the anomalies. The deviations of the anomaly line from the zero line are shaded.

UPWELLING INDEX AT 60N, 149W BY MONTH



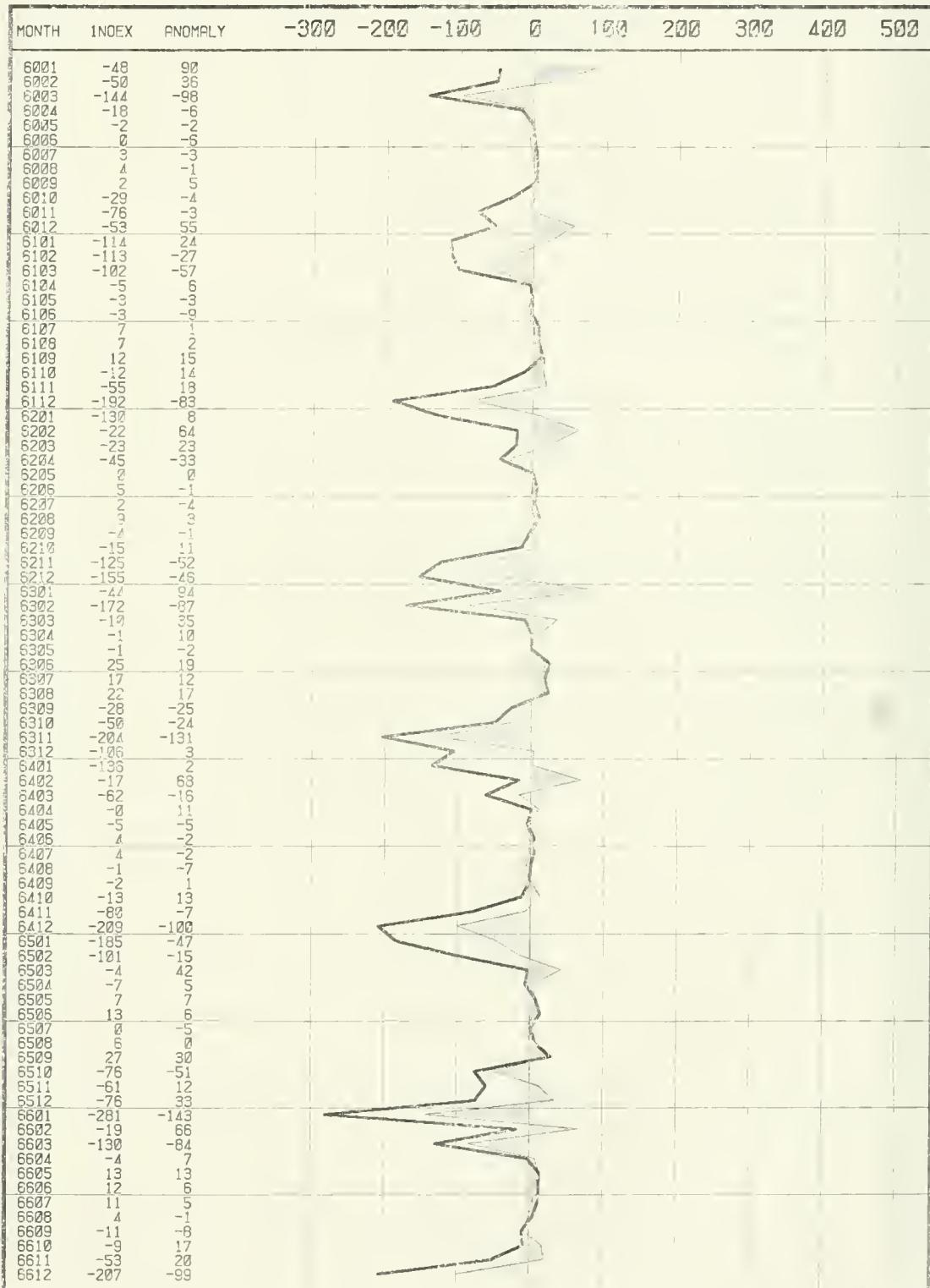
UPWELLING INDEX AT 60N, 149W

BY MONTH

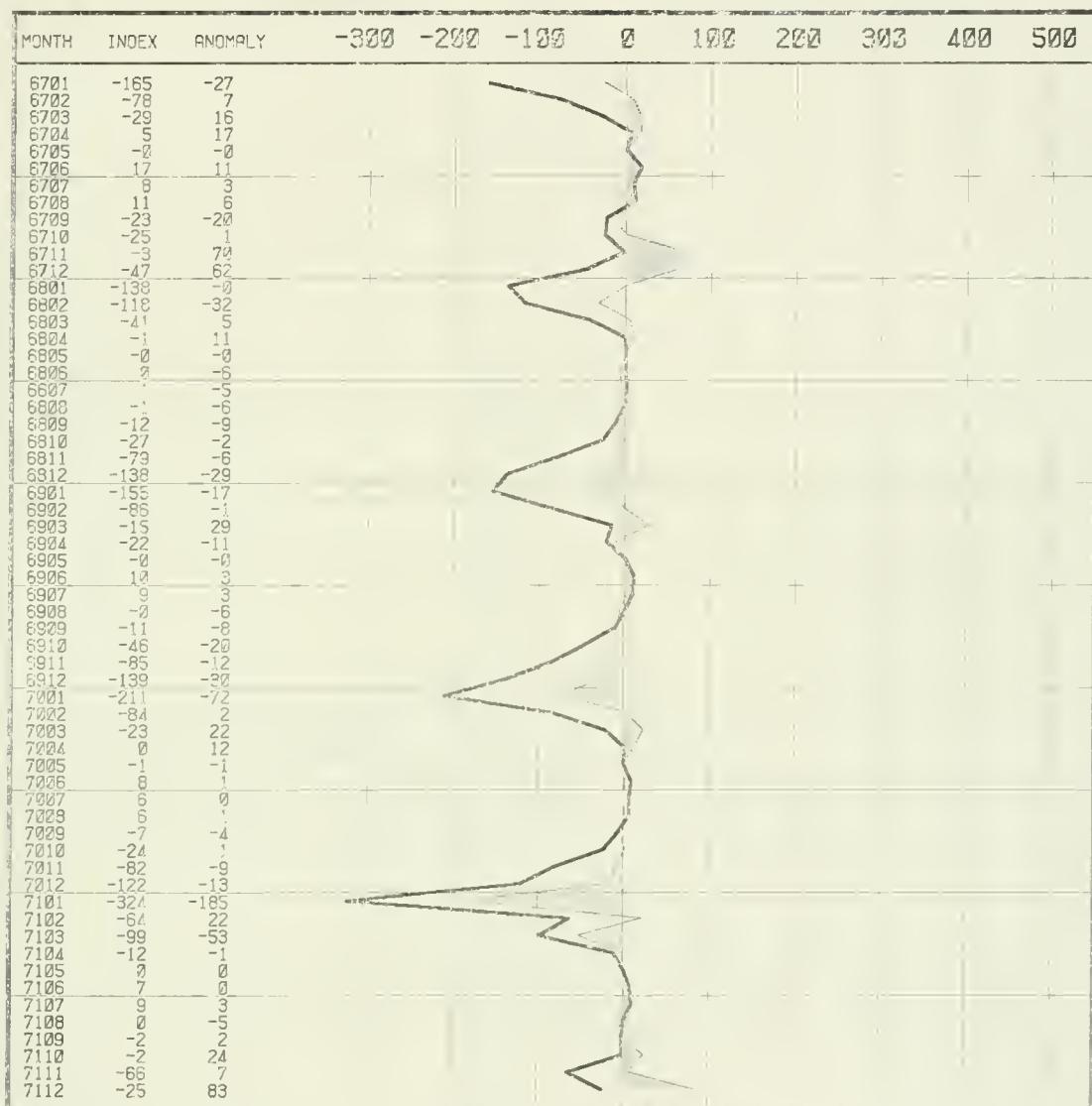


UPWELLING INDEX AT 60N, 149W

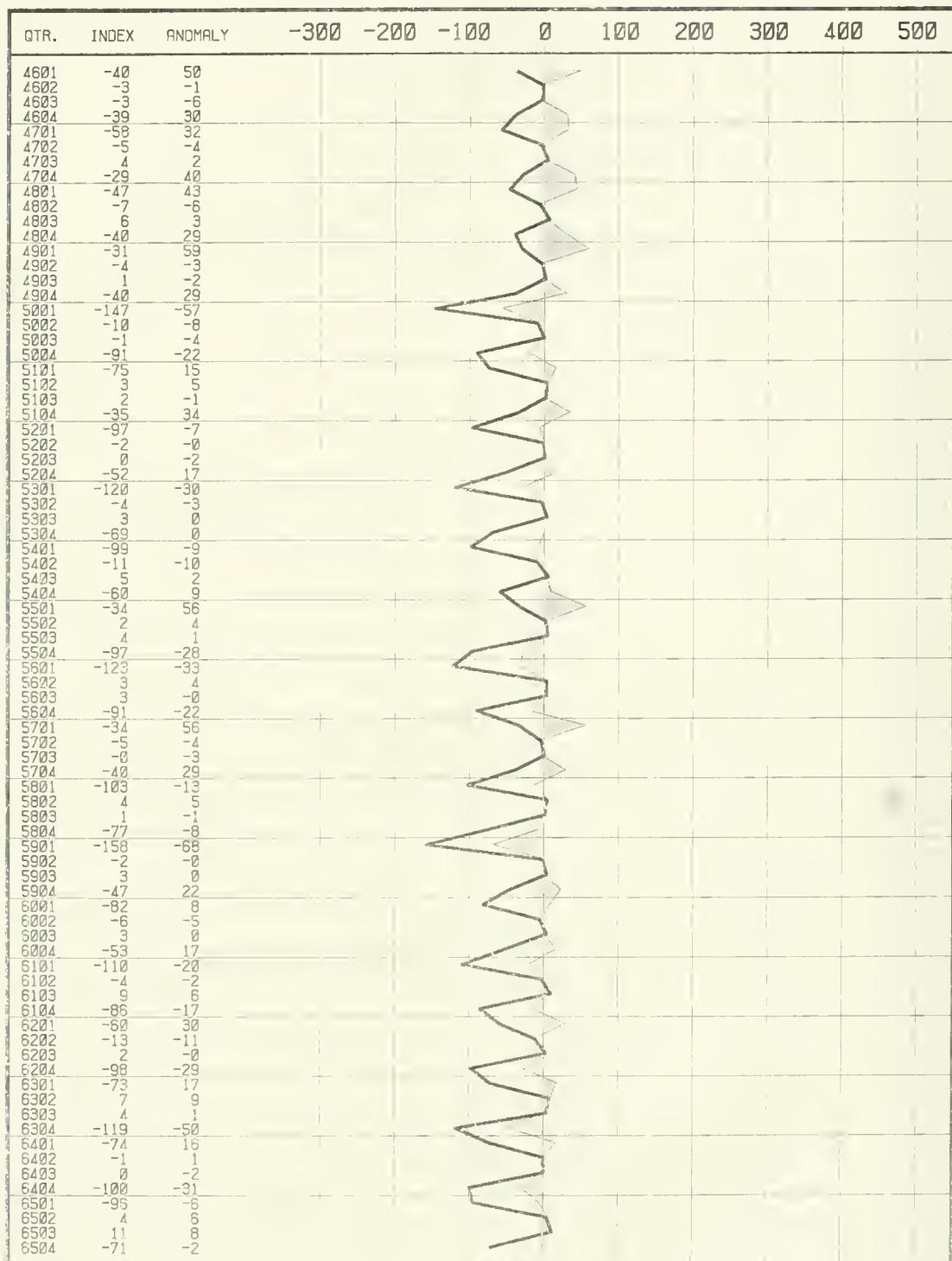
BY MONTH



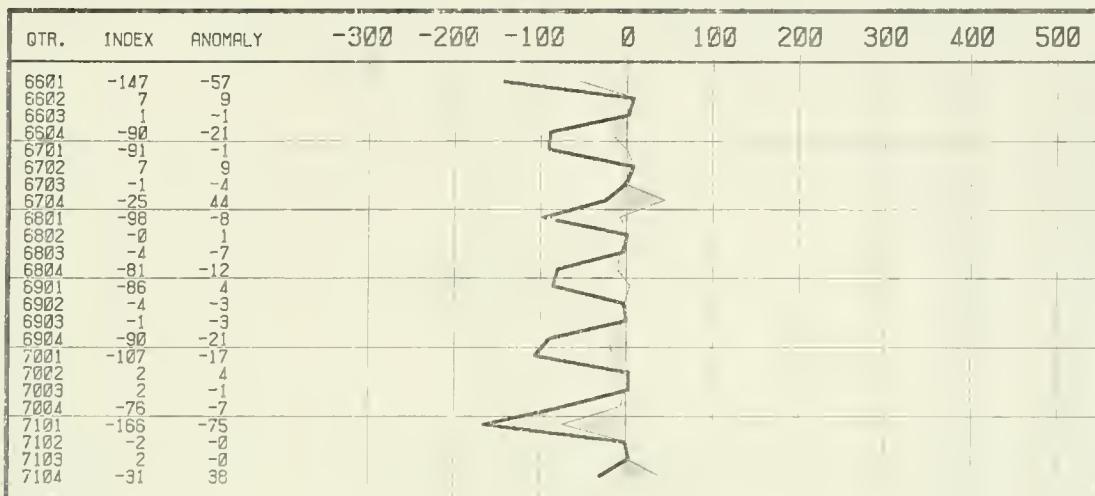
UPWELLING INDEX AT 60°N, 149°W BY MONTH



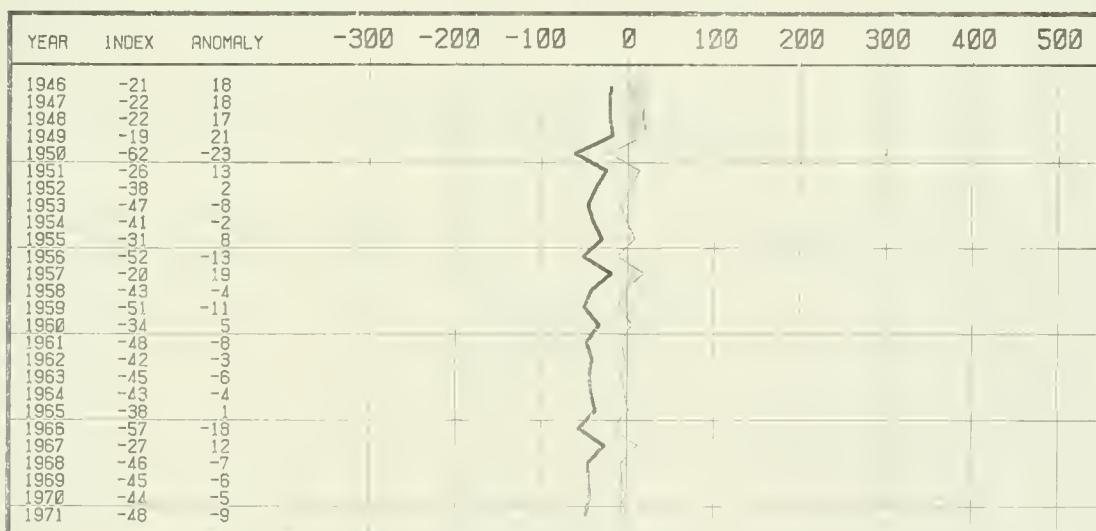
UPWELLING INDEX AT 60N, 149W BY QUARTER



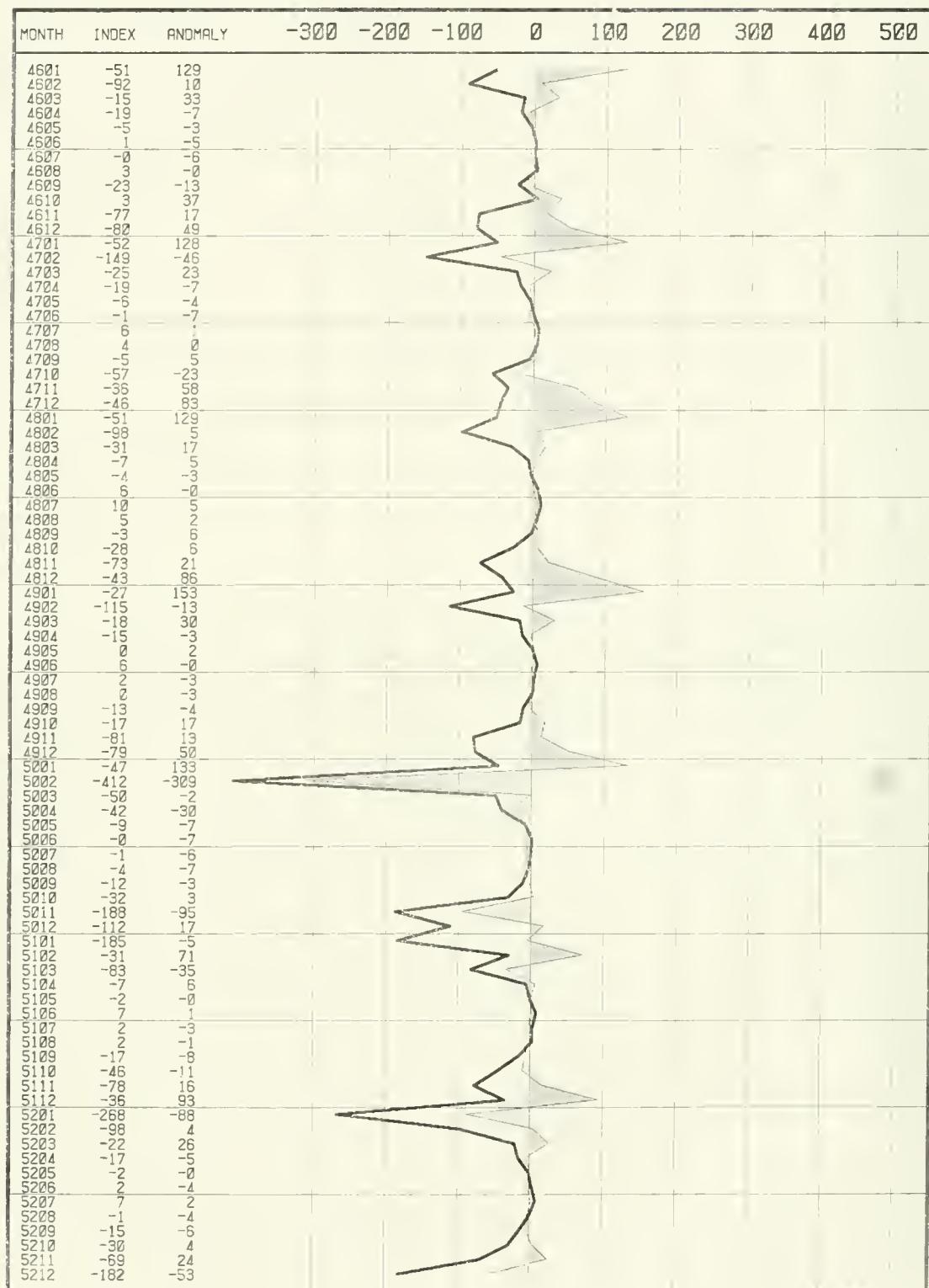
UPWELLING INDEX AT 60N, 149W BY QUARTER



UPWELLING INDEX AT 60N, 149W BY YEAR

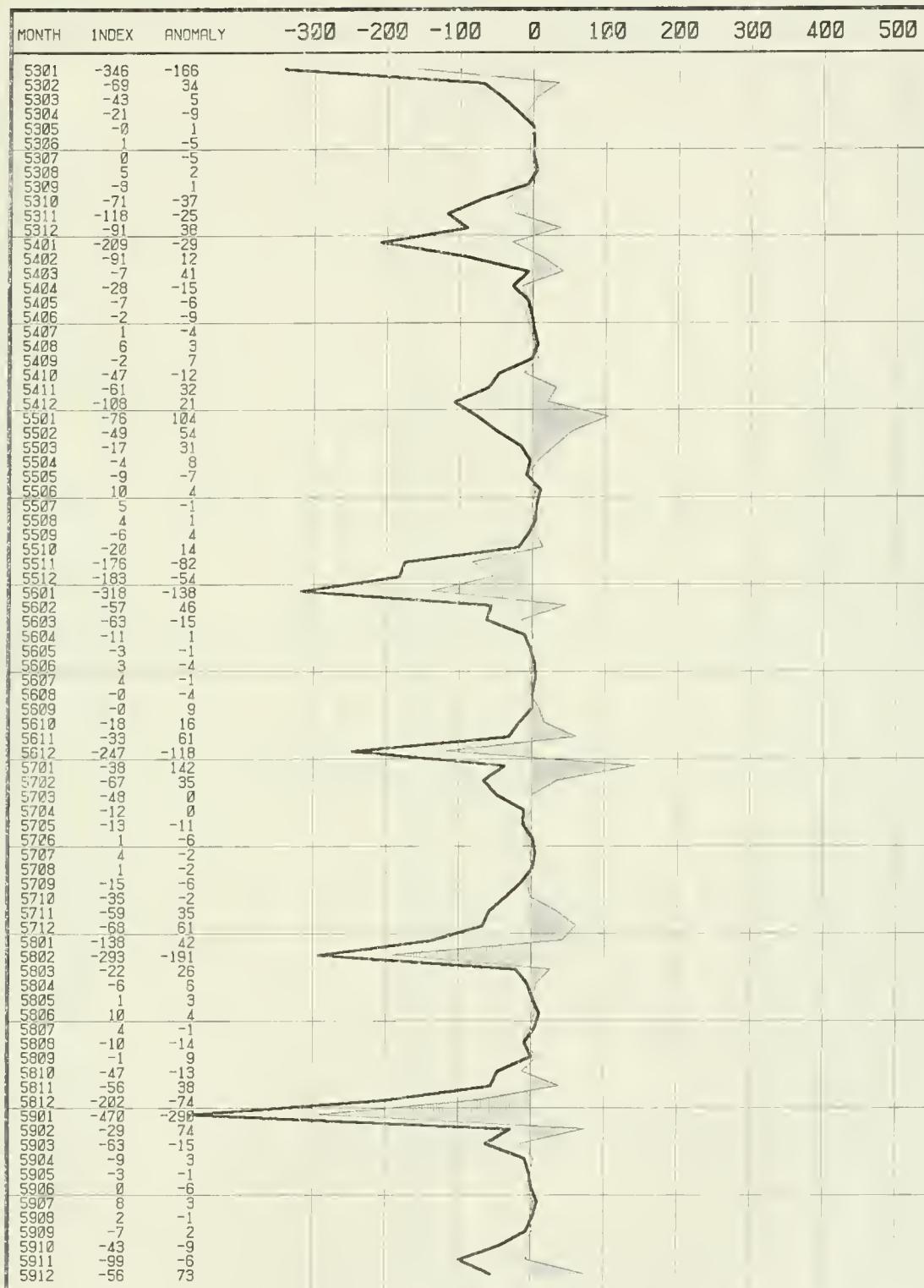


UPWELLING INDEX AT 60N, 146W BY MONTH



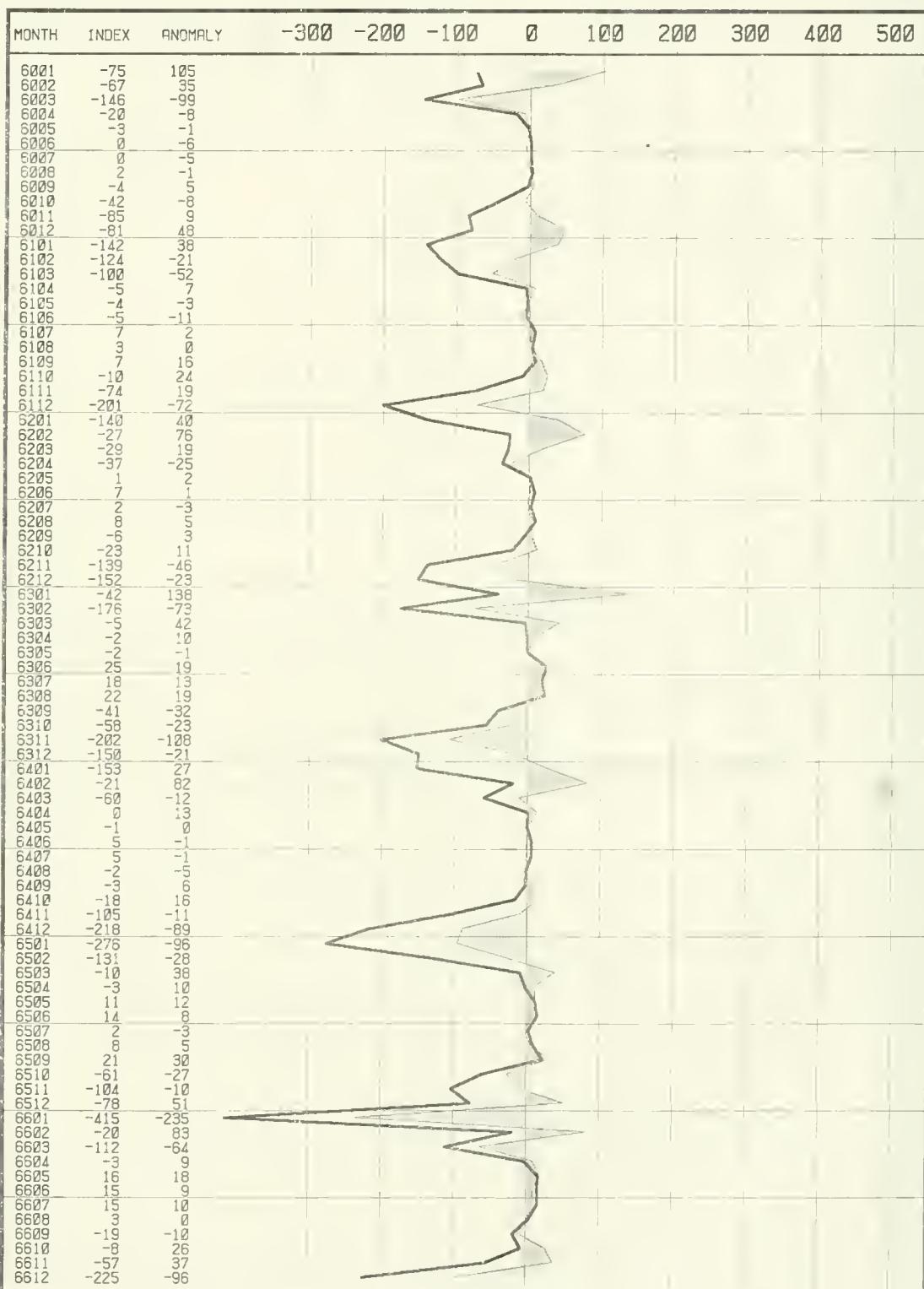
UPWELLING INDEX AT 60N, 146W

BY MONTH



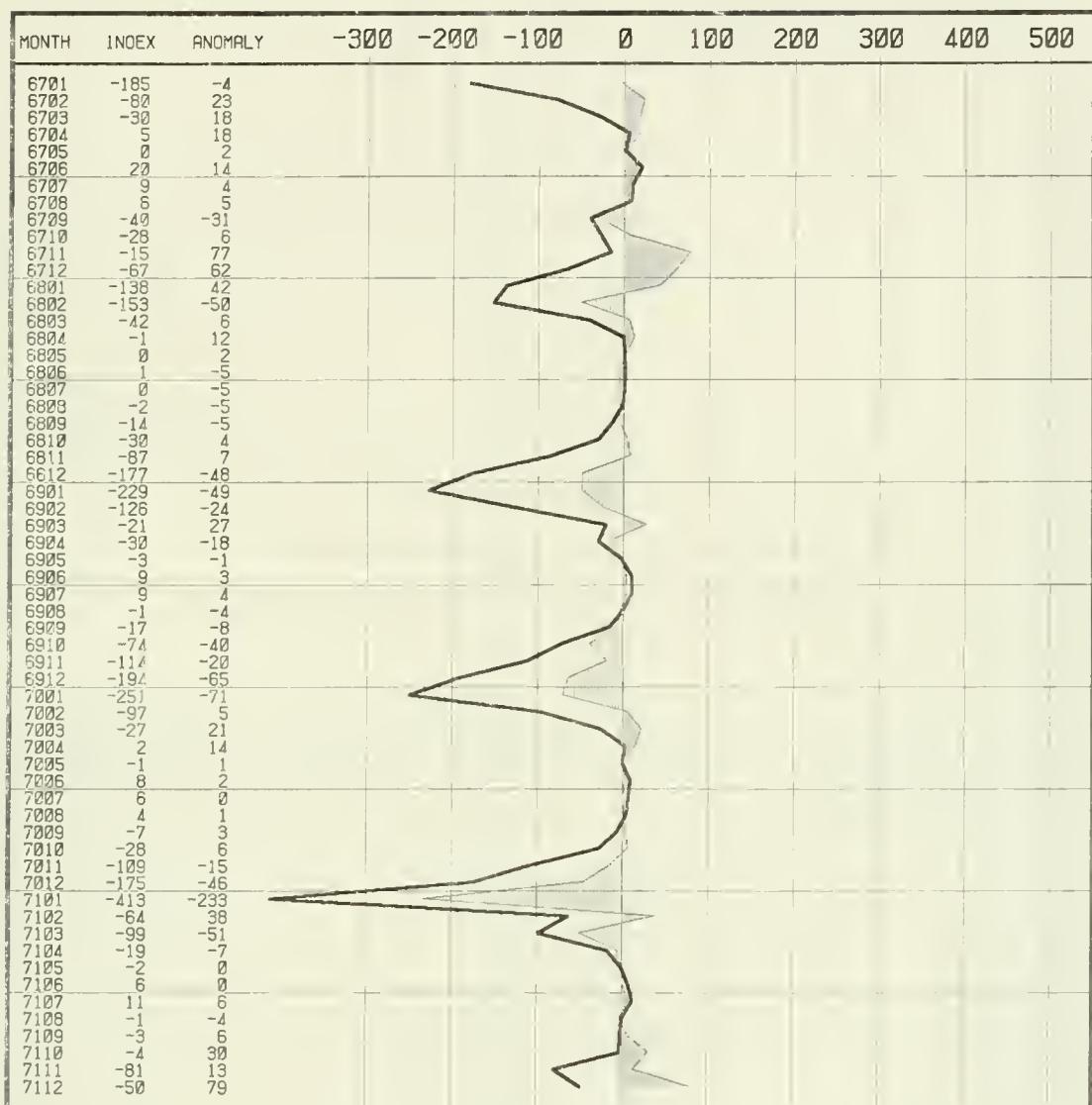
UPWELLING INDEX AT 60N, 146W

BY MONTH

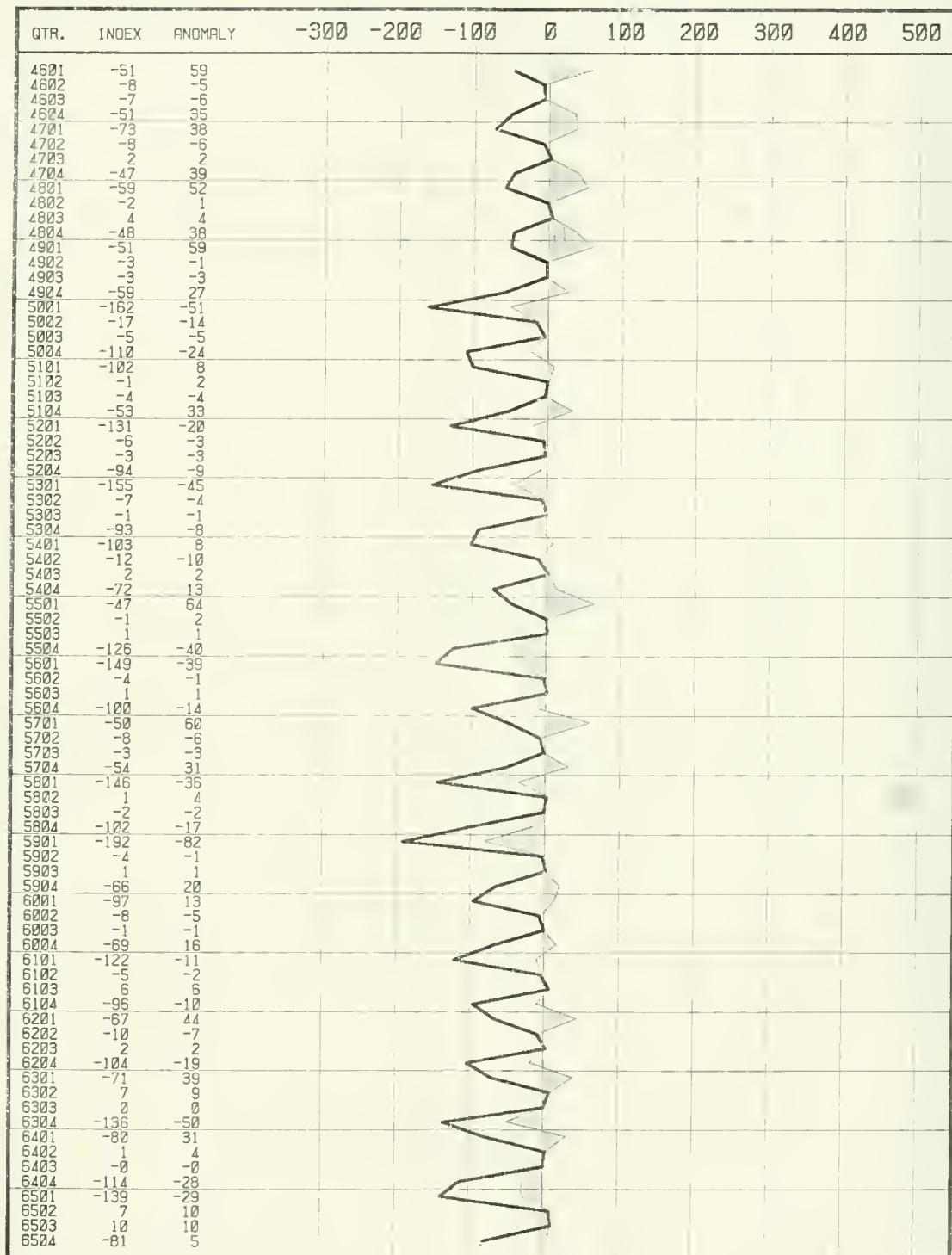


UPWELLING INDEX AT 60N, 146W

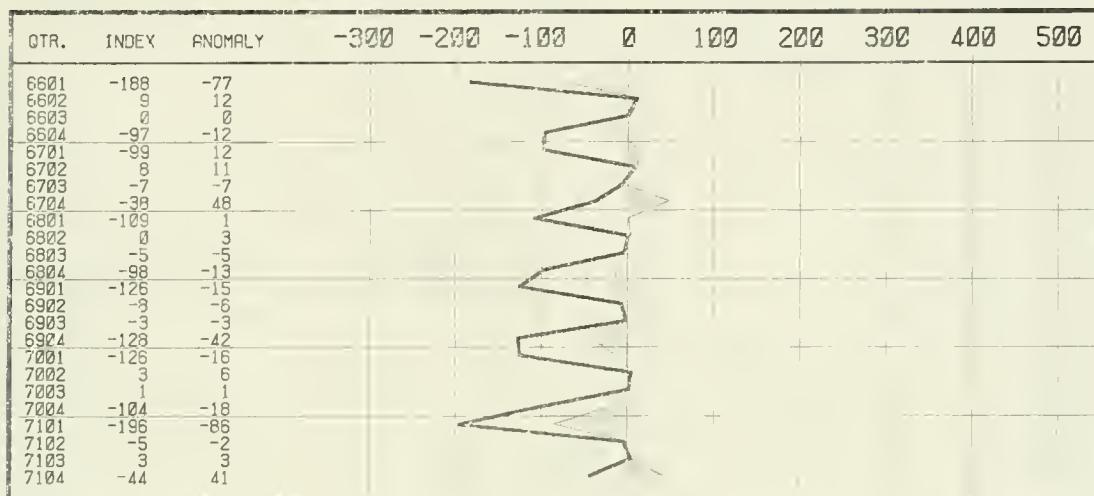
BY MONTH



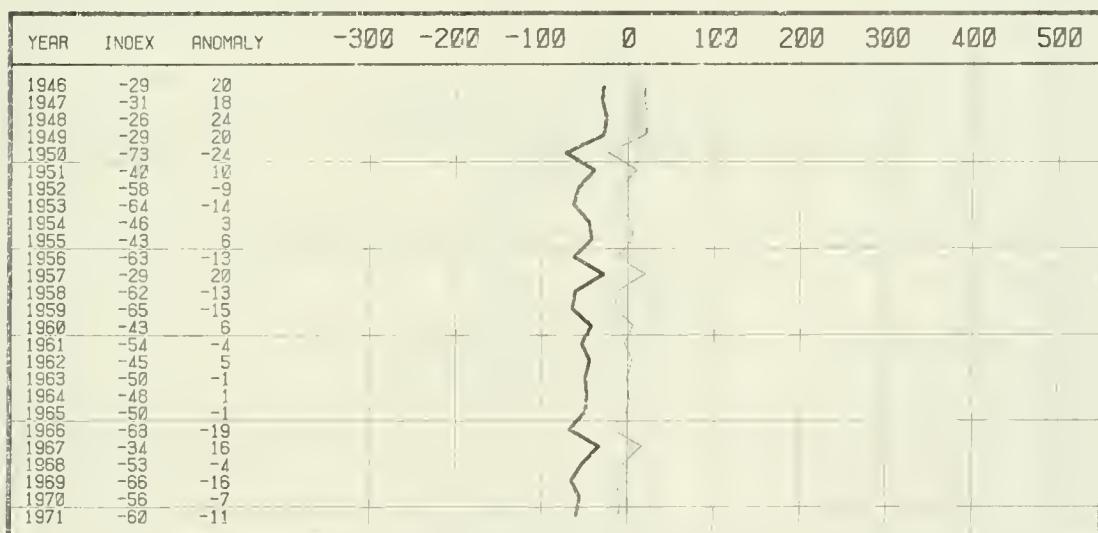
UPWELLING INDEX AT 60N, 146W BY QUARTER



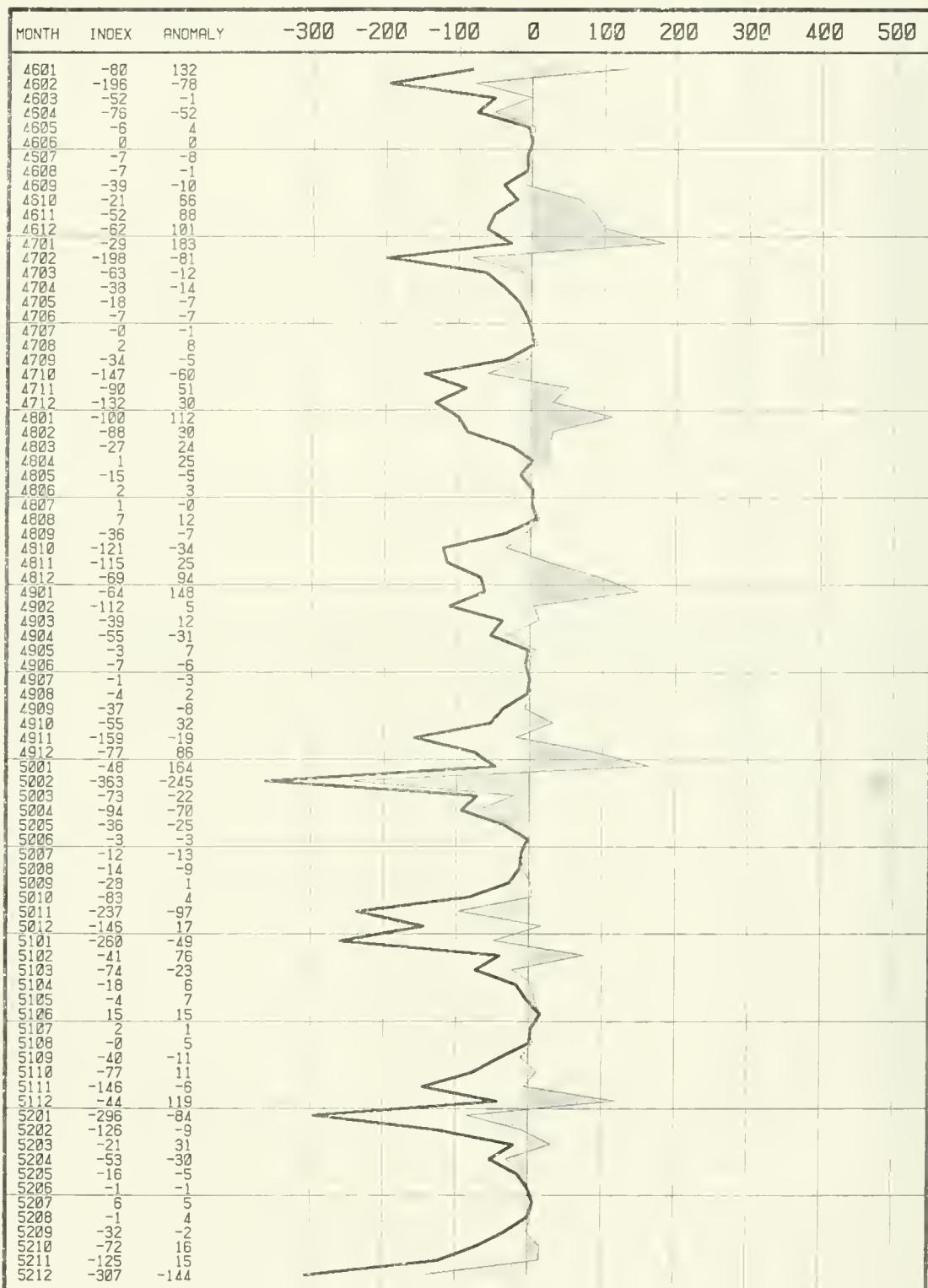
UPWELLING INDEX AT 60N, 146W BY QUARTER



UPWELLING INDEX AT 60N, 146W BY YEAR

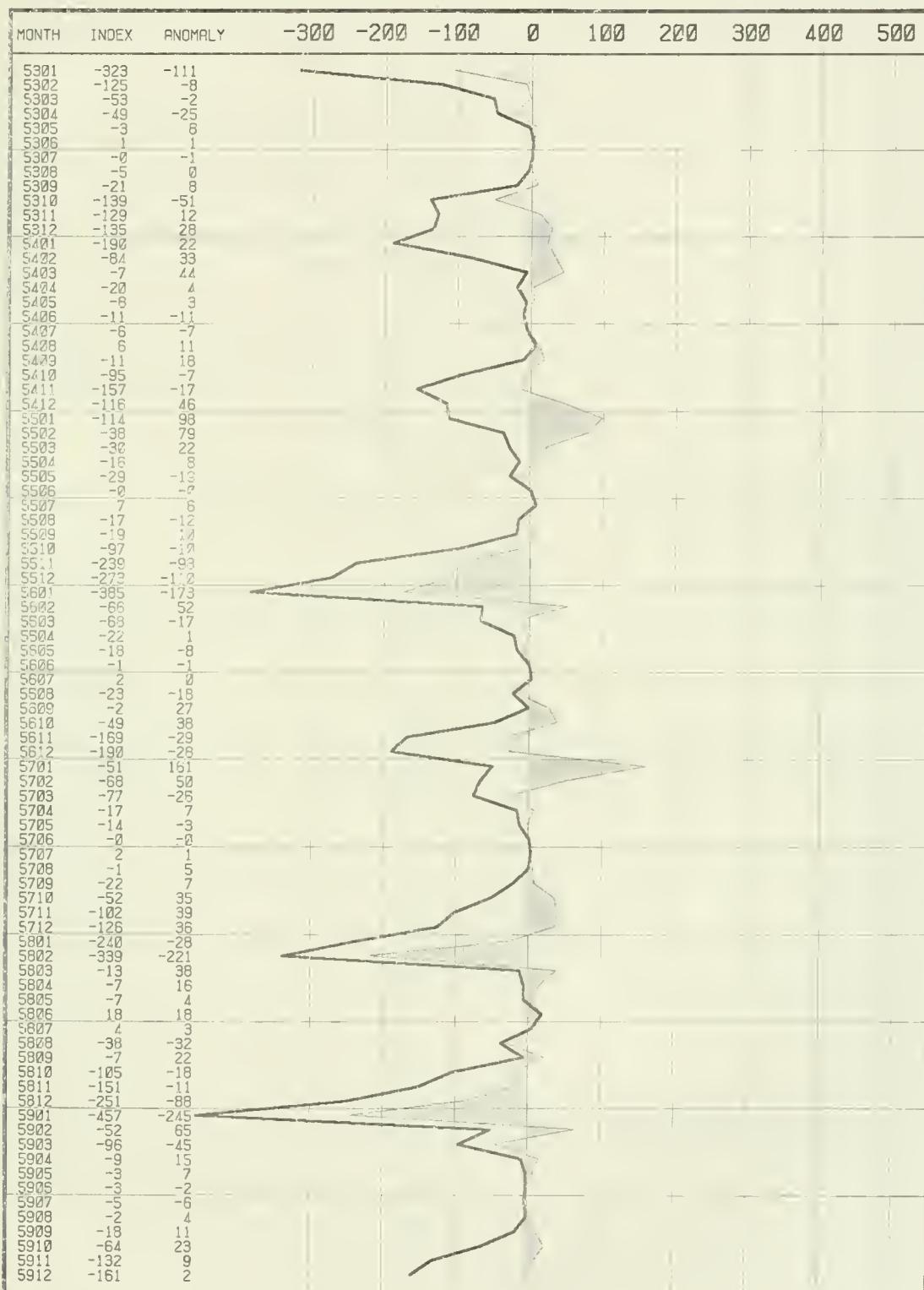


UPWELLING INDEX AT 57N, 137W BY MONTH

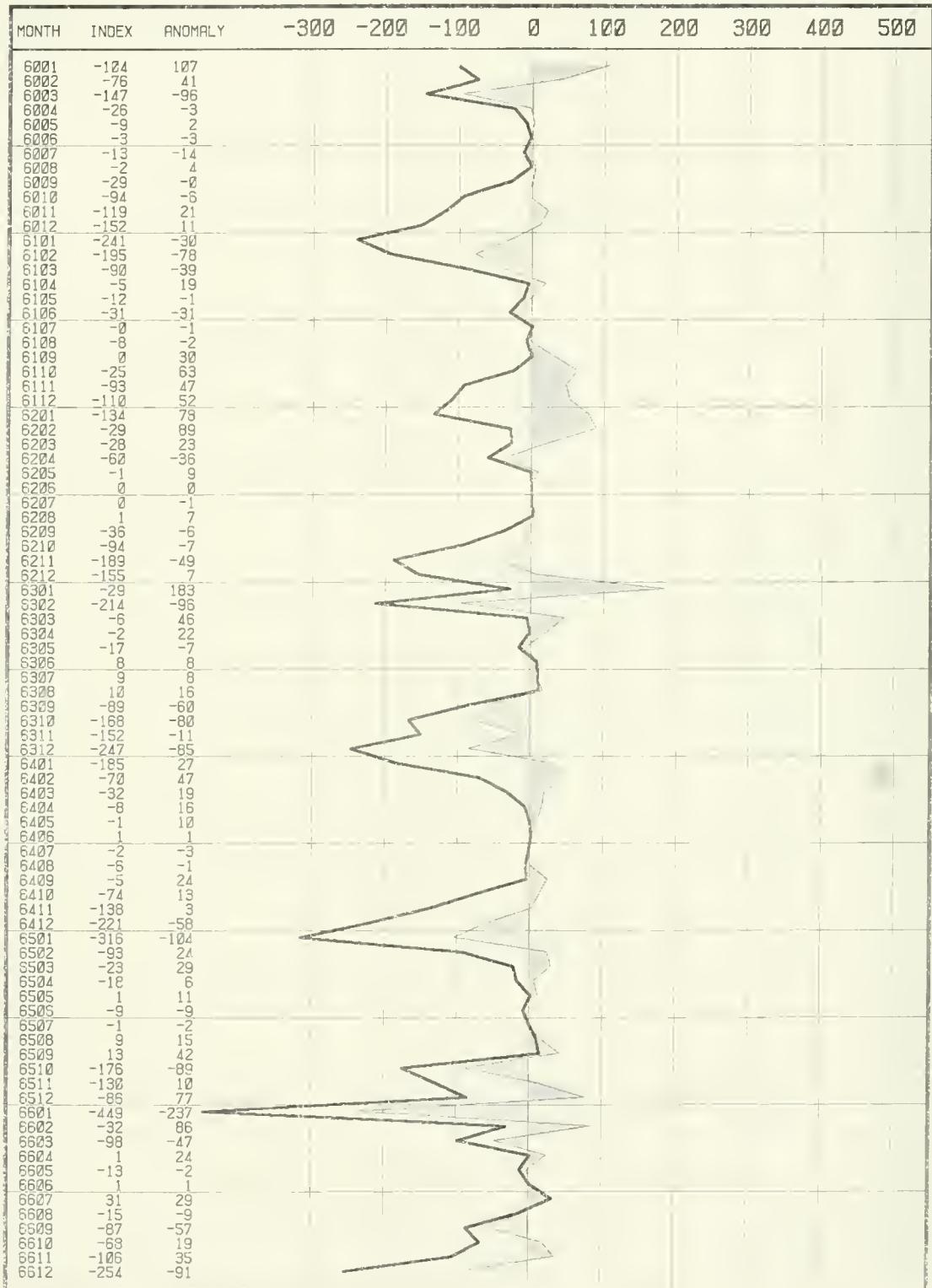


UPWELLING INDEX AT 57N, 137W

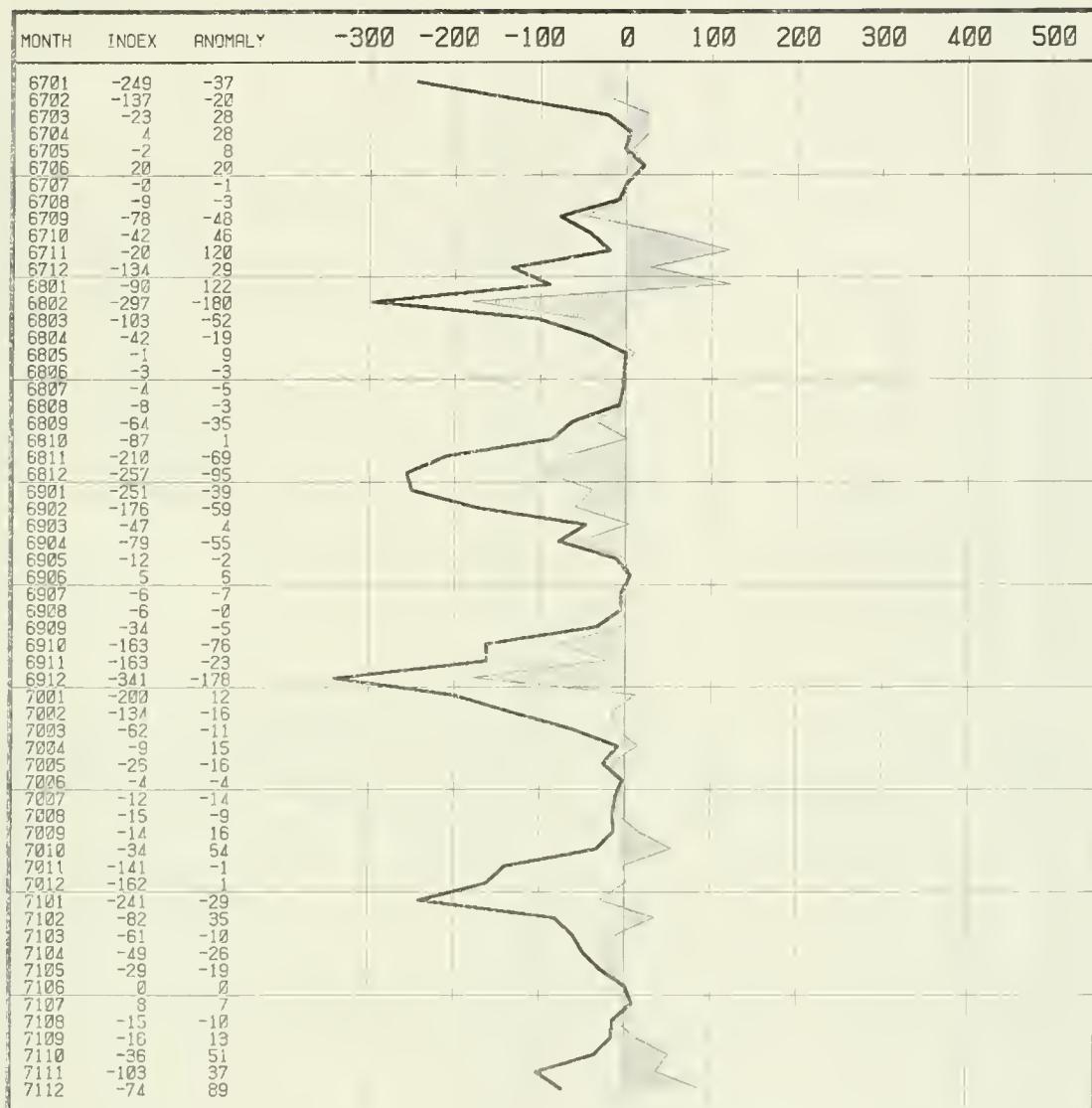
BY MONTH



UPWELLING INDEX AT 57N, 137W BY MONTH



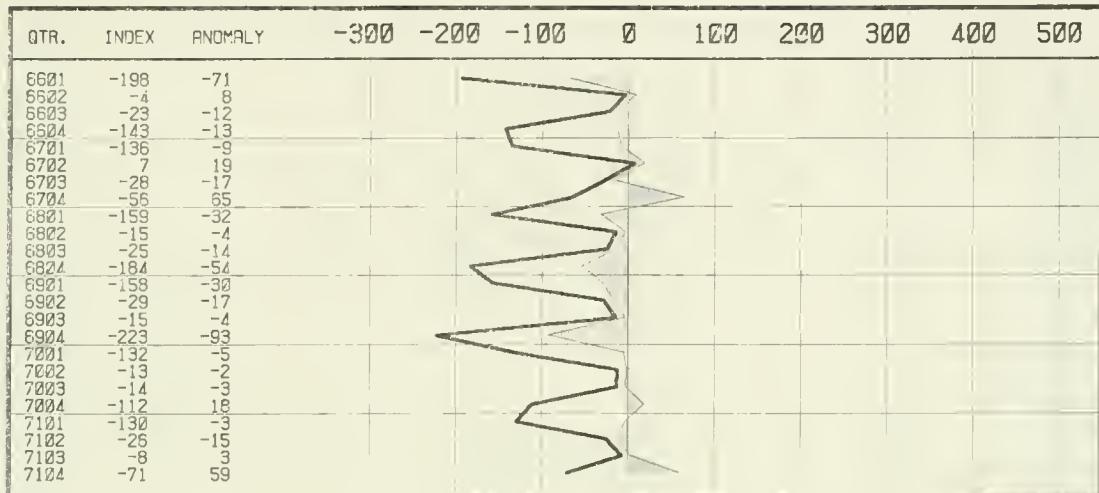
UPWELLING INDEX AT 57N, 137W BY MONTH



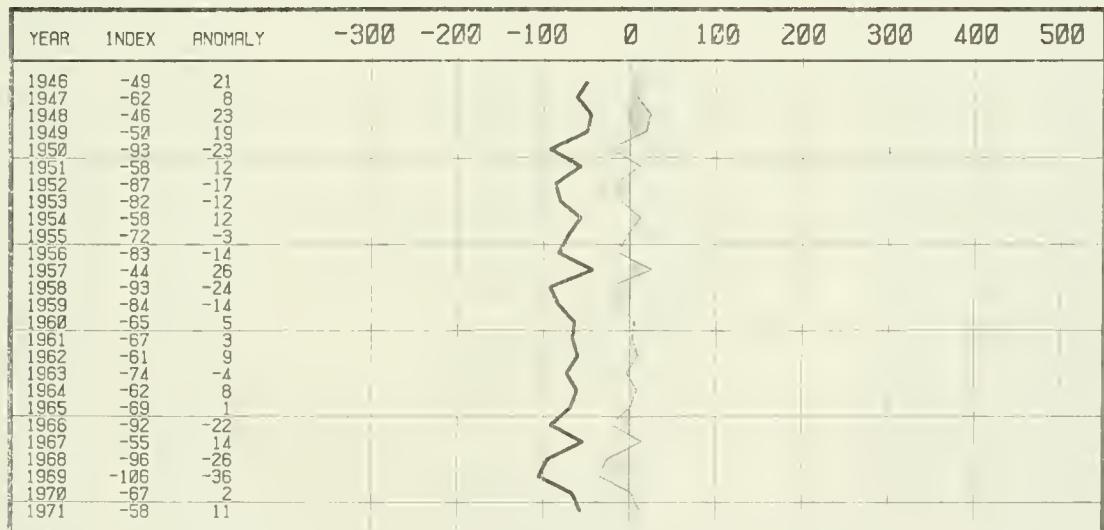
UPWELLING INDEX AT 57N, 137W BY QUARTER

QTR.	INDEX	ANOMALY	-300	-200	-100	0	100	200	300	400	500
4601	-106	21									
4602	-27	-16									
4603	-17	-6									
4604	-45	85									
4701	-93	34									
4702	-21	-9									
4703	-10	1									
4704	-123	7									
4801	-71	56									
4802	-4	7									
4803	-9	2									
4804	-101	29									
4901	-70	57									
4902	-21	-10									
4903	-14	-3									
4904	-97	34									
5001	-155	-28									
5002	-44	-33									
5003	-18	-7									
5004	-154	-24									
5101	-128	-1									
5102	-2	9									
5103	-13	-1									
5104	-88	42									
5201	-143	-21									
5202	-23	-12									
5203	-9	2									
5204	-168	-38									
5301	-166	-41									
5302	-17	-5									
5303	-9	2									
5304	-134	-4									
5401	-94	33									
5402	-13	-1									
5403	-4	7									
5404	-122	8									
5501	-61	66									
5502	-15	-4									
5503	-10	1									
5504	-202	-72									
5601	-177	-50									
5602	-14	-2									
5603	-8	3									
5604	-136	-6									
5701	-65	62									
5702	-10	1									
5703	-7	4									
5704	-93	37									
5801	-193	66									
5802	1	13									
5803	-14	-3									
5804	-169	-39									
5901	-207	-80									
5902	-5	7									
5903	-8	3									
5904	-119	11									
6001	-110	17									
6002	-13	-1									
6003	-14	-3									
6004	-122	8									
6101	-175	-48									
6102	-16	-4									
6103	-3	8									
6104	-76	54									
6201	-65	62									
6202	-20	-9									
6203	-11	-0									
6204	-146	-16									
6301	-78	49									
6302	-4	8									
6303	-23	-12									
6304	-189	-59									
6401	-97	30									
6402	-3	9									
6403	-4	7									
6404	-144	-14									
6501	-145	-18									
6502	-9	3									
6503	7	18									
6504	-131	-1									

UPWELLING INDEX AT 57N, 137W BY QUARTER

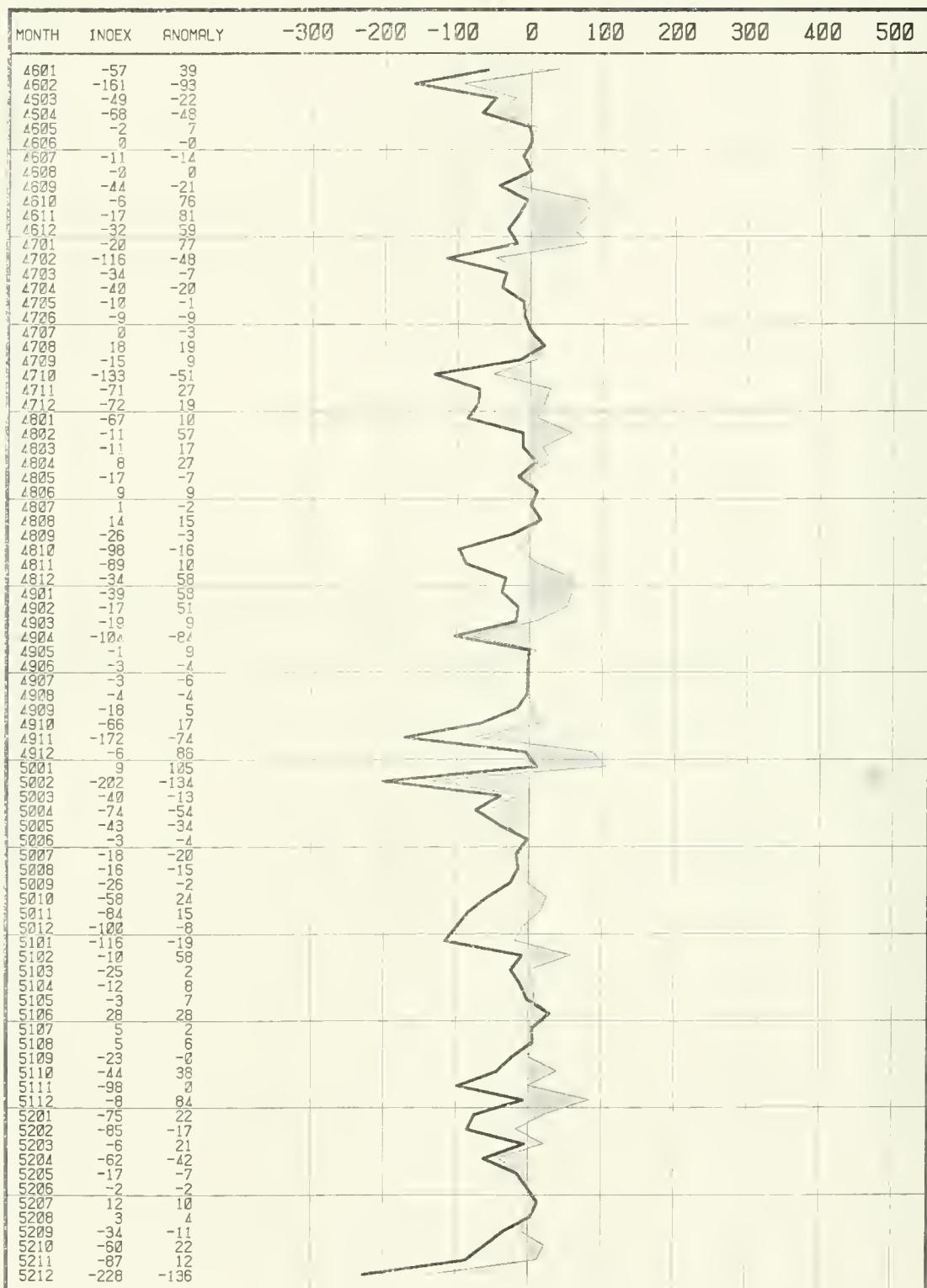


UPWELLING INDEX AT 57N, 137W BY YEAR

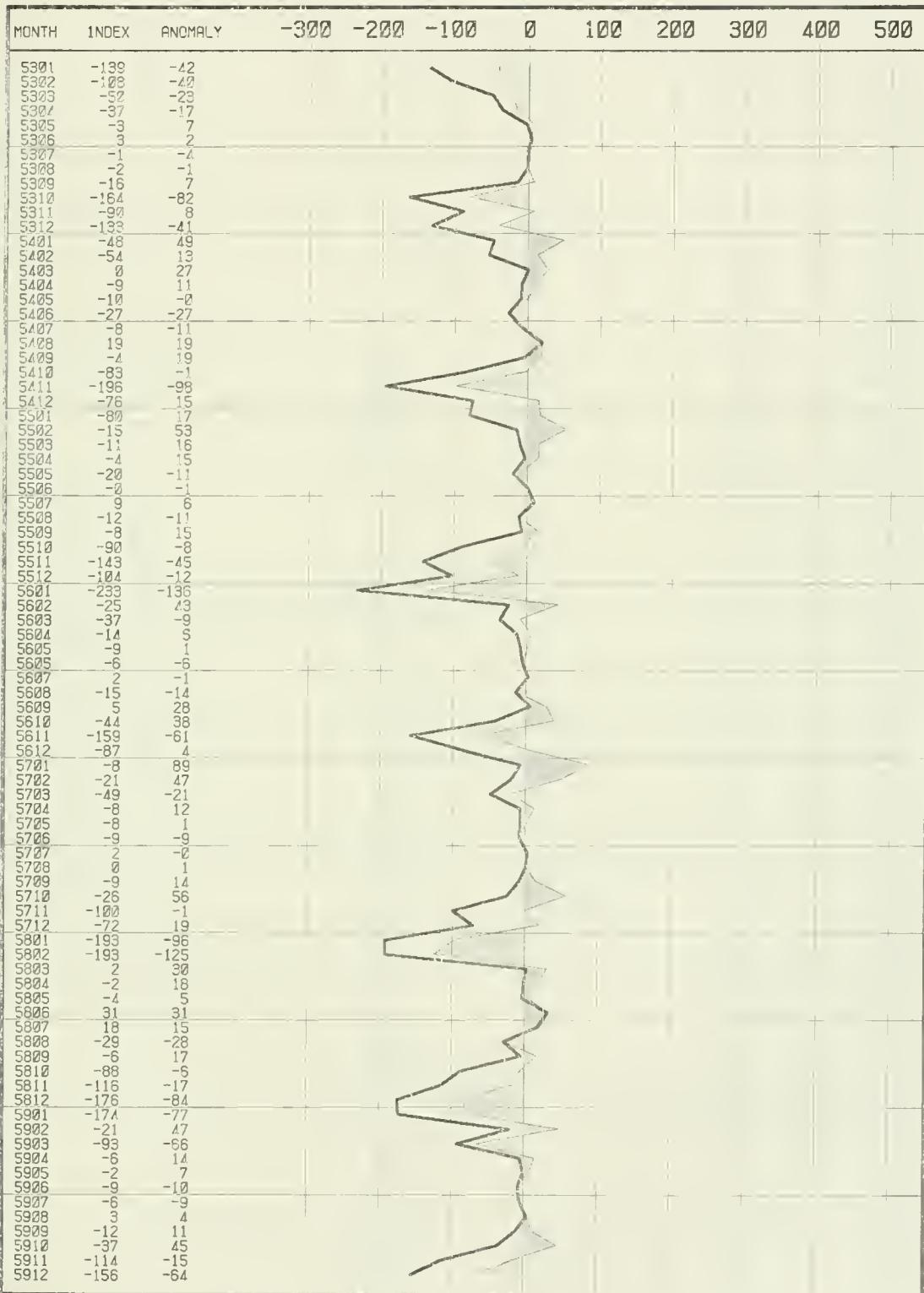


UPWELLING INDEX AT 54N, 134W

BY MONTH

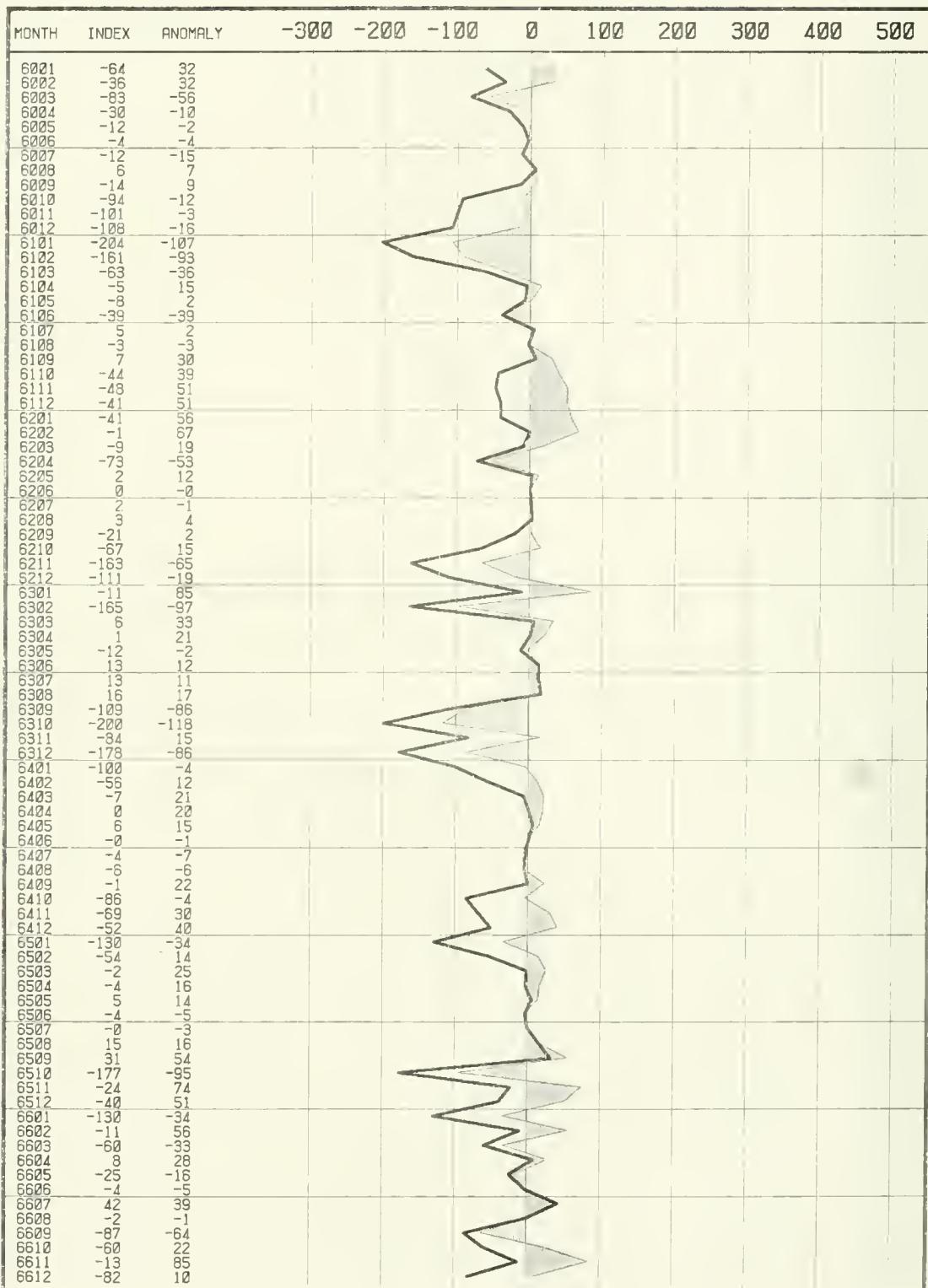


UPWELLING INDEX AT 54N, 134W BY MONTH



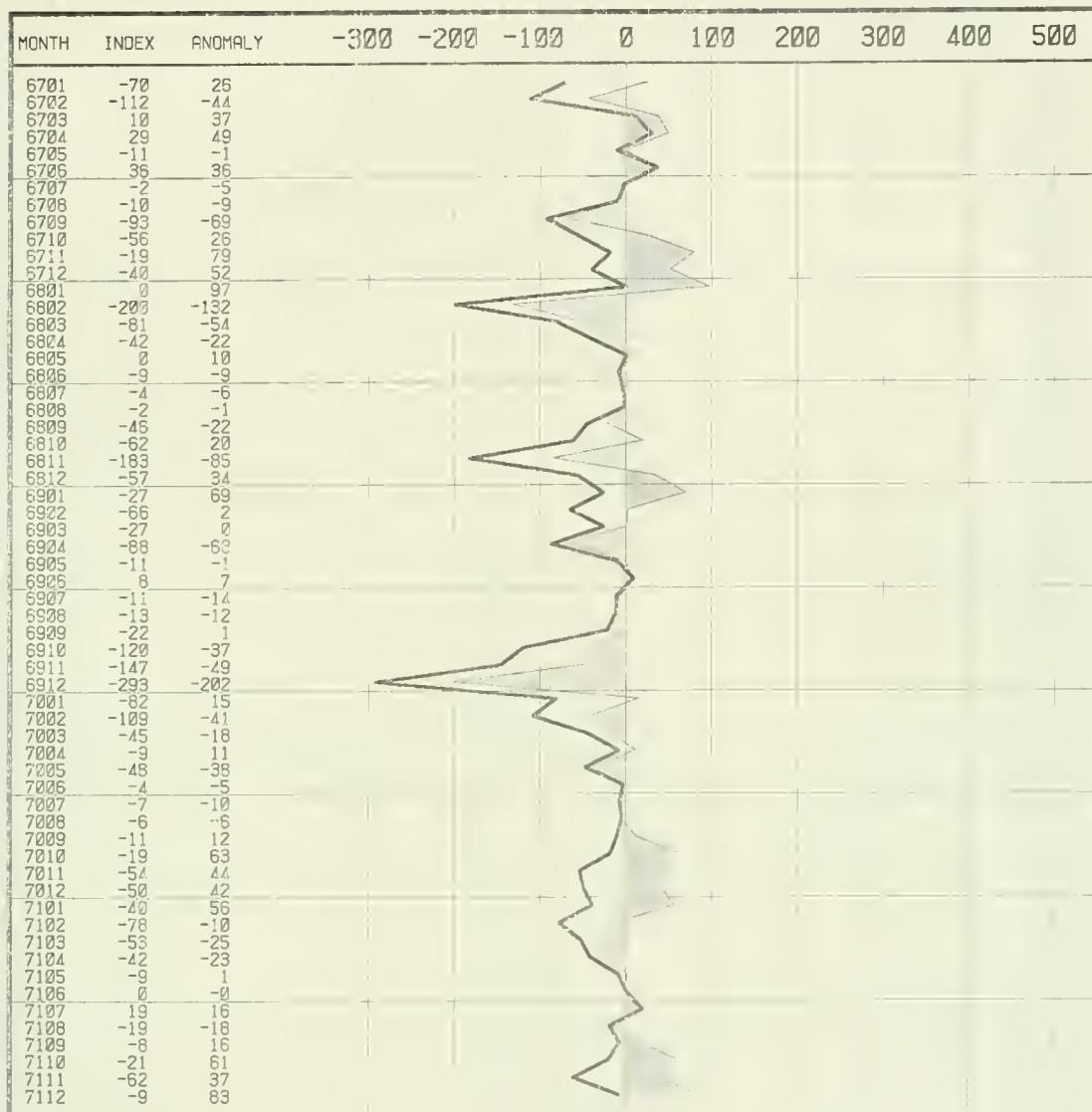
UPWELLING INDEX AT 54N, 134W

BY MONTH

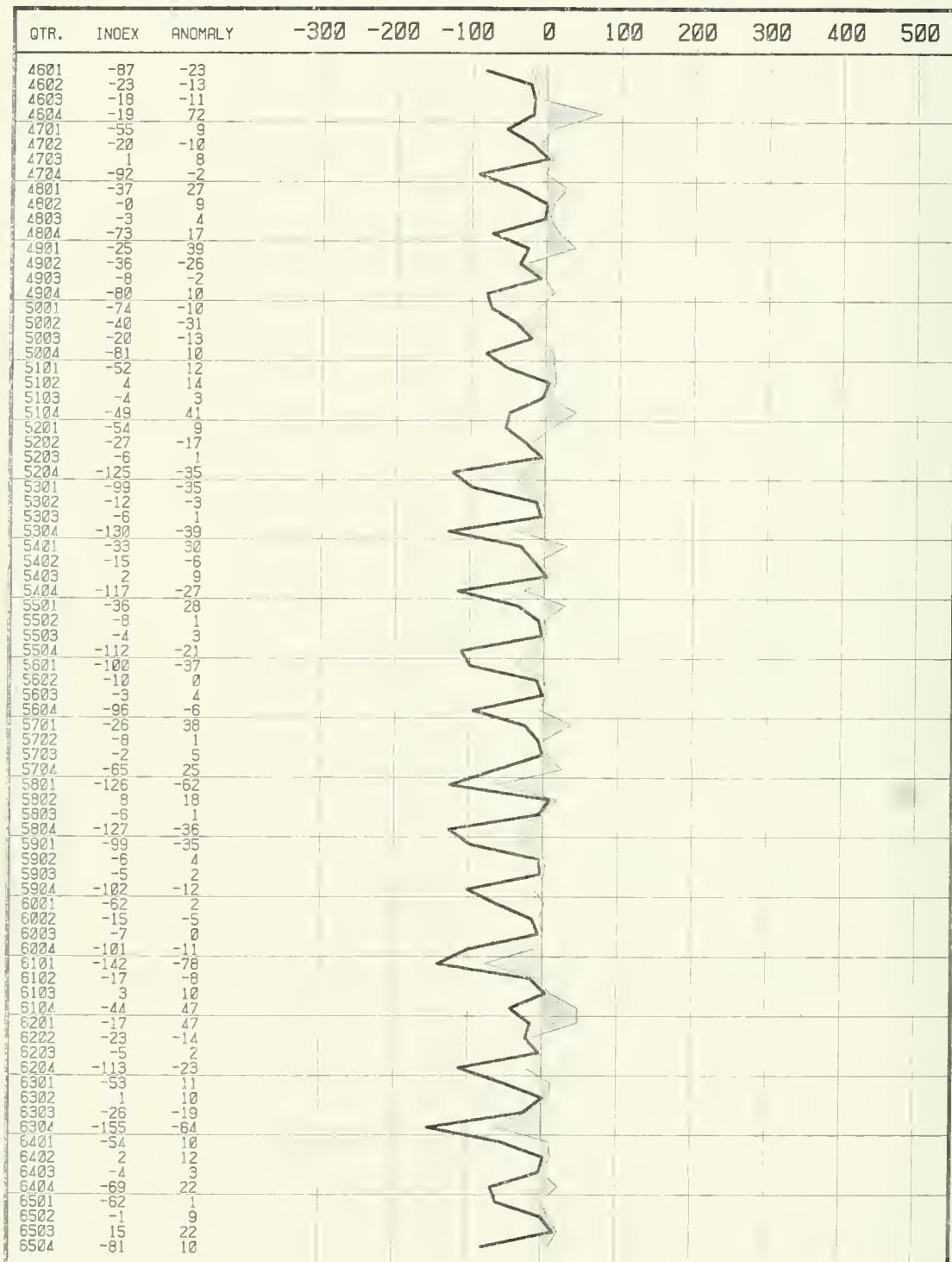


UPWELLING INDEX AT 54N, 134W

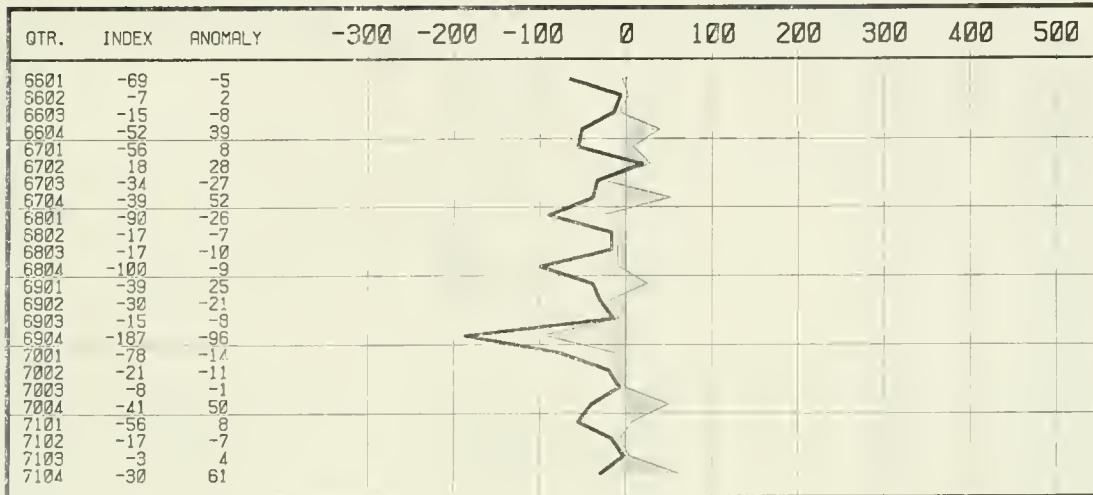
BY MONTH



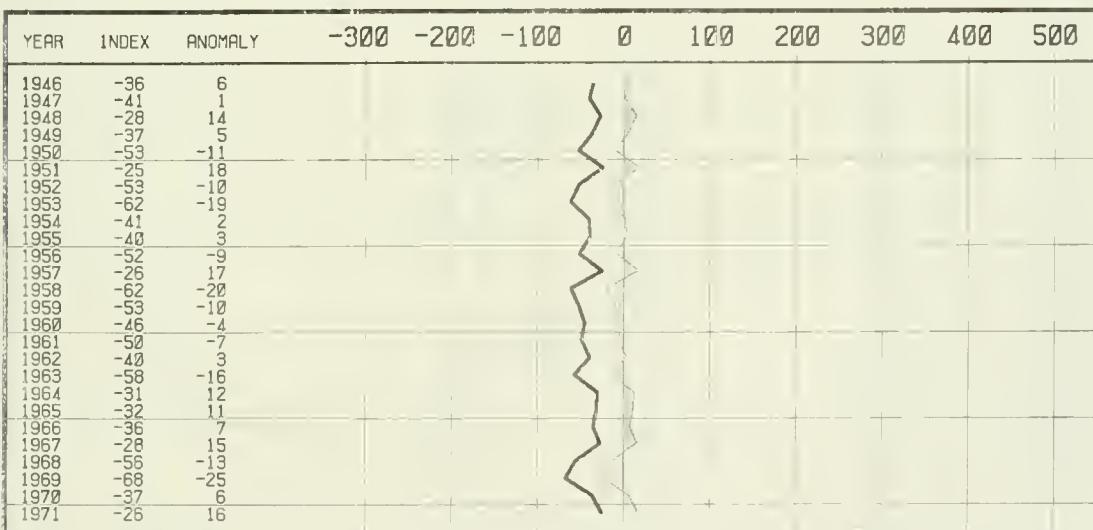
UPWELLING INDEX AT 54N, 134W BY QUARTER



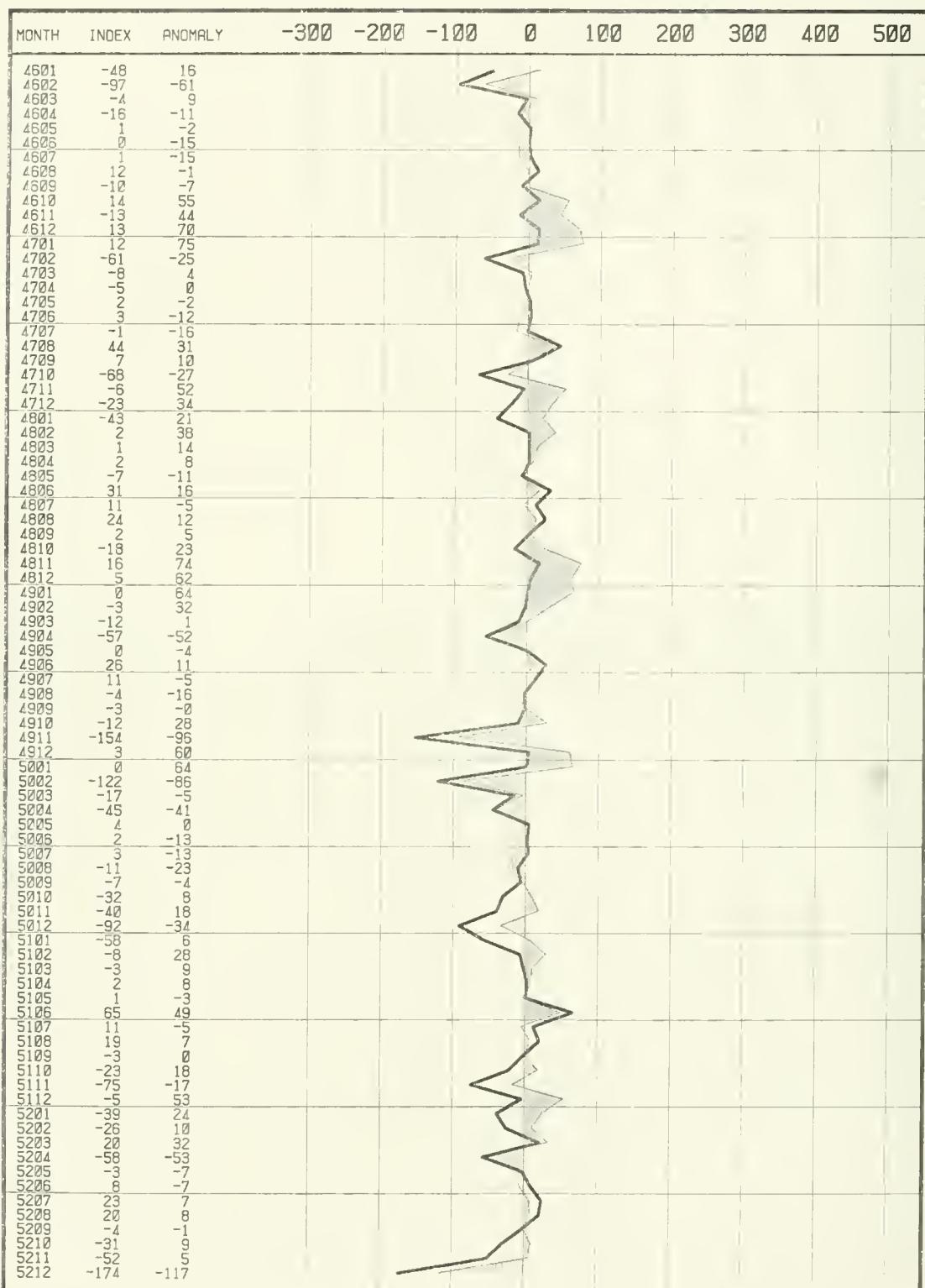
UPWELLING INDEX AT 54N, 134W BY QUARTER



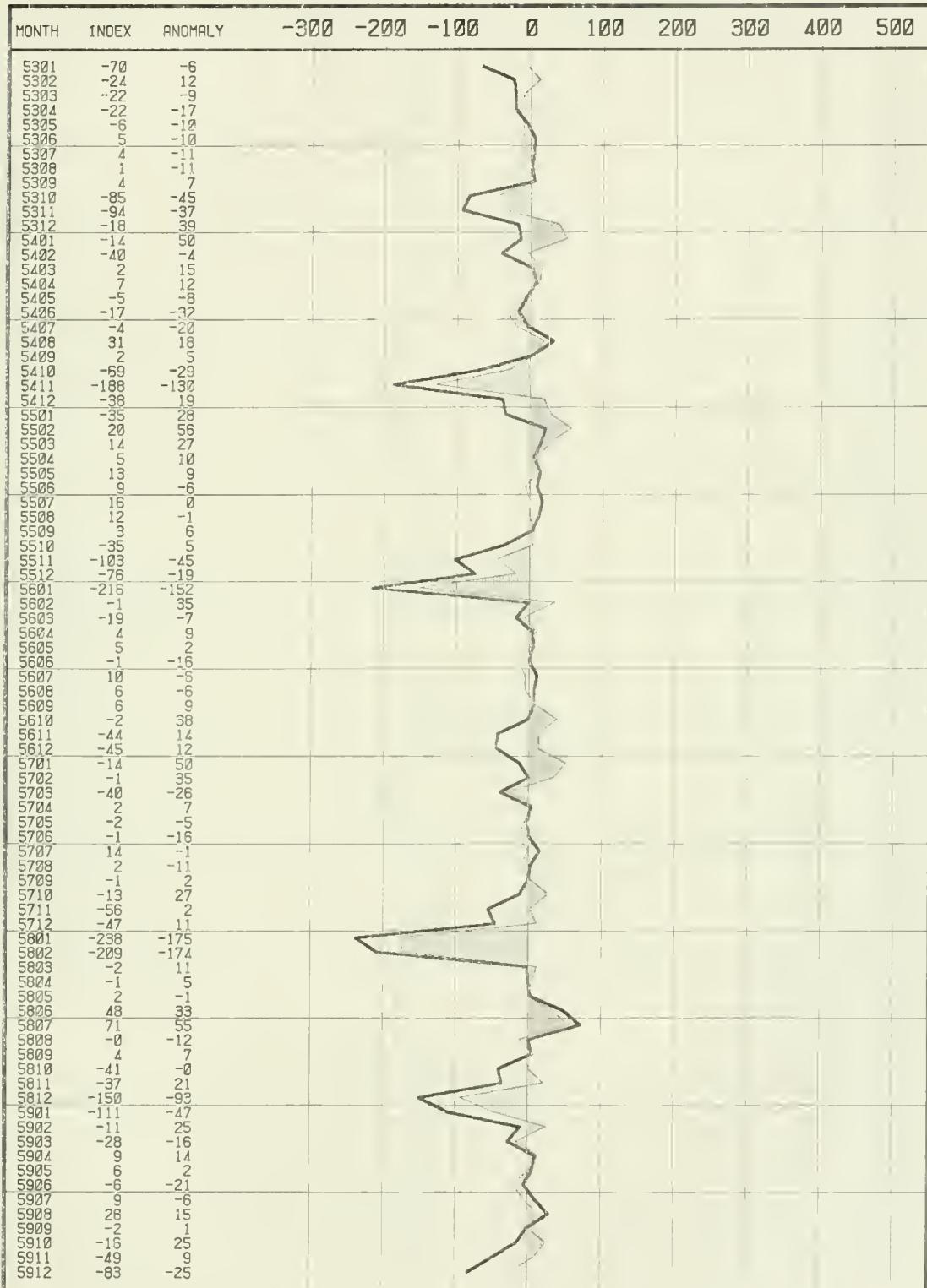
UPWELLING INDEX AT 54N, 134W BY YEAR



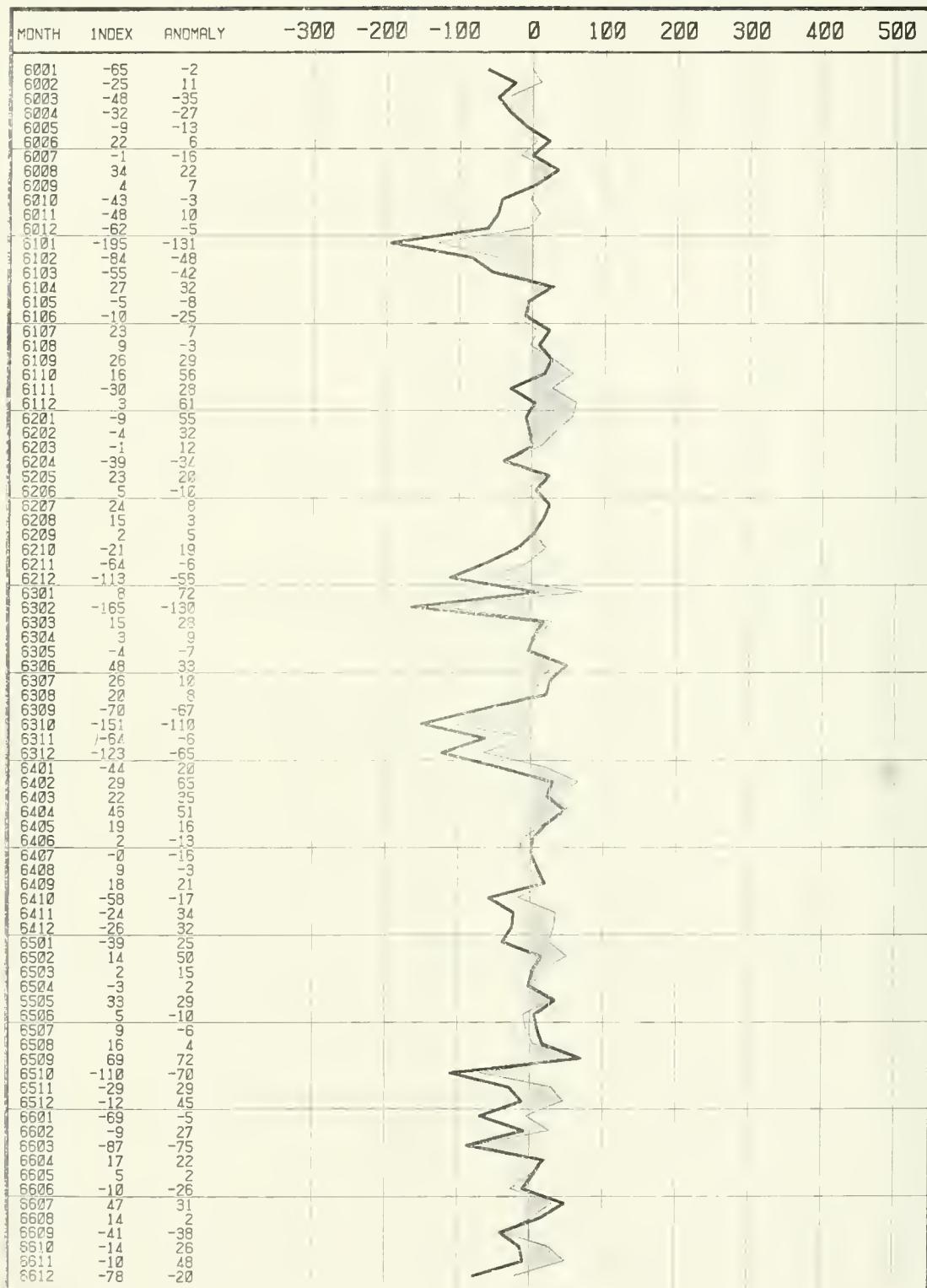
UPWELLING INDEX AT 51N, 131W BY MONTH



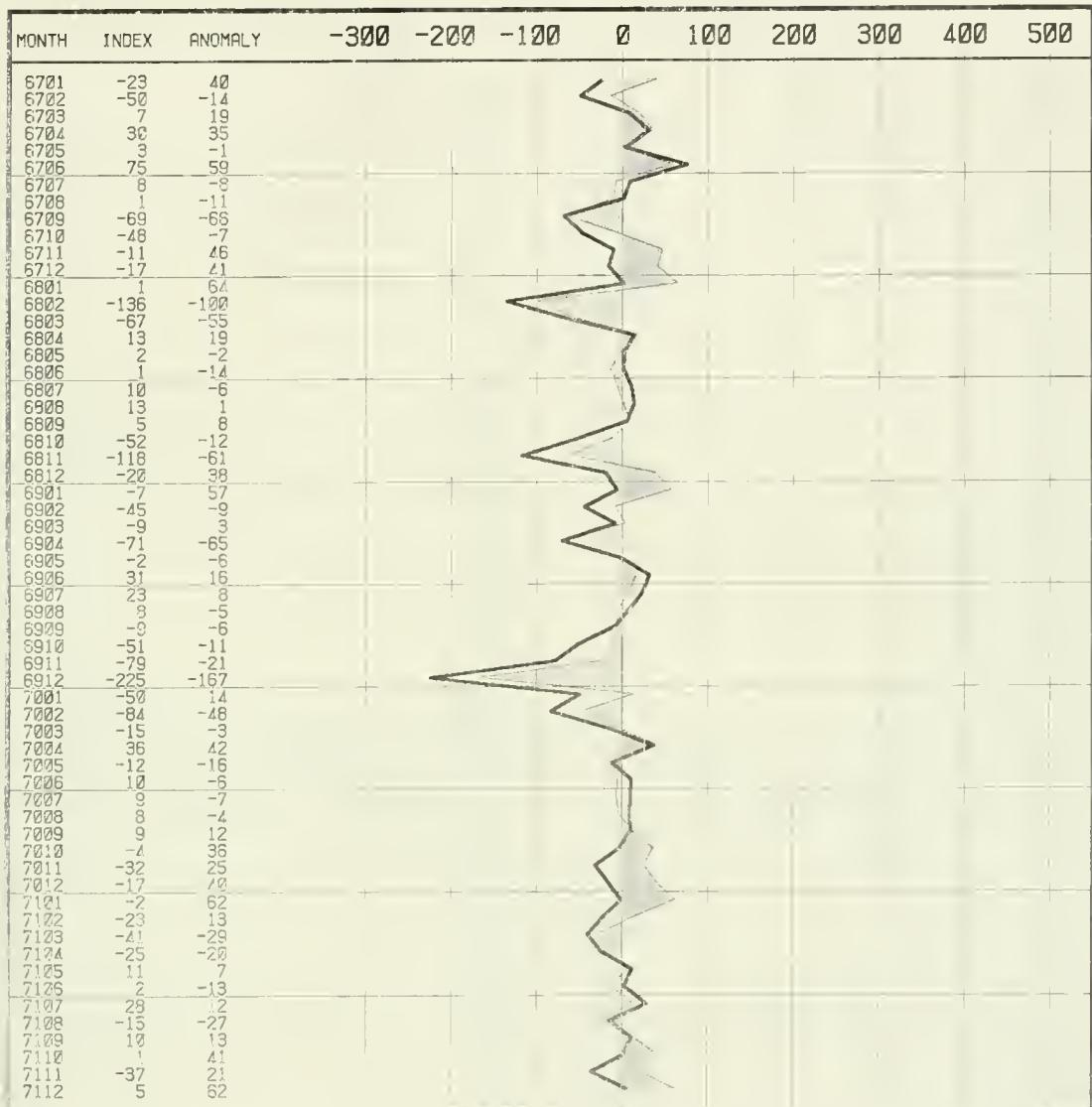
UPWELLING INDEX AT 51N, 131W BY MONTH



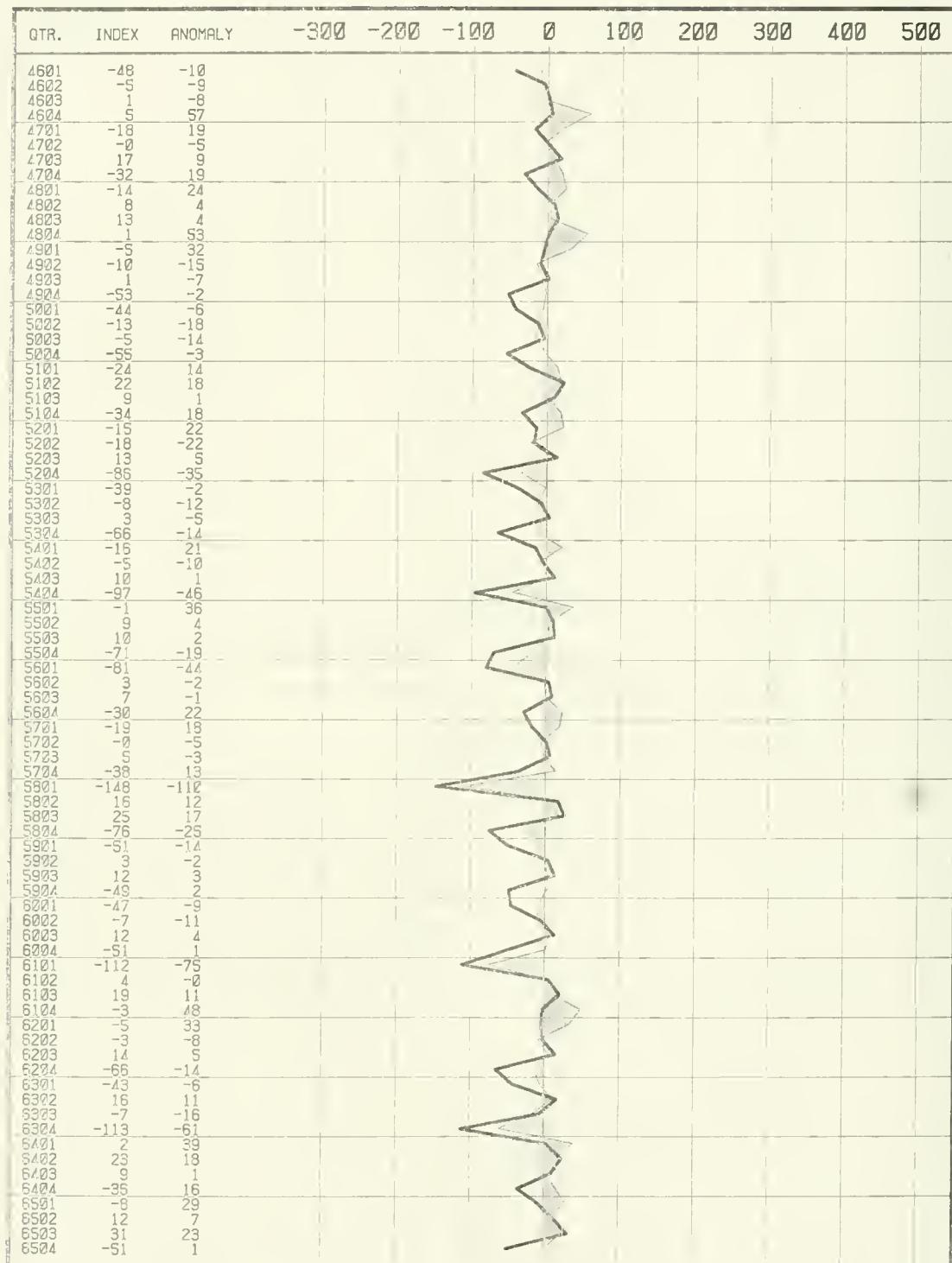
UPWELLING INDEX AT 51N, 131W BY MONTH



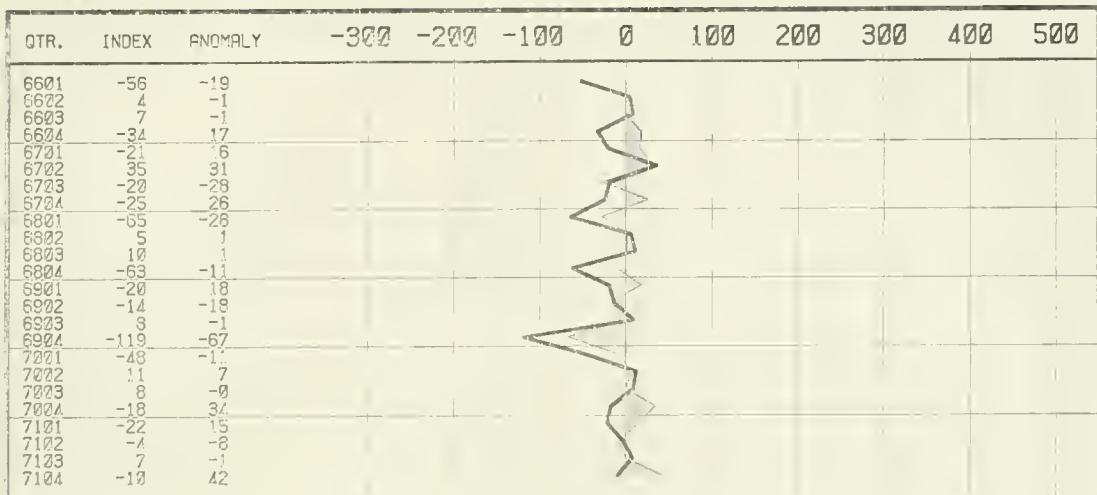
UPWELLING INDEX AT 51N, 131W BY MONTH



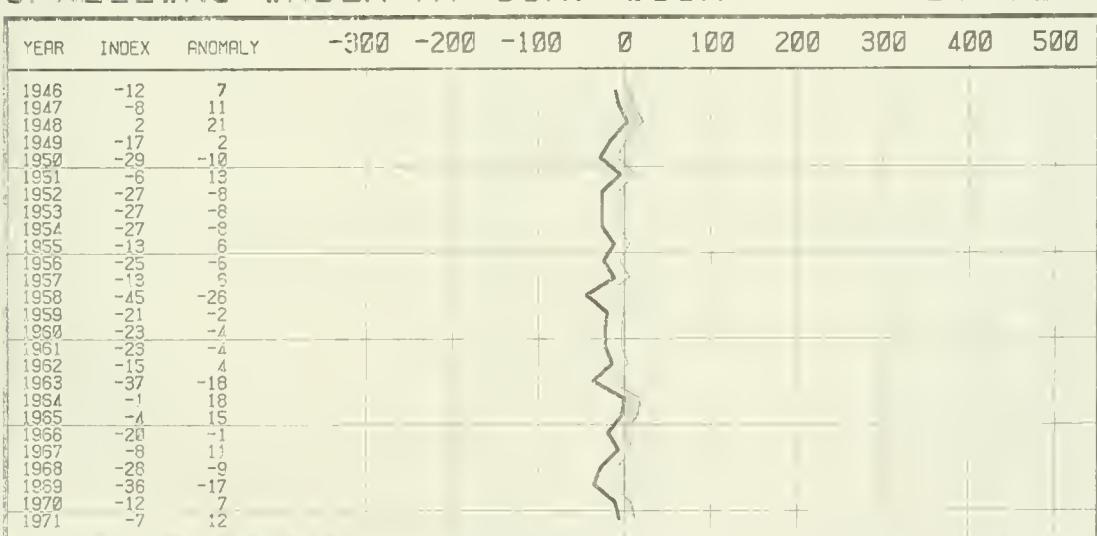
UPWELLING INDEX AT 51N, 131W BY QUARTER



UPWELLING INDEX AT 51N, 131W BY QUARTER

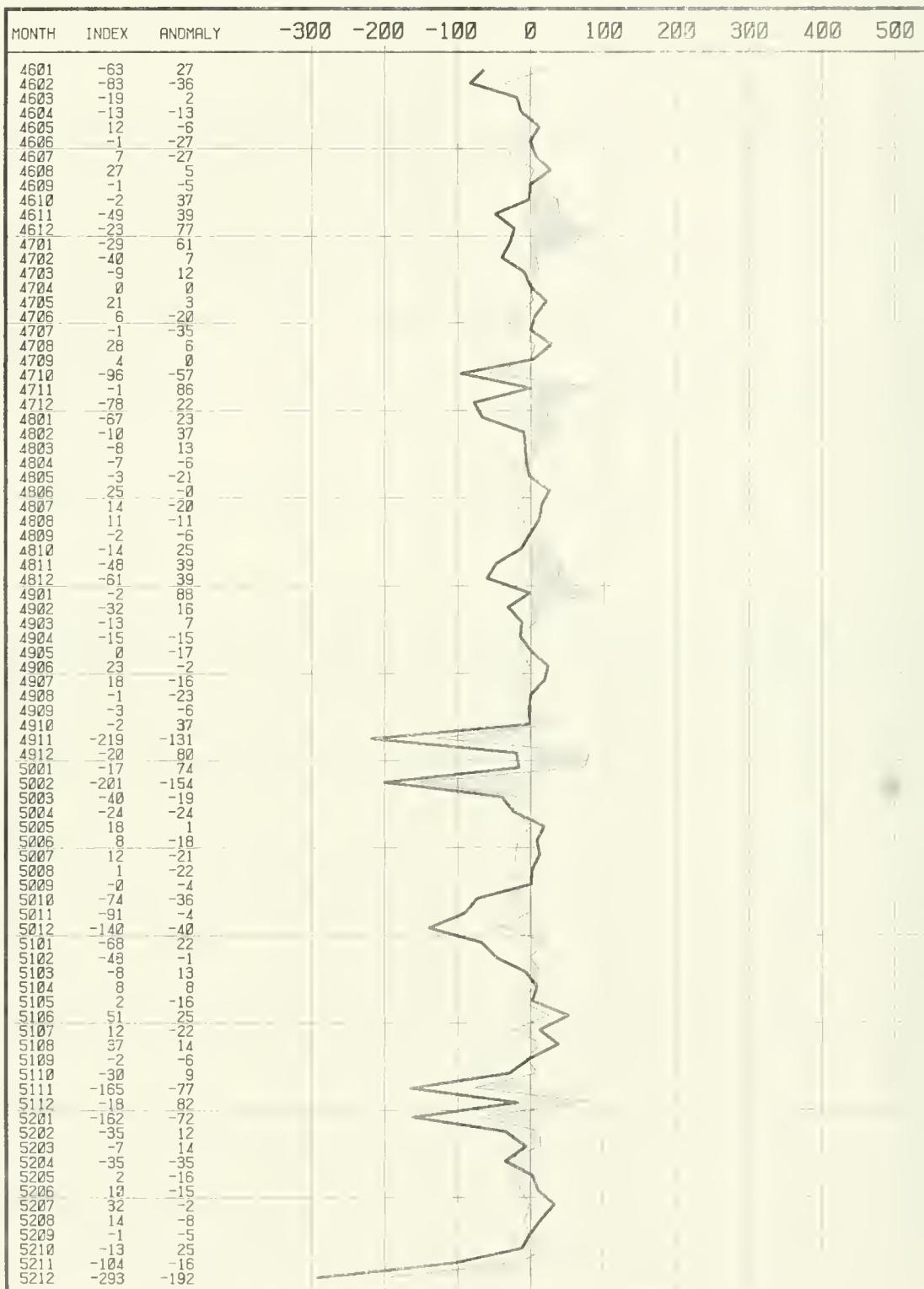


UPWELLING INDEX AT 51N, 131W BY YEAR

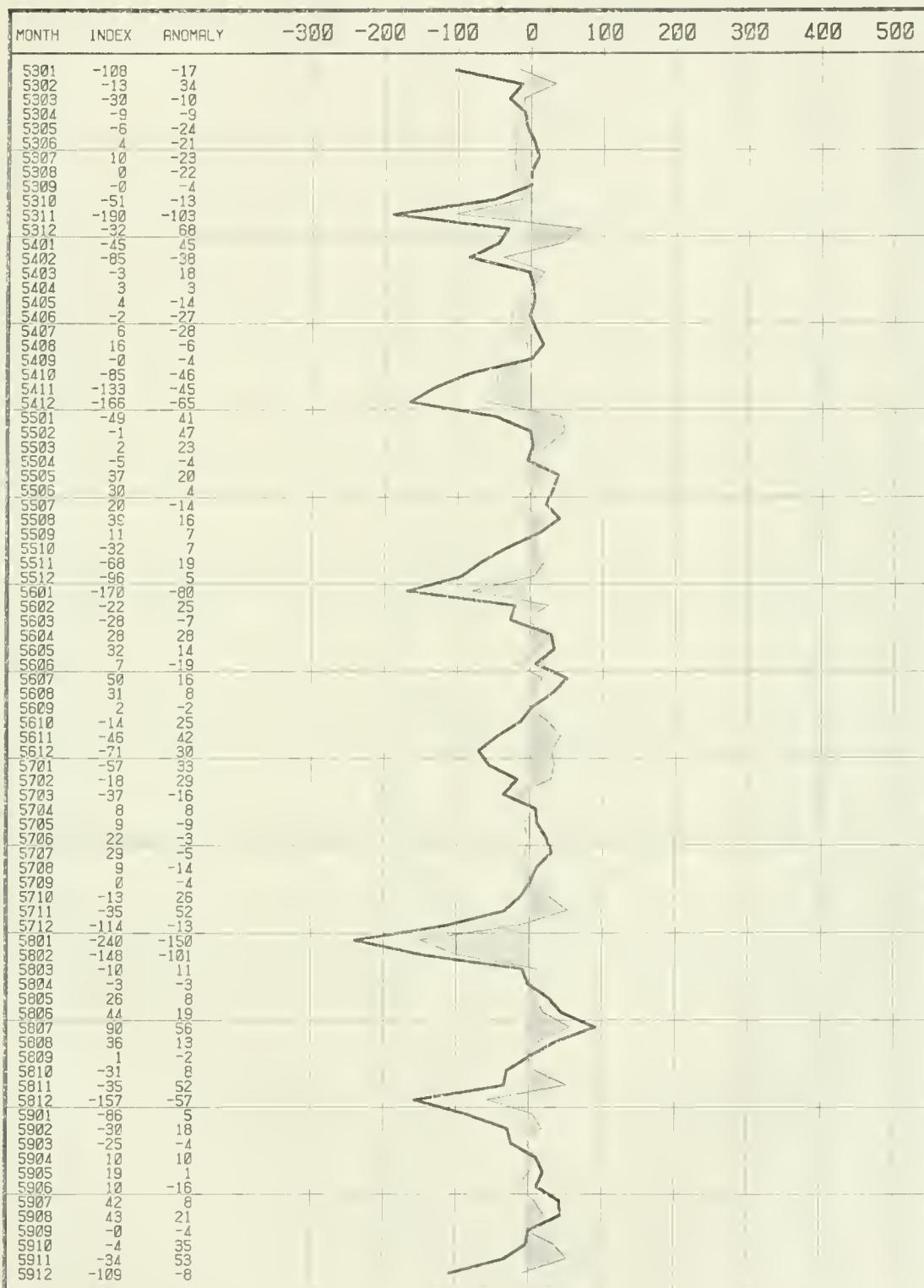


UPWELLING INDEX AT 48N, 125W

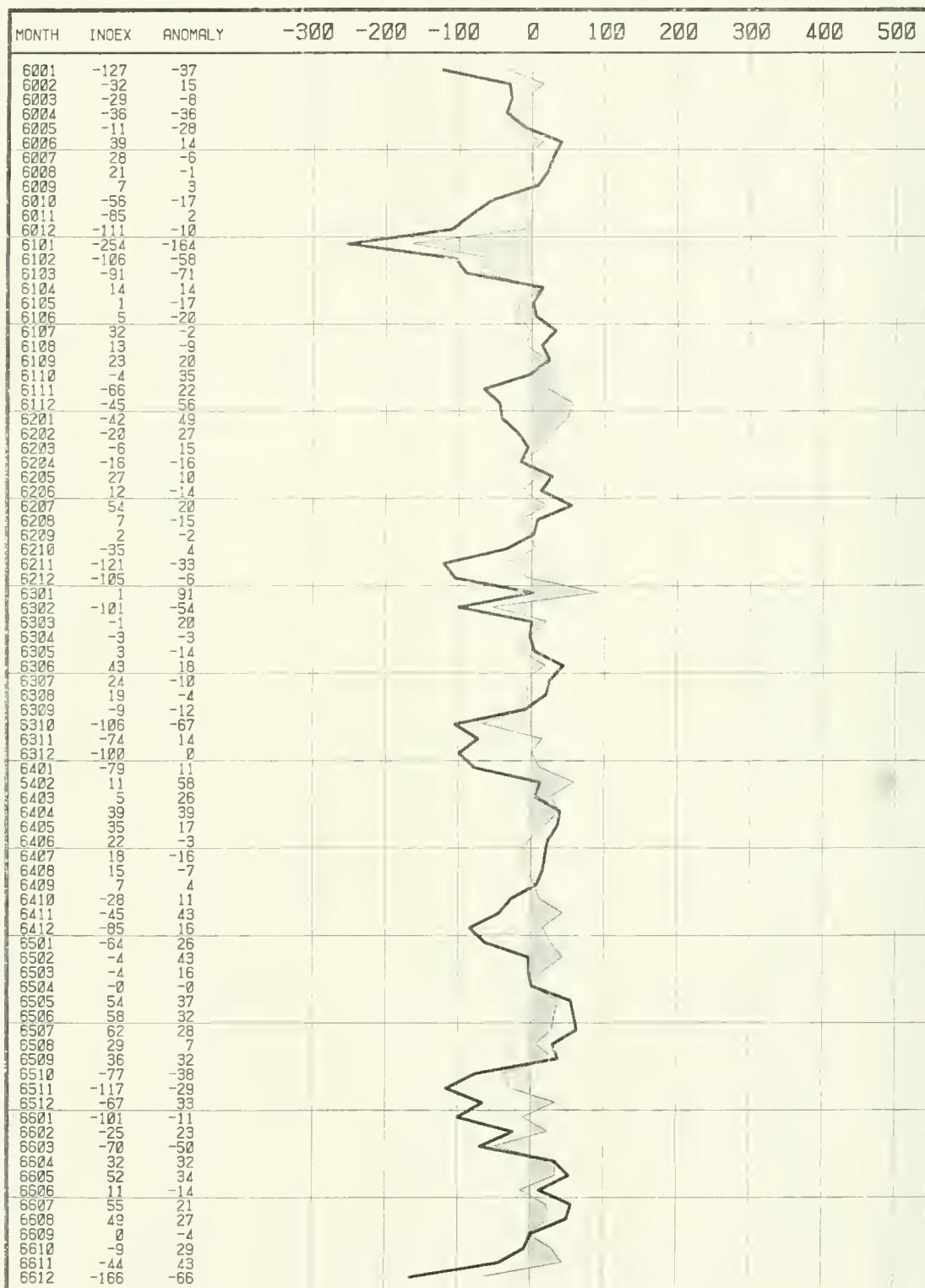
BY MONTH



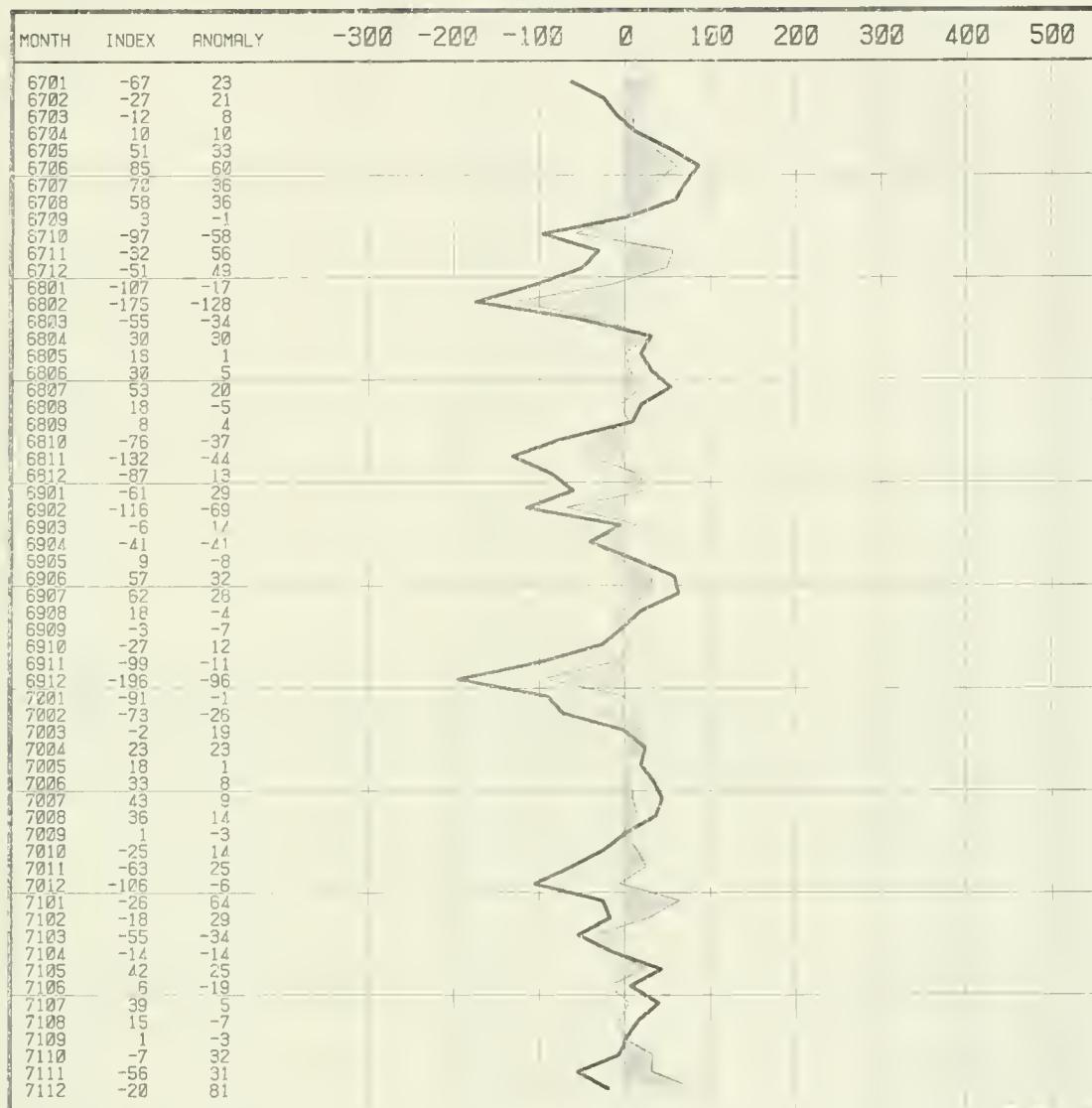
UPWELLING INDEX AT 48N, 125W BY MONTH



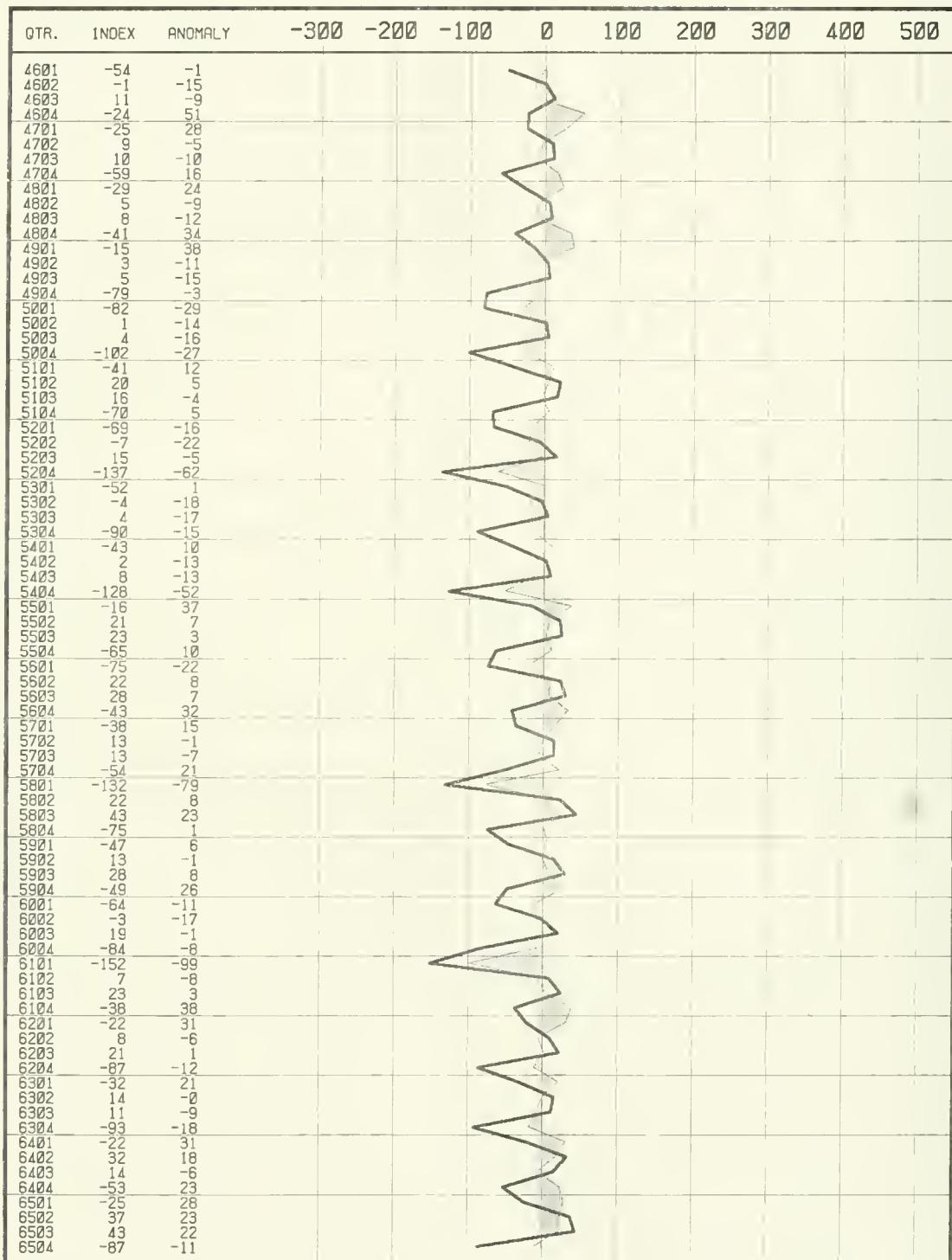
UPWELLING INDEX AT 48N, 125W BY MONTH



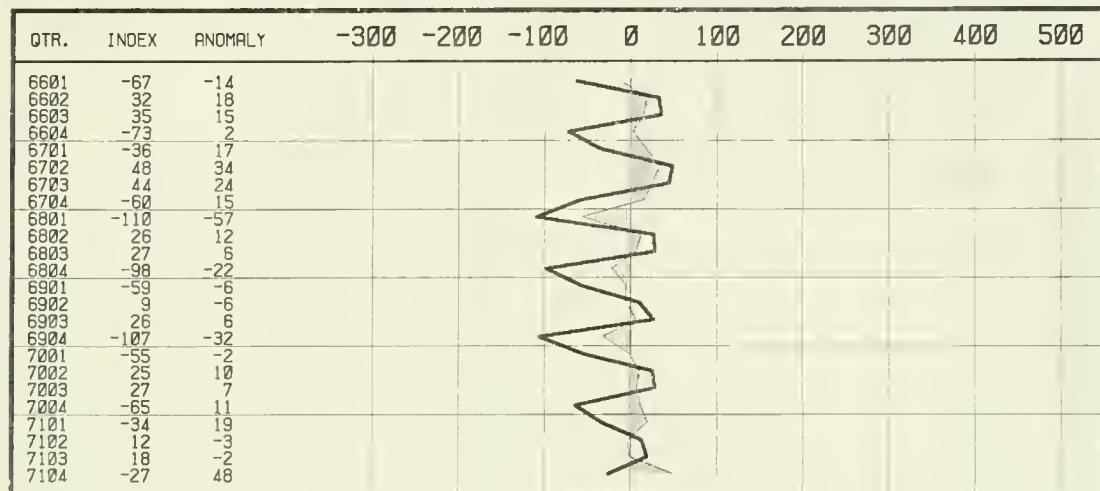
UPWELLING INDEX AT 48N, 125W BY MONTH



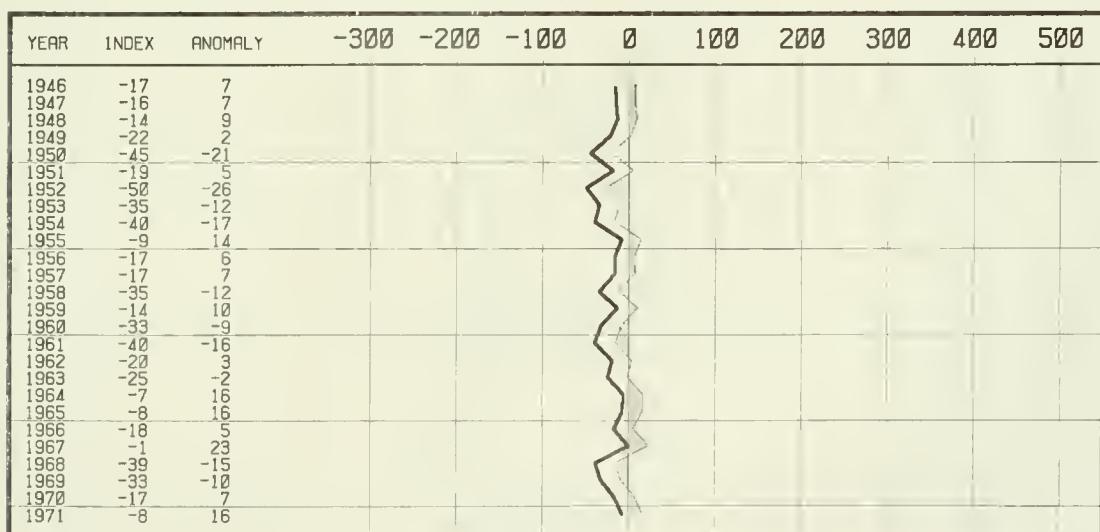
UPWELLING INDEX AT 48N, 125W BY QUARTER



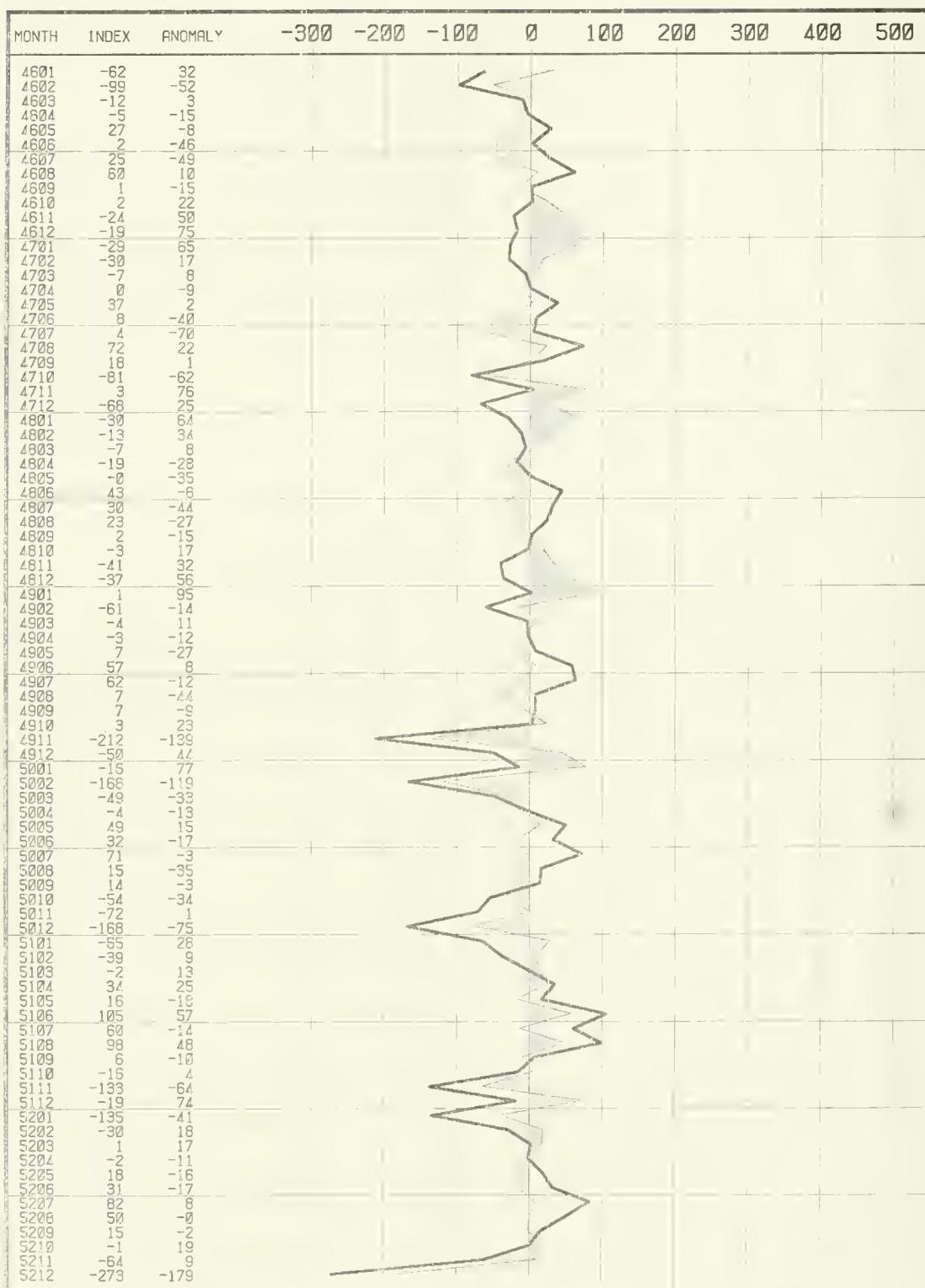
UPWELLING INDEX AT 48N, 125W BY QUARTER



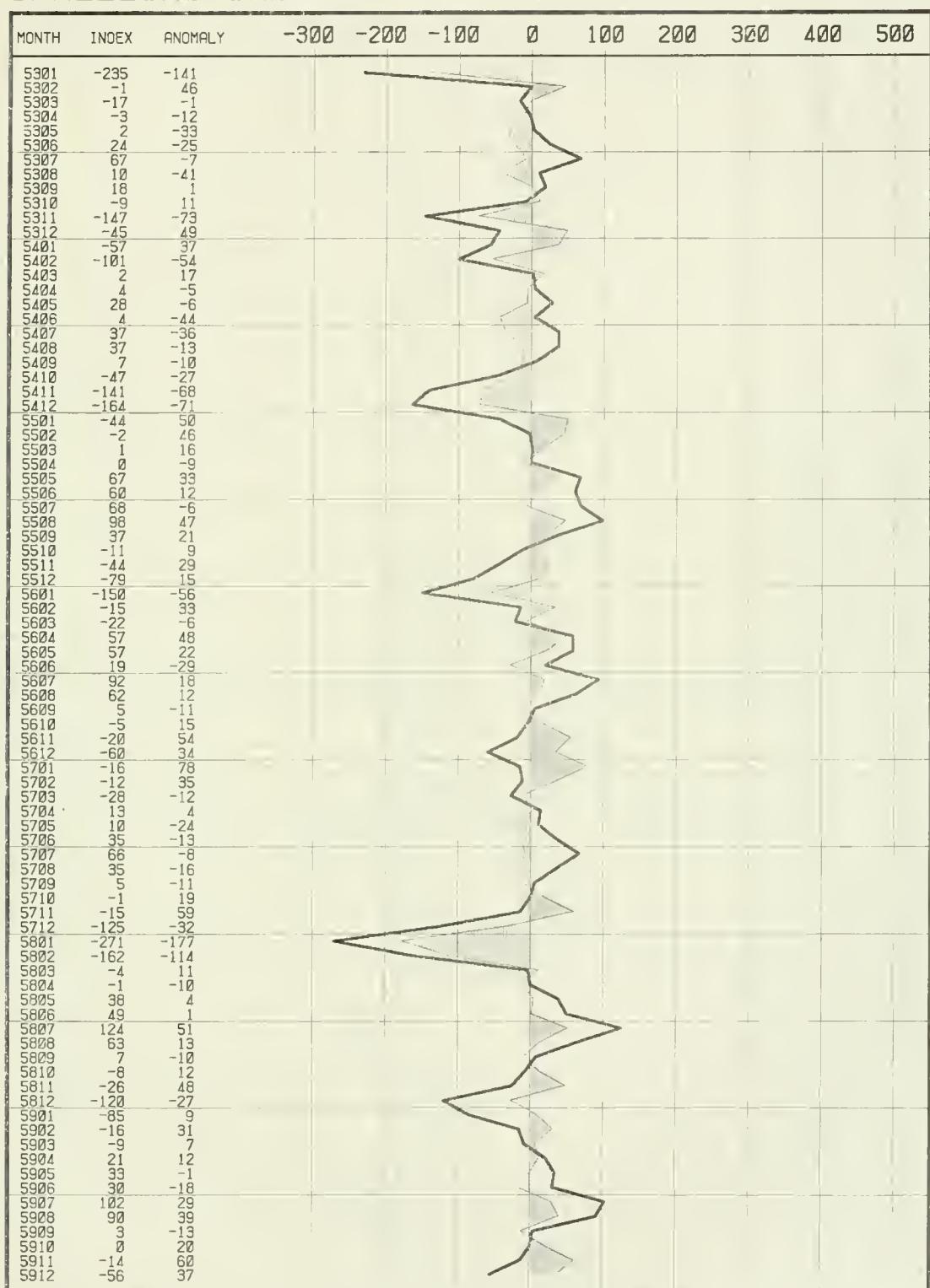
UPWELLING INDEX AT 48N, 125W BY YEAR



UPWELLING INDEX AT 45N, 125W BY MONTH

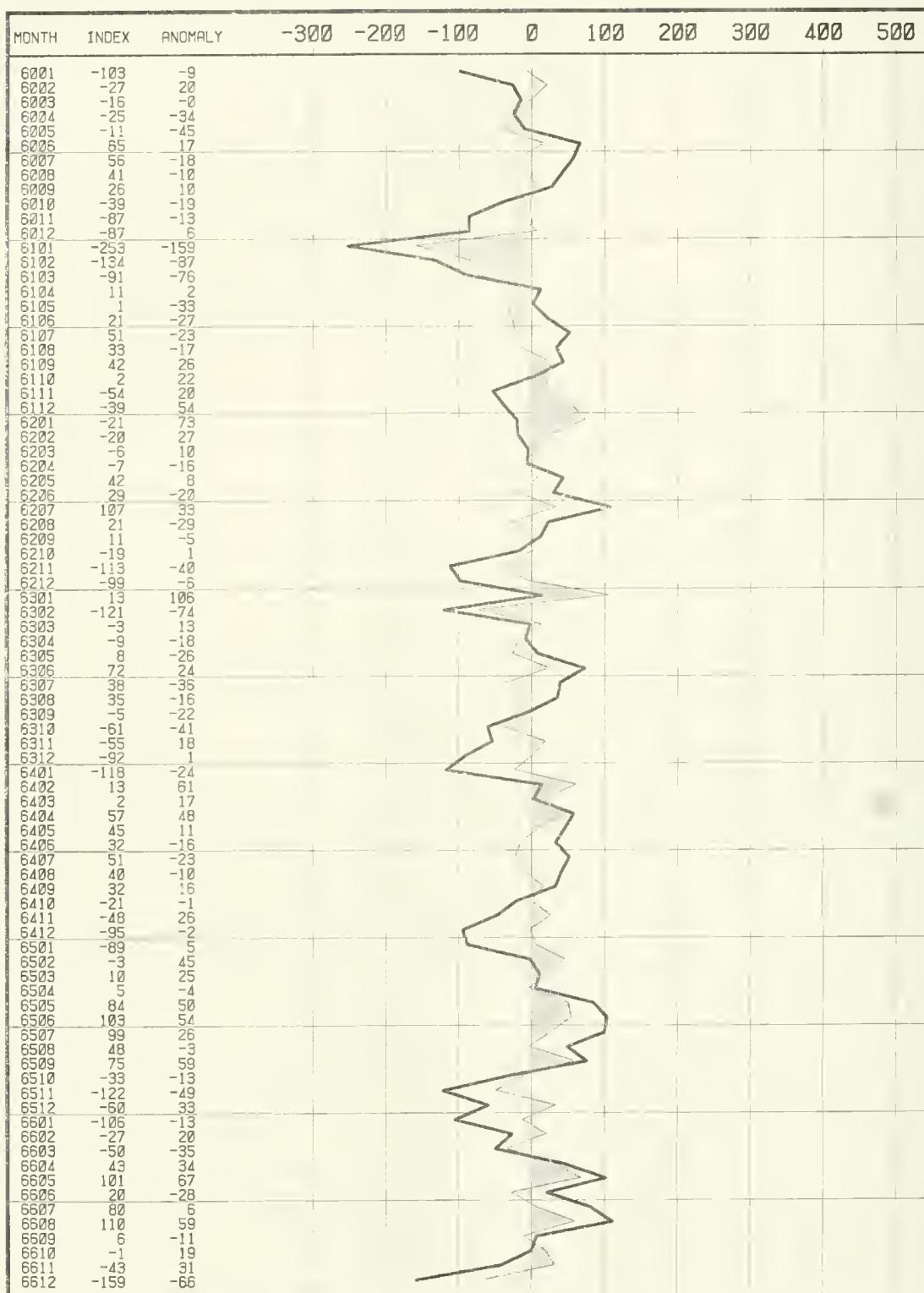


UPWELLING INDEX AT 45N, 125W BY MONTH



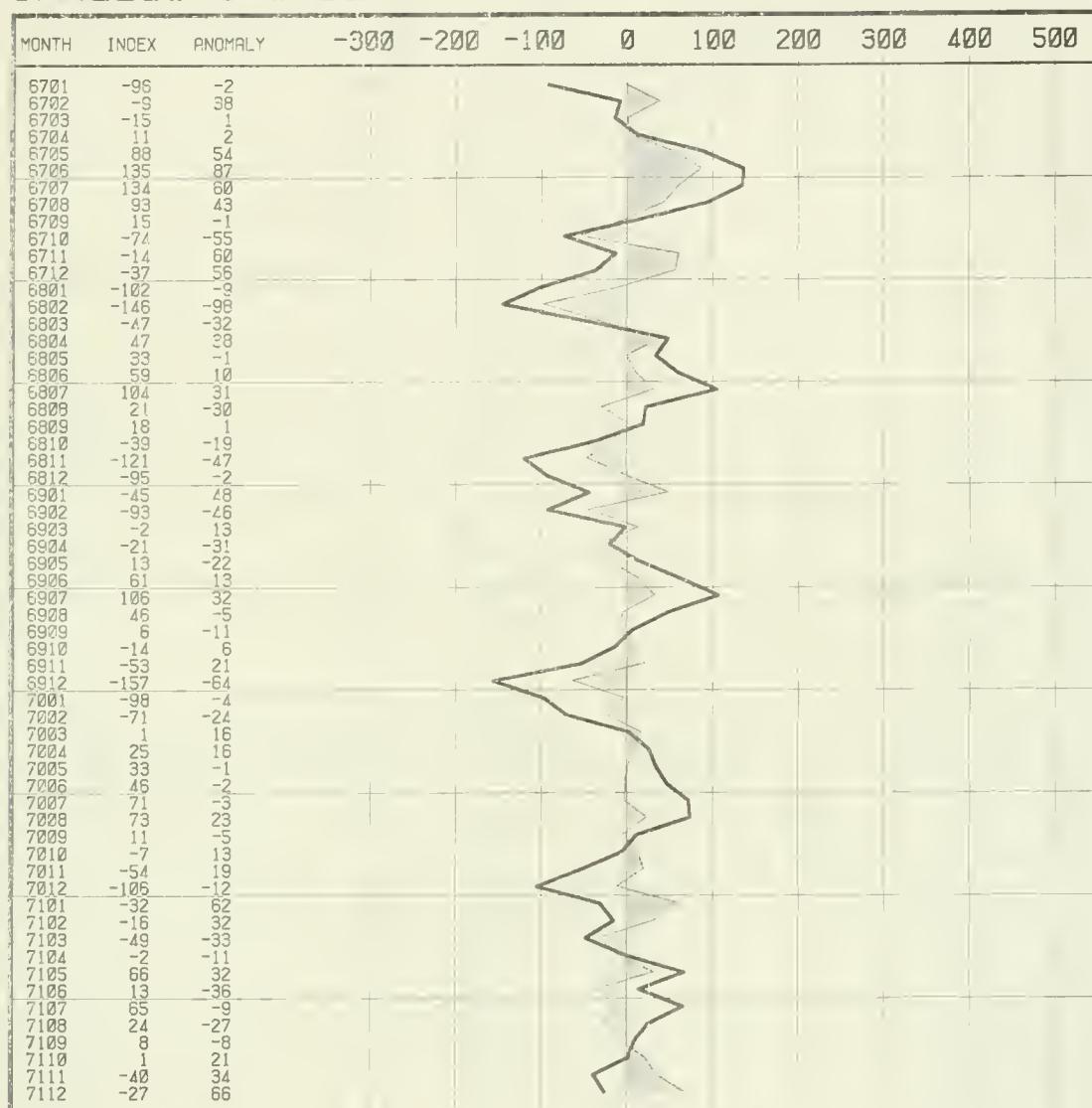
UPWELLING INDEX AT 45N, 125W

BY MONTH



UPWELLING INDEX AT 45N, 125W

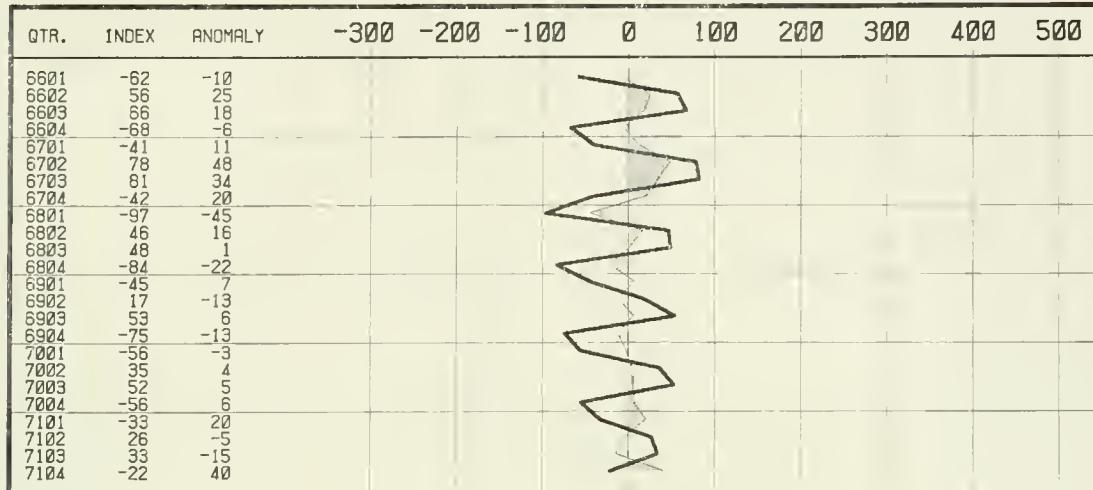
BY MONTH



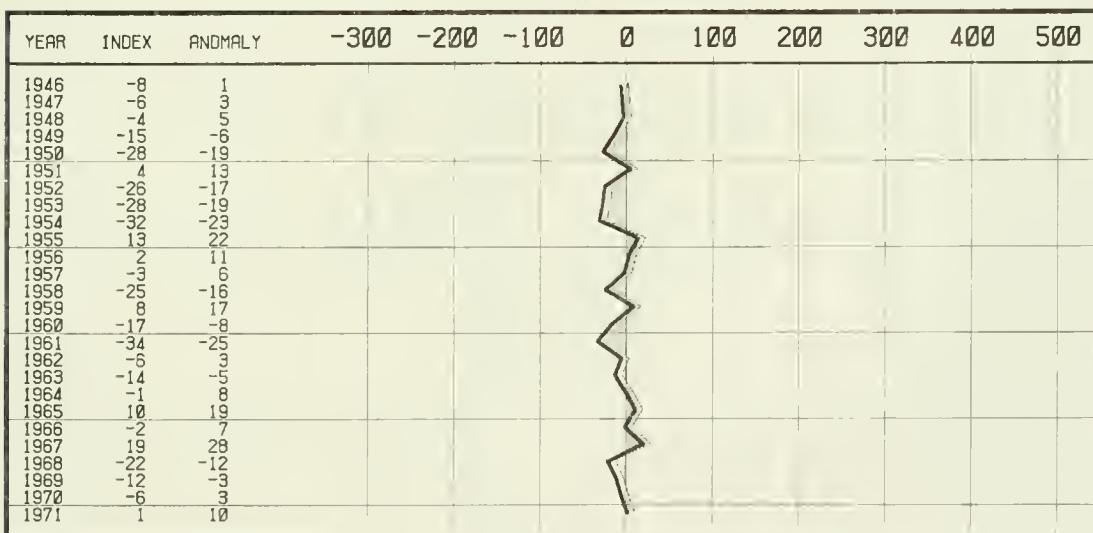
UPWELLING INDEX AT 45N, 125W BY QUARTER

QTR.	INDEX	ANOMALY	-300	-200	-100	0	100	200	300	400	500
4601	-56	-4									
4502	8	-23									
4503	29	-18									
4504	-13	49									
4701	-22	31									
4702	15	-15									
4703	32	-16									
4704	-50	12									
4801	-17	35									
4802	8	-23									
4803	19	-29									
4804	-27	35									
4901	-20	32									
4902	20	-11									
4903	25	-22									
4904	-85	-23									
5001	-74	-22									
5002	26	-5									
5003	33	-14									
5004	-98	-36									
5101	-35	17									
5102	51	21									
5103	55	8									
5104	-57	5									
5201	-55	-3									
5202	16	-15									
5203	49	2									
5204	-113	-51									
5301	-87	-35									
5302	7	-23									
5303	32	-16									
5304	-66	-4									
5401	-50	2									
5402	12	-18									
5403	27	-20									
5404	-117	-55									
5501	-15	37									
5502	43	12									
5503	68	21									
5504	-45	18									
5601	-64	-11									
5602	44	14									
5603	54	7									
5604	-28	34									
5701	-19	33									
5702	19	-11									
5703	36	-12									
5704	-47	15									
5801	-145	-93									
5802	29	-2									
5803	65	18									
5804	-52	11									
5901	-37	15									
5902	28	-2									
5903	66	19									
5904	-23	39									
6001	-49	3									
6002	9	-21									
6003	41	-6									
6004	-71	-9									
6101	-160	-108									
6102	11	-20									
6103	42	-5									
6104	-30	32									
6201	-15	37									
6202	21	-9									
6203	47	-0									
6204	-77	-15									
6301	-34	18									
6302	24	-7									
6303	23	-25									
6304	-70	-8									
6401	-36	16									
6402	45	14									
6403	41	-6									
6404	-55	7									
6501	-28	24									
6502	64	34									
6503	74	27									
6504	-71	-9									

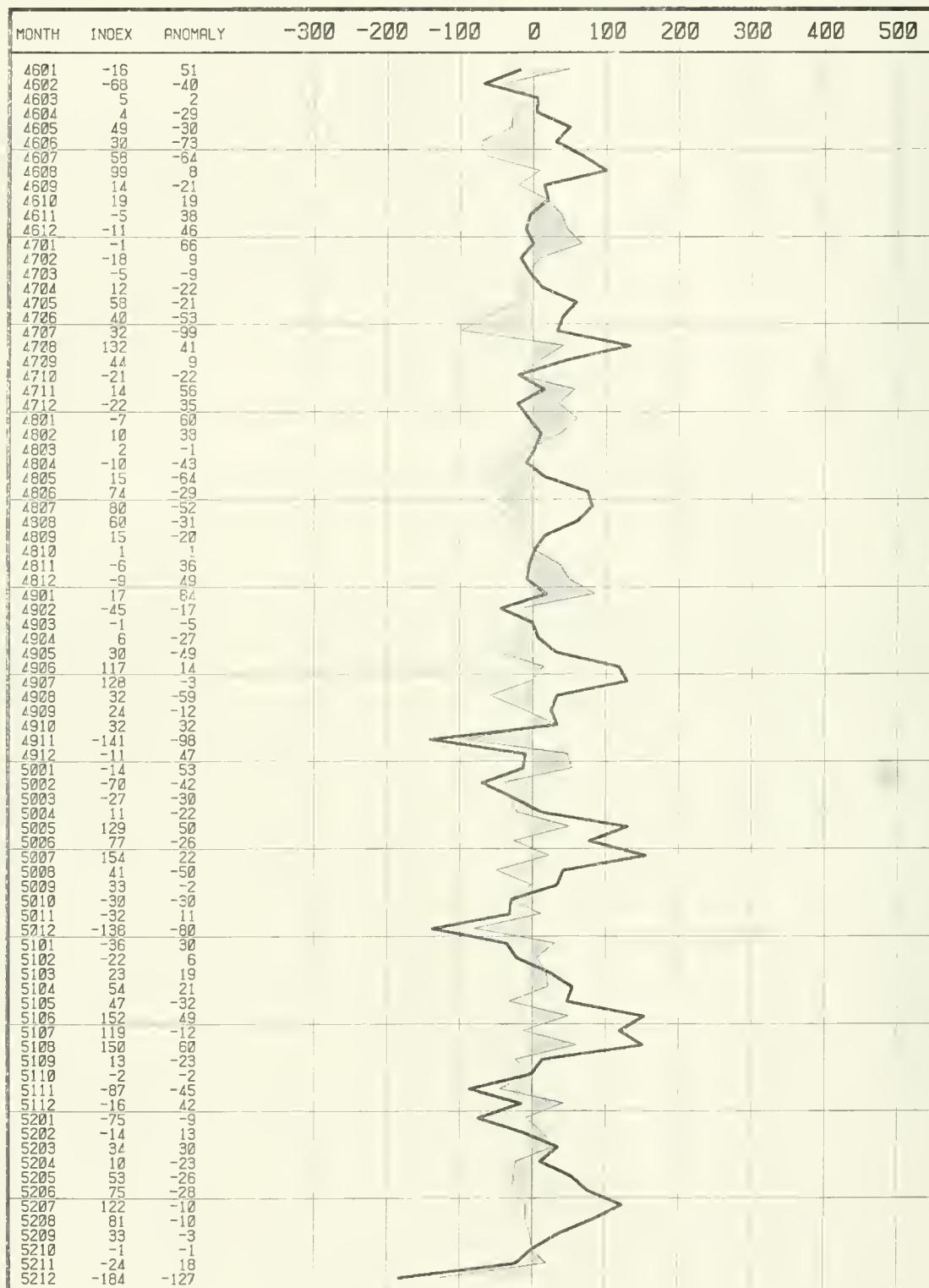
UPWELLING INDEX AT 45N, 125W BY QUARTER



UPWELLING INDEX AT 45N, 125W BY YEAR

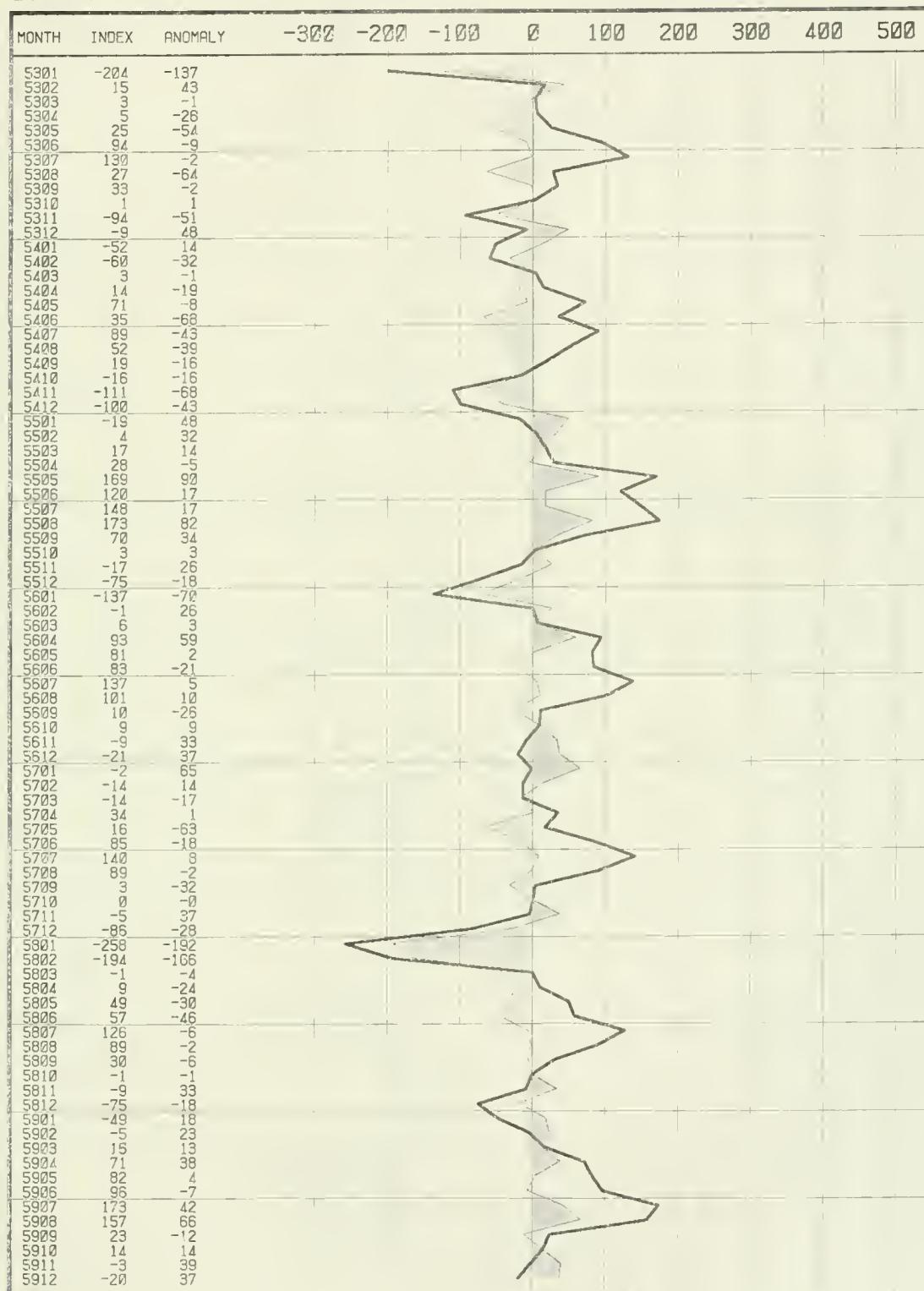


UPWELLING INDEX AT 42N, 125W BY MONTH

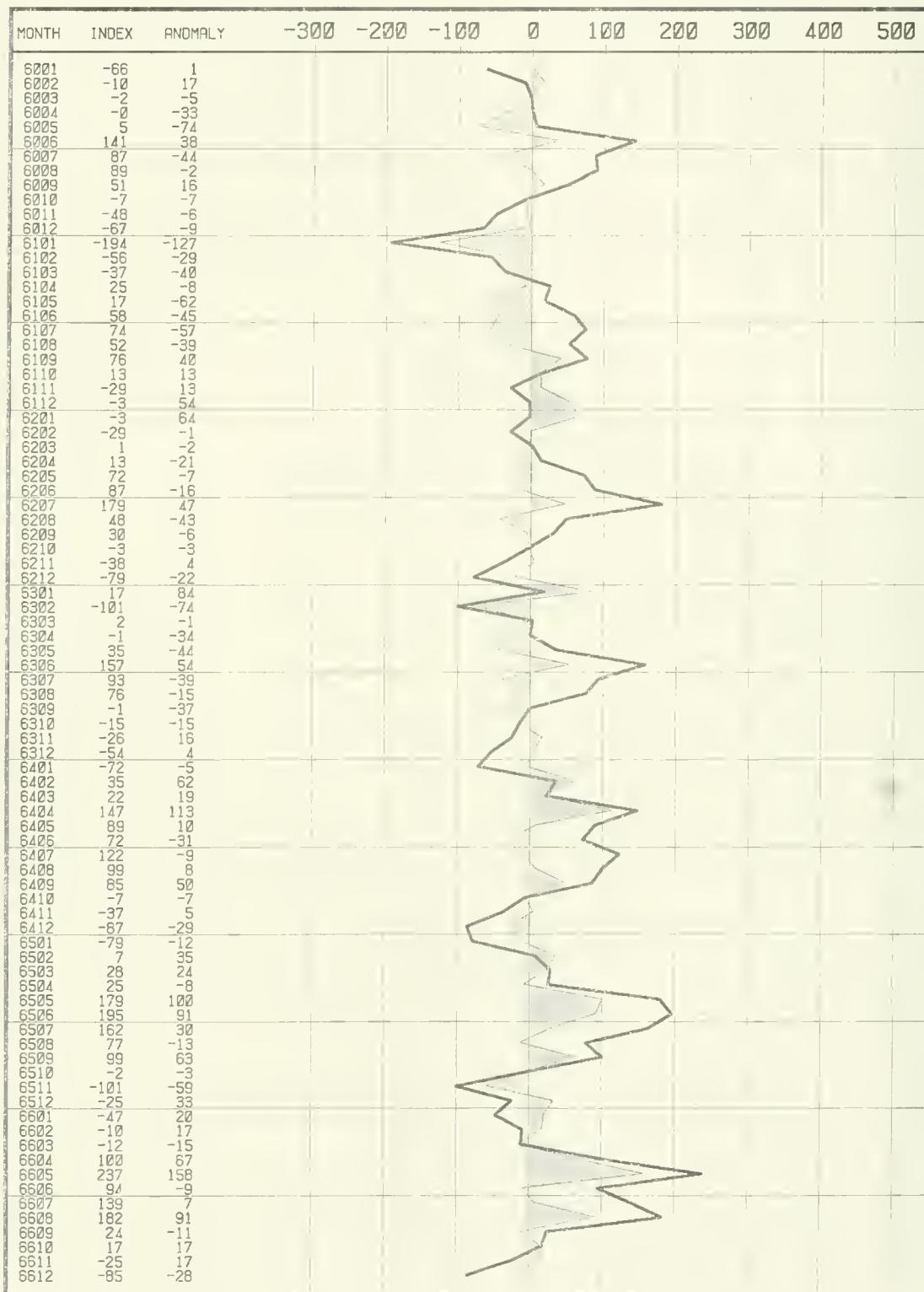


UPWELLING INDEX AT 42N, 125W

BY MONTH

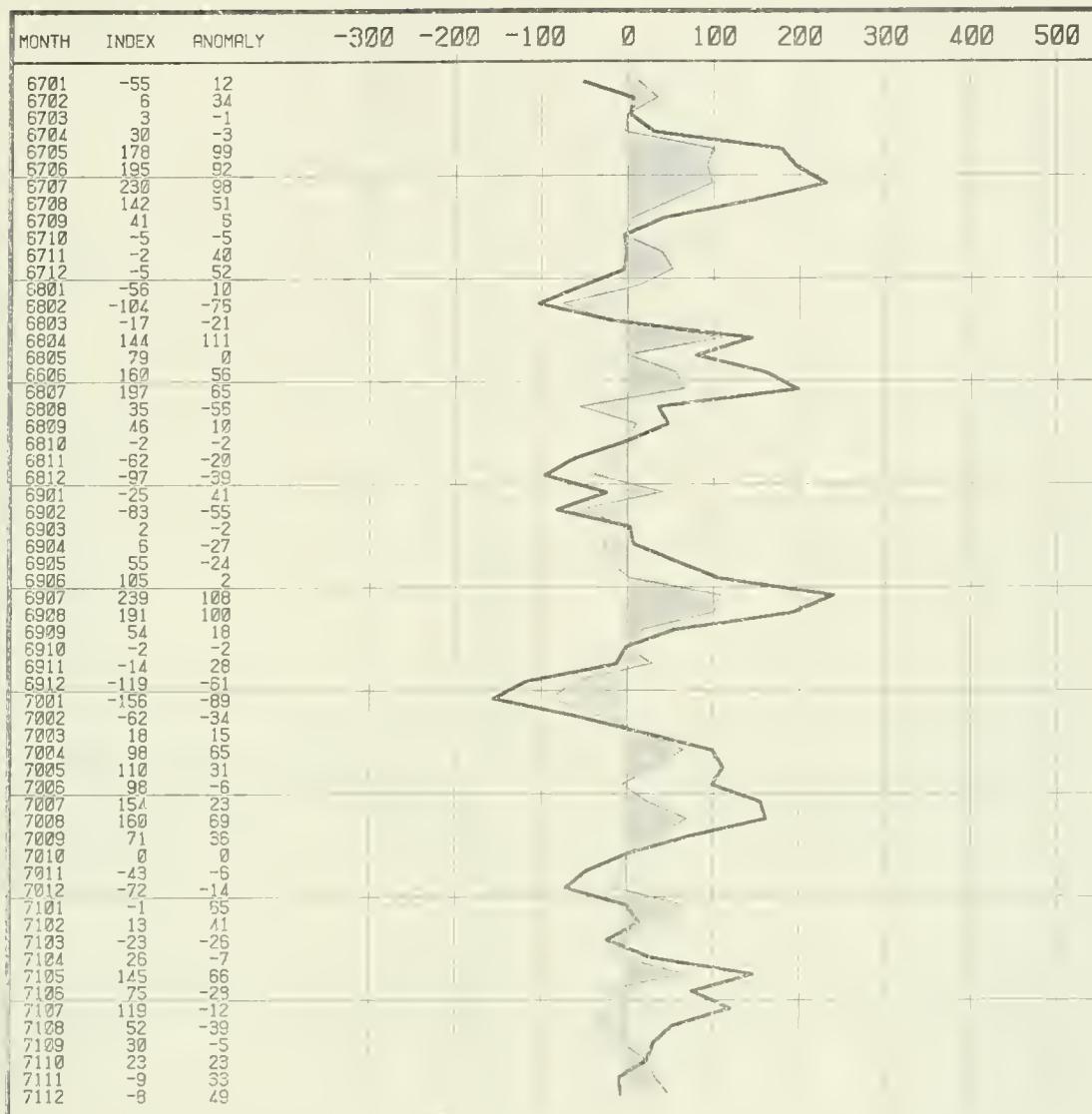


UPWELLING INDEX AT 42N, 125W BY MONTH



UPWELLING INDEX AT 42N, 125W

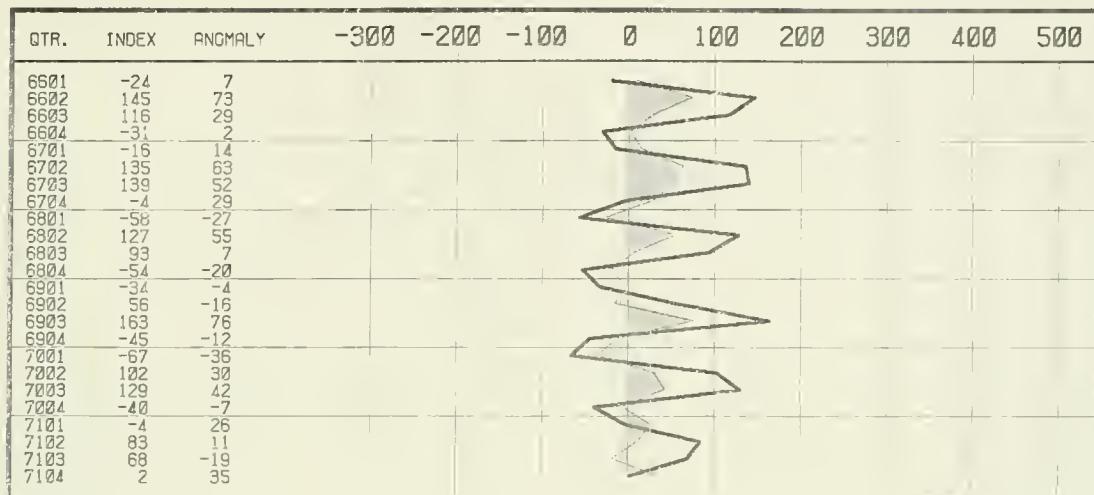
BY MONTH



UPWELLING INDEX AT 42N, 125W BY QUARTER

QTR.	INDEX	ANOMALY	-300	-200	-100	0	100	200	300	400	500
4601	-25	6									
4602	28	-44									
4603	61	-26									
4604	1	34									
4701	-8	23									
4702	37	-35									
4703	70	-17									
4704	-10	23									
4801	1	32									
4802	26	-46									
4803	52	-35									
4804	-5	28									
4901	-9	22									
4902	51	-21									
4903	62	-25									
4904	-39	6									
5001	-36	-5									
5002	73	1									
5003	76	-10									
5004	-67	-34									
5101	-12	19									
5102	84	12									
5103	95	8									
5104	-34	-1									
5201	-19	12									
5202	46	-25									
5203	79	-8									
5204	-70	-37									
5301	-65	34									
5302	41	-31									
5303	63	-23									
5304	-33	0									
5401	-36	-5									
5402	40	-32									
5403	54	-33									
5404	-75	-42									
5501	1	31									
5502	106	34									
5503	131	45									
5504	-30	3									
5601	-45	-15									
5602	85	14									
5603	83	-3									
5604	-7	26									
5701	-10	21									
5702	45	-27									
5703	78	-9									
5704	-30	3									
5801	-149	-119									
5802	39	-33									
5803	82	-4									
5804	-29	4									
5901	-13	18									
5902	83	11									
5903	119	32									
5904	-3	30									
6001	-27	4									
6002	48	-24									
6003	76	-10									
6004	-40	-7									
6101	97	66									
6102	33	-39									
6103	67	-19									
6104	-6	27									
6201	-10	21									
6202	57	-15									
6203	86	-8									
6204	-40	-7									
6301	-25	5									
6302	63	-9									
6303	57	-30									
6304	-32	2									
6401	-8	24									
6402	102	30									
6403	102	16									
6404	-44	-11									
6501	-15	15									
6502	134	62									
6503	113	26									
6504	-42	-9									

UPWELLING INDEX AT 42N, 125W BY QUARTER

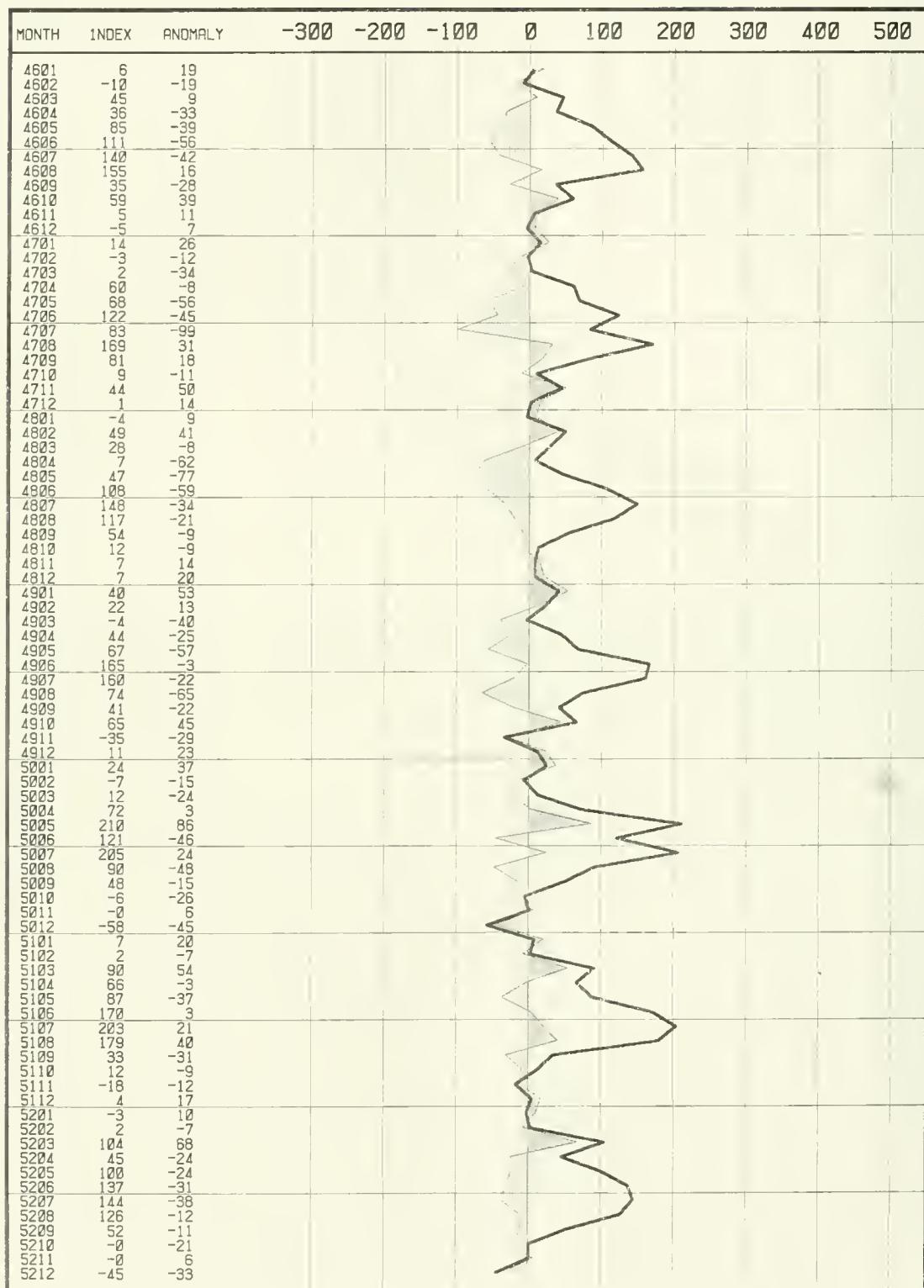


UPWELLING INDEX AT 42N, 125W BY YEAR



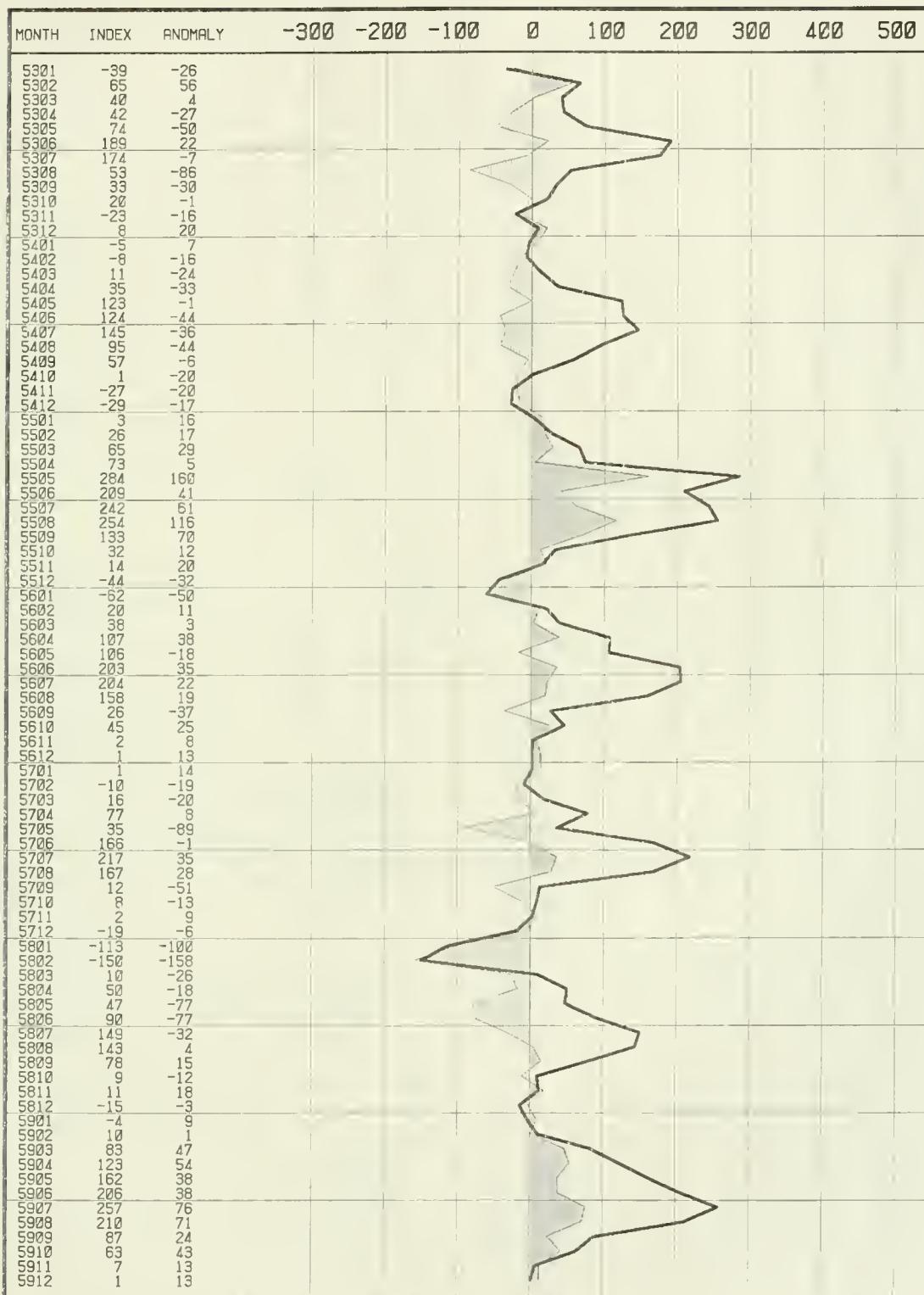
UPWELLING INDEX AT 39N, 125W

BY MONTH

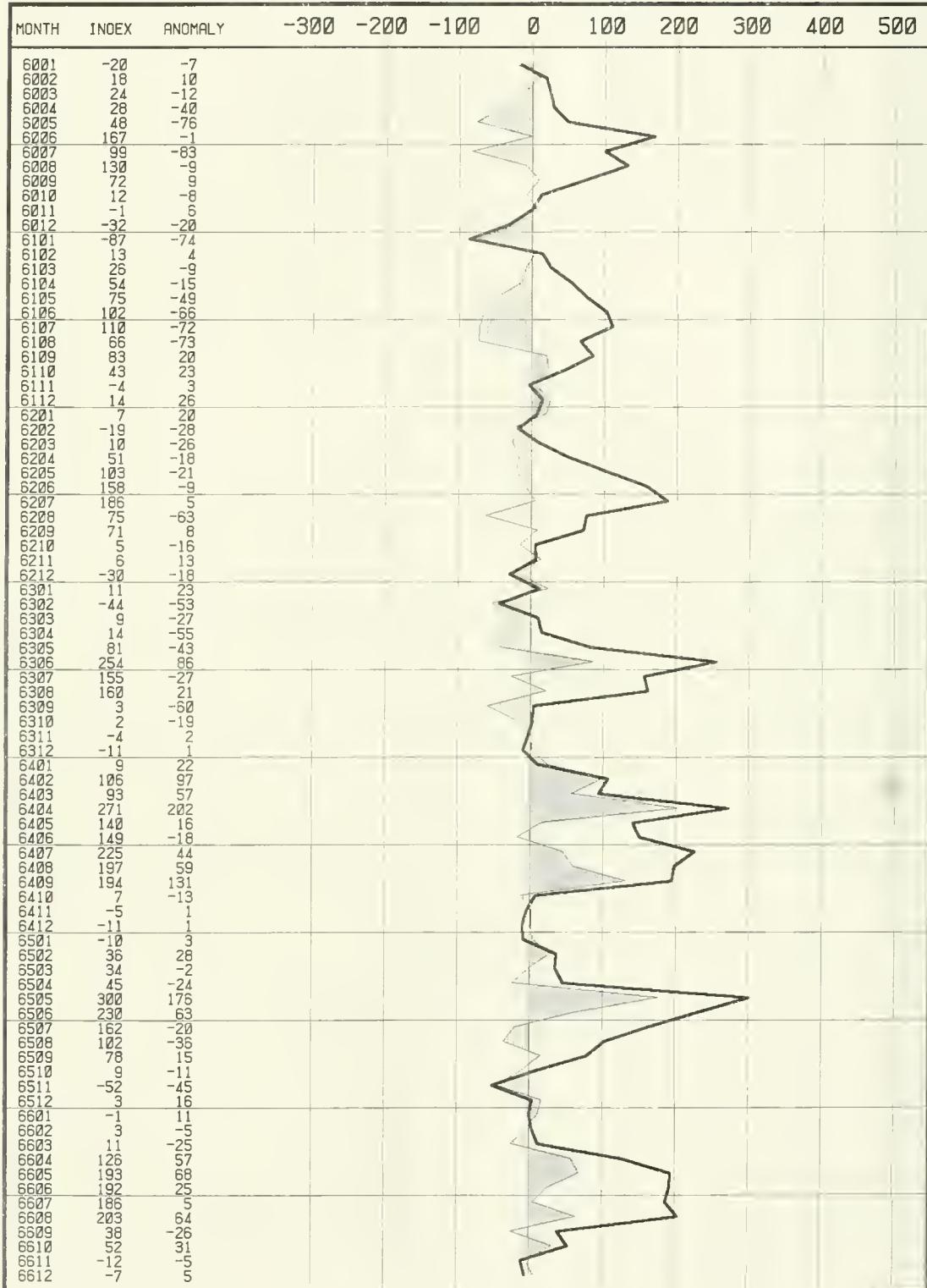


UPWELLING INDEX AT 39N. 125W

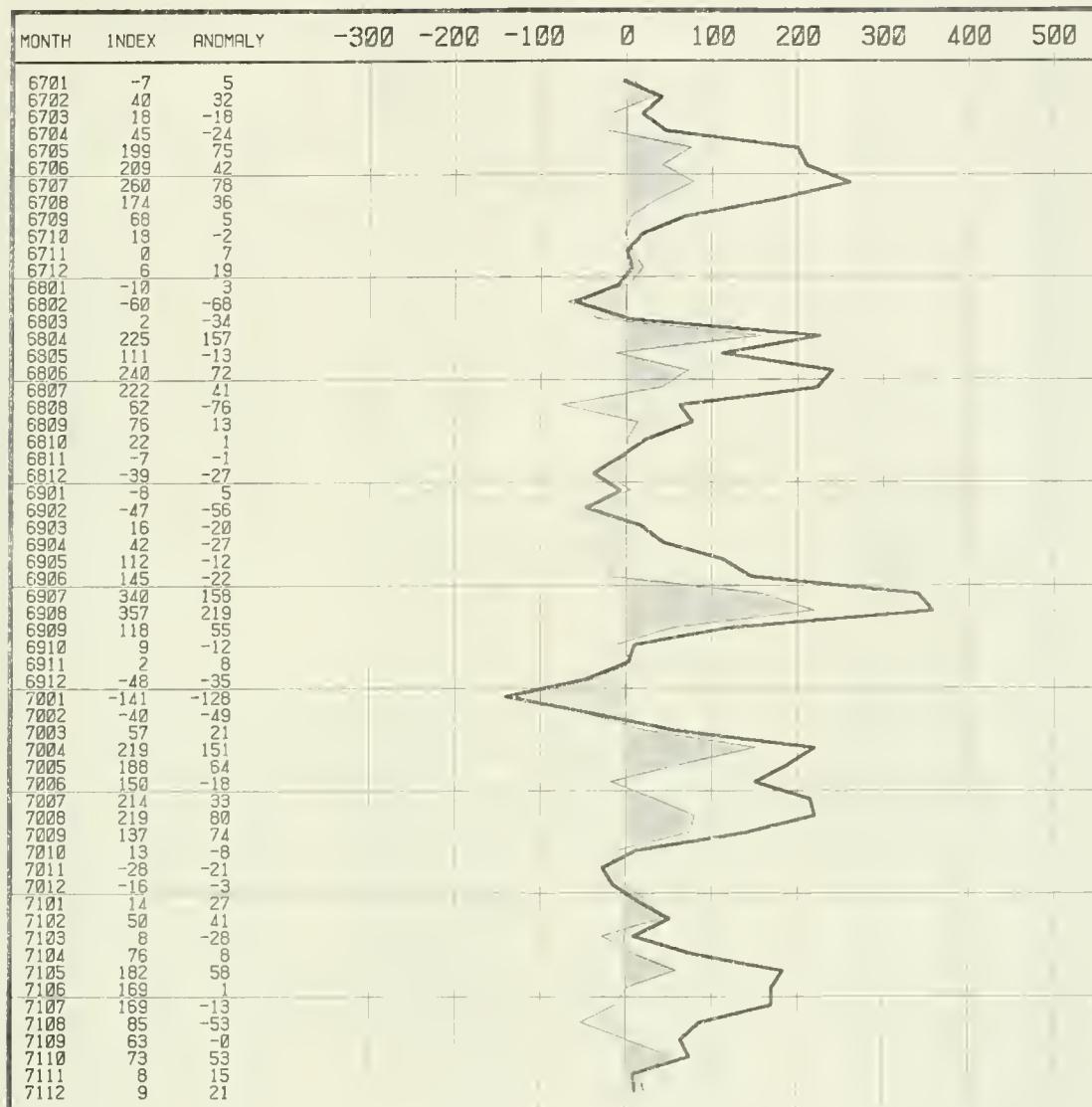
BY MONTH



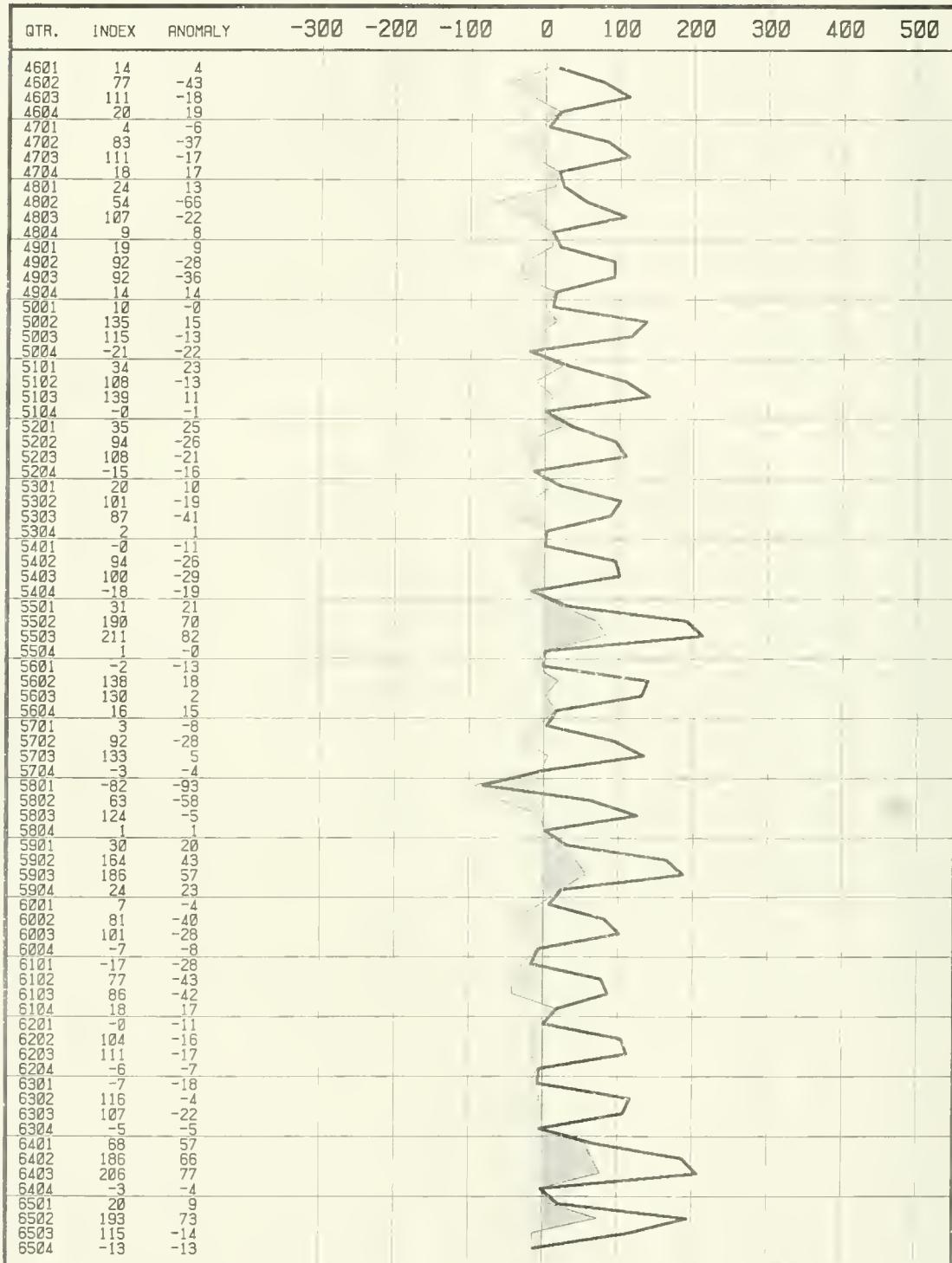
UPWELLING INDEX AT 39N, 125W BY MONTH



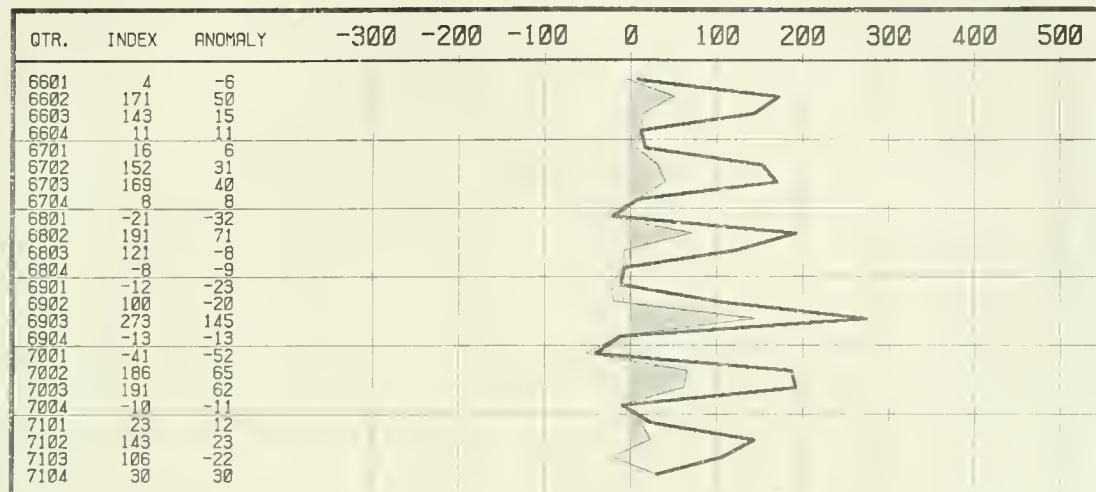
UPWELLING INDEX AT 39N, 125W BY MONTH



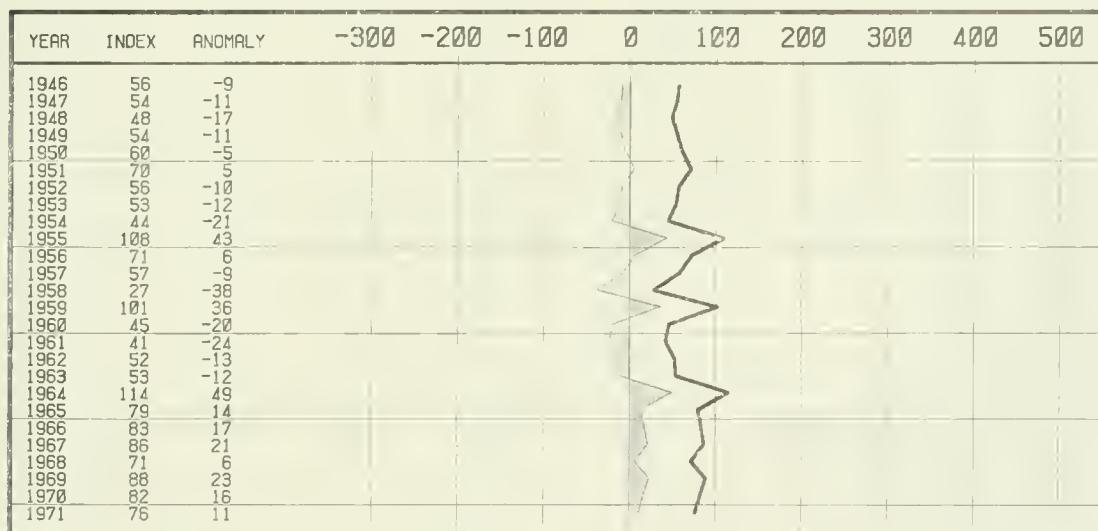
UPWELLING INDEX AT 39N, 125W BY QUARTER



UPWELLING INDEX AT 39N, 125W BY QUARTER

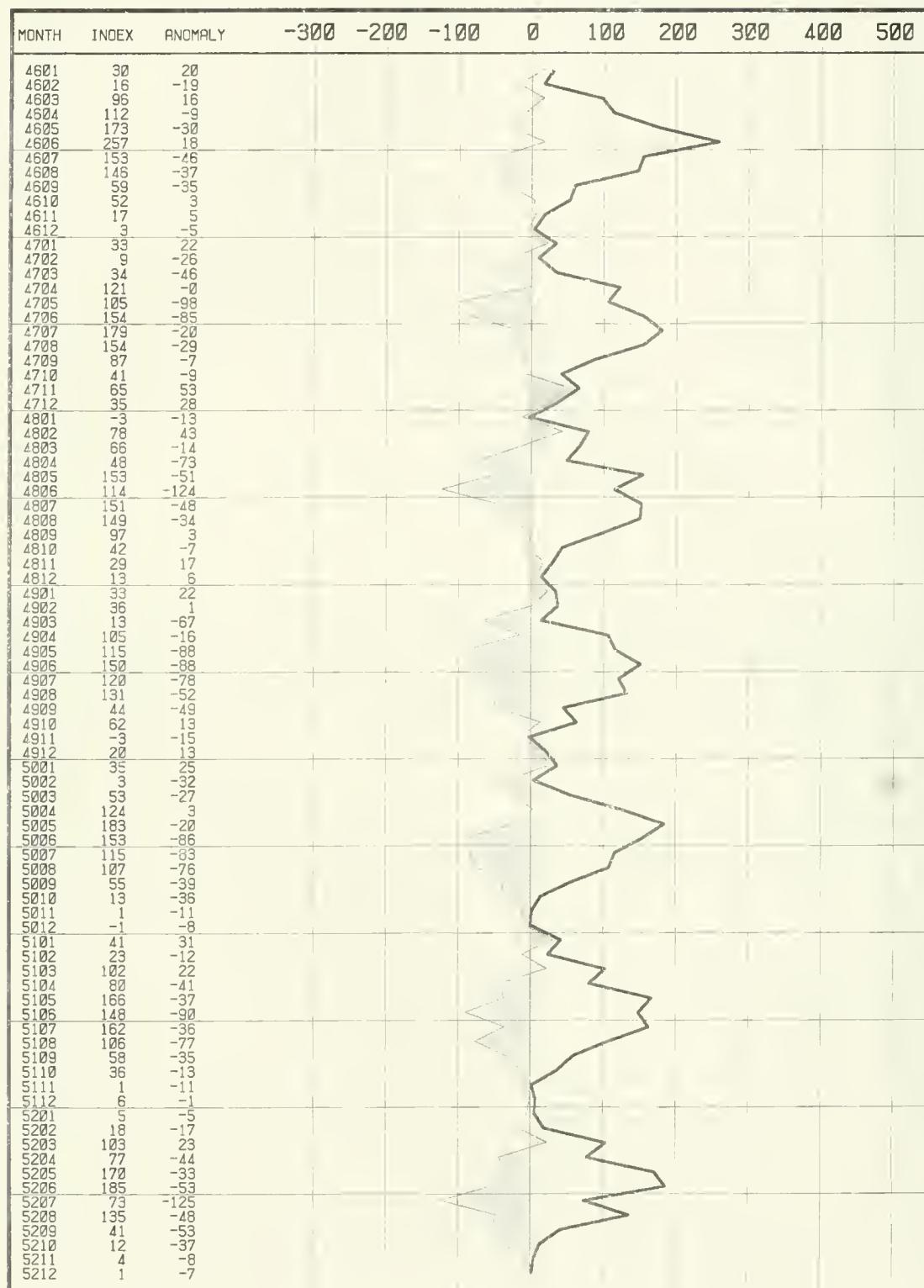


UPWELLING INDEX AT 39N, 125W BY YEAR



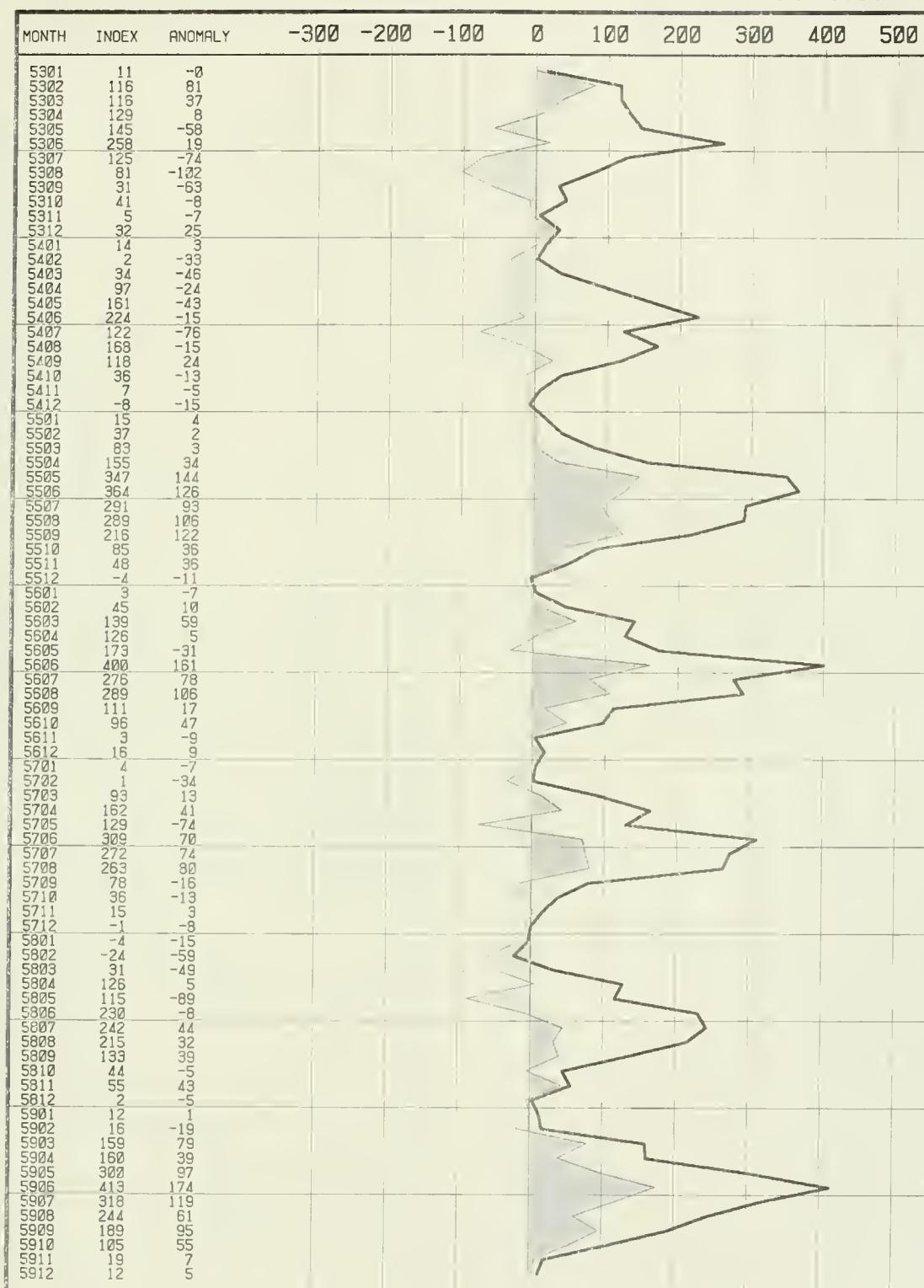
UPWELLING INDEX AT 36N, 122W

BY MONTH



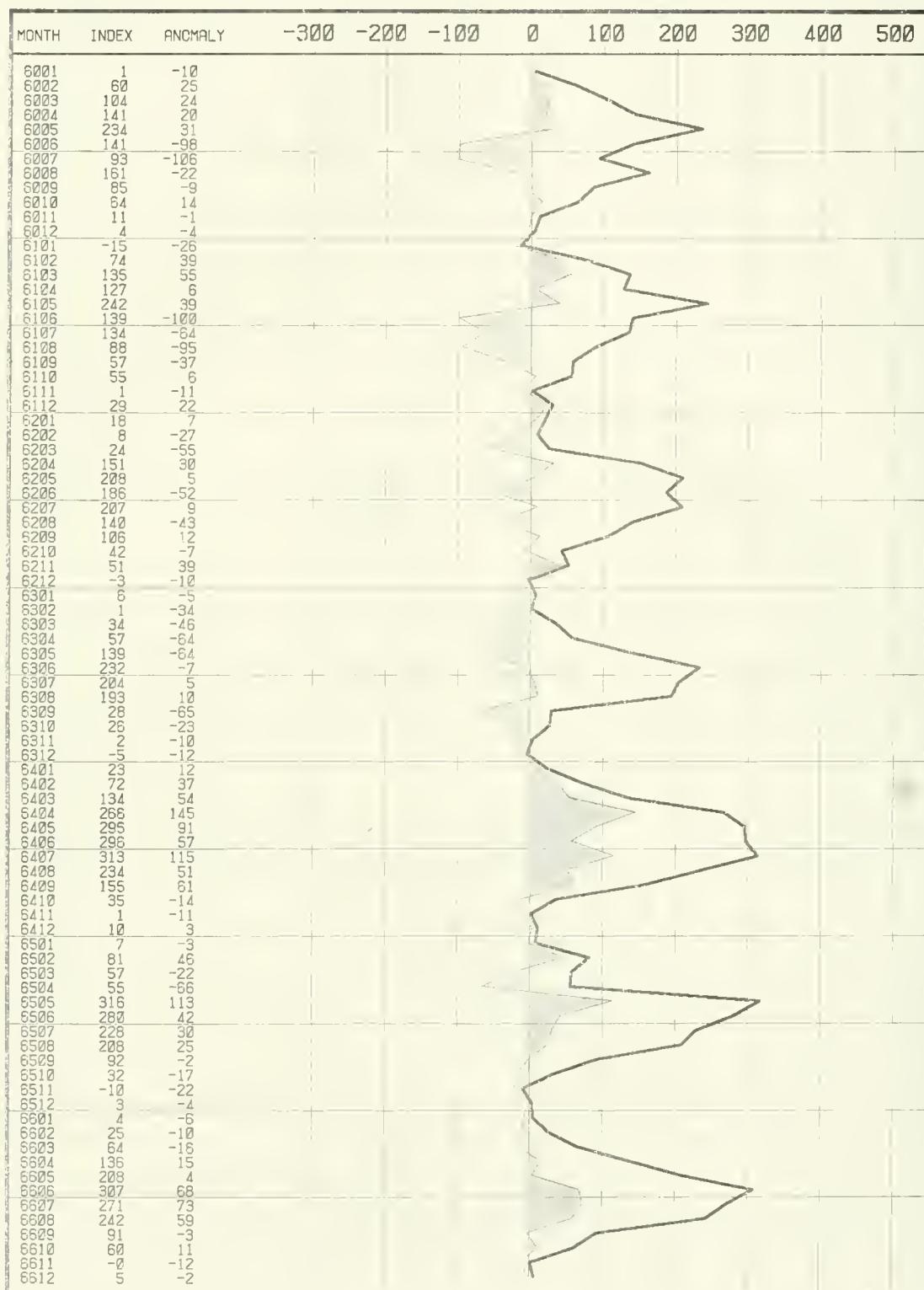
UPWELLING INDEX AT 36N, 122W

BY MONTH

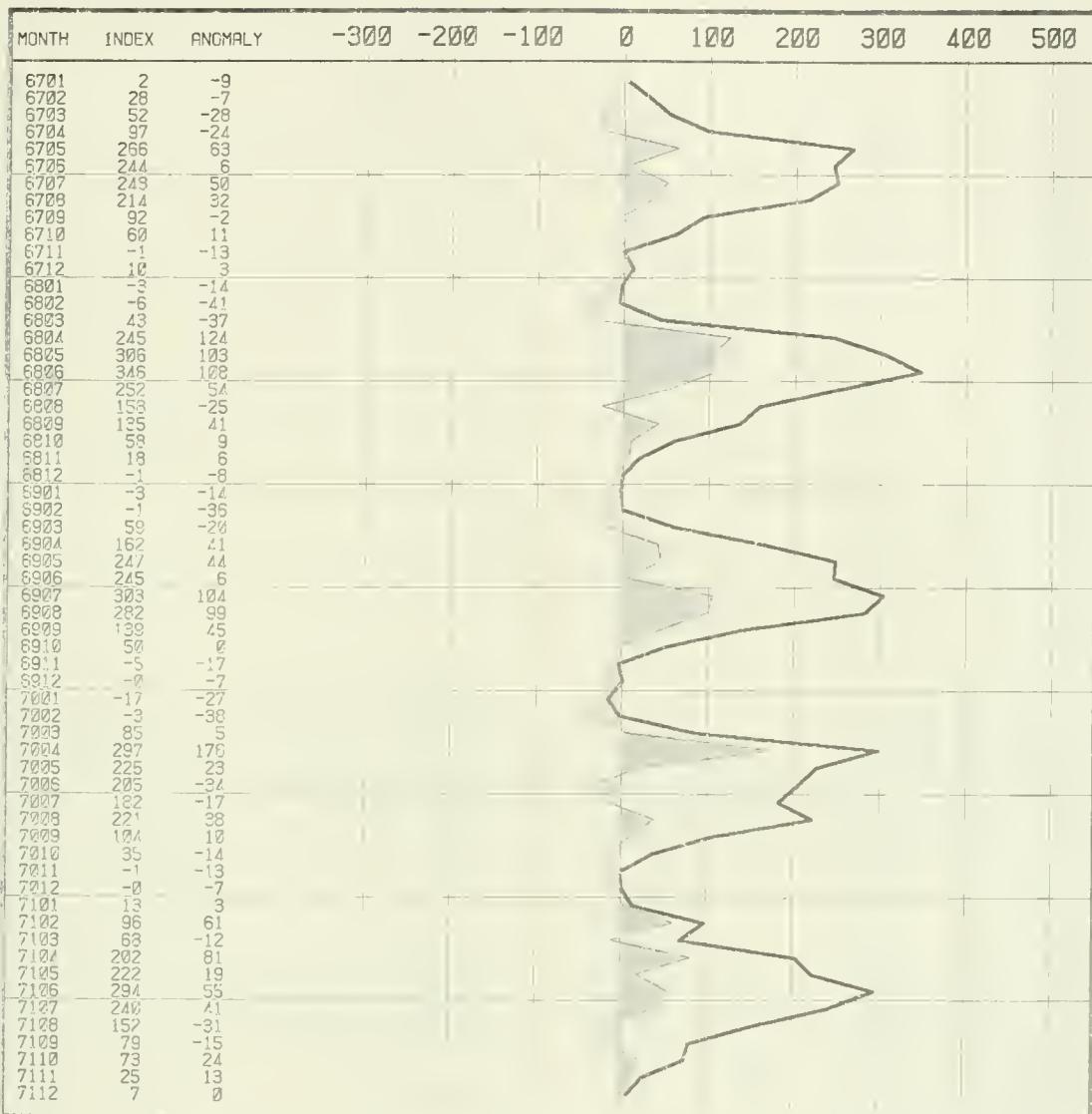


UPWELLING INDEX AT 36N, 122W

BY MONTH

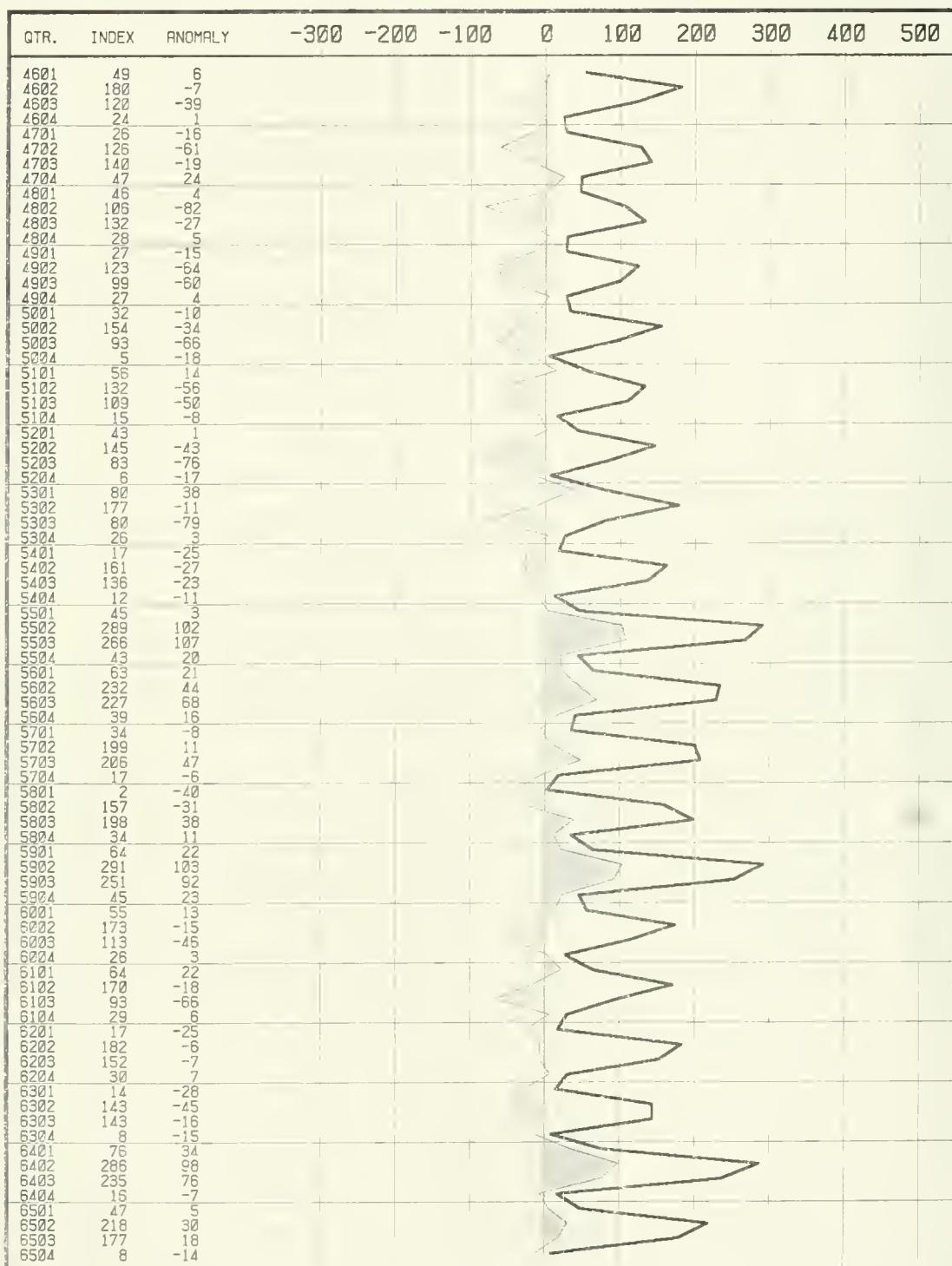


UPWELLING INDEX AT 36N, 122W BY MONTH

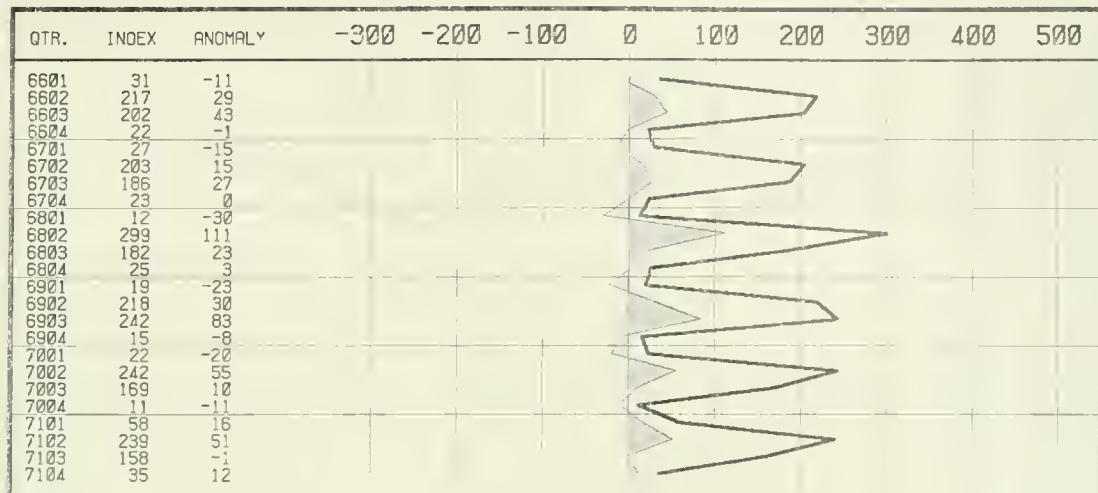


UPWELLING INDEX AT 36N, 122W

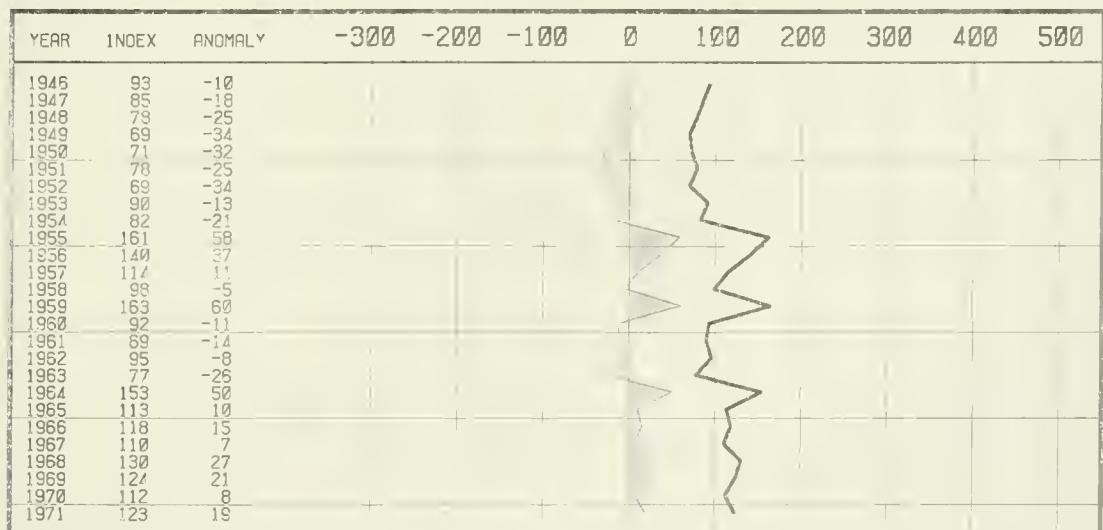
BY QUARTER



UPWELLING INDEX AT 36N, 122W BY QUARTER

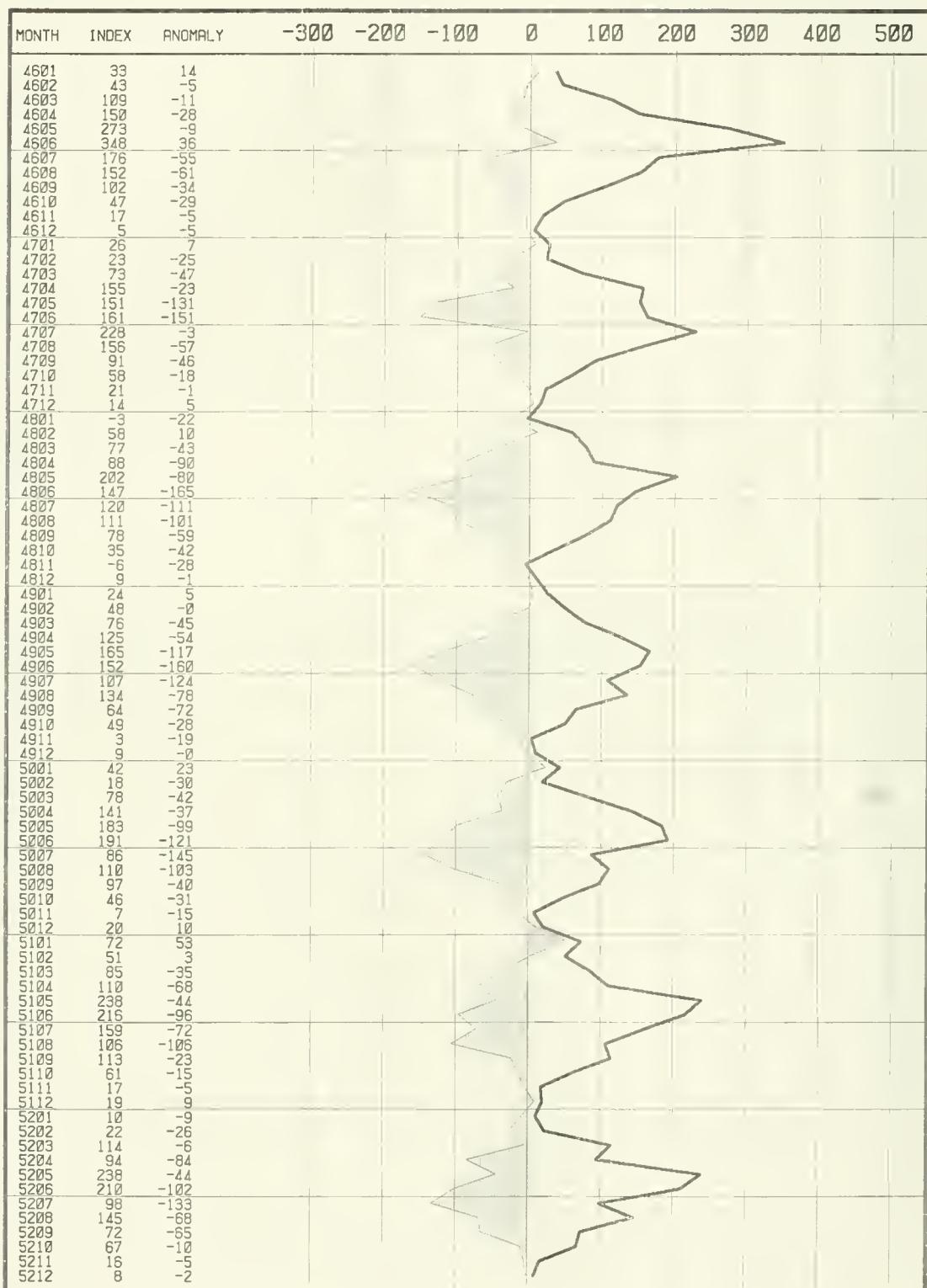


UPWELLING INDEX AT 36N, 122W BY YEAR

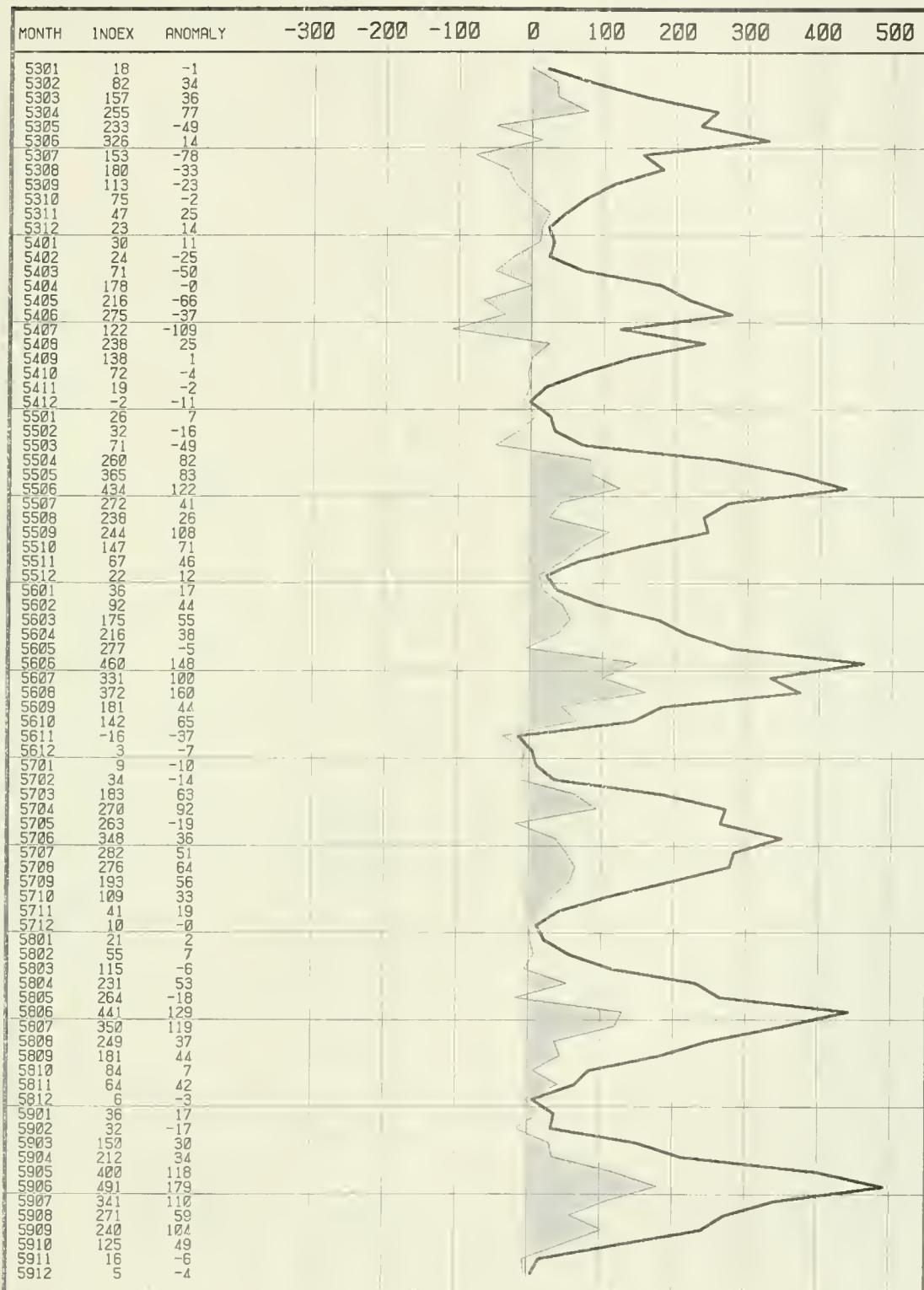


UPWELLING INDEX AT 33N, 119W

BY MONTH

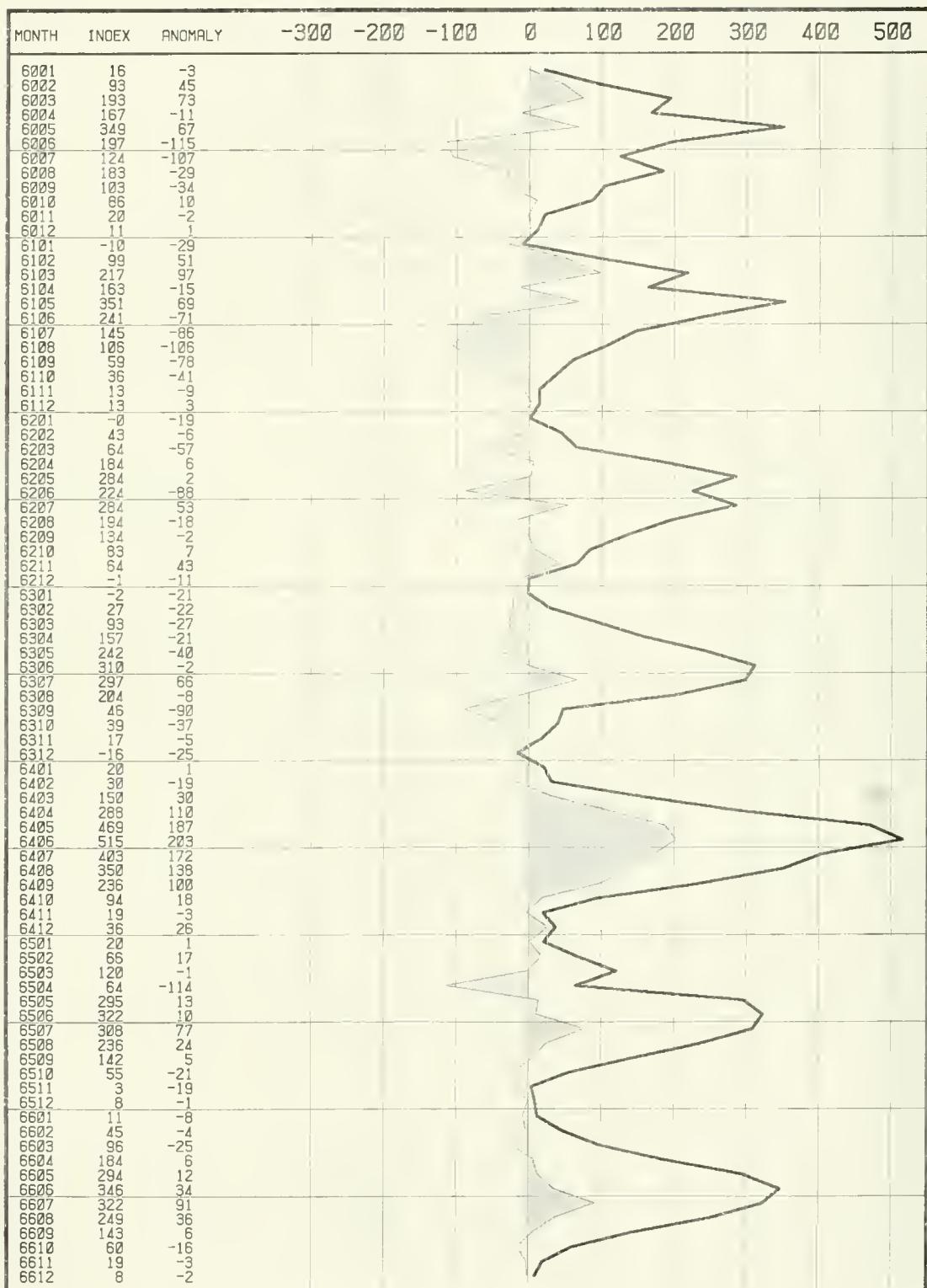


UPWELLING INDEX AT 33N, 119W BY MONTH

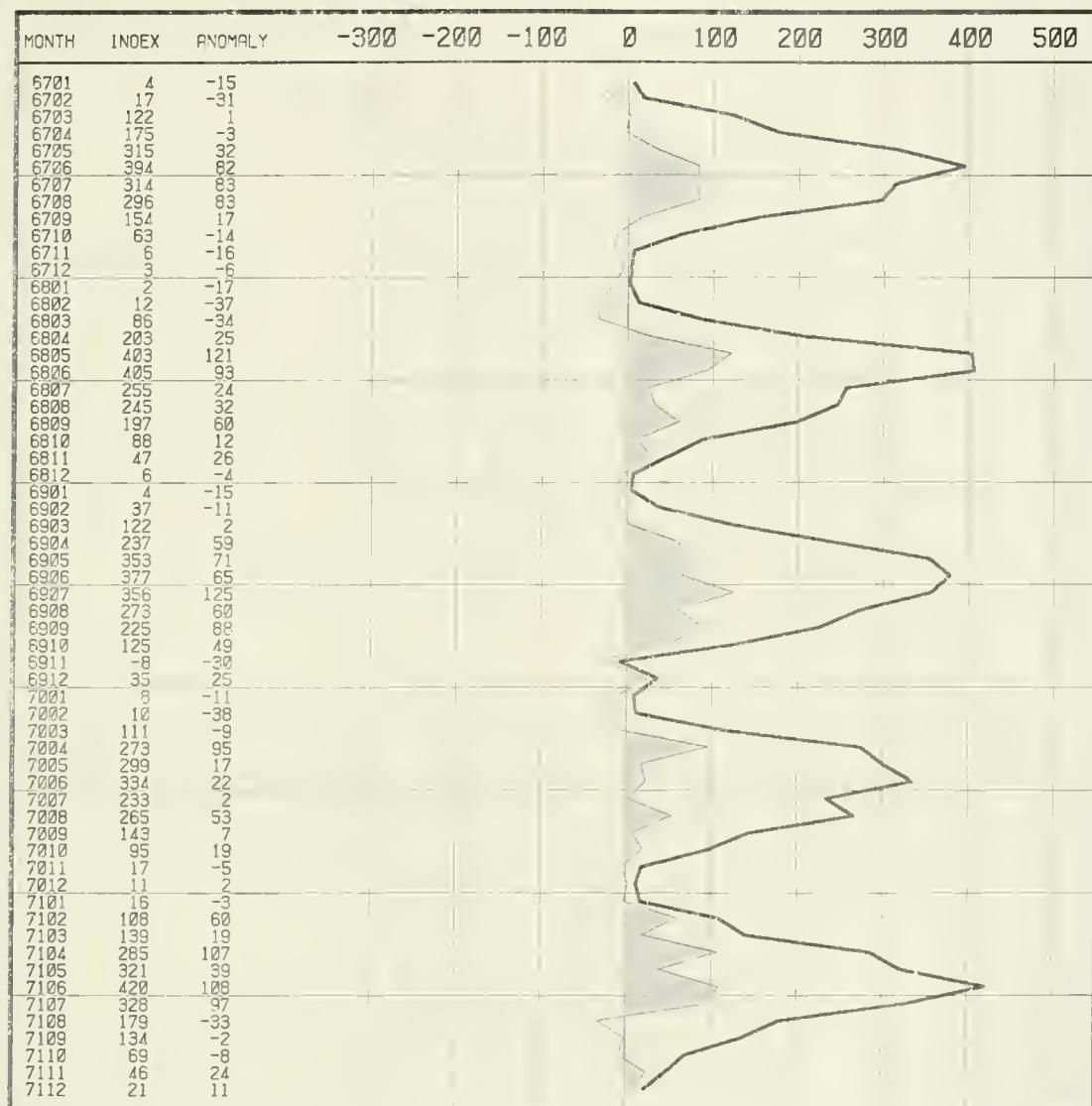


UPWELLING INDEX AT 33N, 119W

BY MONTH

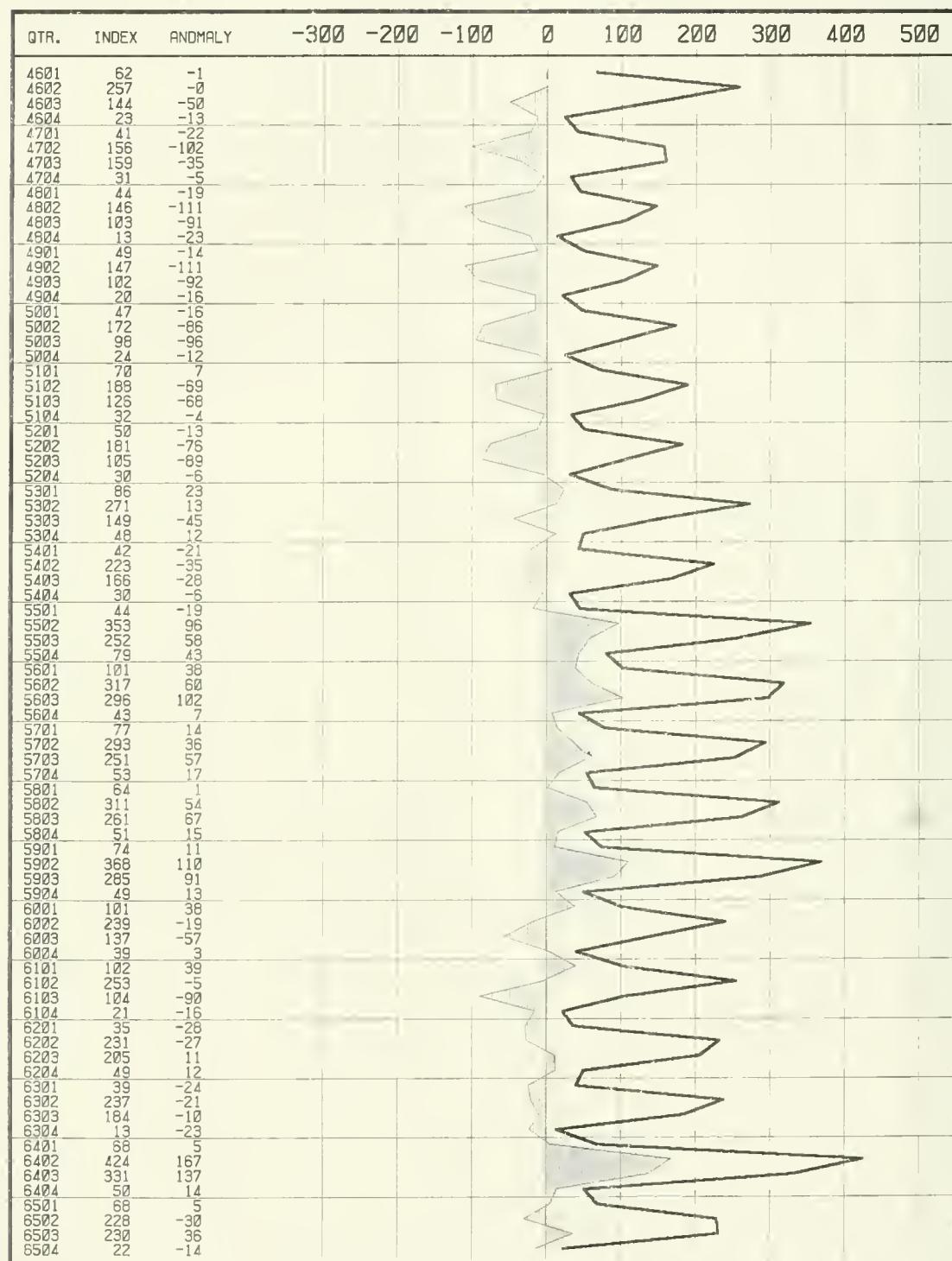


UPWELLING INDEX AT 33N, 119W BY MONTH

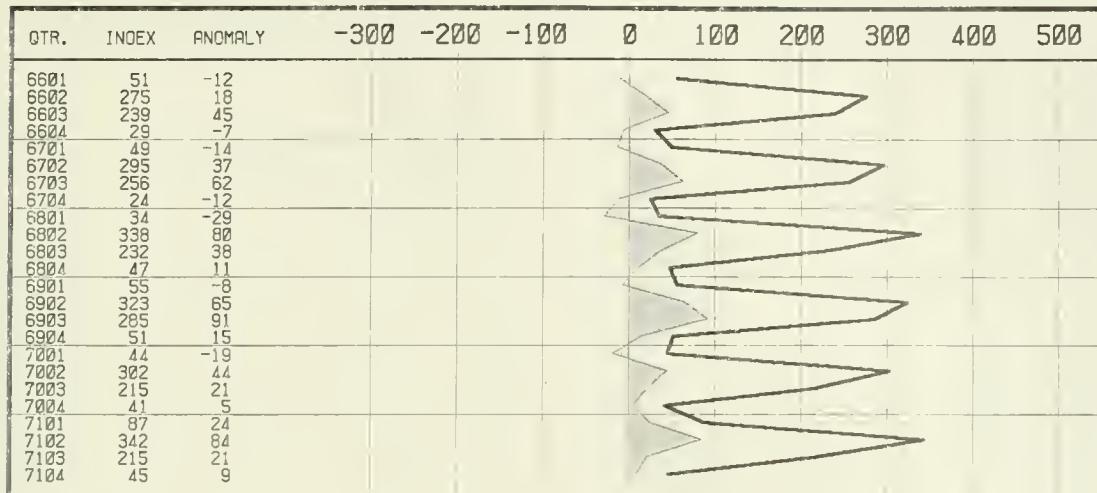


UPWELLING INDEX AT 33N, 119W

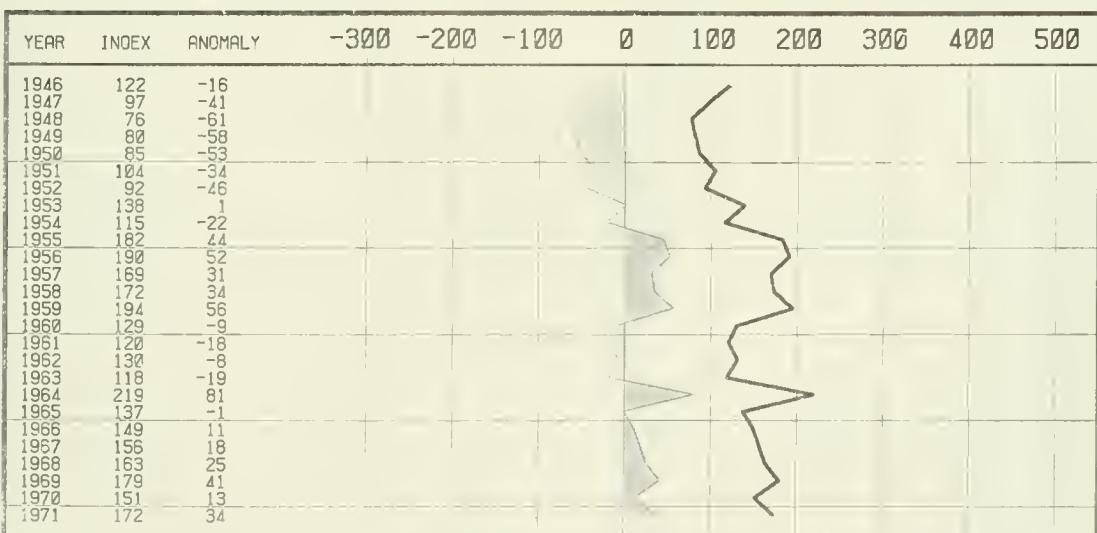
BY QUARTER



UPWELLING INDEX AT 33N, 119W BY QUARTER

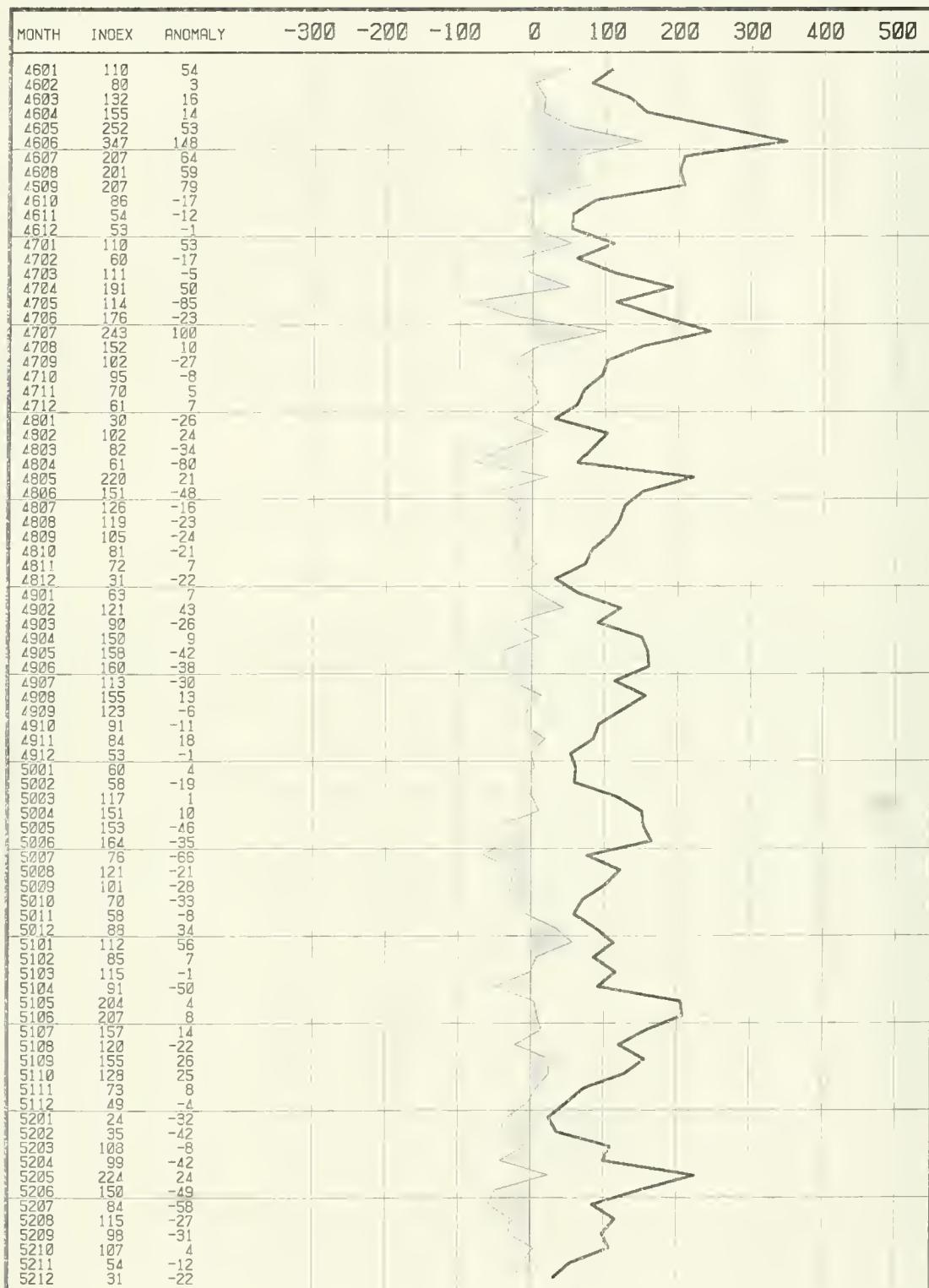


UPWELLING INDEX AT 33N, 119W BY YEAR



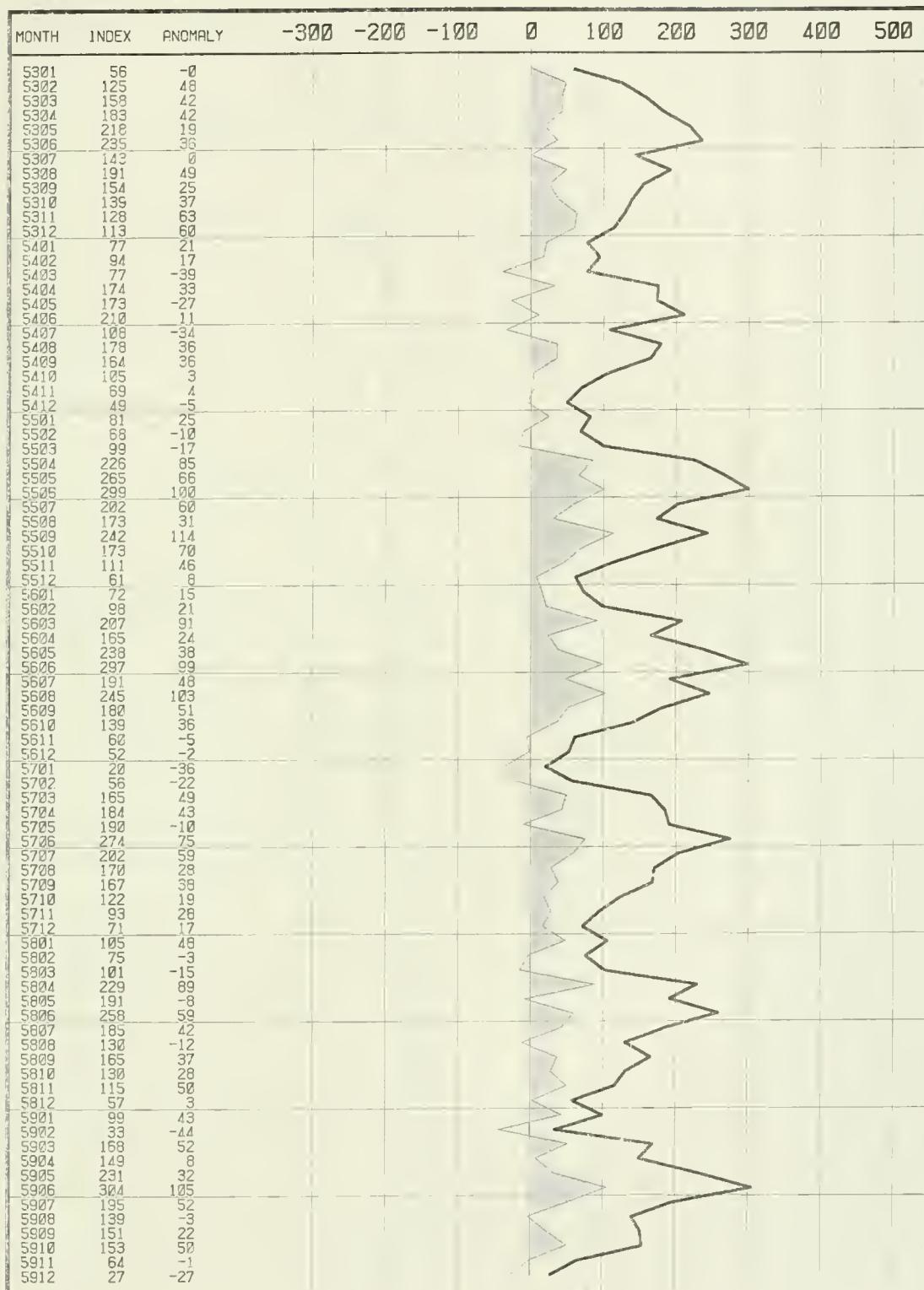
UPWELLING INDEX AT 30N, 119W

BY MONTH



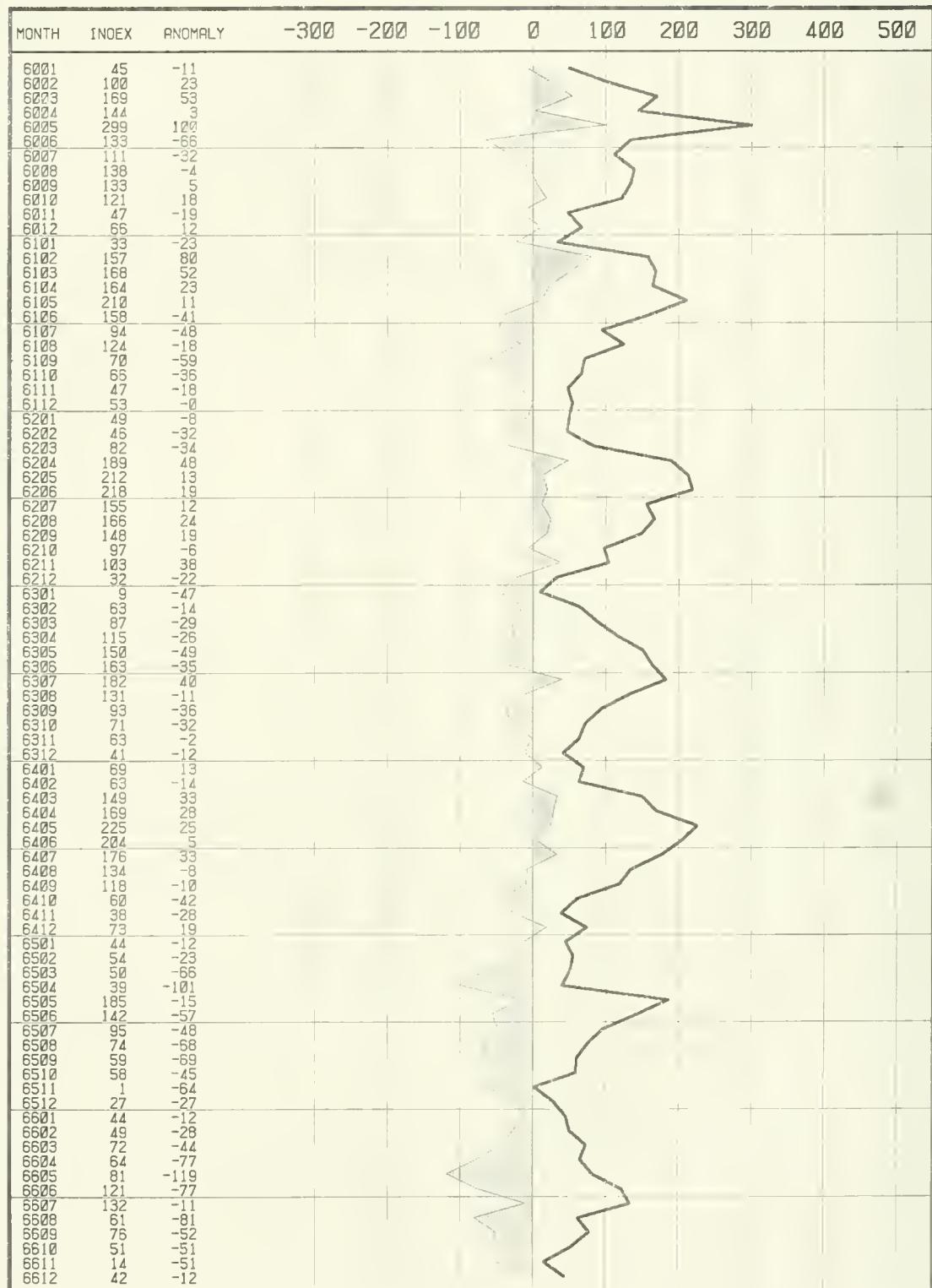
UPWELLING INDEX AT 30N, 119W

BY MONTH

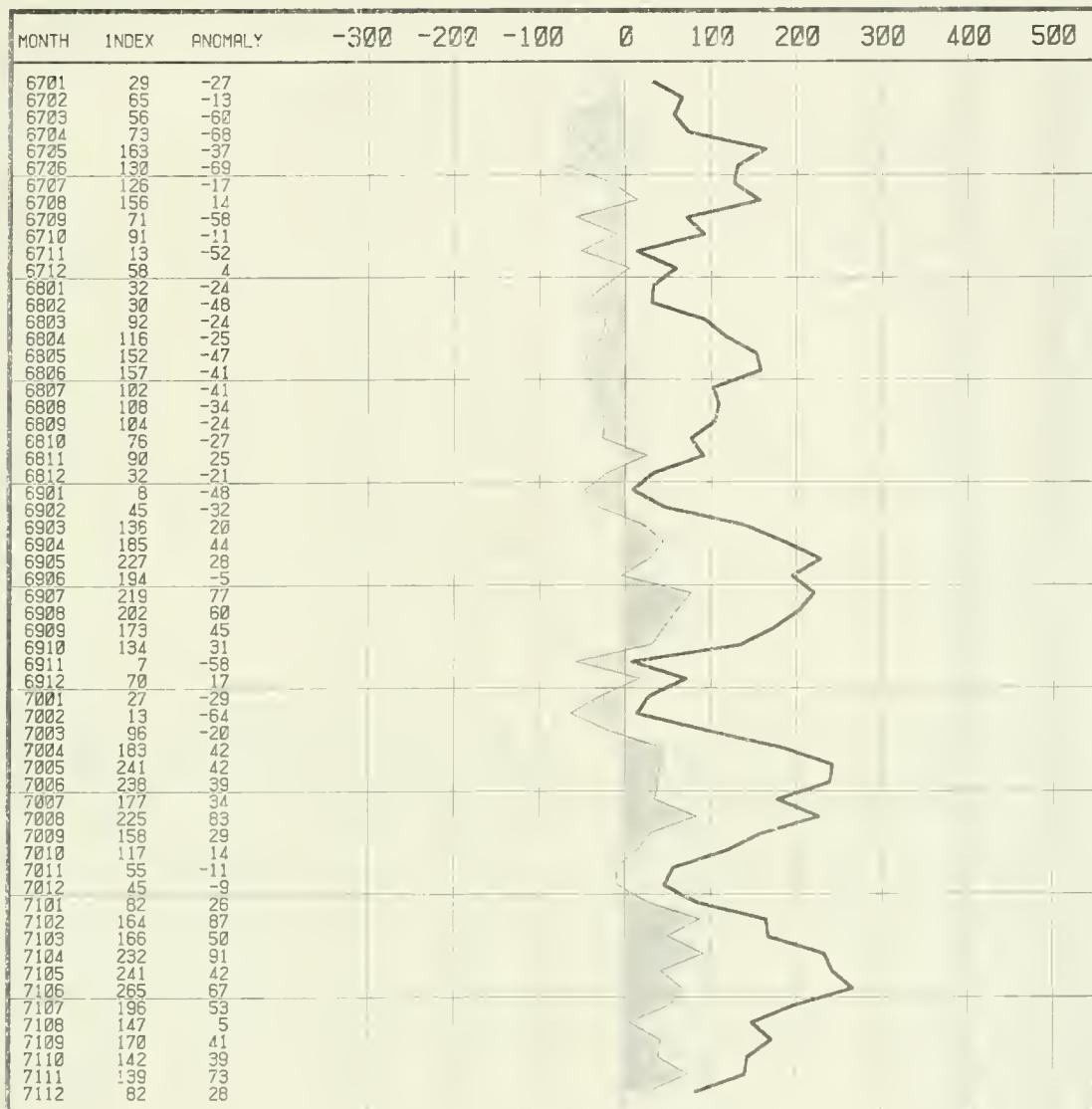


UPWELLING INDEX AT 30N, 119W

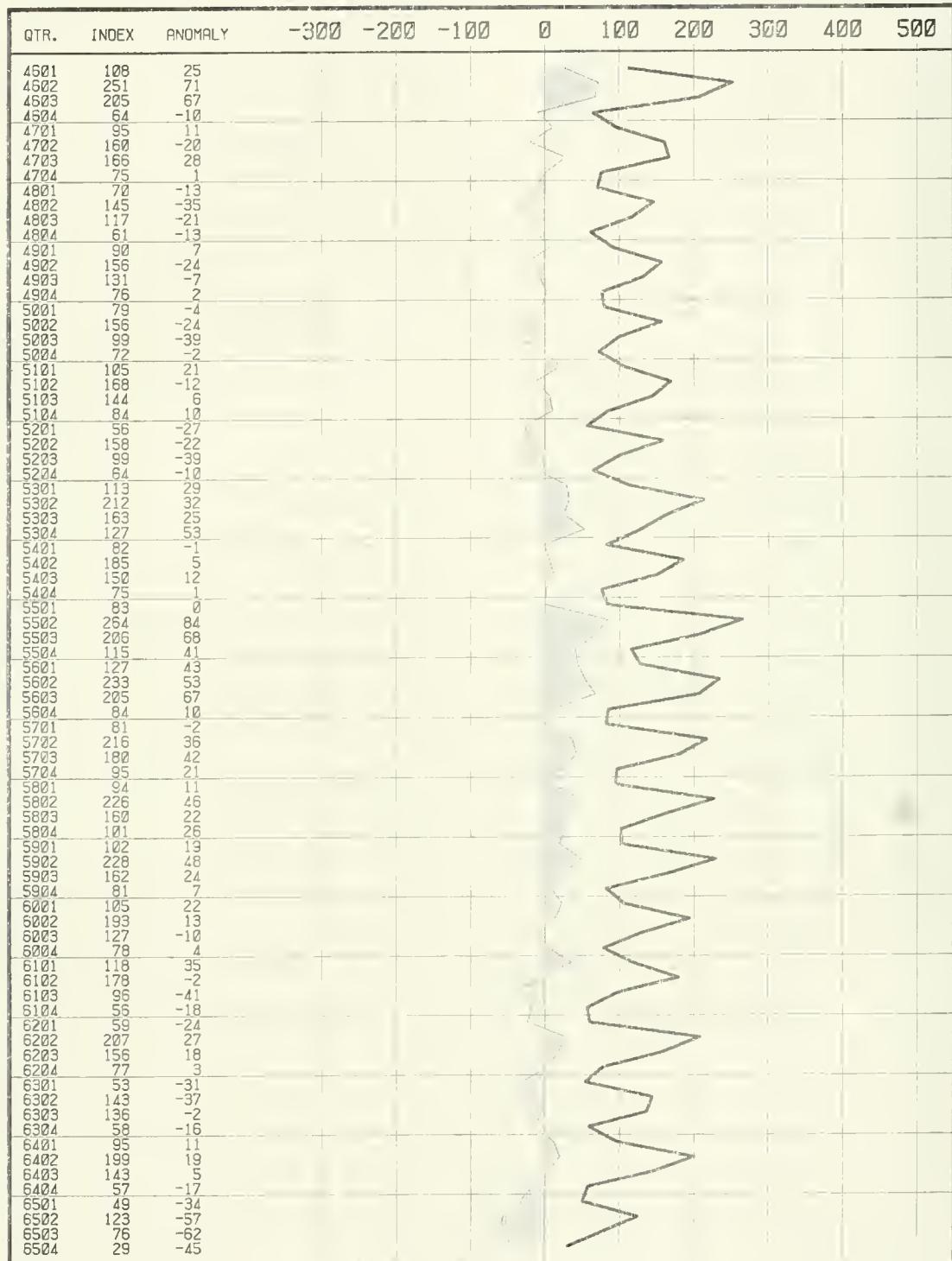
BY MONTH



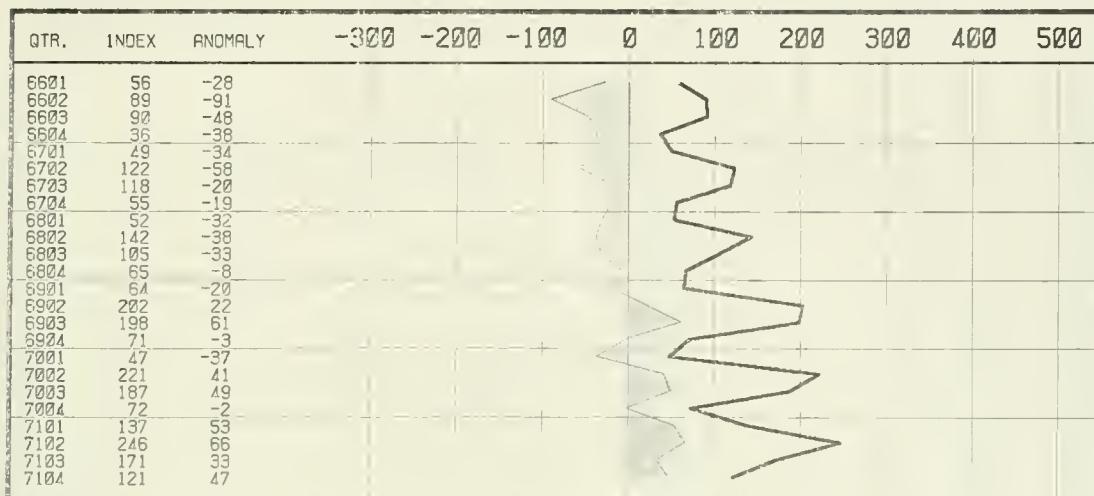
UPWELLING INDEX AT 30N, 119W BY MONTH



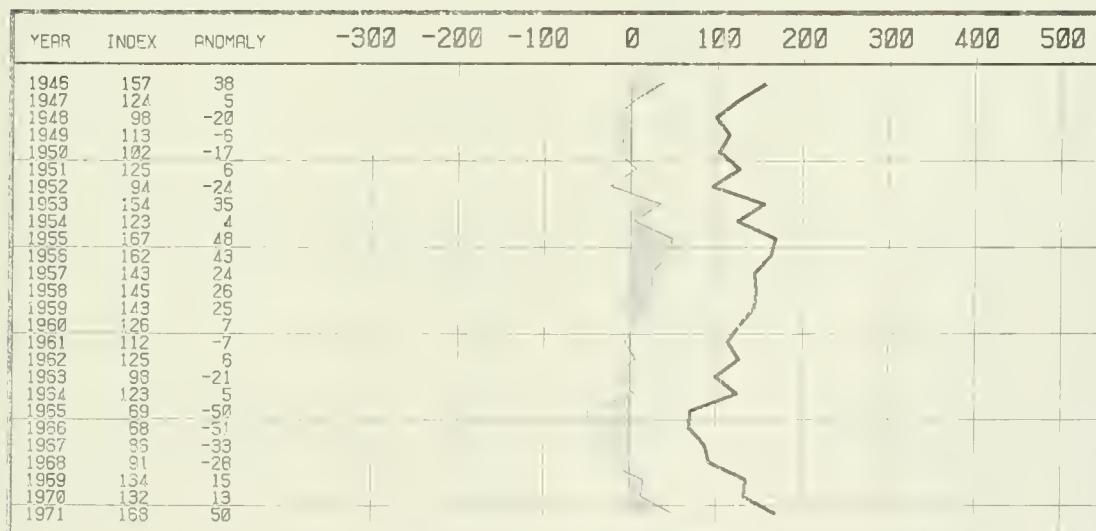
UPWELLING INDEX AT 30N, 119W BY QUARTER



UPWELLING INDEX AT 30N, 119W BY QUARTER

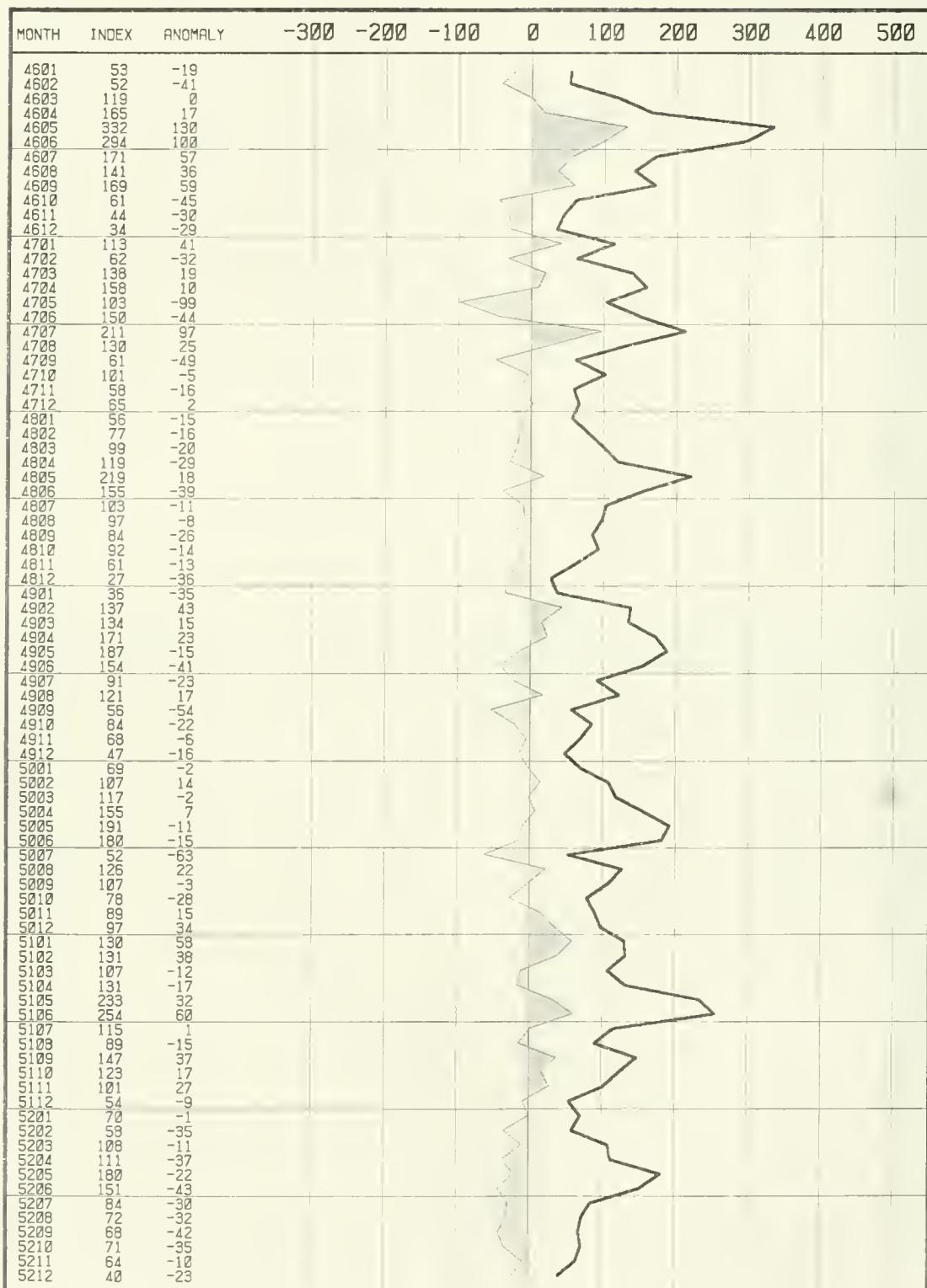


UPWELLING INDEX AT 30N, 119W BY YEAR

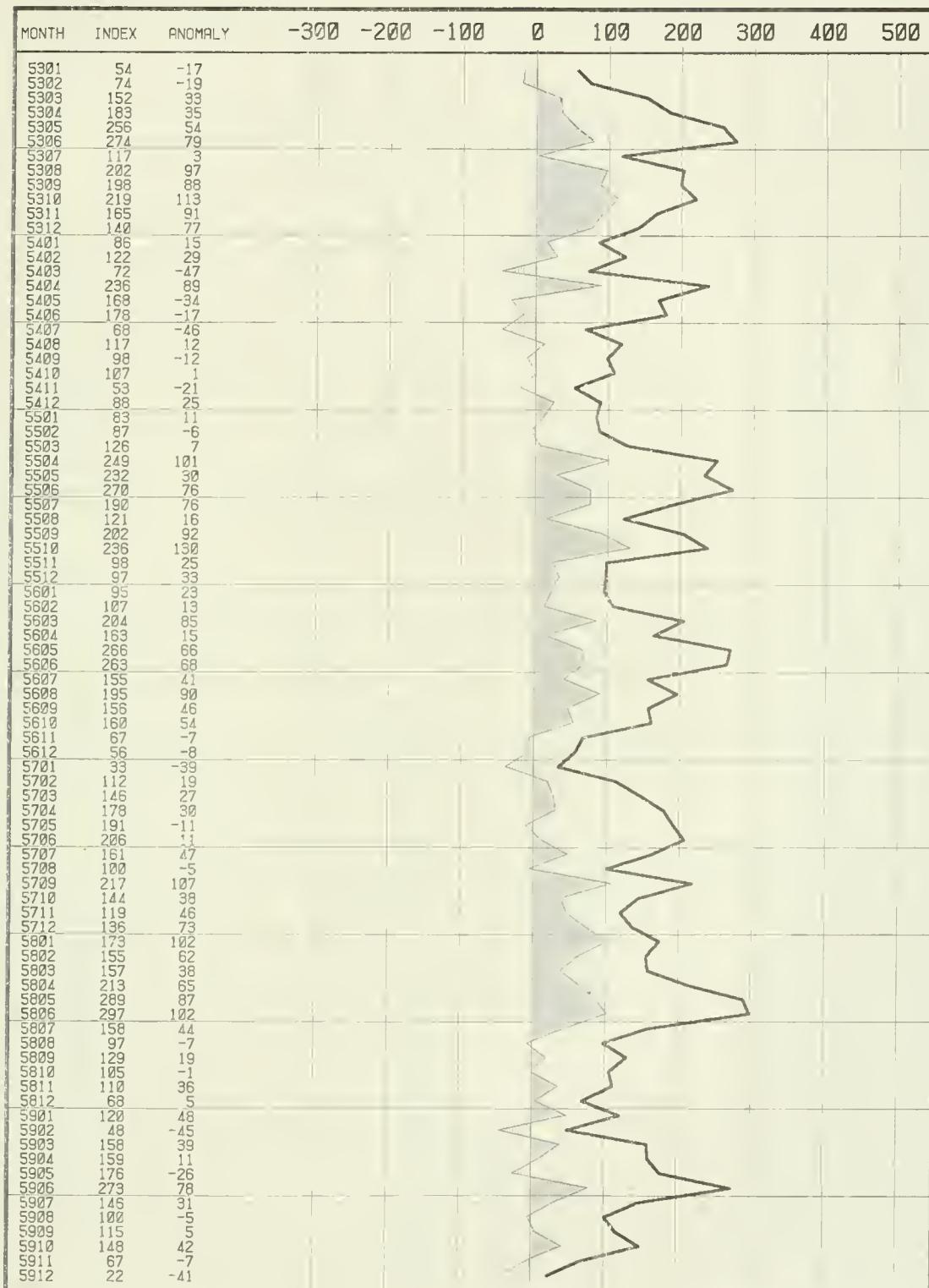


UPWELLING INDEX AT 27N, 116W

BY MONTH

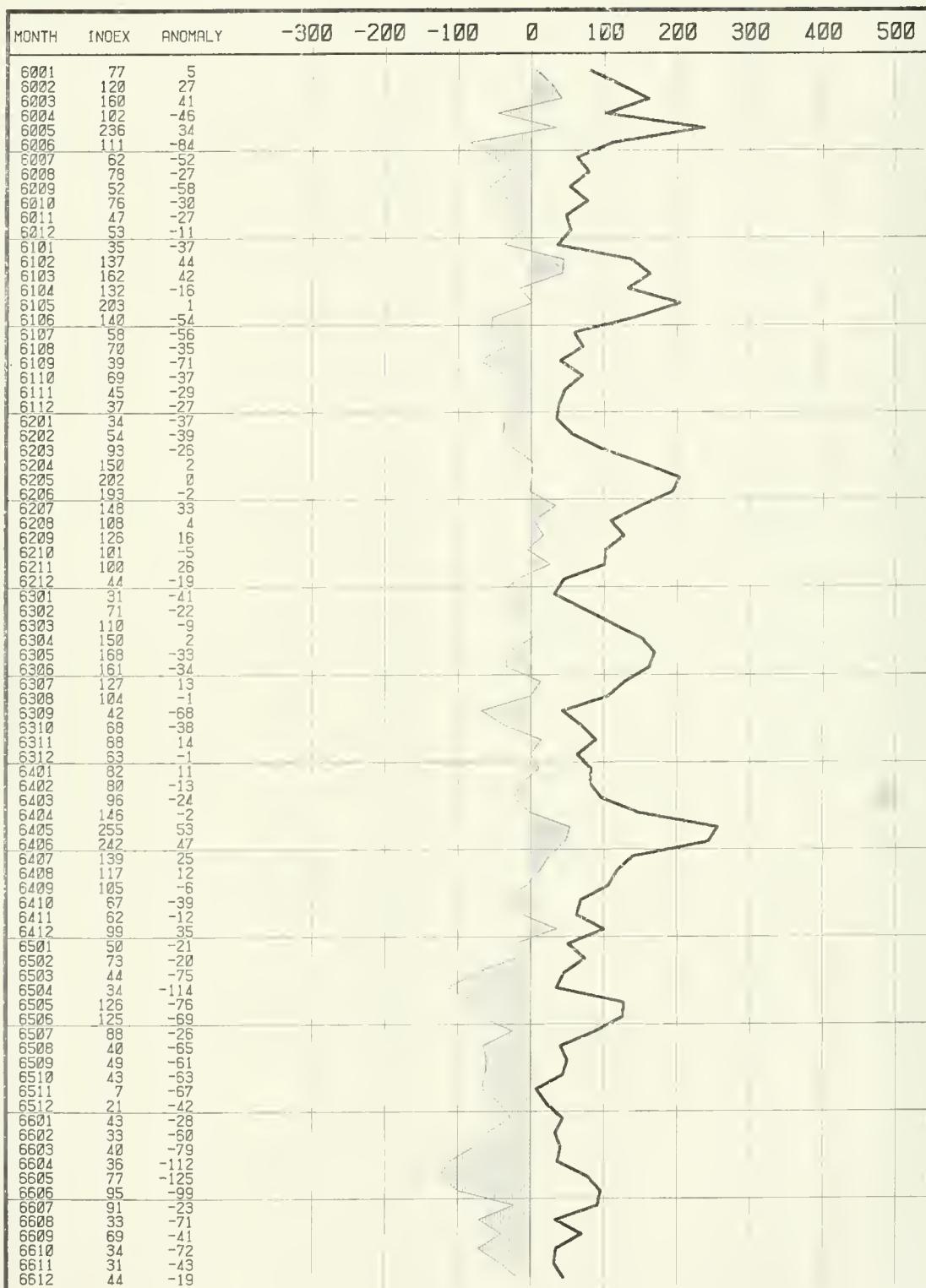


UPWELLING INDEX AT 27N, 116W BY MONTH



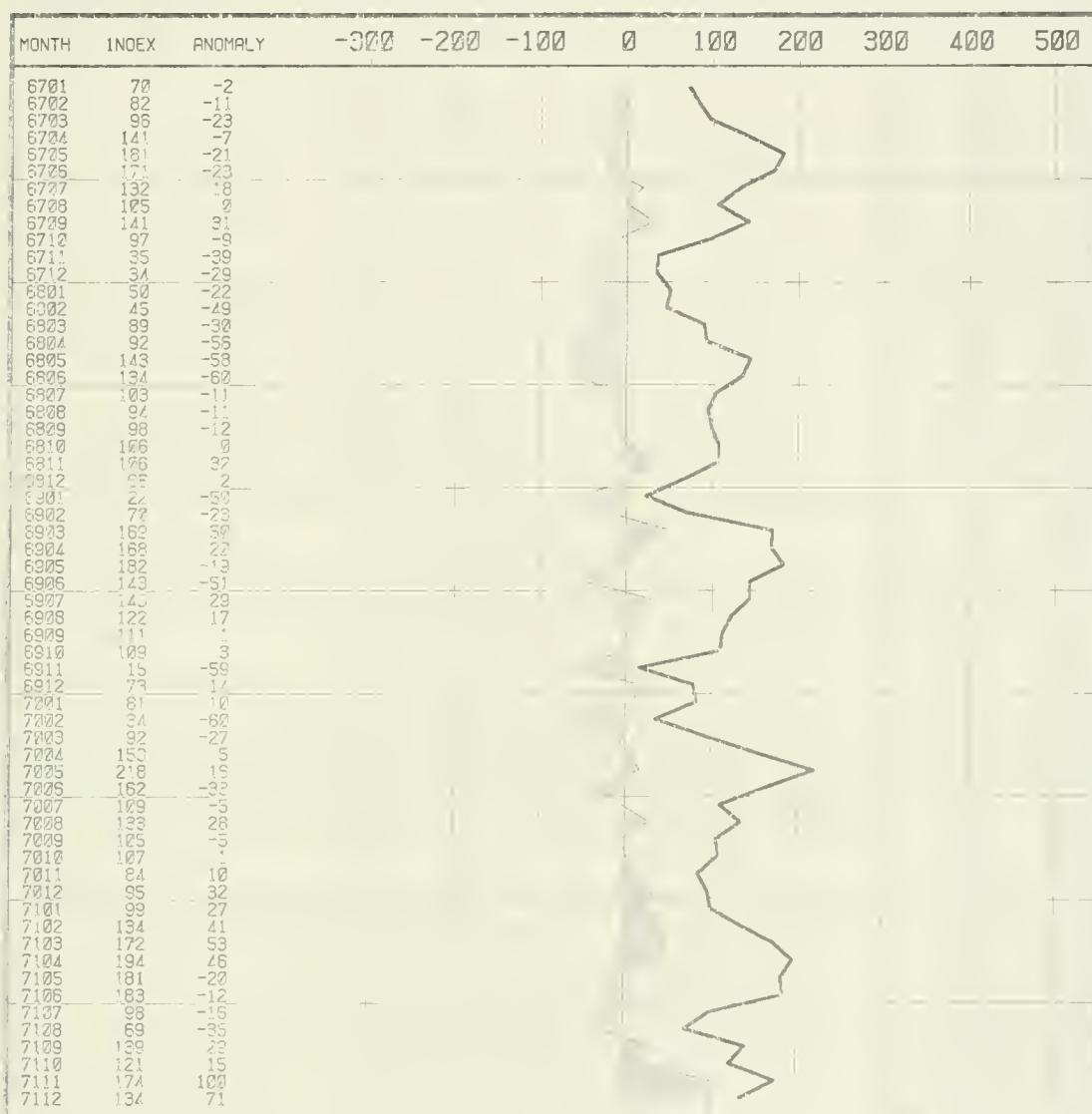
UPWELLING INDEX AT 27N, 116W

BY MONTH

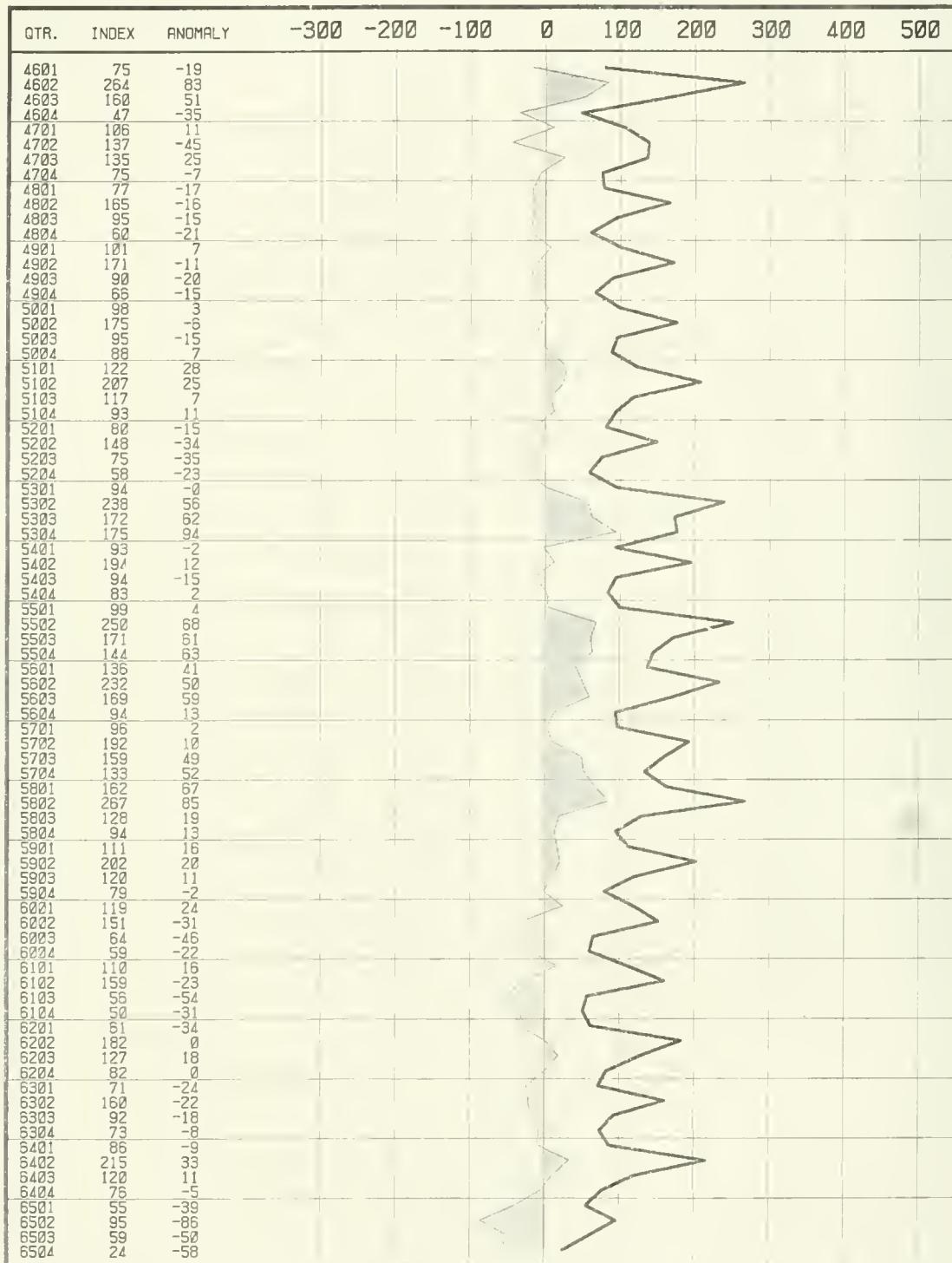


UPWELLING INDEX AT 27N, 116W

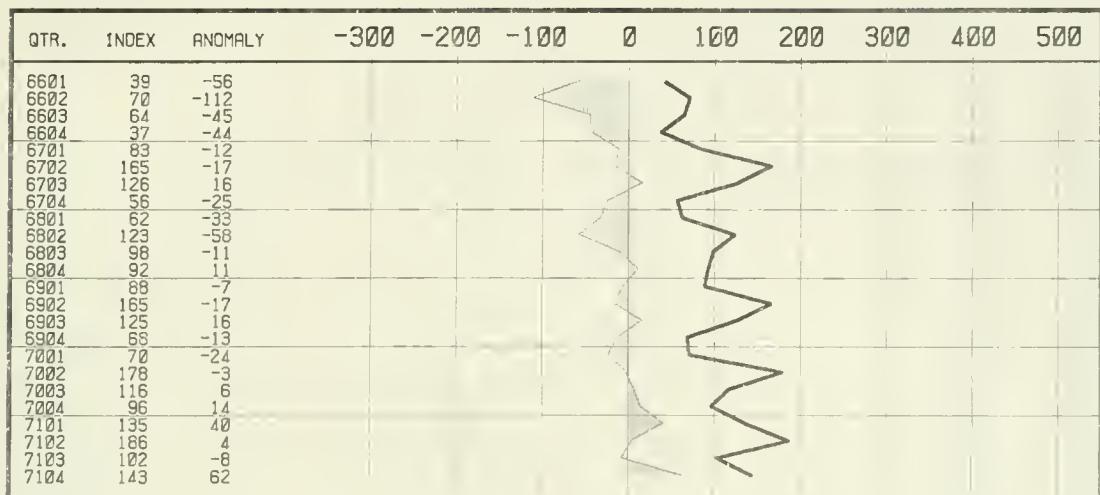
BY MONTH



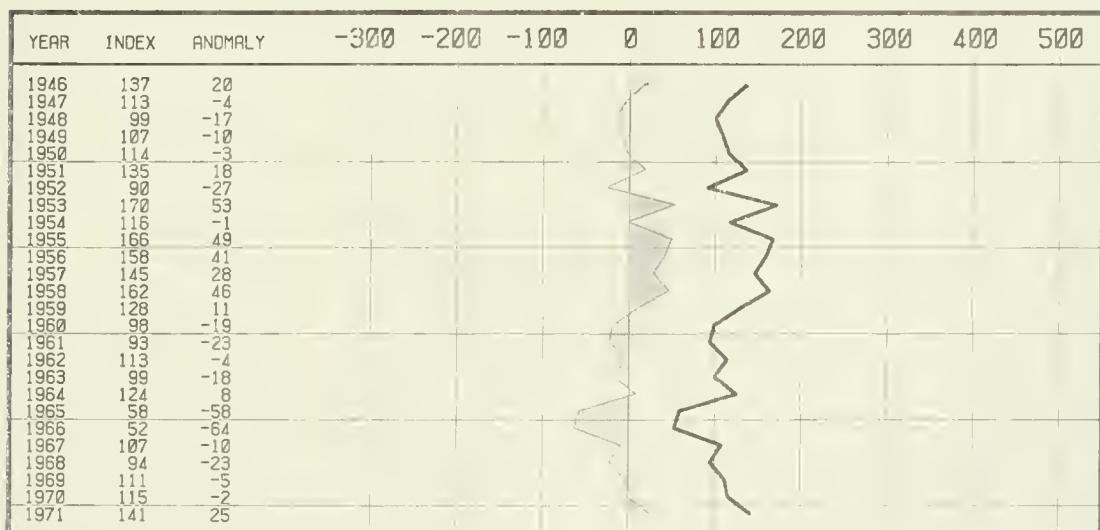
UPWELLING INDEX AT 27N, 116W BY QUARTER



UPWELLING INDEX AT 27N, 116W BY QUARTER

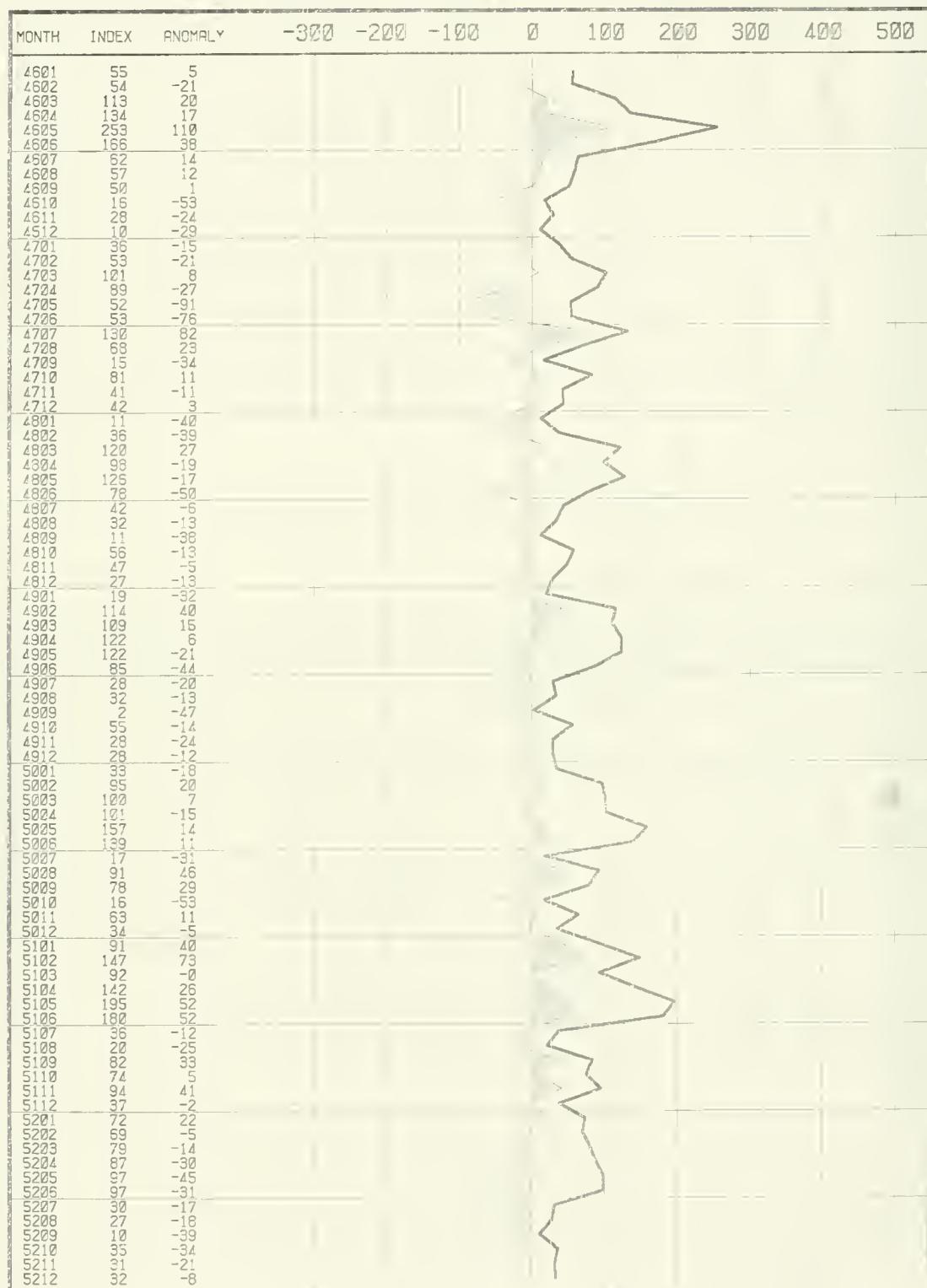


UPWELLING INDEX AT 27N, 116W BY YEAR



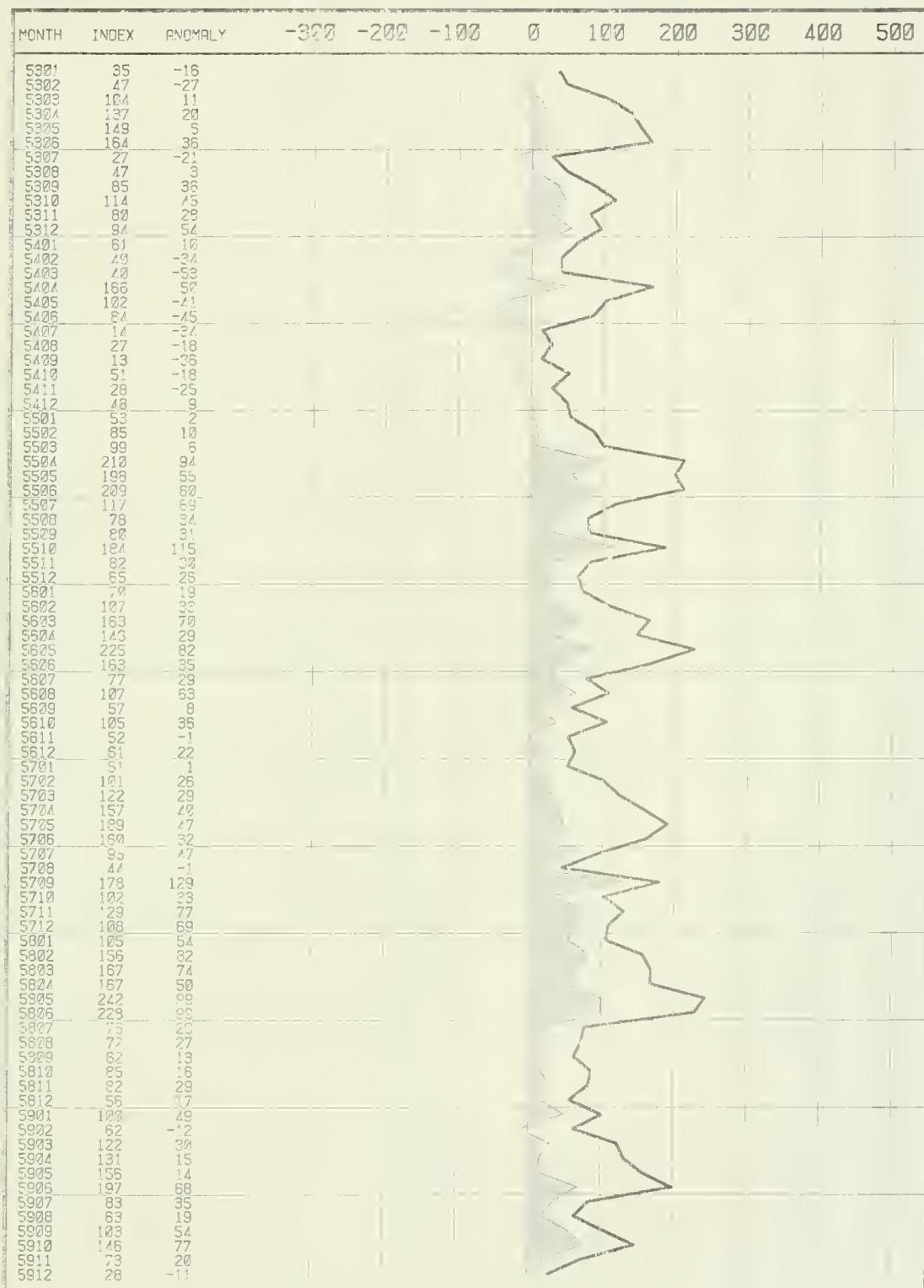
UPWELLING INDEX AT 24N, 113W

BY MONTH



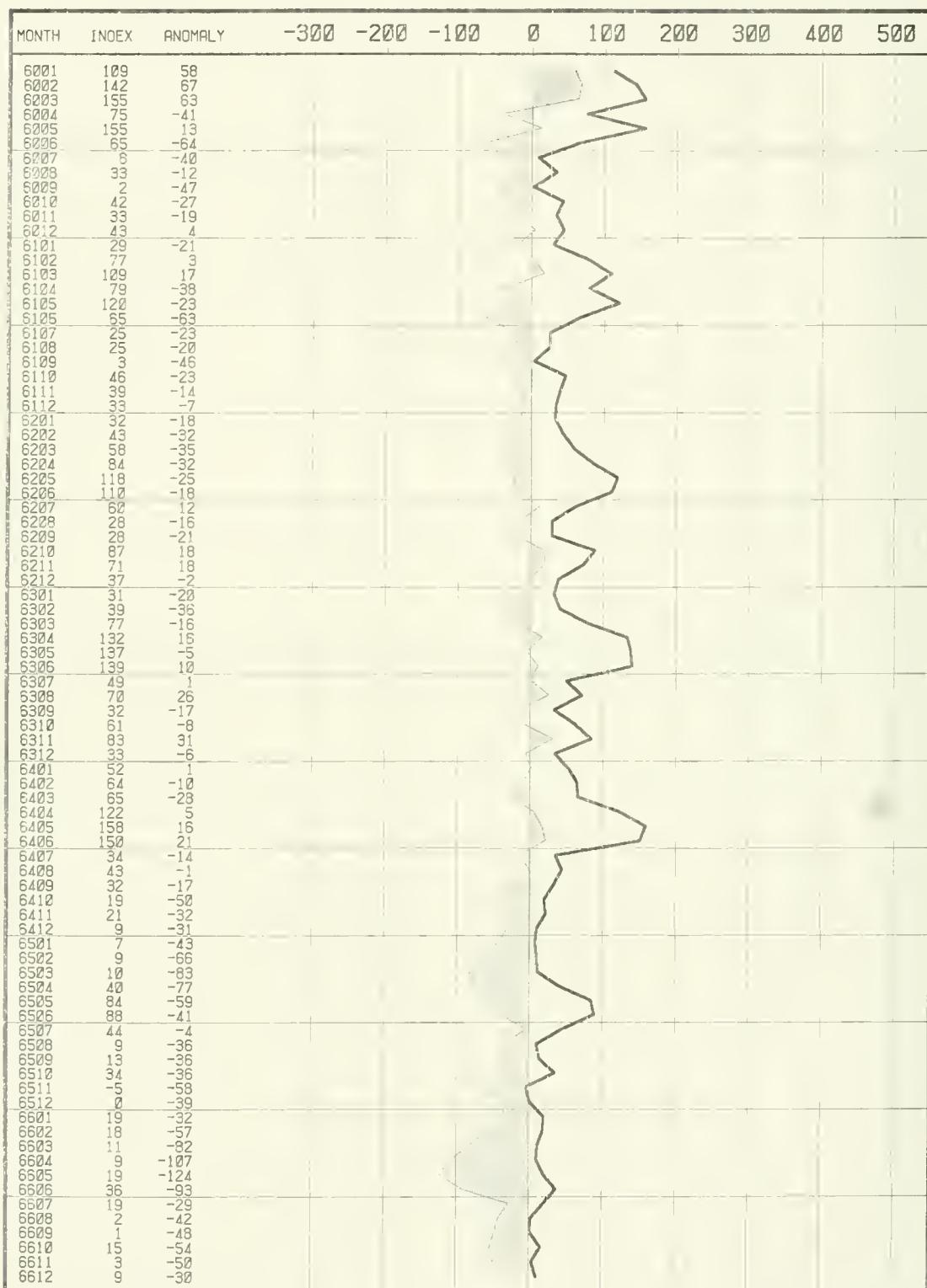
UPWELLING INDEX AT 24N, 113W

BY MONTH

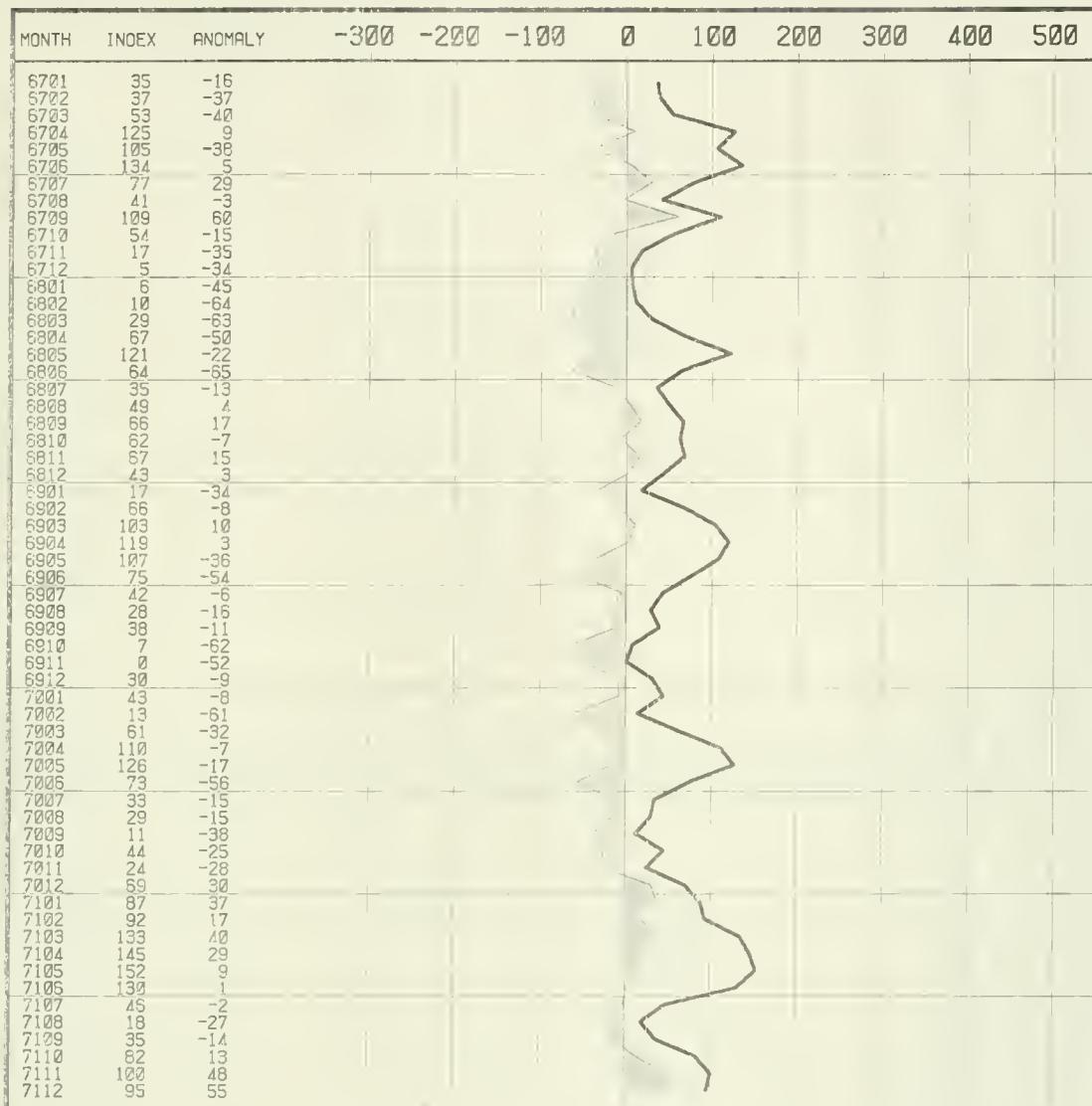


UPWELLING INDEX AT 24N, 113W

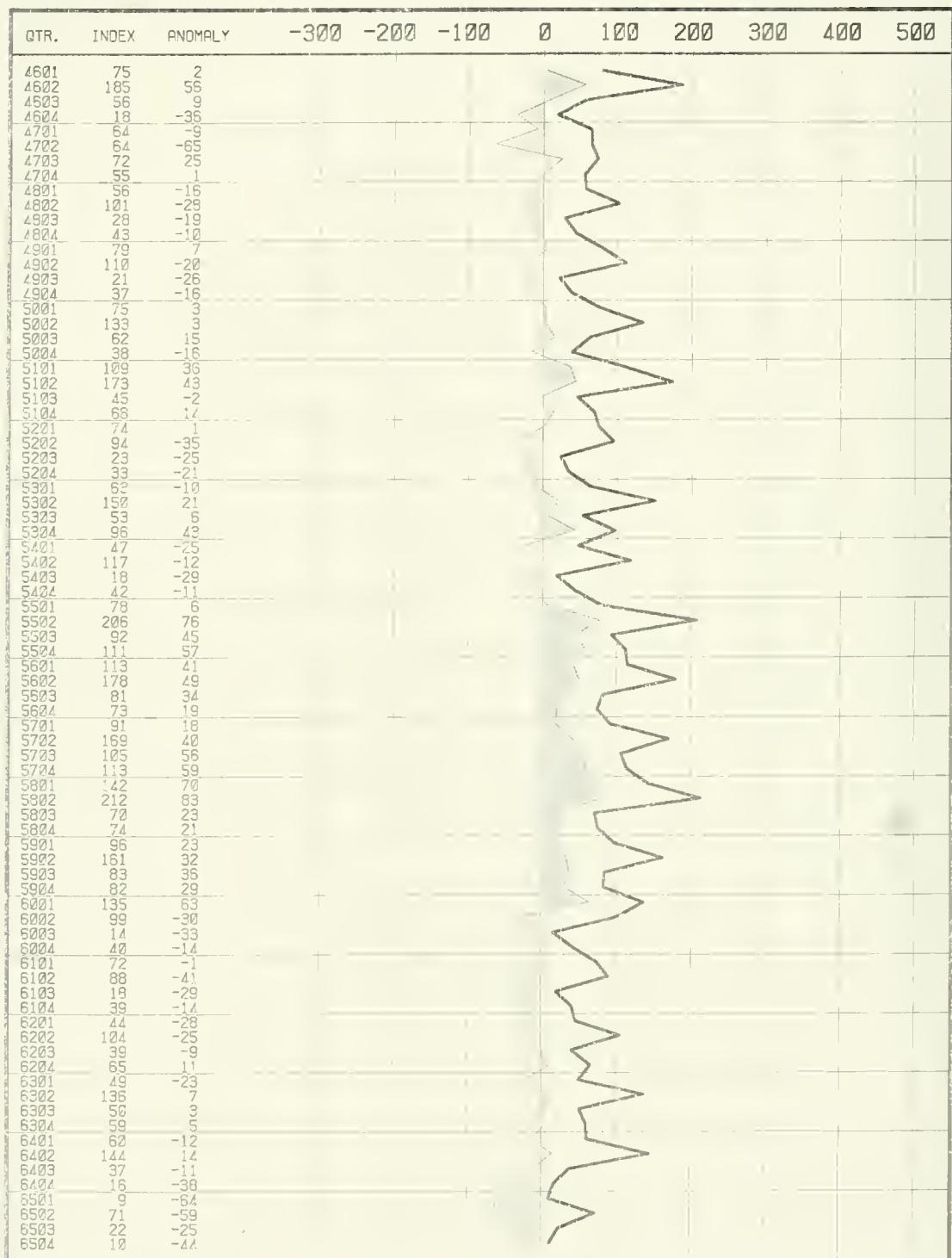
BY MONTH



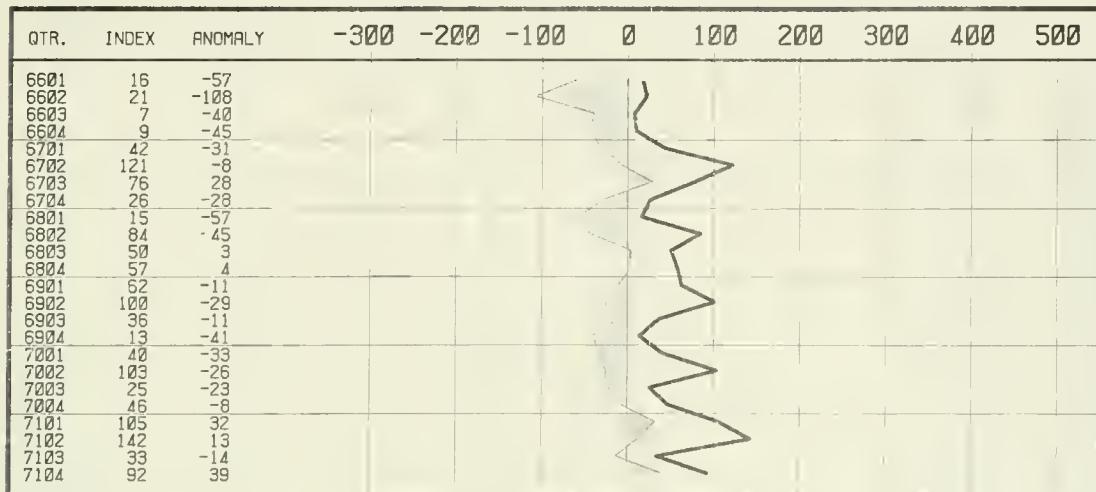
UPWELLING INDEX AT 24N, 113W BY MONTH



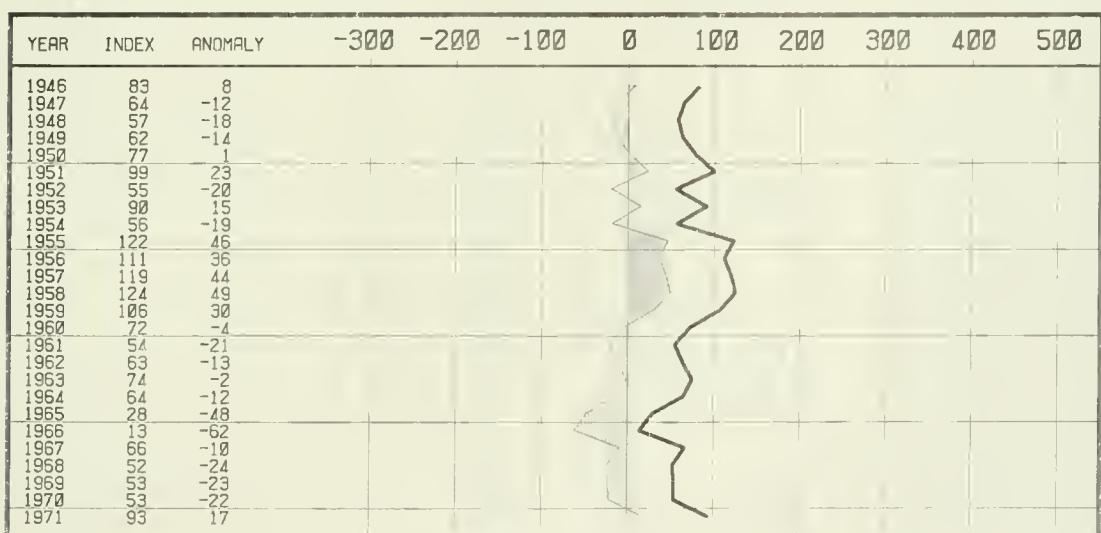
UPWELLING INDEX AT 24N, 113W BY QUARTER



UPWELLING INDEX AT 24N, 113W BY QUARTER

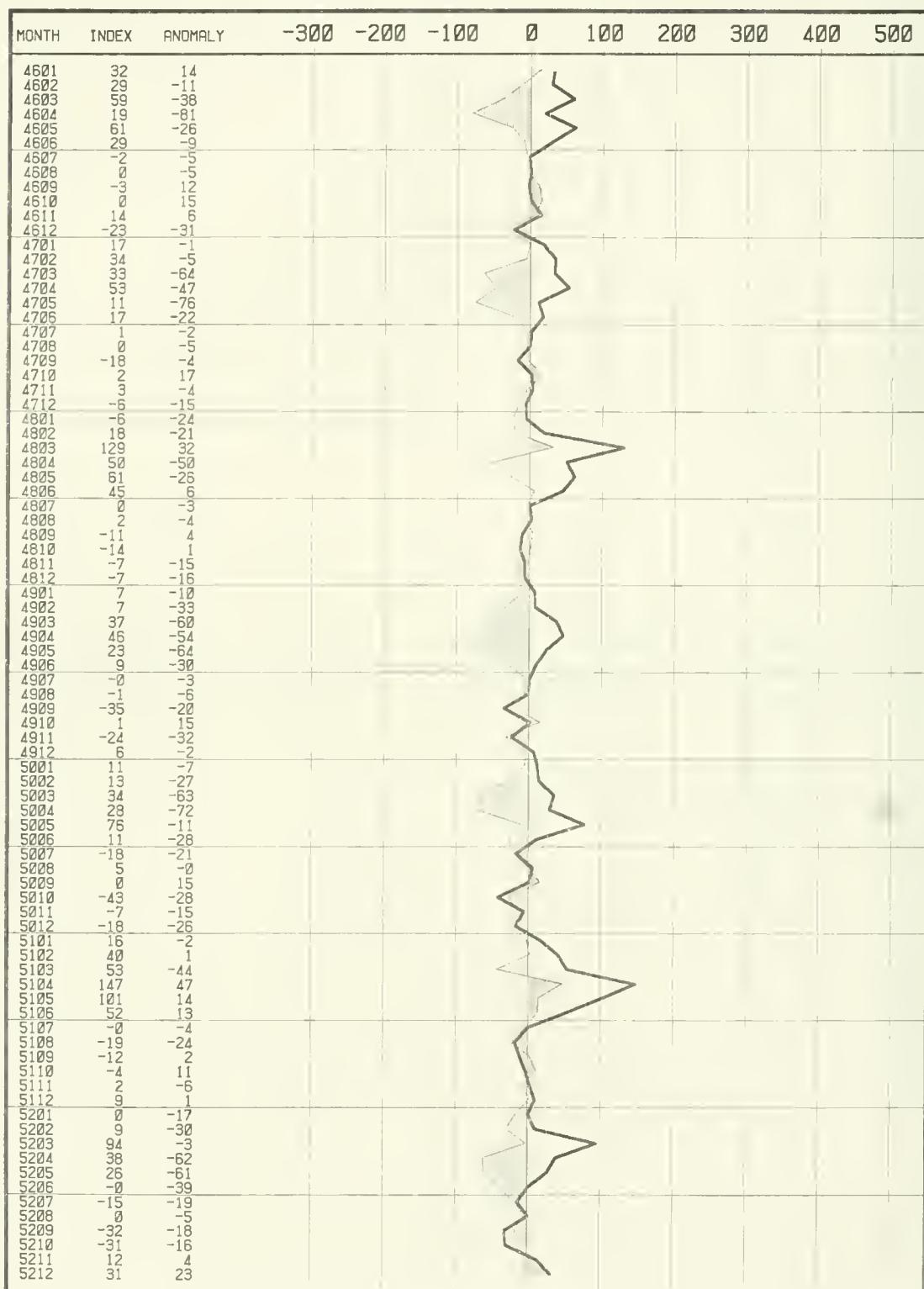


UPWELLING INDEX AT 24N, 113W BY YEAR

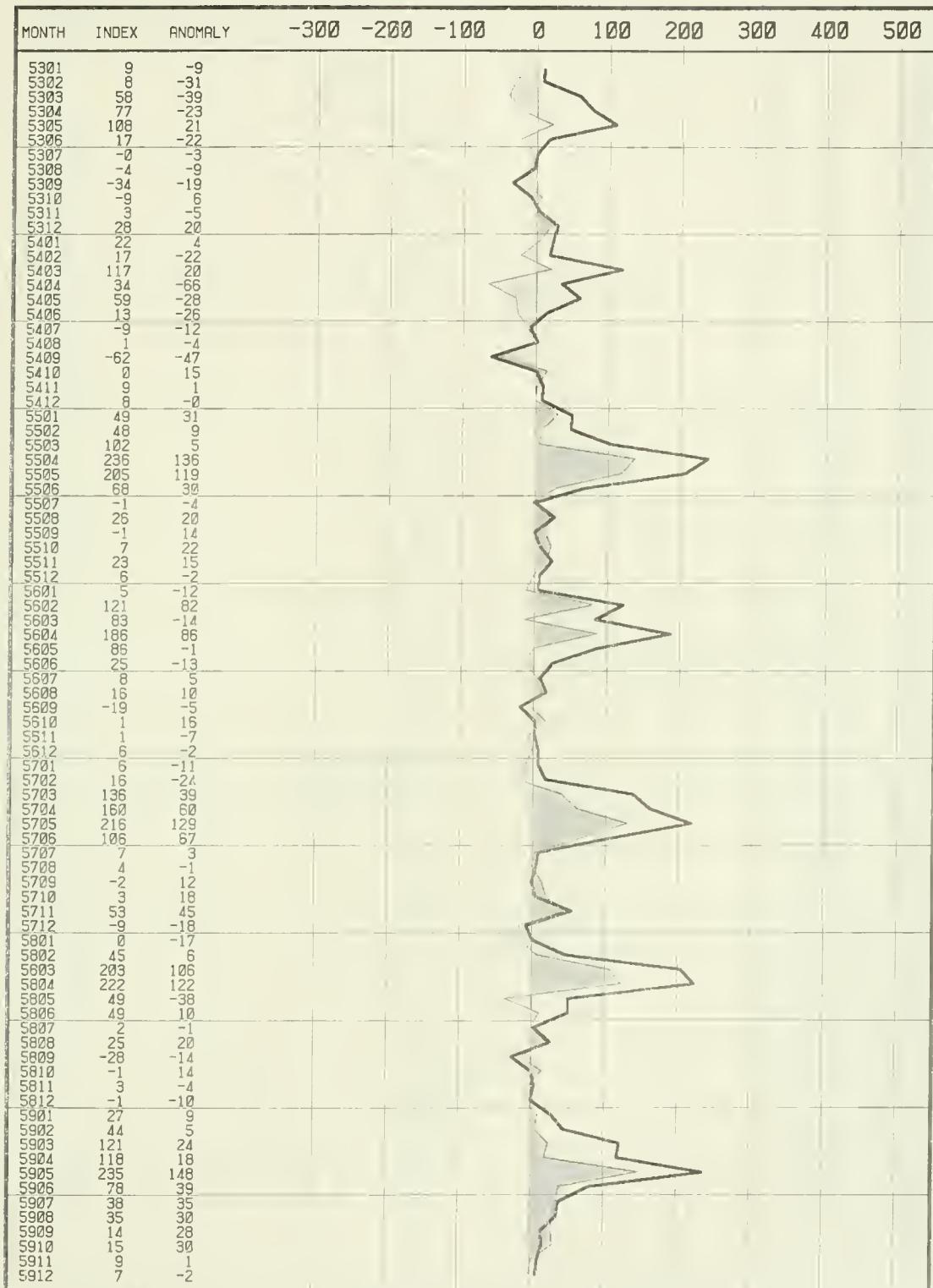


UPWELLING INDEX AT 21N, 107W

BY MONTH

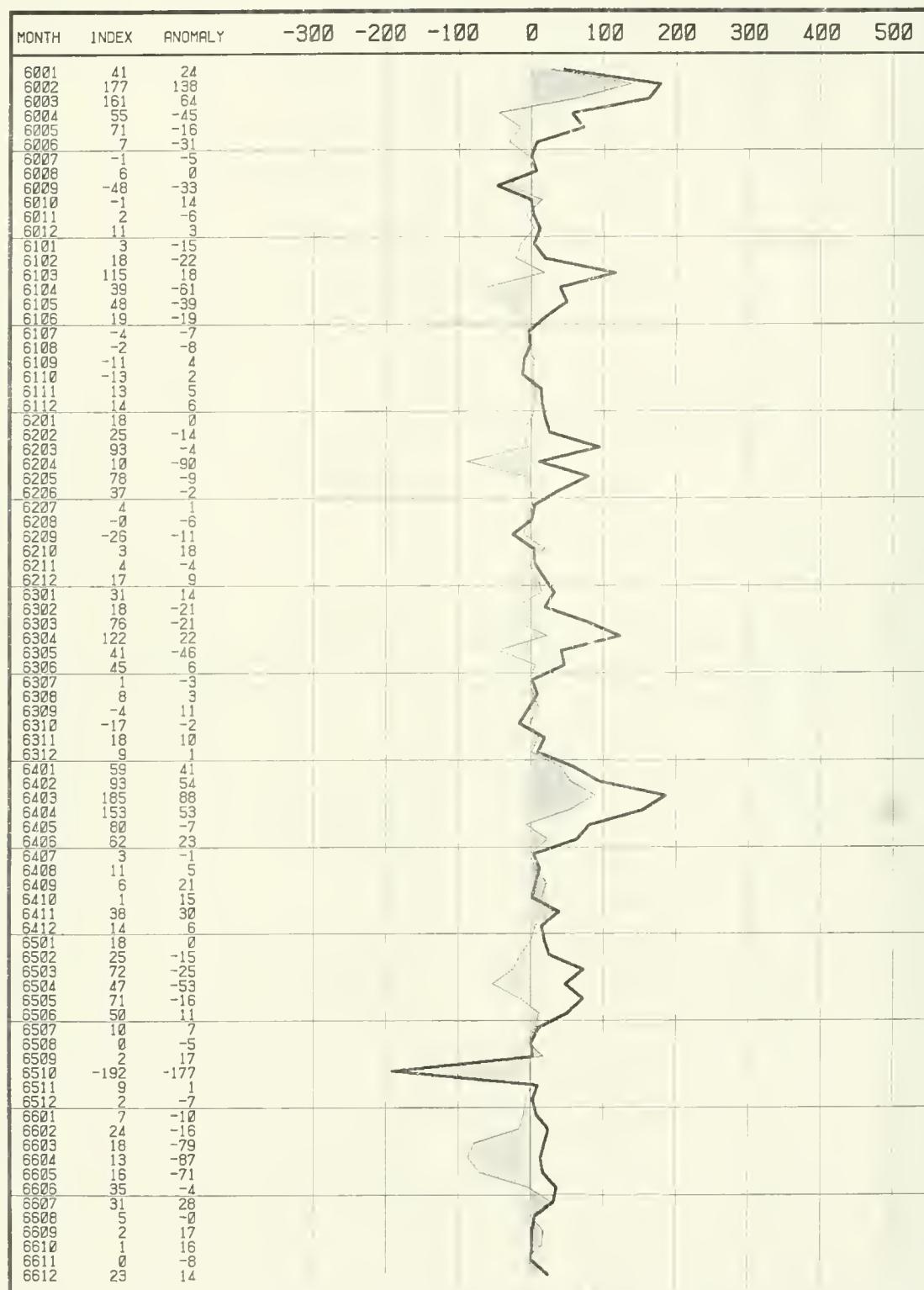


UPWELLING INDEX AT 21N, 107W BY MONTH



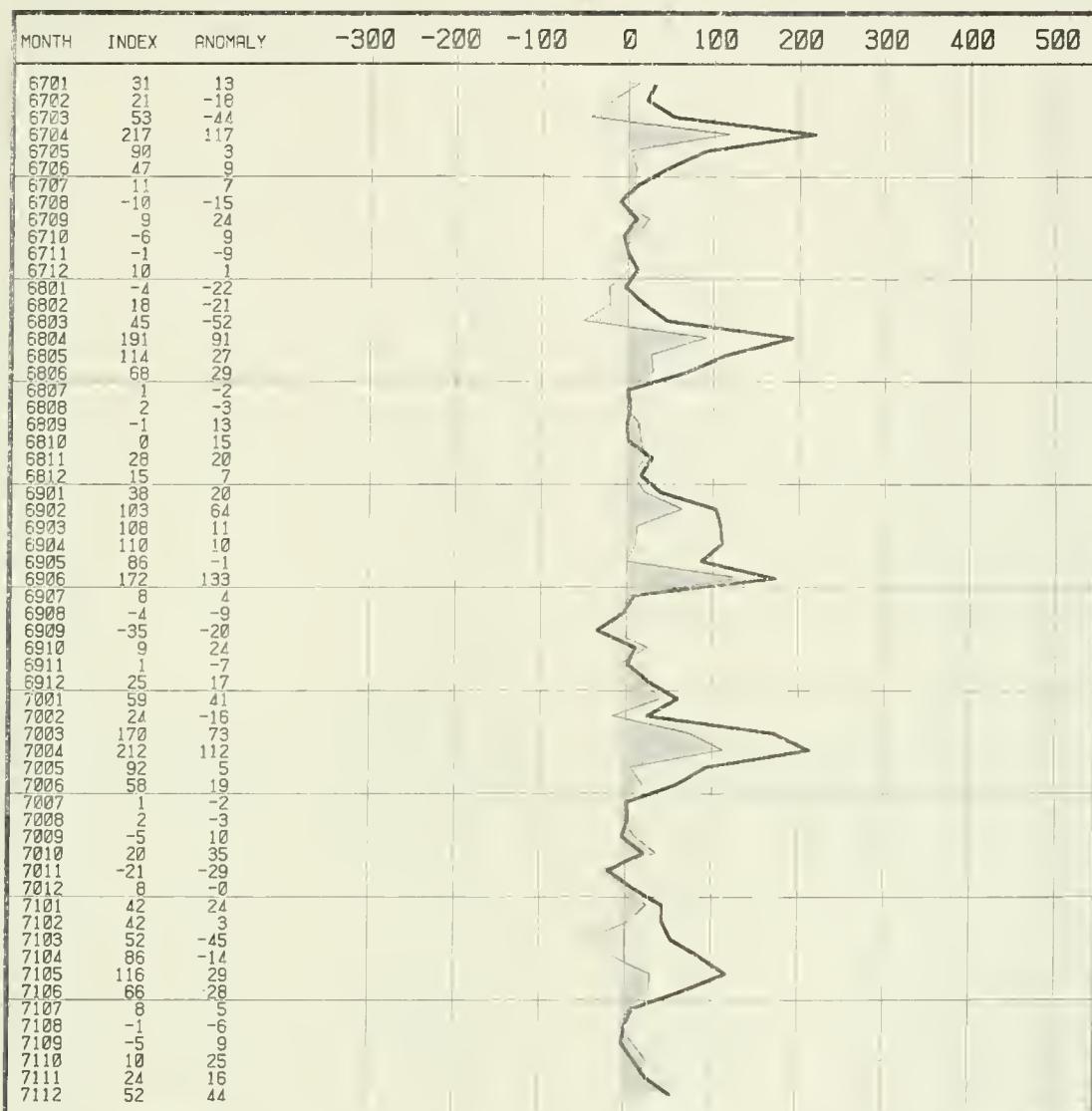
UPWELLING INDEX AT 21N, 107W

BY MONTH

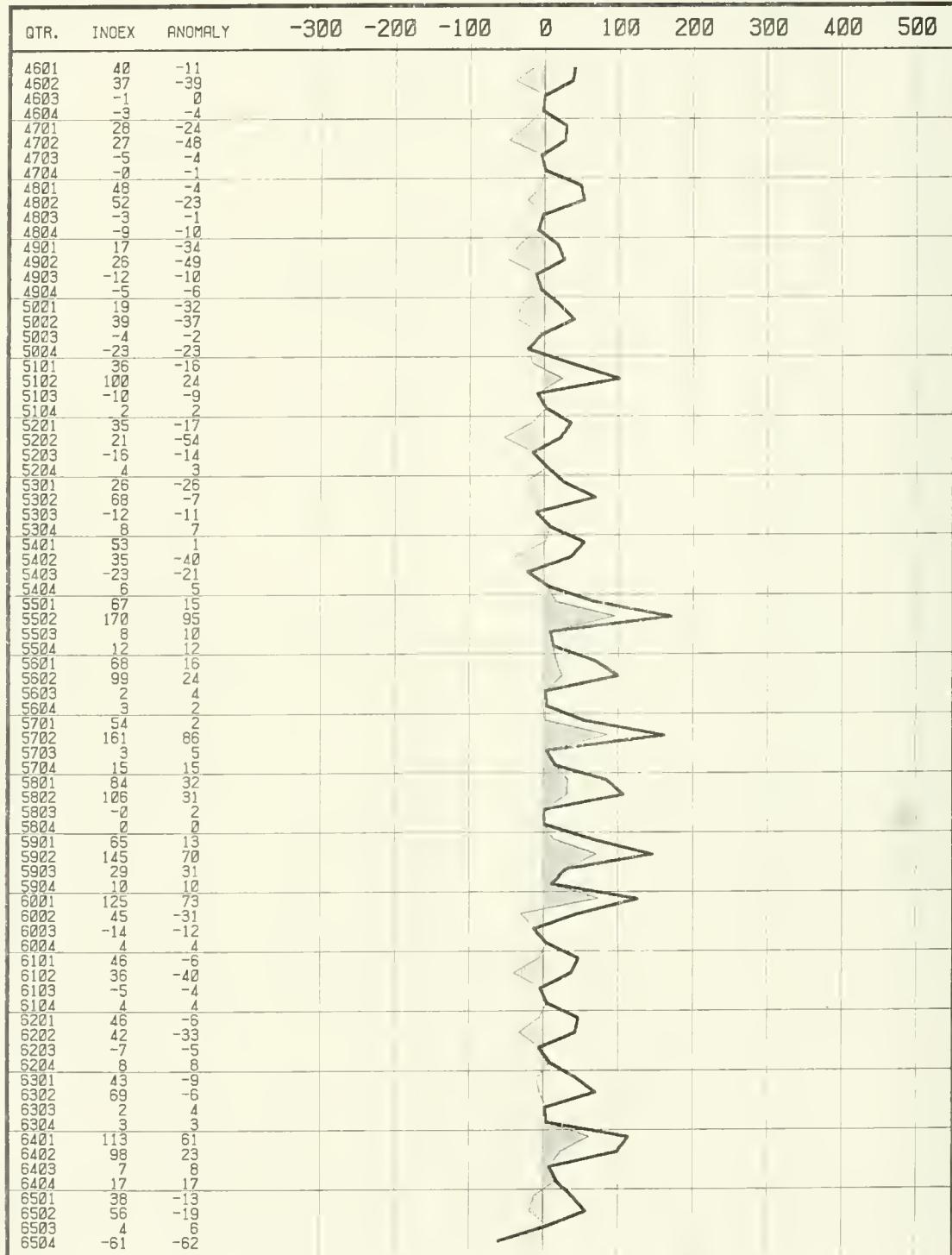


UPWELLING INDEX AT 21N, 107W

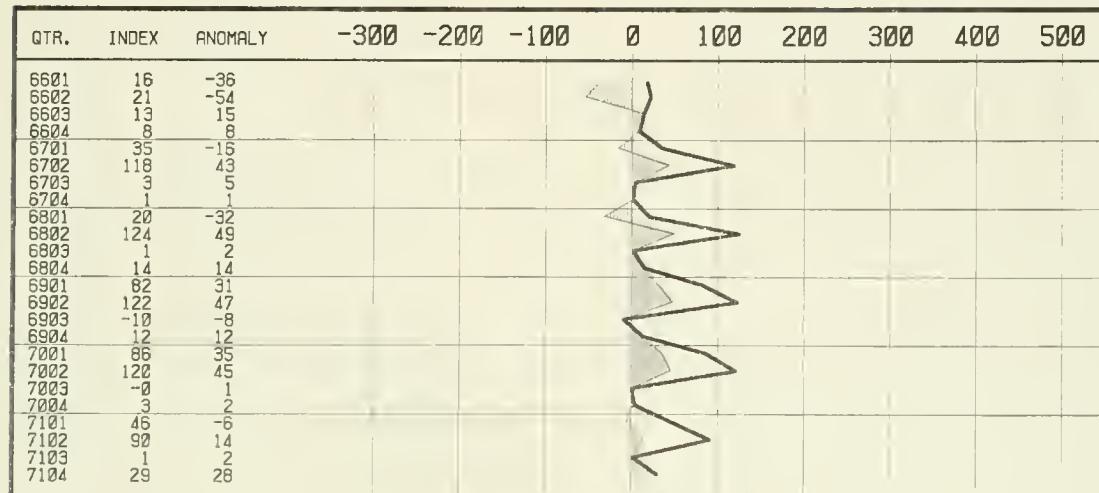
BY MONTH



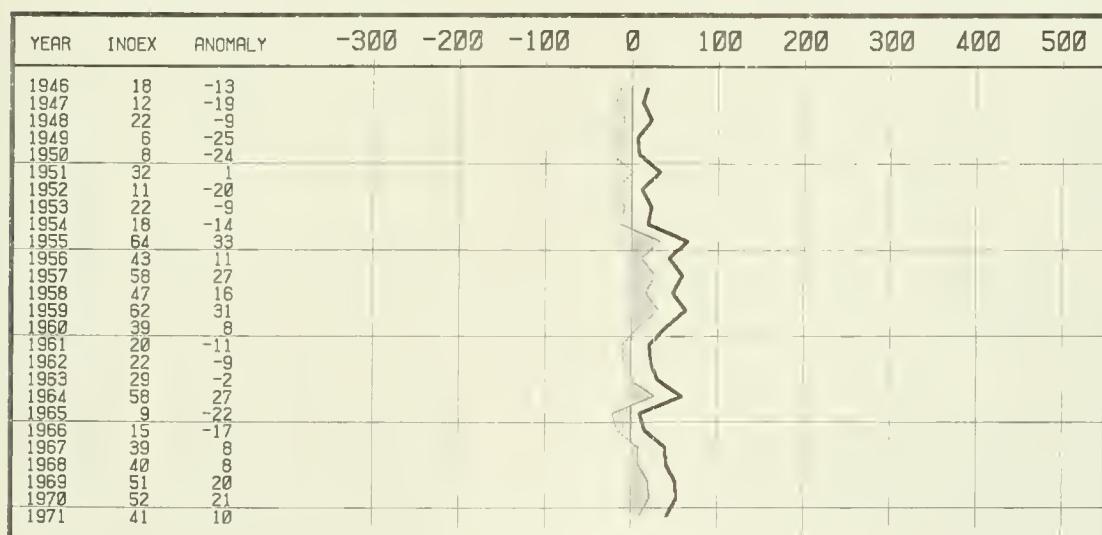
UPWELLING INDEX AT 21N, 107W BY QUARTER



UPWELLING INDEX AT 21N, 107W BY QUARTER



UPWELLING INDEX AT 21N, 107W BY YEAR





5 WHSE 01848

- 636 Oil pollution on Wake Island from the tanker *R. C. Stoner*. By Rinald M. Gooding. May 1971, iii + 12 pp., 8 figs., 2 tables. For sale by the Superintendent of Documents, U.S. Government Printing Office, Washington, D.C. 20402 - Price 25 cents.
- 637 Occurrence of larval, juvenile, and mature crabs in the vicinity of Beaufort Inlet, North Carolina. By Donnie L. Dudley and Mayo H. Judy. August 1971, iii + 10 pp., 1 fig., 5 tables. For sale by the Superintendent of Documents, U.S. Government Printing Office, Washington, D.C. 20402 - Price 25 cents.
- 638 Length-weight relations of haddock from commercial landings in New England, 1931-55. By Bradford E. Brown and Richard C. Hennemuth. August 1971, v + 13 pp., 16 figs., 6 tables, 10 appendix A tables. For sale by the Superintendent of Documents, U.S. Government Printing Office, Washington, D.C. 20402 - Price 25 cents.
- 639 A hydrographic survey of the Galveston Bay system, Texas 1963-66. By E. J. Pullen, W. L. Trent, and G. B. Adams. October 1971, v + 13 pp., 15 figs., 12 tables. For sale by the Superintendent of Documents, U.S. Government Printing Office, Washington, D.C. 20402 - Price 30 cents.
- 640 Annotated bibliography on the fishing industry and biology of the blue crab, *Callinectes sapidus*. By Marlin E. Tagatz and Ann Bowman Hall. August 1971, 91 pp. For sale by the Superintendent of Documents, U.S. Government Printing Office, Washington, D.C. 20402 - Price \$1.00.
- 641 Use of threadfin shad, *Dorosoma petenense*, as live bait during experimental pole-and-line fishing for skipjack tuna, *Katsuwonus pelamis*, in Hawaii. By Robert T. B. Iversen. August 1971, iii + 10 pp., 3 figs., 7 tables. For sale by the Superintendent of Documents, U.S. Government Printing Office, Washington, D.C. 20402 - Price 25 cents.
- 642 Atlantic menhaden *Brevoortia tyrannus* resource and fishery—analysis of decline. By Kenneth A. Henry. August 1971, v + 32 pp., 40 figs., 5 appendix figs., 3 tables, 2 appendix tables. For sale by the Superintendent of Documents, U.S. Government Printing Office, Washington, D.C. 20402 - Price 45 cents.
- 643 Surface winds of the southeastern tropical Atlantic Ocean. By John M. Steigner and Merton C. Ingham. October 1971, iii + 20 pp., 17 figs. For sale by the Superintendent of Documents, U.S. Government Printing Office, Washington, D.C. 20402 - Price 35 cents.
- 644 Inhibition of flesh browning and skin color fading in frozen fillets of yelloweye snapper (*Lutjanus vivanus*). By Harold C. Thompson, Jr., and Mary H. Thompson. February 1972, iii + 6 pp., 3 tables. For sale by the Superintendent of Documents, U.S. Government Printing Office, Washington, D.C. 20402 - Price 25 cents.
- 645 Traveling screen for removal of debris from rivers. By Daniel W. Bates, Ernest W. Murphrey, and Martin G. Beam. October 1971, iii + 6 pp., 6 figs., 1 table. For sale by the Superintendent of Documents, U.S. Government Printing Office, Washington, D.C. 20402 - Price 25 cents. Stock No. 0320-0016.
- 646 Dissolved nitrogen concentrations in the Columbia and Snake Rivers in 1970 and their effect on chinook salmon and steelhead trout. By Wesley J. Ebel. August 1971, iii + 7 pp., 2 figs., 6 tables. For sale by the Superintendent of Documents, U.S. Government Printing Office, Washington, D.C. 20402 - Price 20 cents.
- 647 Revised annotated list of parasites from sea mammals caught off the west coast of North America. By L. Margolis and M. D. Dailey. March 1972, iii + 23 pp. For sale by the Superintendent of Documents, U.S. Government Printing Office, Washington, D.C. 20402 - Price 35 cents.
- 648 Weight loss of pond-raised channel catfish (*Ictalurus punctatus*) during holding in processing plant vats. By Donald C. Greenland and Robert L. Gill. December 1971, iii + 7 pp., 3 figs., 2 tables. For sale by the Superintendent of Documents, U.S. Government Printing Office, Washington, D.C. 20402 - Price 25 cents.
- 649 Distribution of forage of skipjack tuna (*Euthynnus pelamis*) in the eastern tropical Pacific. By Maurice Blackburn and Michael Laurs. January 1972, iii + 16 pp., 7 figs., 3 tables. For sale by the Superintendent of Documents, U.S. Government Printing Office, Washington, D.C. 20402 - Price 30 cents. Stock No. 0320-0036.
- 650 Effects of some antioxidants and EDTA on the development of rancidity in Spanish mackerel (*Scomberomorus maculatus*) during frozen storage. By Robert N. Farragut. February 1972, iv + 12 pp., 6 figs., 12 tables. For sale by the Superintendent of Documents, U.S. Government Printing Office, Washington, D.C. 20402 - Price 25 cents. Stock No. 0320-0032.
- 651 The effect of premortem stress, holding temperatures, and freezing on the biochemistry and quality of skipjack tuna. By Ladell Crawford. April 1972, iii + 23 pp., 3 figs., 4 tables. For sale by the Superintendent of Documents, U.S. Government Printing Office, Washington, D.C. 20402 - Price 35 cents.
- 652 The use of electricity in conjunction with a 12.5-meter (Headrope) Gulf-of-Mexico shrimp trawl in Lake Michigan. By James E. Ellis. March 1972, iv + 10 pp., 11 figs., 4 tables. For sale by the Superintendent of Documents, U.S. Government Printing Office, Washington, D.C. 20402 - Price 25 cents.
- 653 An electric detector system for recovering internally tagged menhaden, genus *Brevoortia*. By R. O. Parker, Jr. February 1972, iii + 7 pp., 3 figs., 1 appendix table. For sale by the Superintendent of Documents, U.S. Government Printing Office, Washington, D.C. 20402 - Price 25 cents.
- 654 Immobilization of fingerling salmon and trout by decompression. By Doyle F. Sutherland. March 1972, iii + 7 pp., 3 figs., 2 tables. For sale by the Superintendent of Documents, U.S. Government Printing Office, Washington, D.C., 20402 - Price 25 cents.
- 655 The calico scallop, *Argopecten gibbus*. By Donald M. Allen and T. J. Costello. May 1972, iii + 19 pp., 9 figs., 1 table. For sale by the Superintendent of Documents, U.S. Government Printing Office, Washington, D.C., 20402 - Price 35 cents.

UNITED STATES
DEPARTMENT OF COMMERCE
NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION
NATIONAL MARINE FISHERIES SERVICE
SCIENTIFIC PUBLICATIONS STAFF
ROOM 450
1107 N E 45TH ST
SEATTLE WA 98105
OFFICIAL BUSINESS

FOURTH CLASS

POSTAGE AND FEES PAID
U.S. DEPARTMENT OF COMMERCE
COM-210



Marine Biological Laboratory S
Library - Periodicals
Woods Hole, Ma 02543